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DOCTORAL THESIS

Presented by

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Modeling of Energy Storage: Technical-Economic Investigation of Gravity Energy Storage

Presented on 03/11/2017 in Front of the Jury:

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Abstract- English

To address challenges associated with global climate change, several countries started restructuring their energy production systems. Policy makers are struggling to identify workable solutions to face the continuous increase of greenhouse gas (GHG) emissions. Alternative methods to the use of fossil fuels have been proposed to achieve sustainable energy systems; these include the development of renewable energy sources. This latter is projected to globally play a significant role in the energy portfolio. However, the increasing penetration of renewable energy in power systems entails several challenges due to the intermittent nature of these resources. Therefore, flexible options need to be implemented to overcome these issues. Examples of solutions include expansion of the electric grid, import and export of electricity, and management of the demand side. However, substantial interests in the deployment of energy storage technologies have been shown. These are mostly due to the increasing share of renewable energy systems, the need to balance the demand and supply of energy, as well as the high capital incurred for maintaining the reliability of power supply. The field of energy storage still requires more exploration and it is considered a subject of great interest for the development of renewable energy.

A well proven storage technology that is commonly used is pumped hydro storage (PHS). However, such a system needs specific height difference which is not always available. Based on the well-established concept of this storage system, several types of hydraulic energy storage systems are under development among them gravity energy storage. Research is needed to investigate the realization of such storage technology. This is addressed in this work by combining technical, economic and political approaches. Models have been developed to examine the different aspects of this storage system which include profitability, feasibility, operation, behavior, and performance. In addition, political considerations and barriers have been discussed to complements these approaches.

This thesis concludes that gravity energy storage is an attractive technology which offers interesting technical and economical perspectives. If energy storage is to play an effective role as part of a low carbon transition, research and development of new storage system is necessary. Barriers facing the development of such systems need to be considered.

Keywords: Energy Storage; Gravity; PHS; Modeling; Feasibility; Economics.

Abstract- French

Pour relever les défis associés aux changements climatiques, plusieurs pays ont commencé à restructurer leurs systèmes de production d'énergie. Les responsables politiques essaient d'identifier des solutions réalisables pour faire face à l'augmentation continue des émissions de gaz à effet de serre. Des méthodes alternatives à l'utilisation des combustibles fossiles ont été proposées pour obtenir un système d'énergie durable. Il s'agit notamment du développement des énergies renouvelables. On s'attend à ce que ces derniers jouent globalement un rôle important dans le portefeuille d'énergie. Cependant, la pénétration croissante des énergies renouvelables dans les systèmes électriques implique plusieurs défis en raison de la nature intermittente de ces ressources. Par conséquent, des options flexibles doivent être mises en œuvre pour surmonter ces problèmes. Des exemples de solutions comprennent : l'expansion du réseau électrique, l'importation et l'exportation d'électricité et la gestion de la demande d’énergie. Cependant, des intérêts substantiels dans le déploiement des technologies de stockage d'énergie ont été démontrés. Cela s'explique principalement par l’utilisation croissante des énergies renouvelable, la nécessité d'équilibrer la demande et l’alimentation électrique, ainsi que le capital élevé requis pour maintenir la fiabilité du réseau électrique. Le domaine du stockage de l'énergie nécessite encore plus d'exploration. Il est considéré comme un sujet d'un grand intérêt pour le développement des énergies renouvelables.

La Station de Transfert d'Energie par Pompage (STEP) est une technologie de stockage bien prouvée et couramment utilisée. Cependant, un tel système nécessite une différence de hauteur spécifique qui n'est pas toujours disponible. Sur la base de ce concept bien établi, plusieurs types de systèmes de stockage d'énergie hydraulique sont en cours de développement comme le système de stockage d’énergie par gravitation ‘Gravity Energy Storage’. Il est nécessaire d'effectuer des recherches pour étudier la réalisation d'une telle technologie de stockage. Ceci est abordé dans ce travail en combinant des méthodes techniques, économiques et politiques. Des modèles ont été développés pour examiner les différents aspects de ce système de stockage qui comprennent la rentabilité, la faisabilité, l'exploitation, le comportement et la performance du system. En outre, les obstacles politiques ont été discutés pour compléter ces approches.

Cette thèse conclut que le stockage de l'énergie par gravitation est une technologie attractive qui offre des perspectives techniques et économiques intéressantes. Si le stockage d'énergie doit jouer un rôle efficace dans le cadre d'une transition à faible émission de carbone, la recherche et le développement de nouveaux systèmes de stockage sont nécessaires. Les obstacles au développement de ces systèmes doivent être pris en considération.

Mots-clés: Stockage d'énergie; Gravité; PHS; Modélisation; Faisabilité; Économie.

Publications

The following publications have resulted from this dissertation in the academic literature with an overall impact factor of 47. Abstract of some papers is presented in Appendix F.

Journal Articles

1. A.Berrada, K.Loudiyi. I.Zorkani. Profitability, Risk, and Financial Modeling of Energy Storage in Residential and Large Scale Applications. **Energy Journal**.119 (2017), 94-109 (Elsevier).
2. A.Berrada, K.Loudiyi, I.Zorkani. Dynmaic modeling and Design consideration of Gravity Energy Storage. Journal of Energy System. **Journal of Cleaner Production**. 159 (2017) 336-345 (Elsevier).
3. A.Berrada, K.Loudiyi. Operation, sizing, and economic evaluation of storage for solar and wind power plants .**Renewable Sustainable Energy Rev**. 2016; 59: 1117–1129 (Elsevier).
4. A.Berrada, K.Loudiyi. R.Garde. Dynamic Modeling of Gravity Energy Storage Coupled with a PV Energy Plant. **Energy Journal**. 134 (2017) 323-335 (Elsevier).
5. A.Berrada, K.Loudiyi. I.Zorkani. Valuation of Energy Storage in Energy and Regulation Markets. **Energy Journal**. 115 (2016), 1109-1118, 10.1016/j.energy.2016.09.093 (Elsevier).
6. A.Berrada, K.Loudiyi, I.Zorkani. System Design and economic analysis of Gravity Storage. **Journal of cleaner production** 156 (2017) 317-326 (Elsevier).
7. A.Berrada, K.Loudiyi, I.Zorkani. Sizing and Economic Analysis of Gravity Storage. **Journal of Renewable and Sustainable Energy** 8 (2016), 024101 (American Institute of Physic AIP).
8. K.Loudiyi, A.Berrada, H. G.Svendsen, K. Mentesidi. Grid code status for wind farms interconnection in Northern Africa and Spain: Descriptions and recommendations for Northern Africa. **Renewable and Sustainable Energy Reviews Journal**. doi.org/10.1016/j.rser.2017.06.065 (Elsevier).

Conference papers:

1. A.Berrada, K.Loudiyi, I.Zorkani. Toward an Improvement of Gravity Energy Storage Using Compressed Air. 9th international conference on Sustainability in Energy and Building, Chania, Crete, Greece (Proceeding with Elsevier’s **Energy Procedia**)
2. K.Loudiyi, A.Berrada. Experimental Validation of Gravity Energy Storage Hydraulic Modeling. 9th international conference on Sustainability in Energy and Building, Chania, Crete, Greece (Proceeding with Elsevier’s **Energy Procedia**)
3. A.Berrada, K.Loudiyi. Modeling and Material Selection for Gravity Storage Using FEA Method.The fourth Edition of the International Renewable and Sustainable Energy Conference (IRSEC 2016). **IEEE Xplore**

4. K.Loudiyi, A.Berrada. Operation Optimization and Economic Assessment of Energy Storage. 2nd International Renewable and Sustainable Energy Conference. (IRESEC’14). Ouarzazate, Morocco. **IEEE Xplore**

5. A.Berrada,I.Zorkani, K.Loudiyi. Modeling the Operation of Grid Connected Energy Storage coupled with a Solar Farm.The Fifth Edition of the International Renewable and Sustainable Energy Conference (IRSEC 2017). **IEEE Xplore**. Accepted
6. A.Berrada, K.Loudiyi, I.Zorkani. Simulation and design for gravity power storage. Poster session presented at (E-MRS 2015) Spring Meeting, Lille, France.
7. A.Berrada, K.Loudiyi, I.Zorkani. Gravity Storage Design and Economic Modeling. Poster session presented at the international School Of Solid State Physics. Erice-Sicily, 13-19 July 2016

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Nomenclature

a: Diametric compression (mm).
A: Water conduit area (m²).
A_A: Area of chamber A (m²).
A_B: Area of chamber B (m²).
A_e area of the electrode;
A_O: Opening area of the valve (m).
A_T: Cross sectional area of the return pipe (m²).
b: Contact width (mm).
BOPc: Plant balance cost (€).
BOPU: Plant balance unit cost (€/kW).
C: Capacitance;
C_A: Effective compliance of chamber A.
C_B: Effective compliance of chamber B.
C_c: Storage capacity cost (€).
C_d : Energy storage degradation cost ($/MWh).
C_S : Energy storage costs ($)
Cost(t): Hourly costs of the hybrid farm
$C_{O\&M}$: Storage operation and maintenance cost in (€/kWh);
d: Diameter of the container & piston (m).
D: Mean diameter of of the O-ring.(mm).
D’: Inside diameter of the pipe (m),
D_c: Damping coefficient.
$d_{O:}$ Project operation delay (years)
D(t): Hourly energy demand in model X (kWh).
D’(t): Hourly energy demand in model Y (kWh).
d_e: Distance between the electrodes
d_S: Cross section diameter of the O-ring.(mm).
e: Relative roughness.
e_f: Regulator output.
E: Elastic modulus of the O-ring material (N/m²)
E_a Compressed air released energy (MWh).
E_c : Storage capacity.
E_D(t): Energy Discharged from the storage at t (W).
E_f : Friction losses.
$E_G(t)$: Energy Generated at time t.
$E_{h\,:}$ Hydraulic released energy (MWh).
E_K: kinetic energy
E_L: Capacity limit of the storage system (kWh).
$E_{max:}$ Maximum storage capacity (kWh).
E_0: Nominal fluid compressibility modulus (kPa).
$E_R(t)$: Energy sold/injected directly to the grid
E_S(t): Energy stored at time t (W).
$E_{t:}$ Total generated energy (MWh).
$E_{th:}$ Stored thermal energy
$E_w(p)$: Bulk modulus of the working fluid as a function of pressure.
$E_{AS}^{DA}(t)$: Energy offered to regulation service in day-ahead ancillary market (MWh).
$E_{AS}^{RT}(t)$: Energy offered to regulation service in real-time ancillary market (MWh).
$E_c^{DA}(t)$: Energy purchased at time t in day-ahead energy market (MWh).
$E_c^{RT}(t)$: Energy purchased at time t in real-time energy market (MWh).
$E_d^{DA}(t)$: Energy sold at time t in day-ahead energy market (MWh).
$E_d^{RT}(t)$: Energy sold at time t in real-time energy market (MWh).
f: Friction factor.
F_A: Pressure forces applied in chamber A (Pa).
F_B: Pressure forces applied in chamber B (Pa).
F_f: Friction force (N).
F_l: Hydraulic loss (N).
F_g: Gravitational force (N).
F_N: Force of the seal against the cylinder wall (N).
F_{net}: Net force on the water in the conduit (N).
F_S: Static friction (N).
g : Gravitational acceleration(m/s²).
G: Gate opening (m).
h: Head across the Turbine (m).
h_{base}:Base head (m).
H: Head at turbine gate (m).
H_d : Discharge head (m).

H_L: Head loss (m).
Hs: Static head (m).
h_{Lmajor}: Major hydraulic losses (Pa).
h_{Lminor}: Minor hydraulic losses (Pa).
H_P: Height of the piston (m).
H_C: Height of the Container (m).
H_t : Water head (Pa).
I: Channel Inductance ($Kg.m^2.s^{-2}.A^{-2}$)
I_c Current flowing through.
I_m: Moment of inertia
I_{stc}: Irradiance at STC (W/m²)
I: Discount rate.
J: Number of payments.
K: Replacement period.
K: Constant.
K_0: Coefficient of earth pressure at rest.
Ke: Feedback gain.
K_h is the specific heat.
K_L: Loss coefficient.
L: Water conduit length (m).
L(t): Energy demand (Load) at time t (W).
L_c/ self-inductance of coil;
L_f : Energy storage lifetime in cycles.
L_T: Length of the return pipe (m).
m: Piston mass (Kg).
m_r : Mass of the piston relative to the water (m/s²)
m_f : mass of the flywheel (kg)
n' : Number of storage replacement.
n : Number of periods (Years).
$O\&M_c$: Operation and maintenance costs (€).
$O\&MU$: Unit cost of operation and maintenance (€/Kwh).
P: Pressure (Pa).
P_S: Storage power (kW).
P_1 : Preset pressure (MPa).
P_2 Tank withstand pressure (MPa).
P_A: Pressure in chamber A (Pa)
P_B: Pressure in chamber B (Pa)
P_{Cp}: Power consumed by the pump in (W).
P_c : Power costs of the storage system (€).
P_d: Pressure at discharge (Pa).
$P_E(t)$: Hourly energy prices (€/kWh).
P_H: Pressure head (Pa).
Pi: Contact pressure due to the initial compression of the O-ring (Pa).
P_L: Energy storage power rating (MW).
Pm: Turbine mechanical power (W).
P_O: PHES generated power
P_{odn}: Reference pressure (Pa).
Pp: Peak nominal power based on 1kW/m² radiation at standard test condition (W).
Pr: Owner’s profit which must be maximized.
P_S: Suction pressure (Pa).
P_U: Useful power (W).
PU_c: Storage system’s power unit costs (€/kWh).
P_x: Pressure of air in the container (MPa).
$P_L(t)$: Power demand at time t; PD(t) is the power discharged from the storage system (W).
Pgrid (t): Power transferred from the grid to the load (W).
$P_S(t)$: Power stored from the PV system (W).
$PV(t)$: Hourly energy generated by the PV system in model X (kWh).
$PV'(t)$: Hourly energy generated by the PV system in model Y (kWh).
PV_{Rev} : Present value of revenue (€).
PV_{Cost} : Present value of cost (€).
P_x^i : Internal pressure at location x (Pa).
P_x^e : External pressure at location x (Pa).
$P^{DA}(t)$: Hourly energy price in day-ahead energy market ($/MWh).
$P^{RT}(t)$: Hourly energy price in real-time energy market ($/MWh).
$P_{AS}^{DA}(t)$: Hourly energy price in day-ahead ancillary market ($/MWh).
$P_{AS}^{RT}(t)$: Hourly energy price in real-time ancillary market ($/MWh).
Q: Flow Rate (m3/s)
Q’: Charge (c).

Q_A: Flowrates in chamber A (m$^{3/}$s).
Q_B: Flowrates in chamber B (m$^{3/}$s).
Q_{base}: Base flow rate (m$^{3/}$s).
Qv: Flow of water (m$^{3/}$s)
q_{nl}: No load flow.
R: Future replacement cost (€).
r_f : Radius of the flywheel (m)
R_T :Temporary drop.
Re: Reynolds number.
Rv : Flow resistance of the valve ((N/m^2)/(m^3/s)).
REP_c: Replacement of the storage system's cost (€).
R(t): Hourly revenues ($).
Rev(t): Hourly revenues of the hybrid farm ($).
s: Second (s)
Sr: Available solar radiation for a particular location (Wh/m^2)
S(t) Storage level (kWh) at time t (Wh).
S(t-1): Storage remaining energy at time (t-1) (Wh).
SG: Specific gravity of water.
$Saving(t)$: Hourly Revenues received by storage system (€).
SU_c: Storage system's capacity unit costs (€/kWh).
t: Time (s).
T': Recharge temperature;
Te: Time constant (s).
Tg: Pilot valve droop (s)
T_P: Pilot valve time constant (s)
Tr: Dashpot time constant (s)
T_R: Reset time (s)
Tw: Water time constant (s).
v Kinematic viscosity of water (Pa.s).
V: Volume of water (m^3)
v: Water velocity (m/s);
V': voltage (V);
V_1 Initial air volume (m^3).
V_2 Compressed air volume (m^3).
V_x Volume of air in the container (m^3).
$V_A(t)$: Volume at time t of chamber A(m^3).
$V_B(t)$:Volume at time t of chamber B (m^3).
$V_{A,0}$: Initial volume in chamber A (m^3).
$V_{B,0}$: Initial volume in chamber B (m^3).
V_{fd}: Exciter voltage (V).
V_S: Volume of the system (m^3);
W_C: Electrostatic energy;
$W_{L:}$ Coil stored energy;
Wp: Maximum power of each module at STC (W)
x_H: Specific location along the container height.
x_p: Piston position (m).
$\dot{x}_P$: Piston velocity (m/s).
$\ddot{x}_P$: Piston acceleration (m^2/s).
$X_c(t)$: Charging period at time t.
$X_d(t)$: Discharging period at time t.
$X_{Sell}(t)$: Energy exchange variables (kWh).
$X_{Buy}(t)$: Energy exchange variables (kWh).
$X_{sg}(t)$: Energy discharged from the storage system to electric grid in model *X* (kWh).
$X_{gs}(t)$: Energy stored from the grid in model *X* (kWh).
$X_{gl}(t)$: Energy transferred from the grid to the load inmodel *X* (kWh).
$X_{sl}(t)$: Energy exchanged between storage and load (kWh).
$X_{pg}(t)$: Energy exchanged between the PV system and the grid in model *X* (kWh).
$X_{pl}(t)$: Energy transferred from the PV system to the load in model *X* (kWh).
$X_{ps}(t)$: Energy transferred from the PV system to the storage in model *X* (kWh).
$X_{pg}(t)$: Energy transferred from the PV system to the grid in model *X* (kWh).
$Y_{Sell}(t)$: Energy exchange variables (kWh).
$Y_{Buy}(t)$: Energy exchange variables (kWh).
$Y_{sg}(t)$: Energy discharged from the storage system to electric grid in model *Y* (kWh).
$Y_{gs}(t)$: Energy stored from the grid in model *Y*.(kWh),.
$Y_{gl}(t)$: Energy transferred from the grid to the load in model *Y* (kWh).
$Y_{sl}(t)$: Energy discharged from the storage to the load in model *Y* (kWh).
$Y_{pg}(t)$: Energy exchanged between the PV system and the grid in model *Y* (kWh).
$Y_{pl}(t)$: Energy transferred from the PV system to the load in model *Y* (kWh).
$Y_{ps}(t)$: Energy transferred from the PV system to the storage in model *Y* (kWh).

$Y_{pg}(t)$: Energy transferred from the PV system to the grid in model Y (kWh).
y: Soil weight (Kg/m^3)
z: Elevation height (m).
α : Conversion coefficient.
δ : Self-discharge rate of the system.
ΔP_f : Contact pressure due to the system pressure difference (Pa).
η : Efficiency.
μ : Friction factor.
ε : Dielectric permittivity;
ξ : Inclination and orientation correction factor of the solar system (W).
ξ_o : Discharge coefficient.
ρ_p : Density of piston (kg/m^3).
ρ_N : Net present value factor
ρ_w : Density of water (kg/m^3).
ψ : Average dispatch to contract ratio (MWh/MW)
ω : Rotor speed (rmp).
ω_f :Flywheel speed (m/s)

List of acronyms

A Annuity.

CAES Compressed Air Energy Storage

CO2 Carbon Dioxide

GAMS General Algebraic Modeling

DoD Depth of discharge.

FV Future value

H2 Hydrogen

kW Kilowatt

kWh Kilowatt-hour

LCOE levelized cost of energy

LET Lifetime energy throughput (MWh).

MILP Mixed integer linear programming

MW Megawatt

MWh Megawatt-hour

NiCd Nickel Cadmium

NPV Net Present Value

NLP Non-Linear Programming

O&M Operation and Maintenance

PHES Pumped-Hydro Energy Storage

PV Present value.

T&D Transmission and Distribution

VRB Vanadium Redox Battery

Chapter 1

1. Introduction

1.1. Background

With the growing industrial development and the improvement in living standards, energy consumption has increased significantly in recent years [1]. Several countries are currently giving more attention to the development of renewable energy and to the strengthening of energy control and management [2]. Renewable electricity generation share is expected to increase up to 35% in 2050 from less than 10% in 2010 [3].With the rapid increase of renewable energy integration, the reliability of the electric grid is facing challenges in coping with the variability of these energy sources. To solve these issues, several solutions are investigated, among which the deployment of energy storage technologies. These latter have been identified as one of the enabling systems in supporting the grid operation [4]. Energy storage systems provide technical and economic benefits from generation, transmission and distribution to end user applications [5]. They enable flexibility in matching the demand profile to the supply of energy in terms of when and where energy is needed. Therefore, energy storage mitigates the intermittency of renewable energy systems and improves the reliability of the electric grid by providing multiple services [5].

Energy storage technologies are mainly classified into distributed and bulk energy storage systems. These latter are used to provide large storage capacity and are located in the transmission in order to deliver services in accordance with the grid needs. In spite of some major developments have been done for the distributed storage category [5,1], bulk energy systems still rely only on pumped hydro storage (PHS) and compressed air energy storage (CAES) [5-6].

Currently, the highly prevalent storage system worldwide is pumped hydro; with more than 120,000 MW [7]. The total installed capacity of this storage technology represents 99% of the global installed storage capacity [8]. The installed PHS capacity is expected to increase to about 20% by 2020 in Europe [9]. This storage technology has been commonly utilized for several years, and it is considered the most valuable energy storage [10]. This storage system is widely deployed worldwide and is used for the integration of renewables. Caralis demonstrates that pumped hydro is considered the most appropriate storage system for enabling high level penetration of wind energy [11]. Research has demonstrated that PHS is suitable for confirming the validity of renewable power sources [12]. In addition, substantial projects [13-14] have proven the feasibility of pumped hydro for remote renewable energy power supply. However, this system is still facing some challenges which include site unavailability and environmental issues.

The future development of PHS and CAES systems is limited and they both suffer from major drawbacks. Pumped hydro energy storage disadvantages include high capital cost, negative environmental impact, and limited geographical implementation. Compressed air energy storage is constrained by low efficiency compared to batteries, and limited availability of natural reservoirs located underground [15]. However, pumped hydro storage is considered one of the most popular energy storage due to its distinguished merits. It is economically viable and technically feasible in comparison with other energy storage technologies because of its long lifetime. The ratio of the storage capital cost/service life makes PHS attractive and commonly used worldwide [16]. Recently, alternative solutions similar to pumped hydro energy storage have drawn the attention of researchers and are of interest to both industry and academia. An interesting concept being considered is underground PHS. This technology realizes the height difference between the two reservoirs by going underground. The lower reservoir of the system could be constructed underground or it could make use of existing caverns and mines. Currently, there is no actual technology built due to technical and economical restraints of such project among them government reactance, construction risks, and long payback period [17]. Several projects are actually under initial phases of development. A conceptual underground pumped storage project is Elmhurst Quarry Pumped Storage Project (EQPS) in the City of Elmhurst, Illinois. This project utilizes an abandoned mine and quarry for its reservoirs [18]. Similar to EQPS, Riverbank Wisacasset Energy Center (RWEC) is another proposed PHS with a capacity of 1,000-MW located 2,200 feet underground in Wisacasset, Maine [19].

Another innovative technology is compressed air in a pumped hydro storage. This system has been studied by Delft University of Technology [20].This technology makes use of a pressurized water container as a replacement of the upper reservoir. Energy is stored in compressed air rather than in elevated water. As water is pumped into the pressure vessel, the air within this latter becomes pressurized [20]. This technology is less dependent on geographical requirements compared to PHS [21]. The Norwegian company Subhydro AS has proposed another promising concept know as undersea pumped hydro [22]. This concept is interesting for off-shore wind turbines. Undersea pumped hydro stores energy using water pressure on the bottom of the sea [23]. The outcomes of this study demonstrate that this system can be economically viable at depths as shallow as 200 m. The cost per megawatt hour of this storage system drops until 1500 m then it begins to trend upward [23]. Although this system has a great potential, it still needs further research related to the sphere construction. The significant undersea pressure needs to be handled by a thick layer of high strength concrete. However, with the advance of research in this field, such innovation may be turned into reality [20].

In 1999, the first sea water PSH, named Yanbaru, was built in Japan [23]. The concept of bottom mounted large structures for PSH was proposed by Morishige, at Mitsubishi Heavy Industries [24]. Others researchers proposed seafloor mounted PSH systems that could be implemented with offshore wind turbines [25-27]. However, none of these projects have moved forward due to impracticality. Ocean renewable energy storage (ORES) was proposed and studied at Massachusetts Institute of Technology [23]. The idea is to store energy underwater in spheres. Schmidt-Bocking and Luther, two German physicists, investigated a concept similar to (ORES). Their proposed system envisions storing 58,000 MWh with a sphere having 280 m diameter deployed under water in 2000m depth [28].

Different alternatives to the improvement of pumped hydro storage have been proposed. Instead of focusing on height difference or pressure, other studies did focus on water discharge rate (Q). Lievense and the Das brothers used a large closed off water area as pumped hydropower storage in Netherlands [29]. This system is known as pump accumulation station. Water level is raised by pumping it during excess power. In peak energy demand periods, energy is generated by running water through turbines [29]. Kibrit applied such project in an existing closed off area in Netherlands [30]. A similar system but operated in an inverse manner was developed by Boer (2007) and is still in research phase [31]. This system is known as "Energy Island"; it stores energy by lowering the water level instead of raising it. A comparable system, called "The Eleventh Province", is planned in Belgium [32]. Other concept designs were performed for Green Power Islands in India, Bahrain, China¸ Florida and Denmark [20].

Heindl (2013) proposed an original idea, known as "Hydraulic Rock", to overcome the height difference problem [33]. Instead of moving water up and down in a mountain, water is pressurized by a large piston in this concept. The idea consists of creating a rock piston by drilling a large circle in the ground. The piston is separated from the natural surrounding rock [33]. A small bored tunnel is needed to connect the underground space to the surface water. This study suggests the production of 1600 GWh storage capacity with a piston radius up to 500 m. This storage system is suitable for storing large amount of energy, in the range of multi-GWh. Although this technology is able to store an interesting amount of power, the construction of the connection between the surrounding structure and the piston is considered challenging [33].

A more recent study (Hanley) - investigated the construction stability of a similar system being proposed for development by Gravity Power, LLC [34]. Gravity energy storage is an interesting concept which uses the established principles of pumped hydro storage. This system is attractive due to its perceived site availability. It consists of a piston placed inside a container which is also filled with water. This latter is linked to a return pipe and to the powerhouse. To generate energy, water is forced to flow down the container as the piston drops. It then goes through the return pipe and spins the turbine which drives the generator to produce energy. In storage mode, the pump converts mechanical energy to kinetic flow energy; which makes the piston moves in the upward direction. This latter is driven by the motor which uses excess off-peak power. Oldenmenger (2013) conducted a feasibility study of such system in a tall building [35].

Unlike batteries, gravity energy storage is a sustainable ecofriendly system that has recently gained attention. This energy storage have been studied in many aspects, such as design and sizing studies [36], economic and risk analysis [35, 37, 38], as well as structural stability [39]. However, further research is needed to investigate the performance and the development of this storage technology.

1.2. Objective of the PhD project

This PhD project investigates an innovative energy storage concept, known as gravity energy storage. A number of aspects related to this storage technology have been analyzed including the system feasibility, design, profitability, value, application, development, risk and policies. The following studies were performed to achieve these objectives:

- Provide information on the “state-of-the-art” of energy storage systems.
- Optimally design gravity energy storage components while avoiding system failure.
- Maximize the owner profit from optimally sizing energy storage connected to a wind farm.
- Assess the potential benefits of energy storage providing energy and ancillary services.
- Study the profitability of energy storage in residential and large scale applications.
- Identify gravity energy storage levelized cost of energy and compare it to other energy storage options.
- Study the different risks associated with this innovative storage concept.
- Examine the value of energy storage in electricity market.
- Develop a complete mathematical model for gravity energy storage coupled with a PV energy plant and implement it in Matlab/Simulink environment. This also entails developing a hydraulic model.
- Conduct a simulation study of the proposed system to investigate the system dynamic behavior.
- Validate the Simulink hydraulic model by the available experimental tests.
- Propose and study an improvement to gravity energy storage technology.
- Investigate policies and barriers which hinder the development of energy storage systems.

1.3. Thesis outline

This thesis is divided into nine chapters as briefly described below:

Chapter 1 provides a general introduction and background. The objectives of the research project are also presented. Chapter 2 gives an overview about energy storage technologies, and their current status worldwide. It also provides a brief discussion about renewable energy and energy storage in Morocco. Chapter 3 proposes a technical design and material selection for gravity energy storage components. In addition, a mathematical model is developed to optimally size an energy storage system based on a specific energy production while satisfying all constraints. In chapter 4, an economic analysis is performed to determine the levelized cost of energy (LCOE) for this technology and compare it to other storage solutions. It also value energy storage participating in energy and ancillary markets. In chapter 5, the economic viability of energy storage in different grid applications has been examined. In addition, a risk study has been conducted to investigate whether the development of this innovative gravity storage system would be feasible. Chapter 6 presents the dynamic modeling of gravity energy storage mechanical and hydraulic components to gain insight into the system performance. The simulation outcomes have been compared to experimental results to validate the proposed model. Chapter 7 analyses the feasibility of combining compressed air with gravity storage. In addition to the technical and economic aspects investigated in this work, policies and market barriers are also examined in chapter 8. Chapter 9 concludes this thesis and presents recommendations for further research.

References:

[1]. Mahlia T, Saktisahdan T, Jannifar A, Hasan M, Matseelar H. A review of available methods and development on energy storage; technology update. Renew Sustain Energy Rev 2014;33:532–45.

[2]. Ferreira HL, Garde R, Fulli G, Kling W, Lopes JP. Characterization of electrical energy storage technologies. Energy 2013;53:288–98.

[3]. IEA. Technology roadmap. Energy Storage 2014:37-8.

[4]. Zhao H, Wu Q, Hu S, Xu H, Rasmussen CN. Review of energy storage system for wind power integration support. Appl Energy 2015;137:545–53

[5]. Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Appl Energy 2015;137:511–36

[6]. Hameer Sameer, van Niekerk Johannes L. A review of large-scale electrical energy storage. Int J Energy Resour 2015;39:1179–95.

[7]. Launchpnt, 2015. Gravity Power Grid-Scale Electricity Storage System.[Online].Available: http://www.Launchpnt.com

[8]. Rastler, D., Electricity energy storage technology options: a white paper primer on applications, costs, and benefits. USA: Electric Power Research Institute (EPRI), Technical Update; 2010.

[9]. Punys P, Baublys R, Kasiulis E, Vaisvila A, Pelikan B, Steller J. Assessment of renewable electricity generation by pumped storage power plants in EU Member States. Renew Sustain Energy Rev 2013;26:190–200.

[10]. Saini, RP., Large-scale energy storage systems. Indian Institute of Technology Roorkee; 2011.

[11]. Caralis G. Hybrid systems (Wind with pumped storage). International Conference: RES & Energy Savings in Islands, local planning and European cooperation, 23, 24 & 25 October 2009, Milos.

[12]. Papaefthymiou SV, Papathanassiou SA. Optimum sizing of wind-pumpedstorage hybrid power stations in island systems. Renewable Energy 2014;64:187–96.

[13]. Manolakos D, Papadakis G, Papantonis D, Kyritsis S. A stand-alone photovoltaic power system for remote villages using pumped water energy storage. Energy 2004;29:57–69.

[14]. Li Y, Yang M, Zhao L, Wang F. The research of wind-light complementary based on pumped storage power system. Adv Mater Res 2012;354–355:1132–6.

[15]. Sciacovelli A, Vecchi A, Ding Y. Liquid air energy storage (LAES) with packed bed cold thermal storage –From component to system level performance through dynamic modelling. Applied Energy 190 (2017) 84–98.

[16]. Locatelli G, Invernizzi DC, Mancini M., 2016.Investment and risk appraisal in energy storage systems: a real options approach. Energy104:114e31.

[17]. Pickard, W. F. (2012). The History, Present State, and Future Prospects of Underground Pumped Hydro for Massive Energy Storage. Proceedings of the IEEE, 100(2), 473-483. doi: 10.1109/JPROC.2011.2126030

[18]. Mansoori A G, Enayati N, Agyarko B L. Energy: sources, utilization, legislation, sustainability, Illinois as model state. World Scientific Publishing Co. Pte. Ltd.(2016).

[19]. ESA. Sub-Surface Pumped Hydroelectric Storage. Available at: http://energystorage.org/energy storage/technologies/sub-surface-pumped-hydroelectric-storage

[20]. Berchum, E.V. 2014 Pumped Hydro Storage: Pressure Cavern Large-scale Energy Storage in Underground Salt Caverns (Master's thesis). Retrieved from TU Delft Repositories.

[21]. Hendriks. M,.2016 Local Hydroelectric Energy Storage. A feasibility study about a small scale energy storage system combining. hydropower,gravity power, spring power and air pressure. (Master's thesis). Retrieved from TU Delft Repositories.

[22]. SINTEF. 2013. Storage power plant on the seabed. ScienceDaily. Retrieved January 1, 2017 from www.sciencedaily.com/releases/2013/05/130515085343.htm

[23]. Slocum, A. H., Fennell, G. E., Dundar, G., Hodder, B. G., Meredith, J. D. C., Sager, M. A., 2013. Ocean Renewable Energy Storage (ORES) System: Analysis of an Undersea Energy Storage Concept. in Proceedings of the IEEE, vol. 101, no. 4, pp. 906-924.

[24]. Morishige, H., Japanese Patent 2755778 (expired)

[25]. Parker, M., PCT patent publication WO 2009/111861 A1

[26]. W. Walters US patent publication 2005/0271501 A1

[27]. Pirkey US Patent 2,962,599

[28]. Faz.In der tiefe der mere: Hohlkugeln speichern uberschussigen Windstrom-Umwelth & Technik-FAZ.[Online]. Available : http://www.Faz.net/aktuell/technick-motor/umwelt-technik/in-der-tiefe-der-meere-Hohlkugeln-speichern-uberschussigen-Windstrom-1680112.html.

[29]. Hendriks. M,.2016 Local Hydroelectric Energy Storage. A feasibility study about a small scale energy storage system combining. hydropower,gravity power, spring power and air pressure. (Master's thesis). Retrieved from TU Delft Repositories.

[30]. Kibrit, B. (2013). Pumped Hydropower storage in the Netherlands (Master Thesis). Delft: TU Delft.

[31]. Boer, W. W. (2007). The Energy Island - An Inverse Pump Accumulation Station. Arnhem: DNV KEMA Consultin, Lievense BV.

[32]. Kusteilanden. 2016. kusteilanden, eilanden voor de kust. Retrieved from http://kusteilanden.be/

[33]. Heindl, E. (2013). Hydraulic Rock Storage An innovative energy storage solution for 24 h energy supply. Retrieved from http://www.heindl-energy.com/

[34]. Gravitypower. 2011. Gravity Power Module. Energy Storage. Grid-Scale Energy Storage. Available at: http://www.gravitypower.net/

[35]. Oldenmenger, W.A. (2013). Highrise energy storage core: Feasibility study for a hydro-electrical pumped energy storage system in a tall building (Master's thesis). Retrieved from TU Delft Repositories.

[36]. Berrada, A., Loudiyi, K., Zorkani, I., 2017a. System Design and economic performance of gravity storage. J.Clean. Prod. 156, 317-32

[37]. Berrada, A., Loudiyi, K., Zorkani, I., 2016. Valuation of Energy Storage in Energy and Regulation Markets. Energy 115, 1109-1118, 10.1016/j.energy.2016.09.093

[38]. Berrada, A., Loudiyi, K., Zorkani, I., 2017b. Profitability, risk, and financial modeling of energy storage in residential and large scale applications. Energy 119, 94-109

[39]. Tarigheh, A., 2014. Master thesis: Gravity Power Module. (Master Thesis), Delft University of Technology, Delft.

Chapter 2

2. Energy Storage Technologies

Energy storage has become an essential part of today's electricity value chain because of the increasing development of variable renewable energy sources, the need to shift away from fossil fuel resources, and the obligation to reduce greenhouse gas emission. Supply and demand of energy has to be balanced to ensure proper functioning of the electricity system. The energy demand fluctuates on a temporally basis and reaches its maximum in certain hours during the day. Therefore, in order to meet the maximum energy demand, the electricity system requires enough power. To overcome this issue, flexible generation in combination with energy storage should be used to maintain the demand-supply balance.

2.1. Overview of Energy Storage Technologies:

The increasing penetration of variable renewable energy technologies and the growth of distributed generation are changing the way the electric grid has to be operated. Yet, because of the high share of intermittent renewable energy such as solar and wind generation, the electricity system will be stressed in the case of extreme events. Energy storage systems are considered the key to enabling the integration of large amounts of intermittent renewable energy generation. Energy storage systems have the ability to store and discharge energy when needed. They play a major role in mitigating the challenges related to the variability of renewable energy generation in the electricity system. Furthermore, they are also important in optimizing the financial and the physical functioning of the plant. An overview of the different energy storage technologies and their status is discussed in this chapter.

2.1.1. Pumped hydro storage

The most widely used large scale energy storage technology worldwide is pumped hydro energy storage. It is a reliable storage option that has been in development since the 1920s [1]. The global installation of large scale energy storage consists of more 99% of PHS [2]. This technology uses elevation changes to store excess energy for later use. The system consists of two reservoirs at different elevations. PHS is a means of storing off-peak energy from the grid, and discharging it during peak demand periods. In the charging mode, surplus energy is used to pump water to the upper reservoir. When electricity is needed, this stored water is released. It flows back to the lower reservoir passing through a turbine which spins the generator producing electrical energy. The height difference between the two reservoirs and the volume of the stored water determines the amount of energy stored. Pumped hydro energy storage system has many advantages over other storage options. It is attractive and readily available as it uses the power of water. In addition, it is a cost-effective and efficient technology. This technology provides reliable energy within a short period of time with an efficiency of 65–85% depending on its scale [3]. The expected lifetime of this system is around 60 years [4]. This technology is also characterized by its low

operation and maintenance and lack of cycling degradation [5]. In addition, it responds to load change within seconds. The major limitations of pumped hydro storage include the need for an appropriate site, long construction time, high capital cost, and environmental concerns. Current researches focus on developing innovative concepts similar to PHS that are able to reduce the aforementioned problems faced by this technology. Such systems include seawater PHS, sub-sea PHS, variable speed PHS, underground PHS, hydraulic rock storage, and pump accumulation stations [6].
The power output of pumped hydro storage follows the basic fluid power equation which is expressed as:

$$P_O = QH\rho_W g\eta \qquad (2.1)$$

Where P_O is the generated power; Q is the flow rate, ρ_W is the water density; H is the hydraulic head height; g is the gravitational acceleration; and η is the efficiency.

2.1.2. Compressed air energy storage

Compressed air energy storage technology has been commercially developed since the late 1970s [7]. This technology is considered the leading alternative to pumped hydro [8]. Compressed air energy storage is also used for commercial applications; CAES system can be developed for small to large scale applications. This system stores energy in the form of high pressure air. Excess electricity, during low energy demand periods, is used to drive a generator which runs a chain of compressors for injecting air into a storage vessel. During peak demand periods, a heat source is used to heat the stored compressed air which is then captured by the turbines. The heat source comes from the combustion of fossil fuel or from the heat recovered from the compression process. The exhaust waste heat can be recycled by a recuperation Unit [9]. Several attractive characteristics are shared between the two energy storage systems. Some of these qualities include high capacity which ranges from 2 h to more than 50 h, large power capacity around 300 MW, over a year of storage period, quick start-up operation of about 12 min and only 9 min in case of emergency, and good efficiency which ranges between 60% to more than 80 % [10]. CAES has an expected life time in the range of 20 to 40 years [6]. Compressed air energy storage suffers from similar issues as pumped hydro; which include dependence on geography, and low energy density of about 122 KWh/m^3 [11,12]. Locating a suitable geographical site for the implementation of CAES is one of the most important barriers facing this technology. Power plants that are close to aquifers, salt caverns, rock mines, or depleted gas fields are economically feasible. However, some dissimilar qualities make these aforementioned storage systems very different. Compressed air energy storage has a lower capital cost of about $400–800/kW compared to pumped hydro. In addition, only a small impact to the surface environment is caused by CAES; because the storage is mostly located underground [11,13]. CAES is not considered a carbon neutral technology as it uses natural gas in its operation. Finally, CAES has only a limited ability to quickly change output generation as compared to pumped hydro storage [11,13].

The CAES technology provides several benefits to the power system. It has the ability to balance the intermittent wind power, and can ease problems caused by the unpredictability and variability of wind generation. It is considered a reliable solution to the system operators. The combination of wind power with compressed air energy storage; increases the overall value of renewable energy firm. CAES can be adapted for use in large-scale facilities, as well as in distributed and small-scale operations [14]. Compressed air energy storage has not been widely used. It is expected to become more attractive; due to the high penetration of renewable energy systems, and the need to have flexibility in the power system. A new type of compressed air energy storage that is currently attracting attention is the advanced adiabatic CAES which integrates a thermal energy storage system and does not require fuel combustion in the expansion mode [9]. Improvements of this technology have been proposed or are under research; these include compressed air storage with humidification (CASH), and small-scale CAES with fabricated small vessels, etc [14].

2.1.3. Flywheel energy storage

Flywheel is an attractive storage technology that is slowly penetrating the energy market. This technology is among the earliest mechanical energy storage technologies. This system stores energy mechanically in the form of kinetic energy. It has high efficiency of about 90-95%, long lifetime which ranges from 15 to 20 years and long life cycle (10,000–100,000) [11, 15, 16]. However, the technology has a high capital cost of about \$1000–5000/kWh, and high daily self-discharge rate of 50% to 100% [16]. Flywheel systems are mainly used for large capacity application and high power output. Hence, these systems are only an effective storage option for short-term, rapid-response, and reliable and standby power. At the moment, electromechanical batteries are mainly deployed to increase and regulate the quality of the current. They are also used to improve the quality of supply when renewable energy production is on the threshold of demand.

Flywheel energy is in the form of rotational kinetic energy. It could be expressed as Eq.2. 2:

$$E_K = \frac{1}{2} I_m \omega_f^{\,2} \text{ with } I = \frac{1}{2} m_f r_f^{\,2} \tag{2.2}$$

Where E_k is kinetic energy; I_m is the moment of inertia, ω_f is the flywheel speed, m_f and r_f are the mass and the radius of the flywheel, respectively. Increasing the speed of the flywheel and its movement of inertia increases the energy production.

2.1.4. Capacitors and Super capacitors

Capacitors store energy by accumulating negative and positive charges [14]. The charging process of capacitors is significantly faster than batteries, but they have low energy density. Capacitors can be cycled more than 100,000 times and have a lifetime of approximately 5 years. Their cycle efficiency ranges between 60% and 70% [11]. The typical use of capacitors in power systems includes harmonic protection, power factor correction, and voltage and VAR support.

Super capacitors are also referred to as ultracapacitors, electric double-layer capacitor and electrochemical capacitors [17]. This technology stores energy in an electric field rather than in a chemical reaction. Hence, it can have much more lifetime cycles than a battery. The first super capacitors were developed in the late 1950s using plates made up of activated charcoal. Since then, progress in science has led to an improvement in the material used. Yet, more effective plates have been developed using carbon nanotubes, barium titanate, and grapheme materials.

Super capacitors have several similar features as capacitors, but have various dissimilarities. They have high cycle lifetime (8-10 years), high power density, and high efficiencies of about 90-95% [10]. In addition, they are quickly rechargeable as they require no chemical reactions, and have excellent low-temperature charge and discharge performance. However, compared to other storage technologies, they are relatively expensive, and have a high self-discharge. The daily loss of charge is approximately 5% [18].

This storage technology differs from a battery in that it can store a higher amount of energy. However, this energy is stored for a shorter period of time; unlike batteries which can deliver and store energy over a longer period. Super capacitors significantly improve power qualities of renewable energy power systems. This is due to their absorption of high-frequency power variations, produced from these energy sources [18]. For applications that require high bursts of power, super capacitors are considered a good storage option.

The energy stored in capacitor is dependent on the voltage across the electrodes and the system capacitance (See Eq. 2.3). By increasing the surface area of the electrode, or by decreasing the distance between electrodes, the capacity of the system could be increased.

$$\begin{cases} Wc = \frac{1}{2}CV'^2 = \frac{1}{2}Q'V' \\ Q' = CV' \\ C = \frac{\varepsilon A_e}{d_e} \end{cases} \tag{2.3}$$

Where W_C is the electrostatic energy; C is the capacitance; V’ is the voltage; Q’ is the charge; ε is the dielectric permittivity; A_e is the area of the electrode; and d_e is the distance between the electrodes.

2.1.5. Batteries

Batteries work by converting chemical energy to electrical energy through reduction and oxidation reactions. There are diverse types of batteries, each having its own distinct features. The specific application is the key to deciding which type is best to use. Batteries are more expensive than many other energy technologies, on a per-kW basis, and can pose environmental hazards. However, they have the advantages of being rapidly responding, small, non-emitting, and quiet [8]. This makes them suitable for smoothing renewable energy resource fluctuations in the grid. The battery characteristics are subject to change in the future because of the rapid technological progress. Some batteries are described in this section. However, there are many other types of batteries in existence, or in development.

2.1.5.1. Lead-acid batteries

Lead acid is considered the oldest rechargeable battery for residential and commercial applications as it has been used for more than 130 years [10]. It is not widely used for commercial applications because of the limitations it has compared to other high energy density and efficiency batteries [3]. Lead–acid batteries have a low cycle life ranging between 2000 and 2500, a round trip efficiency of 70–90%, and an expected lifetime of 5 to 15 years [6]. They are mainly used in automotive starting, uninterruptible power supplies, lighting and ignition because of their cost [6]. In the charged state, the electrodes of lead acid battery consist of lead metal and lead oxide, while the electrolyte is composed of about 37% of sulphuric acid. In the discharged state, both electrodes become lead sulphate and the electrolyte loses sulphuric acid and turns into water. There are numerous types of lead acid batteries such as the flooded battery, the sealed maintenance free battery with a gelled/ absorbed electrolyte, and the valve regulated battery [1]. The current focus of research and development of lead–acid batteries involves improving their performance; by the use of innovating materials, in order to extend the storage number of cycles and enhance their deep discharge capability. In addition, some researches aim to incorporate this battery in applications involving renewable energy technologies and automotive sectors [9]. Currently, advanced lead–acid batteries are being developed, and some are in the demonstration phase such as: Ecoult Ultra Battery smart systems and Xtreme Power advanced lead–acid "Dry Cell" [9].

The positive and negative electrodes of lead acid battery consist of Pb, and PbO2, respectively. The electrolyte solution is made up of H_2SO_4. The electrochemical reaction which takes place in lead acid battery is expressed in Eq. 2.4:

$$Pb + 2PbO_2 + 2H_2SO_4 \longleftrightarrow 2PbSO_4 + 2H_2O \tag{2.4}$$

$PbSO_4$ is produced during the discharging process with a release of water. The chemistry process which occurs during the charging and discharging of lead acid batteries is shown in Fig. 2.1.

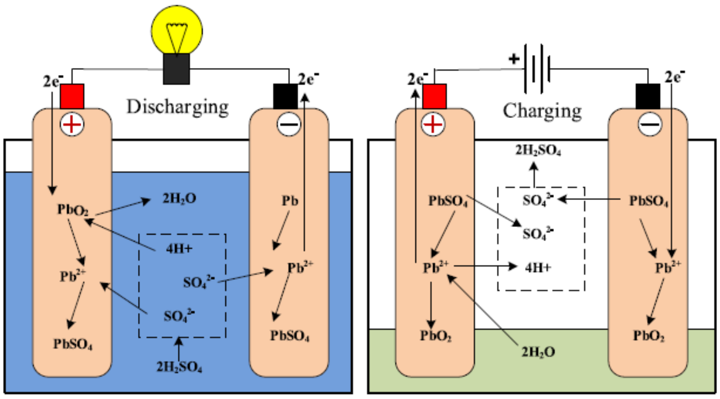


Fig. 2.1. Lead-acid battery chemistry: (a) during discharging, (b) during charging [19]

2.1.5.2. Lithium-ion batteries

Lithium ion batteries are mostly used in transportation, electronics, and power grid applications. Their negative and positive electrodes are made up of graphite and 'lithiated' metal oxide, respectively. The battery electrolyte is made up of a lithium salt such as Lithium hexafluorophosphate ($LiPF_6$) or Lithium perchlorate $LiClO_4$, etc [6]. They are characterized by low self-discharge, high 'energy-to-weight' ratio, and a life cycle of around 10,000 [6]. Compared to other batteries, lithium ion has a high efficiency of approximately 100% [6]. It is considered attractive because it is smaller, lighter and powerful than other batteries. Lithium-ion batteries are one-quarter of the weight, and half the size of lead-acid batteries [4]. The electricity produced by advanced Lithium ion batteries made up of nanowires silicon is 10 times greater than that produced by conventional Li-ion batteries [3]. Currently, research and development focus on the use of nanoscale materials to enhance li-ion battery power capacity. In addition, efforts are concentrated on the development of advanced electrode materials, and electrolyte solutions to improve the battery specific energy [9]. Even though, more than half of the portable devices market is taken by Li-ion batteries, this technology is still facing some challenges which limit its development for large-scale applications. The most important barrier of this technology is its high cost. However, companies are currently trying to reduce their manufacturing cost in order to capture large energy markets [11]. Other drawbacks of this type of batteries are the heat requirement; that leads to a high self-discharge, and the corrosivity caused by the properties of sodium.

The positive electrode of Lithium batteries is made of a 'lithiated' metal oxide such as oxide ($LiCoO_2$), Lithium nickel dioxide powder ($LiNiO_2$) or $LiMnO_2$, and Lithium cobalt (III). Its negative electrode consists of graphite. Lithium salt forms the electrolyte solution. Examples of lithium salt are Lithium perchlorate $LiClO_4$, or Lithium hexafluorophosphate ($LiPF_6$) dissolved in an 'organic carbonate'.

During the charging of the battery, lithium cations are transferred to the anode. This latter is combined with charging electrons (e-) to form lithium atom. Executing the chemical process in reverse, results in the discharging process of the battery.

The chemical reactions which take place during the charging and discharging processes are shown in eq. 2.5 and 2.6, respectively.

$$C + xLi^{+} + xe^{-} \longleftrightarrow Li_{x}C \tag{2.5}$$

$$LiMO_{2} \longleftrightarrow Li_{1-x}MO_{2} + xLi^{+} + xe^{-} \tag{2.6}$$

The discharging and charging of Li-ion battery chemistry are shown in Fig. 2.2.

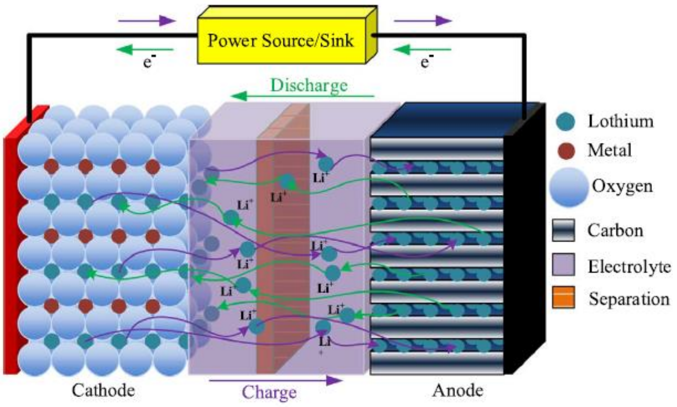


Fig. 2.2.Lithium-ion battery chemistry: (a) during discharging and charging [19]

2.1.5.3. Sodium sulfur batteries

Sodium Sulfur batteries (NaS) are very attractive emerging technologies. Their deployments have grown significantly from 10 MW in 1998 to 305 MW in 2008 [20]. Sodium sulfur batteries have a good efficiency of 75-90%, high power density, and can be cycled 2500 times [19]. They are considered the most economically feasible battery system for energy management; as they have a low levelized cost of energy 0.32 $/kWh [21]. However, this technology requires a high capital cost of approximately $2000/kW - $350/kWh, and must be kept at a temperature of about 300–350 °C [11, 12].

While passing through the electrolyte, positive sodium ions are converted to sodium polysulphides by combining with Sulphur. Eq. 2.7 represents the chemical reactions which take place in the battery.

$$2Na + 4S \longleftrightarrow Na_2S_4 \tag{2.7}$$

Na^+ ions flow through the electrolyte during the discharging process; while the electrons move through the battery external circuit. Fig. 2.3 illustrates the chemical process during the charging/discharging of sodium sulfur battery.

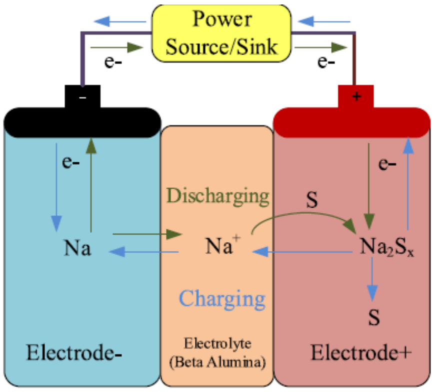


Fig. 2.3. Sodium-sulfur battery chemistry: (a) during discharging and charging [19].

2.1.5.4. Metal-Air Batteries

This battery type is still an emerging technology. It is considered a type of fuel cell which uses ‘metal’ as the fuel and air as the oxidizing agent. This battery option has many advantages over other storage systems. It has higher energy density, longer lifetime and is a cost effective storage option. However, it also has some downsides that need to be resolved in order for this technology to play a major role in the energy market. These major drawbacks are related to the system poor recharging capacity and low efficiency which is less than 50% [11].

The anode of metal air batteries is made of metals such as zinc or aluminum which have high energy density and can release electrons when oxidized. The battery cathode consists of a porous carbon structure or of a metal mesh covered with proper catalysts [11]. The electrolytes which could be in liquid or solid polymer form should usually have a good OH ion conductivity. An example of such electrolyte is KOH.

Zinc-Air battery reactions, for example, are show in Eq. 2.8-2.10:

At the anode:

$$Zn + 4OH^- \longrightarrow Zn(OH)_4^{2-} + 2e^- \tag{2.8}$$

At the cathode:

$$O_2 + 2H_2O + 4e^- \longrightarrow 4OH^- \tag{2.9}$$

Overall reaction:

$$2Zn + O_2 \longrightarrow 2ZnO \tag{2.10}$$

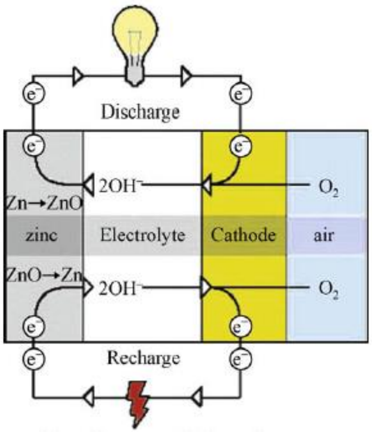


Fig. 2.4. Metal-Air battery [19].

2.1.5.5. Nickel-based Batteries (NiCd, NiMH, and NiZn)

Battery systems which employ nickel-electrode are nickel cadmium (Ni–Cd), nickel–iron (NiFe), nickel hydrogen (Ni–H2), nickel–zinc (Ni–Zn), nickel metal hydride (Ni–MH). The most used one in utility industries is nickel-cadmium (NiCd). However, Ni–Cd and Ni–MH are popular than the other types. The cathode electrode and electrolyte of Nickel-based batteries consist of nickel-hydroxide and an aqueous solution of potassium-hydroxide and lithium-hydroxide, respectively [22]. The anode electrode is made up of cadmium-hydroxide, metal alloy and zinc-hydroxide for NiCd, NiMH, NiZn batteries, respectively. NiCd battery storage has a cycle lifetime of about 1500-3000 cycles [22]. Yet, it has a longer lifetime than lead-acid batteries while NiMH and

NiZn have smaller or almost the same calendar lifetime. The downsides of this technology are high self-discharge rates which is approximately 10% per month, and high cost. Nickel-based batteries are 10 times more expensive, and have lower efficiency range than lead-acid batteries [22]. In addition, the toxic ‘cadmium’ material poses a threat to the environment [11].

The positive electrode of Nickel-based batteries consists of oxyhydroxide, while the negative one is made up of any metal Fe/Cd/ Zn. The electrolyte solution uses potassium hydroxide. The overall electrochemical reaction of nickel-based batteries is shown in Eq. (2.11).

$$\begin{aligned} &X = Fe/Cd/ZnNi \\ &X + 2NiO(OH) + 2H_2O \longleftrightarrow 2Ni(OH)_2 + X(OH)_2 \end{aligned} \tag{2.11}$$

$Ni(OH)^2$ and $Fe/Cd/Zn(OH)^2$ are produced during the discharging process .The chemistry process which occurs during the charging and discharging of lead acid batteries is shown in Fig. 2.5.

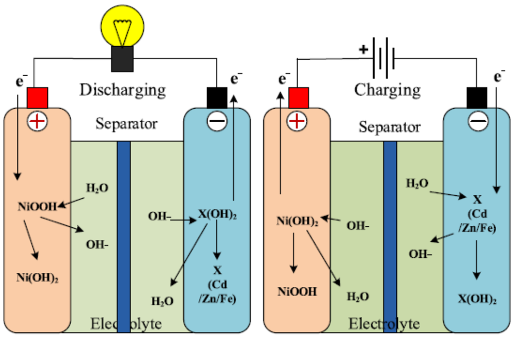


Fig. 2 5. Nickel-based battery chemistry. (a) during discharging, (b) during charging [19]

2.1.5.6. *Flow batteries*

Flow batteries have become popular, and attracted interest and attention; because they can operate at near ambient temperatures. Their components are of low cost, and they are easily scaled up or down in size. The two types of flow batteries are redox (reduction-oxidation), and hybrid flow batteries. The common battery of a redox flow type is vanadium-redox battery (VRB), while the common one for hybrid flow type is the zinc-bromine battery. Flow cells store energy as the electrolytes; while in regular batteries, energy is stored as the electrode material. This is the main difference between conventional batteries and flow batteries. In addition, flow batteries are quickly recharged because the electrolyte fluid can be replaced.

A flow battery is technically similar to a fuel cell and to an electrochemical accumulator cell. It has some similar technical advantages, such as potentially separable liquid tanks, and near unlimited durability over most regular rechargeable batteries. In general, the energy efficiencies of flow batteries are around 75%. In addition, their energy and power ratings are independent of each other. However, flow batteries have low energy densities, and require higher investment costs.

Vanadium redox flow batteries have some advantages which include high energy efficiency of approximately 85%, long cycle life of 1,250 cycles, calendar lifetime of 12 years, and short response time [14]. However, unlike these batteries, zinc bromine batteries have lower efficiency and cost. Their efficiency is approximately 75% [23]. Zinc bromine batteries are made of the same components as vanadium redox batteries.

Vanadium redox flow battery (VRB) stores energy by exchanging electron between the ionic vanadium materials. The storage system charges energy by accepting an electron and hence converting V^{3+} to V^{2+} at the anode. Energy is discharged by releasing an electron and converting V^2+ back to V^{3+}. At the cathode, the same process occurs between V^{5+} and V^{4+}. Fig. 2.6 illustrates the charging and discharging processes of VRB.

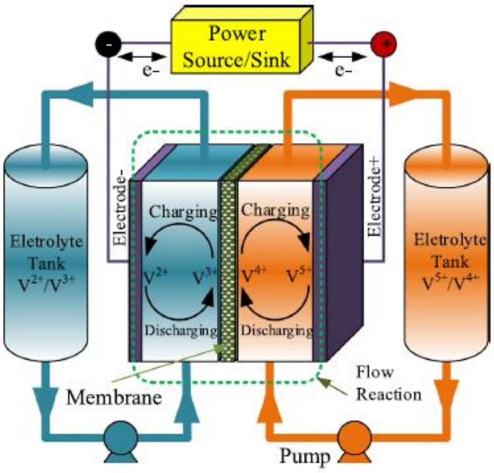


Fig. 2 6.Vanadium redox flow battery system [19]

2.1.6. *Gravity energy storage*

Gravity energy storage is an innovative storage concept that is currently being investigated. This system is considered an alternative to pumped hydro storage because it uses gravity to store energy. This technology eliminates the geological limitations and water requirement encountered with pumped hydro storage technology as it can be implemented everywhere. A schematic of gravity storage is illustrated in Fig. 2.7. The system consists of a large piston, a water filled container, and a return pipe. The return pipe is linked to the powerhouse composed of reversible pump/turbine, and motor/generator. During the charging mode, excess energy is delivered to the motor which spins the pump. This latter force the water to go through the return pipe and lifts the piston. In the discharging mode, energy is produced by the downward motion of the piston which forces the water to flow through the reversible pump/turbine. This latter drives the generator and hence generates electricity. Currently, there exist only demonstration systems and there is no large scale installation of this storage technology. The system's efficiency is around 80% as claimed by developers [3].

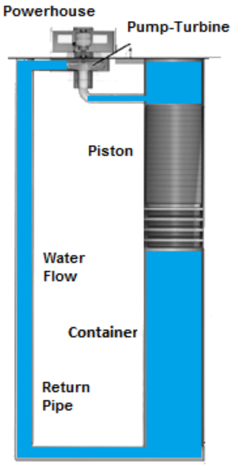


Fig. 2.7.Schematic of gravity storage.

2.1.7. Hydrogen Fuel Cells

Hydrogen has seen an increasing popularity and will play a vital role in the future. It is not only used to generate electricity, it has also become an attractive option to fuel hybrid vehicles. During the charging process, hydrogen fuel cells use electricity to produce hydrogen. Hydrogen feeds the fuel cell to create electricity during peak demand (discharging process). Hydrogen is produced by a process known as electrolysis. The excess electricity is used to split water into hydrogen and oxygen.

A fuel cell structure is very similar to a battery. It consists of an electrochemical cell. The cell components are an anode, a cathode and an electrolyte. The hydrogen ion transfer occurs within the electrolyte. The electrolyte and the reactant of the fuel cell can vary as with batteries. Unlike a battery, the fuel cell is not a closed system. In other words, the fuel cell keeps operating as long as the reactants are supplied, whereas the amount of stored chemical energy is limited within a battery. As flow batteries, fuel cells have the same advantage of separating the power rating and the energy capacity of the system. One disadvantage of this technology is the low round-trip efficiency of the system which is about 59% [24]. Fuel cell is then considered less efficient than many other storage technologies mentioned before. Furthermore, this technology requires some time to start operating which makes it inappropriate for applications that require a quick response time. Fuel cells chemical reaction is shown in Eq. 2.12.

$$2H_2 + O_2 \longleftrightarrow 2H_2O + Electricity \tag{2.12}$$

Hydrogen fuel cell chemistry process is illustrated in Fig. 2.8. The injected hydrogen fuel dissociates on the catalytic surface of the fuel electrode by forming hydrogen and electrons. On the catalytic surface of the fuel electrode, hydrogen and electrons are formed by the dissociation of hydrogen fuel being injected. The hydrogen ions flow to other catalytic surface of the oxygen electrode. At the same time, electrons power the load by passing through the battery’s external circuit. The combination of hydrogen ions, electrons, and oxygen produces water.

In the regenerative process, the cell is fed by oxygen and hydrogen resulted from the separation of water by a power electrolyzer. Therefore, water and electricity is produced by this process [24].

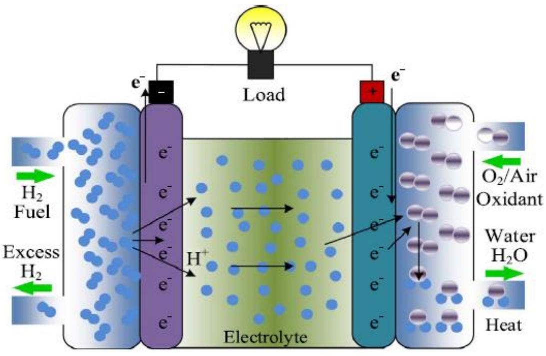


Fig. 14. HFC chemistry [14,46,58].

Fig. 2.8. HFC chemistry [14,46,58].

2.1.8. *Superconducting Magnet Energy Storage (SMES)*

Superconducting magnetic energy storage is an innovative technology that stores electricity from the grid within a magnetic field that is created by the flow of direct current in a coil. During the charging process, the current increases while it decreases in the discharge process. In the standby application, the current circulates the coil. Therefore, magnetic energy can be stored indefinitely. Superconducting magnetic energy storage consists of a magnetic storage unit, and a cryostat. This technology has the ability to store and discharge large amount of energy instantaneously. It is capable of releasing high amount of power within a fraction of a cycle. SEMS plays a crucial role in providing energy during momentary power outages and voltage sags. With the increasing penetration of renewable energy such as solar and wind, injection of momentary bursts of power is necessary to maintain grid reliability.

The system has high efficiencies of approximately 95%, and low loss of charge of about 0.1%. Because this technology is capable of responding in less than 100 ms, it is a great option for load leveling between the transmission network and renewable energy sources. However, this technology is still expensive making it applicable for only short term storage. The power units of SEMS that are currently used are of the order of 1-10MW with a storage time on the order of seconds. SEMS units that can provide up to 100 MW are under development, storing energy on the order of minutes. Large MW units require extra safety measures in order to avoid exposing humans to harmful magnetic fields [25].

The energy stored by this technology is given in Eq. (2.13). This energy is dependent on the self-inductance of coil and the current that flows through the coil.

$$W_L = \frac{1}{2} L_c I_c^{\,2} \tag{2.13}$$

Where W_L is the coil stored energy; L_c the self-inductance of coil; and I_c is the current.

2.1.9. *Thermal Energy Storage (TES)*

Thermal energy storage (TES) stores electricity or other waste heat sources in the form of thermal energy. These storage systems are classified into three categories which include sensible heat, latent heat, and thermochemical heat. The method used by the first aforementioned category is the change in material temperature, while the phase change of a material is used by latent heat. The last category induces thermal changes in a material's chemical structure. The selection of the appropriate thermal energy storage method depends on several factors which include the system application, the storage system temperature range, and media. These systems are also classified into high and low temperature systems depending on the operating temperature range. If this latter is below 200° C, the system is operating in a low temperature. This TES storage category has been developed extensively, and is used in cooling and heating application of buildings. High temperature TES category is mostly utilized in renewable energy applications, thermal power systems, and waste heat recovery.

Eq. 2.14 illustrates the thermal energy stored in sensible heat storage systems. These latter depends on a change of the temperature. The mass of the medium and the specific heat affect the storage capacity.

$$E_{th} = K_h (T'_2 - T'_1) V_s \tag{2.14}$$

Where E_{th} is the stored thermal energy; V_S is the volume of the system; T'_1 and T'_2 are the initial and final recharge temperature; K_h is the specific heat.

2.2. Energy Storage Status worldwide

A number of energy storage projects with varying scales have been developed globally, as shown in Fig. 2.9. Currently, battery energy storage has the highest number of operational projects (more than 350). Pumped hydro energy storage is ranked in the second place with approximately 300 projects. This latter is followed by thermal energy storage systems.

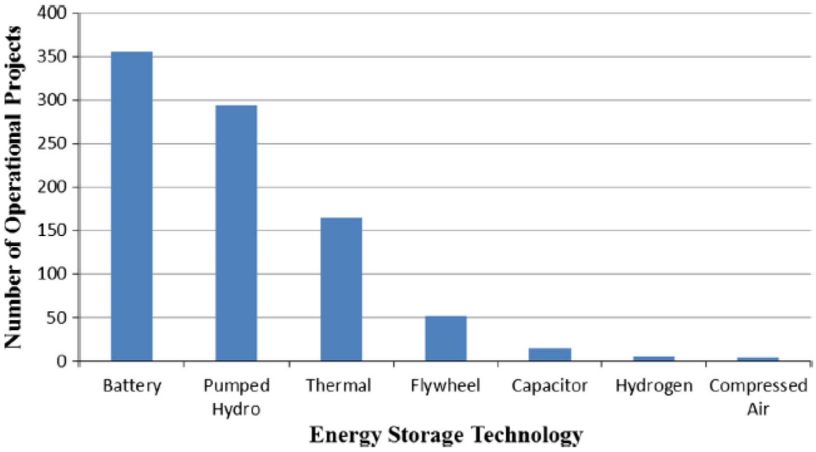


Fig. 2 9. Number of operational projects [3].

Pumped hydro storage constitutes about 98% of the amount of energy stored as seen in Fig. 2.10. This latter is followed by thermal storage and flywheel which represent approximately 1% each. The share of capacitors, hydrogen and compressed air energy storage is very small and less than 1%.

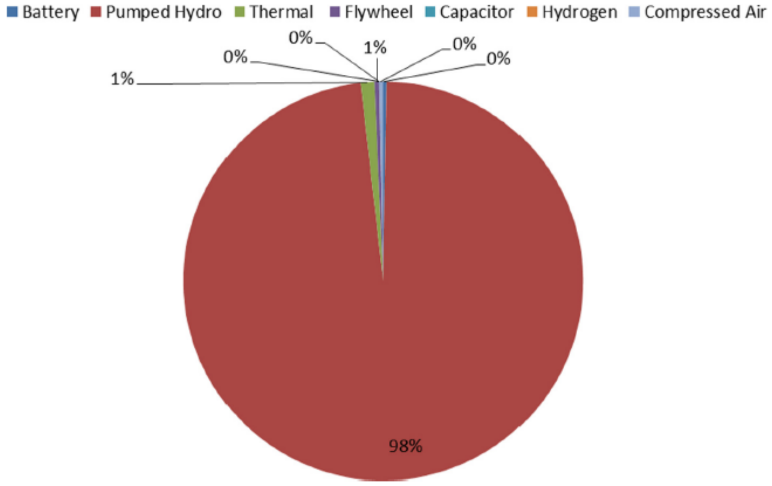


Fig. 2.10. Technology share of quantity of energy stored globally [3].

The operational battery projects are classified into different types of batteries has shown in Fig. 2.11. The most commonly used type is Li-ion battery storage with more than 100 projects followed by Li-ion phosphate, and sodium sulphur batteries. However, the share of Li-ion battery in terms of the amount of energy stored is less than that of sodium Sulphur as illustrated in Fig. 2.12. Li-ion battery represents only 18% compared to 24% of NaS batteries. This later is mostly used for large scale energy application while Li-ion battery is typically used for portable energy storage application. Advanced lead acid battery constitutes an interesting share of 18% compared to other batteries. This battery type has only 15 projects currently operational worldwide. This shows that advanced lead acid batteries are used for large scale applications.

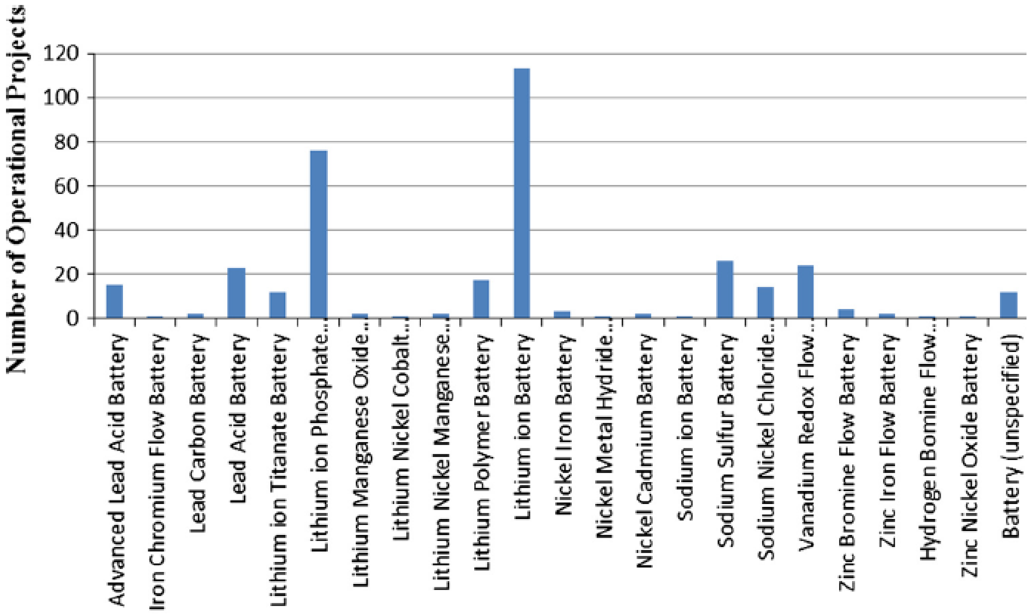


Fig. 2.11.Battery energy storage technology options [3].

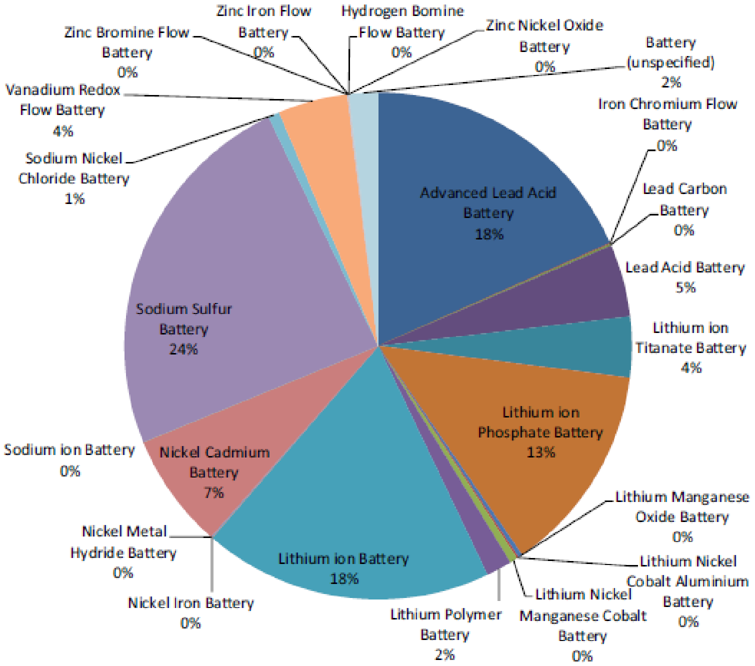


Fig. 2.12. Technology share of the quantity of energy stored using battery system.

Concerning thermal energy storage systems, the highest number of operational thermal plants in the world, goes to ice thermal energy storage followed by molten salt (See Fig. 2.13). Chilled water thermal storage is in the third place followed by heat storage. However, the quantity of energy stored of molten salt is higher than that of ice thermal. This latter represents only 4% compared to 77% of molten salt as illustrated in Fig. 2.14. The reason behind this high difference is because ice thermal storage is used for small scale applications and mainly to provide air conditioning. Molten salt thermal energy storage is used for large scale application such as solar thermal plant.

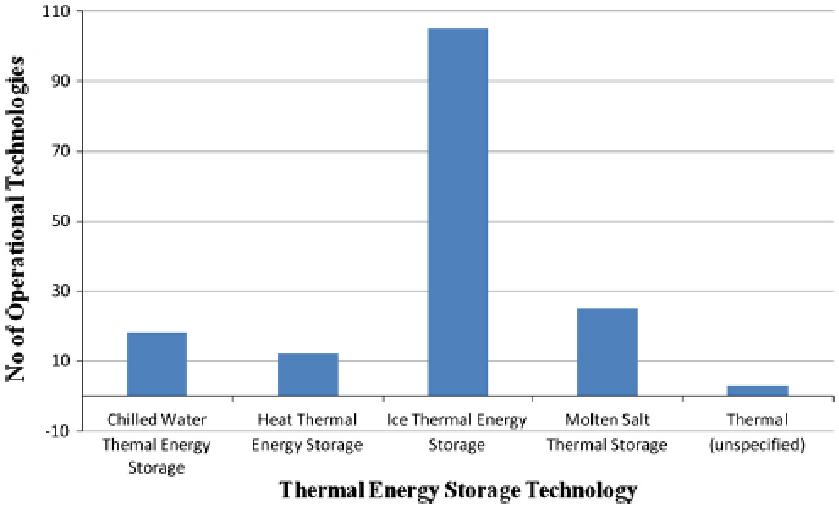


Fig. 2.13.Thermal energy storage technology options [3].

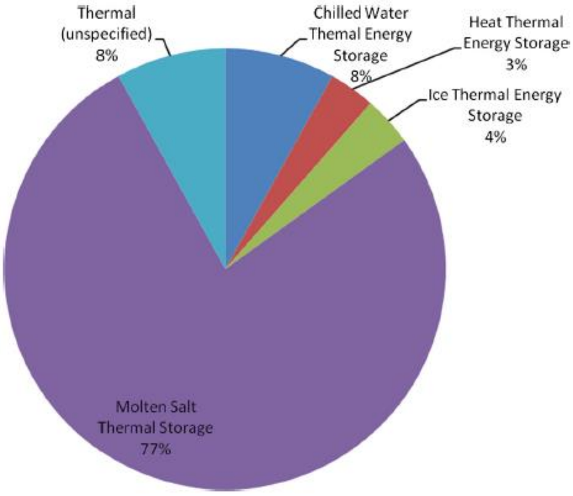


Fig. 2.14.Compressed air energy storage technology options [3].

The most used type of compressed air energy storage system is in-ground natural gas combustion, as illustrated in Fig. 2.15. The two currently operational in-ground natural gas energy storage systems include McIntosh and Huntorf CAES. As for the two remaining types of CAES , they both have only one project currently operational.

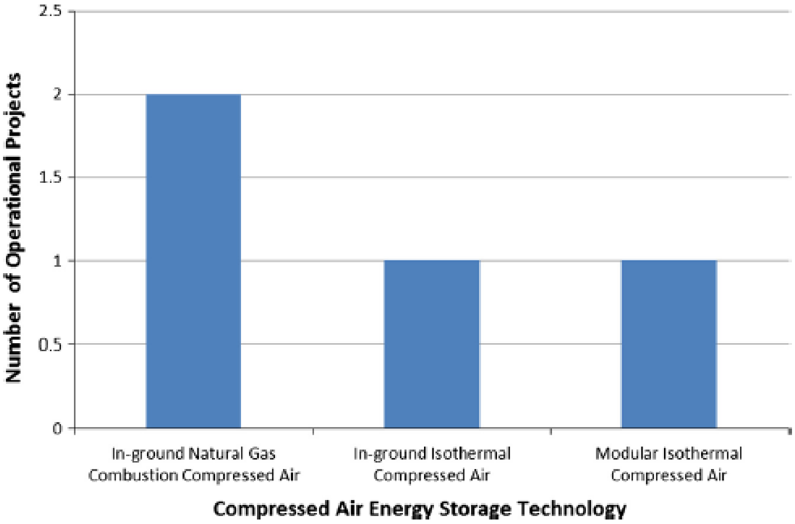


Fig. 2.15. Compressed air energy storage technology options [3].

2.3. Renewable energy and energy storage in Morocco at a glance:

Morocco is the largest importer of energy in North Africa as it is the only country in the region without its own oil resources. Meeting the raising energy demand of the country is a challenging task. To solve this issue, Morocco is pursuing an ambitious energy transition with the aim of producing sustainable and secure energy.

ONEE (Office National de l’Electricité et de l’Eau Potable) is a state-owned operator of electricity in Morocco. It is the main retail supplier and has a dominant role in the power market. It operates throughout the complete energy industry from generation to distribution. It owns the transmission network and a large share of the distribution network. ONEE acts as a single buyer in the energy sector, except for renewable energy generated under the framework of Law 13/09. In addition, ONEE operates a significant portion of the energy generation capacity. However, concessions are provided by ONEE to private operators with purchase guarantees [26]. The energy subsector at the government level consists of the Ministry of Energy, Mines, Water and Environment (MEMEE) and the Ministry of Interior (MI). These supervise ONEE, and the public enterprises responsible for the distribution of water and electricity, respectively. The power distribution subsector of Morocco involves seven local municipal utilities known as “Régies”, and four private distribution utilities, known as “gestionnaires délégués”.

In the Moroccan power market, electricity is generated through a number of ways which include:

- Energy generated by ONEE.
- ONEE buying electricity from an Independent Power Producer with a negotiated Power purchase agreement.
- Self-production.
- Independent power producer selling electricity generated from renewable energy sources to large consumers via power purchase agreement.

2.3.1. *Morocco's Energy Strategy*

Towards sustainable development, the ambitious energy strategy adopted by Morocco puts renewable energy production at the heart of the national energy policy. The target of this strategy is to increase renewable energy production to 42% of the total installed capacity by 2020 and 52% by 2030. To reach this target, Morocco is planning to increase the installed hydro capacity to 2,000 MW, and to develop 2,000 MW of solar capacity and 2,000 MW of wind capacity. This could be achieved by exploiting the excellent wind and solar resources of the country (See Fig. 2.16 and 2.17) [27].

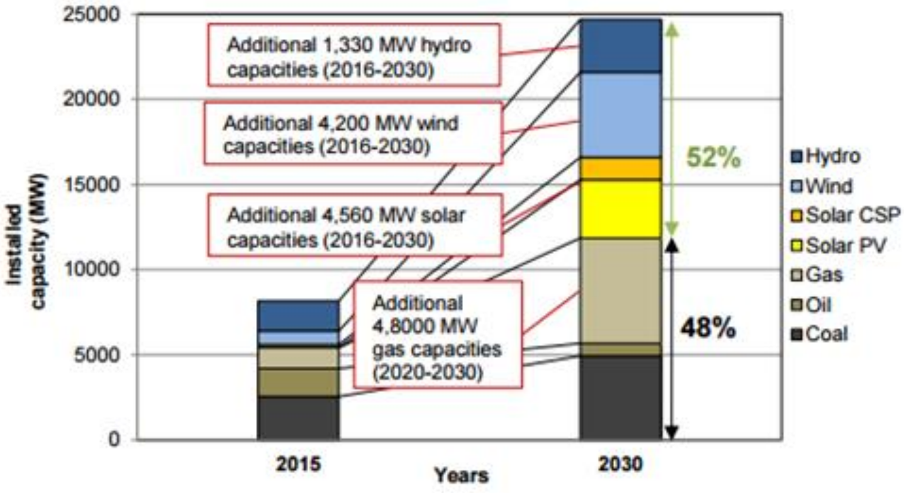


Fig. 2.16. Total and expected installed capacity in Morocco.

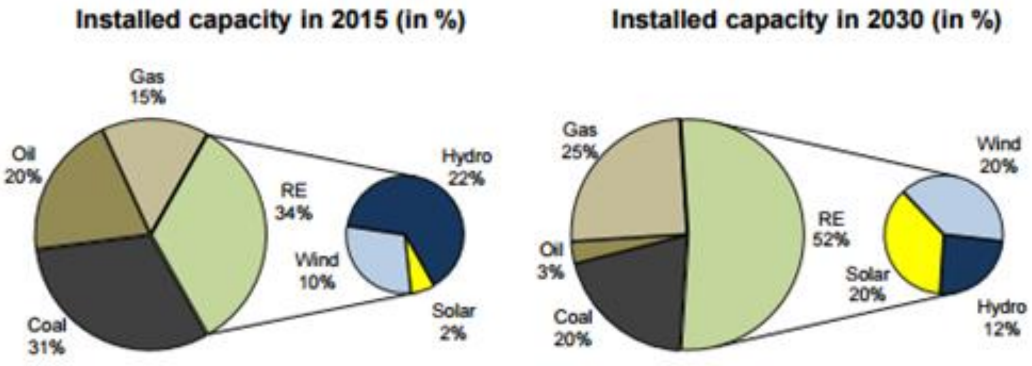


Fig. 2.17. Shares of installed capacity in Morocco

For the past decades, hydropower has been considered an important energy generation system in Morocco. The installed capacity is expected to increase to 2,000 MW, and to 3100 MW by 2020 and 2030, respectively. To boost the development of the solar and wind installed capacity, the kingdom’s ambitious solar program aims to increase the installed solar capacity (Noor plan) to 2,000 MW and to 4,800 MW by 2020 and 2030, respectively. The wind programme, on the other hand, is expected to represent 14% of the total installed capacity. Wind production would be raised to 2,000 MW and 5,000 MW by 2020 and 2030, respectively. To achieve these targets, a number of solar and wind projects would be developed in different regions.

The power transmission grid which covers the entire country is operated by ONEE. The Moroccan grid is interconnected with the Algerian and the European power networks. It contains 37 substations with a transmission network of 2,765 km of 400 kV lines, nearly 9,680 km of 225 kV lines, 147 km of 150kV lines and about 12,000 km of 60 kV lines [28]. Transmission lines connecting between Morocco, Algeria, were constructed in 1990s and 2000s. The Morocco-Spain network is considered the main interconnection as it involves two 400-kV lines commissioned in 1997, and in 2006. The Spanish connection is 1400MW via 2x400kV subsea cables, and the Algerian connection is 1500MW via 1x400kV and 2x225kV lines.

Strengthening power grid interconnections has received political support from North Africa and Europe. Potential interconnectors to external countries would unlock the significant renewable sources available in various part of the country. A larger and stable interconnected power system would contribute to the increasing share of renewable energy integration in the region. In addition, the country would benefit from better business opportunities with an access to external markets, and more financial incentives for renewables energy.

The growing energy demand in Morocco requires substantial investments in transmission and distribution infrastructure, power generation capacity, and energy storage.

2.3.2. Energy Storage in Morocco

Morocco has four energy storage projects which include two pumped hydro energy storage and two thermal energy storage systems. Fig. 2.18 illustrates the location of each storage plant [29].

Fig. 2.18..Energy storage in Morocco.

2.3.2.1. Pumped Hydro Energy Storage

Afourer Pumped Storage Scheme

The Afourer Pumped Storage Station is a located in the hills above Afourer of Azilal Province, Morocco. This project was developed by ONEE. It comprises two power stations with an installed capacity of 465 MW. The plant construction took around 4 years and is currently operational. The plant was funded at a cost of US$220 million by the Arab Fund for Economic & Social Development [29].

Abdelmoumen Pumped Storage Power Station

The Abdelmoumen Pumped Power Transfer Station Project (STEP) is located in the Northeast of Agadir. The plant is sited upstream of the existing reservoir of the Abdelmoumen dam on the Oued Issen. The Abdelmoumen STEP Project has been announced in January 13, 2013. The capacity of the STEP is 616 GWh/ Year with a projected cycle efficiency of 75.86%. The STEP is developed by ONEE with an estimation construction cost of 2 300 million MAD [29]. This project will reinforce the national electricity grid in the South of Morocco.

2.3.2.2. Thermal Energy Storage

Airlight Energy Ait Baha Plant

The technology type is heat thermal storage with a rated power of 650 kW and an estimated production of 2,390 MWh/yr. The plant is located in Ait Baha, Agadir, and is owned by Italgen Maroc. This thermal storage is developed to recover waste heat from the cement factory and deliver additional higher temperature heat to an organic ranking cycle Generator (12MW). The construction of this project has begun in February 01, 2012 and has started operating in March 01, 2014.

NOOR I (Ouarzazate) CSP Solar Plant

The technology type is molten salt thermal storage with a rated power of 160 MW and a capacity of 3 h. The plant is located in Ouarzazat and it is currently operational. It is the first phase of the Noor Solar Project. The plant is developed by the Moroccan Agency for Solar Energy (MASEN) with the help of the Spanish group TSK-Acciona-Sener.

2.4. Conclusion

Energy storage has been suggested as a viable solution to combat the viability of renewable energy. This chapter has presented an overview about the main types of energy storage methods in existence outlining their characteristics. The current energy storage projects worldwide have also been presented. Finally, a brief discussion about renewable energy and energy storage projects in Morocco has been discussed.

References

[1] Rehman S, Al-Hadrani, Alam M. Pumped hydro energy storage system: A technological review. Renewable Sustainable Energy Rev. 2015;44: 586–598.

[2] EPRI. Electricity energy storage technology options. Electric Power ResearchInstitute; 2010

[3] Aneke M, Wang M. Energy storage technologies and real life applications – a state of the art review. Appl Energy 2016;179:350-77.

[4] EPRI-DOE Handbook of Energy Storage for Transmission &Distribution Applications, Palo Alto, CA; Washington D.C. : EPRI; U.S. Department of Energy, 2003.

[5] Ecofys. Energy storage opportunities and challenges [A West Coast Perspective White Paper]. 2012.

[6] Akinyele DO, Rayudu RK. Review of energy storage technologies for sustainable power networks. Sustain Energy Technol Assess 2014;8:74-91.

[7] EPRI.Handbook of Energy Storage for Transmission or Distribution Applications. Palo Alto, CA: Electric Power Research Institute, 2002. 1007189.

[8] Rastler, D. (2008), "New demand for electricity storage," Electric Perspectives, 30-47

[9] Luo X, Wang J, Dooner M, Clarke J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. Appl Energy. 137. 511. 536.

[10] Beaudin M, Zareipour H, Schellenberglabe A, Rosehart W. Energy storage for mitigating the variability of renewable electricity sources: An updated review. Energy for sustainable development. 2010;4: 302–314

[11] Chen H, Cong Y, Yang W, Tan C, Li Y, Ding Y. Progress in electrical energy storage system: a critical review. Prog. Nat. Sci. 2009;19(3):291–312.

[12] Ibrahim H, Ilinca A, Perron J. Energy storage systems characteristics and comparisons. Renewable Sustainable Energy Rev. 2008;12(5):1221–50.

[13] Succar S, Williams R. Compressed air energy storage: theory, resources, and applications for wind power. Tech. rep. Princeton Environmental Institute; 2008. Apr

[14] Chatzivasileiadin A, Ampatzi E, Knight L. Characteristics of electrical energy storage technologies and their applications in buildings. Renewable Sustainable Energy Rev. 2013; 25: 814–830

[15] Ribeiro P, Johnson B, Crow M, Arsoy A, Liu Y. Energy storage systems for advanced power applications. Proc. IEEE 2001;89(12):1744–56 (Dec).

[16] Hadjipaschalis I, Poullikkas A, Efthimiou V. Overview of current and future energy storage technologies for electric power applications. Renewable Sustainable Energy Rev. 2009;13(6–7):1513–22.

[17] Koohi-kamali S, Tyagi V, Rahim N, Panwar N, Mokhlis H. Emergence of energy storage technologies as the solution for reliable operation of smart power systems: A review. Renewable Sustainable Energy Rev. 2013;25: 135–165

[18] Zhou Z, Benbouzid M, Charpentier J,Scuiller F, Tianhao Tang T. A review of energy storage technologies for marine current energy systems. Renewable Sustainable Energy Rev. 2013; 18: 340–400

[19] Hannan M.A, Hoque M.M, Mohamed A, Ayob A. Review of energy storage systems for electric vehicle applications: Issues and challenges. Journal of Sustainable and renewable enegy reviews. 69 (2017) 771–789.

[20] NGK. The vendor's perspective on barriers and issues encountered in U.S. development. NGK Insulators Ltd.; 2009b [Online]. Available: http://www.energy.ca.gov/2009_ energypolicy/documents/2009-04-02_workshop/presentations/2_2%20NGK-NAS% 20-%20Harold%20Gotschall.pdf

[21] Dufo-Lopez R, Bernal-Agustin JL, Dominguez-Navarro JA. Generation management using batteries in wind farms: economical and technical analysis for Spain. Energy Policy 2009;37(1):126–39.

[22] Hadjipaschalis, I., Poullikkas, A., and Efthimiou, V. (2008),"Overview of current and future energy storage technologies for electric power applications," *Renewable and Sustainable Energy Reviews*.

[23] Gonzalez F, Sumper A, Bellmunt O, Robles R. A review of energy storage technologies for wind power applications. Renewable Sustainable Energy Rev. 2012; 12: 2154–2171

[24] Schoenung,S. Characteristics and Technologies for Long-vs. short-term energy storage.Alberquerque, NM: Sandia National Laboratories, 2001. SAND2001-0765.

[25] Polk, C., Boom, R. W., Eyssa, Y. M. (1992), " Superconductive magnetic energy storage (SMES) external fields," IEEE Transactions on Magnetic 28(1),478-481.

[26] T. Amegroud, Morocco's Power Sector Transition: Achievements and Potential IAI Working Papers 15, 2015

[27] B. Schinke et al., Country Fact Sheet Morocco Energy and Development at a glance 2016; MENA SELECT, 2016

[28] ONEE. For a Sustainable Future. Available at: www.oneecop22.ma/fr/fileserveren2.php

[29] DOE Global Energy Storage Database. Available at: http://www.energystorageexchange.org/.

Chapter 3

3. Design, Construction, and Sizing of Gravity Storage

The need to maintain instantaneous equilibrium between supply and demand is a major constraint in the electric power system operations. Energy storage has the ability to solve this issue by allowing energy to be stored and released upon demand. A technical design model of gravity energy storage is presented in this chapter. This design would be first assessed concerning the materials applied to the storage system. Moreover, finite element analysis (FEA) is performed using SolidWorks to study the design performance of this system. In addition, this chapter proposes a methodology to optimally size gravity storage technology and avoid system design failure. It presents an approach to size the system technically and economically.

3.1. Introduction

Energy storage systems provide several benefits to enhance the electric grid such as ancillary services, load following, price arbitrage, regulation, load leveling and many others. However, the current storage systems still face many challenges. The most prominent one is the technology optimal design, construction and sizing.

Materials are necessary to industrial development of renewable energy. They are considered the key innovative trigger in the development of energy products. Materials applied to energy technologies have played a vital role in energy production and storage. This is principally evident due to the demand for high quality technologies [1]. There is an increasing research interest on energy storage materials. Identification of critical materials for energy technologies are a challenge carried out by several researches. In [2], Libowitz et al. discusses the materials science in energy technology. Whittingham in [3] presents materials challenges facing electrical energy storage. Authors in [4] provide an overview of several energy storage systems materials, including mechanical, thermal, hydrogen, electromagnetic and electrochemical energy storage. The strategies for developing these advanced energy storage material is discussed. Fernandez et al. provides an overview of materials suitable to be used in thermal energy storage [5]. Identification of material using finite element analysis has been used by several authors. Deokar et al. in [6] used fuzzy decision making method and FEA method to select materials for biogas storage cylinder. Modeling and analysis of water tank was performed by authors in [7]. Ucar and Unalli have evaluated the performance of a solar heating system with underground seasonal storage using finite element method [8]. There are number of researches about energy storage material selection. However, there are relatively few research papers about this storage technology because gravity storage is a new concept. Authors in [9] presented a an economic analysis about this storage system. The work of this chapter presents material selection and design modeling of gravity storage.

Several methodologies for sizing energy storage have been discussed in literature. Optimal sizing of storage has been determined using a generic algorithm [10], with an objective of minimizing the micro grid operation cost. In addition, the determination of the optimal sizing of energy storage with the aim of reducing microgrids' operational costs; in presence of distributed generators with the use of grey wolf optimization method was carried in [11]. Atwa and El-Saadany [12] proposed a methodology to size energy storage, aiming at reducing annual cost of energy, and minimizing wind energy curtailment. An approach to size and site energy storage, using a hybrid generic algorithm, was covered by the work presented in [13]. Different types of storage systems have been sized, with an objective of maximizing the net present value [14-15]. A cost benefit analysis for distribution networks, aiming at maximizing the operator revenues by optimally sizing energy storage systems, was carried through the work presented by Zheng in [16].

Authors in [17-19] used optimization algorithms, based on the variation of input parameter, to determine the suitable power rating and energy capacity of energy storage systems. Similarly, optimum sizing and energy management, of a hybrid energy storage system for lithium battery life improvement, have been presented by Tehrani el al. in [20]. Stochastic approaches to size energy storage due to the intermittent nature of demand and production profiles were developed by Musolino et al., Feroldi and Zumoffen, Schaede et al., [21-23].

Authors in [24] proposed a sizing model with a purpose of minimizing the cost of the hybrid system, while meeting the service requirement of the renewable energy farm. Two case scenarios have been investigated by the authors. The first restricts the shunting of energy, while the second allows the storage system to charge and discharge energy at the same time. This study demonstrated that the second scenario has a lower energy capacity and cost then the first one. Therefore, the optimum sizing of energy storage, required to meet the demand, has been found through the proposed model that enables the shunting of energy. Bennett et al. [25] proposed a scheduling method to determine the optimal sizing of energy storage in distribution systems with the aim of reducing peak load demands. A particle swarm optimization method was used by Khorramdel el al. to solve a unit commitment problem [26]. The objective of the model was to identify the sizing of energy storage while maximizing the benefits and minimizing the costs in microgrids.

This chapter is organized as follows. Section 2 proposes a design methodology for gravity energy storage. In Section 3, an optimal design of the system is presented. Section 4 presents the investigated materials applied to the different components of this storage technology. Modeling and simulation of gravity storage is realized through SolidWorks (SW). Finite element analysis is performed in this study to evaluate the performance of the container with different applied materials. Section 5 presents a technical-economic sizing methodology for gravity storage system. The proposed sizing method was modeled using technical design, economics, and electricity market parameters. Finally, the conclusion of this chapter is presented in Section 6.

3.2. Design of Gravity Storage Components

Optimization is considered an effective tool for identifying optimal design of energy storage. An approach to optimally size the container and the piston parameters of gravity storage is presented in this section.

3.2.1. Energy Equation

The energy equation of gravity storage is described as:

$$E = m_r g z \mu \tag{3.1}$$

Where E is the storage energy production in (J), m_r is the mass of the piston relative to the water, g is the gravitational acceleration (m/s²), z is the water height (m), and μ is the storage efficiency. This equation can be expressed in terms of: ρ_p (piston density), ρ_w (density of water), D (container/piston diameter), and h (piston height) as;

$$E = (\rho_p - \rho_w)(\frac{1}{4}\pi D^2 h) g z \mu \tag{3.2}$$

The energy equation expressed in (Eq. 3.2) is a function of the storage design parameters. It is crucial to identify the technical design; which allows for increasing the storage system's energy capacity. An increase of the piston height (h) would result in greater energy production. However, this will lead to a lower water depth (z). The optimum piston height would be determined by solving for the critical point of Eq. (3.3).

$$\frac{\delta E}{\delta h} = 0 \tag{3.3}$$

The height of the container is the sum of the piston thickness and the water depth (elevation z). By replacing z with $H_C - h$ in equation (3.2), we obtain the critical value occurring when $h = z$. Thus, to make the energy equation only a function of the container's characteristics, the height of the piston (h) as well as the elevation (z) should be replaced by $H_C/2$. Therefore, the optimum energy equation reduces to:

$$E = \frac{1}{16}\pi \mu g (\rho_p - \rho_w) D^2 {H_C}^2 \tag{3.4}$$

Large variations of sizing are possible for gravity storage depending on the required energy production. The energy production increases as the diameter and the height of the container are increased. The idea is to find the most suitable configuration for implementation. However, increasing the piston diameter will cause the piston to jam. The piston has a probability of jamming if [27]:

$$\mu' > \frac{1}{2}\frac{h}{e} \tag{3.5}$$

Where μ' is the friction coefficient between the piston and the container's wall which is equal to approximately 0.5 in case of steel casing of the piston to concrete wall of the container. Assuming that the loads act on the piston with a maximum eccentricity equal to Eq. 3.6,

$$\mathrm{e} = \frac{\mathrm{D}}{2} \tag{3.6}$$

In order to avoid piston jamming, its high must be strictly greater than half of its diameter according to;

$$\frac{h}{D} > \frac{1}{2} \tag{3.7}$$

3.2.2. *Parametric Study*

The aim of this study is to determine the different parameters of the storage technology which include the thickness of container and the return pipe. The storage container should have an adequate thickness to resist the load pressure applied to it. In fact, the wall of the structure is subject to both internal and external pressure. The internal pressure includes water and piston pressure while the external pressure is due to lateral earth pressure. The hoop tension force acts on the vertical segment of the circular wall. To calculate the thickness of the structure, the hoop tension should be determined first [28].

Max hoop tension in the bottom of the container, H_t , is presented by the following equation,

$$\mathrm{H_t} = \frac{(\rho_{\mathrm{p}}\mathrm{g} + \mathrm{w} - \mathrm{k_0 y})\mathrm{HD}}{2} \tag{3.8}$$

Where K_0: Coefficient of earth pressure at rest; and y: soil weight (kg/m^3)

In order to provide tensile stress in concrete to be less than permissible stress, the stress, σ_{st}, in concrete is calculated using Eq. 3.9 [29].

$$\sigma_{st} = \frac{H_t}{1000t + (m-1)A_{st}} \tag{3.9}$$

Where m is the modular ratio and A_{st} is the area of steel used to reinforce the wall,

$$m = \frac{280}{\sigma_{cbc}} \tag{3.10}$$

$$A_{st} = \frac{H_t}{\sigma_{st}} \tag{3.11}$$

Where σ_{cbc} is the conpression stress developed in concrete; w is the specific weight of the water.

After determining the container dimensions, the return pipe parameters should also be identified. Typically, the return pipe has the same height as the container; as it is used to link the inlet of the container to its outlet. The diameter of the return pipe is calculated using fluid flow equations. Since flow obeys to the continuity equation, the discharge of the system is given by,

$$Q = V_1 A_1 = V_2 A_2 \tag{3.12}$$

The average velocity in the container is found by dividing the distance traveled by the piston over the time it takes to go from the top of the container to its bottom. Barlow's formula is useful for determining the wall thickness required for the return pipe. The rated power of energy storage is determined based on the discharge time and the required energy storage capacity.

The aforementioned equations are used to design an optimal system, allowing for the generation a specified energy production; while meeting the system's technical requirements. A designed system, obtained from this technical study, will be used as a case study to demonstrate the effectiveness of some of the proposed models in this report.

3.2.2.1. Case study

The design of the storage is made according to an energy production of 20 MWh. Choosing a container that has a height of 500 m, the diameter of this latter should be selected according to (Eq. 3.4) as 5.21 m. The thickness of the container's walls and the return pipe were calculated using in (Eq. 3.8-3.12). The different parameters of the storage used in this case study are summarized in Table 3.1.

Table 3. 1. Case Study Storage Parameters

	Container	Piston	Return Pipe
Height (m)	500	250	500
Inner Diameter (m)	5.21	5.21	0.6
Thickness (m)	7.6	-	0.083

Theoretically using Eq.(3.4) and the storage parameters presented in Table 3.2 with an 80% efficiency, the storage capacity is found to be approximately 72×10^9 J which is equal to 20 MWh. The rated power of this storage is determined by the discharge time. In this case study, a 5 MW turbine is used to generate 20 MWh.

3.2.3. System Construction Cost

The excavation cost can be calculated using Eq. (3.13):

$$E_C = E_V + E_{UC}. \tag{3.13}$$

The construction cost of the storage container consists of the concrete cost (C_C), the reinforcing horizontal and vertical steel bars costs (C_R), and the formwork cost (C_F) [30-31]:

$$C_T = C_c + C_R + C_F. \tag{3.14}$$

The cost of concrete is calculated using Eq. 3.15;

$$C_c = V_c C_{cu}. \tag{3.15}$$

Where V is the concrete volume, and C_{cu} is the concrete cost per m^3 (€/m^3).

$$C_R = V_C \gamma_S C_S (\beta_c + \beta_v). \tag{3.16}$$

Here, β_c is the ratio of circumferential steel which can be calculated using Eq. (3.17), V_C is the concrete volume, γ_S is the unit weight of steel (t/m^3), and C_S is the steel cost per t (€/t).

$$\beta_c = \frac{A_S}{A_C}. \tag{3.17}$$

Where A_S is the area of circumferential reinforcement and A_C is the area of concrete section. The vertical steel ratio is typically taken as 1% of concrete gross area. In this work, the reinforcement ratio is valued as 1% for the base and the roof of the container, and 2% for its walls.

The construction process makes use of formwork as mold for the concrete structure. To determine the formwork cost, Eq. (3.18) is used.

$$C_F = A_T C_{FU}. \tag{3.18}$$

C_{FU} is the cost of double face of formwork.

3.3. Design Model Optimization

The design of energy storage is cost-driven. Hence, minimizing the cost of the storage system is crucial as it enables the technology to become attractive compared to other energy storage systems. The objective of this optimization model is to find the storage optimal sizing that minimizes the overall cost of the technology while keeping the same energy production and avoiding system failure. The previously described design problem can be formulated as the following nonlinear program (NLP):

$$min_c\, f(C) = k_1D^2 + k_2D^2H + k_3DH + k_4D + k_5H + k_6 \tag{3.19}$$

Subject to:

$$D^2H^2 - k_7 = 0 \tag{3.20}$$

$$H - D > 0 \tag{3.21}$$

$$0 < H \leq H_L \tag{3.22}$$

$$\mathrm{D} > 0 \tag{3.23}$$

The goal is to minimize the cost objective function by selecting appropriate value of H (container/return pipe height) and D (piston diameter/ inner diameter of the container) that satisfies all constraints. The cost function f(C) takes into account the excavation and construction cost of the different components of gravity storage which include the container, the piston, as well as the return pipe to identify the best possible storage sizing of a specific energy storage capacity.

The aim of this model is to optimally size storage with a specific capacity. Hence, the model is first constrained by the storage capacity (Eq. 3.20) which is represented by only the container parameters (Eq. 3.4). The second linear constraint (Eq. 3.21) is used to prevent the piston jamming as found in (Eq. 3.7). H_L represents the container's height limitation (Ep 3.22); reflecting the fact that the maximum container's high should be provided as an input for the optimization. Finally, both parameters of the container must be positive (Eq. 3.22-3.23).

As an application of the model, this section presents an optimal sizing of the 20 MWh case study presented in section 3.2.3. In this case study, the k values were calculated using (Eq. 3.13-3.18). While k_7 was found using (Eq. 3.4) with an energy capacity of 20 MWh. The different k values of the cost function and the nonlinear constraints are presented in Table 3.1.

The nonlinear optimization model was solved using MATLAB OPTI TOOLBOX. The Matlab code of this model is presented in Appendix A. The result of this optimization is shown in Fig. 3.1. The optimum height of the container was found to be equal to 450 m while the diameter is 5.8 m. The optimal cost function is equal to 30.766 Million Euros.

Table 3.2. k values of the optimization probelm

k_1	1779.4
k_2	397.4
k_3	6886.52
k_4	38183.4
k_5	14134.96
k_6	149748.4
k_7	6805078.2

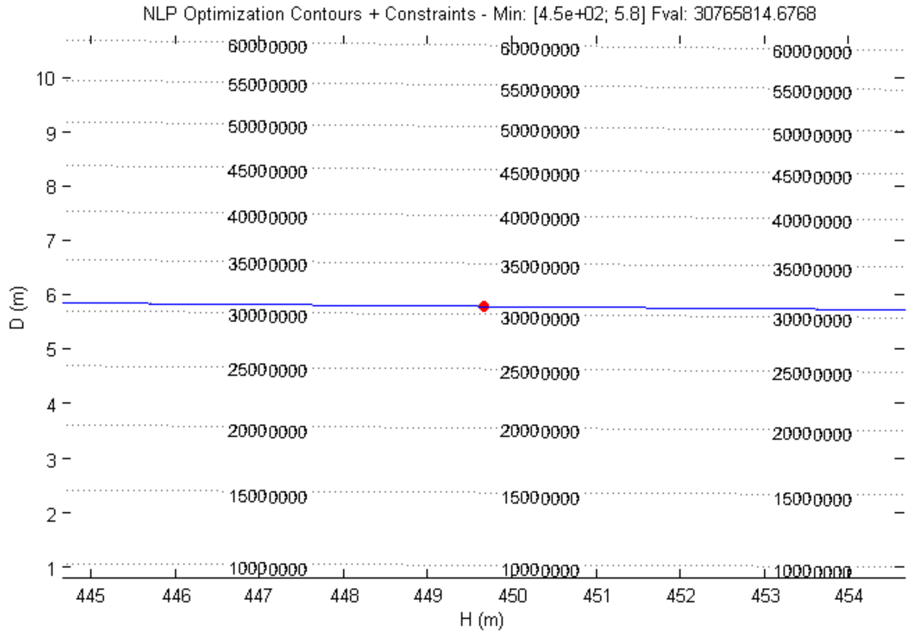


Fig. 3.1. Sizing Optimization with $H_L = 500$ m

The optimization for storage system with $H_L = 100$ m is presented in Fig. 3.2. The cost of the storage increases significantly when decreasing the container's high. As can be observed, this optimization model illustrates that it is more cost effective to construct a container with a higher height H than a larger diameter D.

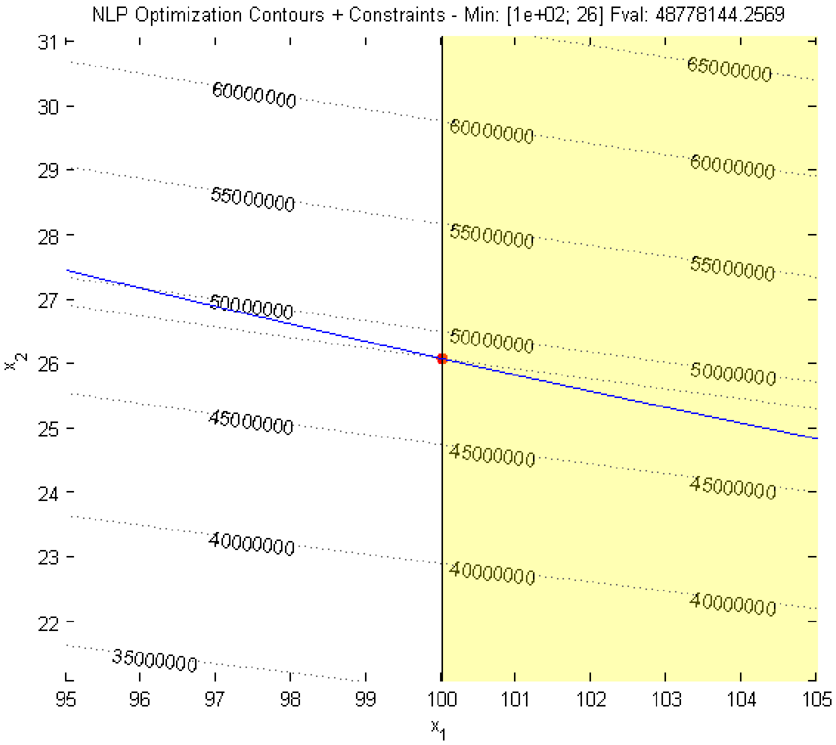


Fig. 3.2. Sizing Optimization with $H_L = 100$ m

3.4. Storage Applied Materials

The design phase of a storage device requires making decisions regarding the appropriate materials applied to the storage components.

3.4.1. *Piston Material*

The piston is considered an important component of gravity storage as it plays a significant role in pressurizing the flowing water. The piston operates in a demanding environment in which the delivery of high pressure is required. With a number of different materials to choose from, each with its own characteristics, choosing the appropriate material is a difficult task. Criteria used, for identifying the optimum materials, to construct the piston include cost and density. The capacity of gravity storage is a function of the piston density as illustrated in Eq. 3. 2. Therefore, the density of the piston has a significant impact; on the overall system energy production. In addition, the cost of the piston’s material is crucial in selecting the most economical piston; that would maximize the energy production.

In this analysis, four potential construction materials were considered which include lead ore, iron ore, concrete, and aluminum. Fig. 3.3 presents the characteristics of the investigated construction materials. The proposed costs do not include processing, transportation, and remaining value of these raw materials after the storage system lifetime. Higher costs may be incurred if these aspects are considered [32].

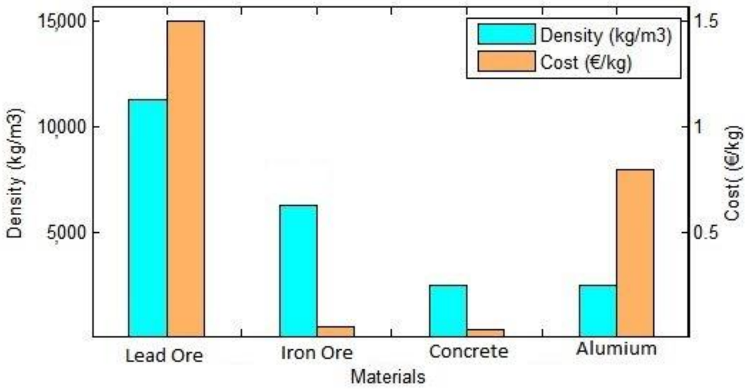


Fig. 3.3. Material Properties.

A comparison of the piston material cost and energy production is illustrated in Fig. 3.4. Among all the investigated materials, lead ore has the highest density. Constructing a piston with this material significantly improves the energy production of gravity storage as illustrated in Fig. 3.4. However, the cost of lead ore is very high compared to other materials. Therefore, it is not economically viable, and should not be selected as an optimum material. Concrete and aluminum are less costly; but they both have low densities. Compared to the cost of iron ore, concrete material is cheaper. However, the density of this later is less than twice the density of iron ore. Therefore, if concrete material is used, the diameter of piston has to be doubled; in order to equate the mass of the piston. This would achieve the same energy production as that obtained with iron ore material. However, doubling the size of the piston will result in higher construction cost of the container. Therefore, low density materials would only incur high construction cost if they are used as they would require bigger sizes to offset their low densities (Fig. 3.5). This material analysis demonstrates that iron ore is the most optimal inner material to be used in the construction of the piston because of its high density and low cost compared to the other investigated materials.

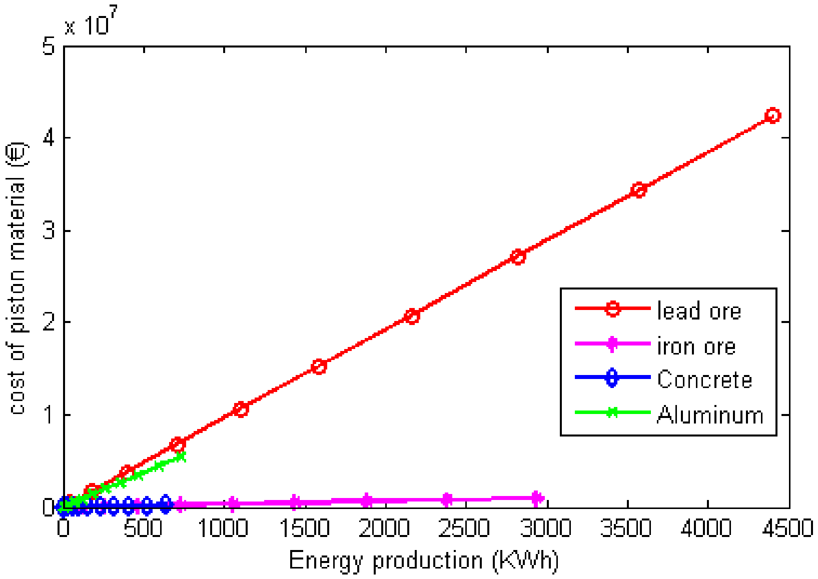


Fig. 3.4. Cost of The Piston vs Energy Production for Different Piston Materials.

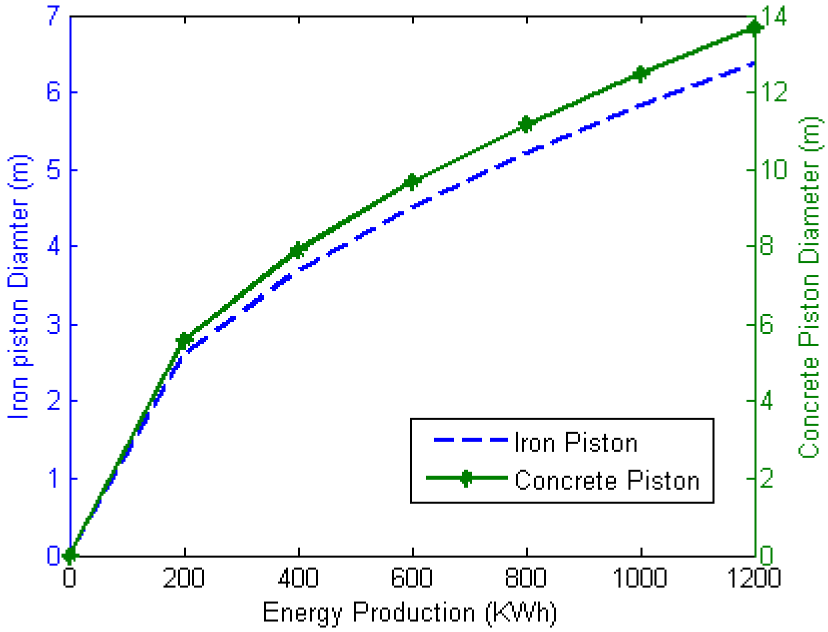


Fig. 3.5. Energy Production vs Iron and Concrete Piston.

Piston inner material should be cased to avoid chemical mixing with water. The strength of the casing should be high because it is used to hold high density materials (iron). Therefore, it is crucial to construct the casing of the piston from robust and water tight materials such as steel. In addition, it must prevent water from flowing across the piston by the utilization of hydraulic seals. These seals build up pressure above/below the piston and minimize leakage. Hydraulic seals have to withstand high pressures, and transverse forces within the cylinder. Common sealing material is Polytetrafluoroethylene. It is typically used in hydraulic, pneumatics and in the field of renewables due to its high wear resistance. Plastic polymers used as sealant reduces piston velocity and friction.

3.4.2. Container Materials

The development of the engineering design and the advance in fabrication technologies and coating processes increased the performance of container products. Properly selecting the right material for the storage container requires an investigation and consideration of a series of factors. Yet, the material selection process of the container is mainly driven by quality and value. This selection is based on the performance requirements which include robustness, lifetime, and cost. In this case, the storage container should be robust; it has to resist the pressure that is due to the piston and the water loads. In addition, it should have a smooth surface to reduce fiction between piston and container inner surface.

For small scale gravity storage, the most commonly used container materials include concrete, steel, plastic and fiberglass. A Finite element analysis (FEA) simulation is performed to investigate the effect of pressure on these applied materials.

Concrete Container: concrete tanks have been used for many years. They are durable and have good quality that can last several decades. To increase the strength of concrete tank, other materials can be added such as plasticizers. Furthermore, to prevent leakage, it is poured into a seamless mold. However, containers that are made of concrete are not easy to repair compared to steel and fiberglass tanks. Concrete tank is vulnerable for tensile stresses. It is often reinforced using steel to increase its tensile resistance. However, the addition of reinforcing steel into concrete can create another problem which affects its durability. These tanks can crack and break in case the reinforcing steel corrodes. They have generally a rough surface that need to be smoothed in order to reduce friction between the piston and container's walls.

Steel Container: This type of tanks is mostly made of galvanised steel; a zinc coating that protects steel from corrosion. However, galvanised steel corrodes and rusts. To overcome this problem, steel tanks, except stainless steel type, are made from material known as Aquaplate steel. However, it is expensive and can break over time. Stainless steel tank is another type of tanks made of steel. This product is much more expensive than all other types of steel tanks. It has a large tensile resistance which is one of the requirements for this application. In addition, it has a surface that is quite smooth. Compared to concrete, steel is relatively more vulnerable to corrosion, expensive and less durable.

Plastic Container: Another common material used to construct containers is plastic. Plastic containers are light and available in various sizes. Polyethylene is one of the most popular tank materials because of its strength, flexibility, lightness, non-corrosion, and low cost.

Fiberglas Container: tanks made of fiberglass materials are less common than plastic tanks. They are very rigid and have a high resistance to corrosion. They are reasonably light and thin which make them relatively brittle and vulnerable to cracking. However, they can be easily repaired.

The container's cost varies depending on the manufacturing material used. Plastic is considered the cheapest material followed by fiberglass, steel, and precast concrete [33].

For large scale gravity storage, the container is subjects to extremely high pressure due to the piston and the water loads. Therefore, the material that could be used to construct the container is either steel or reinforced concrete. The main advantages of reinforced concrete containers over steel containers include high resistance to compression stresses and long life time which is about 50 years compared to steel tanks (up to 20 years) [34]. Another concern about steel as a construction material is that it is sensitive to corrosion problems, geometric imperfections, and buckling. On the other hand, reinforced concrete containers have also some disadvantages which are related to low tensile strength and the large thickness required to satisfy design requirement. Moreover, steel storage containers are leak-free structures and provide high tension resistance compared to reinforced concrete. Steel reinforced concrete containers are the most common type in developing countries because they are cost effective compared to its counterpart [35]. In addition, the masonry and carpentry skills for construction of steel reinforced concrete containers are often locally available.

Despite the advantage of using steel as a construction material for storage tanks, reinforced concrete material is selected in this work as construction material for this storage technology due to the fact that it more cost effective than its counterpart.

3.4.3. Selection of Material using FEA Method

A simulation analysis is done on the piston and hydraulic cylinder under specified boundary conditions in order to examine the impact of the water and piston pressure on the container. A finite element analysis is performed to compare the stress, displacement and strain of the investigated container applied materials. This work investigates the design of a laboratory prototype. The height of the container used in this case study is 1.5 m with a diameter of 0.5 m. SolidWorks was used to design the piston and the container models with different materials that are under analysis.

3.4.3.1. Finite Element Analysis

Finite element analysis is performed using SolidWorks FEA program to analyze the response of the container to the applied pressure loads. The most common use of FEA is in structural analysis. In this context, different materials will be applied to the container under specified pressure.

The container experiences a varying internal pressure along its height due to the increasing water pressure along its depth. In addition, it is also subject to the piston load and to a cyclic load when it is emptied and filled. The internal pressure at a location x of the container height is represented by Eq. 3.24.

$$P_x^i = \rho_w g x_H + (\rho_P - \rho_w) g h. \tag{3.24}$$

Typically, gravity storage is placed underground. An external pressure due to lateral earth pressure is applied and is expressed as:

$$P_x^e = k_0 y x_H. \tag{3.25}$$

To investigate the internal stability of the container, internal load will be applied on the container's walls and bottom. The piston load is not directly applied on the container; rather it is applied on the water. The piston pushes the fluid to all side of the container which creates both vertical and horizontal water pressure. The water pressure has a non-uniform distribution.

In this case study, four simulations would be run to investigate the pressure impact on different material applied to the container which includes plastic, fiberglass, steel, and reinforced concrete. Fig. 3.6, 3.7, and 3.8 present a comparison of these simulations.

Strength of the container is the stress at which it will fail. SolidWorks simulation uses the von-Mises or maximum-distortion-energy theory to predict the structure failure. Fig. 3.6 illustrates the resulting von-Mises equivalent stress. The stress inside the container changes from the top to the bottom. The color changes from dark blue to light blue and green. This change indicates that there has been an increase in stress. The stress concentration near the container outlet is significant. For all scenarios, the maximum stress value is reached in the tank outlet. This value differs slightly depending on the container's material as illustrated in Fig. 3.6. The large stress value at this region is explained by the high pressure applied there. The resulting von-Mises equivalent stress is then compared to the material's yield strength to foresee yielding of the structure and to calculate the factor of safety (FOS). This factor is determined by dividing the yield strength or the ultimate tensile stress of the material over the maximum Von Mises Stress. Several codes require a minimum FSO ranging between 1.5 and 3.0. The lowest factor of safety obtained in this analysis is 2.5 for reinforced concrete container. The FOS results indicate that the container will not fail for all the other investigated materials.

In addition to stress analysis, SolidWorks performs a displacement and strain analysis. The displacement analysis is presented in Fig. 3.7. The material displacement which occurs at the bottom of the cylinder is due to the high water pressure and the large piston load experienced at the bottom of the container. Steel has the lowest displacement ratio followed by glass, and concrete. The maximum displacement occurs in the tank made of plastic and it is equal to 3.207mm. The results indicate that pressure load has more impact on plastic containers.

Strain represents the displacement of a point relative to its adjacent points [36]. Strain analysis is presented in Fig. 3.8. The strain is high for both plastic and concrete container as it is represented in red and orange colors. The maximum strain for plastic is equal to $3.073*10^{-3}$.

Based on the performed analysis, steel should be more commonly applied to the container because of its ability to resist high pressure. However, high strength concrete that is pre-stressed and reinforced with the incorporation of steel can also be used.

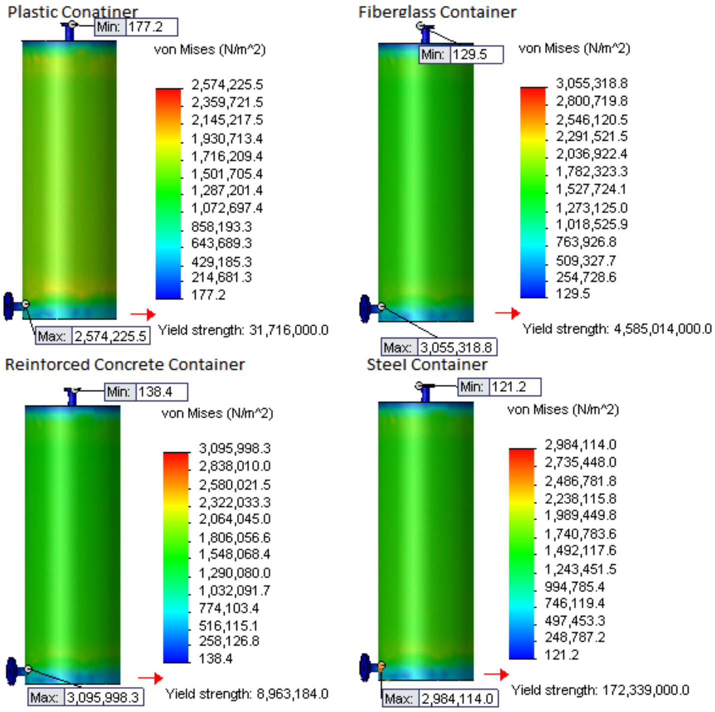


Fig. 3.6. Stress Analysis

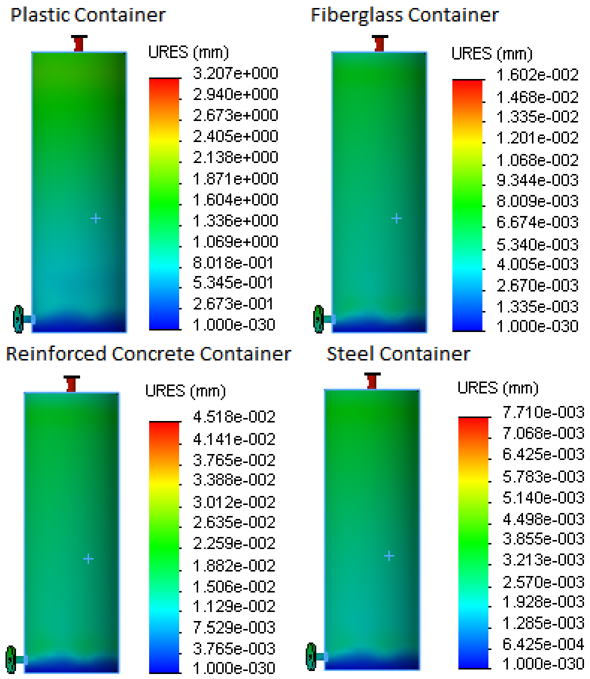


Fig. 3.7. Displacement Analysis

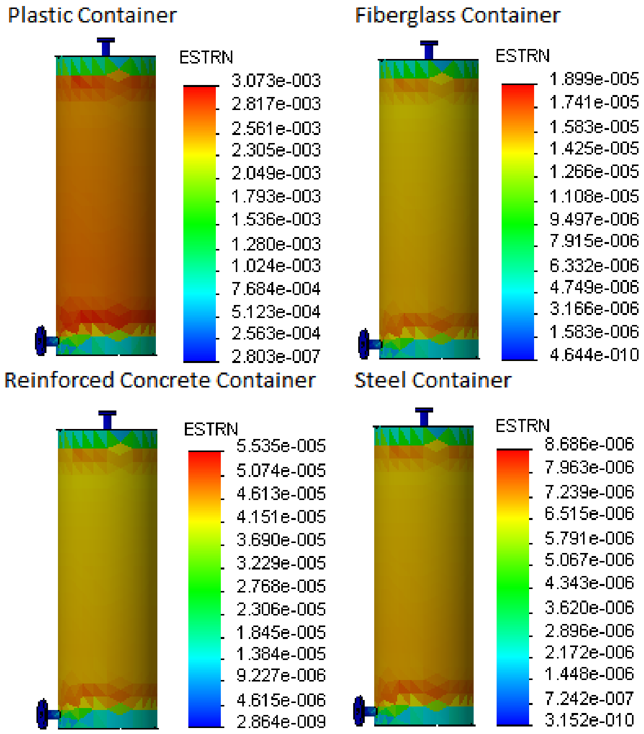


Fig. 3.8. Strain Analysis

3.5. Sizing of gravity storage System

In order to identify the sizing of gravity energy storage system, a model has been proposed. The objective of this problem is to maximize the owner’s profit. This is accomplished by optimally operating the energy dispatch of the hybrid renewable farm (wind plant with storage). Short term forecast of energy prices and electricity generation are provided as input data.

The model considers the main operational restrictions for the hybrid energy system. Modeling assumptions are based on the optimization problem proposed by [24]. Transactions are made only on the day-ahead market, with energy being dispatched on an hourly basis, for a window of 24h. Energy demand and transmission capacity are not considered by the model. In addition, these are assumed to be infinite. Energy output and storage operation performance are presumed to be constant throughout the hour. Start-up of energy storage is considered as being instantaneous. Finally, it is assumed that energy prices remain constant and are not affected by the storage size.

3.5.1. Sizing algorithm

The sizing model is set up as a non-linear programming (NLP) problem. The input parameters of the model include: profiles of renewable power generation, energy market price, energy storage cost, and technical characteristics. The output parameters of this model are: optimal hourly dispatch profile, hourly profit of the hybrid renewable farm, and maximum capacity of storage. The profit that could be generated from the use of energy storage is found by altering the capacity of the storage. Maximum capacity is reached when the profit is maximized. Since the sizing of storage is determined from the perspective of maximizing profit, then the objective function is given as:

$$Max\left[P_r = \mathrm{Re}\,v(t) - \mathrm{Cos}\,t\left(t\right)\right]. \tag{3.26}$$

P_r is the owner's profit which must be maximized. *Rev(t)* and *Cost(t)* are the hourly revenues and costs of the hybrid farm, respectively. The objective function of this model is to maximize the profit of the renewable energy farm. Profit is equal to operation revenue minus service cost.

Hourly revenues are the product of hourly energy sold to the utility grid, and hourly electricity price $P_E(t)$. The energy sold to the grid is the sum of the energy sold/discharged from the storage $E_D(t)$, and the energy sold/injected directly to the grid; from the renewable energy farm without being stored, $E_R(t)$. Rev(t) can be expressed as (Eq. 3.27).

$$\mathrm{Re}\,v(t) = \left[E_D(t) + E_R(t)\right]P_E(t). \tag{3.27}$$

The total cost of energy storage is broken into two types of costs which are fixed and variable costs. Fixed costs are incurred by the hybrid renewable farm, regardless of how much energy it produces. Fixed costs do not vary with energy production levels. On the other hand, variable costs are expenses that depend on the farm energy production level. Only these are considered when making short run decisions. According to the definition of short-term scheduling and unit commitment problems, only short-term costs of fuel, start-up, operation and maintenance, and environmental emissions, identified as operation costs, must be considered as stated in [37-38]. It is to be noted that no fossil fuel is consumed by gravity energy storage and no environmental emissions are produced by this system. Therefore, the storage cost considers only operation and maintenance cost, and is given by:

$$\mathrm{Cos}\,t(t) = C_{O\&M} \sum (E_S(t)). \tag{3.28}$$

Where ($C_{O\&M}$) is the storage operation and maintenance cost in (€/kWh); $E_D(t)$ is the energy stored at time t.

The storage level varies, depending on the amount of energy that flows in and out from the system. The technical characteristics of the storage, such as efficiency and self-discharge, should be taken into account while determining the hourly energy storage level.

$$S(t) = (1\text{-}\delta)S(t\text{-}1) \text{-} E_D(t) + (E_S(t)\eta). \tag{3.29}$$

The storage state ($S(t)$), at a particular time t, is the sum of the existing storage level ($S(t\text{-}1)$) and the energy added to the storage at that time ($E_S(t)$); minus the storage self-discharge, δ, at (t-1) and the storage discharged energy ($E_D(t)$), at time t. Energy losses due to self-discharge and energy efficiency (η) are also taken into account.

Additional constraints on the storage level are presented in Eqs. (3.30-3.31). The state of the storage system must always be positive, and less than the capacity limit of the storage $S_{Limit}(t)$.

$$0 \le S(t) \le S_{Limit}(t). \tag{3.30}$$

This storage level, at a specific time, must as well be greater or equal to the storage discharged energy.

$$S(t) \ge E_D(t). \tag{3.31}$$

To control energy that is charged and discharged from the storage system at time t, constraints introduced through Eqs. (3.32-3.33) are used.

$$E_D(t) \le E_L. \tag{3.32}$$

$$E_S(t) \le E_L. \tag{3.33}$$

Where E_L is the energy storage limit. Another constraint about energy dispatch is presented in Eq. (34). All energy variables must be positive. $E_G(t)$ is the energy generated by the renewable farm.

$$E_S(t),\ E_D(t),\ E_R(t),\ E_G(t) \ge 0. \tag{3.34}$$

Energy generated from the renewable farm is either sold directly to the utility grid, without being stored, or sent to storage for later trade. This constraint is expressed through Eq. (3.35).

$$E_G(t) = E_S(t) + E_R(t). \tag{3.35}$$

Since the objective of this model is to maximize profit, from optimally dispatching energy, a storage control constraint should be added; to optimally charge and discharge the system. In order to make more profit, the storage should not charge and discharge energy at the same time. This is due to the loss of energy in this process, owed to system inefficiencies. Therefore, it is cost-effective to sell energy directly to the grid; rather than simultaneously storing it and discharging it at the same time. This constraint is illustrated by Eq. (3.36).

$$E_S(t)E_D(t)=0. \tag{3.36}$$

3.5.2. Case study

A case study is performed to evaluate the effectiveness of the proposed model. The non-linear programming model is solved; using General Algebraic Modeling System (GAMS) software. The model code is presented in appendix B1. The proposed sizing strategy can be applied to various types of storage. This case study makes use of gravity energy storage which is considered suitable to be used in large scale applications. The technical and economic parameters of this storage system are used as inputs. The system operation and maintenance cost is equal to 0.4 €/kWh with a storage efficiency of 80% [39]. Historical data of wind generation and energy prices are obtained from “Red Eléctrica de España, S.A.” (REE) website, for January 1th, 2017 [40]. The total number of wind farms in Spain is approximately 992. Hourly Wind electricity generation is shown in Fig. 3.9a. Wind farm generation reaches its maximum at 11 PM, while low energy production occurs at noon. Fig. 3.9b illustrates the hourly energy prices. These prices vary throughout the day and tend to be lower from 4 to 7 AM. Energy prices are high during peak periods especially in the evening from 6 to 10 PM.

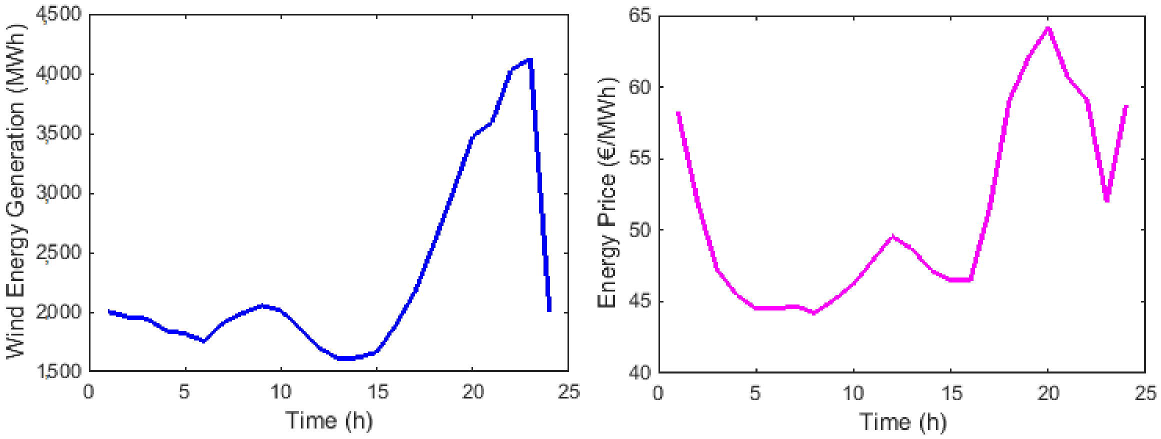


Fig. 3.9. a) Hourly wind energy generation; b) Hourly energy prices

The identified optimal operational strategy of the hybrid farm results in a maximum profit. This profit remains constant even if the storage capacity is increased. Therefore, increasing the capacity of the storage will not be beneficial to the owner. Hence, the maximum capacity of the storage is reached when the profit is maximized. The results obtained from the proposed methodology demonstrate the effectiveness of the proposed sizing strategy. The profit generated by the hybrid renewable farm with different storage capacities is illustrated in Fig. 3.10. It is shown that more profit would be generated with greater storage capacity. However, for capacities exceeding 121 GWh, the profit remains constant. Since the maximum sizing capacity of the storage is determined from the perspective of profit maximization, the maximum capacity of the storage, in this hybrid renewable farm, is equal to 121 GWh. One should keep in mind that this model does not consider the constraint of meeting energy demand, and transmission capacity limits [24]. In this case, the hybrid renewable farm charges the storage, to its maximum energy capacity, when the energy prices are low, and discharges it only if the energy prices are high to maximize the profit.

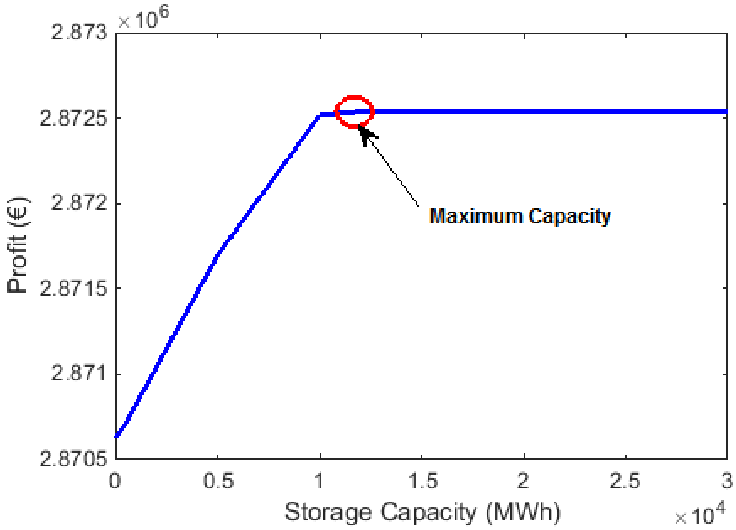


Fig. 3.10. Storage capacity vs profit.

By verifying optimal situations where the objective function takes the maximum value, the presented algorithm calculates the storage owner benefits. Depending on the value of the objective function, the optimum charging and discharging of the storage are identified.

Energy is stored when electricity prices are low. This is illustrated in Fig. 3.11, as the storage system is being charged from 5 to 8 AM. It is then kept on standby, from 8 AM to 7 PM, until the energy prices increase. At that time, energy is discharged from the storage and sold to the utility grid. Fig. 3.12 shows the discharging of the storage from 7 PM to midnight; following an increase in energy prices. Discharging of the storage when energy prices are high; allows the owner to make more profit.

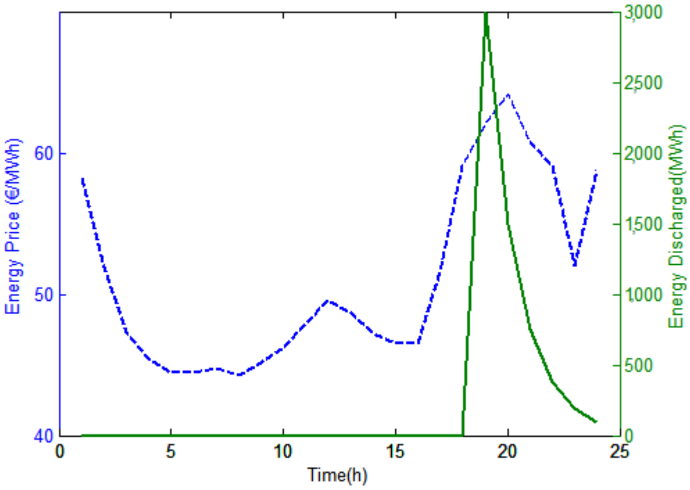


Fig. 3.11. Hourly energy stored vs. energy prices.

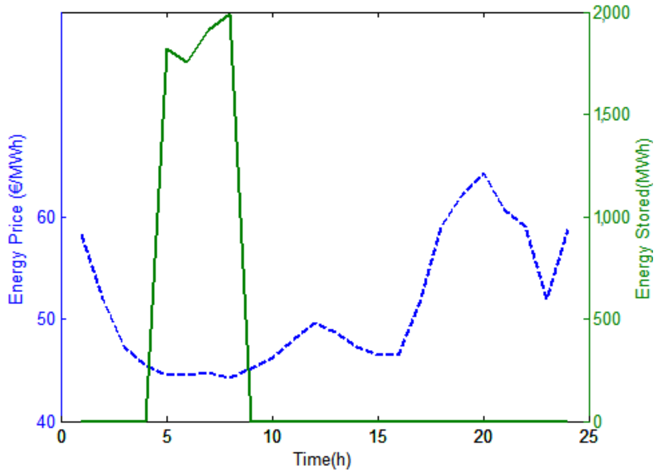


Fig. 3.12. Hourly energy discharged from storage vs. energy prices.

The hourly profit of the hybrid renewable farm is shown in Fig. 3.13. A correlation between hourly electricity prices and profit exists. Profit is increased when energy price goes up. Conversely, the profit is reduced to zero when energy prices are very low. An increase in hourly profit is due to the selling of electricity discharged from the storage. Thus, the hybrid renewable energy farm generates more profit when the energy prices are high. Therefore, profit is maximized by optimally dispatching energy between wind farm, storage, and utility grid using the proposed model.

The implementation of the proposed sizing strategy maximizes the profit of the storage owner under simplifying assumptions, by determining the optimal dispatch schedule of the storage system; Hence identifying the storage capacity able to generate maximum profit.

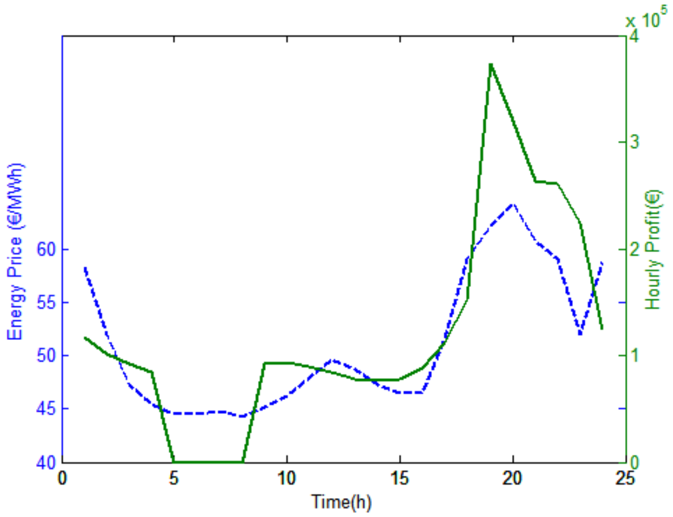


Fig. 3.13. Hourly revenues vs. energy prices.

3.6. Conclusion

A methodology to properly design gravity storage components was presented in this chapter. The implementation of this method increases the energy storage capacity and identifies the system design limitations in order to avoid system failure. A nonlinear optimal design model was then proposed to minimize the cost of gravity storage while satisfying all constraints. This optimization showed that it is more economical to increase the height of the container than its diameter for a specific storage capacity. The dimensions of the storage used in this case study were determined through the parametric analysis.

Identification of critical materials applied to gravity storage components was conducted in this work. Two criteria were taken into consideration for the selection of the piston materials which are density and cost of the material. The piston density has a significant impact on the energy production of the storage system. Among the investigated materials, iron ore would be the best candidate as it has a high density and a low cost compared to other materials. Therefore, a piston made of iron ore would economically increases the energy production of the storage technology. Concerning the materials used to construct the container, the selection was based on the structure performance requirements which include lifetime, cost, and robustness. The performed FEA analysis helps predict failure of the system prior to manufacturing and testing. For small scale gravity storage, steel would be the best candidate based on SolidWorks simulation. In case of large scale gravity storage with high pressure, reinforced concrete has longer lifetime, and lower cost than its counterparts.

An approach to optimally design gravity energy storage system was proposed. This technical analysis allowed for the design of an optimal system that could generate a specified energy production while satisfying all constraints. In addition, a detailed storage model has been developed using technical design, economics, and electricity market parameters. Gravity energy storage has been described by the use of its performance parameters which include storage charge/discharge efficiency, system capacity, and discharging period. These parameters were used to identify the arbitrage potential of the storage system. The objective of the proposed model was to determine the storage operating strategy able to maximize the profit of the storage owner with an attempt to identify the maximum storage capacity. In this manner, gravity storage was sized according to a criterion of maximum owner profit, by determining the optimal charge/discharge schedule. The results obtained from the presented approach demonstrate the effectiveness of the proposed sizing strategy. Wind farms, with a properly sized storage, can take advantage of the hourly energy price fluctuation; to sell energy when the prices go up and make more profit. The proposed sizing model could be applied to various types of storage. By optimizing the design and sizing of this energy storage and by identifying the benefits of its functionality, gravity energy storage might be able to compete with current storage solutions.

References:

[1]. Libowitz, George G & Whittingham, M. Stanley (Michael Stanley), 1941- (1979). Materials science in energy technology. Academic Press, New York

[2]. G.G. Libowitz, M.S. Whittingham, Materials Science in Energy Technology (Academic Press, New York, 1979).

[3]. M. Stanley Whittingham, Materials Challenges Facing Electrical Energy Storage. Binghamton University, USA. [Online].Available: https://www.mtixtl.com/documents/paper.pdf

[4]. Liu, C., Li, F., Ma, L.-P. and Cheng, H.-M. (2010), Advanced Materials for Energy Storage. Adv. Mater., 22: E28–E62. doi:10.1002/adma.200903328

[5]. Fernandez. L.A, Martínez. M, Segarra. M, I. Martorell. L, Cabeza. F. L. Selection of materials with potential in sensible thermal energy storage. Solar Energy Materials and Solar Cells 2010; 94(10): 1723–1729.

[6]. Deokar, A.J.; Yadav, S.D.; Yadav, S.N., "Material selection for biogas storage cylinder using fuzzy decision making method and FEA method," in Energy Efficient Technologies for Sustainability (ICEETS), 2013 International Conference on , vol., no., pp.400-406, 10-12 April 2013

[7]. Chennababu. M., Krishnareddy.V.(2015). Modeling and analysis of water tank stand. International Journal of Research in Mechanical Engineering & Technology.

[8]. Ucar. A, Inalli.M. A finite element model of solar heating system with underground storage. International Journal of Thermal Sciences 2008; 47(12): 1639-1646

[9]. A. Berrada, K. Loudiyi, and I. Zorkani. Sizing and economic analysis of gravity storage. Journal of Renewable and Sustainable Energy 8, 024101 (2016)

[10]. Chen C, Duan S, Cai T, Liu B, Hu G. Optimal allocation and economic analysis of energy storage system in microgrids. IEEE Trans Power Elec 2011;26(10): 2662–773.

[11]. Sharma S, Bhattacharjee S, Bhattacharya A. Grey wolf optimisation for optimal sizing of battery energy storage device to minimise operation cost of microgrid. IET Gener Transm Distrib 2016;10(3):625–37. http://dx.doi.org/ 10.1049/iet-gtd.2015.0429.

[12]. Atwa M, El-Saadany E. Optimal allocation of ESS in distribution systems with a high penetration of wind energy. IEEE Trans Power Syst 2010;25(4):1815–22.

[13]. Carpinelli G, Mottola F, Proto D, Russo A. Optimal allocation of dispersed generators, capacitors and distributed energy storage systems in distribution networks modern electric power systems conference, September 2010, p. 1–6.

[14]. Changsong C, Duan S, Cai T, Liu B, Hu G. Optimal allocation and economic analysis of energy storage system in microgrids. IEEE Trans Power Elec 2011; 26(10):2762–73.

[15]. Pavković D, Hoić M , Deur J , Petrić J. Energy storage systems sizing study for a high-altitude wind energy application. Energy 2014; 76:91-103.

[16]. Zheng Yu, Dong Zhao Yang, Luo Feng Ji, Meng Ke, Qiu Jing, Wong Kit Po. Optimal allocation of energy storage system for risk mitigation of DISCOs with high renewable penetrations. IEEE Trans Power Syst 2014;29(1):212–20.

[17]. J. P. Fossati, A. Galarza, A. Martín-Villate, and L. Fontán, "A method for optimal sizing energy storage systems for microgrids," Renewable Energy, vol. 77, pp. 539-549, 2015.

[18]. A. Zucker and T. Hinchliffe, "Optimum sizing of PV-attached electricity storage according to power market signals–A case study for Germany and Italy," Applied Energy, vol. 127, pp. 141-155, 2014.

[19]. D. Pavković, M. Hoić, J. Deur, and J. Petrić, "Energy storage systems sizing study for a high-altitude wind energy application," Energy, 2014.

[20]. M. Masih-Tehrani, M.-R.Ha'iri-Yazdi, V. Esfahanian, and A. Safaei, "Optimum sizing and optimum energy management of a hybrid energy storage system for lithium battery life improvement," Journal of Power Sources, vol. 244, pp. 2-10, 2013.

[21]. V. Musolino, A. Pievatolo, and E. Tironi, "A statistical approach to electrical storage sizing with application to the recovery of braking energy," Energy, vol. 36, pp. 6697-6704, 2011.

[22]. D. Feroldi and D. Zumoffen, "Sizing methodology for hybrid systems based on multiple renewable power sources integrated to the energy management strategy," International Journal of Hydrogen Energy, vol. 39, pp. 8609-8620, 2014.

[23]. H. Schaede, M. Schneider, and S. Rinderknecht, "Specification and Assessment of Electric Energy Storage Systems based on Generic Storage Load Profile," 13. Symposium Energieinnovation, pp. 1-10, 2014.

[24]. A.Berrada, K.Loudiyi. Operation, sizing, and economic evaluation of storage for solar and wind power plants. Renewable Sustainable Energy Rev. 2016; 59: 1117–1129

[25]. Bennett CJ, Stewart RA, Lu Jun Wei. Development of a three-phase battery energy storage scheduling and operation system for low voltage distribution networks. Appl Energy 2015;146(15):122–34. http://dx.doi.org/10.1016/j. apenergy.2015.02.012.

[26]. Khorramdel H, Aghaei J, Khorramdel B, Siano P. Optimal battery sizing in microgrids using probabilistic unit commitment. IEEE Trans Ind Informatics 2016;12(2):834–43. http://dx.doi.org/10.1109/TII.2015.2509424.

[27]. A. V. Beek, Advanced Engineering Design, 2012.

[28]. Civil Engineering Projects, see http://www.civilprojectsonline.com/building-construction/reinforced-circular-water-tankdesign- of-rcc-structures/ for Reinforced Circular Water Tank/Design of RCC Structures.

[29]. G. S. Suresh, Design of Water Tanks, National Institute Of Engineering, Mysore.

[30]. 2M. A. El Reedy, Construction management and design of industrial concrete and steel structures (Taylor & Francis Group, 2011), p. 576.

[31]. M. Tareq, “Behaviour of reinforced concrete conical tanks under hydrostatic loading,” M.S. thesis (University of Western Ontari, 2014).

[32]. Indexmundi, 2015. Commodities Market Prices. Available at: http://www.Indexmundi.com/commodities/.

[33]. Material Cost. .[Online].Available: www.infomine.com

[34]. Cheremisinoff P. N,. Advances in Environmental Control Technology, Storage Tanks Gulf Professional Publishing, Houston, Texas; 303 pp.

[35]. Gerard F.J, (2011). Gravity Driven Water Network: Theory and Design

[36]. CAD Animation. .[Online].Available: www.solidworks.com

[37]. M. E. Nazari M E, and M. M. Ardehali M M. Optimal coordination of renewable wind and pumped storage with thermal power generation for maximizing economic profit with considerations for environmental emission based on newly developed heuristic optimization algorithm. Journal of Renewable and Sustainable Energy 8, 065905 (2016); doi: http://dx.doi.org/10.1063/1.4971874

[38]. R. A. Abarghooee, T. Niknam, A. Roosta, A. R. Malekpour, and M. Zare. Probabilistic multiobjective wind-thermal economic emission dispatch based on point estimated method. Energy 37, 322 (2012).

[39]. Aneke, M. & Wang, M., 2016. Energy storage technologies and real life applications - A state of the art review. Applied Energy, 179, pp.350-377

[40]. Ree, 2017. Red Eléctrica de España, S.A. (REE). URL: http://www.ree.es/en.

Chapter 4

4. Economic Analysis and Valuation of Energy Storage

High share of intermittent renewable energy sources disrupts the reliability and the proper operation of the electric grid. Power systems are now on the starting point of a new transformation where high cost requirements have been imposed to secure the supply of energy. Energy storage technologies are considered as one of the solutions for stabilizing the electric grid. Currently, there are only a limited number of storage options as several technologies are at very early stage of development. This work performs an economic analysis to determine the levelized cost of energy (LCOE) for this technology, and then compares it to other storage alternatives. The obtained results demonstrate that gravity storage provide sound operating and economic characteristics compared to other storage technologies. In addition, it is still unclear whether or not energy storage will generate enough profit by interacting with energy and ancillary markets. Current economic studies on the energy storage technologies are limited because they do not explore possibilities of using storage in arbitrage and ancillary services in both day-ahead and real time markets. This chapter focuses on the economics of energy storage participating in arbitrage and regulation services within different markets. A case study on gravity storage system is used to verify the effectiveness of the proposed operation optimization model. Finally, this chapter discusses the value of storage in various grid applications.

4.1. Introduction

Energy storage technologies ensure proper balancing between demand and supply by dispatching the stored energy to fit the demand. Moreover, when the demand is low, they store the excess energy generated by renewable systems until there is a need. In addition, energy storage plays multiple functions such as stabilizing the power grid. However, the high costs of energy storage systems is a challenge that needs to be overcome in order to facilitate the increasing penetration level of renewables.

Currently, the most used storage system worldwide is pumped hydro. Alternative solutions which use the established principle of pumped hydro storage are of interest to industry and have drawn the attention of researchers. These include underground PHS, sea PHS, compressed air PHS, pump accumulation station, ocean renewable energy storage, hydraulic rock, and others. An interesting concept being considered is gravity energy storage. The economic analysis of this system is the subject of this chapter. Although a limited number of publications dealt with different aspects of gravity storage [1-4], a significant number of studies are available proposing economic analysis of other various energy storage technologies.

Recently, more focus has been moved towards the economics of energy storage. Due to the different technical characteristics of energy storage systems, it is difficult to compare them on a common basis. Several profitability studies have been performed focusing on the levelized cost of energy approach. Pawel valuated the LCOE for a PV coupled with storage systems such as Lithium-Ion, Redox-Flow and Lead-Acid [5]. The obtained results show that the LCOE is significantly affected by the storage C-rate. Zakeri and Syri performed a life cycle costs assessment for several energy storage systems [6]. These authors have studied the cost of three applications which include energy arbitrage, frequency regulation, and transmission and distribution (T&D) support. The outcomes of this analysis demonstrate that the lowest LCOE for energy arbitrage was obtained by PSH and CAES. In addition, compared to other batteries, Natrium sulfur batteries are the most economic option for both energy arbitrage and T&D support. Concerning frequency regulation applications, flywheel is considered the most cost-efficient technology. Authors in [7] presented a cost analysis approach using LCOE to determine the cost per kWh to store energy. Several storage technologies have been considered in this work. In [8], a comparison of the cost per charge/discharge cycle has been done by Ibrahim et al. for electrochemical capacitors, batteries, PHS, CAES, and flywheels. A calculation of LCOE for vanadium redox flow batteries has been performed by Viswanathan et al. [9]. Greenhouse gas emissions and Levelized cost of storage (LCOS) associated with CAES, PHS, lithium-ion batteries and Power to gas systems (PtG) have been calculated by Abdon et al. for a 1 MW and 100 MW systems [10]. The obtained results show that batteries are economically suitable technologies for short time scale, while CAES and PSH display similar LCOS. For long-term energy storage, PtG are considered the most economical technologies. In addition, Fichtner assessed the LCOS of adiabatic CAES (aCAES), PHS, and hydrogen storage for short, medium, and long term applications [11]. The outcomes of this analysis demonstrate that PSH is currently the most profitable system while hydrogen could become, in 2030, a cost efficient storage system. A similar study has been conducted by Weiss et al. for a system with 500 MW discharge power [12]. The authors show that a low cost of 2.5 €ct/kWh has been achieved by PSH without taking into consideration the cost of charged electricity. The LCOS costs of aCAES, lead-acid batteries, are of 5.3 €ct/kWh, and 15.9 €ct/kWh, respectively. It has been shown by Härtel et al. that cost per kWh rises with larger storage sizes [13]. Lazard compared the levelized cost of storage for several storage technologies to fossil alternatives [14]. The author has found that the LCOS of CAES and PSH is competitive to that of gas turbines in transmission investment deferral application. The results also show that Lithium-Ion batteries are cost efficient in frequency regulation application. In addition, it has been shown that the LCOS is mostly affected by the storage capital expenditure (CAPEX). Finally, this study revealed that some energy storage systems will substitute gas-fired power plants in the future if the cost of storage declines as expected.

The topic of gravity energy storage economical evaluation has never been explored in literature. For this reason, a framework is presented in this chapter as follows. Section 2 presents an economic analysis of this technology. This analysis identifies costs associated with the construction of the system, mechanical equipment costs, in addition to, operation and maintenance (O&M) costs. Then, a study to determine gravity storage levelized cost of energy is discussed. This later is compared to the LCOE of different energy storage systems. Section 3 identifies the value of energy storage in energy and ancillary service. Finally, Section 4 concludes with a summary of the results found in this work.

4.2. Economic analysis

It is challenging to understand the economics of energy storage installations because of the tailored nature of their potential value. Evaluating the feasibility of installing energy storage requires the performance of an economic analysis. Looking only at the initial cost of acquiring a storage technology fails to account for several aspects that impact the total cost of energy storage. A cost-oriented methodology, which takes into consideration these factors such as the system efficiency, life cycles, O&M costs, and lifetime expected power output, is known as the levelized cost of energy (LCOE). This method is used to compare the cost of energy storage systems. The LCOE is calculated by dividing the total life cycle cost over the system's total lifetime energy production. This calculation takes into consideration the time value of money with a discount rate over the system lifetime. To calculate the levelized cost of gravity energy storage, the system investment cost is found by adding all relevant construction, and equipment costs for the installation of the system.

A storage capacity of 20 MWh is used in the calculation of the levelized cost of energy. The technical design of the system has been determined according to this energy production. In addition, the height of the container has been taken as 500 m. Using this information, the geometry of the storage system is found using Eqs. (3.4), (3.8-3.12) presented in chapter 3.

In this case study, the discharge time is assumed to be 4 h [15]. This assumption allowed for the calculation of the storage flow rate, return pipe diameter, and thickness. In addition, the storage rated power (5 MW) is determined from this discharge time assumption. Storing energy will take about 5h due to the system losses. These losses include hydraulic losses due to leakage around the seals and the piston, frictional losses, and losses associated with the mechanical equipment (pump/ motor). The storage geometry simulated in this case study is presented in Table 4.1.

Table 4.1. Case study storage parameters.

Parameter	Container	Piston
Height (m)	500	250
Diameter (m)	5.21	5.21
Thickness (m)	7.6	-

To determine the levelized cost of gravity storage, the cost of the complete system is found by adding all relevant initial, variable and end-of-life costs for its installation.

4.2.1. Construction cost

The construction cost of gravity energy storage consists of the excavation costs of the container and the return pipe, in addition to the costs of the materials used to build the piston, the container structure, and the return pipe.

4.2.1.1. Excavation cost

Excavation cost, using tunnel drilling machine, was estimated based on world wide experience. Tunnel excavation costs are very high especially for difficult ground. Hoek identified typical tunnel costs incurred in major projects from various parts of the world [16]. These costs varies from 200 to 420 k€/m [17], depending on several factors such as soil conditions. In this study, tunnel excavation cost has been estimated as 310 €/m^3. The total excavation cost is obtained from the product of the tunnel volume, and the excavation cost per m^3. Hence, the excavation cost of the container and the return pipe used in this case study are equal to 1.99×10^7 €, and 83,100 €, respectively.

4.2.1.2. Piston material cost

This material investigation discussed in chapter 3, led us to consider iron ore as the most convenient inner material, for the construction of the piston.

The total cost of the inner material, used to construct the piston, is a product of iron cost per kg and mass required. For a piston with geometry of 5,347 m^3 volume; the required mass is calculated as 42,084,813 kg; this is obtained from using the material density and the piston volume. Therefore, the piston material's cost is estimated as 2 M€.

4.2.1.3. Container and return pipe material costs

Materials used to build the storage container and return pipe should be tough, durable, and cost effective. The system structure should resist the internal and external loads applied to it. In addition, because gravity storage is intended to have a long lifetime, a long-lasting material is required. As discussed in chapter 3, the most economical material that matches the discussed criteria is reinforced concrete.

Construction cost of the container includes the costs required to build the structure which consist of labor and material costs. Labor cost has been neglected in this estimation.

Construction cost of the storage container has been discussed in chapter 3 Section 2. The container structure has been divided into three modules which include: base, roof, and walls. The cost of materials and construction is estimated according to the volume of concrete and the reinforcing ratio of circumferential (i.e., horizontal) and longitudinal (i.e., vertical) steel as well as the surface area for the formwork.

Table 4.2 presents an estimation of the container and return pipe construction costs.

Table 4.2. Cost estimation of the storage components.

Construction	Cost (€)
Container's walls	8.40×10^6
Container's Roof	4.11×10^4
Container's Base	2.70×10^5
Return Pipe	9.30×10^3

4.2.1.4. Equipment cost

An estimation of the powerhouse cost is needed for calculating the total investment cost. Equipment cost is the cost of the machine sets consisting of pump/turbine and motor/generator. Gravity storage requires similar mechanical equipment used by pumped hydro storage system. This includes pump, turbine, and motor/generator. Several types of turbines can be used to convert kinetic energy, of the flowing water, to rotational energy. However, it is crucial to select the most appropriate type of turbine; that would be able to work under the specified conditions. This selection should be based mainly on the container dimensions, flow variation within the system, and equipment cost.

Besides reaction and impulse turbines, there exist pump-turbines. These later types of turbine could be used as pumps, when they operate in reverse direction. The selection, of the appropriate turbine, involves the consideration of several factors, such as: head, rpm, and starting characteristics of the turbine. The wide variety of turbines that could be implemented is mainly limited by the water head. The other design criteria should be likewise considered in the selection process. Moreover, the cost of turbines varies; as the technology depends on various setup configurations.

The most appropriate turbines that could be used by gravity storage are Kaplan and Francis turbines. After a comparison of these turbines, reversible Francis pump-turbine has been selected due to its good efficiency in both operating modes and lower cost.

Another concern, which should be taken into consideration, is the use of centralized or decentralized units. In the case of centralized generation, several storage systems (containers) are connected to a single powerhouse. On the other hand, in the decentralized generation, energy is produced from separate storage; each connected to its own powerhouse. Due to pressure losses incurred from the piping network, used in the centralized case, we opted for using decentralized unit. The costs of 5 MW Francis pump-turbine with a suitable generator, in the decentralized case, is about 900 €/kW, with a contingency of 50%. Consequently, the total investment cost for the powerhouse is around 4.5 M€ [18].

Cost division representing the different investment costs of gravity storage is illustrated in Fig. 4.1. Excavation incurs more than half (57%) of the total cost, followed by construction (31%) and equipment (13%) costs. The manufacturing costs of different system components, included within the construction cost, are also presented. The construction of the container is higher than the other manufacturing costs; as it includes formwork, reinforcement, and concrete costs. On the other hand, the return pipe requires a lower investment; as it represents only 1% of the total construction cost.

4.2.1.5. Other costs

Gravity storage and pumped hydro storage technologies uses similar equipment. For this reason, balance costs as well as operation and maintenance costs (O&M) for both storage systems are estimated to be equal. In this study, O&M cost and storage balance cost have been estimated as 1.9 €/kW and 4 €/kWh, respectively [18].

It is important to mention that the estimation of the aforementioned costs include only direct costs of the storage components such as container and piston raw materials. This estimation does not take into consideration the engineering, design and installation costs, as well as wiring and sealing costs. It is difficult to accurately estimate these costs. Therefore, the estimated costs should be regarded as preliminary; undertaking a detailed engineering study will properly estimate the system cost.

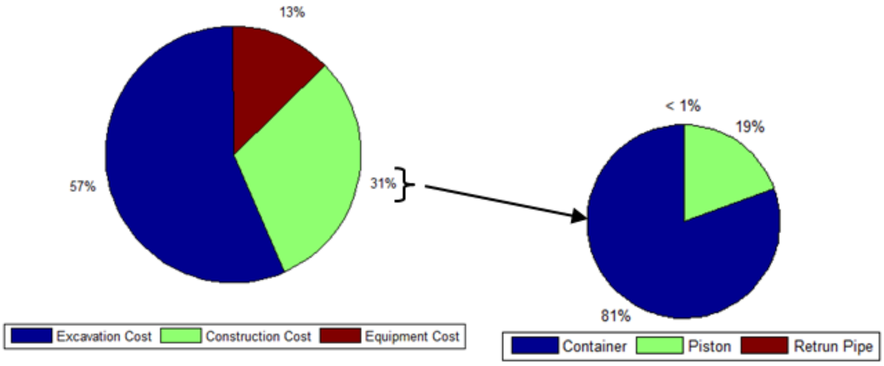


Fig. 4.1. Cost partition of storage components.

4.2.2. Gravity storage levelized cost of electricity

The levelized cost of energy (LCOE) is determined using the approach proposed in [7]. The LCOE is the annual capital cost of the storage, divided by the expected energy discharge of the system. Capital cost for gravity storage has been estimated in section 4.2.1. On the other hand, the expected energy discharge depends on the number, and length of charge and discharge cycle per day.

Energy storage systems, used for generation applications, are typically intended to store energy at night and discharge it during the day. It is estimated that the length of discharge/charge, of this type of storage, is 8h with a single cycle per day. On the other hand, energy storage used for transmission and distribution (T&D) applications; have a lower discharge length of 4h, and thus is intended to discharge twice per day. Therefore, for this case study, storage is assumed to operate in transmission and distribution applications, with a discharge of 4 h two times per day. Using this information and the results of investment costs, the levelized cost of energy was found as 0.123 €/kWh.

To examine the behavior of gravity storage levelized cost of energy, with different charge/discharge times, calculation of LCOE using various scenarios for generation and T&D applications, is carried out. Gravity storage LCOE used in generation applications, with different discharge lengths, is shown in Fig. 4.2. It is deduced that the length of discharge has a significant impact on gravity storage LCOE.

Similarly, gravity storage LCOE for transmission and distribution applications, with different discharge lengths, is presented in Fig. 4.3. Here we notice energy cost decreases as the length of charge and discharge increases. However, longer cycles do not enable the storage to efficiently participate in energy price arbitrage. On the other hand, lower charge and discharge lengths; increase the ability of taking advantage of peak electricity prices throughout the day. Therefore, if storage is used in lower cycle length applications, it needs to perform other functions; in order to increase its revenues and economically justify its operation.

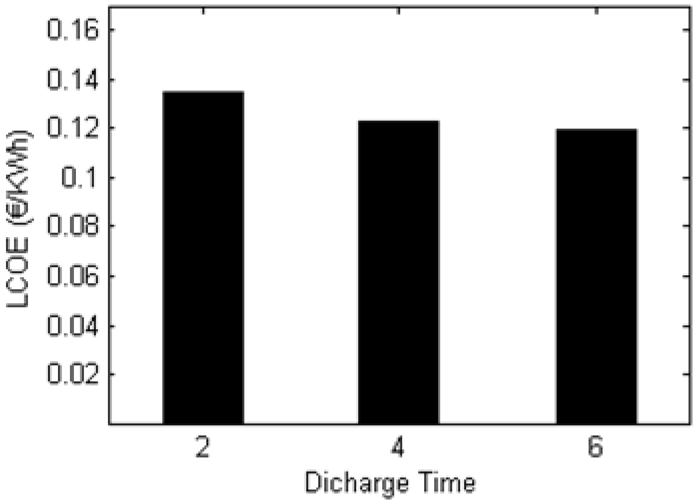


Fig. 4.2. Storage LCOE versus discharge time in generation applications.

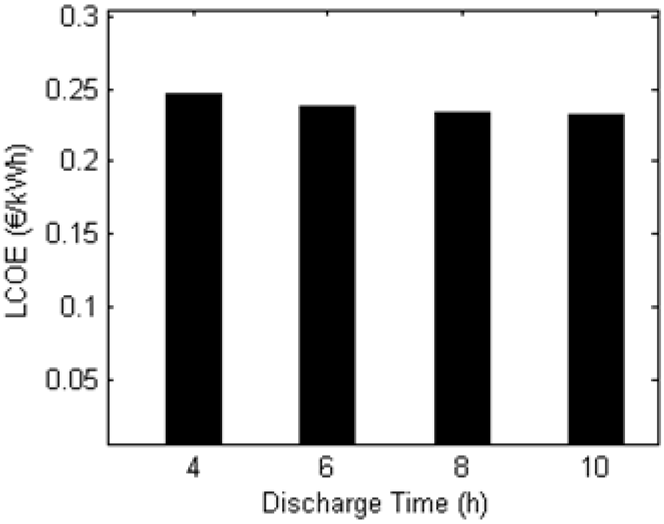


Fig. 4.3. Storage LCOE versus discharge time in transmission & distribution applications.

The levelized cost of energy was calculated for the three scenarios of storage sizing investigated in this work for a discharge time of 4 h. This is demonstrated in Figure 4.4 showing that the LCOE is significantly affected by the sizing of energy storage.

4.2.3. Cost comparison with other storage systems

LCOE is a cost based metric which attempts to compare different energy generation technologies on a comparable basis. The levelized cost of energy is considered as the minimum cost at which energy must be sold in order to achieve break-even over the system lifetime. The objective of LCOE is to provide a comparison of different energy storage technologies of unequal capital cost, life spans, capacities, and risks. This methodology enables for quick and easy assessment of different storage technologies.

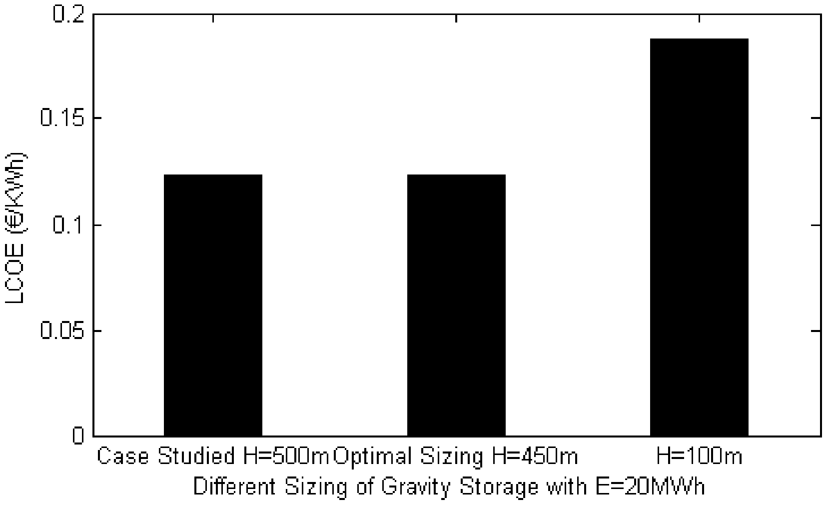


Fig. 4.4. LCOE for the three sizing scenarios

A review of the literature allowed for the quantification of the levelized cost of electricity delivered by energy storage used for bulk application. The energy storage technologies that have been used in this study include Pumped hydro storage (PHS), above ground and underground compressed air energy storage (CAES), lead-acid, vanadium-redox flow battery (VRFB), iron–chromium (Fe-Cr), sodium–sulfur (NaS), and nickel–cadmium (Ni–Cd). This quantification has been done in [6,19]. The results obtained from the comparison of energy storage LCOE are illustrated in Fig. 4.5.

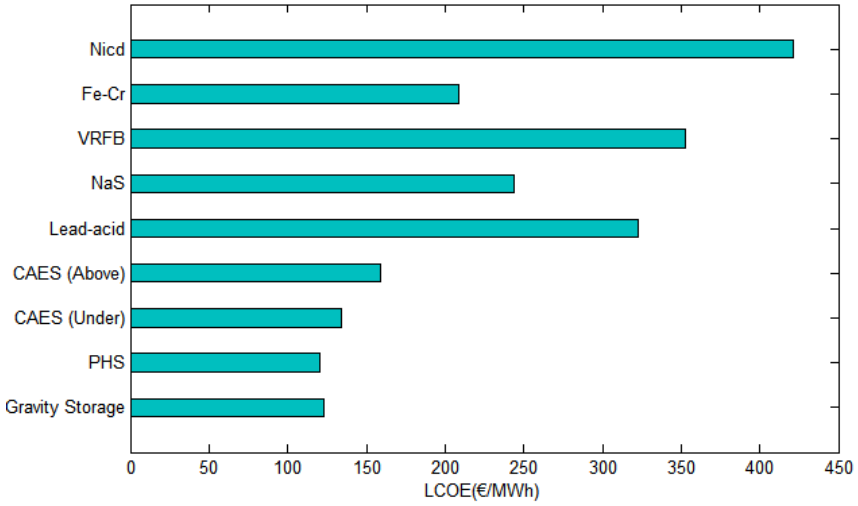


Fig. 4.5. Levelized cost of electricity for bulk energy storage

The levelized cost of energy is dependent on the power market, the service characteristics, and the storage system features as it relies on the number of cycles per year, the interest rate, and other storage aspects such as replacement time and depth of discharge. The results obtained from the economic comparison of energy storage indicate that the LCOE delivered by PHS and gravity storage of approximately 120 €/MWh, and 123 €/MWh, respectively are the lowest ones. CAPEX has the most significant influence on LCOE delivered by PHS, CAES and gravity energy storage. The highest cost share of CAPEX, for these technologies, is attributed to the storage unit cost.

A broad range of LCOE is found for batteries because of the wide difference in the CAPEX of these. Ni-cd is found to deliver the highest LCOE among all investigated storage technologies. The LCOE of Ni-Cd is at the higher end and is about 0.421 €/kWh. VRF batteries have LCOE of 0.353 €/kWh due to their high CAPEX. Lead-acid delivers LCOE of 0.323 €/kWh; followed by NaS and Fe-Cr with values of 0.244 €/kWh and 0.209 €/kWh, respectively. Ni-Cd, lead-acid and VRFB have high LCOE due to the high replacement costs incurred during their lifetime In the next few decades, the LCOE of batteries are projected to decrease significantly because of technological developments and declining CAPEX. PHS, CAES, and lead-acid batteries are considered mature systems as they have been used for a long time. However, some of the presented storage technologies are still under development or at market entry; hence their costs are expected to decrease in the near future.

PHS and gravity storage are considered the most cost-efficient storage options due to their low LCOE. Therefore, the calculated gravity storage LCOE appears to be competitive compared to other storage options. This technology might become attractive in the near future.

Storage technologies that are comparable to gravity power storage are Pumped Hydro Storage (PHS) and Compressed Air Energy Storage (CAES). These technologies are mainly considered for bulk storage. Typically, to compare and characterize different energy storage technologies, key performance parameters of each technology are used as an indicator. These parameters are determined from literature [20-26]. Table 4.3 presents investment cost, operational cost, lifetime, and LCOE of the previously stated storage technologies.

Table 4.3. Comparison of Energy Storage Cost

Technology	Investment Cost (€/kW)	Operational Cost (€/kW-yr)	Lifetime (yr)
Gravity Storage	5,840	1.9	40-60
PHS	600-5200	1.9	40-60
CAES	400-700	1.9	20-40

A comparison between pumped hydro and CAES with gravity storage is presented in Table 4.3. The investment cost (€/kW) is the system total capital cost divided by storage capacity in kW. The investment cost of gravity storage is higher than that of pumped hydro and CAES systems, while the operational costs of the three systems are considered equal. The operational costs include system charging cost, labor associated with plant operation, plant maintenance, replacement/repair costs, and decommissioning and disposal costs. In this case study, the operation cost and lifetime of gravity storage are estimated to be equal to those of pumped hydro storage, as both systems require similar equipment for their operations. The lifespan of pumped hydro and gravity storage are greater than the lifetime of CAES.

4.3. Valuation of Energy Storage in Energy and Regulation Markets

Energy is a real time product which must be consumed when produced because it cannot be easily stored. To achieve this simultaneity of production and consumption, operators have to properly dispatch energy between loads and generators. This real time balancing can be realized with the help of energy storage systems. Storage technologies have the ability of storing electricity when there is an excess and realizing it during periods of needs.

Energy storage systems participate in energy markets in a number of ways depending on their characteristics. These technologies can serve multiple roles simultaneously such as arbitrage, ancillary services, and congestion relief [27]. Regardless the benefits that could be offered by some energy storage technologies, several markets still do not approve their participation in some services such as spinning, non-spinning reserves, and regulation services [28].

Due to the increasing penetration of renewable energy technologies, there is a high interest of economically evaluating energy storage [29]. Most energy storage systems have been considered historically unprofitable to install except for pumped hydro storage [30]. Methodologies to accurately identify storage systems’ benefits are needed in order to determine the likely deployment of these technologies.

Much research has been devoted to economic studies about energy storage with the emergence of competitive energy markets. Multiple articles have valued storage while performing one or more grid functions; however, it is challenging to quantify the value of these services [31]. Drury et al. presented a co-optimized dispatch model to identify the value of compressed air energy storage (CAES) in energy and reserve markets; in multiple U.S. regions. The outcomes of this study indicate that revenues received from performing only energy arbitrage do not support CAES investment in most simulated markets locations. However, conventional CAES system is able to support its investment if revenues received from providing operating reserve are also taken into account. On the other hand, arbitrage and reserve revenues are unlikely to support adiabatic CAES investment in the investigated market regions [31].

Different programming methods have been used to model energy storage dispatch [32]. LP (linear programming) is usually used as a benchmark model while MILP (Mixed integer linear programming) is considered very powerful and has been applied successfully for large-size scheduling problems [32]. Pousinho et al. proposed a MILP approach to optimally schedule wind power with concentrated solar power plants having thermal energy storage [33]. The model outcomes show that the presented coordination results in an improvement of profitability for energy producers that trade in day-ahead energy and spinning reserve markets. Garcia et al. developed a two-stage stochastic optimization model of a wind farm combined with pumped hydro storage in an energy market [34]. The presented model is an effective approach to model decision of wind farm operators in a spot time market under uncertainty. In [35], Sioshansi et al. investigated the value of arbitrage in PJM (Pennsylvania New Jersey Maryland) interconnection for six years to determine the impact of fuel mix, efficiency, fuel prices, storage capacity, and transmission constraints. The quantification of energy storage varies significantly with contract, ownership, and market structure [35]. Denholm and Sioshansi conducted an economic analysis to determine the potential advantages of co-locating energy storage and wind. This co-location is less attractive if storage system is able to gain potential values from providing ancillary or capacity services. The authors claim that further studies are necessary to investigate the benefit of using CAES system to provide ancillary services [36]. In [37], DeCarolis and Keith evaluated the economics of using compressed air energy storage with wind plant while Bathurst and Strbac, in [38], analyzed the utilization of battery system combined with wind power plant to perform both energy arbitrage and reduce penalties from imbalance production. The results of this study show that this joint optimization of the battery storage and wind farm generates additional value.

Several articles investigated the economical profitability of energy storage used for arbitrage in different market locations. Perekhodtsev determined the potential revenues of pumped hydro energy storage in PJM market [39]. Arbitrage profit is investigated by [40] in North American, and European energy markets. The PJM interconnection was studied in [35], while the NYISO (New York Independent System Operator) interconnection was analyzed by [41]. The value of energy storage has been investigated in seven U.S. wholesale markets by Bradbury et al. [29]. Locatelli et al. assessed the economics of large energy storage plants with an optimization methodology in UK [42]. The results of this analysis demonstrate that energy storage working as price arbitrage and operating reserve requires subsidies.

Walawalkar et al. undertook an economic study to value storage providing both energy arbitrage and regulation in New York. Their analysis demonstrates that the installation of energy storage is attractive due to the potential opportunities that exist for regulation services in New York State. Deferral of system upgrades has been also quantified by these authors and is considered an important benefit that should be considered while making decision about the deployment of energy storage [41]. In [43], Kazempour et al. propose a self-scheduling approach for energy storage to determine the maximum potential of expected profit among multi-markets. The economics of emerging and traditional technologies have also been compared in this analysis. Economic viability of NaS battery plant and VRB energy storage in a competitive electricity market has been conducted in [44] and [45], respectively. He et al. presented a multi-stream value assessment of compressed air energy storage on the French energy market. Their analysis incorporate both regulated and deregulated sources of revenue [46]. Sioshansi et al. performed a value comparison between pure storage (pumped hydro) and compressed air energy storage. The output of this analysis indicates that the net annual arbitrage value of pure storage systems is significantly greater than that of CAES [47]. Hessami and Bowly developed a computer program which model the operation of three energy storage systems combined with a Portland Wind Farm (PWF). The objective of the model is to determine the maximum generated revenues. The simulated storage systems include pumped seawater hydro storage, thermal energy storage, and compressed air energy storage. It has been found that CAES is the most profitable storage system [48]. McKenna et al. evaluated the economic value of integrating lead-acid batteries in grid-connected PV under feed-in tariff in UK. The outcome of this analysis shows that the net value of the battery is negative and the financial loss for the systems is considered significant (£1000/year) [49]. An evaluation of the potential operating profit available through arbitrage operation for a price-maker storage facility in Alberta has been performed in [50]. It is shown that energy storage operation significantly affect market price, especially during high price hours. Fares and Webber proposed an optimal charge-discharge schedule to maximize daily revenue without violating the battery's operating constraints [51]. It has been demonstrated that energy storage used for only wholesale energy arbitrage in ERCOT (Electric Reliability Council of Texas) would be very negative. This analysis has also shown that it is important to consider the material degradation cost of performing a charge/discharge cycle in battery operational management.

Studies that are limited only to arbitrage do not reflect the actual value of energy storage. Participation in ancillary services markets demonstrates interesting opportunities for energy storage. These services which include regulation, in addition to spinning and non-spinning reserves, make sure that real-time supply and load are in balance [52]. Regulation is considered more valuable and is particularly well served by energy storage due to the short and fast response time [27]. Other potential values for storage technologies include offering congestion relief to transmission lines and providing back up capacity for line outage [34]. Berrada and Loudiyi compared two operation models to demonstrate that more revenues could be generated by the renewable energy farm if energy storage is permitted to participate in ancillary service markets [53]. Krishnan and Das presented a framework for optimally allocating energy storage in the electric grid. The proposed model dispatches power for both energy and ancillary services and compares the benefits of the optimal allocation to transmission expansion solution [54].A market modeling methodology was used by Das et al. to investigate the co-optimized value of energy storage in electricity and ancillary service markets. The authors of this article presented a dispatch model applied to compressed air energy storage, based on cross-arbitrage in both energy and ancillary markets. To formulate their dispatch model, Das et al. used both economic dispatch and unit commitment programs. This later program is run a day-ahead, while the economic dispatch program is run after taking commitments decisions [55].

In this chapter, we extend the literature by investigating the value of energy storage simultaneously operating in multiple markets which include day-ahead, real-time energy, and ancillary markets. The co-optimization model proposed considers various revenue streams, allowing for the possibility to accurately value the daily operation of storage system. We focus on regulation as ancillary service. The proposed model does not explore revenue from reserve service; because a typical contract for spinning reserve is set to only about 20 dispatches per year. The occurrence of this ancillary service is low compared to regulation service (around 400 calls per day) [56].

4.3.1. Electricity markets

Energy is traded, bought, and sold in wholesale and retail markets. The wholesale market refers to the selling and purchase of energy between generators and resellers. Resellers, also known as suppliers, include energy marketers, utility companies, and competitive power providers. These entities purchase energy produced by generators through the wholesale market, and then, resell it to end users in the retail market. The purchase of energy is done through markets or contracts between individual sellers or buyers.

In the retail market, energy is sold to customers after being bought by resellers though wholesale market. For the purchase of electricity, customers can choose a service that best fits their needs from a range of options. They can buy electricity from their local utility or from competitive retailers. Fig. 4.6 illustrates electricity market players. The right-to-left arrows in Fig. 4.6 refer to the buying of power ($) while the left-to-right arrows indicate the selling of power (MW or kW).

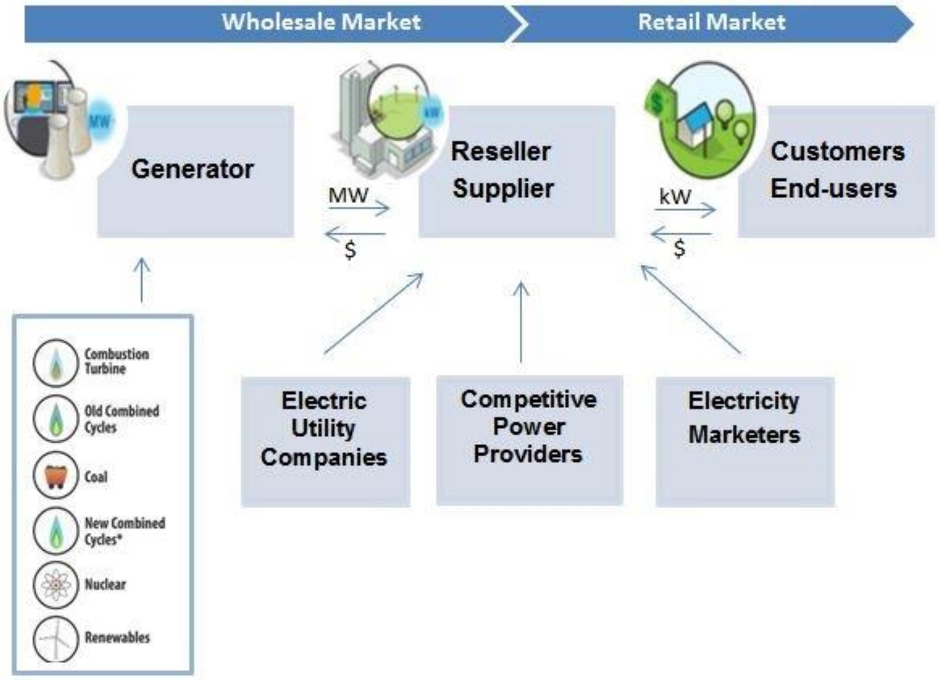


Fig. 4.6. Electricity markets players.

4.3.1.1. Energy arbitrage

Energy markets meet the demand of electricity both in real time and in the near term. The electric energy market operates two markets of energy: day ahead and real time energy markets. The day-ahead market is a forward market; it creates financial schedules for the consumption and production of energy one day before operating day. Based on demand bids, generation offers, and scheduled bilateral transactions; the locational marginal prices are determined for the next operating day. On the other hand, the real-time market is a spot market; it balances variances between day-ahead scheduled quantities of energy and actual real-time necessities. Based on actual grid operating conditions, locational marginal prices of this market are determined. The daily energy price fluctuations provide a good potential profit for arbitrage, by purchasing energy when prices are low during off peak hours, and selling it at higher energy prices during peak hours. Energy storage systems allow an offset in time between energy production and consumption. The capability of storing energy has a significant impact on both the physical characteristics of the electric grid, and on the potential revenues of energy market participants.

4.3.1.2. Ancillary services

In the power system, ancillary services market is correspondingly important to ensure grid reliability. Storage may be utilized to perform several ancillary services which include regulation and reserve services. The ancillary market provides services for balancing demand and supply, in addition to supporting transmission of energy to serve load. Fluctuations in demand and supply are tracked moment to moment by regulation services, while reserve services meet the hour changes in load and supply [57]. Generators equipped with automatic generation control provide regulation continuously and respond quickly by either increasing or decreasing power output. Some regions still do not allow energy storage to participate in ancillary services. Regulation services are well provided by some storage systems such as flywheel energy storage. However, due to the short duration of flywheel devices, they cannot be used for energy applications such as arbitrage. Other storage systems such as pumped hydro generate high potential revenues while providing frequency regulation [39]. In this work, we are concerned with regulation services which aim of controlling grid frequency and voltage to targeted values. This service maintains interconnection frequency, matches energy generation/consumption, and balances between actual/scheduled power flow. Regulation requirement is determined as a percentage of the scheduled load. Bids are submitted to energy and ancillary markets by energy firms to provide electricity. Successful bids in ancillary markets receive the ancillary service market clearing price, in addition to the energy market price; in case they are called for ancillary service. Hence, firms can choose to supply or promise to offer their power, to either ancillary or energy markets.

4.3.2. Research objective and Methodology

The objective of this chapter is to quantify the profit generated from the most common applications of storage which are arbitrage and regulation services in multiple markets including day-ahead and real-time energy markets as well as ancillary market. The storage system is modeled as a "price taker" in these markets using historical energy price data. Several articles have studied the value of energy storage by analyzing the arbitrage profitability in electricity markets. However, in order to determine the accurate value of energy storage, it is necessary to consider the possibility that storage systems can also provide energy to ancillary markets with extra profits. This work develops a method that values energy storage by considering multiple sources of revenue. The revenue opportunity developed, which includes participating in three different markets and considering the cost of using the energy storage, has not been considered in previous literatures. This valuation model complements other models discussed in the literature which only consider one or two sources of revenue. In this analysis, energy storage may charge/discharge energy into either real-time or day-ahead markets, or sell capacity into the ancillary market (regulation service). It can as well perform any combination of the stated functionalities.

To determine whether or not energy storage is profitable given these three opportunities, a linear programming model is developed to generate daily profit. A time period of one hour is chosen in this analysis. For each period, the model determines how much energy to charge and discharge, from the storage, for the energy market, and decides on the amount of capacity to sell in the regulation service. These decisions are based on the state of the market and the storage level. Charging can be either from day-ahead or real-time markets. Discharging, on the other hand, occurs through three different markets which provide energy and regulation services. The hourly operations of energy storage are simulated to determine the bidding decisions, and the corresponding maximum daily value of the storage. The hourly decisions include cases of bidding or not for energy or ancillary services. Even though the benefits of storage systems are well understood, the valuation and viability of these technologies remains a debatable topic since storage systems are not considered economical in some applications [28]. Thus, it is always essential to investigate whether an energy storage system must fill a need in order to be cost-effective.

Since the economic value of energy storage is equal to operation revenues minus costs; the objective function which maximizes profit is formulated as (Eq. (4.1)).

$$\mathrm{MAX}\left[\mathrm{Profit}=\sum_{t}\left[\begin{array}{l}\mathrm{P}^{\mathrm{DA}}(\mathrm{t})(\mathrm{E}_{\mathrm{d}}^{\mathrm{DA}}(\mathrm{t})\text{-}\mathrm{E}_{\mathrm{c}}^{\mathrm{DA}}(\mathrm{t})) \\ +\mathrm{P}^{\mathrm{RT}}(\mathrm{t})(\mathrm{E}_{\mathrm{d}}^{\mathrm{RT}}(\mathrm{t})+\psi\mathrm{E}_{\mathrm{AS}}^{\mathrm{RT}}(\mathrm{t})+\psi\mathrm{E}_{\mathrm{AS}}^{\mathrm{DA}}(\mathrm{t})\text{-}\mathrm{E}_{\mathrm{c}}^{\mathrm{RT}}(\mathrm{t})) \\ +\mathrm{P}_{\mathrm{AS}}{}^{\mathrm{RT}}(\mathrm{t})\mathrm{E}_{\mathrm{AS}}^{\mathrm{RT}}(\mathrm{t})+\mathrm{P}_{\mathrm{AS}}{}^{\mathrm{DA}}(\mathrm{t})\mathrm{E}_{\mathrm{AS}}^{\mathrm{DA}} \\ \text{-}\mathrm{C}_{\mathrm{d}}(\mathrm{E}_{\mathrm{c}}^{\mathrm{DA}}(\mathrm{t})+\mathrm{E}_{\mathrm{c}}^{\mathrm{RT}}(\mathrm{t}))\text{-}\mathrm{C}_{\mathrm{S}}\end{array}\right]\right] \tag{4.1}$$

The model arbitrages day ahead and real-time energy markets, while participating in the regulation market. The first term in the objective function represents revenues, obtained from selling energy in the day-ahead market. Revenues generated from providing power for energy service, at hour t, are the product of energy sold and energy price at that time.

Revenues generated from ancillary service are calculated differently. Bidding in this market provides two payments. The reserve capacity payment is always paid, regardless of whether the storage is called into ancillary service or not. If the call is placed, a second payment is provided for the energy discharged. Therefore, revenues for regulation include a payment for availability (in US$/MWh), and a payment per kWh when energy is produced. Daily revenues from regulation, in the day-ahead market, are calculated using Eq. (4.2).

$$\mathrm{R}(\mathrm{t})=\mathrm{P}_{\mathrm{AS}}^{\mathrm{DA}}(\mathrm{t})\mathrm{E}_{\mathrm{AS}}^{\mathrm{DA}}+\mathrm{P}_{\mathrm{AS}}^{\mathrm{RT}}(\mathrm{t})\psi\mathrm{E}_{\mathrm{AS}}^{\mathrm{DA}}(\mathrm{t}) \tag{4.2}$$

The grid operator is responsible for controlling regulation. This service is called upon for around 400 times per day with varying power [56]. The actual dispatched energy for this service is the fraction of the actual amount of regulation, called in real-time, and the amount of capacity procured by the ISO [58]. Kempton et al. and Tomi et al. estimated the average dispatch to contract ratio, using several years of historical data, and found ψ equal to 0.08-0.1 [56, 59]. In this study, the dispatch to contract ratio of 0.1 is used. This corresponds to 0.1 kWh of regulation energy being called in real time, for every kW of capacity sold during one hour in the regulation market. The dispatch to contract ratio is estimated to be constant for all periods. In reality, this ratio is variable. Assuming a fixed ratio probably overstates the revenue of participating in the regulation market.

In order to obtain the value of storage system; the cost of providing energy and ancillary services is deducted from revenues. The cost of storage is computed from capital cost and storage degradation cost. The storage degradation cost (C_d) is equal to the storage cost over its lifetime throughput energy, for the specific cycling regime. The lifetime of energy storage is expressed in cycles, and is measured at a certain depth-of-discharge. The storage life in energy throughput is expressed as:

$$\mathrm{LET}=L_f E_c \mathrm{DoD} \tag{4.3}$$

The objective function stated in Eq. (4.1) is subject to the charge state, S (t), of storage at any time given by:

$$S(t)=S(t-1)(1-\delta)+\eta(E_c^{DA}(t)+E_c^{RT}(t))-(E_d^{DA}(t)+E_d^{RT}(t)+\psi(E_{AS}^{DA}(t)+E_{AS}^{RT}(t)) \tag{4.4}$$

The storage level, at a particular time, is the sum of energy remaining in the storage device, at (t-1), and the energy used to charge the storage, subtracted from the discharged energy at time t. The state of charge is adjusted for system losses. While modeling the operation of energy storage, it is important to take into consideration the system losses which include the storage self-discharge rate and round-trip efficiency of the system.

Additional constraints include storage power and capacity limits. The energy stored from day-ahead and real-time energy markets, during a given period, is restricted by the maximum charging/discharging rate, and the proportion of the hour spent charging/ discharging the system.

$$E_c^{DA}(t)+E_c^{RT}(t)\leq X_c(t)P_L \tag{4.5}$$

$$E_d^{DA}(t)+E_d^{RT}(t)+\psi(E_{AS}^{DA}(t)+E_{AS}^{RT}(t))\leq X_d(t)P_L \tag{4.6}$$

Within a given hour, the storage system may charge and discharge but not perform both functions simultaneously. Since, the objective of this model is to optimally operate the storage; this latter should not charge and discharge energy at the same time in order to make more profit. This restriction is defined by Eq. (4.7).

$$X_c(t)+X_d(t)\leq 1 \tag{4.7}$$

Similarly, the storage state, at time t, must be less than or equal to the storage capacity, in addition to the energy discharged from the storage cannot be more than the storage level at that time.

$$S(t)\leq E_c \tag{4.8}$$

$$E_d^{DA}(t)+E_d^{RT}(t)+\psi(E_{AS}^{DA}(t)+E_{AS}^{RT}(t))\leq S(t) \tag{4.9}$$

Finally, the lower bound of energy, flowing in/out of the storage, should be greater than zero. This constraint is presented in Eq. (4.10).

$$E_d^{DA}(t), E_d^{RT}(t), E_c^{DA}(t), E_c^{RT}(t), E_{AS}^{DA}(t), E_{AS}^{RT}(t), X_c(t), X_d(t) \geq 0 \tag{4.10}$$

4.3.2.1. Case study

A case study is used to demonstrate the proposed model. This linear programming model is solved using General Algebraic Modeling System (GAMS) software. The model code is presented in Appendix B2. NYISO market was chosen in this case study. Historical data were obtained from NYISO website [50]. The wholesale energy markets in New York are administrated by the NYISO. The storage operation is optimized over 24 hours, of the selected day (Dec 1st, 2015), to evaluate the maximum potential arbitrage in both: day-ahead and real-time markets, and the opportunity to participate in the regulation market. This case study uses a 5MW/20MWh grid-connected gravity energy storage system, with a round trip efficiency of 85%. Gravity storage is a new energy storage system that is being developed by Gravity Power, LLC. This technology is similar to pumped hydro storage (PHS) system. The cost inputs used in this simulation are determined using gravity storage characteristics obtained from literature [61]. Both PHS and gravity storage do not suffer from degradation [62]. Therefore, the system degradation cost (C_d) is considered equal to zero in this study. The storage cost (C_S) was calculated using the system investment cost of 5840 €/kW with an interest rate of 5%; It was found to be equal to 4838 $. The variable operations and maintenance (VOM) costs of the system are neglected in this work.

4.3.2.2. Real-time, Day-ahead, and Ancillary Energy Prices

Results of day-ahead and real-time prices in both energy and ancillary markets are presented in Fig. 4.7. We notice that these differ considerably. Hourly real time energy prices are much more variable than those of day-ahead energy market, as illustrated in Table 4.4. The standard deviation and variance of real-time energy market is very high compared to other markets. Volatility of real time prices is due to the unexpected events that may occur in real time. These can be sudden changes in weather, or outage that may be forced in both transmission and generation equipment. In addition, prices in real-time energy market are sometimes negative since generators should be turned off, when running at their low-operating limit, due to low demand of energy. Consequently, this result in a unit startup costs.

Real time prices may be lower than day-ahead prices because of two reasons. The first one is about safety; some customers prefer to pay more for energy in day-ahead market, in order to avoid dealing with high volatility of energy prices in real-time market. The second reason is about security, some suppliers prefer to withhold a certain capacity of energy from day-ahead market and sell it in real time market, in order to provide protection against outage. These two factors lead to higher day-ahead prices. On the other hand, real time prices are sometimes higher than day-ahead prices. This is due to the fact that not all generators and energy storage systems can participate in the real-time and ancillary markets. Mainly, because these markets requires participants to respond within few minute of dispatch signals. Not all generators have this flexibility. Therefore, they get restricted from participating in these markets, which causes the energy price of this latter to be higher.

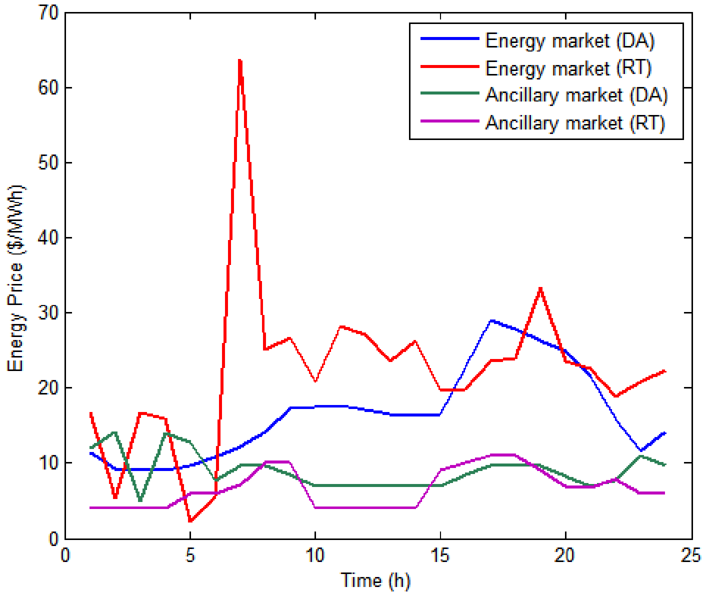


Fig. 4.7. Energy prices in different markets.

Table 4.4. Statistical Characteristics of Energy Prices in Different Markets.

	Day-ahead Energy Market	Real-time Energy Market	Day-ahead Ancillary Market	Real-time Ancillary Market
Mean (Average)	16.63	22.19	9.045	6.620
Standard Deviation	6.056	11.51	2.401	2.550
Variance	36.68	132.5	5.769	6.505

Fig. 4.8 demonstrates the participation of energy storage in each of the three markets. The regulation market accounts for the highest dispatch of energy by the storage. Participation of energy storage in day-ahead and real-time markets represents only a small portion. More energy is charged to the storage through day-ahead market ($E_c^{DA}(t)$) due to lower energy prices compared to real-time market. Prices in real-time market experience more volatility as shown in Table 4.4. This volatility of prices results in better cost-effective opportunities for storage to be used in arbitrage in real-time market.

The optimum strategy used by storage is to offer the majority of its energy to regulation market, with a very small participation in day-ahead and real-time markets. This optimum operation requires the storage to provide energy services in both day-ahead and real- time ancillary markets. The participation of the storage in the energy market is very limited, and occurs only when the state of charge of the storage system has to be increased; especially when the prices of energy are very low, as illustrated in Fig. 4.9. In this case, the storage is charged either from day-ahead or real-time energy markets. Offering more energy to the regulation market maximizes the revenue; as it will be demonstrated later in this section.

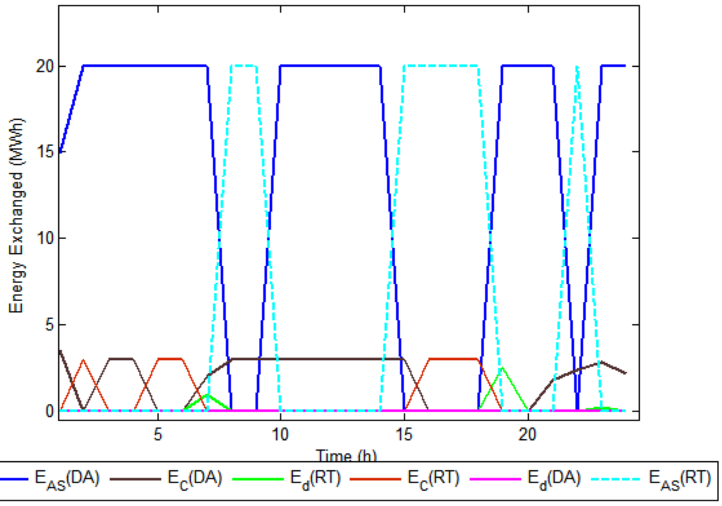


Fig. 4.8. Hourly energy dispatch

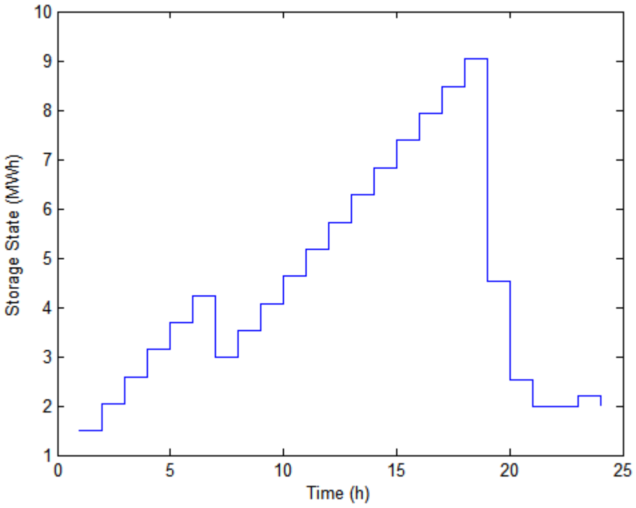


Fig. 4.9. Hourly storage level.

4.3.2.3. Participation in Day-ahead, Real-time, and Regulation markets

The participation of energy storage in day-ahead and real time markets is illustrated in Fig. 4.10. The optimal strategy used by the storage is to purchase energy, when the price is low, during early morning and afternoon hours. Then sell it, when energy prices are high in morning, late afternoon, and evening. Most energy is purchased from day-ahead market due to the lower prices it offers. Energy purchased in day-ahead market, $E_c^{DA}(t)$, occurs mainly during the day between 7 AM and 4 PM. However, $E_d^{DA}(t)$ is constant and equal to zero since energy is only sold to real time and ancillary markets. Energy sold through real time energy market occurs only during a limited period of one hour (t) at 7 AM, 7 PM, and 11 PM.

The contribution of energy storage in day-ahead and real-time ancillary markets is shown in Fig. 4.11. More energy is provided to regulation service in day-ahead ancillary market than in real-time ancillary market; due to higher prices offered by day-ahead market.

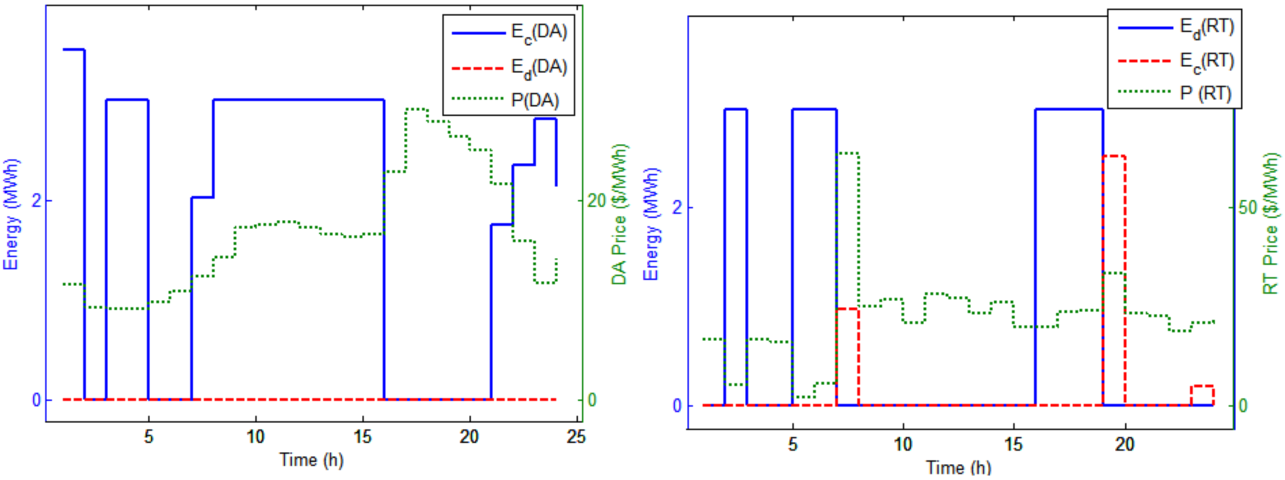


Fig. 4.10. Energy exchange with a) day-ahead market, b) real-time market

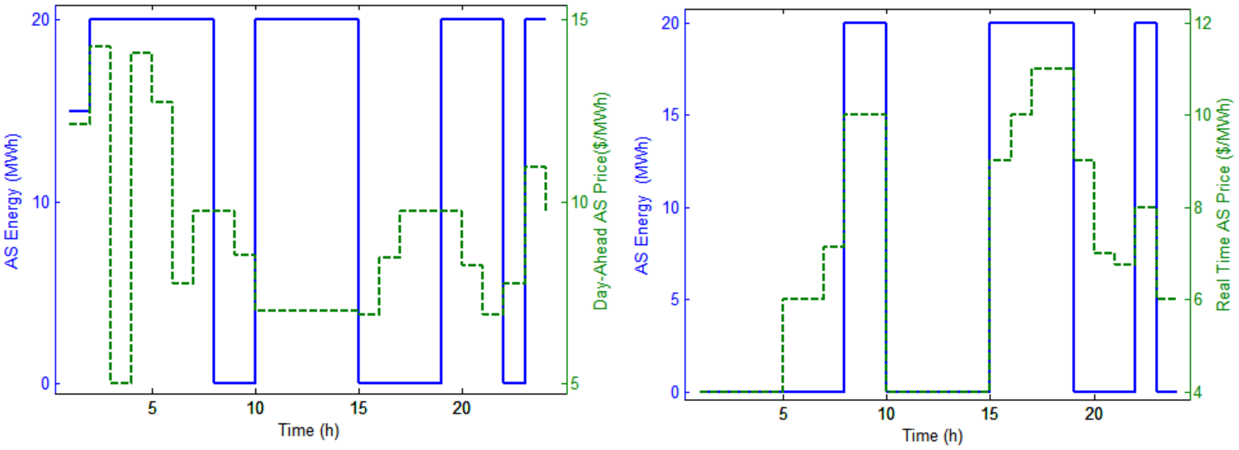


Fig. 4.11. Hourly energy dispatch for regulation service in a) day-ahead market, b) real-time market.

4.3.2.4. Storage Revenues:

Hourly and total potential revenues from participating in the three markets are presented in Fig. 4.12a and b, respectively. The ancillary market accounts for about 97 % of the revenue generated by the storage; only 3% of revenues are generated in real-time market, and zero profit from day-ahead market. As mentioned before, the system does not sell energy though the day ahead market, $E_d^{DA}(t)$, due to the lower prices offered by this market compared to real time and regulation markets. That is why; a zero profit is received in this market.

The highest potential revenues are received from participating in the regulation service market, due to the two payments provided by this market. These include the energy price received from dispatching energy for regulation purpose, and the clearing price for clearing capacity. On the other hand, the day ahead energy market incurs the highest amount of expenses compared to other markets due to the high amount of energy purchased from this market ($E_c^{DA}(t)$).

Based on the presented results, it is found that energy storage systems have a high probability of generating positive net present value (NPV). This is obtained from participating in energy arbitrage and regulation services; in both day-ahead and real-time markets. Significant opportunities exist in the deployment of energy storage in these applications. In general, profit generated from arbitrage and ancillary services depends on the market flexibility and energy mix.

Currently, some markets still do not permit most energy storage systems to participate in 10 min synchronous spinning reserve markets. These markets can offer around 15% of potential revenue offered from regulation services [63].

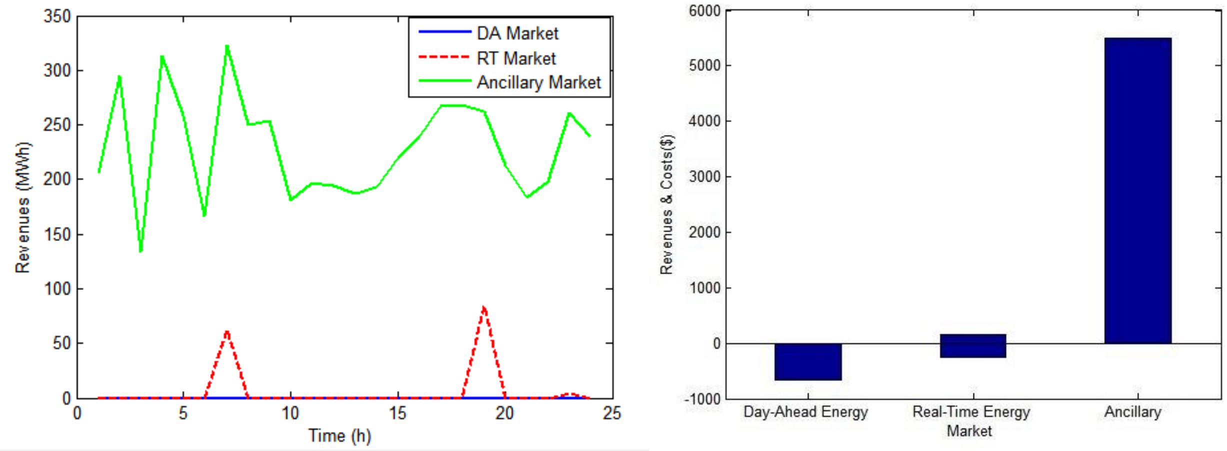


Fig. 4.12. Revenues in day-ahead, real-time, and ancillary markets a) hourly, b) total revenues and costs.

4.3.2.5. Comparison with Other Storage

The daily profit generated by gravity storage from participating in arbitrage and ancillary service is illustrated in Fig. 4.13. This profit is negative because the system costs exceed the revenues received form providing the two simulated services. To compare the daily profit of gravity storage, two other simulation were run for two different storage options which include pumped hydro storage (PHS) and compressed air energy storage (CAES). These two technologies are mainly used for bulk storage and are considered an alternative option to gravity storage. Key performance parameters of the compared technologies are determined from literature [61]. Fig. 4.13 shows that a high potential daily profit is generated by CAES followed by PHS. These two storage technologies are considered economically profitable while operating in the three simulated markets. However, due to the negative profit received by gravity storage, it is considered unviable while performing arbitrage and regulation services.

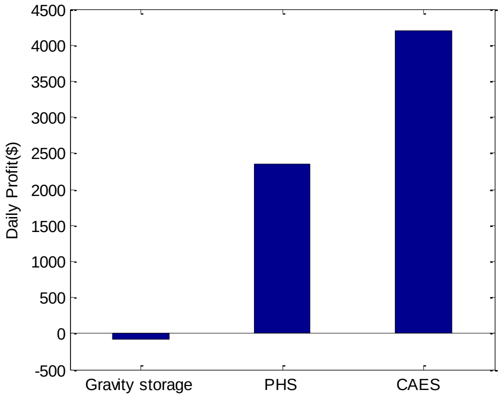


Fig. 4.13. Profit comparison between gravity storage, PHS and CAES.

4.3.3. *Additional benefits*

A review of the literature allowed for the quantification of other benefits provided by energy storage. Reliability and power quality are valued by industrial and commercial customers. The quantification of these benefits has been done in [64-66].

Quantification of other applications along the storage value chain including end use and regulated sectors has been conducted by author in [53,67]. The value of energy storage by application specifying the desired characteristics of the technology is discussed by [68]. Benefit estimation of storage value is illustrated in Fig. 4.13.

System upgrade cost deferral is an important benefit provided by energy storage. Utilities can defer transmission and distribution upgrade costs by properly locating storage systems. Storage may be located in regions characterized by slow demand growth and by intermittent load; with peak demand occurring only for few hours during a day. In these regions, energy storage is used to defer the high transmission and distribution upgrade charges. The value of system upgrade cost deferral ranges from 50 to 1,000 ($ /kW-year) [65-66].

Although energy storage is technically capable of generating high revenues from participating in some services, the technology has to be combined with other applications to become profitable and economically justify its deployment. To verify the profitability of gravity storage, a cost-benefit assessment is presented in Fig. 4.14. The assumption made for this valuation is that the system is utilized only for few applications; which include T&D upgrade deferral, avoiding outage, and generation or demand side capacity investment. In this case, the annual cost exceeds the storage annual benefits from participating in the three presented applications. The value of gravity storage has been underestimated and the system is not profitable if its operation is limited to these applications. Consequently, capturing the full value of storage is necessary for the deployment of a technology at a system-wide efficient scale.

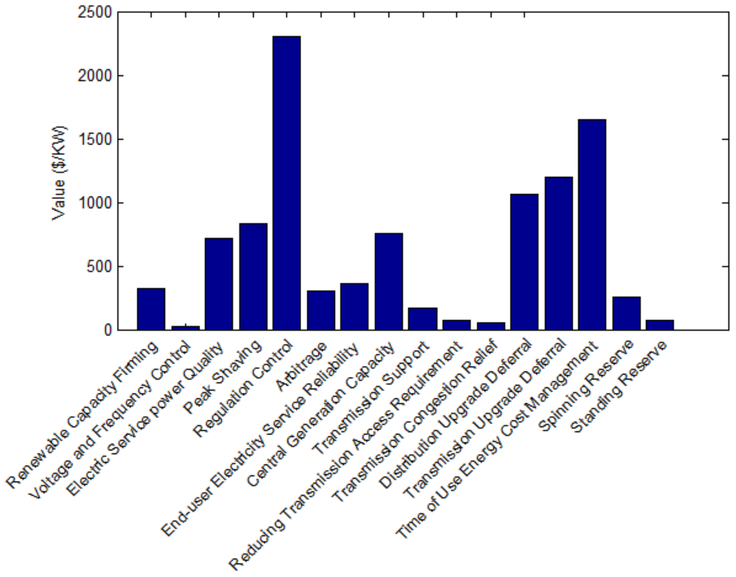


Fig. 4.14. Value of energy storage in different applications (based on literature review)

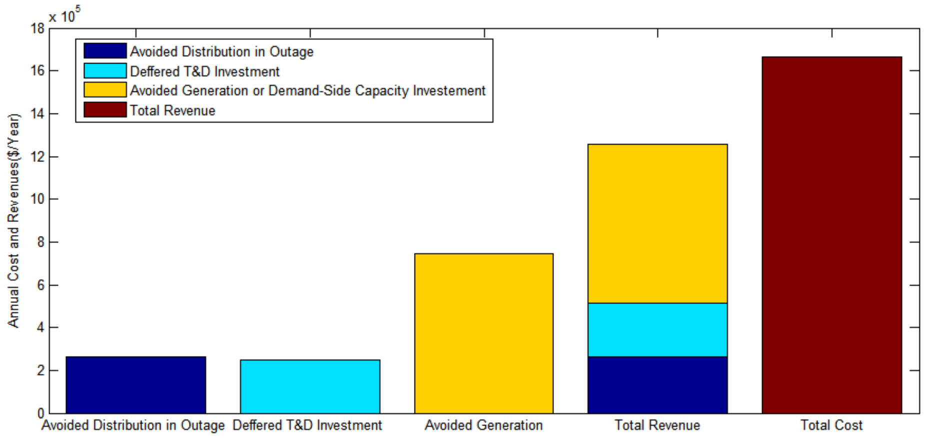


Fig. 4.15. Annual storage benefits vs costs.

4.4. Conclusion

An economic study was performed to calculate the levelized cost of energy of gravity storage .The LCOE is a convenient measure of the overall competiveness of different storage technologies. Therefore, this methodology was used to investigate whether or not gravity storage is a viable storage option. The LCOE is calculated by accounting for the system's expected lifetime costs including construction, maintenance, and operation, divided by the system's lifetime expected power output (kWh). The calculation takes into account the time value of money with an appropriate discount rate over the life of the system. In this work, an estimation of investment costs which include construction and equipment costs, as well as operation & maintenance costs; allowed for determining the storage LCOE. In addition, a comparison with other energy storage was conducted. The results obtained from this study reveal that gravity energy storage has a very attractive LCOE compared to other storage alternatives. Therefore, gravity storage may be considered in the near future an alternative technology to pumped hydro.

An energy storage model has been proposed to evaluate the maximum potential revenues. These could be generated by, storage system, participating in both day-ahead and real-time energy markets; as well as regulation market. The optimization model determines the optimal energy quantities that should be offered into the regulation market; in addition to the optimum amount of energy that should be sold and purchased form real-time and day-ahead markets. The results of the model demonstrate that high potential revenues could be generated from participating in the regulation service market. However, the participation in these three markets results in a negative profit generated by gravity storage. In addition, the performed comparison demonstrated that this technology is less attractive compared to similar storage options (PHS and CAES) which resulted in a positive profit. In this work, an average fixed dispatch to contract ratio has been assumed. This assumption has an impact on the revenues received for regulation services as this latter is a function of this ratio. A lower ratio will decrease regulation service revenues and hence lower the total potential profit generated by the system.

Additional benefits could be captured by energy storage from performing in other grid functions. Based on the presented cost assessment, gravity storage is not profitable if it only participates in a limited number of applications. Therefore, even though gravity storage is capable of increasing revenues of the renewable farm, it needs to perform multiple functions to economically justify its operation.

Reference

[1]. Oldenmenger, W.A., 2013. Highrise energy storage core: Feasibility study for a hydro-electrical pumped energy storage system in a tall building (Master's thesis). Retrieved from TU Delft Repositories

[2]. Berrada, A., Loudiyi, K., Zorkani, I., 2017. Profitability, risk, and financial modeling of energy storage in residential and large scale applications. Energy 119, 94-109.

[3]. Berrada, A., Loudiyi, K., Zorkani, I., 2016. Valuation of energy storage in energy and regulation markets. Energy 115, 1109-1118. http://dx.doi.org/10.1016/ j.energy.2016.09.093.

[4]. Tarigheh, A., 2014. Master thesis: Gravity Power Module. (Master Thesis), Delft University of Technology, Delft

[5]. Pawel, I., 2014. The cost of storage e how to calculate the levelized cost of stored energy (LCOE) and applications to renewable energy generation. Energy Procedia.46, 68-77.

[6]. Zakeri, B., Syri, S., 2015. Electrical energy storage systems: a comparative life cycle cost analysis. Renew. Sustain Energy Rev. 42, 569-596.

[7]. Berrada, A., Loudiyi, K., Operation, sizing, and economic evaluation of storage for solar and wind power plants. Renew Sustain Energy Rev 59 (2016) 1117–1129

[8]. Ibrahim, H., Ilinca, A., Perron, J., 2008. Energy storage systems dcharacteristics and comparisons. Renew. Sustain Energy Rev. 12 (5), 1221-1250

[9]. Viswanathan, V., Crawford, A., Stephenson, D., Kim, S., Wang, W., Li, B., et al., 2014. Cost and performance model for redox flow batteries. J. Power Sources 247,1040-1051.

[10]. Abdon, A., Zhang, X., Parra, D., Patel, M.K., Bauer, C., Worlitschek, J., 2016. Techno economic and environmental assessment of energy storage technologies for different storage time scales. In: International Renewable Energy Storage Conference IRES.

[11]. Fichtner, 2014. Erstellung eines Entwicklungskonzeptes Energiespeicher in Niedersachsen. Stuttgart.

[12]. Weiss, T., Meyer, J., Plenz, M., Schulz, D., 2016. Dynamische Berechnung der Stromgestehungskosten von Energiespeichern für die Energiesystemmodellierung und-einsatzplanung. Z Energiewirtsch 40 (1), 1-14.

[13]. Härtel, P., Doering, M., Jentsch, M., Pape, C., Burges, K., Kuwahata, R., 2016. Cost assessment of storage options in a region with a high share of network congestions J. Energy Storage. http://dx.doi.org/10.1016/j.est.2016.05.010.

[14]. Lazard, 2015. Lazard's Levelized Cost of Storage Analysis - Version 1.0.

[15]. Gravitypower, 2011. Gravity Power Module. Energy Storage. Grid-scale Energy Storage. Available at: http://www.gravitypower.net/.

[16]. Hoek, E., 2001. Big tunnels in bad rock. ASCE J. Geotechnical Geoenviron. Eng. 127 (9), 726-740.

[17]. Madlener, R., Specht, J., Feb 2013. An Exploratory Economic Analysis of Underground Pumped-storage Hydro Power Plants in Abandoned Coal Mines. Institute for Future Energy Consumer Needs and Behavior (FCN). Available at: https://www.rwth-aachen.de/global/show_document.asp?id¼aaaaaaaaaagvvyq.

[18]. ALMÉN J, FALK J, 2013. Subsea Pumped Hydro Storage- A technology assessment (Master's thesis). Chalmers University of Technology, Sweden.

[19]. Jülch, V., 2016. Comparison of electricity storage options using levelized cost ofstorage (LCOS) method. Appl. Energy 183, 1594-1606.

[20]. D. Akinyele and R. Rayudu, "Review of energy storage technologies for sustainable power networks," Sustainable Energy Technol. Assess. 8, 74–91 (2014).

[21]. IRENA, Electricity Storage—Technology Brief (IEA-ETSAP and IRENA, 2012).

[22]. D. Rastler, Electricity Energy Storage Technology Options (Electric Power Research Institute (EPRI), Palo Alto, 2010).

[23]. Europe's Energy Portal, see http://www.energy.eu for Natural Gas Industry (last accessed June 3, 2013).

[24]. A. Evans, V. Strezov, and T. J. Evans, "Assessment of utility energy storage options for increased renewable energy penetration,"Renewable Sustainable Energy Rev. 16, 4141–4147 (2012).

[25]. Independent Statistics & Analysis U.S. Energy Information Administration, see http://eia.gov for Electricity Storage Cost.

[26]. IRENA, for Electricity Storage—Technology brief, 2012, see https://www.irena.org/DocumentDownloads/Publications/IRENAETSAP%20Tech%20Brief%20E18%20Electricity-Storage.pdf.

[27]. Denholm, P., Ela, E., Kirby, B., Milligan, M., 2010. The Role of Energy Storage with Renewable Electricity Generation. Golden, CO, National Renewable Energy Laboratory.

[28]. House Economic Matters Committee, Maryland General Assembly. Energy Storage: Considerations for Maryland. January 2016. Available at: http://energy.maryland.gov/Reports/FY15_Energy_Storage_Report.pdf

[29]. Bradbury K, Pratson L, Patiño-Echeverri D. Economic viability of energy storage systems based on price arbitrage potential in real-time U.S. electricity markets. Appl Energy 2014;114:512–9. http://dx.doi.org/10.1016/j. apenergy.2013.10.010 [ISSN 03062619]. <http://linkinghub.elsevier.com/retrieve/pii/S0306261913008301>.

[30]. Schubert, E., Zhou, S., Grasso, T., Niu, G., A Primer on Wholesale Market Design. Market Oversight Division White Paper. Available at: https://www.hks.harvard.edu/hepg/Papers/TXPUC_wholesale.market.primer_11-1-02.pdf

[31]. Drury, E., Denholm, P., Sioshansi, R., 2011. The value of compressed air energy storage in energy and reserve markets. Energy 36(2011), 4959-4973

[32]. Ommen T, Markussen WB, Elmegaard B. Comparison of linear, mixed integer and non-linear programming methods in energy system dispatch modelling. Energy. 10.1016/j.energy.2014.04.023.

[33]. Pousinho, H.M.I., Silva, H., Mendes, V.M.F., Collares,M., Cabrita, P.C., Self-scheduling for energy and spinning reserve of wind/CSP plants by a MILP approach. Energy 2014; 78: 524–534

[34]. Garcia-Gonzalez, J., R. de la Muela, R. M., Santos, L. M., Gonzalez, A. M., 2008.Stochastic Joint Optimization of Wind Generation and Pumped-Storage Units in an Electricity Market. IEEE Transactions on Power Systems 23(2), 460-468.

[35]. Sioshansi, R., Denholm, P., Thomas, J., Weiss, J., 2009. Estimating the value of electricity storage in PJM: Arbitrage and some welfare effects. Energy Economics 31(2), 269-277.

[36]. Denholm, P., Sioshansi, R., 2009. The value of compressed air energy storage with wind in transmission-constrained electric power systems. Energy Policy 37(8), 3149- 3158.

[37]. DeCarolis, J.F., Keith, D.W., 2006. The economics of large-scale wind power in a carbon constrained world. Energy Policy 34 (4), 395–410.

[38]. Bathurst, G. N., Strbac, G., 2003. Value of combining energy storage and wind in shortterm energy and balancing markets. Electric Power Systems Research 67(1), 1-8.

[39]. Perekhodtsev, D., 2004. Two essays on problems of deregulated electricity markets. Ph.D. Dissertation, Tepper School of Business Carnegie Mellon University: Pittsburgh, PA. 99pp. Available at /http:// wpweb2.tepper.cmu.edu/ceic/theses/Dmitri_Perekhodtsev_PhD_Thesis_2004.pdf

[40]. Figueiredo, C., Flynn, P., Cabral, E, 2005. The economics of energy storage. In: Proceedings of the 2005 Annual Meeting of Energy Storage Association, May 23–26 2005, Toronto, Canada.

[41]. Walawalkar R, Apt J, Mancini R. Economics of electric energy storage for energy arbitrage and regulation in New York. Energy Policy 2007;35 (4):2558–68. http://dx.doi.org/10.1016/j.enpol.2006.09.005 [ISSN 03014215], <http://linkinghub.elsevier.com/retrieve/pii/S0301421506003545>.

[42]. Locatelli, G., Palerma, E., Mancini, M., Assessing the economics of large Energy Storage Plants with an optimisation methodology. Energy 2015; 83: 15-28

[43]. Kazmpour SJ, Moghaddam MP, Haghifam MR, Yousefi GR. Electric energy storage systems in a market-based economy: comparison of emerging and traditional technologies. Renew Energy 2009;34(12):2630–9.

[44]. Kazmpour JS, Moghaddam MP. Economic viability of NaS battery plant in a competitive electricity market. In: 2009 International conference on clean electrical power, 2009. p. 453–9.

[45]. Mogaddam IG, Saeidian A. Self scheduling program for a VRB energy storage in a competitive electricity market. In 2010 International conference on power system technology (POWERCON); 2010. p. 1–6.

[46]. He X Lecomte R, Nekrassov A, Delarue E, Mercier E. Compressed air energy storage multi-stream value assessment on the French energy market. In PowerTech, 2011 IEEE Trondheim; 2011. p. 1–6.

[47]. Siohansi R, Denholm P, Jenkin T. A comparative analysis of the value of pure and hybrid electricity storage. Energy Econ 2011;33(1):56–66.

[48]. Hessami M-A, Bowly DR. Economic feasibility and optimisation of an energy storage system for Portland Wind Farm (Victoria, Australia). Appl Energy 2011;88(8):2755–63.

[49]. McKenna E, McManus M, Cooper S, Thomson M. Economic and environmental impact of lead–acid batteries in grid-connected domestic PV systems. Appl Energy 2013;104:239–49.

[50]. Shafiee, S., Zamani- Dehkordi, P., Zareipour, H., Knight, M.A., Economic assessment of a price-maker energy storage facility in the Alberta electricity market. Energy 2016; 111: 537–547

[51]. Fares, R. Webber, M., A flexible model for economic operational management of grid battery energy storage. Energy 2014; 78: 768-776.

[52]. Xi, X., Sioshansi, R., Marano, V., 2011. A Stochastic Dynamic Programming Model for Co-optimization of Distributed Energy Storage. Working paper, The Ohio State University, Columbus, OH.

[53]. Berrada, A., Loudiyi, K., Operation, sizing, and economic evaluation of storage for solar and wind power plants. Renew Sustain Energy Rev 59 (2016) 1117–1129

[54]. Krishnan, V., Das, T., Optimal allocation of energy storage in a co-optimized electricity market: Benefits assessment and deriving indicators for economic storage ventures. Energy 2015; 81: 175-188.

[55]. Das T, Krishnan V, McCalley JD. Assessing the benefits and economics of bulk energy storage technologies in the power grid. Appl Energy 2015;139:104–18. http://dx.doi.org/10.1016/j.apenergy.2014.11.017 [ISSN 03062619]. <http:// linkinghub.elsevier.com/retrieve/pii/S0306261914011660>.

[56]. Kempton W, Tomic J. Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. Journal of Power Source;144:268-270

[57]. NYISO, 2005. Ancillary Services Manual: Available at /http://www.nyiso. com/public/webdocs/documents/manuals/operations/ancserv.pdf.

[58]. Xi X, Sioshansi R.A Dynamic Programming Model of Energy Storage and Transformer Deployments to Relieve Distribution Constraints. Computational Management Science

[59]. Tomi´c J, Kempton W (2007) Using fleets of electric-drive vehicles for grid support. Journal of Power Sources 168:459–468.

[60]. New York Independent System Operator (NYISO), New York Electricity Market Data: ISO Ancillary Services Prices and Quantities, Data retrived from:http://www.nyiso.com/public/index.jsp

[61]. Berrada, A., Loudiyi, k., Zorkani, I., Sizing and economic analysis of gravity storage. Journal of Renewable and Sustainable Energy 8, 024101 (2016)

[62]. Ecofys., 2014 Energy Storage opportunities and challenges. A West Coast perspetive White paper. Available at: http://www.ecofys.com/files/files/ecofys-2014-energy-storage-white-paper.pdf.

[63]. Walawalkar, R., Kamath, H., Mancini, R., Fernands, S., Crudele, D., Gomatom, K., 2005. Electric Energy Storage: Opportunities and Challenges in NY; Electric Energy Storage: Applications and Technologies, San Francisco, October 17–19, 2005.

[64]. Butler, P., Iannucci, J., Eyer, J., 2003. Innovative business cases for energy storage in a restructured electricity marketplace. Sandia National Laboratories report SAND2003-0362. Available at /http://www.prod.sandia.gov/cgi-bin/techlib/access-control.pl/2003/030362.pdf.

[65]. EPRI, 2003. EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications. EPRI, Palo Alto, CA, and the US Department of Energy, Washington DC.

[66]. Eyer, J., Iannucci, J., Corey, G., 2004. Energy storage benefits and market analysis handbook: a study for the DOE energy storage systemsprogram; Prepared by Sandia National Laboratories SAND2004- 6177. Available at /http://www.prod.sandia.gov/cgi-bin/techlib/ access-control.pl/2004/046177.pdf.

[67]. SANDIA, “Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide,” Sandia National Laboratories, Albuquerque, New Mexico, 2010.

[68]. Beaudin M, Zareipour H, Schellenberglabe A, Rosehart W. Energy storage for mitigating the variability of renewable electricity sources: An updated review. Energy for sustainable development. 2010;4: 302–314

Chapter 5

5. Profitability, Risk, and Financial Modeling of Energy Storage in Residential and Large Scale Applications

The increasing share of renewable energy plants in the power industry portfolio is causing grid instability issues. Energy storage technologies have the ability to revolutionize the way in which the electrical grid is operated. The incorporation of energy storage systems in the grid help reduce this instability by shifting power produced during low energy consumption to peak demand hours and hence balancing energy generation with demand. However, the deployment of some energy storage systems will remain limited until their economic profitability is proven. In this chapter, a cost-benefit analysis is performed to determine the economic viability of energy storage used in residential and large scale applications. Revenues from energy arbitrage were identified using the proposed models to get a better view on the profitability of the storage system. Moreover, the feasibility of energy storage projects relies on the readiness of investors to invest in the project. This willingness is significantly affected by several factors such as the risk of the innovative storage concept. To analyze the profitability risk associated with such energy project, a sensitivity analysis is performed in this study.

5.1. Introduction

Energy consumption varies significantly throughout the day and ramps up and down during peak and off-peak hours. Utility administrators launched several incentive programs and policies to encourage customers to reduce their peak energy consumption. Pricing policy which consists of buying energy at high price during peak hours is an example of energy policies applied by utility companies. Given this pricing policy, residential customers are encouraged to shift load consumption from high energy demand hours to off peak periods [1, 2]. However, the effectiveness of this technique is limited since only few household tasks can be transferrable. The deployment of residential energy storage is another method that could be used. Residential customers can store energy during low demand hours and use the stored electricity during peak hours. This methodology allows them to reduce their electric bill because the stored energy will be bought at low prices during off-peak hours and consumed during peak hours. Consequently, high energy prices during peak demand periods will be avoided. Zhu et al. [3] proposed a model to control different types of residential energy storage with the aim to reduce the user's electric bill.

Other methods have been deployed in residential applications to reduce the energy bill such as the use of local energy generation which include solar power, wind power and geothermal. By directly supplying energy from the generation source to the load, the consumption of energy bought from the grid at high prices is reduced. However, the hourly energy generated by a photovoltaic (PV) system, for example, does not match the household peak demand hours. Therefore, to fully capture the benefit of energy generation sources, an energy storage system could be used as a management device. Residential customers can store the excess generated power for future use (during peak hours). Few research papers have discussed control algorithms for residential energy storage combined with PV systems. McKenna et al. investigated the economic value of integrating lead-acid batteries in grid-connected PV under feed-in tariff in UK. The results of their study demonstrated that lead acid battery has a negative value and its financial loss is considered significant (£1000/year). A mixed integer linear programming (MILP) algorithm has been proposed by Ha Pham et al. in [5] to model household PV and energy storage system. In [6], a predictive control model is proposed to reduce electricity bills by performing peak shaving. Wang et al present a hierarchical system for predicting energy generation and demand, as well as monitoring energy storage technologies [7]. Most of the literature work focus on implementing control algorithm for managing the flow of energy in households with a goal to minimize the electric bill.

Utilities have been for a long time interested in energy storage systems due to their great potential to support the operation of the electric grid. However, the deployment of these systems both in small and large scale applications is significantly dependent on to their viability. An energy storage system has to fulfil some conditions in order to be considered economically viable. A positive net present value (NPV) ranks as being the first condition; meaning the generated revenues must exceed the system costs. The second condition concerns being more economically profitable compared to other alternative storage systems. The last condition is related to the system associated risks. Investment risk has to be taken into consideration when evaluating the economic viability of energy storage.

The benefits of energy storage can be captured from different applications; among these revenues generated from arbitrage, and those received from transmission and distribution (T&D) upgrade deferral depending on the investigated scenario. Previous researches have proposed methods for optimizing the operation of energy storage systems, with a focus on maximizing the owner revenues [8]. This simulation results demonstrated that renewable farms can take advantage of the hourly energy price fluctuation, and sell more electricity when the prices are high to increase their revenues. An economic study was undertaken by Walawalkar et al. to evaluate the revenues obtained from performing energy arbitrage and regulation service in New York. The outcome of this study reveals that the installation of storage in this city is profitable. since New York is characterized by potential opportunities for regulation services. In addition, this study quantifies the value of T&D system upgrade deferral [9]. Energy storage arbitrage potential has been investigated by authors in [10–18] for different storage systems in particular markets. Bradbury et al. [19] proposed an optimization algorithm to model the maximum profit received by energy storage from energy arbitrage in a number of U.S. real-time electric markets. Different energy storage technologies including mechanical, electrical and chemical systems were evaluated in this analysis. The energy and power capacities of these systems were also identified based on maximum profit. Hittinger et al. [20] presented a high resolution model to evaluate the value of batteries in micro-grid systems. Their model takes into consideration several battery aspects such as temperature effects, rate-based variable efficiency, and operational modeling of capacity fade. In some of the discussed scenarios, this study suggests that aqueous hybrid ion batteries are often more cost-effective than lead acid batteries. The economics of large energy storage plants were assessed by Locatelli et al. in [21] with an optimization methodology. This work quantified the potential for energy storage for energy reserve and price arbitrage. The outcomes of this analysis demonstrate that without subsidies, none of the existing storage technologies is economically viable.

The topic of profitability and risk evaluation of a storage system known as gravity storage, similar to the traditional pumped hydro storage, has never been explored in literature. For this reason, a framework here is presented as follows. Section 2 discusses the different classification of energy storage. Section 3 presents the proposed structure about profitably modeling. It investigates the viability of residential energy storage considering different scenarios. Then it encompasses a cost benefit study for large scale energy storage followed by a strategic analysis (section 4). Finally, risk analysis along with sensitivity study is undertaken in section 5 and 6, respectively. Section 7 provides a summary of the work carried in this chapter.

5.2. Classification of energy storage

Energy storage systems can be categorized into small and large scale systems. Small scale technologies such as batteries are mainly used by residential and industrial customers while large scale systems such as compressed air energy storage and pumped hydro are used by power suppliers [22].

5.2.1. Small scale energy storage: (Residential storage system)

Residential customers are urged to invest in renewable energy technologies because of the numerous advantages received by local energy generation. However, small scale generation is not that much beneficial compared to large scale solutions. In large systems, there is a huge need of matching the demand to the supply while this need is very limited for a single household [22]. Therefore, the generated revenues for small scale applications could be less than the technology investment cost; as it will be demonstrated in section III.

Conventional energy storage technologies used in residential applications are batteries. These mature systems efficiently store electrical energy at small scale while this synergy benefit is limited for large batteries. A typical disadvantage of batteries is their limited expected lifespan which is associated with the number of charge/discharge cycles. However, the amount of cycles per day is rather small for residential household in comparison with large scale systems. Therefore, batteries used by single households have higher lifetime and lower expected replacement period.

The efficiency of a hybrid residential energy system composed of PV system and battery can be high, reaching 98% under correct deep cycle charging and optimal conditions [22]. This efficiency is a little bit difficult to achieve in practice because it is significantly affected by several factors, which include ambient temperature, speed of charging and battery age. Under normal conditions, the efficiency of batteries is lower; for example, nickel cadmium batteries have a round-trip efficiency of 65%, while the efficiency of lead-acid batteries ranges from 75 to 85% [23]. Additionally, storing energy produced by solar photovoltaic systems does not require a rectifier; since both systems produces a direct current (DC). The generated DC could be used by several appliances without the need of a converter. However, extra costs are incurred for use by appliances requiring an alternating current (AC).

Recently, the use of lithium-ion batteries for residential applications has increased because of the benefit this storage system has over other batteries. However, from an economic perspective, these advantages are not so important. There is a significant need for a reduction in kWh price of these technologies before they become much attractive. In general, the unit price per kWh of a small scale battery is almost the same as the cost of larger systems [22].

5.2.2. Large scale energy storage

5.2.2.1. Local grid storage system

Energy storage technologies used in local grid systems are operated more often than those used in residential applications. Thus, the number of charge and discharge cycles is higher for large scale systems. In this case, some of the benefits of lithium-ion batteries, which include storing energy over a longer amount of charge/ discharge cycles, are more important to the grid than to residential applications [22]. Grid stabilization is the main role of local grid energy storage systems. It helps the distribution network to overcome overloading during peak demands.

Batteries are also used as storage systems in local grid. Sodium-Sulphur batteries are considered appropriate for such application, but their high cost compared to other batteries limits their implementation. This technology is not as much attractive as lithium-ion technology, even if it has better characteristics such as higher efficiency [23]. Flywheel energy storage is another alternative that has been proven for several applications, including motion smoothing, and providing ride-through power for disturbances and voltage fluctuations damping. Since this technology is expensive, and is characterized by high unit costs, it is not used for load shifting.

5.2.2.2. Main grid storage system

Pumped hydro storage (PHS) is currently the most widely used energy storage system in large scale applications [24,25]. The system characteristics, which include large storage capacity and high initial cost, make PHS mostly suited for main grid applications [24]. Its role is to stabilize the grid through load balancing, reserve generation, peak shaving, and frequency regulation. However, its dependence on geography which impacts the siting of the technology is a potential disadvantage of this technology is [23,26]. Pumped hydro could be located far away from customers and power generators. This implies losses related to transmission and requires extra investments. Currently, a number of developers are proposing new concepts similar to pumped hydro such as seawater PHS, underground PHS, compressed air PHS, and gravity storage. Compressed Air Energy Storage (CAES) is another promising system that is used in large scale application. This system is also geographically dependent as it requires large underground cavern [27]. The environment impact of CAES is lower than that of PHS. Large amount of energy can be stored in these systems for much lower prices compared to storage used in local grid

[28]. The unit cost of power of these technologies is the same for similar systems in local grid. It is then convenient to use these technologies for long term applications, mainly due to their low self-discharge and ability to store electricity over long periods of time. The discharge length of these storage systems used in the main grid is several hours to multiple days. Therefore, with the increasing share of intermittent renewable energy sources, these storage solutions will tide over days with low energy production until overproduction occurs.

5.3. Profitability Modeling

Investigating the profitability of energy storage system requires taking into consideration all the different scenarios that the storage system could be part of. Energy storage could be connected to the power system or it could play the role of the grid. The demand side of the analysis could be a household (small scale) or a city (large scale) depending on the investigated application. The supply side could be represented by either wind turbines or PV systems depending on the implemented source of energy.

5.3.1. Problem Formulations

The objective of this problem is to determine the economic viability of residential energy storage system. In this analysis, four scenarios have been identified. The three first scenarios represent a storage system connected to the utility grid; while the fourth one represents a standalone system. All scenarios are illustrated in Fig. 5.1. The storage system in the first scenario does not supply energy to the demand side. The structure consists of storage system with an electrical grid connection. Opposite to the first scenario, the second case deals with load consumption and is, at the same time, connected to the electrical grid. The third situation consists of generation source, storage system, and load; all connected to the electric grid.

For the fourth scenario, the energy storage is not connected to the electric grid, and it is responsible of balancing the demand and supply of energy. Such system could represent remote areas or islands. It is simulated as a system consisting of energy generating source (solar/wind), load, and storage system. Moreover, in Fig. 1 two model categories are presentsed. The X models make use of energy storage while the Y models do not incorporate enegry storage . These two models have been used to identify the benefits of using residential energy storage. These benefits are equal to model X revenues minus revenues received from model Y. These two model are used to capture revenues received by only the storage system.

The objective of this problem is to determine the profitability of energy storage by calculating the net present value of the storage system. Cash flow streams of energy project need to be expressed in terms of present value (common denominator) to become comparable. These cash flows are related to the present value based on the discount rate. Net present value (NPV) is the difference between the present value of cash in-flow and the present value of cash out flow (Eq. 5.1).

$$NPV = PV_{\mathrm{Re}v} - PV_{\mathrm{Cos}t} \tag{5.1}$$

Both costs and revenues of the storage need to be estimated, this will be presented in the following subsections.

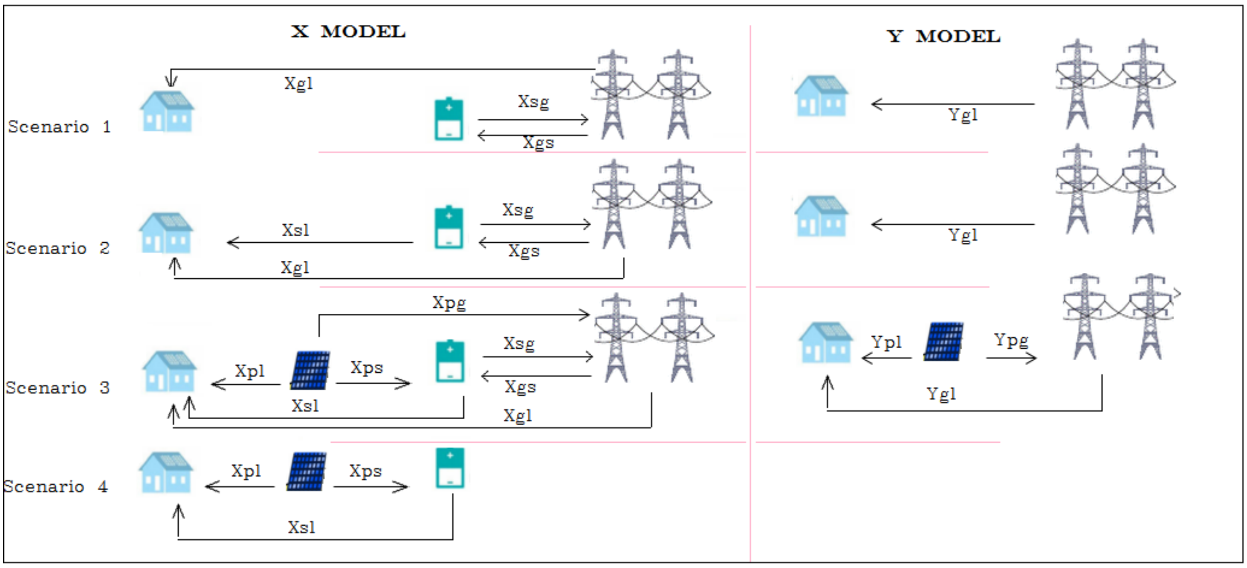


Fig. 5.1. Schematic of residential scenarios.

5.3.2. *Energy storage revenues*

To determine the economic gain of the system, a mathematical problem is formulated. The aim of this model is to identify the maximum revenues that could be received from optimum operation of energy storage in the proposed system. This is achieved by optimally selling and buying energy; while taking into consideration load consumption, operational restrictions of the investigated energy system, and energy market prices. This analysis is performed through a linear programming model using General Algebraic Modelling System (GAMS). The model code is presented in Appendix B3.

The benefits of the project are discounted over the years according to the principle that the value of money decreases over time. The future cash flows of the received annuities are discounted by the factor ρ. The present value of revenues is the product of maximum generated revenues and ρ as expressed in Eq. 5.2.

$$PV_{\text{Rev}} = Max\left[Saving(t)\right]\rho_N \tag{5.2}$$

With $\rho_N = \dfrac{\left[1\text{-}(1+i)^{\text{-}j}\right]}{i}$.

The revenues' model is formulated as (Eq.5.3)

$$\begin{cases} Max\left[Saving(t)\right] = Max\left[X\text{ - }Y\right] \\ \mathrm{X}{=}\sum(X_{Sell}(t) - X_{Buy}(t))P_E(t) \\ \mathrm{Y}{=}\sum(Y_{Sell}(t) - Y_{Buy}(t))P_E(t) \end{cases} \tag{5.3}$$

$X_{Sell}(t), X_{Buy}(t), Y_{Sell}(t), Y_{Buy}(t)$ are energy exchange variables and $P_E(t)$ is the hourly energy prices. The input parameters of this model include energy storage characteristics, hourly energy generation and price. The storage system characteristics include energy capacity, rated power, efficiency, and lifetime. The output parameters are the hourly dispatch profile and the system hourly savings. The hourly energy dispatch depends on the system operation and will be discussed separately in every scenario.

5.3.2.1. Scenario 1

The system consists of energy storage connected to the electric grid. In this case, the energy storage objective is to make profit from energy arbitrage with the grid and without supplying energy to the load. In other words, the demand is met by energy supplied only from the electric grid. The model was used to identify the optimal sell/buy schedule of the system. The output of this scenario is the hourly energy exchanged between the storage system and the grid. Model X and Y of this scenario were compared to identify the revenues generated by the use of energy storage in a residential application. In this case, the model variables are:

A. Model X (System with energy storage)

$$\begin{cases} X_{Sell}(t) = X_{sg}(t) \\ X_{Buy}(t) = X_{gl}(t) + X_{gs}(t) \end{cases} \tag{5.4}$$

Where $X_{sg}(t)$ is the energy discharged from the storage system to the electric grid. $X_{gs}(t)$ is the energy stored from the grid. The demand side constraint is expressed in Eq. 5.5.

$$D(t) = X_{gl}(t) \tag{5.5}$$

B. Model Y (System without energy storage)

$$\begin{cases} Y_{Sell}(t) = 0 \\ Y_{Buy}(t) = Y_{gL}(t) \end{cases} \tag{5.6}$$

Where $Y_{gl}(t)$ is the energy transferred from the grid to the load in model Y. The demand constraint $D'(t)$ is presented in Eq. 5.7.

$$D'(t) = Y_{gl}(t) \tag{5.7}$$

5.3.2.2. Scenario 2

As in scenario 1, this system is composed of energy storage connected to the electric grid. However, here the energy storage is allowed to supply energy to the load. The demand is met by both the storage system and the electric grid. To capture only the benefits generated by the storage system, model X is compared to model Y.

The output parameters of this scenario include the optimal charge/discharge of the storage system, as well as the energy dispatched from both the grid and the energy storage to meet the load.

A. *Model X (System with energy storage)*

$$\begin{cases} X_{Sell}(t) = X_{sg}(t) \\ X_{Buy}(t) = X_{gl}(t) + X_{gs}(t) \end{cases} \tag{5.8}$$

Demand Constraint: $$D(t) = X_{sl}(t) + X_{gl}(t) \tag{5.9}$$

B. *Model Y (System without energy storage)*

This model is similar to model Y of scenario 1, as illustrated in Fig. 5.1. The energy demand is met by the electric grid and without the use of energy storage. In this case, Eqs (5.6-5.7) are used to derive the model variables.

5.3.2.3. Scenario 3

The third scenario deals with energy storage combined with a generation source (PV system). The role of the storage system in this case is to balance energy between the demand and the supply side. The demand is met by the PV generated energy, the energy storage and the electric grid. Similarly, to derive only the storage revenues, model X is compared to model Y. The model outputs include hourly energy stored and discharged from the storage system, as well as optimal energy exchanged between the PV system, the grid and the storage to meet the load.

A. *Model X (System with energy storage)*

$$\begin{cases} X_{Sell}(t) = X_{sg}(t) + X_{pg}(t) \\ X_{Buy}(t) = X_{gl}(t) + X_{gs}(t) \end{cases} \tag{5.10}$$

Model constraints:

$$PV(t) = X_{pl}(t) + X_{ps}(t) + X_{pg}(t) \tag{5.11}$$

$$D(t) = X_{gl}(t) + X_{pl}(t) + X_{sl}(t) \tag{5.12}$$

$$E_s(t) = X_{ps}(t) + X_{gs}(t) \tag{5.13}$$

$$E_D(t) = X_{sl}(t) + X_{sg}(t) \tag{5.14}$$

In these Equations, $PV(t)$ is the hourly energy generated by the PV system, $E_s(t)$ and $E_D(t)$ are the hourly energy stored and discharged from the storage, respectively. $X_{pl}(t)$, $X_{ps}(t)$, $X_{pg}(t)$ are the energy transferred from the energy generation source (PV system) to the load, storage, and grid respectively (See Fig. 5.1).

B. *Model Y (System without energy storage)*

$$\begin{cases} Y_{Sell}(t) = Y_{pg}(t) \\ Y_{Buy}(t) = Y_{gl}(t) \end{cases} \tag{5.15}$$

Model constraints:

$$PV'(t) = Y_{pl}(t) + Y_{pg}(t) \tag{5.16}$$

$$D'(t) = Y_{gl}(t) + Y_{pl}(t) \tag{5.17}$$

Where *PV'(t)* is the hourly energy generated by the PV system used in model Y, *D'(t)* is the hourly energy demand, and Y(t) variable are presented in Fig. 5.1.

5.3.2.4. Scenario 4

Revenues received in this scenario are from transmission and distribution deferral (T&D). A rough quantification of this benefit was made based on literature review. This benefit is important to utilities rather than to industrial or commercial customers. Utilities can defer transmission and distribution upgrade by properly locating energy storage systems. These locations could be remote areas, or could simply be characterized by irregular maximum load days, with only few hours of peak load during a day. Energy storage can then be used for few years to avoid T&D high upgrade charges for remote areas, or location with slow load growth. An estimation of these benefits ranges from \$150,000 to \$1,000,000/MW-year [9]. The average value was used in this analysis.

5.3.3. Energy storage constraints

Storage system energy level varies with time due to the charging and discharging operation. Eq. 5.18 is used to control the energy that flows in and out from storage level, and to keep track of the storage level, while taking into consideration the system efficiency (η) and self-discharge (δ).

$$S(t) = (1-\delta)S(t-1) - E_D(t) + \left(E_S(t)\eta\right) \tag{5.18}$$

Where $S(t)$ is the storage level, which is the energy left in the storage at S*(t-1)* plus the stored energy $E_s(t)$, minus the energy that flows out from the system, ($E_D(t)$) at time *t*. This level is bounded by zero and the maximum storage capacity (E_{max}). In addition, the storage energy level has to be more than or equal the discharged energy at a specific time (Eq. 5.19).

$$0 \le E_D(t) \le S(t) \le E_{\max}(t) \tag{5.19}$$

The charged and discharged amount of energy at a specific time interval must be less than the power and capacity limit of the storage system E_L.

$$\begin{cases} E_D(t) \le E_L \\ E_s(t) \le E_L \end{cases} \tag{5.20}$$

The model is also constrained by positive energy transactions. All energy variables must be positive.

5.3.4. Energy storage Cost

The present value of the storage system cost is expressed as:

$$PV_{\cos t} = P_{\mathrm{c}} + C_{\mathrm{c}} + BOP_{\mathrm{c}} + O\,\&\,M_{\mathrm{c}} + REP_{\mathrm{c}} \tag{5.21}$$

These different cost variables are calculated using Eq. 5.22.

$$PV_{\cos t} \begin{cases} P_c = PU_c . P_S \\ C_c = SU_c E_c / \eta \\ BOP_c = BOPU_c . P_S \\ O\,\&\,M_c = O\,\&\,MU_c . P_S . \eta \\ REP_c = R \sum_{k=o}^{k} (1+i)^{-kn'} \end{cases} \tag{5.22}$$

5.3.5. Case study for residential application

To test the effectiveness of the proposed energy model, case studies on small and large scale systems are performed. Short term forecast of load consumption, PV energy generation, and energy prices are used as input. The models decisions are made on hourly basis (twenty four hours). Input data for day-ahead energy prices were obtained from “Red Eléctrica de España, S.A.” (REE) [29]. Energy consumption of a single household was estimated as 11 kWh. The specifications of residential application used are summarized in Table 5.1. Gravity storage is used in this case study.

Table 5.1. Residential application specification

Hybrid System Specifications	**Specification value**
PV system	3 kWh
Storage capacity	11 kWh
Number of cycles per day	1 x discharge/charge per day
Expected lifetime of the storage	40 Years

Electricity demand and energy prices in a utility system vary hourly and from season to season. There is a strong relationship between residential electricity usage and energy prices. Summer days cause the wholesale price of electricity to increase significantly compared to a typical normal day. In addition, even the energy generated from a PV system differs throughout the year. Therefore, to properly estimate the revenues received from arbitrage, energy consumption data as well as energy generation and prices were obtained for different days from three scenarios including summer, winter and normal days (different from summer and winter). These input data would be incorporated in modelling the problem.

5.3.5.1. Energy storage revenues

To approximate the yearly revenues, it was estimated that a year has 94 summer days, 90 winter days, and 181 normal days. Fig. 5.2 presents the hourly energy prices as well as the hourly consumption; of a typical household vs energy produced by a 3kW PV system.

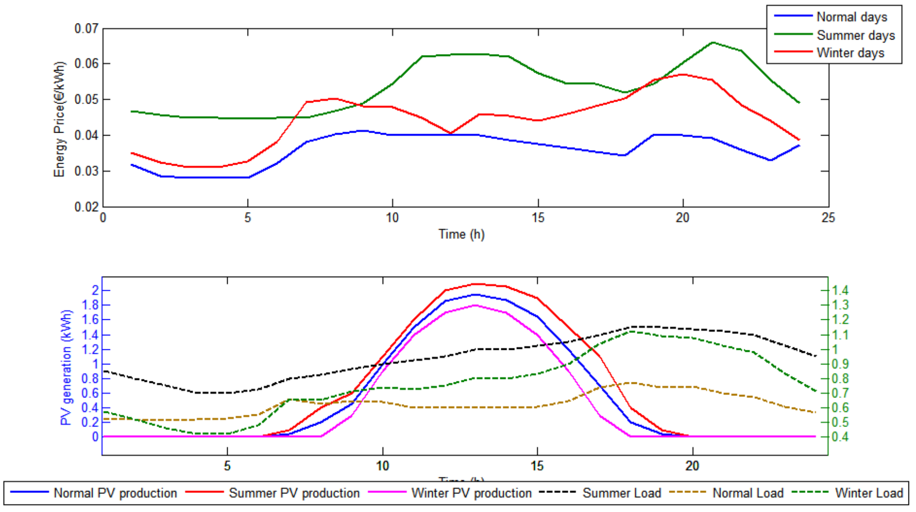


Fig. 5.2. Hourly energy price vs hourly PV production for normal, summer, and winter days.

The electricity demand increases significantly during summer days due to the use of air-conditioning, for example. This increase puts pressure on the regional power grid, and leads to an increase in energy prices as illustrated in Fig. 5.2.

The proposed model optimally schedule the selling and buying of energy to maximize the revenues. Residential customer can make profit from selling energy to the grid; when the electricity prices are high. Hourly revenues of the different investigated models are shown in Fig. 5.3.

Based on results of comparison between the three first scenarios of energy storage application, it is found that hourly revenues of scenario 1, 2 and 3 are almost identical, except for the small difference shown by the black circle in Fig 5.3. For example, this difference occurs during summer days at 4 am and 6 am, where energy price is the same. Hence, exchanging energy with the grid at 4 am or at 6 am does not affect the total maximum revenues.

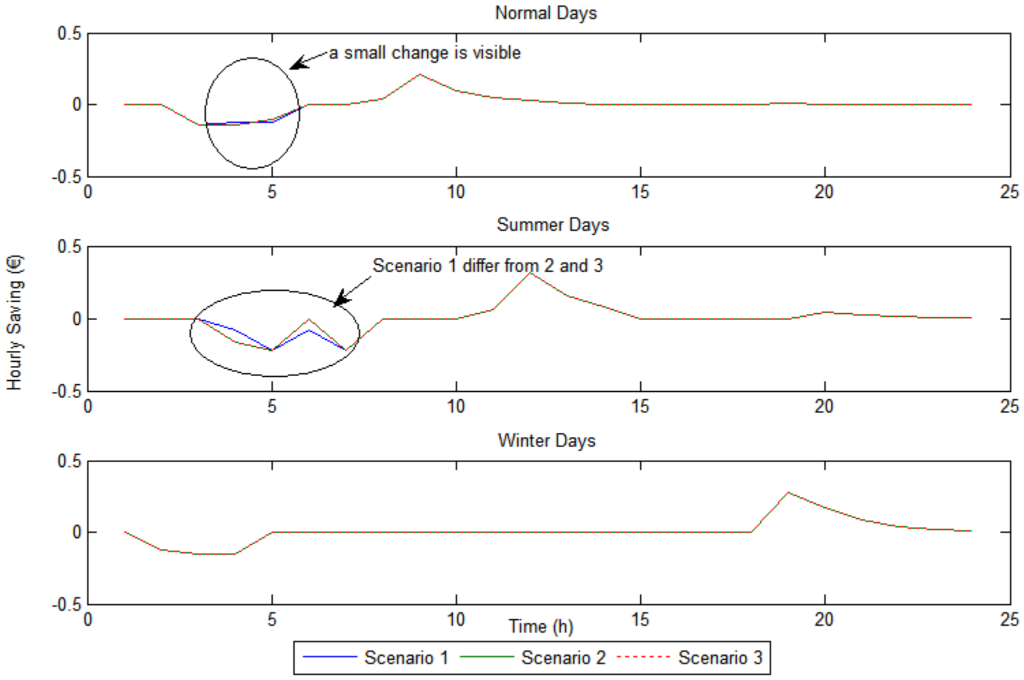


Fig. 5.3. Hourly revenues of the three investigated scenarios

This comparison demonstrates that all three scenarios operate similarly on daily cycles. Since, the main objective of the model is to optimally sell and buy energy, while meeting the demand requirement, the storage system in scenario 2 and 3 has chosen to operate in a similar manner as scenario 1 (see Fig 5.4). Therefore, the benefit of energy storage is almost the same whether it has been combined with a PV system or not. In all cases, energy is stored only when the price of electricity is low and discharged when the energy price goes up. This makes energy storage operates likewise in the three investigated scenarios.

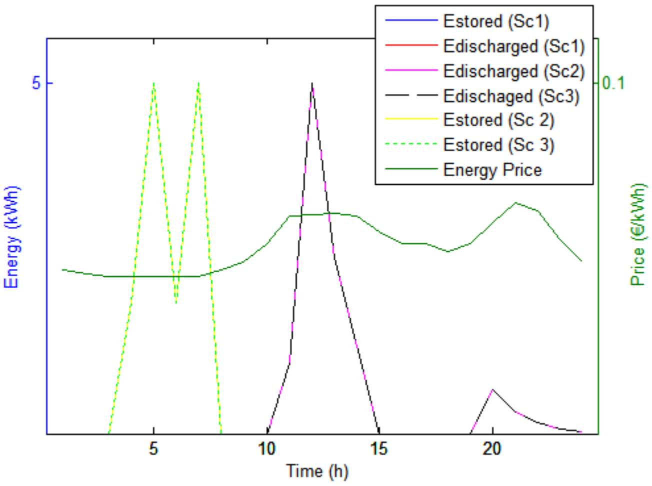


Fig. 5.4. Energy exchange of the first three scenarios.

As for the comparison of present value of revenues for the different scenarios, the same conclusion, as discussed above, is deduced. The present value of the storage is the same for scenario 1, 2 and 3. Scenario 4 generates more revenues compared to the other scenarios; since it receives revenues from T&D upgrade deferral, rather than from energy time shift application. It is to be noted that revenues generated from scenario 4 were not represented in Fig 5.4, for the reason that they do not vary hourly, and are estimated as a constant amount of 550 € /year. Varying the application of energy storage resulted in the different present value of revenues as shown in Figure 5.5.

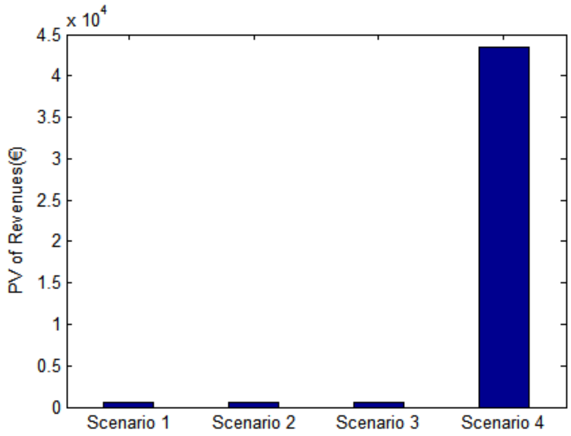


Fig. 5.5. Present value of revenues of all investigated scenarios

5.3.5.2. Residential Energy storage cost

In this section, the present value of cost of the investigated storage system (gravity storage) is identified, and compared to other proven and promising storage technologies; used in residential application such as lead acid and lithium ion batteries. These storage systems, having the same scales, are compared based on their initial costs, O&M costs, and specifications for small scale application.

To compare the different technologies, an economic lifetime of 40 years is used; as presented in Table 5.2. It is to be noted that this expected lifespan represents a long term investment, which makes the replacement cost an important variable for battery systems, as they are characterized by a limited lifetime. The usable storage capacity chosen for this case study is 11 kWh with a power-to-energy ratio of 1:2. The present value of the different costs has been calculated with an interest rate of 5%. The accuracy of these cost calculations may be affected by several factors; such as location of technology, market conditions and technological progress.

The characteristics of lead acid, lithium ion battery and gravity storage system are given in Table 5.2. The installed capacity of lead acid battery is two times the usable capacity due to the 50% DOD. In addition, the transportation cost of lead acid battery is much higher than for lithium ion batteries; due its higher weight and size.

In this assessment, lead-acid battery storage has to be replaced 25 times based on the expected lifetime of the system. Lithium-Ion battery needs to be replaced 7 times while gravity storage system is not replaced during its operation.

Table 5.2. Energy storage systems characteristics

	Lead Acid Battery [30]	**Lithium Ion Battery [30]**	**Gravity Storage[31]**
Installed Capacity	22 kWh	11 kWh	11 kWh
Usable Capacity	11 kWh	11 kWh	11 kWh
Storage Cost	150 €/kWh	700 €/kWh	31,464 €
Power Unit Cost	405 €/kW	1350 €/kW	600 €/kW
O&M Cost	9 €/kW	9 €/kW	1.9 €/kW
BOP Cost	90 €/kW	90 €/kW	4 €/kW
Replacement Cost	30% of Equipment Cost	50% of Equipment Cost	0
Efficiency	75%	93%	80%
Lifetime	500 cycle at 50% DoD	2000 Cycles at 100% DoD	40 Years
	1.5 Years	5.5 Years	
Installation Cost	200 €	200 €	200 €
Transportation Cost	28 €/ kWh	10 €/ kWh	-

5.3.5.3. *Cost per Kwh per cycle*

To understand the business model of energy storage, it is important to identify the cost per cycle of the system. This value is the product of the technology replacement number and its total cost. This includes system capital cost, plus installation and transportation costs, divided by the system expected consumption, which is equal to the number of years the system is used multiplied by the number of cycle in a year. The cost per cycle of energy storage measured in € / kWh / Cycle of the investigated residential energy storage systems is shown in Table 5.3.

Table 5. 3. Energy storage systems cost per cycle

Energy Storage	**Lead Acid Battery**	**Lithium Ion Battery**	**Gravity Storage**
Cost per kWh/ cycle	2.18	2.10	0.25

The cost per kWh per cycle of gravity storage is very low compared to lead acid and lithium batteries. This is due to the high expected lifetime of the technology; even if it requires higher initial investment costs. It is also interesting to note that despite the higher unit power and capacity costs of lithium ion battery, its cost per kWh per cycle remains lower than that of lead-acid battery. This is due to the intrinsic qualities of lithium-ion batteries.

5.3.5.4. *Energy Storage NPV*

The present value of costs for the three storage systems was determined using Eqs (5.21-5.22). The different storage characteristics presented in Table 5.2 were used as inputs. The calculated present value of costs are compared in Fig 5.6. As expected, gravity storage has lower present value of cost than lithium ion, followed by lead acid battery system. This is due to the fact that batteries have short lifetimes compared to that of gravity storage. This difference is captured by frequent replacement (cash outflows) of batteries.

This cost assessment does not imply whether gravity storage should be used in residential application or not. To evaluate the economic performance of this system, the NPV financial metric is considered for each of the investigated scenarios.

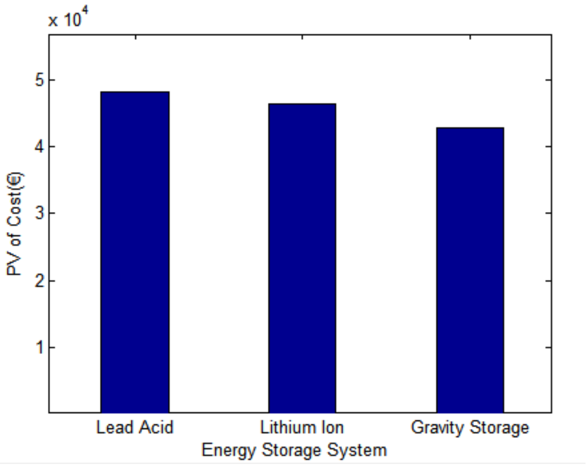


Fig. 5.6. Present value of costs of lead acid and lithium ion batteries vs gravity storage

The net present value (NPV) is an approach to explore costs and revenues while accounting for the time value of money. It is a valuable metric to consider for comparing storage systems, since these technologies have different characteristics. The storage system investment is expected to provide a return on investment; greater than the initial and ongoing cash expenditures, related to the ownership and operation of the system, if the NPV is positive. A negative NPV, on the other hand, indicates that installing the storage system does not show a financial benefit, since the returns are worth less than the cash outflows. For the four investigated scenarios, the total net present value of the system is presented in Fig. 5.7.

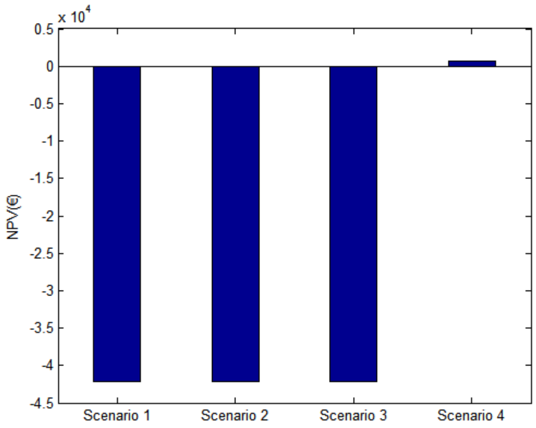


Fig. 5.7. Total net present value of all investigated scenarios

Installing gravity storage yielded a negative NPV for the three first considered storage applications. Adding a generation source (PV system) to the model (scenario 2 and 3) did not offset the negative NPV of the system. However, installing gravity storage system, for T&D upgrade deferral application, yields a positive NPV in the fourth scenario. Therefore, gravity storage is not considered profitable for residential applications except if it is used as a stand-alone system. Hence, it may become possible, under certain conditions, that a small scale residential gravity energy storage system may make economic sense by providing positive NPV.

5.3.6. Case study for large scale system

The aim of this analysis is to determine the economic viability of large scale energy storage system. As the previously discussed study, scenario 1 is used in the simulation of this application. This choice is based on the fact that scenario 1 was identified as the most optimal scenario for small scale application. In addition to the objective of this problem, which is determining the maximum revenues received by a storage system; without including the benefits of the generation source.

The benefit of this storage could be received from energy time shift and/or T&D upgrade deferral. Hence, the total revenues, of this system, are the sum of revenues received from these two storage functionalities. Fig. 5.8 illustrates the present value of revenues, received from arbitrage and T&D upgrade deferral, separately as well as the total present value of revenues. The cost of the investigated large scale gravity storage was estimated using the system characteristics, presented in Table 5.4.

The obtained net present value of revenues and costs of the technology, as well as the system total NVP are presented in Fig. 5.8.

Table 5.4. Gravity storage system costs

Parameters	**Gravity Storage[31]**
Storage Capacity	20 MWh
Power rating	5 MW
Storage Cost	1540.32 €/kWh
Power Unit Cost	600 €/kW
O&M Cost	1.9 €/kW
BOP Cost	4 €/kW
Replacement Cost	0
Efficiency	80%
Lifetime	50 Years
Other cost:	200 €
-Design cost	5%
-Acquiring permit cost	0.5%
- Land Cost	50€/m²

Since, the system total NVP is positive, it can be deduced that gravity storage system is able to generate benefits that exceed the costs of the technology. Hence, it is considered technically feasible for large scale applications. The payback period of this system is calculated by dividing the project investment cost over its annual received revenues. In this scenario, the payback period of gravity storage is approximately 12 years and the rate of investment, which is the reciprocal of payback period, is equal to 8.22%.

The NPV of gravity storage is compared to that of other storage systems considered for bulk applications. Storage technologies that are comparable, to gravity storage, are pumped hydro storage and compressed air energy storage. The key performance parameters of each technology, used in this simulation, are presented in Table 5.5 [24]. The results of this comparison are shown in Fig. 5.9.

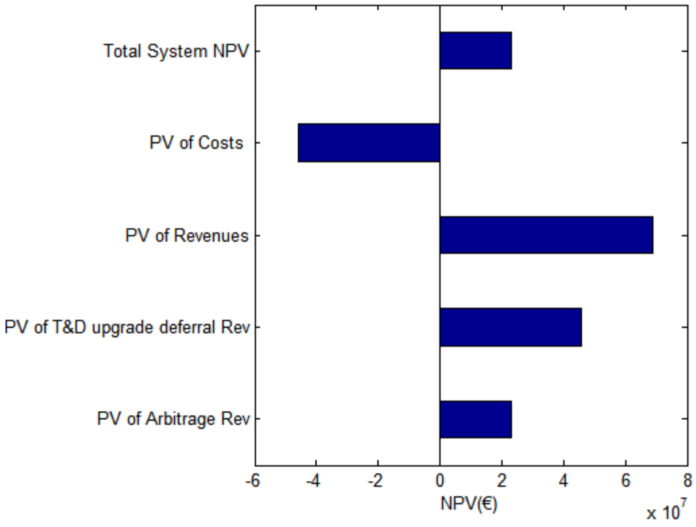


Fig. 5.8. Large scale gravity storage NPV

This simulation was run for a period of 50 years. Although CAES system needs to be replaced in year 40, it still has the lowest prevent value of costs. The comparison between these technologies indicates that CAES has the lowest NPV, followed by pumped hydro; due to the fact that gravity storage requires a high ($/kWh) cost.

Table 5.5. CAES and PHS system costs [24]

Parameters	**CAES**	**PHS**
Storage Capacity	20 MWh	20 MWh
Power rating	5 MW	5 MW
Storage Cost	45 €/kWh	93 €/kWh
Power Unit Cost	750 €/kW	1860 €/kW
O&M Cost	1.9 €/kW	1.9 €/kW
BOP Cost	4 €/kW	4 €/kW
Replacement Cost	Storage cost (1 replacement)	0
Efficiency	80%	80%
Lifetime	20-40	50

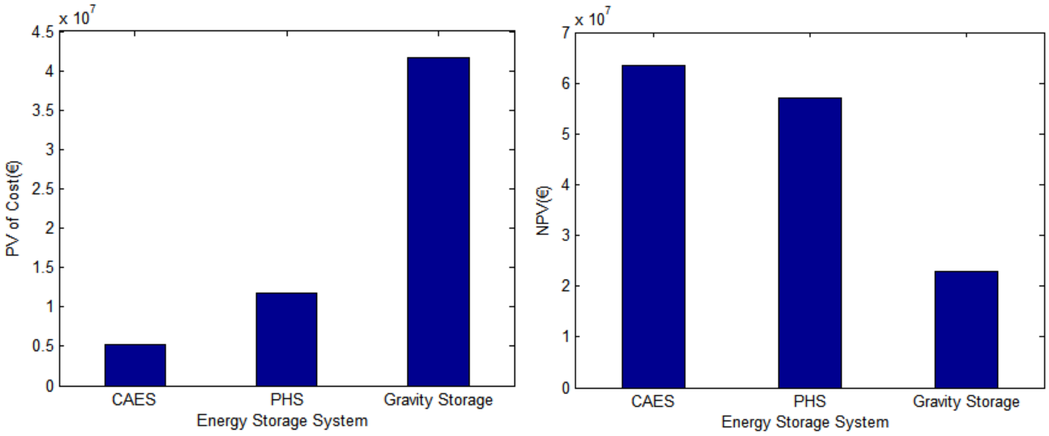


Fig. 5.9. PHS, CAES, and Gravity Storage a)Present value of cost b) NVP

5.4. Strategic analysis

There exists a variety of energy storage systems in the power sector. To compare a technology to its main competitors, it is necessary to recognizing the system’s advantages and drawbacks. These are regarded as strengths to be enhanced and weaknesses to be avoided respectively. In addition, external factors associated to the current energy market situation, and the prospects for future developments; have to be examined with the objective of identifying opportunities to be exploited and threats that have to be overcome, for a successful market penetration. Therefore, a SWOT analysis has been conducted on gravity storage system, to distinguish this technology form other storage options, and to compete successfully in the energy market. SWOT analysis studies about different energy storage systems; including PHS, CAES, batteries, flywheel, hydrogen, supercapacitors, and superconducting magnetic energy storage have been conducted by authors in [32-35].

Figure 5.10 presents the SWOT analysis of gravity energy storage. It involves accessing the strengths (S), weaknesses (W), opportunities (O) and treats (T), while taking into account the energy sector and markets.

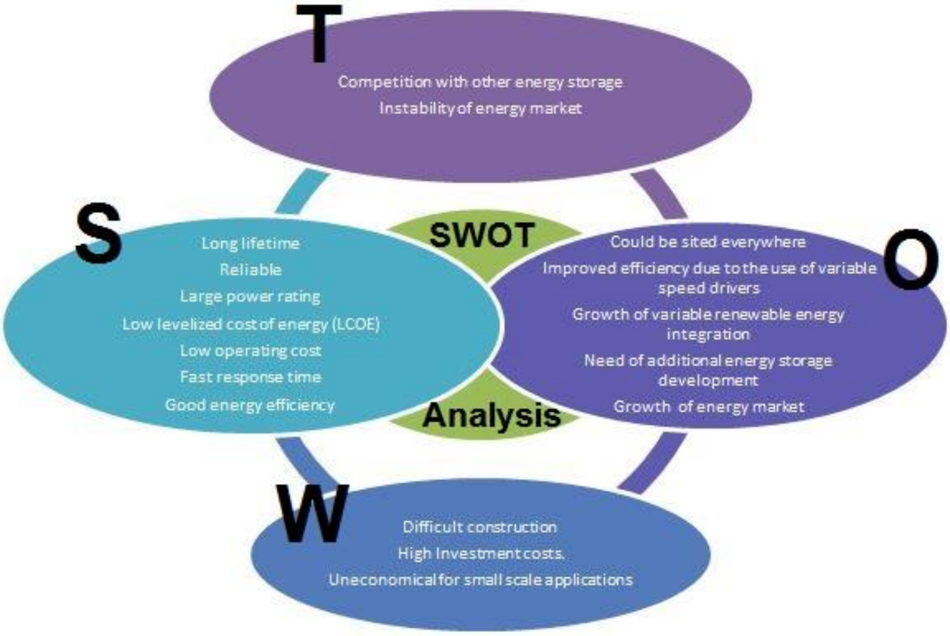


Fig. 5.10. SWOT analysis of gravity energy storage

Gravity storage is a technology similar to pumped hydro storage (PHS). This is currently the most widely used energy storage worldwide. Therefore, some of gravity storage characteristics are like those of PHS; thus making this storage option reliable. The technology has good energy efficiency, low self-discharge, long lifespan with large power rating and fast response time. It has, at the same time, low operating cost and an attractive LCOE compared to other energy storage systems [31].

One important aspect of gravity storage, over PHS, is its independence on favorable geographic locations. This technology has been able to overcome the PHS constraint, which has limited its further development [33]. Yet, gravity storage can be sited everywhere in accordance with demand. Due to the increasing need for additional storage development, potential opportunities exist for such storage system. The growth of energy markets and the high share of intermittent renewable energy sources have augmented this need.

The high investment cost and the difficult construction are serious weaknesses of this technology. Similar to PHS, Only large units connected to the transmission grid are economical [34]. This high cost has made gravity storage not economically viable for small scale applications. An important threat that should be taken into account is the development of other energy storage systems that can be able to compete with gravity storage with respect to several parameters, such as power and capacity costs. Finally, the instability of the energy market is another threat which should be taken into consideration. This risk has been investigated further in section 5 and 6.

A SWOT analysis in the energy sectors, as a whole, should also be conducted to distinguish this technology from other traditional sources of power. The strengths of gravity storage are in the range of services it offers to the power network. Some of these services include delaying network reinforcement, balancing the electric system, complementing intermittent renewables, generating revenues in energy and ancillary services [36]. The main weaknesses of energy storage, in general, are related to their costs. Gravity storage is still expensive compared to traditional power generation and requires large up-front costs which may put investors off [35]. However, these costs are expected to fall in the upcoming years. The evolution of storage technologies, including gravity storage, is expected to take off in the next few years; this is an important opportunity for the development of this technology. Some of the threats are related to the technology risks, as this system is still being developed, and there is a risk that it will not perform as specified [35]. Risks associated with this technology are discussed in section 5.

5.5. Risk Analysis

Investment in renewable energy sector may be considered risky due to the economic, financial, and political situation of a country. Additional risk sources may also affect the viability of the project. Thus, investors' interests tend to decrease as a result of unsafe project investment [37]. Therefore, it is important to determine the different aspects that could have an impact on the project, and identify the extent at which these perceived risks could influence the project economic profitability. In this study, the investment risks associated with gravity energy storage were determined based on literature review [38-43], due to the resemblance of this storage technology to conventional pumped hydro storage.

Risks about gravity storage system can be classified into two categories: internal and external risks. The internal risks are mainly related to the technology itself not performing as desired. The external risks, on the other hand, are associated with external factors not reacting like expected.

5.5.1. Internal / Technological risks

The internal risks are about the system malfunction. The main uncertainties about gravity storage technology are related to the storage construction components failure and equipment faults.

Concerning the system components, the piston/container sealing make use of a large sealing system that is not common. The piston may get stuck inside the container during its regular motion. This will result in buckling and will put additional bending moment on the concrete walls. It is also challenging to construct an underground container for large meters, such as 2000 m depth. However, this construction would not cause failure as long as the geotechnical analysis has been performed properly. Storage container and pipeline malfunction can also result due to leakage and breach of these components. This latter can be caused by corrosion, or fatigue of the material used to construct these components. Serious consequences may happen because of these risks; as the technology works with fluids under pressure [44]. In general, all construction components of the system may lead to system failure, if they are not well designed to handle their required functionalities [43].

Failure of the technology may also result from malfunctioning of the mechanical equipment used. The first form of failure may occur due to fault in pump/turbine, motor/generator, and transformers. Pump/turbine clogging is an example of factors that could lead to obstruction of the system. If one of the stated equipment malfunction, the repair of the system may take time, which will affect the operation of the storage system, and hence significantly impact the revenues that would be generated by the technology. The second risk is related to control equipment of the technology which include sensors, wires, and control house. Sensors are needed to provide information about the current condition of the storage system; such as pressure. Sensors' errors could result in wrong decisions made by the control room. Hence, sensors should be developed as reliable as possible. In addition, the control room is also subject to some risks such as fire and security issues. The last risk which could lead to technology operation failure is about the connection with the utility grid. This risk is related to transmission wires and towers that could malfunction, due to a number of factors, as they are placed in open air [43].

Occurrence quantification of the stated risks has been done; to investigate which technological risks are more important than others. Table 5.6 illustrates the occurrence per year of the aforementioned risks based on literature review.

Table 5.6. Internal risk occurrence per year

Risk	**Occurrence per year**	**Rank**	**Ref**
Equipment Malfunction			
Pump/turbine	2.4*10^-3	2	[45] [43]
Generator malfunctions	3*10^-4	5	[43]
Sensor malfunction	3*10^-5	8	[45]
Control panel connection malfunction	8*10^-4	3	[45] [43]
Control room malfunction	2*10^-4	6	[45]
Transformer malfunction	3*10^-3	1	[45]
Transmission tower malfunction	7*10^-4	4	[45]
Storage Components Failure			
Pipeline leak	6*10^-5	7	[45]
Breach of the pipelines (per meter)	3*10^-7	9	[46] [43]
Breach of shaft due to corrosion or fatigue (per meter)	1*10^-7	10	[46], [43]

This quantification demonstrates that the system chance of failure is rather small. The most vulnerable components of the system are identified by this analysis. The most risky events include transformer, pump/turbine, and control panel connection malfunction. To reduce these risks, proper maintenance and regular check of equipment are needed. Hence, the system risks are rather easy to control and no serious operation problems are expected to occur.

5.5.2. External risks

The most relevant external risks that were identified in this analysis include: economic, financial, political, completion, technological, geological, environmental, force majeure and sociocultural risks.

The financial condition of a project can be significantly affected by financial risks. During the realization and the effectuation phases, a project is exposed to financial risks [47]. This risk deals with uncertainties concerning interest and exchange rates, inflation risk as well as complications in acquiring financing. The decrease in loans causes a reduction in investments, while an overrated exchange rate contributes significantly to the fall in exports. Interest rate and inflation risks can be controlled by certain economic measures. The likelihood of an increase in interest rate and inflation is low, and the possibility of its detection is high [48]. Variation in interest rate is investigated in the sensitivity analysis.

A change in existing legislation is considered a legal or political risk that has an impact on project investments in the energy sector. The profitability of a project could be compromised due to unexpected changes in government policies. The occurrence of frequent volatility could result in uncertainty among future investors. This risk is related to market risk which deals with volatility of the energy purchase price. The volatility of energy price is mainly caused by the increase of renewable power plants. The possibility of extreme price movements increases the risk of trading in electricity markets; and significantly influences the final decision-making by investors [49].These changes could have an effect on the revenue, as they represent a major source of cash inflow for renewable energy projects. The likelihood of price volatility is moderate to high [48] and its impact is low [50].

The completion risk takes into account the possibility of not completing the project by the end date; according to the planned specifications and within the planned budget [48]. Several factors could lead to unfinished project; such as underestimation of investment costs, inaccuracies in the design, contractual issues, supplier problems, and unexpected failure in a construction phase. The consequence of this delay could have major impacts on the revenues, which would strongly affect the economic viability of the project. The likelihood of this risk is moderate, detection is low and severity evaluation is moderate as it will be shown in the sensitivity analysis.

The economic risk is associated with all economic aspects related to the project. An increase in the project related costs; or mismanagement of the project could be considered as important economic risk factors. The economic risk may make it difficult for investors to recover all costs throughout the lifetime of the project; which will make the technology uneconomically viable and hence prevent future investment [51]. Reuter et al, [52] presented a model for the economic evaluation of the adoption of a hybrid system combing wind power and hydro pumped storage. This study demonstrates that without substantial public support, the system is not profitable and will not be adopted for realistic premia. In case other objectives are taken into accounts such as CO2 mitigation, and grid stabilization, intervention to promote this system would be done [52]. The likelihood for this risk is low and it cannot be clearly detected.

The geological risk is important for gravity storage because it is constructed underground. The construction site should be able to accommodate the container being excavated for hundreds of meters. The geological condition of the storage location has to be determined. This study identifies the site flows and seismic activity beforehand which could significantly impact the approximated costs to construct the system. In addition, environmental risk should also be considered. A delay in the project development could be caused by environmental oppositions. This risk is present and its detection and occurrence likelihood is low.

Force majeure risk refers to problems that occur as a consequence of unpredicted events, such are fires, floods, strikes or catastrophic events, which can influence the proper operation of the system. The likelihood of this risk is low to moderate and its detection is high [48].

Finally, sociocultural risk is considered important for investors and promoters. This risk is associated with cultural and social differences between the project workers, authorities and investors. It has a significant impact on the net present value of the project as it could increase the cost and reduce the revenues of the project due to complaints, boycotts and other similar sociocultural issues. The likelihood of this risk is low while its impact is high. This risk can led to abandonment of projects, loss of revenues, and reputation damage of investors and promoters.

Locatelli et al in [50] classify the most important risks affecting the profitability of energy storage systems. Their analysis was done on PHS and CAES which are considered alternatives to gravity storage system. The high volatility and unpredictability of energy prices is considered major risks and have a high impact on energy storage NPV. In addition, the value and the uncertain level of incentives would have a major impact on the profitability of the energy storage. Other important risks affecting the NPV of storage systems are the construction delay and cost overrun. These two risks have a very high impact on the profitability and high probability to occur. The major challenge, within these aforementioned risks, is the costs overrun because the capital costs of gravity storage, similar to PHS, represents a high weight of the technology life cycle cost [50].

To describe which risks are more important than others, a failure mode and effects analysis (FMEA) is used [48]. This analysis determines a risk priority number (RPN); which is equal to the mathematical product of the occurrence, detection, and severity of the risk. The higher this number, the more serious the failure of the project could be and the more it should be addressed. The occurrence, detection and severity terms are defined by [53-54] as follow. The risk occurrence rating measures the probability of the risk occurrence. The detection rating refers the ability to detect the risk before it occurs, while the severity rating is about risk effects. The scale of these rating varies from 1 to 10, minor to extreme, respectively as shown in Table 5.7.

Table 5.7. Risk rating scale

Rating	Occurrence	Detection	Severity
1-2	Minor	Very High	Minor
3-4	Low	High	Low
5-6	Moderate	Moderate	Moderate
7-8	High	Low	High
9-10	Extreme	Very Low	Extreme

Table 5.8. Ranking of external risks

Risk	Occurrence	Detection	Severity	RPN	Rank	Ref
Financial risk	4	4	6	96	4	[48] [43]
Interest rate	4	4	6	96		
Inflation	4	4	6	96		
Exchange rate	4	4	6	96		
Political risk	5	4	9	180	2	[48]
Completion risk	6	4	6	144	3	[50][48]
Economic risk	7	8	7	392	1	[50][48]
Geological risk	3	4	3	36	7	[43]
Environmental risk	4	3	4	48	6	[48]
Sociocultural risk	3	2	8	48	6	[48]
Force Majeure risk	4	8	2	64	5	[48]][43]

Table 5.8 ranks the investigated risks based on the resulted RPN. Risks that have an RPN over 125 are considered high risks and should be given special attention [48]. In this context, economic, political and completion risks must be addressed to create favorable conditions for investors to invest in this type of projects. Environmental, sociocultural and Force majeure risks are less important than the other listed risks as illustrated in Table 5.8.

5.6. Sensitivity analysis

A sensitivity analysis was performed in this section to investigate the impact of changing some variable on the project profitability. The accessed risks include economic, financial, political and completion risks which are considered major risks as shown in section 5.

5.6.1. Economic risk

The profitability of energy storage is significantly affected by the investment cost of the technology. Therefore, an increase of this cost is considered an economic risk that should be accessed. Capital expenditures constitute the main component of the total investment cost of gravity storage. Hence, an unexpected increase of this latter would have major implication as illustrated in Fig. 5.11. The net present value of the project (NPV) is equal to zero at approximately 18% increase of the storage investment cost. Therefore, at a cost increase of 18% and beyond, the project is not considered profitable due to the negative NPV.

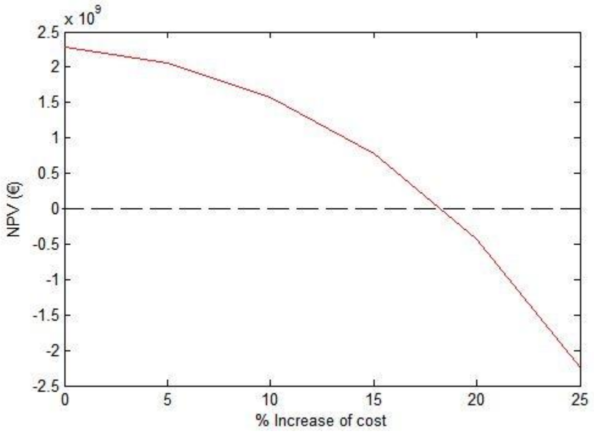


Fig. 5.11. Storage NPV vs percent increase in system cost.

5.6.2. *Completion & operation risk*

Gravity storage requires a difficult construction process. This issue may affect the estimated completion schedule. It is then crucial to take into account the completion risk of the project while investigating its profitability. This risk assessment investigates the impact of delaying the revenues gained due to a delay in the operation of the technology. This revenues delay could be caused by the non-completion of the project in time or by the project not operating even if it is competed. Fig. 5.12 illustrates the completion and operation risks vs system profitability.

It could be noticed that the project NPV remain positive even after a long delay of the project completion. This is due to the fact that the system generates high revenues during its lifetime. However, for project being completed but not operated, the system is not considered profitable if the delay exceed 30 years.

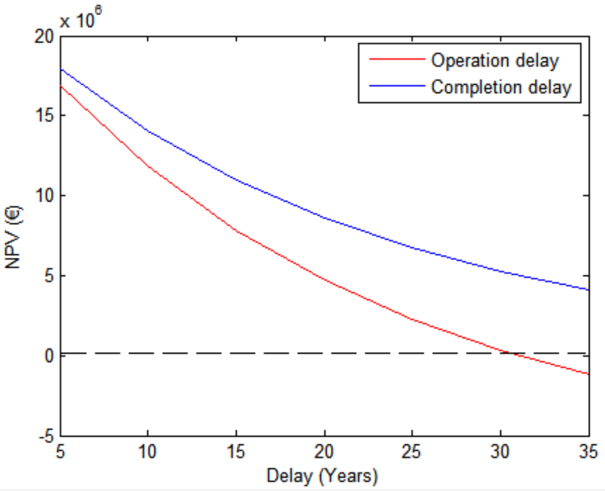


Fig. 5.12. Storage NPV vs construction delay in years.

The project operation delay is calculated as follow. The annual revenues generated per year, from arbitrage and T&D, are first estimated for n years of the project lifetime; using the model presented in section 3.3 of this chapter. The Present value of these equal annuities is then found using Eq. 5.23.

$$PV = A\left[\frac{1-(1+i)^{-n}}{i}\right] \tag{5.23}$$

Assuming that the operation of the project is delayed for d years, the revenues, in this case, occur at the end of each period stating year d until year 50 (project lifetime). The n in Eq. 5.23 is equal to the project lifetime minus the operation delay period (d_O). The present value at (year d) of the annual annuities represents a future value of the current year (year 0). One dollar in the future is worth $1/(1+i)^n$ now as illustrated in Eq. 5.24.

$$PV = FV\frac{1}{(1+i)^n} \tag{5.24}$$

In Eq. 5.24, n is equal to the project operation delay (d). After determining the present value of revenues, the NPV is then calculated using Eq. (1) which takes into account the project revenues and costs.

For the completion delay, the same procedure is used; the only difference is in the n period of Eq (5.23). This latter is equal to the project lifetime.

5.6.3. Political risk

The political risk is about any change in the energy prices or revenues received from transmission and distribution deferral (T&D). Hourly energy prices in both day-ahead and real-time markets vary throughout the year. Therefore, a decrease in the estimated prices is expected to occur. Similarly, benefits from T&D deferral range from \$150 to \$1,000 /KW-year, according to the literature. To be conservative, the average value was used in this case. This estimate may be lower for some locations. Therefore, it is interesting to investigate the effect of this decrease on the profitability of the project.

Three scenarios are used in this case as illustrated in Fig 5.13. The first scenario is about a decrease in energy prices which results in a decrease in NPV. The second scenario deals with a decrease in revenues received from T&D deferral. This scenario results in a negative NPV in case these revenues are decreased by 50%. The last scenario is a combination of both scenarios (scenario 1 and 2). In this case, the NPV reaches a value of zero at 33% decrease. Therefore, the project would not be economically viable starting this latter percent decrease.

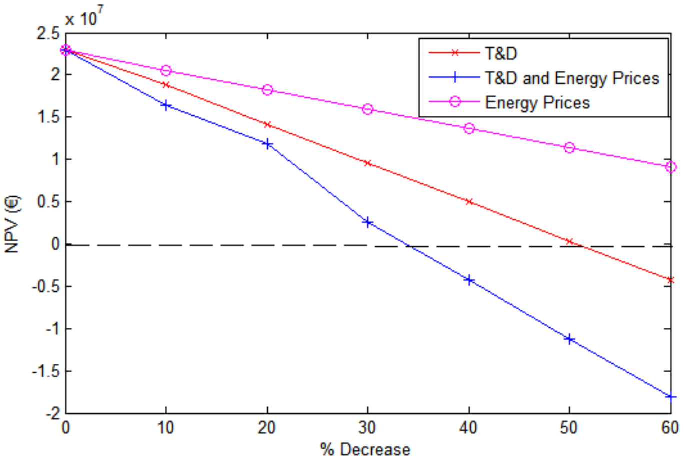


Fig. 5.13. Storage NPV vs percent decrease in energy prices and revenues

5.6.4. *Financial risk*

In this analysis, volatility in the interest rate has been investigated as a risk. This latter is used for evaluating projects and can vary between them. The value of the discount rate is not universal nor is it essentially valid geographically on a country-wide basis. One of the factors resulting in an increase of the discount rate is the economic crisis. Therefore, it is important to take into account the impact of discount rate variations; while considering the viability of the project. Figure 5.14 presents the effect of discount rate increase on gravity storage NPV. It can be deduced that for each percent increase in the discount rate, there is a significant decrease in the NPV. The higher the discount rate, the lower the net present value of the project. The energy project is not considered profitable beyond an 8% discount rate.

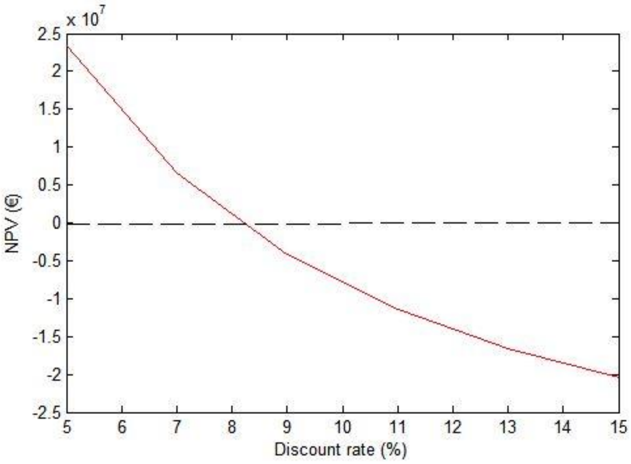


Fig. 5.14. Storage NPV vs percent increase in investment discount rate

5.7. Conclusion

A cost-benefit analysis was performed in this work to determine the economic viability of energy storage. The proposed models were used to identify the maximum savings that could be received from the utilization of energy storage. Four scenarios have been simulated for small scale residential application. Case studies based on gravity storage were performed to determine the profitability of this storage system. The obtained results reveal that the net present value of energy storage is the same for the first three scenarios. However, it is found that scenario 1 (energy storage that is connected to the electric grid and which does not supply energy to the load) is the most optimal case for residential storage system to be part of.

Additionally, the output of the NPV calculations reveals that gravity storage is not considered profitable for residential applications except if it is used as a stand-alone system. However, for large scale application, this technology has been demonstrated as a viable storage option.

A risk study allowed us to demonstrate whether this innovative gravity storage system would be more viable than other competitive storage options. These risks are related to construction and operation of the system. As most concepts similar to traditional pumped hydro storage are considered risky, it is crucial to perform a risk analysis for gravity storage system while evaluating its profitability. One of the techniques carried out in this work is the sensitivity analysis. The performed sensitivity analysis demonstrated that the project is considered economically sound, with positive NPV, for each of the simulated variables (economic, completion, political, and financial risks). However, they were possibilities of obtaining negative NPV for the studied cases. As for the economic risk evaluation, it was shown that above an 18% increase in the investment cost of the project, this latter would not be considered economically viable. Moreover, the completion risk is not considered as a potential risk since the NPV of the project reaches a zero value with a delay of more than 30 years. Such a high delay should not be expected. The impact of the political risk has also been assessed in this study. Three case scenarios were investigated which include a decrease in energy prices, a decrease in revenues received from T&D deferral, and a combination of both scenarios. The results demonstrate that a reduction in the revenues, received from both arbitrage and T&D deferral, has a significant impact on the project NPV. As for the financial risk, a 3% increase in the discount rate put in evidence the economic vulnerability of such a project characterized by a large investment cost.

References:

[1] A.-H. Mohsenian-Rad and A. Leon-Garcia, “Optimal residential load control with price prediction in real-time electricity pricing environments”, IEEE Transactions on Smart Grid, 2010.

[2] S. Yue, J. Chen, Y. Gu, C. Wu and Y. Shi, "Dual-pricing policy for controller-side strategies in demand side management," SmartGridComm, 2011.

[3] D. Zhu, et al, "Maximizing return on investment of a grid-connected hybrid electrical energy storage system," ASP-DAC, 2013

[4] McKenna E, McManus M, Cooper S, Thomson M. Economic and environmental impact of lead–acid batteries in grid-connected domestic PV systems. Appl Energy 2013; 104:239–49.

[5] T. T. Ha Pham, W. Frédéric, and S. Bacha. "Optimal operation of a PV based multi-source system and energy management for household application," IEEE International Conference on Industrial Technology, 2009.

[6] Y. Riffonneau, S. Bacha, F. Barruel, and S. Ploix. "Optimal power flow management for grid connected PV systems with batteries." IEEE Transactions on Sustainable Energy, vol. 2, no. 3, pp. 309-320, 2011.

[7] Y. Wang, S. Yue, M. Pedram, L. Kerofsky, and S. Deshpande, "A hierarchical control algorithm for managing electrical energy storage systems in homes equipped with pv power generation," IEEE Green Technologies Conference, 2012.

[8] A. Berrada, K.. Loudiyi. Operation, sizing, and economic evaluation of storage for solar and wind power plants. Renew Sustain Energy Rev 59 (2016) 1117–1129

[9] Walawalkar R, Apt J, Mancini R. Economics of electric energy storage for energy arbitrage and regulation in New York. Energy Policy 2007;35(4):2558–68.

[10] Schoenung S, Eyer J. Benefit/cost framework for evaluating modular energy storage – a study for the DOE energy storage system program. Sandia report SAND, vol. 978; 2008.

[11] Eyer JM, Corey GP. Energy storage for the electricity grid: benefits and market potential assessment guide, SAND 2010-0815. Sandia National Labortories;

[12] Kazempour SJ, Moghaddam MP, Haghifam MR, Yousefi GR. Electric energy storage systems in a market-based economy: comparison of emerging and traditional technologies. Renew Energy 2009;34(12):2630–9.

[13] Kazempour JS, Moghaddam MP. Economic viability of NaS battery plant in a competitive electricity market. In: 2009 International conference on clean electrical power, 2009. p. 453–9.

[14] Moghaddam IG, Saeidian A. Self scheduling program for a VRB energy storage in a competitive electricity market. In 2010 International conference on power system technology (POWERCON); 2010. p. 1–6.

[15] He X, Lecomte R, Nekrassov A, Delarue E, Mercier E. Compressed air energy storage multi-stream value assessment on the French energy market. In PowerTech, 2011 IEEE Trondheim; 2011. p. 1–6.

[16] Drury E, Denholm P, Sioshansi R. The value of compressed air energy storage in energy and reserve markets. Energy 2011;36(8):4959–73.

[17] Sioshansi R, Denholm P, Jenkin T. A comparative analysis of the value of pure and hybrid electricity storage. Energy Econ 2011;33(1):56–66.

[18] Hessami M-A, Bowly DR. Economic feasibility and optimisation of an energy storage system for Portland Wind Farm (Victoria, Australia). Appl Energy 2011;88(8):2755–63.

[19] Bradbury K, Pratson L, Patiño-Echeverri D. Economic viability of energy storage systems based on price arbitrage potential in real-time U.S. electricity markets. Appl Energy 2014;114:512–9. http://dx.doi.org/10.1016/j.apenergy.2013.10.010 [ISSN 03062619]. <http://linkinghub.elsevier.com/ retrieve/pii/S0306261913008301>.

[20] E. Hittinger, T. Wiley, J. Kluza, J. Whitacre. Evaluating the value of batteries in microgrid electricity systems using an improved Energy Systems Model. Energy Conversion and Management 2015; 89: 458–472

[21] G. Locatelli, E. Palerma, M. Mancini.Assessing the economics of large Energy Storage Plants with an optimisation methodology. Energy; 83: 15–28

[22] Oldenmenger, W.A. (2013). Highrise energy storage core: Feasibility study for a hydro-electrical pumped energy storage system in a tall building (Master's thesis). Retrieved from TU Delft Repositories.

[23] Akinyele, D.O. & Rayudu, R.K., 2014. Review of energy storage technologies for sustainable power networks. Sustainable Energy Technologies and Assessments, 8, pp.74-91.

[24] Aneke, M. & Wang, M., 2016. Energy storage technologies and real life applications - A state of the art review. Applied Energy, 179, pp.350-377.

[25] EPRI. Electricity energy storage technology options. Electric Power Research Institute; 2010.

[26] Ecofys, 2012. Energy Storage Opportunities and Challenges. A West Coast Perspective White Paper.

[27] Luo. X, et al., Overview of current development in electrical energy storage technologies and the application potential in power system operation. Applied Energy, 137, pp.511-536.S. Sundararagavan et al. “Evaluating energy storage technologies for wind power integration”. In: *Solar Energy* 86.9 (July 13, 2012), pp. 2707–2717

[28] Progress in electrical energy storage system: A critical review. Progress in Natural Science, 19(3), pp.291-312.

[29] Red Eléctrica de España,S.A. (REE). ⟨http://www.ree.es/en⟩.

[30] Battery Cost. PowerTech System. http://www.powertechsystems.eu/

[31] A. Berrada, K. Loudiyi, and I. Zorkani. Sizing and economic analysis of gravity storage. Journal of Renewable and Sustainable Energy 8, 024101 (2016)

[32] Cole, S., et al., (2005). SWOT analysis of utility side energy storage technologies,” 5th WSEAS / IASME international conference on electric power systems, high voltages, electric machines, pp. 16–18.

[33] Andrijanovits, A., et al., Comparative Review of Long-Term Energy Storage Technologies for Renewable Energy Systems. Elektronika ir Elektrotechnika, North America, 118, feb. 2012. Available at: <http://www.eejournal.ktu.lt/index.php/elt/article/view/1168>.

[34] Fuchs, M. et al., (2012). Technology Overview on Electricity Storage. Overview on the potential and on the deployment perspectives of electricity storage technologies.

[35] Goodfellow. R, et al.,(2016) Battery Storage : A SWOT analysis. Available at: https://www.addleshawgoddard.com/en/insights/insights-briefings/2016/energy/battery-storage-a-swot-analysis/

[36] A.Berrada, K.Loudiyi. I.Zorkani. Valuation of Energy Storage in Energy and Regulation Markets. Energy Journal. Elsevier. 10.1016/j.energy.2016.09.093

[37] Leach A, Doucet J, Nickel T, Renewable fuels: Policy effectiveness and project risk, Energy Policy 39 (7) (2011) pages 4007–4015.

[38] Agrawal A, Risk mitigation strategies for renewable energy project financing. Strategic Planning for Energy and the Environment 32 (2) (2012) pages 9–20.

[39] Carneiro P, Ferreira P, The economic, environmental and strategic value of biomass, Renewable Energy 44 (2012) pages 17–22. *http://dx.doi.org/10.1016/j.renene.2011.12.020*

[40] Cucchiella F, D'Adarno I, Feasibility study of developing photovoltaic power projects in Italy: An integrated approach, Renewable & Sustainable Energy Reviews 16 (3) (2012) pages 1562–1576. *http://dx.doi.org/10.1016/j.rser.2011.11.020*

[41] Rangel LF, Competition policy and regulation in hydro dominated electricity markets, Energy Policy 36 (4) (2008) pages 1292–1302. *http://dx.doi.org/10.1016/j.enpol.2007.12.005*

[42] Nikolic DM, Jednak S, Benkovic S, Poznanic V, Project finance risk evaluation of the Electric power industry of Serbia, Energy Policy 39(10) (2011) pages 6168–6177. *http://dx.doi.org/10.1016/j.enpol.2011.07.01*

[43] Berchum, E.V. (2014) Pumped Hydro Storage: Pressure Cavern Large-scale Energy Storage in Underground Salt Caverns (Master's thesis). Retrieved from TU Delft Repositories.

[44] Hendriks. M,.(2016) Local Hydroelectric Energy Storage. A feasibility study about a small scale energy storage system combining. hydropower, gravity power, spring power and air pressure. (Master's thesis). Retrieved from TU Delft Repositories.

[45] Taw. (2003). Leidraad Kunstwerken. http://www.helpdeskwater.nl/publish/pages/5175/ad012-leidraadkunstwerken.pdf

[46] RIVM. (2009). Handleiding Risicoberekeningen Bevi. Retrieved from http://www.rivm.nl/dsresource?objectid=rivmp:22449&type=org&disposition=inline&ns_nc

[47] Gary, L., 2005. Managing Project Risk. Harvard Business School Publishing Corporation 3.

[48] Makajic, D, et al., 2011. Project finance risk evaluation of the Electric power industry of Serbia. EnergyPolicy, 39, pp.6168–6177.

[49] Weron, R. Energy price risk management. Physica A 285 (2000) 127–134

[50] Locatelli, G., Invernizzi, D.C. & Mancini, M., 2016. Investment and risk appraisal in energy storage systems: A real options approach. Energy, 104, pp.114-131.

[51] Sovacool BK, Gilbert A, Nugent D, Risk. Innovation, Electricity Infrastructure and Construction Cost Overruns: Testing Six Hypotheses. Energy2014;74(September):906–17

[52] Reuter, W.H. et al., 2012. Investment in wind power and pumped storage in a real options model. Renewable and Sustainable Energy Reviews, 16(4), pp.2242-2248.

[53] Ericson II, C.A., 2005. Hazard Analysis Technique for System Safety. John Wiley & Sons.

[54] Ayyub, B.M., 2003. Risk Analysis in Engineering and Economics. Chapman and Hall/CRC.

Chapter 6

6. Dynamic Modeling of Gravity Energy Storage

The dynamic behavior of gravity storage including the mechanical machines and the hydraulic storage components is analyzed in this chapter to gain insight into the performance of this system. A dynamic modeling of gravity storage coupled with PV energy plant has been performed. This model has been developed through interconnection of the different plant equipment models using Matlab/Simulink application. This work details the operation modeling of a hybrid renewable energy system. The proposed model is able to simulate the interaction between the power plant, the storage system, and the electric grid. To evaluate the performance of the Simulink model, a simulation study is carried out on a large scale system. In addition, a mathematical model is needed for descripting the hydraulic component of gravity storage as it includes various time variant parameters. The model can predict the chambers volume and pressure, as well as the piston motion throughout the charging and the discharging of the storage system. The hydraulic model was demonstrated by a case study and validated by experimental results.

6.1. Introduction

The increasing penetration of Renewable Energy Sources (RES) into the grids and their unreliability and fluctuating nature cause concerns in terms of security of supply and grid stability. The intermittency and variability of wind power and PV energy impact the grid operation at diverse time scales. From seconds to minutes more regulation reserves and frequency control are needed to overcome frequency and voltage related issues; from minutes to hours, additional capacity for load levelling services is required and at larger scale effects on the schedule and generation portfolio are observed [1,2]. To deal with those challenges different methods to provide additional flexibility to the energy System are being developed and analysed such as demand response technologies, electromobility or new flexibility capabilities of conventional generation. Energy Storage Systems (ESS) take part of these flexibility solutions as well not only due to the numerous available technologies but also the wide range of functionalities or services they can provide [3-5].

In spite of some studies have been developed in the last years to evaluate the performance and dynamic behavior of these systems while being connected to the grid, additional work to analyse their effect on the networks and Renewable Energies integration, is necessary. Some of those studies focused on modelling off-grid and isolated systems where the tandem RES-ESS has proved to be competitive compared to conventional solutions for energy supply. Thus, Maclay et al. [6] analysed the performance of diverse configurations of a hybrid storage system to support the integration of PV energy for residential energy supply in a stand-alone system and concluded that the use of Reversible Fuel Cells in collaboration with batteries ensure grid independent operation while the hybrid based on supercaps and RFC has not enough energy density to meet the load demand.

Similar analyses were developed by C.-H. Li et al. [7] in order to optimize the size and operation of hybrid PV/storage systems using batteries and Fuel Cells. Jayalakshmi N.S. et al. [8] investigated a detailed dynamic model and the control strategy developed in the MATLAB/SIMULINK platform of a hybrid solar-battery system and determined that the control strategy is capable of controlling the voltage and frequency irrespective of the load variability and PV power uncertainty. Regarding grid connected systems, there are interesting results published as well. Among others, we can mention the studies focused on microgrids applications in [9,10] and power systems with high RES shares [11-15].

Several works have been developed about dynamic modeling of energy storage technologies. These systems may be classified according to their form of energy stored which includes chemical, thermal, electric, and mechanical energy storage. As for the chemical energy storage classification, Sharifi Asl el al. [16] developed two mathematical models for computing the steady-state and dynamic voltage/current characteristics of proton exchange membrane fuel cells. This analysis shows that the dynamic interaction effects within the cell are significant, and there is a high need for detailed modelling for such effects [16]. Douglas in [17] presented mathematical models for dynamic simulation for a hybrid battery and hydrogen energy storage coupled with solar-PV system. The aim of this chapter is to investigate the performance of this hybrid system. The results of this study indicate that battery storage has longer operating period and can satisfy low power loads. Unlike batteries, fuel cell operates for longer periods and can be used for high power loads. The dynamic response of fuel cell was limited because of the flow conditions of the reactants nearby the electrodes which lead to an increase in the internal resistances [17]. Yigit et al. modelled a high pressure PEM electrolyzer system using Matlab/Simulink. The objective of this study is to examine the system behavior and estimate the losses at different operating conditions [18]. Some of the obtained results indicate that the system efficiency is significantly reduced at high working current density (more than 1A/cm^2).

Concerning thermal energy storage, Harish et al. [19] published a review about the different methodologies adopted for modeling energy storage system of buildings. Their study mainly focuses on works related to the development of the control strategies by modeling the system [19]. Wu et al. developed a dynamic model for simulating the transient behavior of refrigeration - PCM (Phase Change Material) energy storage system. In this study, the system was represented by equivalent electrical capacitance and resistance circuits with lumped parameters. This methodology allows for the representation of the storage by a set of differential equations. The results of the simulated model were very close to experimental ones [20].Arabkoohsar et al. [21] studied the dynamic modeling of a High Temperature Heat and Power Storage System. The system makes use of hot rock cavern thermal energy storage. This work investigates the system ability and performance to support multiple wind turbines over a long period of time. As for the electrical energy storage type, Zhu et al. [22], developed a model for High-temperature superconducting magnetic energy storage systems model. A Simulink simulation was done to verify the control strategy of the system.

The most developed large scale energy storage systems are pumped hydro (PHES), compressed air (CAES) and power to gas systems but only PHES is widely deployed accounting for more than 97% of the energy storage capacity installed all over the world [23]. Dynamic models were constructed to study the performance of mechanical energy storage technologies. JP Maton et al [24] evaluated by modeling the impacts and capabilities of compressed gas energy storage to support wind power integration. They demonstrated that hydrogen based solutions can store more energy than air based ones due to their higher energy density and provide more grid services. In a recent study, the dynamic modeling and simulation of an Isobaric Adiabatic Compressed Air Energy Storage system has been performed by Mazloum et al [25] to analyze the transient states of the system. The objective of their model is to evaluate the response time of the technology and investigate the system capability of meeting energy demand. M. Saadat et al. [26] proposed a dynamic modeling and control strategy of an innovative CAES system coupled with wind turbines. The system stores the turbines produced energy as compressed fluid in a high pressure dual chamber liquid-compressed air storage vessel.

As for pumped hydro storage, the working principle of this system is similar to that of hydropower plants. There are many contributions to the modeling of hydropower and its dynamic response. Several published articles discussed the modeling of this system's components which include the synchronous generator, hydro turbine, governor, and penstock [27]. The characteristics of the water flow affect the performance of the hydro-turbine system. Some of these characteristics include water compressibility and inertia, as well as elasticity of the penstock walls [28]. Both linear and nonlinear models of hydro-turbine exist with consideration of elastic and non-elastic water column effects. The conduit system models were proposed by authors in [29,30]. Previous works, such as in [31], adapted non-elastic water column for their modeling. Long and short pipelines used elastic and no-elastic models, respectively. Concerning the modeling of hydro turbine, different assumptions were used in different paper to represents the hydro-turbine output. In [32], an approximate estimation is used which states that this output is proportional to the product of the flow rate and the head. Other authors make use of first-order Taylor formula to develop the hydro-turbine model [33]. The modeling of hydro turbine and governor system (HTGS) is complex as it involves mechanical dynamics, hydrodynamics, and electrical dynamics [34-36]. Nonlinear dynamical modeling of HTGS with a surge tank has been by Chen et al. [36]. With regard to the generator and load, there exist first order, second order, and third order models of these systems [37-39].

The performance of power systems is significantly affected by the dynamic characteristics of hydraulic turbine and its governor during load change or occurrence of faults. Analysis about large variation in power output necessitates a nonlinear model of the turbine [40]. Different models of the hydro system response have been presented in several research articles. Simulation about transition process could include either large or small fluctuation. Authors in [41-51] developed hydro-turbine governing system models suitable for small fluctuation. These models do not describe large fluctuation process. Zhang et al [52], proposed a nonlinear dynamic model of hydro-turbine governing system in process of load rejection transient. The presented methods and analytic results provide theoretical groundwork for further studies about hydropower station in the process of load rejection transient [52]. Other works, such as [53-56] dealt with dynamic modeling of comparable systems.

It appears, from the available literature, that the mathematical modeling of the dynamic behavior of gravity energy storage has never been investigated and documented in literature. The novelty of this work lies in the detailed dynamic modeling of this new and innovative energy storage system to gain insight about the technology performance and dynamic response. The characteristics of the mechanical equipment used by gravity storage are very complex with respect to changes of energy demand. Therefore, research about dynamic modelling of energy storage needs attention. The approach used by this study is considered interesting as it presents analytical models of the different system's components created by numerically integrating the system governing equations. In addition, the operation and ability of the technology to meet the electrical demand are examined. Finally, the simulation results are analyzed and discussed in details. The proposed model is verified by a case study where it has been coupled to a renewable energy plant and connected to the grid.

The chapter is organized as follows. Section 2 describes the principle of operation of gravity storage. In section 3, governing equations of the system dynamic mathematical models are discussed. Section 4 presents the developed models for dynamic simulation and analyzes the system performance and behavior in the process of meeting residential electrical loads. Section 4 proposes a hydraulic modeling of gravity energy storage components. In section 5, the simulation results are analyzed and validated followed by a sensitivity analysis in section 6. This latter analysis is performed to investigate the effect of some parameters on the simulation results. Section 7 closes the chapter.

6.2. Dynamic modeling of gravity storage system

The aim of this model is to describe the response of gravity storage while being connected to a PV energy plant. This hybrid energy system which is linked to the grid, has to meet the energy demand of a residential load. The model is represented by system governing physic equations. These equations are based on the fundamental theory of hydraulics, mechanics and electricity. A simulation model of the hybrid system has been developed using Matlab/Simulink. A case study is used to evaluate the system performance.

6.2.1. Gravity Storage discharging mode

Several hydraulic models have been developed over the past years. In this work, a basic hydraulic station model is used to represent the discharging mode of gravity energy storage [57]. The objective of this work is to investigate the dynamic response of the system mechanical components. The different governing equations are presented first, in addition to some simplifying hypotheses. This sub-model would have the reference power as input and would output the generated power. The turbine model includes the opening dynamics of the valves and the interaction between water and the turbine blades. This sub model is developed using existing SimPowerSystems blocks. Fig. 6.1 shows the relationship between the different components of the hydraulic turbine model.

Mechanical power is generated by the hydraulic turbine block and is used to drive a synchronous generator which produces electrical energy. In addition, the synchronous generator is suppled excitation voltage by the excitation system block. Both the turbine mechanical power and the excitation voltage are regulated by PID controllers. The generator output is injected to step-up power transformer which feed a transmission line. A dynamic load is also added to represent varying energy demand. All the aforementioned system components are modeled in interconnected form to simulate the discharge mode of gravity energy storage.

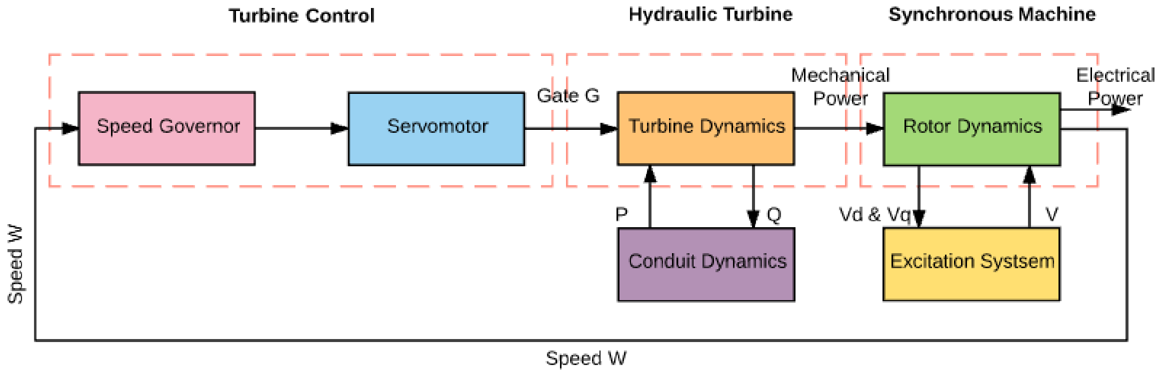


Fig. 6.1. Relationship between the hydraulic turbine components.

6.2.1.1. Hydraulic Turbine Model

Assumptions commonly used in the representation of water column and hydraulic turbine models include negligible hydraulic resistance, inelastic and incompressible water, as well as varying water velocity as a function of gate opening and pressure head. The power of the turbine is also assumed proportional to the product of the flow rate and the square root of net head.

The characteristics of the turbine and the water conduit (return pipe) are determined by governing equations which relates the turbine power, the water velocity and acceleration, as well as the turbine inlet [58]. The mechanical power output and the hydraulic characteristics of the system have been used to model the turbine.

The amount of water flowing into the turbine is adjusted by changing the opening of the gate. This change also adjusts the mechanical output power of the turbine. Eq. 6.1 relates the flow rate and the head across the turbine (h) as this latter has been represented by the valve characteristics [57].

$$h = \frac{Q^2}{G^2} \tag{6.1}$$

Where G is the gate position between 0 and 1 (fully open gate). Q is the flow rate.

The water flow rate is derived from the net force (F_{net}) on the water in the conduit. This force can be expressed in terms of the rate of change of momentum of the water at steady state, as well as in terms of the pressure head at the conduit. Eq. 6.2 presents the aforementioned equations.

$$\begin{cases} F_{net} = \rho L \dfrac{dQ}{dt} \\ F_{net} = \rho (H_S - H_l - H) A g \end{cases} \tag{6.2}$$

Where Q is the flow rate, L, and A are the water conduit length and area, respectively. ρ is the density of water, and g is the gravitational acceleration. H, Hs, and H_L are the head at turbine gate, static head, and head loss, respectively. The force on the water at the pipe entry is proportional to the static head (H_S), while it is proportional to the head across the turbine (H_T) at the wicket gate. Head loss (H_l) should also be considered due to the friction effect on the water in the conduit.

Combining these two equations results in (Eq. 6.3) which describe the volumetric flow rate:

$$\frac{dQ}{dt} = \frac{(H_S - H_l - H)Ag}{L} \tag{6.3}$$

This equation is normalized using common bases which include h_{base} and q_{base}. In this case, the static head represents the base head, while the base flowrate is represented by the turbine flowrate with fully open gates. Eq. 6.4 can then be expressed as:

$$\frac{dq}{dt} = \frac{(1 - h_l - h)Agh_{base}}{Lq_{base}} = \frac{(1 - h_l - h)}{T_W} \tag{6.4}$$

Where Tw is water time constant; it represents the times necessary for water with a given head h_{base} to obtain the flow rate Q_{base}. The water starting time is equal to (Eq. 6.5) [57]:

$$T_W = \frac{Lq_{base}}{Agh_{base}} \tag{6.5}$$

The Francis turbine drives the generator shaft with a mechanical power (Pm). This latter is related to the hydraulic pressure and the water flow rate. Turbine mechanical power is expressed by non-linear Eq. 6.6 [59-61].

$$P_m = \eta q \rho g h \tag{6.6}$$

The turbine produced mechanical power is proportional to the flow rate and the pressure head. The developed power is also dependent on the efficiency η and it is represented by no-load flow (q_{nl}).

$$P_m = h(q - q_{nl}) \tag{6.7}$$

This expression is written as Eq.6.8 to take into account a different per-unit system of the generator.

$$P_m = A_t h(q - q_{nl}) \tag{6.8}$$

Where A_t is the factor that account for the different in per units. This factor is represented by Eq. 6.8 which takes into consideration, a turbine operating at rated load [57].

$$A_t = \frac{Turbine\_Power(MW)}{generator\_MVA\_rating} \frac{1}{h_r(q_r - q_{nl})} \tag{6.9}$$

A damping effect is also taken into consideration and it is dependent on the gate opening. Therefore, the turbine power, at any load condition, can be modeled using eq. 6.10 [57].

$$P_m = A_t h(q - q_{nl}) - D_c G\Delta\omega \tag{6.10}$$

Where D_c is the damping coefficient, ω is the rotor speed.

Hydraulic Turbine can also be modeled using the classical transfer function expressed in eq. 6.11. This expression is based on the water transmission inertia in the pipe and on the pressure on turbine blades [62]:

$$W_H(S) = \frac{\Delta\overline{Pm}}{\Delta G} = \frac{1 - T_W s}{1 + 0.5T_W s} \tag{6.11}$$

Where $\Delta\overline{P_m}$ is the change in mechanical power and ΔG is the change in gate position. This equation demonstrates the response of the hydraulic turbine in terms of power output relative to a change in gate position.

The turbine nonlinear model is represented by the aforementioned equations and is shown in Fig. 6.2 [57].

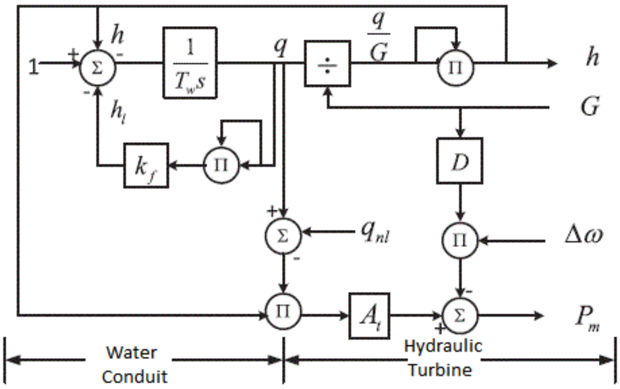


Fig. 6.2. Turbine non-linear model.

6.2.1.2. Hydraulic governor

Turbine governor is an important component of a hydro power plant. Its main function is to control the speed variation of the generator in order to keep a constant generated frequency. The different components of this system include permanent droop feedback, gate servomotor, speed sensing, relay valve, dashpot, and computing functions [63].

The controller compares the rotor speed with the reference one and modifies it using the permanent droop compensation. Transient droop compensation is developed, during a change in gate position, to prevent fast changes of this latter. The deviation in speed creates a signal at the servo motor input which responds by directing the valve according to the signal. The valve monitors the flow rate in order to maintain a constant generated frequency. Hence, mechanical motion transmits signals, through floating levers system, to pilot valve [64].

The relay valve and the gate servomotor transfer function is [57]:

$$\frac{\Delta G}{b}=\frac{K_2}{s} \tag{6.12}$$

The pilot servo and pilot valve transfer function is [57]:

$$\frac{b}{a}=\frac{K_1}{1+T_P s} \tag{6.13}$$

Where K_2 is determined by the feedback lever ratio and T_P is determined by port areas of the pilot valve and K_2. Combining Eq. (6.12-6.13) results in:

$$\frac{\Delta G}{a}=\frac{K_1 K_2}{(T_p s+1)s}=\frac{1}{T_g}\frac{1}{(T_p s+1)s} \tag{6.14}$$

The dashpot transfer function is expressed as [57]:

$$\frac{c}{\Delta G}=R_T\frac{T_R s}{1+T_R s} \tag{6.15}$$

R_T is the temporary drop and is determined by the lever ratio. T_R is the reset time and is determined by needle valve setting.

Old speed governors used both mechanical and hydraulic systems to realize its function. Permanent droop feedback, speed sensing, and computing functions were performed through mechanical components while functions requiring higher power are realized with the use of hydraulic components. Transient droop compensation is provided through a dashpot. To disable this latter, a bypass arrangement is typically provided.

New hydraulic governors, on the other hand, make use of electrohydraulic systems. These systems operate in a similar manner as mechanical-hydraulic governors. The dynamic features of the electric governor are regulated to match those of the mechanical-hydraulic governors. In this case, permanent droop, speed sensing, and other measuring tasks are done electrically. Better performance and flexibility with respect to time lags and dead bands are provided by these electrical components. These modern systems make use of PID controllers which include the proportional (P), Integral (I), and derivation (D) elements. The PID algorithm provides both transient gain increase and reduction to achieve higher response speeds. The derivation action of the PID controller is more useful for plants with a Tw (starting time) greater than 3s. A typical proportional gain value is 3; while it is 0.7 and 0.5 for integral and derivative gains, respectively. The derivative gain is commonly set to zero to avoid instability and excessive oscillations when the generating limit is coupled to an interconnected system. In this case, the controller become PI governor and is similar to that of the mechanical-hydraulic governor. The PI gains may be chosen according to the desired reset time and temporary droop [65].

Governors with PID control offer various functionalities which include control of the turbine speed and load, restoration of normal conditions with sensitive operation and response to errors; provision of minimum dead band and self-regulating feature to stab, as well as favorable dynamic response.

6.2.1.3. Synchronous Generator and Excitation system

The synchronous machine block of Simulink library operates in both generator and motor modes. The mechanical power sign determines the machine mode of operation. A sixth-order state space is used to model the electrical part of the synchronous generator. The rotor reference frame (qd) represents the model circuit. The generator model takes also into consideration the inertia of the generator turbine assembly. The dynamics of the damper windings, the stator, and the field are also taken into account by the model block. The inputs used by the machine include hydro turbine mechanical power, and excitation voltage. The outputs, on the other hand, are active and reactive power. The values of the generator parameters are taken from documentations of power plants [66].

The synchronous generator is supplied excitation voltage by an excitation system block. The generated excitation voltage is regulated by PID controllers. The transfer function representing the excitation system is expressed in Eq. 6.16 which relates the regulator output (e_f) and the exciter voltage (V_{fd}) [67].

$$\frac{V_{fd}}{e_f} = \frac{1}{K_e + sT_e} \tag{6.16}$$

Where K_e is the feedback gain and T_e is time constant.

6.2.2. Gravity Storage Charging mode

The upward motion of the piston stores the excess power as potential energy of the water within the container. The operation of a centrifugal pump involves three parameters which includes flow rate, head, and velocity as illustrated in Eq. 6.17.

$$f(H, Q, V) = 0 \tag{6.17}$$

This equation is solved by making one the three parameters constant; typically, the water velocity is considered constant. The volumetric flowrate is expressed by Eq. 6.18:

$$Q_v = \frac{V}{t} = vA \tag{6.18}$$

Where Q_v is the flow of water ($m^{3/}s$); V is the volume of water (m^3); v is the water velocity (m/s); and A is the pipe area (m^2).Pump pressure at discharge is expressed as Eq. 6.19.

$$H_d = \frac{P_d}{\rho g} \tag{6.19}$$

Where H_d is the discharge head (m); P_d is the pressure at discharge (Pa), ρ is the density of water (kg/m^3); and g is the acceleration of gravity (m/s^2). Pump pressure at suction is given by eq.6.20:

$$H_S = \frac{|P_S|}{\rho g} \tag{6.20}$$

Where H$_S$ is the suction head (m); and P$_S$ is the suction pressure (Pa).

Pump total head is the sum of the discharge and suction heads. The pump head is calculated using Eq. 6.21

$$H_T = H_d + H_S = \frac{P_d + |P_S|}{\rho g} = \frac{P_d - P_S}{\rho g} \tag{6.21}$$

From Eq. (6.20-6.21), the pressure difference is equal to Eq. 6.22

$$\Delta P_P = P_d - P_S = \rho g H_T \tag{6.22}$$

The pump useful and consumed powers are:

$$\begin{cases} P_{pu} = \Delta P_P Q_v = Q_m g H_T \\ P_{Cp} = g \dfrac{Q_v \rho H_T}{\eta_P} \end{cases} \tag{6.23}$$

The pump efficiency is expressed by eq. 6.24

$$\eta_P = \frac{P_U}{P_{Cp}} \tag{6.24}$$

Where P$_U$ is useful power (W); P$_{Cp}$ is the electrical power consumed by the pump in (W).

6.2.3. Energy management model

The energy management system controls the energy that flow in and out from the storage system. Two cases are dealt with which corresponds to the storing and generating of energy. If the energy produced by the PV system is greater than the load demand, the excess energy which is the difference between them is stored by gravity storage. This latter generates energy when the energy demand is less than the PV generated energy. In this case, the storage generated energy is equal to load minus the energy produced by the PV system. The model takes into consideration the capacity and power limits of the storage system as illustrated by the red boxes in Fig. 6.3. The storage energy level should be checked before storing or generating energy from the storage system. Therefore, the energy being discharged at a specific time must not exceed the storage level at that time. In addition, the energy stored must be less than or equal to the storage capacity. Storage charging and discharging algorithms are illustrated in the following flowchart (Fig. 6.3).

Storage state at a particular time is expressed by Eq. 25:

$$S(t) = (1-\delta)S(t-1) - E_D(t) + (E_S(t)\eta) \tag{6.25}$$

The storage level is the sum of the stored energy at time t, and the storage remaining energy at time (t-1), minus the discharged energy at time t. System losses which include the storage round-trip efficiency (η) and self-discharge rate (δ) of the system are taken into consideration. The storage level must be modeled to not exceed the maximum storage capacity and should always be positive.

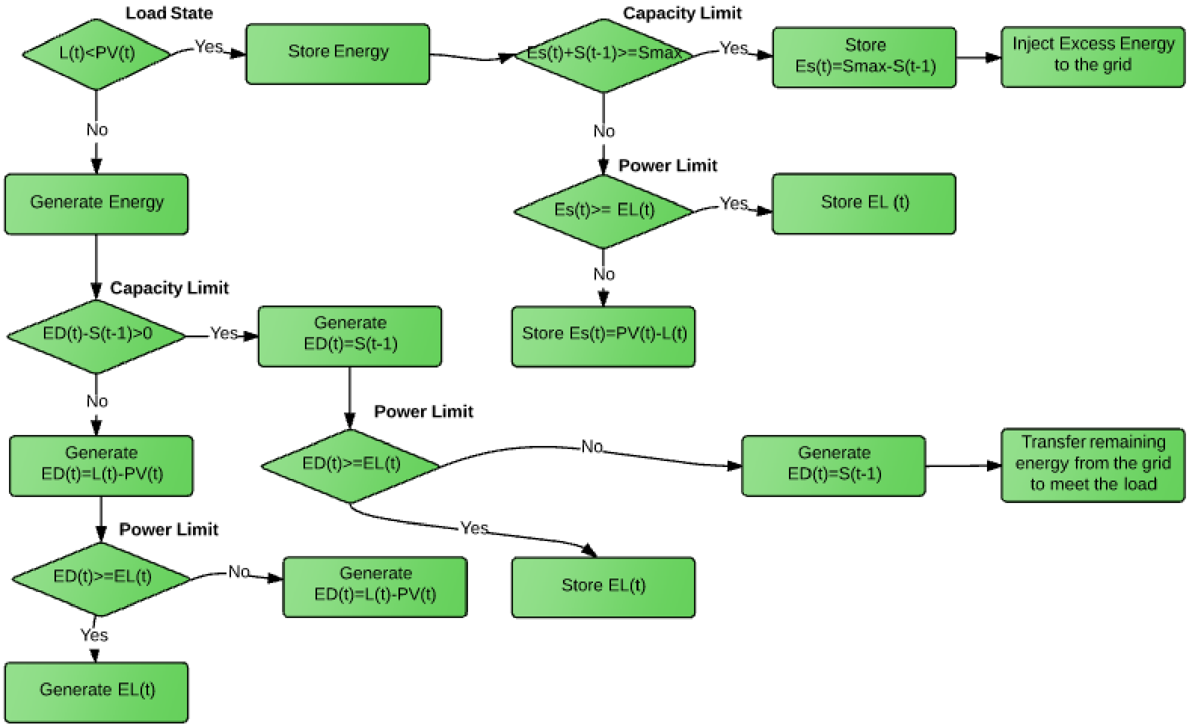


Fig. 6.3. Energy management system flowchart.

6.2.4. PV system and grid models

The PV system was modeled using the following governing equations (6.26-6.28). The maximum rated nominal power of a solar array composed of n modules is expressed by [68]:

$$P_p = nW_p \tag{6.26}$$

Where Pp is the peak nominal power based on 1kW/m² radiation at standard test condition (STC); Wp is maximum power of each module at STC. The average energy produced by the PV system per year is given by:

$$E_p = \frac{S_r P_p}{I_{stc}} \eta \tag{6.27}$$

Where S_r is the available solar radiation for a particular location which depends on the weather conditions and the time of the year; η is the cell efficiency; I_{stc} is the irradiance at STC (1000 W/m²). Taking into account the inclination and orientation correction factor (ξ) of the solar system, the average produced energy would yield to [68]:

$$E = E_p \xi \tag{6.28}$$

The temperature derating factor which is given as (Eq. 6.29) is taken into account by the system overall efficiency (75%) [68].

$$\eta_t = 1 - [\gamma \times (T_c - T_{stc})] \tag{6.29}$$

Where γ is the power temperature coefficient and is typically equal to 0.005 for crystalline silicon [68].

The demand load has been modeled as a dynamic load block in Simulink. The electric grid is modeled to meet the dynamic load in combination with the hybrid renewable farm. The grid model combines all the presented sub-models. It optimally allocates power between the different components of the hybrid system. The governing equation of the electric grid model is given by:

$$P_{grid}(t) = P_L(t) - P_D(t) - P_{PV}(t) + P_S(t) \tag{6.30}$$

Where P_{grid} (t) is the power transferred from the grid to the load; $P_L(t)$ is the power demand at time t; $P_D(t)$ is the power discharged from the storage system; $P_S(t)$ is the power stored from the PV system; and $P_{PV}(t)$ is the power produced by the PV system.

6.2.5. Simulink Model and Simulation analysis

The effectiveness of the proposed model is validated by a case study presented in this section. The utilized case study includes a hybrid renewable plant composed of a PV farm coupled with gravity storage. This hybrid system is connected to the electric grid. Real data for solar radiation and load demand are used. The objectives of this case study are to analyze the operation of the hybrid farm with regard to meeting energy demand; to investigate the output profile of both the PV and the storage system; to quantify the power supplied to the network; and to observe the behavior of the storage system while dealing with an intermittent PV output. The simulated model is presented in Fig. 6.4. The individual sub-models are discussed in the following sub sections.

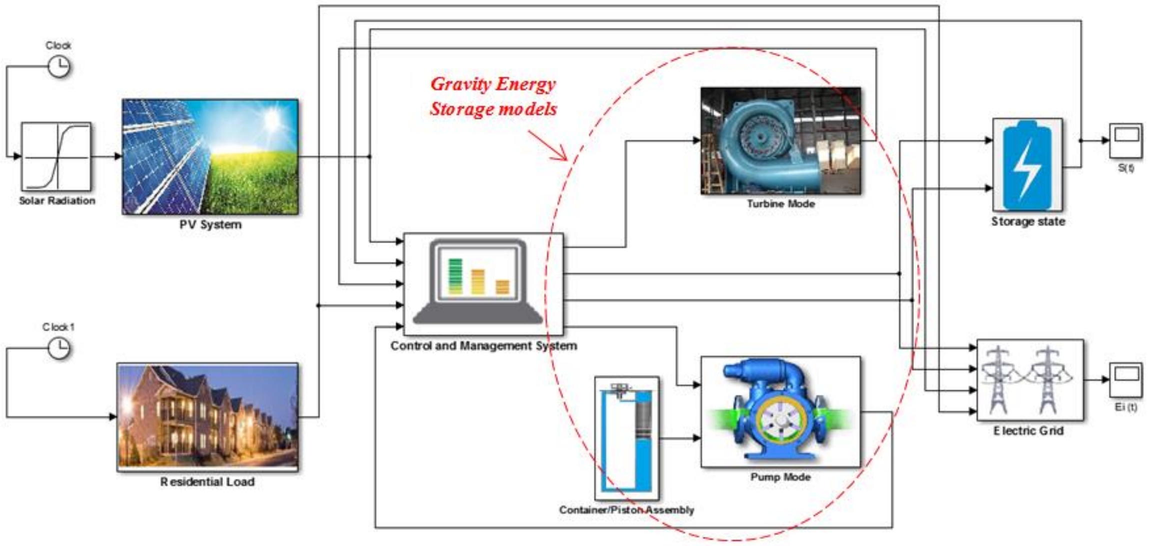


Fig. 6.4. Simulink model of the case study.

The residential load block is connected to the PV system, the storage discharging block, and the grid. The energy generated by these systems as well as the electricity from the grid is fed to the load block in order to meet the demand. The storage pump mode block uses both energy from the PV system and the flow rate from the valve as input to provide power as output to the storage state block. This latter keeps track of the energy that flows in and out from the storage. It also uses the energy generated by the discharging mode block. The container/piston assembly block allows for the determination of the system characteristics among them the pressure which is used for the calculation of the flow rate. This block is linked to the valve which fed the value of the flow rate to the charging mode block. The model is highly coupled as illustrated by the system block diagram in Fig. 6.4.

6.2.5.1. Gravity Storage Sub-models

The sub-model of gravity storage responsible for generating energy is presented in Fig. 6.5. This model is composed of several block diagrams linked together. These include a synchronous generator, excitation system, hydro turbine governor, and three phase RLC load.

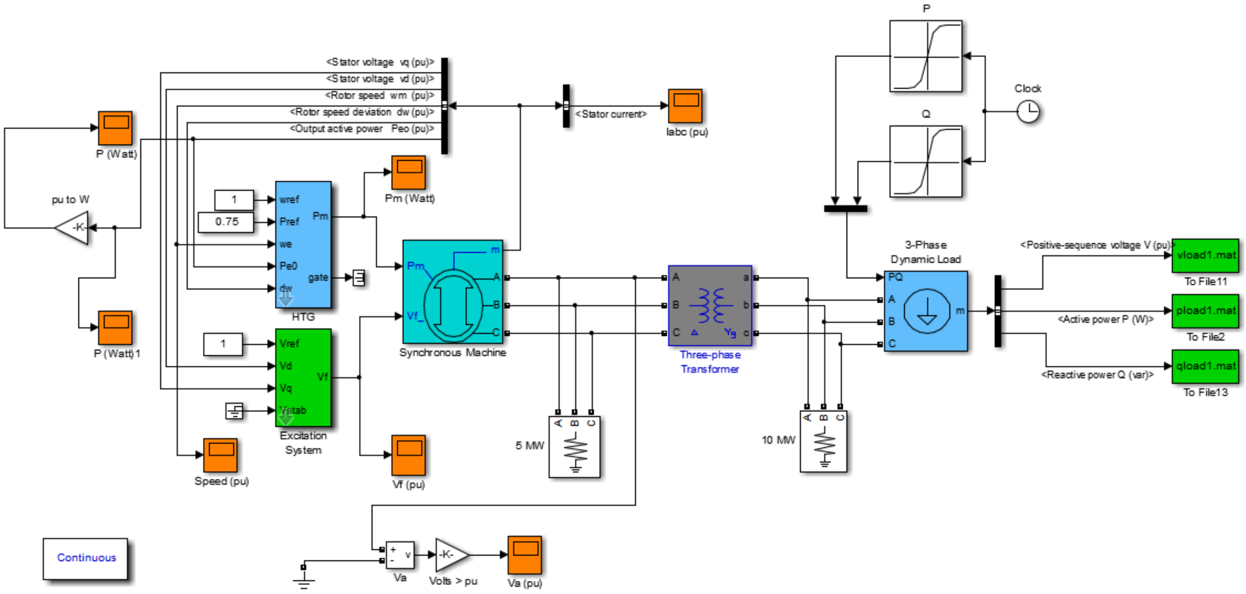


Fig. 6.5.Sub-model storage discharging mode.

The hydro turbine block (HTG) produces mechanical power Pm and fed it to the synchronous generator. This power output is used to drive the generator shaft at synchronous speed in order to generate power at the three phase terminal. At terminal **'*m*'** of the generator, the speed and electromechanical torque developed by this latter are multiplexed. A bus selector block is used to demultiplex the output signals from m terminal of the generator. In the presented model, the demultiplexed signals include the active power output, the stator voltages V_q and V_d, as well as the rotor speed. The hydro turbine governor is fed by two of these feedback signals which include the output active power and the rotor speed. The stator voltages V_d and V_q are used as feedback signals to the excitation system. This latter is responsible for providing excitation requirement to the synchronous generator.

The reference speed is used for comparison with the actual speed of the generator. The difference between them represents a speed error and is used as input to the PID controller. The stability of HTG is improved by minimizing this error which is done by properly selecting the PID controller’s constants. The servo system of the HTG uses the output signal of the governor as input to change the gate opening of the wicket and hence stabilize the system. In case the generator speed is more than the reference speed, the gate opening is reduced by the servo system after receiving a signal from the PID controller. Consequently, a reduction of the gate opening leads to a decrease in the flow rate and the mechanical power generated by the hydro turbine. Therefore, the generator speed is reduced to rotate at synchronous speed.

Sub-models of gravity storage charging mode and hydraulic components are presented in Fig. 6.6 and 6.7 respectively. Additional sub-models are presented in Appendix C.

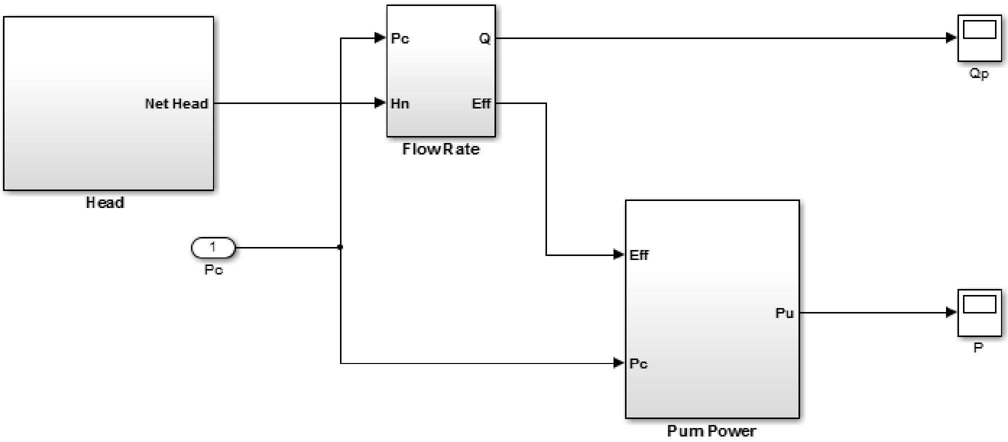


Fig. 6.6. Sub-model storage charging mode.

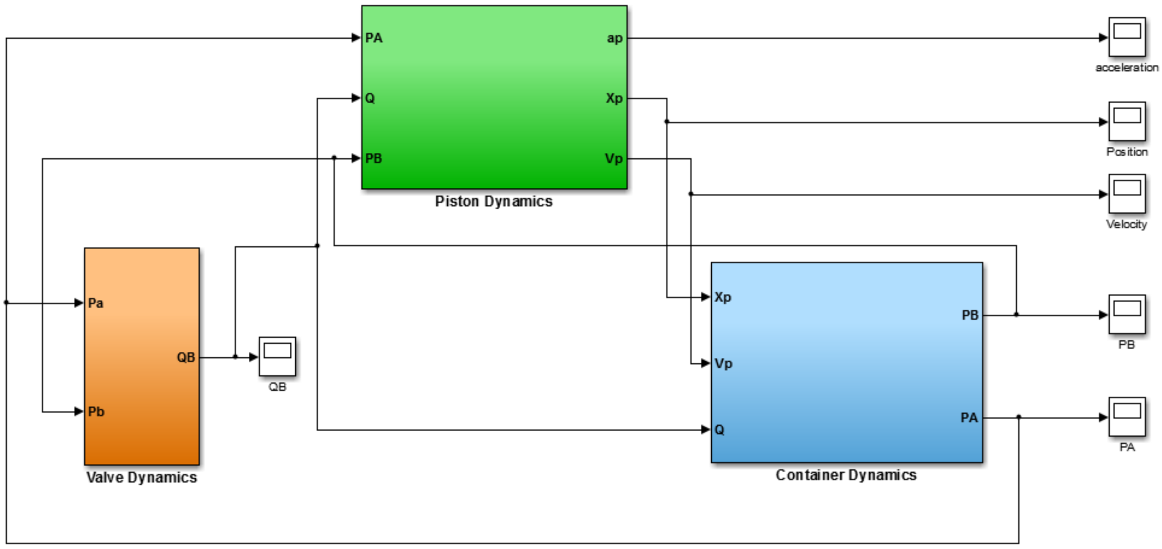


Fig. 6.7. Sub-model of the storage hydraulic components.

6.2.5.2. *Case input data*

The hourly energy demand and solar radiation are provided as input to the model. Real recorded solar radiation data were obtained from ref [69, 70]. The simulated period of the year corresponds to the spring season in Kuala Lumpur, Malysia. Fig 6.8a presents the hourly solar radiation.

The PV generated power is computed based on solar radiation and the system efficiency. Eq. 3.27 was used to estimate the farm generated power output. For this study, a 918 MWh solar farm is modelled (P_p=918 MWp) with a system efficiency of 75%. The PV generated output is shown in Fig. 6.8b. PV output has almost a bell-shaped distribution. It increases gradually in the morning; reaches its maximum at noon, and decreases gradually in the afternoon. Energy demand fluctuates during the day; it reaches its maximum at peak hours while it decreases at night. The energy demand is presented in Fig. 6.9.

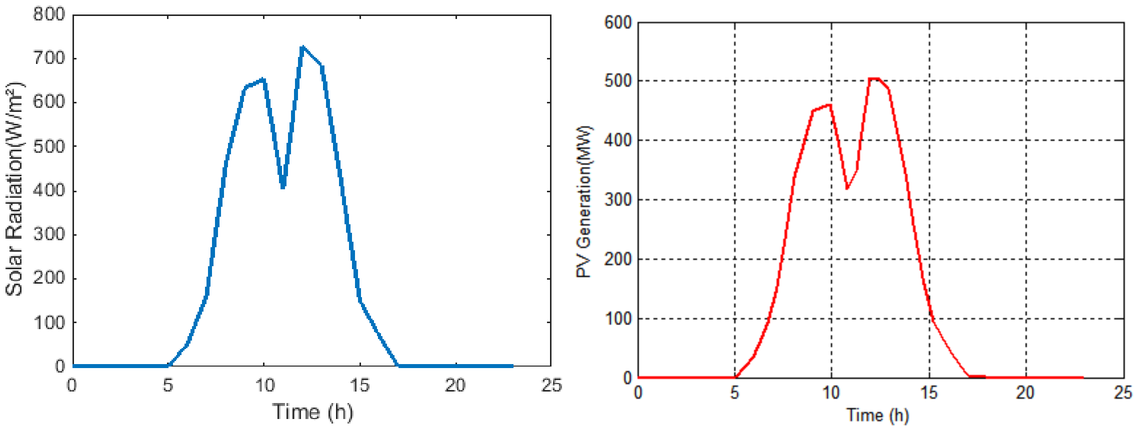


Fig. 6.8. a) Hourly solar radiation, b) Energy Generated by PV plant.

Synchronous machine of 200 MVA is used in this case study. The excitation system controls the terminal voltage of the synchronous machine which is set at 1pu. The input parameters of synchronous machine, excitation system, and turbine are presented in Table 1 [71].

Table 6.1. Parameters of the mechanical equipment used in the case study

Component	**Parameter**	**Symbol**	**Value**	**Unit**
Synchronous Machine	Mechanical Power	Pm	Pm	MW
	Rotor Type	-	Salient-pole	-
	Nominal Power		200	MVA
	Line –to line Voltage	Vn	13800	Vms
	Frequency	fn	60	Hz
	Stator	Rs	2.8544e-3	pu
	Time Constants	[Td' Td" Tqo"]	[1.01, 0.053, 0.1]	s
	Reactances	[Xd Xd' Xd" Xq Xq" Xl]	[1.305, 0.296, 0.252, 0.474, 0.243, 0.18]	pu
	Inertia coeficient, friction factor, pole pairs	[H(s) F(pu) p()]	[3.2 0 2]	-
	Initial conditions	[dw, th, ia,ib,ic, pha,phb,phc, Vf]	[0 -94.2826 0.750185 0.750185 0.750185 -24.943 -144.943 95.057 1.29071]]:	[dw(%) th(deg) ia,ib,ic(pu) pha,phb,phc(deg) Vf(pu)]:
Hydro Turbine	Turbine	Gmax	0.01	-
		Gmin	0.97518	-
		beta	0	-
		Tw	2.67	s
	Servomotor	Ka	10/3	-
		ta	0.07	s
	PID	Rp	0.05	-
		Kp	1.163	-
		Ki	0.105	-
		Kd	0	-
		td	0.01	s
Excitation System	Transient time constants	Tc, T_B	0	-
	Regulator Gain	Ka	300	-
	Regulator Time	Ta	0.001	s
	Exciter Gain	Ke	0	
	Exciter Time Constant	Te	0	s
	Damper Gain	Kf	0.001	
	Damper Time Constant	Tf	0.1	s

6.2.5.3. Results and discussion

As stated earlier, energy demand is met by the PV system, energy storage, and electric grid. A comparison between energy demand and energy generation curves is shown in Fig. 6.9. This comparison demonstrates that the demand is met by one or a combination of these systems. Fig. 6.9b presents the participation of each system. The participation of the electric grid occurs at night; Energy is supplied by the grid when the PV system is not producing energy and when the storage is empty. Between 5 and 7 a.m., a small amount of energy is generated by the PV system and is fed to the residential load. At that time, energy is also exchanged between the grid and the residential load. The participation of both the PV system and the grid is necessary in this case in order to meet the demand. From 7 a.m. till 3 p.m., energy is met by only the PV system. During this period, the storage is being charged by the excess energy generated by the PV system. It reaches its maximum capacity around 3.p.m. (See Fig. 6.9b).

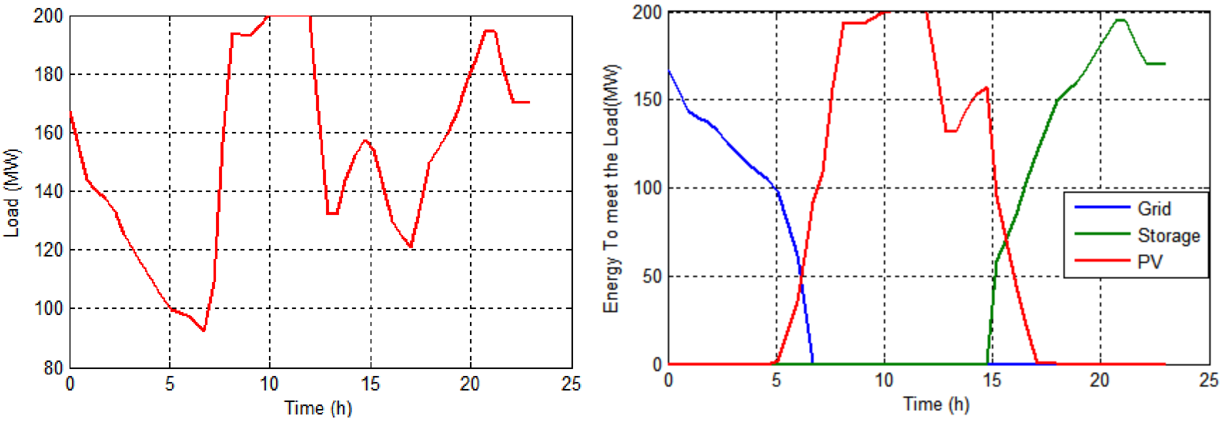


Fig. 6.9. a) residential load energy demand, b) Energy generation to meet the demand.

The participation of the storage system is required, between 3 and 5 p.m, as the energy produced by the PV system is rather small. Therefore, both the PV and the storage systems generate energy. Starting 6 p.m. the residential load is fed energy from the storage system. The state of the storage system is shown in Fig. 6.10a. The charging of the storage occurs at 6 a.m. as the PV system starts generating energy. The system discharges its energy at peak demand and when the PV system is not producing energy. The storage charging and discharging is shown in Fig. 6.10b. The green color illustrates the energy consumed by the pump system while the red one presents the storage useful energy. The difference between them is due to the energy efficiency of the system. The blue color is the energy generated by the storage system.

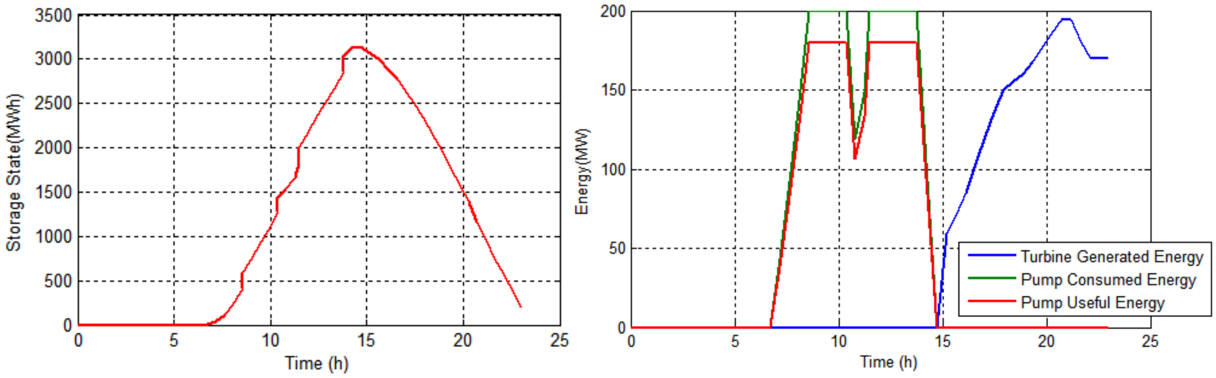


Fig. 6.10. a) Energy storage state, b) Charging and discharging of the storage system.

The energy transferred from and to the electric grid is shown in Fig. 6.11. As stated before, energy is only discharged from the grid at night when the PV is not able to generate energy and when the storage state is very low. Only a limited amount of energy is injected to the grid and it occurs at 10 and 12 a.m. At noon, energy generated by the PV system reaches its maximum; some of this energy is fed to the residence load; used to charge the storage; and injected to the grid.

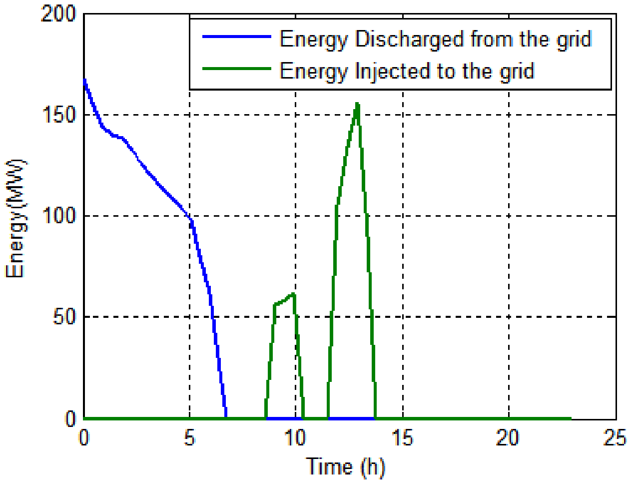


Fig. 6.11. Energy exchanged with the electric grid.

Hydro turbines are characterized by a peculiar response because of water inertia. A change of the power produced by hydraulic turbines is due to a change in gate position. This latter is caused by the production of a control signal by the governor. In this manner, the turbine drives the generator which produces electrical power output (See Fig. 6.12). Eq. 10 demonstrates how a change in gate position results in a change in the turbine power output. The response of the storage system with respect to a change in the storage operation from standby mode to discharging mode is shown in Fig. 6.13. As illustrated, the initial turbine power output is equal to half the time necessary for an immediate gate opening due to water inertia, represented by T_W [62]. A rapid drop in power output is observed between (1 and 1.335 s) due to an initial step increase in gate position. This effect is due to the minus sign in the numerator of Eq. 6.10 [65]. The power output starts increasing as the system flow rate increases.

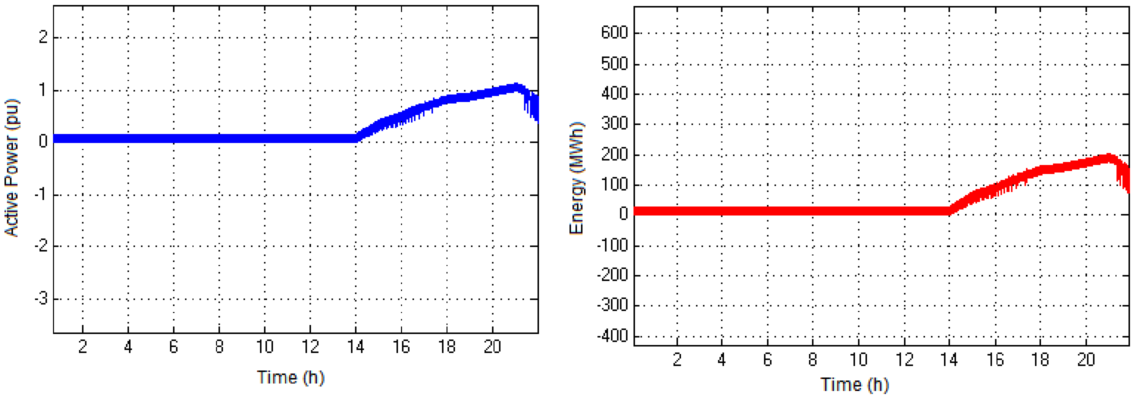


Fig. 6.12. a) Synchronous generator active power in pu, b) Energy output of the synchronous machine in W.

On the contrary, if the system is moving from the discharging mode to standby with an aim to reduce the turbine power output, the gate position should be closed. In this case, the system flow rate cannot change instantaneously, so an initial increase of the flow velocity will be observed. This implies an initial increase in the power output for a short period of time. This latter will be reduced when the flowrate reduces after a short delay [65].

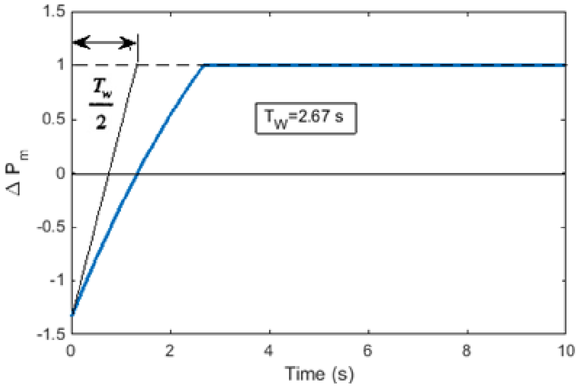


Fig. 6. 13. Power output response to a change in gate position.

Gravity storage requires similar mechanical equipment to hydropower plants which are characterized by quick response times. This capability makes this storage system able to instantly follow changes in energy demand and supply, and ensure grid stability.

A simulation was performed according to various loading conditions to analyze the response of gravity storage system. The synchronous generator active power characteristics are shown in Fig. 6.14b-6.15. The curve displays a steady state value of 0.6 pu which can be converted into W of the actual load connected to the plant. The steady state is obtained when the generator starts operating. The overshoots and undershoots of the power characteristics occur due to few oscillations used to reach the stable operating point on power.

Fig. 6.14a presents the generated voltage (Va) and the stator currents of the generator. The terminal voltage is stator phase voltage (Phase A). It has three phase voltages and lags each other by 120 deg. The plot shows that the voltage has steady state characteristics and follows a sinusoidal pattern. The phase voltage magnitude is 1 pu and is equal to the rated voltage output of the generator. Load change does not have an effect on the terminal voltage as this latter remain constant.

Fig. 6.14b shows the stator current. It changes slightly due to load variation at 960 min (4 pm). When the load is altered, the three phase current envelop displays underdamped response. Steady state characteristics are obtained after a period of time. Figure 6.14d present the same characteristics from a close view.

The waveforms of the excitation voltage (Vf) in pu with respect to time is shown in Fig. 6.14c. Before load variation, the system runs in steady state condition. As the load increases, the excitation voltage increases. A decrease of the resistive load causes also a decrease in this voltage before re-experiencing a steady state condition.

The rotor speed characteristic is shown in Fig. 6.15. The steady state value of the synchronous speed is 1.02 pu. It is observed that the speed reaches steady state after few oscillations. With an increase of the load, the speed of rotor decreases before returning back to its state. The speed is kept near synchronous speed with proper selection of the governor setting (PID control parameters). The simulation results are similar to the outcomes obtained by prior work explored in literature which deals with dynamic modeling of comparable systems [22, 7, 40, 54, 55, 56, 57, 65].

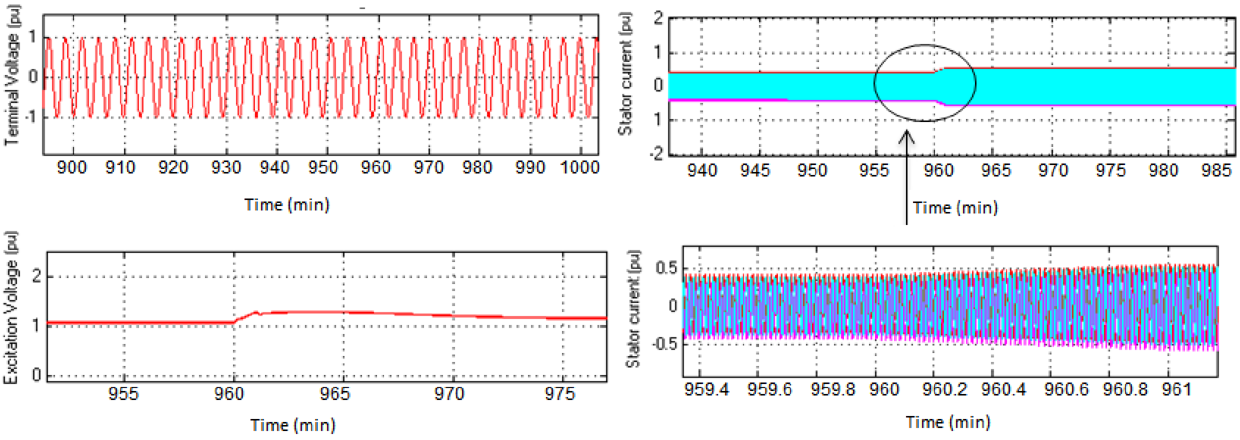


Fig. 6.14. a) Stator voltage (V_a), b) the stator current (I_{abc}), c) Excitation Voltage (V_f), d) Closer view of the stator current.

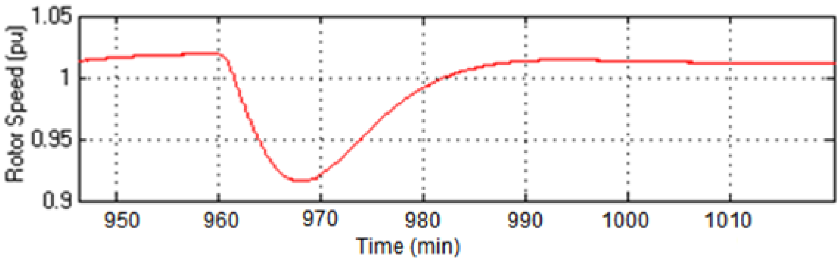


Fig. 6.15. Rotor speed characteristics of the synchronous generator.

6.3. Hydraulic Modeling of Gravity Storage

6.3.1. Dynamic mathematical model of the system

The mathematical models for individual components of gravity storage system are proposed in this section. These include relevant non-linear effects and encountered dynamics of the system. First, the equilibrium forces of the container are examined for the system's static state. Then, the dynamic behavior of the assembly is formulated. The model takes into consideration friction effect as well as pressure drop. The different parameters of the system and the applied forces in the discharging mode of the storage are illustrated in this Fig. 6.16. They are used for the derivation of the model governing equations.

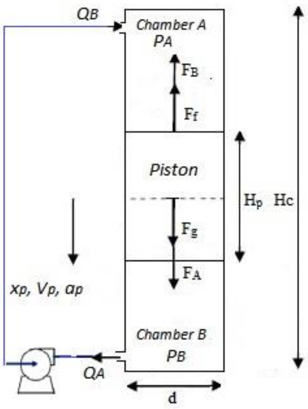


Fig. 6.16. System sketch with its parameters

The physical model has a cascade nature as shown in Fig. 6.16. There exists a high interaction between different components of the system. The piston movement inside the container is affected by a change of the valve slider position. Moreover, this piston motion is dependent on the flow inside the chambers, the pressure difference, the liquid compressibility, and the flow rate. All these parameters are regulated by the valve. A change in one parameter, will affect the other parameters. The relationship between the different components of the hydraulic system is illustrated in Fig. 6.17. The model is highly coupled as each parameter is dependent on other components' parameters.

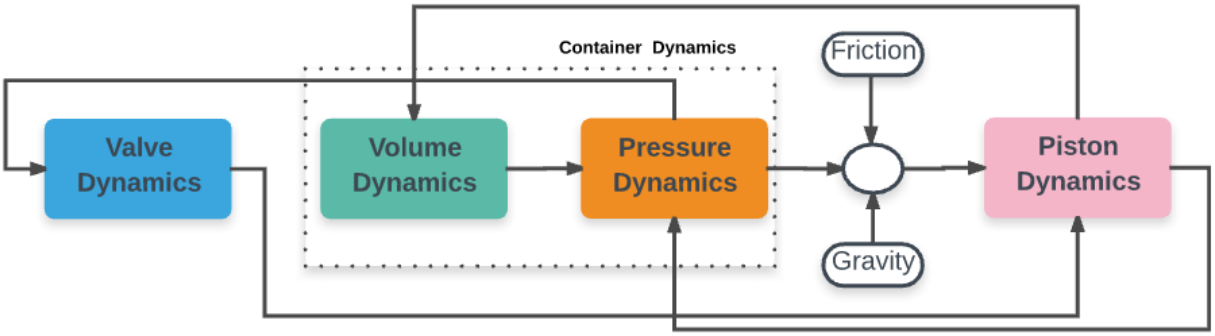


Fig. 6.17. Model flowchart.

6.3.1.1. Volume dynamics

The initial conditions for the water volume of both reservoirs in the static mode (x_p=0) are:

$$\begin{cases} V_{A,0} = 0 \\ V_{B,0} = (H_C - H_P)A_B \end{cases} \tag{6.31}$$

The volume dynamic behavior of both chambers is expressed as:

$$\begin{cases} V_A(x_p) = V_{A,0} + x_P \dfrac{\pi d^2}{4} \\ V_B(x_p) = (H_C - H_P)A_B - x_P \dfrac{\pi d^2}{4} \end{cases} \tag{6.32}$$

6.3.1.2. Pressure dynamics

To describe in detail the behavior of the container chambers, mass conservation equations have been specified. In a hydraulic system, the mass of substances remain constant regardless of the process that acts on the system (Eq. 6.33).

$$\dot{V} = \sum Q \tag{6.33}$$

The principle of mass conversation is given by:

$$\dot{m} = \rho \dot{V} = \rho v A = const \tag{6.34}$$

Fluid mass conservation is represented by the continuity equation as follow:

$$\begin{cases} \dfrac{dm_A}{dt} = \rho_W (Q_A - Q_L) \\ \dfrac{dm_B}{dt} = -\rho_W (Q_B + Q_L) \end{cases} \tag{6.35}$$

The investigated hydraulic system operates in high pressure range; therefore, it is essential to take into consideration the fluid bulk modulus. The response of the system could be compromised if the bulk modulus is ignored. A significant amount of energy is used to compress the fluid when high pressure is applied. This causes a delay in the system response. The behavior of the system is also affected by the applied pressure. The motion of the piston may not start until the upstream fluid has been compressed adequately. In addition, the stored energy by the compressed fluid may lead the piston to continue its movement even though the valve has been closed [72]. The density of the fluid is then expressed as a function of the container pressure.

$$\rho_W(p) = E_W(p) \frac{\delta \rho_W(p)}{\delta p} \tag{6.36}$$

Bulk modulus has been estimated by several researchers such as Jelali el al. and Totten et al. [72-73]. Most of the proposed equations require experimental determination of several parameters. In this work, an estimation of the bulk modulus based on literature review has been used. The bulk modulus of liquid elasticity is described as:

$$E_W(p) = \frac{1}{2} E_0 \log_{10}(k_1 \frac{P}{P_{odn}} + k_2) \tag{6.37}$$

Where E_W is the liquid compressibility modulus; E_0 is the nominal fluid compressibility modulus; P is Pressure; and P_{odn} is a reference pressure. Combining Eq. 35 and 36 we obtain,

$$\begin{cases} \frac{dP_A}{dt}\frac{V_A\rho_W}{E_W(p)} + \frac{dV_A}{dt}\rho_W = \rho_W(Q_A - Q_L) \\ \frac{dP_B}{dt}\frac{V_B\rho_W}{E_W(p)} + \frac{dV_B}{dt}\rho_W = -\rho_W(Q_B + Q_L) \end{cases} \tag{6.38}$$

The derivative of pressure is expressed as:

$$\begin{cases} \frac{dP_A}{dt} = \frac{E_W(p)}{V_A(x_p)}(Q_A - Q_L - A_A\frac{dx_P}{dt}) \\ \frac{dP_B}{dt} = -\frac{E_W(p)}{V_B(x_p)}(Q_B + Q_L - A_B\frac{dx_P}{dt}) \end{cases} \tag{6.39}$$

6.3.1.3. Piston motion dynamics

The piston movement depends on the pressure forces applied on its sides. Using Newton's second law, the piston motion governing equations are,

$$m\ddot{x}_P = F_A - F_B + F_g - F_f \tag{6.40}$$

Where m and $\ddot{x}_P$ are the piston mass and acceleration; F_A and F_B are the applied pressure forces by chamber A and B, respectively. F_g and F_f are the gravitational and friction forces, respectively. The piston acceleration, velocity, and position can then be expressed as:

$$\begin{cases} \ddot{x}_P = \frac{1}{m}\left[(P_A A_A - P_B A_B + mg - F_f\right] \\ \dot{x}_P = \frac{\Delta x_P}{\Delta t} \\ x_P = \int \dot{x}_P \end{cases} \tag{6.41}$$

Friction is regarded as one important aspect of piston motion [74]. The contact between the piston seal and the container, as well as the flow of water in the container and the return pipe, result in friction forces which significantly affect the motion dynamics of gravity energy storage. Typically, friction in hydraulic systems depends on several factors which include roughness, surface and medium type, tolerances, temperature, pressure difference, as well as the seal shape, size, wear and material. Hydraulic systems are typically characterized by strong dry friction forces due to the tight sealing they require. This latter's behavior is complex [75]. Friction in this model is taken into account as an external disturbance. To estimate the friction force, total force of the seal against the cylinder wall is multiplied by the friction factor. Since it is difficult to derive the friction factor value without tests, an average of 0.1 is assumed based on literature [76]. This value is determined experimentally using a reciprocating seal in a steel cylinder.

$$F_S = \mu F_N \tag{6.42}$$

Lindley's formula is conventionally used to derive the force that act on the seal by the O-ring initial deformation [77]. The normal force acting on the cylinder is expressed by:

$$F_N = b\pi D(P_i + \Delta P_f) \tag{6.43}$$

Where b is the contact width, D is the O-ring mean diameter, (ΔP_f) is the system pressure difference, and P_i is the contact pressure due to the initial compression which can be written as:

$$P_i = d_S E(1.25C^{1.25} + 50C^6) \tag{6.44}$$

Where C is the fractional compression and is equal to the fraction of a (diametric compression) and d_S (the cross section diameter of the O-ring). Based on literature, the initial fractional compression is assumed as 25%. A lower fractional compression represents less friction and stricter tolerances. E is the elastic modulus of the O-ring material.

An empirical equation to determine the contact pressure due to the system pressure difference (ΔP_f) as derived by Yokoyama et al. [78] is given by,

$$\Delta P_f = \alpha \frac{P_1(d\pi/2 - a)}{a} \tag{6.45}$$

In here α is a conversion coefficient; estimated as 0.4 by [53]. The contact width, b, can be obtained from Eq. 6.46 and the Hertz theory, as [79]

$$b = \sqrt{\frac{6P_1 d_S}{\pi E}} \tag{6.46}$$

The aforementioned equations do not consider time factors such as relaxation. A constant effective contact stress is assumed over time. In addition, temperature effects are also neglected because the system sealing is less sensitive.

6.3.1.4. Hydraulic losses

The integration of renewable energy sources requires the use of highly efficient energy storage technologies. The efficiency of the storage system drops with energy losses. Hydraulic loss which is the energy loss within a moving fluid should be determined. This loss could be caused by frictional effects due to the pipe walls or the fluid viscosity. It could also be due to physical components such as the pipe bends or the valve. There are two different types of hydraulic losses which include major and minor losses.

$$H_L = h_{Lmajor} + h_{L\min or} \tag{6.47}$$

Major losses, h_{Lmajor}, known as linear losses, are mainly caused by friction and are determined by Eq. 6.48, known as Darcy-Weisbach equation. It is valid for both horizontal and on hill pipes, with incompressible and steady flow.

$$h_{Lmajor} = f * \frac{L}{D'} * \frac{V^2}{2g} \tag{6.48}$$

Where f is friction factor, L is longitude of the pipe (m), D’ is inside diameter of the pipe (m), V is the average water velocity (m/s), and g is the standard gravity (m/s^2). The friction factor is determined using Eq.6.49 for turbulent flow [80].

$$f = \frac{1.325}{\left[\ln\left(\frac{e}{3.7D'} + \frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^2} \tag{6.49}$$

Here, e is the relative roughness and is given by $e = \frac{\varepsilon}{D'}$; Re is the Reynolds number expressed as $\mathrm{Re} = \frac{VD}{\nu}$; and ν is the kinematic viscosity of water.

Minor losses, h_{Lminor}, also known as singular losses, are caused by fittings, valves, bends, …etc. They can be quantified using a loss coefficient (K) depending on the type of loss. These losses are proportional to the flow velocity squared. To calculate the system minor losses, Eq.6.50 is used [81]:

$$h_{L\min or} = K_L \frac{V^2}{2g} \tag{6.50}$$

K_L is the loss coefficient.

Water head (H_t) in meter is converted to pressure head (P_H), in Kg/cm², by using a multiplicative constant involving the water specific gravity (SG) shown in Eq. 6.51.

$$H_t = P_H \frac{10}{SG} \tag{6.51}$$

6.3.1.5. Valve dynamics

The incorporation of energy storage technologies with the electric grid reduces the imbalance between demand and supply. Energy is discharged from the storage device during peak energy consumption. The discharging process of gravity storage starts by the opening of the relief valve. This latter controls the flow of water from one chamber to the other. It rectifies the flow by its opening and closing. The dynamics of the valve are modelled using a governing equation which relates the flow rate and the pressure drop across the valve. This equation is given as:

$$P_B - P_A = R_v Q_B{}^2 + I\frac{dQ_B}{dt} \tag{6.52}$$

Where P_A, and P_B are the pressure in chamber A and B, respectively. A_O is the opening area of the valve, and ξ_o is the discharge coefficient. I is the channel Inductance and is expressed as:

$$I = \frac{\rho L_T}{A_T} \tag{6.53}$$

A_T, and L_T are the cross sectional area and the length of the return pipe.
Rv is the valve's flow resistance and is given by:

$$R_v = \frac{1}{2}\rho C_d \frac{1}{A_O{}^2} \tag{6.54}$$

Here A_O is the opening area of the valve, and C_d is the discharge coefficient.

The described equations of the respective essential hydraulic components are solved simultaneously by Simulink. One of the objectives of this mathematical model is to gain insight into the performance of gravity storage hydraulic system. This model allows for identification of important parameters of the storage system including flow rate, pressure, volume, as well as piston velocity, acceleration and position as functions of time. A control system, which will be described in the following section, is needed to ensure the proper operation of the storage system.

6.3.1.6. Control system

To correctly describe the real physical behavior of the piston motion, the velocity and position of this latter must be controlled. The physical limitation of the container is not properly represented by a saturation block and a double integrator. Even if the upper saturation limit of the velocity is reached, the integration block is still operating and does not stop. To solve this issue, a control system is developed based on non-linear elements. This sub-model assigns a zero to the velocity as soon as the piston reaches the container limitations. Fig. 6.18 presents the control system model.

6.3.2. Simulink Models

6.3.2.1. System-level model

The Simulink model of the top level diagram has been developed using the described mathematical sub-models. Fig. 6.19 presents the high level model of the system. The control system is also used to monitor the operation of the hydraulic components. The presented governing equations were used to determine the connections between the blocks of the model. The flow rate is taken by the piston and container sub-models as input from the control valve. This latter makes use of the chambers' pressure as inputs. These pressures have also to be fed to the piston motion block. The resulting dynamics of the aforementioned block, which include the piston position and velocity, are taken by the container block as inputs. In addition, this latter block uses the flow rate and the volume change of both chambers; to output the pressure of each chamber as a function of time. The developed Simulink sub-models are presented in Appendix C.

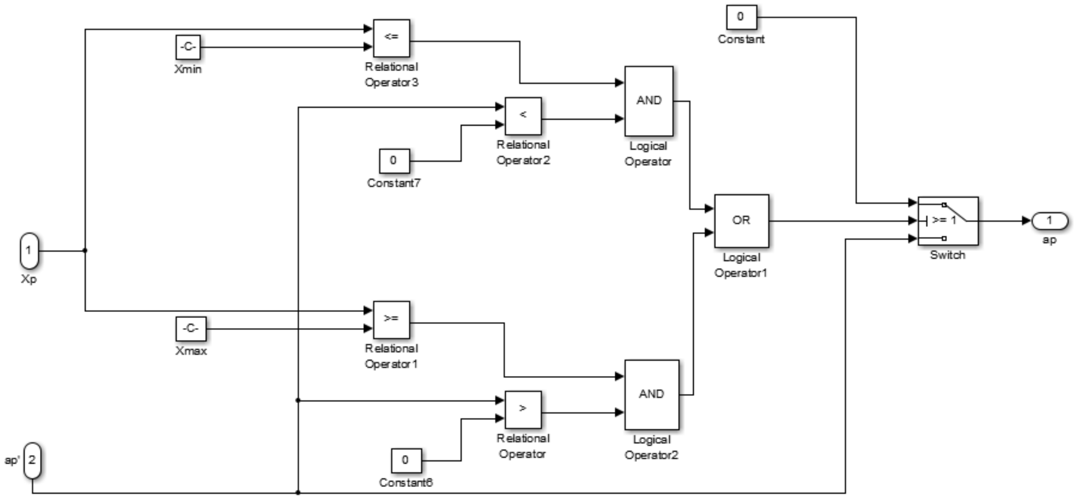


Fig. 6.18. Control system of the piston motion.

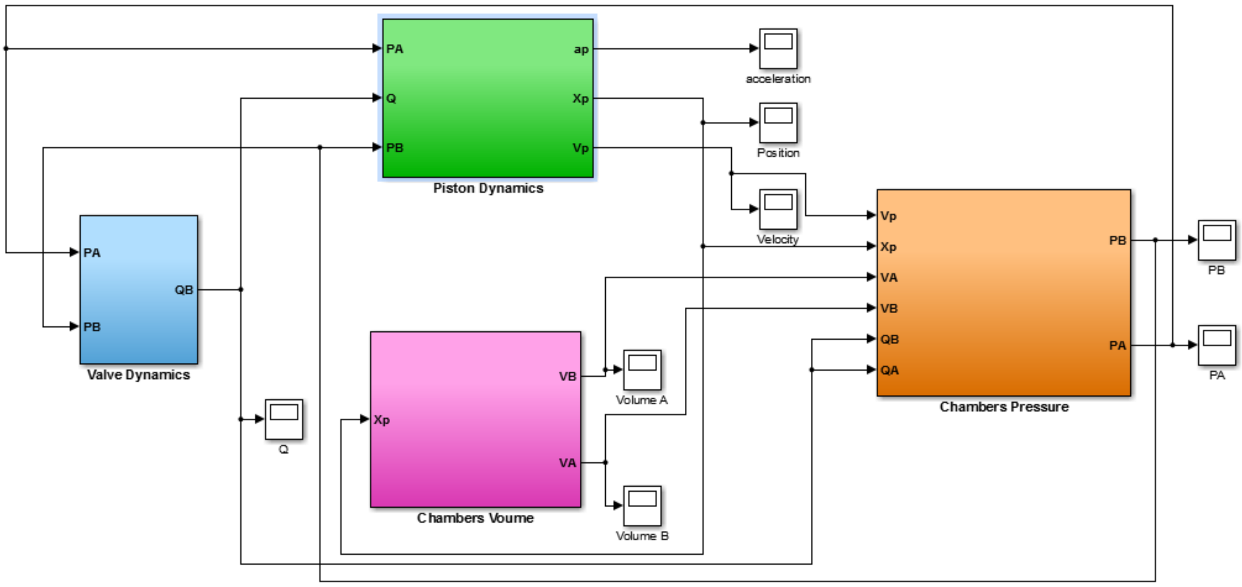


Fig. 6.19. System-level Simulink model

6.3.2.2. Valve model

The sub-blocks of the top level model are developed using the derived governing equations presented in Section 6.3.1.

Fig. 6.20 presents the block diagrams of the valve dynamics. The model takes the pressure in both chambers as input and outputs the flow rate through the valve. The return pipe geometry and the valve flow resistance are also needed to model the dynamics of the valve.

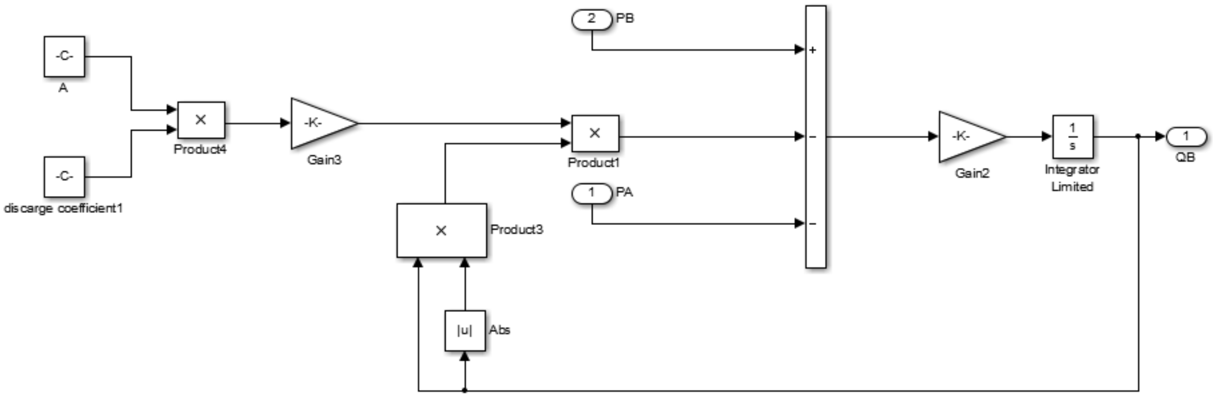


Fig. 6.20. Simulink model of the valve

6.3.2.3. Pump model

Centrifugal pumps are often best suited for this type of systems if separate pump turbine are used. The centrifugal pump that is able to satisfy the head, flow and power requirements of the system, used in the case study, is operated at 3600 rpm. Fig.6.21 presents the pump model developed using SimHydraulics. This latter is a block package used to model hydraulic systems in Simulink. The system model contains a centrifugal pump, electro motor subsystem, and sensors. The pump inputs include a rotational speed and a control signal. It provides the system with the flow. The electro motor subsystem consists of an ideal angular velocity source; connected to an angular velocity reference signal and to a mechanical reference blocks. This subsystem provides rotational speed to the pump shaft. The model also contains variable orifice, hydraulic fluid reference and solver configuration block. The flow and pressure sensors are also included to measure flow rate and pressures of the hydraulic system, respectively. Gains are added to the model in order to convert SI units to hydraulic units.

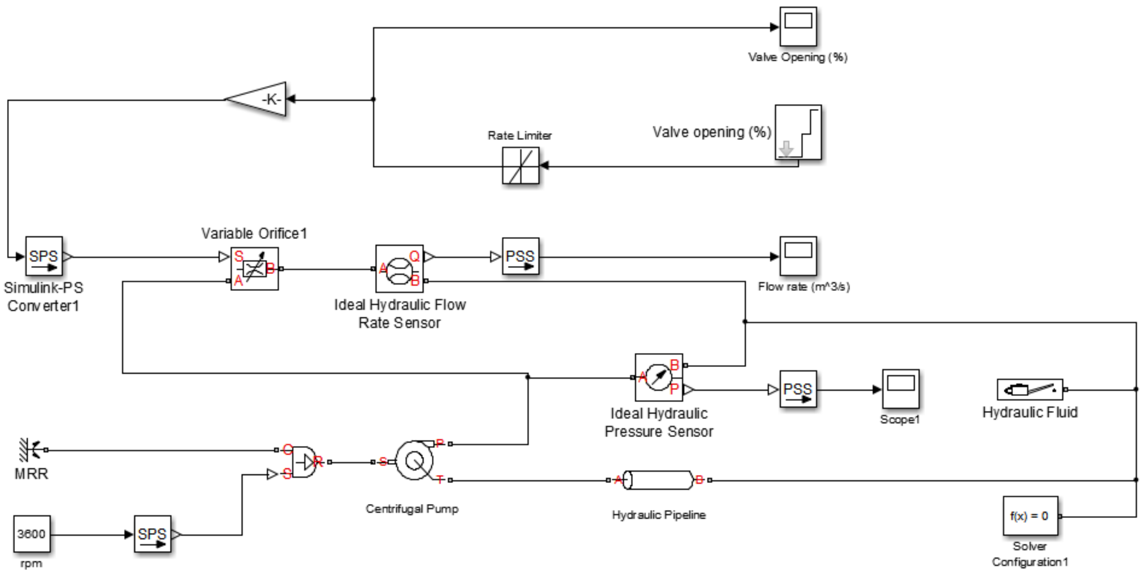


Fig. 6.21. Pump model

6.3.3. *Simulation results analysis*

6.3.3.1. Case study

A complete model of the system is obtained through interconnecting its different components (sub-models), described in form of differential equations in the previous sections. To simulate the system, parameterization of the model is necessary. The value of the different parameters may be taken directly from components specification, or indirectly through experimental measurements or through calculations. The storage geometry simulated in this case study is summarized in Table 6.2. Data regarding the liquid bulk modulus were taken from literature, while the frictional force has been estimated in this case using Eq. 6.42-6.46.

Table 6.2. Parameters of gravity energy storage used in the case study.

Component	**Parameter**	**Value**
Container	Height	2 m
	Diameter	0.4 m
Piston	Height	1 m
	Diameter	0.4 m
	Mass	988 Kg
Return pipe	Length	2 m
	Cross sectional area	0.0005 m²
Valve	Opening Area	0.00006 m²
	Discharge coefficient	0.611
Sealing	O-ring cross section diameter	8 mm
	O-ring mean diameter	400 mm
	E elastic modulus of the O-ring material	5.52 MPA
	Fractional compression	25%

6.3.4. *Simulation results*

The characteristics of the piston motion are presented in Fig. 6.22. It is shown that the piston takes 368 s to reach its final position which is the container upper limit. The piston is not accelerating during its motion; it is moving with a constant velocity equal to 0.0027 m/s. Once the piston reaches its maximum position, the simulation stops.

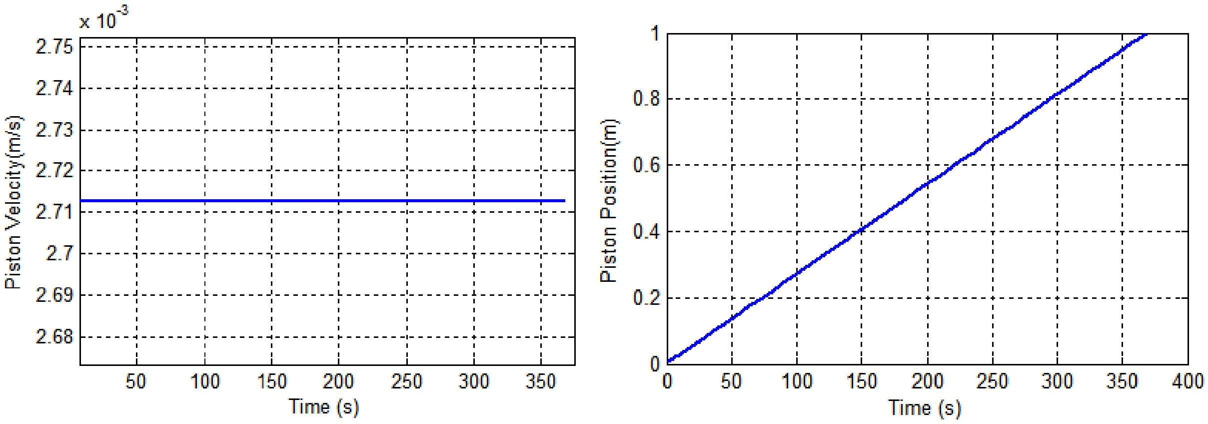


Fig. 6.22. Piston motion a) velocity, b) position.

Fig. 6.23a illustrates the volume of the liquid entering and leaving both chambers of the storage system. We notice that when the volume increases in chamber A it decreases in chamber B, as expected. The filling up of the upper chamber and emptying of bottom chamber B takes 368 s. As this process is taking place the flow rate through the valve (Q) is 3.4×10^{-4} m^3/s as noticed in Fig. 6.23b.

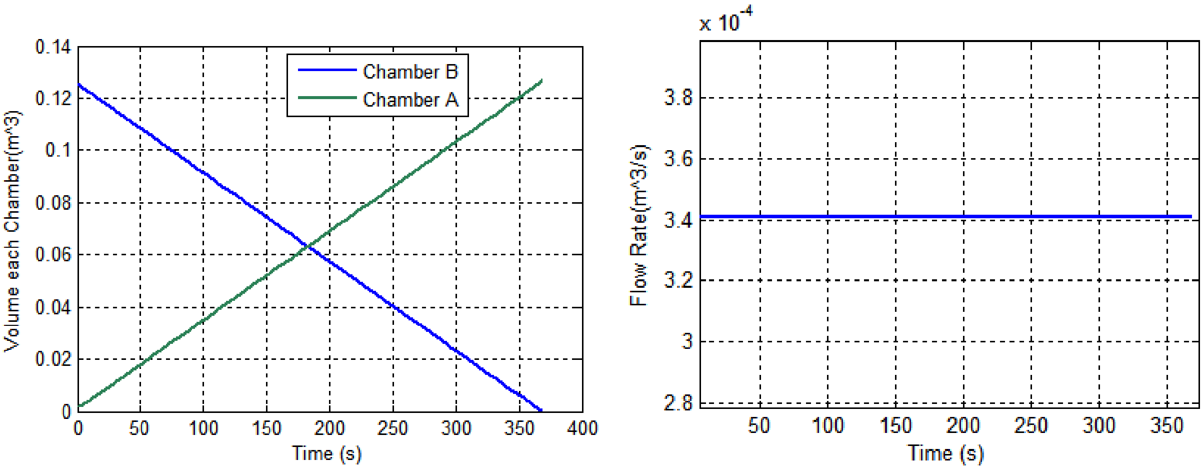


Fig. 6.23. Volume variation of chamber A and B during piston downward motion, b) System flow rate.

The behavior of pressure in each chamber is illustrated in Fig. 6.24. When the piston is at the top of the storage container, chamber B is completely filled with water while chamber A is empty. In this case, the pressure P_B is equal to 43.18 kPa while the pressure in chamber A is negligible. The high pressure in chamber B is due to the water and the piston pressures. The pressure force of the piston is greater than that of the water column. Pressure in chamber B is constant as the piston moves down to generate energy.

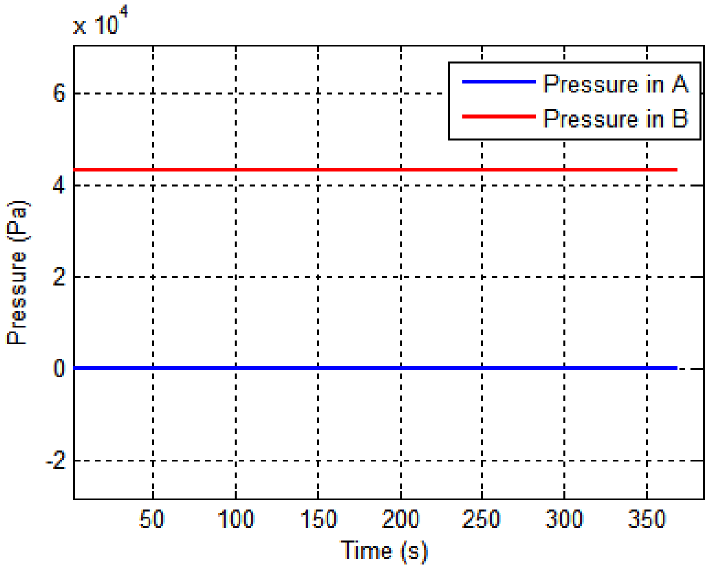


Fig. 6.24. Pressure variation of both chambers

To visualize the pressure response due to the valve opening, a close view of the pressure vs time is illustrated in Fig. 6.25. Typically, valves are developed to have a fast response. They play a crucial role in the system dynamics as they are responsible for converting the control signal into water flow. In this simulation, the valve opening attains its maximum value in a very short period of time 0.82 seconds. The pressure changes as the valve gate is being opened. During the opening process, the system pressure increases rapidly until reaching its stable condition. When this latter is fully opened at less than 1 s, the pressure is equal to 43 kPa. The system pressure remains stable because it is a function of the flow rate and the piston velocity. These latter are constant throughout the discharging process of the storage system (See Fig 22a, and 23b).

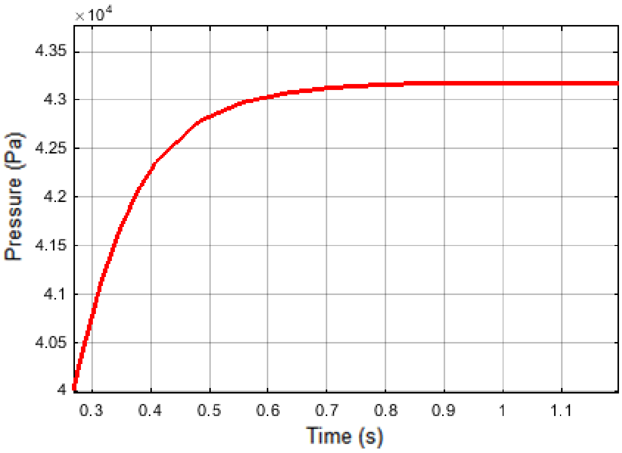


Fig. 6.25. Close view of pressure variation in chambers B

The results obtained for the system hydraulic losses are presented in Fig. 6.26 and 6.27. The total losses are the sum of the major and the minor losses and they are equal to 968 Pa. Major losses, of 482 Pa, are associated with estimated container and return pipe frictional energy losses. These are dependent on the flow velocity, as well as the pipe diameter and length. The container major losses are very low and negligible 6×10^{-4} Pa; while the return pipe frictional losses are large and estimated as 482 Pa. The return pipe losses are greater than the container losses due to high water velocity in the return pipe. On the other hand, minor losses compromise losses associated with the flow through the pipe entrance, exit, elbows, and valve. These latter are equal to 486 Pa. In addition, we notice that the exit losses represent the largest minor losses followed by pipe elbows, and entrance losses. The valve losses represent the lowest minor losses. This difference in minor losses is due to the loss coefficient (k) which varies based on the component's geometry and physical properties.

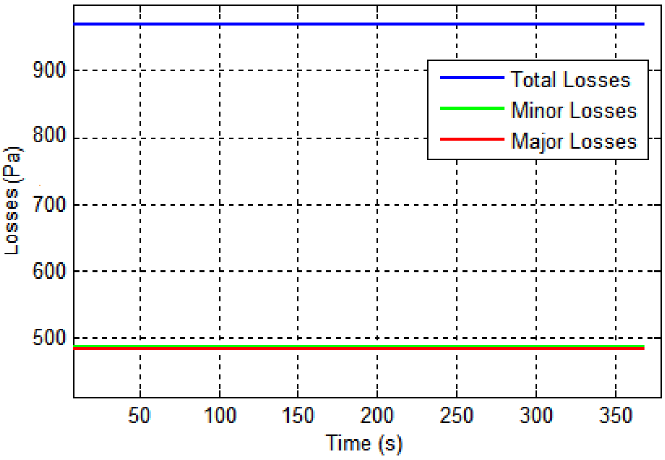


Fig. 6.26. System hydraulic losses

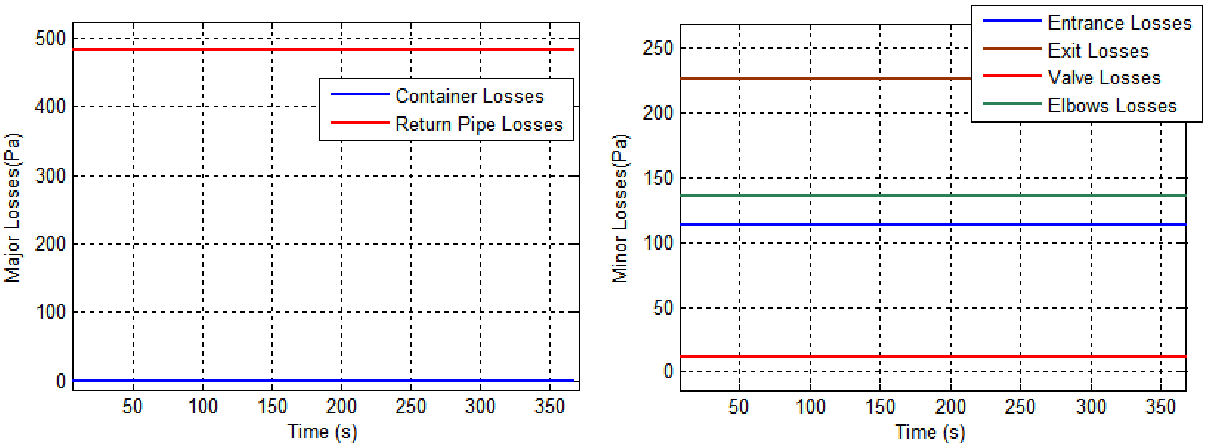


Fig. 6.27. System losses a) Major losses components b) Minor losses components.

The pump flow rate vs the valve gradual opening as a function of time is presented in Fig. 6.28. It can be seen that the flow rate increases gradually as the valve is being opened. It takes less than 1s for the flow rate to reach its stable value when the valve is fully opened.

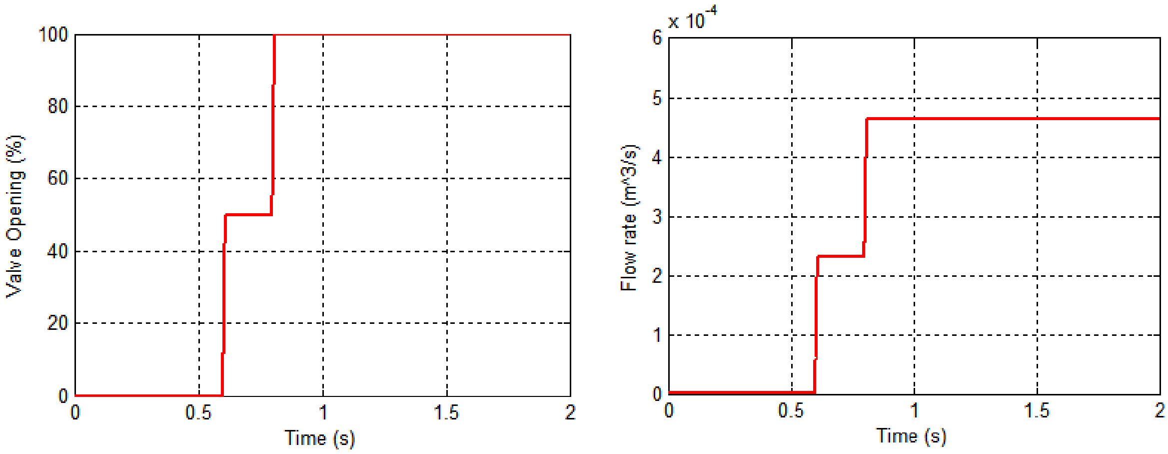


Fig. 6.28. a) Valve opening vs time, b) Flow rate vs time

6.3.5. Verification of the simulation results

A comparison between the simulation obtained results with experimental results has been performed to validate the proposed model. An experimental test has been carried out in University of Innsbruck. Aufleger et al. developed an experimental prototype known as "Powertower 1" (See Fig. 6.29). Since there is a difference in the system dimensions between our simulated case study and the experimental test, we have run another simulation with data from the experimental test done by Aufleger et al. [82].

The provided data about the system geometry are limited and include the height of the container which is equal to 2.2 m with a diameter of 0.6 m. The piston used is made of stainless steel and has a mass of 1500 kg. The dimensions of the experimental model are presented in Table 6.3 [82]. Using the available data, other input data were derived using physic theories. These data are shown in Table 6.4.

Other missing parameters have to be estimated in order to run the simulation. It has been assumed that the valve has a discharge coefficient of 0.611 and an opening area is equal to 2.32×10^{-4} m². To determine the friction losses, some parameters related to the sealing, O-ring, have been estimated. The cross section diameter of the sealing is 8mm while the mean diameter is 600 m. The elastic modulus of the O-ring material used is estimated as 5.52 MPA.

Table 6.3. Provided experimental data.

	Experimental Model
Container's height	2.2 m
Container's diameter	0.6 m
Piston Mass	1500 kg
Density	7850 kg/m^3
Pressure	4 mWs
Storage Capacity	3.5 Wh
Storage Power	40 W

Fig. 6.29. Power Tower Prototype [82]

Table 6.4. Derived data.

	Value
Piston height	0.67 m
Piston diameter	0.6 m
Water height	1.524 m
Return Pipe Height	2.2 m

Simulation results, which correspond to the discharging process of the system, are shown in Table 6.5. The piston moves inside the container with a velocity of 0.00452 m/s and takes about 336 second to reach its final position. The pressure inside the container (chamber B) is equal to 40.6 kPa. This high pressure is due to the water pressure and the piston load. The resulting friction and the hydraulic losses are presented in Table 6.5.

Table 6.5. Simulation Results.

	Value
Piston Velocity (m/s)	4.52×10^{-3}
Discharge time (s)	336
Pressure (kPa)	40.6
Flow Rate (m^3/s)	1.27×10^{-3}
Friction Loss (kN)	6.584
Minor Losses (Pa)	6838
Major Losses (Pa)	5036

To validate the proposed model, the results obtained from the simulated case study are compared to those obtained from experimental model. Time histories, which are illustrated as energy storage cycles of the system, are presented in Figure 6.30. There exists a small difference between the experimental and the simulated model which may be due to the estimated geometry parameters. The storage discharging time of the experimental model was derived from the available data which include storage capacity and power; it was found to equal 315 s. On the other hand, the results obtained from the simulated model shows that the piston takes about 336 s to reach its final position during a half cycle. This difference is expected because the system losses which include friction, minor and major losses were approximated using formulas from literature. In addition, it should be noted that the valve area has been estimated. A lower discharge time could be obtained if a higher valve opening area has been chosen. Therefore, a sensitivity analysis would be performed to investigate the impact of a change in the valve size on the system simulated results.

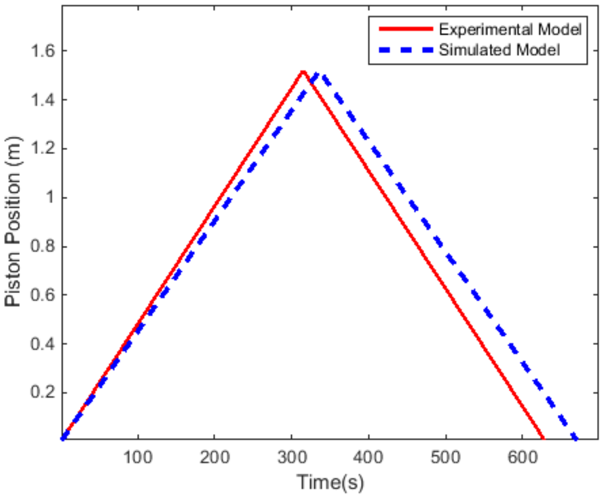


Fig. 6.30. Piston position

A comparison of the pressure course of both systems is shown in Fig. 6.31. The experimental pressure head is equal to 4 mWs which is about 39.2 kPA; while the simulated one is equal to 40.6 kPa. There is a small difference between the two compared results.

The liquid filling and emptying of the systems' chambers are shown in Fig. 6.32. Chamber A and B represents the areas that is above and below the piston, respectively. During the downward motion of the piston, the volume in chamber A increases with a decrease of chamber B volume. When the piston reaches its final positon, chamber B is completely emptied. This occurs at 315 s and 336 s for the experimental and simulated models, respectively. The difference in the presented curves is due to the discharging time difference of the two compared model. The simulated model takes more time to fill and discharge than the experimental one.

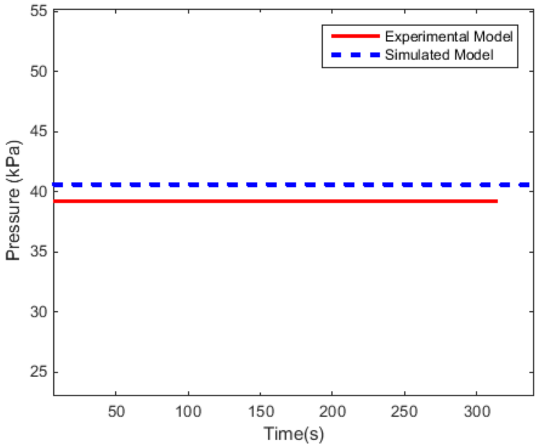


Fig. 6.31. System Pressure Head

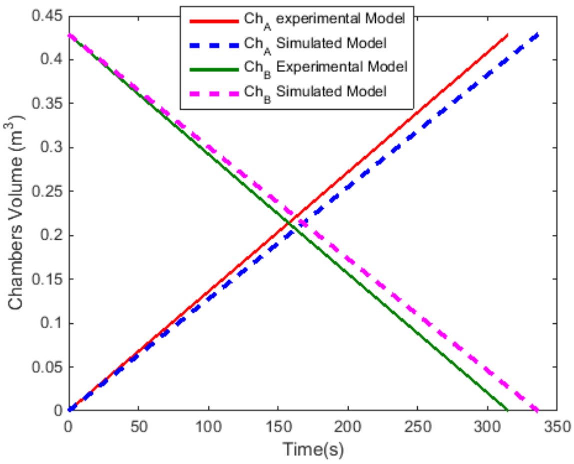


Fig. 6.32. Chambers' volume during piston downward motion.

The results obtained from the proposed simulated model are close those of the experimental model. % errors of the obtained results are presented in Table 6.7. The obtained errors may be due to the estimations done related to the model input parameters; especially those associated with the valve dimensions. To investigate the influence of the valve size on the system pressure and discharge time, scenarios with relatively large and small variation of the valve parameters are simulated. Fig 6.33 illustrates the effect of this change on the system performance.

It is shown that the valve opening area has a signifiant impact on the system pressure and discharge time. As the area is increased, the pressure is increased, while the dicharge time is decreased. In order to reduce the pressure % error between the experimental and simulated models, a smaller valve size is preferred. However, this latter will cause an increase in the dicharge time % error of the comapred models. From the performed sensitivity analysis, it could be deduced that the system dynamics is influenced by estimations done with respect to the valve size. In addition, a valve opening area of 2.32×10^{-4} m^2 used in the simulated model has lead to relativetly close results in compariosn with the experimental model.

Table 6. 6. Comparison of results.

	Experimental Model	**Simulated Model**	**% Error**

Time	315	336	6.2%
Pressure	39.2	40.6	3.4%

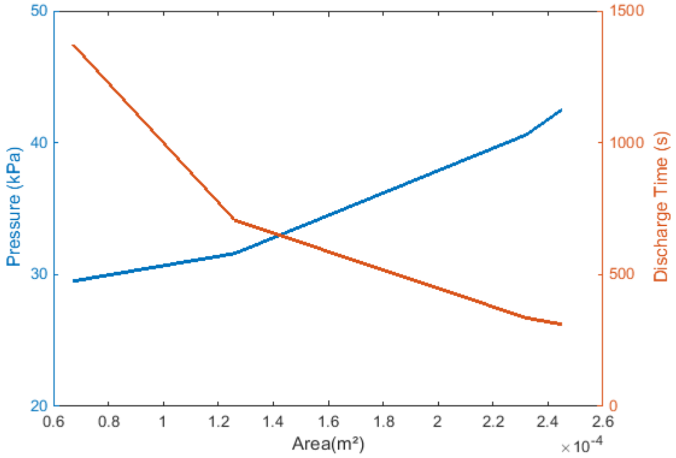


Fig. 6.33. Impact of valve opening area on the discharge time and Pressure.

Table 6.7. % errors with the variation of valve size.

Valve Diameter (in)	**Valve Opening Area $(10^4$ m$^2)$**	**Pressure %Error**	**Discharge Time % Error**
0.37	0.67	34%	77%
0.5	1.26	32%	55%
0.68	2.32	3.4%	6.2%
0.7	2.45	7%	1.2%

6.4. Sensitivity study and design considerations

6.4.1. Sensitivity analysis

In this section, a sensitivity analysis is performed in order to investigate the effects of assumptions used in different sources of inputs on the model outputs. Some parameters estimated in the carried out simulation are investigated further to observe their impact on the system behavior. These parameters include bulk modulus, valve discharge coefficient, friction and hydraulic losses coefficients, as well as piston mass. The objectives of this analysis are to test the robustness of the simulation results and to reduce the model uncertainty. This is accomplished by identifying parameters that have significant influence on the simulation outputs.

Since the model priority is about the system hydraulics, it is obvious that carrying out a sensitivity analysis on the flow hydraulic losses and valve discharge coefficient is crucial to reveal possible variations in the system dynamics. The piston mass can differ based on several design variations. A sensitivity analysis is performed on this parameter to observe the impact of this variation on the system which could lead to system optimization.

Various formulas to model the fluid effective empirical bulk modulus have been proposed in the literature. In this simulation, it is interesting to investigate the impact of the selected bulk modulus model. In addition, friction force is affected by various unknown conditions. Hence, it is also interesting to see if it affects the simulation outputs. Different scenarios with variation of these parameters were investigated in the sensitivity analysis. The different studied parameters are increased and decreased by 20% and 40%.

The obtained results are presented in Table 6.8. The impact of the valve discharge coefficient, bulk modulus, and hydraulic losses on the system flow rate is directly proportional to the change in these parameters. For example, a 20% variation in these parameters resulted in exactly 20 % change in the flow rate. As for the system pressure, the impact of the aforementioned parameters is very low and does not exceed 2%; even for high variation of these latter. However, the mass of the piston has a significant influence on the chamber pressure, while it has less impact on the flow rate compared to other parameters. Variation in the piston mass leads to significant change in the chamber dynamics; larger mass increases the pressure level.

Table 6. 8. Impact on system flow rate and pressure.

		Actual Value	**Increase of 20%**	**Increase of 40%**	**Decrease of 20%**	**Decrease of 40%**
% Change in Flow rate	**Discharge Coefficient**	3.40 ×10^{-4} m^3/s	20%	41.4%	-20.2%	-40%
	Hydraulic Losses		21.1%	42.9%	-20.2%	-40%
	Piston Mass		17%	31.7%	-20.2%	-48.2%
	Fluid Bulk Modulus		20%	41.7%	-20.2%	-40%
% Change in Pressure	**Discharge Coefficient**	4.31 kPa	0.92%	2%	-0.69%	-1.39%
	Hydraulic Losses		1.6%	3.94%	-0.9%	-1.62%
	Piston Mass		36%	72.85%	-36.42%	-73%
	Fluid Bulk Modulus		2%	2%	-0.69%	-1.39%

The flow rate is mostly affected by the flow hydraulic losses estimations followed by the fluid bulk modulus, the valve discharge coefficient, and finally, the piston mass. Concerning the pressure chamber, this latter is mostly altered by the variation of the piston mass, followed by the hydraulic losses, bulk modulus, and the valve discharge coefficient.

The performed sensitivity analysis demonstrated that the flow hydraulic losses are crucial parameters for the estimation of the system flow rate and should be carefully investigated. On the other hand, thorough identification of the piston mass is necessary as it is considered an important parameter for the determination of the system pressure. Even though, the other simulated parameters do not have major influence on the system dynamics, a sensitivity analysis was necessary to investigate their impacts. Moreover, valid assumptions of the different parameters are essential to avoid major errors related to the system dynamic behavior.

As mentioned before, it is difficult to estimate the friction force without experimental tests. However, using formulas available in the literature, it was possible to approximate this force. The friction force has an impact on the piston velocity. However, its influence decreases when this force is increased by 20-40% as illustrated in Table 6.9. Similar effects are observed for the flow rate. The pressure, on the other hand, is significantly affected by friction. This impact is greater than that caused by the above investigated parameters, expect for the piston mass. Therefore, friction force estimation affects the dynamics of the system significantly.

Table 6.9. Friction force variation impact on piston velocity, Flow rate, and pressure.

(% change)	**Actual Value**	**Increase of**	**Increase of 40%**	**Decrease of 20%**	**Decrease of**

		20%			40%
Piston Velocity	2.71	9.96%	15.8%	-14%	-31.3%
Flow Rate	3.40	10.2%	15.8%	-13.8%	-31.1%
Pressure	4.31	-15.5%	-31.5%	15.5%	31.5%

The dynamics of the system is influenced by estimations done related to the model input parameters. Therefore, theses parameters must be estimated carefully in order to develop a robust model. Fluid hydraulic losses, bulk modulus, valve parameters, as well as piston friction force and mass must be carefully selected by investigating the system properties and by using appropriate equations and assumptions from literature.

6.4.2. Design Considerations

The mass of the piston presses the fluid in chamber B which is underneath the piston. This will make the flow circulates toward the unpressed water which is located in chamber A. The least resistance path is always chosen by the fluid. Therefore, a sealing connection between the container walls and the piston has to be added in order to prevent the flow of water between the two chambers and guide the movement of the piston. To make sure that the pressured fluid does not leak between the chambers, a watertight closure is necessary. Seals made of plastic polymer in combination with a rubber O-ring, as well as composite seals which include a plastic polymer and a steel spring, are common solutions. Even under high pressure conditions, these sealing are watertight as they consist of O-rings made of self-energizing elastomer. This latter has to be made from incompressible materials that have high Poisson-ratio in order to accommodate the ring deformation. A regular replacement of the sealing is necessary to avoid the seal wear.

The sealing used between the piston and the container comes with some friction when the piston is moved upward and downward. This friction significantly impacts the total efficiency of the energy storage system. Plastic polymers sealing reduces the fiction between the container’s wall and the piston. An example of plastic polymers that could be used is Polytetrafluoroethylene (PTFE) which is characterized by high wear resistance and low elasticity. An integrated steel spring or energizing O-ring is required to overcome the material low elasticity. The surface roughness of the container walls should be low to reduce the seal wear and the friction. In this case, proper operation of the PTFE sealing requires a surface roughness less than 0.25μm [83]. Typically, the friction force is related to the roughness of the container, the pressure difference, and the velocity of the piston, as well as the shape, the size, the material, and the wear of the sealing used.

The total friction losses impact the system round-trip efficiency. These losses for a storage cycle which include the charging and the discharging of the energy storage system are expressed by Eq. 6.55.

$$E_f = 2\mu \int_{Z_2}^{Z_1} F_N dz \tag{6.55}$$

The magnitude of hydraulic energy losses which are caused by the entrance and the exit losses at the inlet and outlet of the pipe respectively, as well as friction losses, are related to the flow velocity as illustrated by Eq.47-49. To minimize these losses, larger pipes can be applied while designing the return pipe, in addition to minimizing the length of the pipe and the number of elbows and other fitting. As much as the piping system is restrictive, more energy is lost attempting to overcome these limitations. The surface roughness of the piping should also be reduced. In addition, reducing the friction coefficient of the valve and the pipe also minimizes these losses. Hydraulic losses have to be overcome by the extra power delivered by the pump. One other important consideration is the type of pump used to transport the fluid. To maximize the storage operational ability, it is important to optimally design the piping system and to effectively select the pump equipment that satisfies the system requirement.

The mass of the piston has an important impact on the pressure head of the storage system and hence significantly impacts the storage capacity of the system. The capacity of gravity energy storage is a function of the piston density as illustrated by Eq. 6.56. The optimal mass of the piston can be derived by making the height of this latter equal to half the container's height.

$$E_c = \frac{1}{4}\pi(\rho_p - \rho_w)d^2hgz\eta \tag{6.56}$$

6.5. Conclusion

The development of renewable energy systems is driven by the increasing concerns about climate change and energy security. Renewable energy systems are clean potential resources characterized by intermittent energy generation. To address the challenges faced by the integration of these sustainable energy systems, researchers are focusing on the development of energy storage systems. A novel gravity energy storage is investigated in this work.

In this chapter, the performance of gravity storage to support the use of renewable energies for energy supply has been analysed by simulation. For that, dynamic modeling of a hybrid system composed of a PV plant and gravity storage has been developed and an electric grid has been used to exchange energy between the hybrid system and the residential load. Gravity storage was used to balance the power and meet the load demand through discharging power and storing the excess energy from the PV system. Detailed mathematical models of the different system components developed by Matlab/Simulink, have been integrated into a single block diagram and discussed in the chapter.

A case study was undertaken to investigate the performance of the hybrid system and the accuracy of the models. The results of this case study demonstrate that the presented model is able to meet the load according to the proposed management strategy. The dynamic modeling of gravity storage mechanical components allowed for the investigation of system response to energy demand. The effect of load variation on generator parameters was also studied. It was observed that oscillations occurred in the stator current of the generator, the excitation voltage, and the generated power when the load was changed. In addition, it was shown that no oscillations occur in the terminal voltage and low oscillations are observed when the system approaches its steady state. These systems make use of similar mechanical equipment such as hydropower plants, and pumped hydro storage system. The developed model has the ability of representing real behaviors of the hydro turbine and the synchronous generator. To reduce the system oscillations, future work may focus on properly tuning the PID controller parameters.

This study proposed a mathematical model and simulation for hydraulic components of gravity storage. This model was developed by Matlab/Simulink; considering fluid flow properties, as well as system characteristics and requirements. A case study was carried out to investigate the performance of this system. The developed Simulink model functions like a virtual gravity storage system. Behavior of the system with respect to time was obtained without physically testing these components. The results reveal the dynamics of the system which include identification of crucial parameters. These parameters are the system discharge time, and the piston motion characteristics; as well as the chambers' pressure, volume, and flow rate. The numerical simulation results indicate that the storage discharge time is about 368 s. The system critical parameters are determined which include flow rate and pressure. These latter are equal to 3.4×10-4 m3/s and 43.1 kPa, respectively. The results obtained from the simulated case study are compared to experimental results of other researchers, and evaluated. The obtained % errors of the system pressure and discharge time are 3.4%, and 6.2%, respectively. The difference in the results obtained from the experimental and simulated models could be due to the derived and estimated input parameters, or due to the approximated system losses.

A sensitivity analysis was also performed in this work to evaluate the response of the system to changes in different parameters of the proposed simulation. It was important to conduct such study because some input parameters were estimated. Various scenarios with an increase and decrease of 20% and 40% of the estimated parameters were investigated to evaluate their impacts on the system flow rate, and pressure. The effect on the flow rate is proportional to the change of the valve discharge coefficient, bulk modulus, and hydraulic losses values. Concerning the system pressure, it is found that the piston mass has a significantly impact on the pressure. The outcomes of this analysis demonstrate that it is crucial to properly approximate the values of aforementioned parameters, especially those related to the system losses which include hydraulic losses and friction losses.

Important design considerations were discussed in this work. The obtained results show that the system efficiency depends on the type of sealing material used. In addition, hydraulic energy losses could be reduced by optimally designing the piping system and properly selecting the hydraulic valve and the pump. The energy capacity of the storage system could also be improved by optimally dimensioning the piston as this latter has a significant impact on the system pressure. These design considerations will result in a more cost-effective energy storage with less energy losses and reduced system maintenance.

References:

[1]. Albadi MH, El-Saadany EF. Overview of wind power intermittency impacts on power systems. Electr Power Syst Res 2010;80(6):627e32.

[2]. Smith JC, Milligan MR, DeMeo EA, Parsons B. Utility wind integration and operating impact state of the art. IEEE Trans Power Syst 2007;22(3):900e8.

[3]. Beaudin M, Zareipour H, Schellenberglabe A, Rosehart W. Energy storage for mitigating the variability of renewable electricity sources: an updated review. Energy Sustain Dev 2010;14(4):302e14.

[4]. Moura PS, De Almeida AT. The role of demand-side management in the grid integration of wind power. Appl Energy 2010;87(8):2581e8.

[5]. H Lopes Ferreira, R Garde, G Fulli, W Kling, J Pecas Lopes, Characterisation of electrical energy storage technologies / Energy 53 (2013) 288e298

[6]. JD. Maclay, J Brouwer, G. S Samuelsen Dynamic modeling of hybrid energy storage systems coupled to photovoltaic generation in residential applications / Journal of Power Sources 163 (2007) 916–925

[7]. C-H Li, X-J Zhu, G-Y Cao, S Sui, M-R Hu Dynamic modeling and sizing optimization of stand-alone photovoltaic power systems using hybrid energy storage technology / Renewable Energy 34 (2009) 815–826

[8]. Jayalakshmi N. S., D. N. Gaonkar, Anusree Balan, Prasanna Patil, Syed Adil Raza Dynamic Modeling and Performance Study of a Stand-alone Photovoltaic System with Battery Supplying Dynamic Load, International Journal Of Renewable Energy Research Vol.4, No.3, 2014

[9]. M Nemati, S Tenbohlen, M Braun, M Imran, Development of Generic Dynamic Models for Distributed Generators in Microgrids.http://www.unistuttgart.de/ieh/forschung/veroeffentlichungen/2013_Nemati_Development_of_Generic_Dynamic_Models.pdf.

[10]. AE Sarasua, MG Molina, PE Mercado, Dynamic Modelling of Advanced Battery Energy Storage System for Grid-Tied AC Microgrid Applications, Chapter 12 Energy Storage - Technologies and Applications, book published by Intech http://dx.doi.org/10.5772/52219

[11]. Majid Nayeripour, Mohammad Hoseintabar A Comprehesnive Dynamic Modeling of Grid Connected Hybrid Renewable Power Generation and Storage System, International Journal of Modeling and Optimization, Vol. 1, No. 1, April 2011

[12]. Marcelo Gustavo Molina (2010). Dynamic Modelling and Control Design of Advanced Energy Storage fo Power System Applications, Dynamic Modelling, Alisson V. Brito (Ed.), ISBN: 978-953-7619-68-8, InTech, Available from: http://www.intechopen.com/books/dynamic-modelling/dynamic-modelling-and-control-designof-advanced-energy-storage-for-power-system-applications

[13]. R Dugan, J Taylor, G Delille, Storage Simulations for Distribution System Analysis. Paper 1340, 22nd International Conference on Electricity Distribution Stockholm, 10-13 June 2013.

[14]. P Bazan, R German HYBRID SIMULATION OF RENEWABLE ENERGY GENERATION AND STORAGE GRIDS. Proceedings of the 2012 Winter Simulation Conference C. Laroque, J. Himmelspach, R. Pasupathy, O. Rose, and A.M. Uhrmacher, eds

[15]. N DiOrio, A Dobos, S Janzou, A Nelson, B Lundstrom Technoeconomic Modeling of Battery Energy Storage in SAM, Technical Report NREL/TP-6A20-64641 September 2015

[16]. Shaifi Asl S-M, Rowshanzamir S, Eikani M-H. Modeling and Simulation of Steady-State and Dynamic Behavior of a PEM fuel cell. Energy 35 (2010) 1633-1646.

[17]. Douglas T. Dynamic modelling and simulation of a solar-PV hybrid battery and hydrogen energy storage system. Journal of Energy Storage 7 (2016) 104–114

[18]. Yigit T, Selamet O-F Mathematical modeling and dynamic Simulink simulation of high-pressure PEM electrolyzer system. International Journal of Hydrogen Energy. 41(2016) 1301-13914.

[19]. Harish V-S-K-V, Kumar A. A review on modeling and simulation of building energy systems. Renew Sustain Energy Rev 56(2016)1272–1292

[20]. Wu J. Experimental investigation of the dynamic behavior of a large-scale refrigeration e PCM energy storage system. Validation of a complete model. Energy 116 (2016) 32-42.

[21]. Arabkoohsar A, Andresen G. Dynamic energy, exergy and market modeling of a High Temperature Heat and Power Storage System. Energy 126 (2017) 430-443.

[22]. Zhu J , et al. Design, dynamic simulation and construction of a hybrid HTS SMES (high-temperature superconducting magnetic energy storage systems) for Chinese power grid Energy 51 (2013) 184-192

[23]. European Commission (2017). Energy Storage-The Role Of Electricity. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/swd2017_61_document_travail_service_part1_v6.pdf .

[24]. J-P Maton, L Zhao, J Brouwer, Dynamic modeling of compressed gas energy storage to complement renewable wind power intermittency International journal of hydrogen energy 38 (2013) 7867-7880

[25]. Mazloum Y, Sayah H, Nemer M Dynamic modeling and simulation of an Isobaric Adiabatic Compressed Air Energy Storage (IA-CAES) system. Journal of Energy Storage 11 (2017) 178–190.

[26]. M. Saadat, F.A. Shirazi, P.Y. Li, Modeling and control of an open accumulator Compressed Air Energy Storage (CAES) system for wind turbines, Appl. Energy 137 (2015) 603–616.

[27]. De Jaeger E, Janssens N, Malfliet B, et al, Hydro turbine model for system dynamic studies, IEEE Trans. Power Syst. 9 (1994) 1709–1715

[28]. Singh, M., and Chandra, A. 2010. Modeling and Control of Isolated Micro-Hydro Power Plant with Battery Storage System. National Power Electronic Conference, Roorkee, India

[29]. Guo A-W, Yang J.D, Self-tuning PID control of hydro-turbine governor Based on genetic neural networks, Adv. Comput. Intell. 4683 (2007) 520–528

[30]. Pennacchi P, Chatterton S, Vania A, Modeling of the dynamic response of a Francis turbine, Mech. Syst. Sig. Process. (2011), http://dx.doi.org/10.1016/ j.ymssp.2011.05.012.

[31]. Bhaskar, M. A. 2010. Non Linear Control of STATCOM. IEEE Internaltional Conference on Recent Trends in Information Telecommunication and Computing, pp. 190-195.

[32]. Sanathanan C.K. Accurate low order model for hydraulic turbine-penstock, IEEE Trans. Energy Convers. EC-2 (1987) 196–200.

[33]. Hannett L.N, Feltes J.W, Fardanesh B. Field tests to validate hydro turbine-governor model structure and parameters, IEEE Trans. Power Syst. 9 (1994)1744–1751.

[34]. Jiang C.W, Ma Y.C, Wang C.M, PID controller parameters optimization of hydro-turbine governing systems using deterministic-chaotic-mutation evolutionary programming (DCMEP), Energy Convers. Manage. 47 (2006) 1222–1230.

[35]. Liu Y.J, Zhu X.M, Fang Y.J, Modeling of hydraulic turbine systems based on a Bayesian–Gaussian neural network driven by sliding window data, J. Zhejiang Univ. Sci. C 11 (2010) 56–62

[36]. Chen D, Ding C, Ma X, Yuan P, Ba D. Nonlinear dynamical analysis of hydro-turbine governing system with a surge tank. Applied Mathematical Modelling 37 (2013) 7611-7623

[37]. Shen Z.Y, Hydraulic Turbine Regulation, China Waterpower Press, Beijing, 1998 (in Chinese)

[38]. Fang H.Q, Chen L, Dlakavu N, et al, Basic modeling and simulation tool for analysis of hydraulic transients in hydroelectric power plants, IEEE Trans. Energy Convers. 23 (2008) 834–841.

[39]. Inayat-Hussain J.I, Nonlinear dynamics of a statically misaligned flexible rotor in active magnetic bearings, Commun. Nonlinear Sci. Numer. Simul. 15 (2010) 764–777.

[40]. Nanaware R. A., Sawant S. R, Jadhav B. T. Modeling of Hydraulic Turbine and Governor for Dynamic Studies of HPP. IJCA (2012)0975 – 8887

[41]. Fang HQ, Chen L, Shen ZY. Application of an improved PSO algorithm to optimal tuning of PID gains for water turbine governor. Energy Convers Manage 2011;52:1763–70.

[42]. Das S, Pan I, Das S. Fractional order fuzzy control of nuclear reactor power with thermal-hydraulic effects in the presence of random network induced delay and sensor noise having long range dependence. Energy Convers Manage 2013;68:200–18.

[43]. Zhu H, Huang WW, Huang GH. Planning of regional energy systems: an inexact mixed-integer fractional programming model. Appl Energy 2014;113:500–14.

[44]. Zhu H, Huang GH. Dynamic stochastic fractional programming for sustainable management of electric power systems. Int J Electr Power Energy Syst 2013;53:553–63.

[45]. Ozdemir MT, Sonmez M, Akbal A. Development of FPGA based power flow monitoring system in a microgrid. Int J Hydrogen Energy 2014;39:8596–603.

[46]. Chilipi RR, Singh B, Murthy SS, Madishetti S, Bhuvaneswari G. Design and implementation of dynamic electronic load controller for three-phase selfexcited induction generator in remote small-hydro power generation. IET Renew Power Generation 2014;8:269–80.

[47]. Chen DY, Ding C, Ma XY, Yuan P, Ba DD. Nonlinear dynamical analysis of hydro-turbine governing system with a surge tank. Appl Math Model 2013;37:7611–23.

[48]. Jiang CW, Ma YC, Wang CM. PID controller parameters optimization of hydroturbine governing systems using deterministic–chaotic-mutation evolutionary programming (DCMEP). Energy Convers Manage 2006;47:1222–30.

[49]. Xu Y, Li ZH. Computational model for investigating the influence of unbalanced magnetic pull on the radial vibration of large hydro-turbine generators. J Vib Acoust Trans ASME 2012;134:051013.

[50]. Kishor N, Singh SP, Raghuvanshi AS. Dynamic simulations of hydro turbine and its state estimation based LQ control. Energy Convers Manage 2006;47: 3119–37.

[51]. Zeng Y, Guo YK, Zhang LX, Xu TM, Dong HK. Nonlinear hydro turbine model having a surge tank. Math Comput Model Dyn Syst 2013;19:12–28.

[52]. Zhang H, Chen D, Xu B, Wang F. Nonlinear modeling and dynamic analysis of hydro-turbine governing system in the process of load rejection transient. Energy Conversion and Management 90 (2015) 128–137

[53]. De Jaeger, E., et al., Hydro turbine model for system dynamic studies. Power Systems, IEEE Transactions on, 1994. 9(4): p. 1709-1715.

[54]. Y. Oğuz, A. Kaysal, S. Köroğlu. Adıgüzel Hydroelectric Power Plant's Modelling and Load-Frequency Control by Fuzzy Logic Controller", Int. Journal of Engineering Research and Applications, Vol. 6, Issue 5, (Part – 5), pp.61-66, August 2016.

[55]. Vineesh V, Selvakumar A, Design of Micro Hydel Power Plant. Int. Journal of Engineering and Advanced Technology, Vol 2, Issue-2, December 2012.

[56]. Singh A. Modeling and Simulation of Micro Hydro-Diesel Hybrid Power System for Localized Power Requirement using Matlab/Simulink. Master Thesis. May 2013. Jadavpur University.

[57]. W. Li, L.Vanfretti, Y.Chompoobutrgool, Development and implementation of hydro turbine and governor models in a free and open source software package Simulation Modelling Practice and Theory 24 (2012) 84–102

[58]. Gencoglu, C. (2010). Assessment of the Effect of Hydroelectric Power Plants Governor Settings on Low Frequency Inter-area Oscillations, Ms Thesis, Middle East Technical University.

[59]. Sattouf, M. (2014). Simulation Model of Hydro Power Plant Using Matlab / Simulink. 6th EUROSIM Congress on Modelling and Simulation, 4(1), 295–301

[60]. Bhoi R and Ali. S. M (2014). Simulation for Speed Control of the Small Hydro Power Plant using PID Controllers. International Journal of Advanced Research in Electrical and Instrumentation Engineering, 3(4), 8392–8399.

[61]. Nassar, I. (2010). Improvements of Primary and Secondary Control of the Turkish Power System for Interconnection with the European System. PhD thesis submitted to Faculty of Computer Science and Electrical Engineering, Rostock University, Turkey.

[62]. L.G.anskas, A.Baranauskas, K. A.A. Gamage, M.Azubalis .Hybrid wind power balance control strategy using thermal power, hydro power and flow batteries. Electrical Power and Energy Systems 74 (2016) 310–321

[63]. R.A. Lone, Modeling and Analysis of Canal Type Small Hydro Power Plant and Performance Enhancement Using PID Controller. IOSR-JEEE 6 (2013) 06-14

[64]. D. Ramey, J. Skooglund, Detailed hydrogovernor representation for system stability studies, Power Apparatus and Systems, IEEE Transactions on PAS- 89 (1970) 106–112.

[65]. M.Sattouf, Data Acquisition and Control System Of Hydroelectric Power Plant Using Internet Techniques. (Doctoral Thesis). Retrieved From Brno University Of Technology

[66]. Gbadamosi S. L and Ojo O. Adedayo, Dynamic Modeling And Simulation Of Shiroro Hydropower Plant In Nigeria Using Matlab/Simulink. International Journal of Scientific & Engineering Research 6 (2015)

[67]. IEEE Standards Board, IEEE Recommended Practice for Excitation System Models for Power System Stability Studies, IEEE Std 421.5-1992.

[68]. S. Mcfadyen. Photovoltaic (PV) - Electrical Calculations. Available at: http://myelectrical.com/notes/entryid/225/photovoltaic-pv-electrical-calculations

[69]. Tan R, Chow T. A Comparative study of feed in tarrif and net metering for UCSI University North Wing Campus with 100 kW Solar Photovoltaic System.Energy Procedia 100 (2016) 86 – 91.

[70]. Tan R. (2016). PV Feed-in-Tariff and Net Metering Model, MATLAB Central File Exchange.

[71]. MATLAB/Simulink Release 2012b, The MathWorks, Inc., Natick, Massachusetts, United States.

[72]. Jelali, M., & Kroll, A. (2004). Hydraulic Servo-systems: Modeling, Identification and Control. London: Springer-Verlag London Limited.

[73]. Totten, G. (2000). Handbook of hydraulic fluid technology. New York, NY: Marcel Dekker, Inc

[74]. Ilango, S., & Soundararajan, V. (2012). Introduction to Hydraulics and Pneumatics (Vol.Second Edition). New Delhi: PHI Learning Private Limited.

[75]. Olsson H, Astrom K J, de Wit C C, Gafvert M, Lischinsky P. Friction models and friction compensation. European J. Control.

[76]. Samyn, P., Quintelier, J., Ost, W., De Baets, P., Schoukens, G., 2005. Sliding behavior of pure polyester and polyester-PTFE filled bulk composites in overload conditions. In: Polymer Testing 24.5, pp. 588-603.

[77]. Hyung-Kyu Kim et al. "Approximation of contact stress for a compressed and laterally one side restrained O-ring". In: Engineering Failure Analysis 14.8. Papers presented at the Second International Conference on Engineering Failure Analysis (Toronto, Canada, 12–15 September 2006) Part II, pp. 1680 –1692.

[78]. Kazutaka Yokoyama et al. "Effect of contact pressure and thermal degradation on the sealability of O-ring". In: JSAE Review 19.2 (July 4, 1997), pp. 123 –128.

[79]. Johnson KL. Contact mechanics. Cambridge: Cambridge University Press

[80]. Imnoeng, 2014. Moody friction Factor Calculation. LMNO Engineering, Research, and Software, Ltd. Retrived from. http://www.lmnoeng.com/moody.php.

[81]. Larock, B., Jeppson, R. and Watters, G. (2000). Hydraulics of pipeline systems. 1st ed. Boca Raton, FL: CRC Press.
[82]. Aufleger, M., Neisch, V., Robert Klar, R., Lumassegger, S.A., 2015. Comprehensive hydraulic gravity energy storage system eboth for offshore and onshore applications. In: E-proceedings of the 36th IAHR World Congress (Netherlands).
[83]. Robert Flitney. Seals and Sealing Handbook (Fifth Edition). Ed. by Robert Flitney. Fifth Edition. Oxford: Elsevier Science, 2007.

Chapter 7

7. System Improvement Using Compresseed Air

The use of energy storage has received increasing attention due to the rapid growth of renewable energy generation. Among all energy storage systems, pumped hydro energy storage and compressed air are mature and large scale commercialized technologies. Combining the working principles of these two systems, a new concept is proposed in this chapter, known as, compressed air gravity energy storage system. The feasibility of such technology has been analyzed in this study by modelling the system components. In addition, its characteristics have been explored to investigate the optimal design of such system. The energy production of this technology has been compared to that of gravity energy storage without the incorporation of compressed air. The obtained results demonstrate that the use of compressed air significantly improves the system storage capacity. Therefore, compressed air gravity storage could be considered an attractive solution to the integration of large-scale intermittent renewable energy.

7.1. System improvement

The growing interest in renewable energy is pushing the need for the development of energy storage technologies. Storing large quantities of energy is a challenging problem that has been addressed by several researches. Only few types of storage could be used in large scale application. Lithium-ion batteries are commonly used for electric vehicles or cell phones. Example of batteries that are suitable for utility scale applications include sodium sulphur, lead acid, nickel cadmium, and sodium nickel chloride [1]. In addition, the two well-known technologies used for large scale applications are pumped hydro and compressed air energy storage (CAES) [2]. However, both systems suffer from some disadvantages such as the limited geographical sites for pumped hydro storage (PHS), and the low efficiency of compressed air energy storage. To overcome the aforementioned issue faced by pumped hydro storage, a novel system, named gravity energy storage, is under development. Toward the improvement of this latter system, this chapter proposes the combination of gravity energy storage with compressed air.

Energy storage systems are considered hot research topics in the power industry field. Various useful ideas have been proposed by researchers and are now employed worldwide. A similar system combining pumped hydro and compressed air energy storage has been proposed by [3]. The system consists of a tank filled with gas and water, a reservoir, an air compressor, a pump/turbine and a motor/generator. The air compressor is used to compress air in the tank before the storage cycle begins. This gas is compressed further during the storage process as water is pumped from the reservoir to the tank. Another system has been investigated by [4]. The difference between this system and the aforementioned one is in the use of the high pressure tank. In this system, only compressed air is stored in the tank while the previous proposed system combines water with gas. Wang et al. [5]

explored the performance and working principle of this novel mixed energy storage. A thermodynamic analysis of this system has been presented by the authors. Yao et al. [6] performed an energy and exergy analysis for a constant-pressure pumped hydro compressed air system. The storage vessel pressure and the compressor efficiency have less impact on the exergy efficiency of the whole system. This latter could be improved by increasing the pre-set pressure in the high pressure vessel, or by enhancing the operating efficiency of the pump/turbine. In addition, it has been found that the water-air volume ratio has no influence on the system efficiency and the exergy efficiency. Bi et all [7] presented a mathematical model to analyze the storage and generation processes of pumped hydro compressed air system. Storage power calculations of both isothermal and adiabatic compression processes were investigated. Kim et al. performed an energy and exergy analysis of a constant-pressure compressed air energy storage system combined with pumped hydro storage to understand the system operating characteristics [8].

Even though a significant number of literature is available discussing the combination of pumped hydro and compressed air energy storage, few if any investigated the design and the performance of compressed air gravity energy storage system.

This work is organized as follow. Section 2 presents the physical model and its working principle. In section 3, the proposed system has been modeled in order to obtain an optimal design of the system. The results obtained from the performed simulation are discussed in section 4. The characteristics of this system with a comparison to PHS and CAES are presented in section 5. Finally, section 6 closes the chapter.

7.2. System Description and Working Principles

Pumped hydro energy storage is a commonly used storage technology. The system consists of a lower and an upper reservoir connected to a reversible pump-turbine and a motor/generator. Excess electricity is used during off-peak periods to store energy by moving water from the lower to the upper reservoir. During peak hours, energy is generated by releasing water from the upper reservoir to the lower one. The most crucial issue facing this storage system includes the geological conditions as it requires a high difference between its two reservoirs. As a substitute to pumped hydro storage in terms of bulk energy storage, CAES is considered a promising technology with economic feasibility and high reliability [9]. Off-peak electricity is used by CAES to compress air. This latter is then stored in underground cavern or aboveground vessels. During peak periods, the stored air is used to produce electricity through turbine-generator after being heated and expended.

A good solution to overcome pumped hydro storage limitation is the development of gravity energy storage. An improvement of gravity energy storage technology is investigated in this chapter. The proposed system is a combination of gravity storage with compressed air. This is an interesting approach to increase the water pressure. In addition to gravity storage components, a pressure vessel with an air compressor has been added to form the proposed system. Combining the aforementioned equipment results in a system named compressed air gravity energy storage. The addition of high air pressure is equivalent to increasing the height difference in PHS. For instance, adding a 1 MPa air pressure is equivalent to raising the water by 100 m. In this manner, energy is stored in compressed air and released in the discharging mode of the storage. Compressed air gravity storage solves some of the problems encountered by bulk energy storage such as compressed air energy storage and pumped hydro storage. The proposed system does not consume fossil fuel, or require specific siting (height difference). In addition, it does not make use of gas turbine and air turbo- expander. Moreover, it is more efficient and effective to use hydro turbine in terms of reliability.

7.3. System modeling and Design

A schematic of compressed air gravity energy storage is shown in Fig. 7.1. The volume of the air tank is V_1, and its initial preset pressure is (P_1). This latter is compressed by the gas compressor before the storage stage. During the storage charging mode, excess energy is used to pump water into the container. During this process, the air volume decreases. Hence, the pressure of air is increased as this latter is being compressed by the pumped water. The compressed air reaches a maximum pressure P_2 which is the withstand pressure value of the container. At that time, the air volume is V_2. During the generation mode, the high pressured air pushes the piston down which applies a high pressure on the water. The pressured water passes through the turbine driving the generator which produces electrical energy.

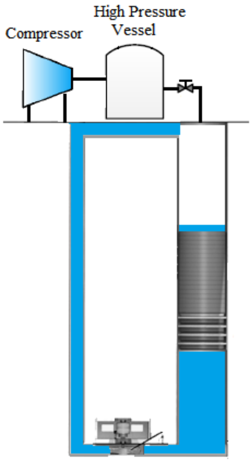


Fig. 7.1. Compressed air gravity energy storage schematic.

The maximum storage capacity is obtained if air is compressed to a maximum pressure value P_2. In addition, the energy released by the storage is also dependent on the compressed air volume (V_2). An investigation of the system withstand pressure and air-water ratio should be performed in order to maximize the storage capacity. The relationship between compressed air volume, preset and withstand pressures, and the energy released is discussed in this work.

To estimate the energy capacity of compressed air gravity storage, the amount of energy stored in the compressed air part (E_a) and hydraulic part (E_h) by gravity storage should be identified. Therefore, the energy equation of compressed air gravity energy storage (E_t) can be expressed as:

$$E_t = E_a + E_h \tag{7.1}$$

Authors in [7] proposed mathematical models to determine the optimal capacity of compressed air pumped hydro energy storage. The presented models were deduced from different compression situations which include isothermal and adiabatic.

The isothermal compression occurs when the system temperature remains constant while the air compression is very slow. However, if this latter occurs very rapidly and there is a change in the air temperature, the compression process is adiabatic. In compressed air gravity storage system, air is compressed before the start of the storage cycle by the compressor; then it is compressed further during the storage mode by the water pumped into the container. The container is considered a good heat conductor and the compression of air occurs very slowly. Therefore, it is assumed that the compression process of this system is isothermal. Authors in [5] have shown that the compression process of compressed air pumped hydro energy storage should be recognized isothermal since water temperature does not change much (less than 5 °C).

Using the isothermal process, the storage capacity in the generation model, is expressed as [7]:

$$E_a = \int_{V_2}^{V_1} P_x dV_x \tag{7.2}$$

Where P_x and V_x are the pressure and volume of air in the container. After discharing all the water from the container, the energy generation process is over. Therefore, the energy released is given by:

$$E_a = P_2 V_2 \ln(\frac{V_1}{V_2}) \tag{7.3}$$

Authors in [7] identified the maximum energy that could be generated from a vessel with a capacity V_1 and a maximum pressure P_2, by deriving the energy equation (Eq. 7.3) to V_2 and setting it equal to zero. The results obtained identify the system different parameters such as preset pressure (P_1), and air volume (V_2) in the discharging mode. These parameters are expressed as:

$$\begin{cases} P_1 = \dfrac{P_2}{e} \\ V_2 = \dfrac{V_1}{e} \end{cases} \tag{7.4}$$

Where e is a constant and is equal to 2.72. P_1 is the initial preset pressure and is derived from the tank maximum withstand pressure (P_2). V_2 is the volume of air when it is compressed to the maximum pressure P_2.

The energy delivered by compressed air is the product of the air volume inside the container with its pressure. The maximum released energy (E_a) is given as:

$$E_a = P_2 \frac{V_1}{e} \tag{7.5}$$

For the hydraulic part, the amount of energy stored in gravity energy storage is expressed as:

$$E_h = (\rho_p - \rho_w)(\frac{1}{4}\pi d^2 h)gz\eta \tag{7.7}$$

Where ρ_p and ρ_w are the density of the piston and water, respectively; D, and h are the container diameter and the piston height, respectively; g is the gravitational acceleration (m/s²); z is the elevation high (m); and η is the efficiency.

The energy equation of compressed air gravity energy storage is given by:

$$E_t = P_2\frac{V_1}{e} + \left[(\rho_p - \rho_w)(\frac{1}{4}\pi d^2 h)gz\mu\right] \tag{7.8}$$

7.4. Simulation

To investigate the performance value of compressed air in gravity energy storage system, a simulation has been carried out on a sample geometry; where the height of the container is 500 m. The diameter of this latter is 5.21 m and the piston height is half the container's height. The container maximum pressure depends upon the design and material construction of the tank. In this case study, a withstand pressure of 10 MPa has been used.

The system design parameters which include the maximum allowable pressure, container's volume, and air-water ratio influence the total energy production of compressed air energy storage. Therefore, the main objectives of this simulation is to investigate the optimum air-water ratio pressure in the container; to visualize the effect of the storage parameters (height, withstand pressure, and diameter) on the storage generated energy; and to determine and compare the energy production of gravity storage with and without the use compressed air.

7.4.1. Effect of water-air ratio on storage capacity

Energy production vs air-water ratio in the container is illustrated in Fig. 7.2. It is shown that an increase in this ratio leads to an upward trend in the energy delivered by the storage system. Maximum energy capacity is reached when the air -water ratio is maximized. This results in a capacity of 23 MWh when this ratio is equal to 1. Therefore, designing a system with compressed air representing half of the container's size would optimize the system capacity. This system is shown in Fig. 7.3. It is to be noted that the piston constitutes the other half of the container's size. In this case, the return pipe should not be linked to the container, and should have a diameter equal to half the container's diameter in order to hold the discharged water.

It is important to design a system with high withstand pressure, and maximum air –water ratio in order to improve the system performance. Good prospects have been shown for the potential storage capacity of compressed air gravity energy storage. An interesting amount of 23 MWh could be stored in this system rather than 19.88 MWh which represents the actual capacity of gravity storage without the inclusion of compressed air.

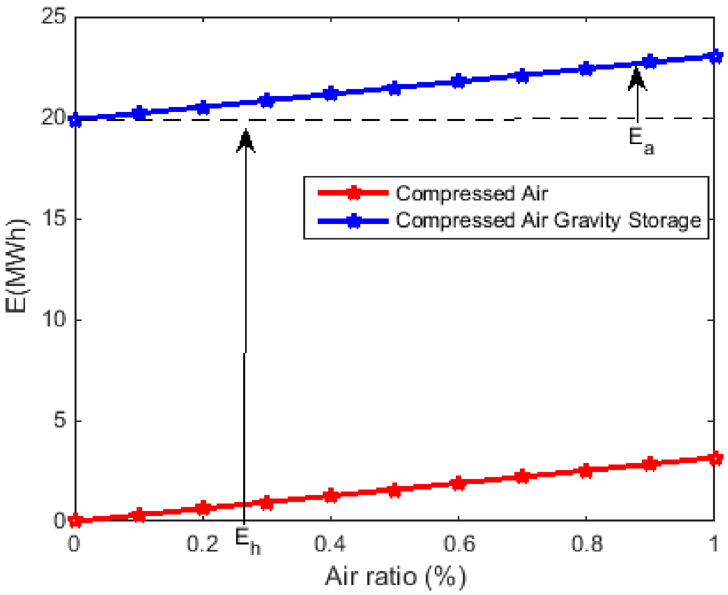


Fig. 7.2. Energy released according to air-water ratio.

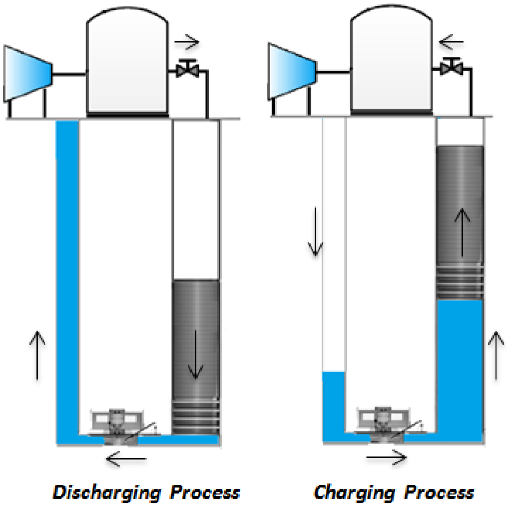


Fig. 7.3.Compressed air gravity storage optimal system

7.4.2. *Effect of container height on storage capacity*

It is important to investigate the effect of height on the system storage capacity. Applying this system on a large scale application requires constructing a system with a high container's height. However, the excavation costs increases with depth. In addition, an increase in excavation unit costs would add a major cost and would significantly increase the system construction cost. An alternative solution to increasing gravity storage height would be the incorporation of compressed air.

When changing the height of the container, the variation of the system capacity is obtained (See Fig. 7.4). An increase of the container's height results in large energy storage production. This increase is more significant if the system is combined with compressed air.

As illustrated in Fig. 7.4, with the addition of compressed air to gravity storage system, one could reduce the height of the system while keeping the same energy production. For example, gravity storage with a height of 500 m results in an energy production of 19.88 MWh; adding compressed air to the system while reducing its height to 450 m would results in the same energy production. Therefore, the incorporation of compressed air in this case is equivalent to reducing the height by 50 m.

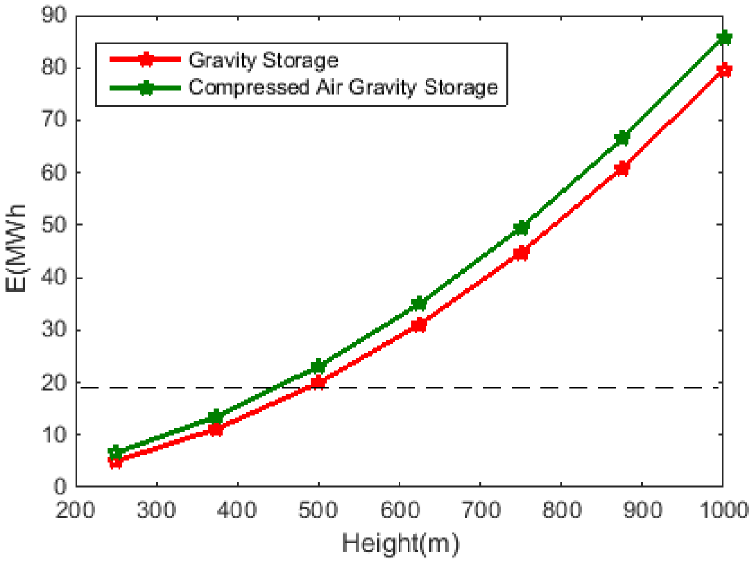


Fig. 7.4. Energy released according to the container's height.

It is interesting to compare the energy delivered by gravity energy storage with and without the addition of compressed air. A Combination of gravity storage with compressed air results in a larger energy storage capacity.

7.4.3. *Effect of container pressure and diameter on storage capacity*

The container withstand pressure has a significant influence on the energy released by the whole system. As illustrated in Fig. 7.5a, the energy capacity of the storage system is increased linearly with increased pressure. The capacity reaches 26.21 MWh with maximum withstand pressure of 20 MPa. On the other hand, the energy capacity of gravity energy storage without the addition of compressed air is about 19.88 MWh which is less than the energy obtained for the compressed air gravity system. Therefore, a combination of compressed air with hydraulic power generation, would considerably improve the potential amount of energy generation. In addition, designing a system with high allowable pressure, would increase the energy capacity of this latter.

The energy production of compressed air is a function of the air pressure and volume. The aforementioned parameters are both dependent on the container's diameter. However, the container allowable pressure and diameter have an inverse relationship; as the pressure is increased, the system diameter is decreased. While the dependence between pressure and diameter is to the power one, the power dependence relation between volume and diameter is two. Therefore, greater potential energy is obtained with larger diameter than higher pressure. The effect on the container's diameter on the storage capacity is illustrated in Fig. 7.5b. It has been assumed that the withstand pressure remain constant as the diameter is increased.

For large scale gravity energy storage systems, an interesting amount of energy could be added from compressed air. Fig. 7.6 illustrates the amount of energy that could be released from the addition of compressed air to gravity storage systems. For example, combining gravity storage with compressed air would results in an addition of 223 MWh to a system of 2.8 GWh.

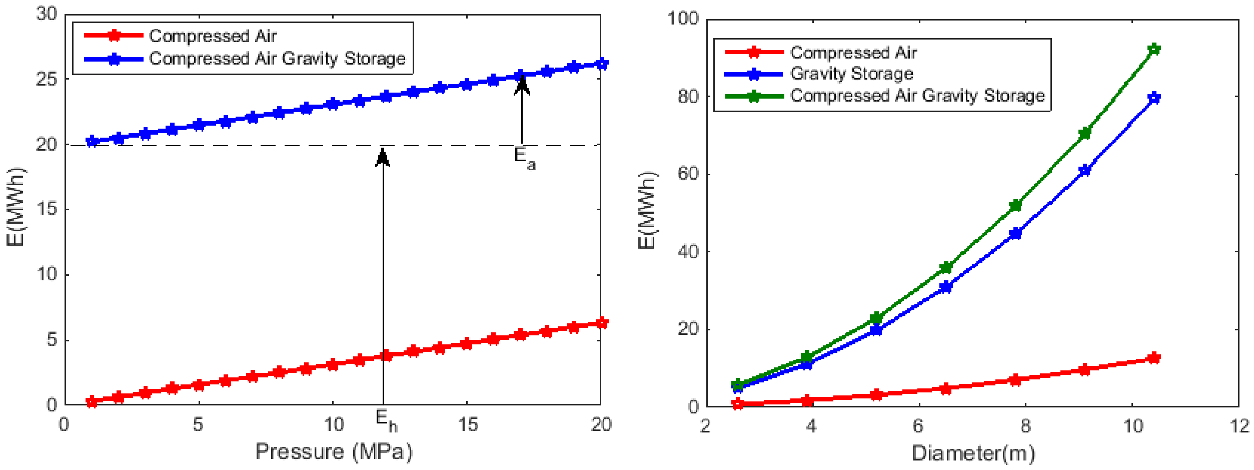


Fig. 7.5. Energy released according to a) a variation in the withstand pressure, b) container's diameter

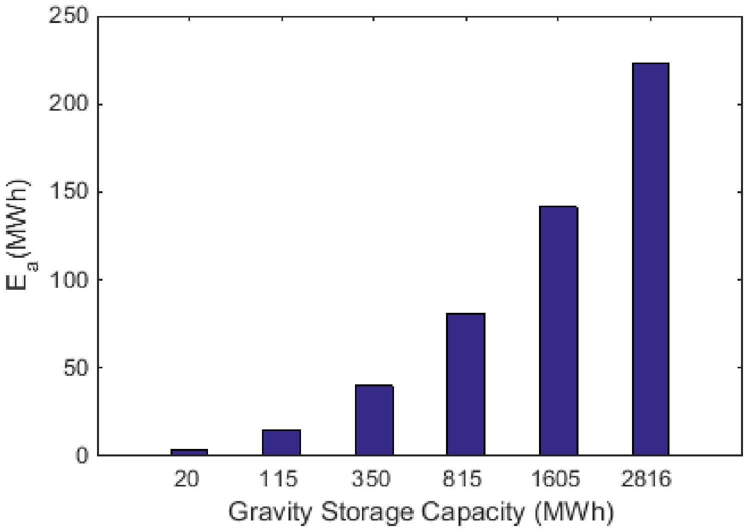


Fig. 7.6. Energy from compressed air according to different Sizing of Gravity Storage

7.5. System characteristics

Compressed air gravity energy storage could be considered an interesting technology because of the benefits it offers compared to CAES and PHES. As for its comparison with CAES, the system structure is simple; it does not require cooling and heating processes. In addition, the system efficiency is expected to be similar to PHS efficiency since the system requires similar equipment used by PHS. The efficiency of the water pump/turbine is higher than the expander efficiency used by CAES.

The use of hydraulic equipment provides the system with a number of advantages compared to the traditional CAES system. These include a quick start-up; ability to stabilize the electric grid by providing frequency and voltage regulations; and the capability to provide services such as spinning reserve.

The cost of the system is also expected to be lower than that of CAES as compressed air gravity storage does not need a heater/cooler. In addition, the costs of hydraulic equipment are less than the cost of the expander as compared in Table 7.1.

Finally, compressed air gravity energy storage does not require specific topographic conditions and large water supply compared to PHS.

Table 7.1. Equipment cost [10,5].

Equipment	**Cost ($/kW)**
Expander	220
Low Pressure Expander	140
High Pressure Expander	60
Compressor	84
Heat Exchanger	33
High Pressure Vessel	75
Hydro Turbine	95
Pump	47

7.6. Conclusion

An analysis of compressed air gravity energy storage has been presented in this chapter. The system working principle and characteristics have been discussed in details. A model has been used to calculate the storage energy capacity. It has been found that the container diameter and height influence the amount of potential energy capacity. In addition, increasing the withstand pressure increases the energy production of the system.

The energy capacity of the compressed air gravity storage could be improved by increasing the air-water volume. Maximization of the storage capacity would set this ratio equal to 1. In other words, the volume of air in the container should be dominant and equal to half the container's volume. The compressed air gravity energy storage demonstrates good prospects for the amount of potential storage capacity. A relatively large amount of energy could be stored with the combination of compressed air and gravity energy storage.

References:

[1]. H. Chen, T.N. Cong, W.Yang, C.Tan, Y. Li, Y. Ding. Progress in electrical energy storage system: A critical review. Progress in Natural Science 19 (2009) 291–312

[2]. D.O. Akinyele, R.K. Rayudu. Review of energy storage technologies for sustainable power networks. Sustainable Energy Technologies and Assessments (2014); 8, 74-91.

[3]. H. R. Wang, "Water-gas Encompassing Electric Power," Energy Storage System: CN, 102434362A [P/OL]. 2012- 05-02[2013-01-23]

[4]. EBO Group, Inc., Compressed Air Pumped Hydro Energy Storage and Distribution System: US 7281371 B1 [P/OL]. 2007-10-16 [201-01-23].

[5]. H.R. Wang, L.Q. Wang, X.B. Wang, E.R. Yao, A novel pumped hydro combined with compressed air energy storage system. Energies 2013, 6, 1554–1567.

[6]. E. Yao, H. Wang, L. Liu and G. Xi, A Novel Constant-Pressure Pumped Hydro Combined with Compressed Air Energy Storage System. Energies 2015, 8, 154-171; doi: 10.3390/en8010154

[7]. J. Bi, T. Jiang, W. Chen, X. Ma, Research on Storage Capacity of Compressed Air Pumped Hydro Energy Storage Equipment Energy and Power Engineering, 2013, 5, 26-30

[8]. Kim, Y.M.; Favrat, D. Energy and exergy analysis of a micro-compressed air energy storage and air cycle heating and cooling system. Energy 2010, 35, 213–220.

[9]. A. Cavallo, Controllable and affordable utility-scale electricity from intermittent wind resources and compressed air energy storage (CAES). Energy 2009; 32:120-7

[10]. E. Drury, P. Denholm, R.Sioshansi, The value of compressed air energy storage in energy and reserve markets. Energy 36 (2011) 4959-497

Chapter 8

8. Policy Consideration and Future Prospects

There is no doubt that energy storage systems increase the integration of variable renewable energy sources, and reduce greenhouse gas emissions. As discussed in chapter 1, there are currently a number of energy storage systems that have been successfully developed such as pumped hydro storage, thermal system, and compressed air energy storage. These systems have been proven for their availability and reliability. Other storage systems, such as batteries have seen great improvement and advance in their field. In spite of all these progresses, energy storage technologies are still facing significant challenges.

8.1. Energy Srorage Worlwide

The economical aspect of energy storage is one of the main challenges faced by these systems. Several factors influence the economics of energy storage which make it difficult to evaluate. These include the system size, application, type, and location [1]. In addition, energy storage technologies are still very expensive. Their costs have to decrease in order to be economically viable and attractive. The capital cost of energy storage consists of costs of per unit of energy capacity ($/kWh) and per unit of power ($/kW). Some storage systems have low capital cost per unit of power but high cost in energy capacity such as flywheel and supercapacitors. Others systems such as PHS and CAES have low cost per unit of energy but high capital costs per unit of power. The storage costs include also the system operating cost which consists of energy-related and non-energy related operating cost [2]. The energy related costs is about the cost of energy used to charge the system and the cost to purchase power used to make up for the energy losses due to the system round trip efficiency. The non-energy related costs compromise the cost of labor associated with plant operation, maintenance cost, frequency of charging and discharging cycles, equipment depreciation cost, and all costs associated with decommissioning and disposal [2]. The aforementioned costs vary widely from one storage system to another, in addition to the storage system size. For instance, operating large scale CAES and PHS require costs associated with labor, while battery used for small scale may not require these costs as they are designed to operate autonomously. In general, the most cost-effective technologies for large scale storage are CAES and PHS with frequent cycles. When the number of cycles is low, batteries are expected to be the cheapest option, whereas supercapacitors and flywheel are more ideal for frequent use and very short periods [1].

Another challenge faced by these technologies is associated with the system efficiency. The challenge lies in investigating and identifying methods to improve energy storage efficiencies. In real life applications, PHES have a round trip efficiency of 72–75% while its theoretical prediction demonstrates that it can achieve an efficiency of 90%.

The third challenge is related to the lack of standard for the physical connections of energy storage technologies to the grid. In addition, some storage systems still suffer from the difficult and complexity of being developed in a modular design. This later helps to promote the flexibility that the system provides. It enables for better optimization of the system behavior in response to varying conditions. Batteries are an example of storage systems that are modularized and standardized. For a better prosper of energy storage, there is a high need for policy support from the government.

The development of energy storage systems has lagged far behind the growth of intermittent renewable energy sources. To accommodate the variability of these resources, several flexibility methods are being tapped more extensively. Emphasis is being given to cost-effective ways such as demand side management and market efficiencies. However, with the high penetration of renewable energy sources, power systems have to include other flexibility ways beyond what may be available today. This should be done in a reliable, economic, and environmental manner.

Competition on efficiency and price are considered the main barriers reasonably faced by developers. However, it is essential to analyze policies that obstruct the development of energy storage, and investigate new policies required to overcome unnecessary obstacles to the cost-effective deployment of energy storage.

Changes in policy should be considered in four areas which include energy storage valuation and markets, regulatory actions, system development risk, and standardization [3]. Important efforts are currently underway to address some of the obstacles encountered by energy storage. Opening ancillary service markets to energy storage system are tackled by the Federal Energy Regulatory Commission (FERC) orders (755 and 784). Policies are being executed for implementing these orders to encourage the development of energy storage. These policies are considered a huge step forward for energy storage.

8.1.1. Valuation and Markets

The most significant barrier facing the development of energy storage is the incapability of quantifying the multiple value streams provided by this latter to the electric grid [4]. The real value of energy storage is not based only on the difference between purchasing energy at low price and selling it at higher prices. It is rather associated with all the services they provide including ancillary services; regulation and load following reserve; as well as transmission and distribution system support. Energy storage brings other benefits such as low or zero emissions, rapid response, and bi-directionality of reserve capability [3].

Before the initiation of restructured markets in the US, only two types of services were usually considered while valuating energy storage. These include load-leveling and firm capacity. The valuation of other benefits such as ancillary services was rarely performed. This is mainly due to the limitations of capacity-expansion and simulation software used by utilities in regulated markets [4]. The advent of restructured markets and the initiation of ancillary service markets have resulted in the valuation of some services such as fast response services which are provided by certain types of energy storage systems. Yet, the deployment of batteries and flywheels was mostly located in regions with restructured markets in order to perform frequency regulation reserves services. For example, the development of a 1 MW battery in PJM market and a 3 MW flywheel project as well as a 20 MW plant in the New York ISO market. These projects were made possible mostly by the Federal

Energy Regulatory Commission (FERC) issued Order (890) which required wholesale markets to consider non-generation resources such as energy storage for electric grid services. Consequently, several market operators have proposed new tariffs enabling energy storage to participate in ancillary markets. Policies associated with standard utility valuation should compromise other values brought by energy storage. Ancillary services markets have been in operation for a long time in (CAISO) California Independent System Operator (CAISO), and were generally irrelevant to total market value. However, because of the efforts placed on improving the quality of frequency regulation and response, they have attracted more attention.

As discussed in chapter 4, storage can potentially provide a large number of services, and many of the values could be generated in existing restructured markets. Some of the benefits provided by energy storage are shown in Fig. 8.1.An important issue with the valuation of energy storage is that most studies and analysis examine only one or two storage applications. For example, the published works which focus mainly on energy arbitrage [5-11] usually conclude that this service is unlikely to support the high investment costs of most energy storage systems. As a contrary, work of studies which include other services [11] such as providing ancillary services demonstrate that among different ancillary services, regulation is considered the most valuable, followed by spinning and non-spinning reserves. Therefore, as previous noted maximizing storage value will likely require multiple value streams.

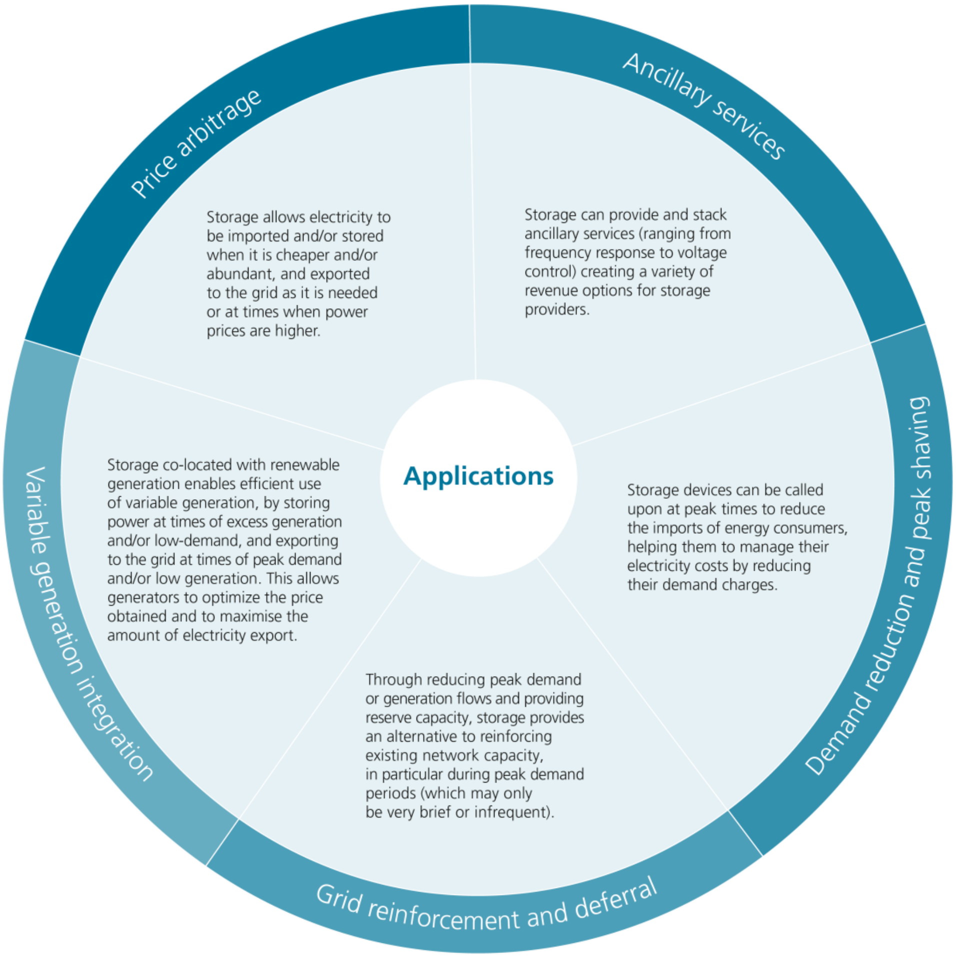


Fig. 8.1. Energy storage applications.

8.1.2. Regulatory Treatment

In a traditional regulated market, “prudent” and reliable generation, transmission, and distribution investments are rate based by utilities. In a similar manner, storage systems are also rate based if they are shown to be the least-cost alternative to offer a service. However, this is difficult to do in reality because of the inability of the standard capacity expansion tools to accurately value energy storage. An asset is classified traditionally in restructured markets as either generation, transmission, or distribution. Investment in storage presents challenges because of its hybrid operation. Whether investment costs are recovered through the market or rate base is dependent on this classification, and this poses barriers for energy storage systems because they can have all of these characteristics. The absence of a regulatory definition of energy storage has resulted in its classification as a generation asset [12]. The value of energy storage is underestimated by this treatment because it neglects its capability to perform multiple services.

Techniques used to evaluate energy storage are becoming available, but they are still not commonly used. In addition, ancillary services are not recognized completely or well defined by regulators. Treatment of emissions is another aspect which should be considered in the regulatory environment. In the past, regulators and utilities concentrated on environmental compliance. Environmental regulation associated with carbon dioxide emissions is still at an early phase. Carbon pricing has been approved by some utilities while considering competing resource expansion decisions. Example of explicit expressions of carbon cost that may be taken into account is the California’s cap and trade system, and British Columbia’s carbon tax. The regulation of carbon emissions has been tackled also by the environmental protection agency.

The path towards reduced carbon emissions is well defined and some utilities are becoming more worried about the risk of future strict carbon emission regulation. A higher share of renewable energy accompanied with energy storage would be driven by expected reduction in fossil fuels use and cost of renewable energy resources.

The use of energy storage systems as an alternative to transmission line expansions for addressing congestion is one of the most interesting value of energy storage. In USA, Regional transmission planning entities have been formed following FERC’s Order 1000 in 2011 which recognized the requirement for a better coordination among generation planning and transmission. However, those efforts are still at an early phase. Better communication between transmission planning functions and generation expansion is necessary or perhaps should be mandated by regulations.

8.1.3. Development Risk

Energy storage development risk is increased by the uncertainty and inability to reflect the real value of these systems. Potential new market entrants are also discouraged by this risk. Reasonably more complicated valuation approaches needed to reflect energy storage prudency to regulators would discourage utility planners and management. The dependence on market prices in emerging markets for new services increases the uncertainty for recovering capital-intensive costs. The highly variable markets associated with arbitrage value for ancillary services and energy shaping adds more uncertainty to the recovery of capital cost. Energy storage value may be mainly based on the provision of energy arbitrage and ancillary services, as well as the reduction of greenhouse gas emissions. The reliance on these sources of revenue adds risk to energy storage projects. In addition, the actual regulatory treatment of storage adds more risk to the deployment of new energy storage system. This latter suffer from a lack of incentives in regulated markets.

Although regulatory risk and market are important challenges, technology risks are also considered a significant issue for storage deployment. A number of storage technologies appear to be technologically viable, but they suffer from developers' reluctance which has led to a delay in the development of these systems. For example, the construction of a second CAES plant in the US has not yet occurred even though the operation of McIntosh CAES plant is successful and reliable. One of its main barriers is geologic requirement [4].

The development risk is affected by the aforementioned uncertainties. These latter also discourage third party development. Therefore, these risks should be addressed. In addition, their share between power system participants should be known. It is important to spread these risks among the potential beneficiaries, and to reduce them where possible. In order to encourage an accurate development, policies should be implemented to manage risks. Policies used to overcome obstacles or encourage the development of energy storage are examples of mechanisms for risk handling.

The development of small but significant scale of energy storage inspects and provides a market over which project proposals and systems may compete. The development risk would be left open with a loss of opportunities and technologies undeveloped if some level of development has not been tried. However, there should not be an over-development of energy storage technologies at the expense of other potential alternatives such as demand management and renewable generation control strategies. A balance among the different existing strategies should be adopted, particularly with respect to system-specific incentives, in order to allow the implementation of competing alternatives.

Examples of mandates which have an impact on minimizing energy storage development risk are the California's and Puerto Rico Energy Authority's policies [13]. The development of cost effective energy storage is mandated by California. In addition, the policy of Puerto Rico Energy Authority states that the deployment of new PV resources should be complemented by energy storage to maintain frequency control and system reliability. These two policies have an aim to evaluate the need for energy storage.

8.1.4. Industry Acceptance and Standardization

A boarder adoption of energy storage systems is faced by a key challenge associated with utility industry acceptance. Requirements set by regulators tend to create a high degree of caution among utilities in implementing new technologies.

8.1.4.1. Lack of Standardized Controls and Interfaces

The lack of standardized interfaces and controls is considered a significant obstacle to industry acceptance of energy storage. This is considered a technical challenge that may have policy implications. Policies to work across systems and utilities in order to develop standardized interfaces may be anticipated. National Institute of

Standards and Technology (NIST) is working on standardization. This latter is also addressed by the International Electrotechnical Commission (IEC). Recommendations stated by IEC include [14]:

“The development of energy storage management systems which enables the utilization of single storage in a variety of applications discussed in the IEC study. Management and controllers systems are necessary and should operate independently of the battery type being controlled. In addition, the functioning of the control system should be open to other applications which belong to other actors such as end-use supplier, grid operator, and consumer.”

There exist various IEC standards for mature energy storage systems such as PHS, Li-ion, lead-acid batteries. These standards include technical features, integration, and testing. There are only a few standards for the other storage options. Up to now, there is no storage system -independent standard for the integration of these systems into a stand-alone or utility grid. A standard dealing with any type of rechargeable batteries is planned.

Standardization of energy storage system includes:

- Terminology
- Characterization of energy storage system components for technical evaluation (power, capacity, lifetime, size, discharge time, etc.)
- Communication (security, and protocols)
- Requirements for grid interconnection (synchronization , power quality, frequency voltage tolerances, and metering)
- Mechanical and electrical safety
- System testing
- Implementation guidelines.

Control standards would likely be addressed by utilities given the large variety of energy storage system exciting in the marketplace, with a variety of characteristics and different control considerations. Standardization is currently an area that is open for discussion and research as there is a lack of maturity of energy storage in marketplace.

Standardizing communication protocols require a combination of efforts from several parties which include grid operators, manufacturers, regulatory bodies, and utilities. However, it is still unknown whether the best solution for energy storage is a single communication standard or a new refined approach is required given the variety of the existing utility scale and the diversity of energy storage technologies.

Compared to other power system components, energy storage may face other barriers due to its different nature. To evaluate realistic interactions between energy storage systems with the electric grid, procedures should be developed by transmission provider. An assessment of energy storage interconnection request should be performed as these systems consume and generate energy during low and peak periods. More realistic operating regimes should be recognized by standardized guidelines which require energy storage systems to generate power only when other sources are limited, and to consume power only when energy demand is low.

8.1.4.2. Grid code

The fast expansion of renewable energy into the electric grid, from being negligible to becoming important for system stability, has implications for grid planning and operation. In this situation, grid operators need to ensure that the grid continues to operate in a safe, secure and economic way. To achieve this, grid codes have been introduced as common rules that regulate these responsibilities and define standardized and transparent requirements for any facility connected to the grid, including energy storage systems.

The integration standard of renewable energy currently exists at the national level or grid company level. Several counties are updating their grid code, or developing standards documents based on experiences learned from other countries. These include requirements or guidelines to meet the increasing penetration of renewable energy generation.

An elaborated and detailed overview about grid codes status in Northern Africa and Europe is included in Appendix D. It describes technical grid connection requirements particularly relevant for renewable energy integration in general and more in-depth for Spain, Morocco and Egypt. Challenges regarding grid code standardization and grid code compliance of renewable energy are addressed, and recommendations for further development of grid codes in North Africa are made, building on experiences from Europe.

8.2. Energy Storage in Morocco

The Moroccan legislative framework does not separately define energy storage. The rules regarding the issue of energy storage systems are not stated by the law applicable to the production of energy. However, the development of legislation on energy storage is expected in the near future because of the increasing penetration of renewable energy.

Specific recommendations for a “successful transition into a Green Economy” have been issued by the Economic and Social Council for Green Energy; among which the need to accomplish a competitive electricity market. In this regards, a number of recommendations are proposed [15]:

- Solving peak power demand and energy storage issues.
- Providing a diverse mix of energy sources such as the use of biomass, clean coal, and pumped hydro storage.
- Installing small and medium power stations; especially renewable energy installations.

Tasks which should be accomplished by the Ministry of Energy have been set out by the legislative decree n° 2-14-541. In the framework of the consolidation of a liberalised energy market in Morocco, the Ministry of energy has to develop a strategic energy storage policy and to control the functioning and organization of the energy markets as stated by Article 1.

Battery storage standards have been enacted recently by the Moroccan Institute for Standardization (IMANOR) [16]. These standards include NM CEI 61427-1, NM EN 12977-3, NM EN 12977-4 which regulate the general conditions, the performance testing methods applying to the storage installations for water solar heating, and the conditions applying to the combined storage methods for solar heating; respectively [17].

Concerning the legislation related to renewable energy, the conditions under which renewable energy systems can be installed and operated are specified by law 13-9 [18]. This law has liberalised the system of energy production based on renewable energy sources. The development of law 58-157 which amends the law 13-09 has brought some interesting modifications [19]; such as increasing the threshold of electricity production from hydro, providing access to low voltage electricity grid to electricity stations referred to in law 13-09, and allowing the selling of excess electricity production to the National Electricity Office (“ONEE”) or to the electricity transmission system operator. Therefore, future consequences related to energy storage in Morocco might results because of the development of these laws. However, the question of energy storage is currently not regulated.

Energy storage is facing a number of challenges in Morocco as it is still at a development stage. These include:

- Energy storage regulation barrier due to the lack of a specific legislation.
- Limitation of reselling electricity to ONEE: even though the Law 58-15 permits the resale of excess energy production to ONEE or to the energy transmission operator, the resale is restricted to 20% of the produced energy.
- Variability of energy production: For example, the production of energy from hydro sources in Morocco depends on pluviometry and can significantly vary from one year to another. In 2012, the energy produced by hydro power stations dropped by 15% in comparison with 2011 due to drought [20].
- Public regulation entities: Morocco does not currently have an energy transmission system operator. The legislation n° 48-15 emphasizes the need to establish an independent entity in charge of this role within ONEE; along with the creation of an independent regulator. ONEE is responsible for the production, the transmission and the distribution of energy. In addition, ONEE is responsible for the production of electricity based on renewable energy sources, in parallel with public and private entities. In this respect, ONEE is the relevant entity concerning all projects that are related to energy storage. In 2015, the Council of Government has implemented the legislation n° 48-15 regulating the energy sector, and creating a National Authority for Electricity Regulation (ANRE) “Autorité Nationale de Régulation de l’Electricité” [21]. According to this draft, ANRE will be responsible for controlling the energy market.

8.3. Conclusion

Although technical and economic issues are considered as the main challenges facing energy storage, market and policy issues represent important barriers to the development of energy storage. These latter barriers include the incomplete and inaccurate valuation of energy storage benefits, the regulatory treatment, the lack of requirement and standardization, as well as the development risk. The lack of clear requirements for energy storage operation presents challenges. Moreover, the current markets are not fully developed for all ancillary services. In addition, they do not identify emission savings that may be realized from energy storage projects. Therefore, the real value of energy storage is not reflected and may be insufficient to justify its investment.

The difficulty of energy markets to value all the different benefits of energy storage systems, and the high investment risks put forward a need for policy intervention. Several policies have been executed to support other energy generation technologies for various purposes such as feed-in tariffs, regulatory requirements, production tax credits, and others. Similar policies are necessary to obtain the complete economic and environmental benefits available through the use of energy storage systems.

References

[1]. SBC. SBC energy institute analysis based on US DOE energy storage program planning document, 2011.

[2]. Ibrahim H, Ilinca A. Techno-economic analysis of different energy storage technologies. InTech; 2013.

[3]. Interesting paper

[4]. Market Policy Barriers to Deployment of Energy Storage, Sioshansi, Denholm, Jenkin, Economics of Energy and Environmental Policy, 2012.

[5]. Graves et al. (1999); from new paper in the same folder as the chapter

[6]. Figueiredo, F. C., Flynn, P. C., Cabral, E. A., 2006. The economics of energy storage in 14 deregulated power markets. Energy Studies Review 14, 131–152.

[7]. Sioshansi, R., 2011. Increasing the value of wind with energy storage. The Energy Journal 32, 1–30.

[8]. Sioshansi, R., 2010. Welfare impacts of electricity storage and the implications of ownership structure. The Energy Journal 31, 189–214.

[9]. Sioshansi, R., Denholm, P., Jenkin, T., January 2011. A comparative analysis of the value of pure and hybrid electricity storage.Energy Economics 33, 56–66

[10]. Schill, W.-P., Kemfert, C., 2011. Modeling strategic electricity storage: The case of pumped hydro storage in germany. The Energy Journal 32, 59–88.

[11]. Walawalkar, R., Apt, J., Mancini, R., April 2007. Economics of electric energy storage for energy arbitrage and regulation in New York. Energy Policy 35, 2558–2568.

[12]. Giorgio Castagneto Gissey, Paul E. Dodds, Jonathan Radcliffe, Regulatory barriers to energy storage deployment: the UK perspective. Available at: http://www.restless.org.uk/documents/briefing-paper-1

[13]. December 12, 2013 Puerto Rican Power Authority press release: http://www.prepa.com/spanish.asp?url=http://www.aeepr.com/noticias.ASP

[14]. IEC, Electrical Storage White Paper, December 2011

[15]. M. Veuillot, N. Lardy. CMS Guide to Energy Storage: Morocco. Available at : https://eguides.cmslegal.com/energy_storage?_ga=1.26647742.2054083135.1467878055#morocco

[16]. Decision n° 746-15 of the Moroccan Institute for Standardization, dated 5 March 2015 (Government’s official gazette n°6348)

[17]. https://webstore.iec.ch/publication/5449

[18]. Dahir n° 1-10-16 dated 11 February 2010, in Government’s official gazette n° 5822 dated 18 March 2010.

[19]. Dahir n° 1-16-3, in Government’s official gazette n° 6436 dated 4 February 2016

[20]. http://rabatinvest.ma/index.php?option=com_content&view=article&id=4820:electricite-propre--le-marche-libre-arrive&catid=2:actualite&Itemid=174&lang=fr&listing=1

[21]. http://www.sgg.gov.ma/portals/0/AvantProjet/129/Avp_loi_48.15_Fr.pdf

Chapter 9

9. Conclusion

The question of how to achieve a sustainable power future is considered one of the main issues faced by modern society. An answer to this question could be the use of renewable energy sources. However, a significant implementation of these latter requires the deployment of energy storage systems. This work has explored the modeling of energy storage technologies used to solve the variability issues involved with renewable energy generation. Particular attention has been paid to gravity energy storage. It has looked at this storage system from both technical and economic perspectives. In addition, it has investigated the feasibility, the profitability, and the development of such a system with an aim of answering the different questions of this thesis.

Gravity energy storage is still in the demonstration and research stage as there is yet no operational life project to ascertain the system characteristics, applicability and viability. More research is therefore necessary to investigate the realization of such storage technology. This chapter summarizes the key achievements of the presented PhD research work, provides major conclusions, and gives some direction to future work.

9.1. Summary and key chapter conclusions

The different conducted studies have shown that there is certainly potential in the investigated storage concept. A number of aspects were investigated and explained to achieve an overall study of the system. Although still some facets need further investigation, the following key conclusions were reached:

An introduction to energy storage systems was provided in chapter 2. An increasing need of energy storage is expected in the next upcoming years. There exist several energy storage options. The most satisfactory and dominated method is pumped hydro energy storage with more than 97% of the total installed capacity all over the world. However, this technology has an important environmental impact and needs large height difference between its two reservoirs. This latter issue prevents its development in low-lying countries. Other storage systems have different potentials and barriers. Compressed air energy storage is a profitable system. However, it does not provide pure and sustainable energy storage, as it uses natural gas. Batteries are also profitable, but they suffer from large environmental and safety challenges. In addition, they are not yet implemented on large scale. They require high costs which will need to be dramatically decreased in order to become widespread. Capacitors, superconducting magnetic energy storage, and hydrogen storage demonstrate great promises but are not used in large scale energy storage applications. Currently, there is no storage technology able to compete with the profitability of PHS. Therefore, based on the principle and the main components of the conventional PHS, alternative storage options are being proposed and developed such as gravity energy storage. This latter is a concept based on the idea of using the proven pumped hydro storage technology in an innovative manner.

Chapter 3 investigated the design, construction, and sizing of gravity energy storage. The proposed design methodology had an objective to maximize the storage capacity and minimize the construction cost while avoiding system failure. The obtained results demonstrate that in order to obtain an economical design for a specific storage capacity; the container height has to be increased while decreasing the size of its diameter. In addition, an investigation of the storage construction material was also conducted. It was found that iron ore is an optimal material which could be used to construct the piston due to its high density and lower cost compared to the investigated materials. Concerning the construction of the container, reinforced concrete material would be the best candidate. Finally, this chapter presented a methodology to optimally size and operate storage systems when coupled to wind farms. The aim of the proposed approach is to maximize the owner profit. The outcomes of this study show that a proper sizing of energy storage can increase the revenues obtained by optimally charging and discharging energy while taking advantage of energy price fluctuation.

The economics of energy storage have been discussed in Chapter 4. The LCOE approach was used to examine the viability of gravity energy storage and compare it to other storage alternatives. It was found that the system has an interesting LCOE. Therefore, it is economically feasible to develop such technology. In addition, this chapter presented an explanation of electricity market structure. A model has been proposed to identify the different revenues available to energy storage participating in arbitrage and ancillary services within multiple markets including day-ahead and real-time energy markets as well as ancillary market. The outcomes of this study show that operating in regulation market is likely to provide the most potential benefits. However, gravity storage has to perform multiple grid functions in order to generate a positive NPV.

Chapter 5, built on the work performed in Chapter 4, investigates the profitability of energy storage in residential and large scale applications. This has been performed by taking into consideration all the different scenarios that the storage system could be part of. A cost-benefit analysis demonstrates that gravity storage is not profitable for residential applications except if it is installed for T&D upgrade deferral application. However, the system generates a positive NPV when used for large scale application.

The concept of the gravity energy storage is considered a low risk solution, as it uses the principle of the proven pumped hydro storage technology in an innovating way. As structural components, only a container, return pipe, sealed piston, and pump turbine-station are required. The key risks of further commitment to the construction of this storage system are mainly based on uncertainties concerning the difficulty of excavating deep shafts and the use of large sealing system. In addition, the development of such energy storage project is affected by external risks associated with the economic, financial, and political aspects of the project. A Sensitivity analysis has been carried out to investigate the impact of changing these variables on the project profitability. The results reveal that this system is not economically viability if faced by an 18% increase of the project investment cost. Moreover, the project NPV is significantly affected by a decrease in potential revenues generated from performing arbitrage and T&D deferral. Finally, an increase in the discount rate negatively impacts the viability of this storage technology. It has been observed that a 3% increase of this latter would results in a negative NPV.

Chapter 6 presented a dynamic modeling of gravity energy storage. The behavior of this energy storage including the mechanical machines and the hydraulic components is analyzed to gain insight into the performance of this system. In addition, this study details the operation modeling of this storage system coupled with a PV energy plant. The obtained results show that the proposed model is able to meet the load according to the presented management strategy. As for the hydraulic modeling, it will be possible to predict, using the proposed model, some of the important model parameters such as dynamics of piston motion, fluid flow rate, chambers pressure and volume, and charging/discharging cycle time of the storage system. The results obtained from the simulated case study were compared to experimental results of other researchers, and evaluated. The obtained % errors of the system pressure and discharge time are 3.4%, and 6.2%, respectively. The proposed model has been proven as being able to simulate the dynamic hydraulic response of the system with high accuracy. Therefore, it is possible to obtain a system model, whose resulting characteristics are similar to the real one.

Towards the improvement of this energy storage technology, a novel concept has been proposed. This system is based on the addition of compressed air to gravity energy storage. In chapter 7, this new concept is introduced and studied. Modeling approaches are presented in order to determine the system feasibility. The outputs of this study demonstrate that the use of compressed air significantly improves the system storage capacity. Therefore, an interesting amount of energy could be added with the combination of compressed air and gravity energy storage.

In addition to the economic and technical barriers faced by energy storage developers, there is also challenges associated with policies and markets which lead to more reluctance toward the development of energy storage. This thesis ends up with a discussion about policies consideration and future prospects in chapter 8. Interest in energy storage has been fueled by the increasing development of intermittent renewable energy generation. However, the deployment of energy storage systems have been hampered by their relatively high capital costs compared to traditional generating resources. In addition, energy storage development faces other barriers which suggest the intervention of policies. It is still complex to determine the real value of energy storage which results in a failure to recognize the full system benefits.

With the growing share of renewable energy sources, there will be an increasing demand for energy storage services. Even if energy storage is not the only provider of these services, there is actually a significant emphasis on their development. This latter is fostered by policies that reduce challenges and makes incentives available for developing energy storage. Standardized integration of energy with utility system is also needed and merits development. In addition, energy storage may become economic if policies are adopted. These policies and standards would attract investors and provide support to the implementation of promising energy storage systems that are still in development phase.

9.2. Future Research

Several parts of this energy storage project still need further detailed research in order to make appropriate investment decisions. The current research has been based on estimations and common assumptions. This could be enough to identify the potentials of the project. However, it may not be a sufficient to prove that the project would be profitable when executed in the form of a pilot storage system. Therefore, a number of essential studies have to be conducted in order to increase the possibility of developing such a system in the future.

Further details about the subject could be researched; these include practical implementation of the system. Some prominent technical research areas in this subject are system stability, failure cases, piston sealing, and optimization of the system's different components for achieving a more economical sound storage option.

Further research could compromise different sizing methodologies as for modeling other grid applications. It should be noted that energy storage provides multiple services besides energy arbitrages such as regulation, black start capability and backup. Therefore, other applications for this storage system could to be investigated further. The proposed model could be performed for different time periods instead of one day in advance, or for different time frame instead of hourly basis. The sizing model presented in this thesis could be formulated using other constraints and assumptions which include, for example, the demand and transmission capacity. In addition, the renewable farm parameters could also be modelled in the sizing problem.

The economic analysis could include a more detailed estimation of the system components. The determination of the storage capital cost should as well include other costs such as engineering costs. In addition, costs are changing rapidly because of the technological development; this implies a regular update of all costs. The current research has investigated some of the project benefits; other benefits could be analyzed and quantified such as the offset of carbon emissions. In addition, a preliminary risk study has been carried out in this thesis. In order to achieve a more realistic development of the system, further and comprehensive risk analysis has to be examined. Experimental studies are also necessary to investigate the concept in real life. The development and test prototypes of this system with different scales are required.

The research conducted in this thesis assumes a cylindrical shaped container linked to a return pipe and a powerhouse. Additional quantitative research might show different opportunities when using a different shape. Another interesting design might be to use multiple containers linked to one single powerhouse. In addition, a detailed technical analysis about the proposed gravity compressed air energy storage could be performed to investigate the system development.

Appendix A

This section presents Matlab codes used in the design of gravity energy storage proposed in chapter 3.

```
clc
optiSolver('NLP')
% Objective
fun = @(x)
(1779.4*x(2)^2)+(38183.4*x(2))+(149748.4)+(397.4*(x(2)^2)*x(1))+(6886.52*x(2
)*x(1))+(14134.96*x(1));

% Nonlinear Constraints (cl <= nlcon(x) <= cu)
nlcon = @(x)   x(2)^2*(x(1)^2)-6805078.2 ;



cle = 0;
%cu = 0;

% Bounds (lb <= x <= ub)
lb = [0;0];
ub = [500;499];



% Constraints
A = [-1 1];      %Linear Inequality Constraints (Ax <= b)
b = 0;

% Initial Guess
x0 = [100 15]';

% Options
opts = optiset('solver','ipopt','display','iter');

% Build OPTI Problem
Opt =
opti('fun',fun,'ineq',A,b,'nl',nlcon,cl,cu,'bounds',lb,ub,'x0',x0,'options',
opts)



% Solve NLP
[x,fval,exitflag,info] = solve(Opt)

plot(Opt)
set(gcf,'color','g');
```

Appendix B

This section presents GAMS codes used in chapter 3, 4, and 5.

1. GAMS Code for sizing of energy storage

```
sets
t scheduling period /1*24/

*Define input parameters
scalar
i /0/
Storage_cap Storage nominal capacity (MWh)  /0/
h diacharge hour/4/;

Parameters

d    storage self-discharge  /0/
eff storage efficiency    /0.80/
C Operation and management cost /4/;


parameter P_generated(t) power generation
/
1 2004.4
2 1959.3
3 1945
4 1845.2
5 1819
6 1757.1
7 1909.5
8 1990.2
9 2056.1
10 2012.9
11 1859.6
12 1699.6
13 1609
14 1619.7
15 1664.9
16 1894.9
17 2176.3
18 2586.8
19 3021.4
20 3474.9
21 3592.1
22 4033.5
23 4124.9
24 1999.1
/

parameter E_price(t) electricity prices
```

```
/
1  58.23
2  51.95
3  47.27
4  45.49
5  44.5
6  44.5
7  44.72
8  44.22
9  45.13
10 46.23
11 47.91
12 49.57
13 48.69
14 47.2
15 46.51
16 46.52
17 51.59
18 59.07
19 62.1
20 64.2
21 60.69
22 59.07
23 52
24 58.82
/
variables

P_stored(t) Power sent to storage (MW)

P_discharged(t) Power discharged from storage (MW)

S_level(t) Storage Level (MWh)

P_injected Power injected directly to the grid (MW)

HourlyRevenue(t)  the plant hourly revenue

cost (t) System cost

Revenue total revenue;

positive variables
P_stored,P_discharged, P_injected, S_level;

equations

ObRevenuefn The revenue objective function

HourlyrevenueEq(t)    the plant revenue at time t

Storage_flowEq(t) the energy flow balance in the storage system

Power_BalanceEq(t) total generation must meet the load
```

```
Storage_Control(t) ess control

S_cap(t) equation
Eq1 (t)  equation 1
Eq2 (t)  equation 2
hourlycost(t)    Hourly cost equation
Storage_Discharge(t) the storage discharge constraint ;

HourlyrevenueEq(t)..  HourlyRevenue(t)=e=(P_discharged(t) + P_injected(t))*
E_price(t);

hourlycost(t).. cost(t)=e= C* P_stored(t);

ObRevenuefn..    Revenue =e= sum(t, HourlyRevenue(t))- C*
sum(t,(P_stored(t)));

Storage_flowEq(t).. S_level(t) =e= S_level(t-1)*(1-d)+ (P_stored(t)*eff) -
(P_discharged(t));

Power_BalanceEq(t)..  P_injected(t) + P_stored(t) =e= P_generated(t) ;

Storage_Control(t).. P_discharged(t)*P_stored(t) =e= 0;

Storage_Discharge(t).. P_discharged(t) =l= S_level(t);

*Added equations

S_cap(t).. S_level(t) =l= Storage_cap;

Eq1 (t).. P_stored(t) =l= Storage_cap/h;

Eq2 (t)..P_discharged(t) =l= Storage_cap/h;

set b set of Storage capacities /1*300/

model Storage / all / ;

S_level.lo(t) = 0;

P_stored.lo(t) = 0;

P_discharged.lo(t) =0;

loop(b,
storage_cap=i;
solve Storage using NLP maximizing Revenue;
i=i+100;
);

display P_stored.l,P_discharged.l,Revenue.l,cost.l, HourlyRevenue.l;
```

2. GAMS Code for energy storage valuation model

```
sets

t scheduling period /1*24/

scalar

c_eff maximum charge rate per MW of capacity (MW per period) /0.85/

d_eff maximum discharge rate per MW of capacity (MW per period) /0.85/

cost daily capital cost of energy storage plus O&M cost/4838/

Storage_lf  Storage lifetime cycles /18250/

dcr regulation dispatch to contract ratio /0.1/

Storage_cap Storage nominal capacity (MWh) /20/;

Parameters

d storage self-discharge /0/

SPowerLimit Storage Power Limit(MW) /5/

C service Cost  /0/

p_da(t) day-ahead energy price
/
1 11.48
2 9.25
3 9.12
4 9
5 9.68
6 10.83
7 12.27
8 14.24
9 17.24
10 17.54
11 17.75
12 17.17
13 16.47
14 16.28
15 16.5
16 22.85
17 29.07
18 27.82
19 26.29
20 25.01
21 21.61
22 15.85
23 11.66
24 14.14
/
```

```
p_rt(t) real-time energy price
/
1 16.79
2 5.4
3 16.73
4 15.99
5 2.16
6 5.49
7 63.68
8 25.15
9 26.72
10 20.78
11 28.31
12 27.07
13 23.48
14 26.33
15 19.74
16 19.78
17 23.59
18 24.02
19 33.34
20 23.5
21 22.6
22 18.87
23 20.86
24 22.36

/

p_a_rt(t) ancillary services price
/
1 4
2 4
3 4
4 4
5 6
6 6
7 7.14
8 10
9 10
10 4
11 4
12 4
13 4
14 4
15 9
16 10
17 11
18 11
19 9
20 7
21 6.74
22 8
23 6
```

```
24 6
/

p_a_da(t) ancillary services price

/
1 12.1
2 14.23
3 5
4 14.07
5 12.73
6 7.75
7 9.75
8 9.75
9 8.53
10 7
11 7
12 7
13 7
14 7
15 6.89
16 8.46
17 9.75
18 9.75
19 9.75
20 8.25
21 6.91
22 7.75
23 10.96
24 9.7

/

positive variables

qb(t) the quantity of energy in the storage (MWh)

q_a_rt(t) capacity sold from storage into ancillary services in real time
market(MW)

q_a_da(t)  capacity sold from storage into ancillary services in day-ahead
market(MW)

qd_da(t) energy sold from storage into day-ahead energy market(MWh)

qd_rt(t) energy sold from storage into real-time energy market (MWh)

qc_rt(t) energy stored into the storage from the wind site-real time energy
market (MWh)

qc_da(t) energy stored into the storage from the wind site-day ahead energy
market (MWh)
```

```
x_c(t) portion of the hour spent charging
x_d(t) portion of the hour spent discharging
Rev_DA(t) Revenues from Day Ahead
Rev_RT(t) Revenues from real time
S_level(t) Storage Level (MWh)
HRev_DA(t) Hourly Revenues from Day Ahead market
HRev_RT(t) Hourly Revenues from Real time market
HRev_RG(t)  Hourly Revenues from Regulation market
Revenu_DA   Day-ahead Revenues
Revenu_RT   Real-time Revenues
Revenu_RG  regulation service Revenues
cost_DA  Day-ahead cost
cost_RT  real-time cost
E_discharged(t)  Energy Discharged
Rev_RG(t) Revenues from regulation;
x_c.up(t) = 1;
x_d.up(t) = 1;
variables z profit maximizing;
equations obj objective of profit maximization ($)
storage_lvl(t) level of energy stored in the storage in period 't' (MWh)
chrg(t) upper limit on storage charging per period
dchrg(t) upper limit on storage discharging per period
storage_cap(t) upper limit on energy stored in the storage
HourlyRevenue_DA(t)  Hourly Revenues Day-ahead
HourlyRevenue_RT(t) Hourly Revenues Real-time
HourlyRevenue_RG(t)  Hourly Revenues Regulation Services
Storage_Discharge(t) Hourly Energy Storage Discharge
TotalRevenu_DA  Total Revenues in day-ahead market
```

```
TotalRevenu_RT  Total Revenues in real-time market

TotalRevenu_RG  Total Revenues in regulation market

Costofcharging_DA  Cost of charging in day-ahead

Costofcharging_RT  Cost of charging in real-time

int_var(t)

reg_up(t);

obj.. z =e= sum(t,(p_da(t)*qd_da(t))+(p_rt(t)*qd_rt(t)) -

(p_da(t)*qc_da(t))- (p_rt(t)*qc_rt(t)) +

(p_rt(t)*dcr*q_a_rt(t))+(p_rt(t)*dcr*q_a_da(t))+

(p_a_rt(t)*q_a_rt(t))+(p_a_da(t)*q_a_da(t)))

-C* sum(t,qc_da(t)+qc_rt(t))-cost;

storage_lvl(t).. qb(t) =e= qb(t-1)*(1-d)+ c_eff*(qc_da(t)+qc_rt(t)) -
(qd_da(t) +qd_rt(t)+dcr*q_a_rt(t)+dcr*q_a_da(t));

storage_cap(t).. qb(t) =l= storage_cap;

chrg(t).. qc_da(t)+qc_rt(t) =l= x_c(t)*SPowerLimit;

dchrg(t).. (qd_da(t) +qd_rt(t)+(dcr*q_a_rt(t))+(dcr*q_a_da(t))) =l=
x_d(t)*SPowerLimit;

Storage_Discharge(t)..

qd_da(t)+qd_rt(t) +(dcr*q_a_rt(t))+(dcr*q_a_da(t)) =l= qb(t);

reg_up(t).. q_a_rt(t)+q_a_da(t) =l= storage_cap;

int_var(t).. x_c(t) + x_d(t) =l= 1;

HourlyRevenue_DA(t)..   HRev_DA(t)=e=p_da(t)* qd_da(t);

HourlyRevenue_RT(t)..   HRev_RT(t)=e=p_rt(t)* qd_rt(t);

HourlyRevenue_RG(t)..
HRev_RG(t)=e=(p_rt(t)*dcr*q_a_rt(t))+(p_rt(t)*dcr*q_a_da(t))+(p_a_rt(t)*q_a_
rt(t))+(p_a_da(t)*q_a_da(t));

TotalRevenu_DA ..     Revenu_DA =e= sum(t, HRev_DA(t));

TotalRevenu_RT ..     Revenu_RT =e= sum(t, HRev_RT(t));

TotalRevenu_RG ..     Revenu_RG=e= sum(t, HRev_RG(t));

Costofcharging_DA.. cost_DA=e=sum(t, p_da(t)* qc_da(t));
```

```
Costofcharging_RT.. cost_RT=e=sum(t, p_rt(t)* qc_rt(t));

model Storage / all / ;

solve Storage using LP maximizing z;

display z.l, qb.l, qd_da.l,qc_rt.l, qd_rt.l, qc_da.l, q_a_rt.l,q_a_da.l,
HRev_DA.l, HRev_RT.l, HRev_RG.l, Revenu_DA.l, Revenu_RT.l, Revenu_RG.l,
cost_DA.l, cost_RT.l ;
```

3. GAMS Code for System profitability (Scenario 1 is presented as an example)

```
* Scenario 1
sets
t scheduling period /1*24/

*Define input parameters
Parameters

d    storage self-discharge  /0/
eff storage efficiency    /0.80/

E_price(t) electricity prices for Mars 21 2016 (Winter )
/
1 0.03179
2 0.02868
3 0.02801
4 0.02801
5 0.02801
6 0.03201
7 0.03800
8 0.04014
9 0.04122
10 0.04000
11 0.04000
12 0.04005
13 0.04000
14 0.03869
15 0.03752
16 0.03646
17 0.03543
18 0.03437
19 0.04020
20 0.04005
21 0.03929
22 0.03586
23 0.03278
24 0.03733

/
Demand(t) electricity consumption (Demand)Winter
/
1 0.575
2 0.52
3 0.465
4 0.42
5 0.425
6 0.48
7 0.66
8 0.655
9 0.71
```

```
10 0.74
11 0.725
12 0.75
13 0.805
14 0.8
15 0.83
16 0.9
17 1.04
18 1.12
19 1.0925
20 1.08
21 1.025
22 0.975
23 0.83
24 0.715
/

*Define Variable
variables

E_sell(t) Energy sold to the grid (KWh)
E_buy(t) Energy bought from the grid (KWh)

E_Dg(t)   Energy sold to the grid (KWh)   from storage
E_stored(t) Energy stored (kWh)
E_Gl(t) Energy sent from grid to the load (Kwh)

S_level(t) Storage Level (MWh)

HourlyRevenue(t)  the plant hourly revenue
saving (t)
save
Revenue total revenue;

*Set lower bounds equal to zero
positive variables  E_sell,E_buy, E_Dg, E_stored, E_discharged,  E_Gl,
S_level ;

*Define objective and constraint functions
equations

ObRevenuefn The revenue objective function

HourlyrevenueEq(t)the plant revenue at time t

Storage_flowEq(t) the energy flow balance in the storage system

Storage_Control(t) ess control

Buy(t)
Sell (t)
DemandEQ (t)
Discharged  (t)
Saved1(t)
```

```
Saved2
Storage_Discharge(t) storage discharge constraint   ;

HourlyrevenueEq(t)..  HourlyRevenue(t)=e=(E_sell(t)-E_buy(t))* E_price(t);

ObRevenuefn..    Revenue =e= sum(t, HourlyRevenue(t));

Discharged(t)..        E_discharged(t)=e=E_Dg(t) ;

Buy(t)..           E_buy(t)=e=E_stored(t)+E_Gl(t);

Sell(t)..            E_sell(t)=e=E_Dg(t);

Storage_flowEq(t).. S_level(t) =e= S_level(t-1)*(1-d)+ (E_stored(t)*eff) -
(E_discharged(t));

DemandEQ(t).. Demand(t)=e=E_Gl(t);

Storage_Control(t).. E_discharged(t)*E_stored(t) =e= 0;

Storage_Discharge(t).. E_discharged(t) =l= S_level(t);

Saved1 (t)..            saving
(t)=e=HourlyRevenue(t)+(Demand(t)*E_price(t));
Saved2 ..                  save=e=  sum(t, saving(t)) ;

model Storage / all / ;

*Set Value and Bounds

S_level.up(t) = 11;

E_stored.up(t) = 5;

E_discharged.up(t) =5;

S_level.lo(t) = 0;

E_stored.lo(t) = 0;

E_discharged.lo(t) =0;

solve Storage using NLP maximizing Revenue;

display E_stored.l,E_discharged.l,Revenue.l, S_level.l, HourlyRevenue.l,
E_sell.l,E_buy.l, E_Dg.l,  E_Gl.l, saving.l, save.l
```

Appendix C

Simulink Block diagrams are presented in this section.

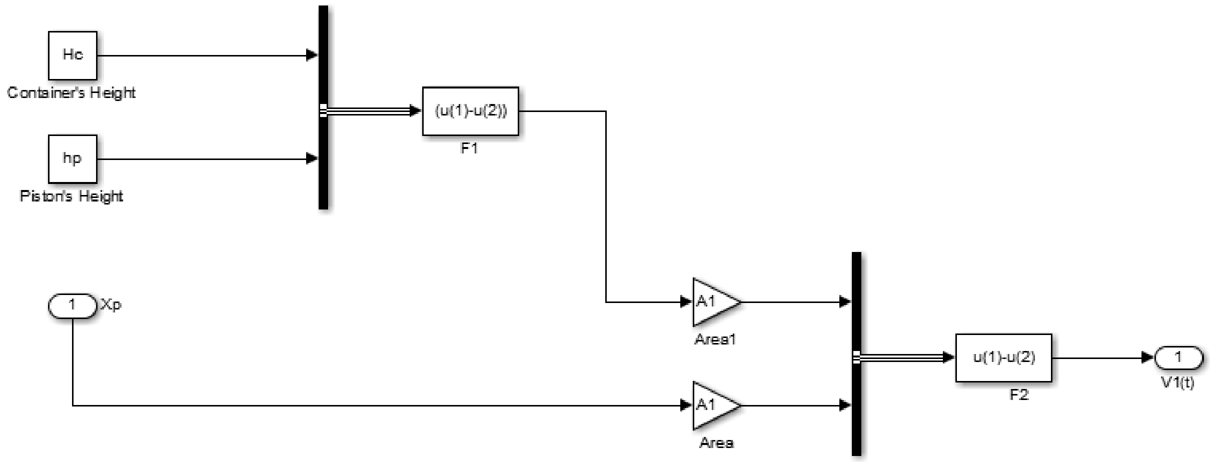


Fig. C. 1. Volume dynamics sub-model

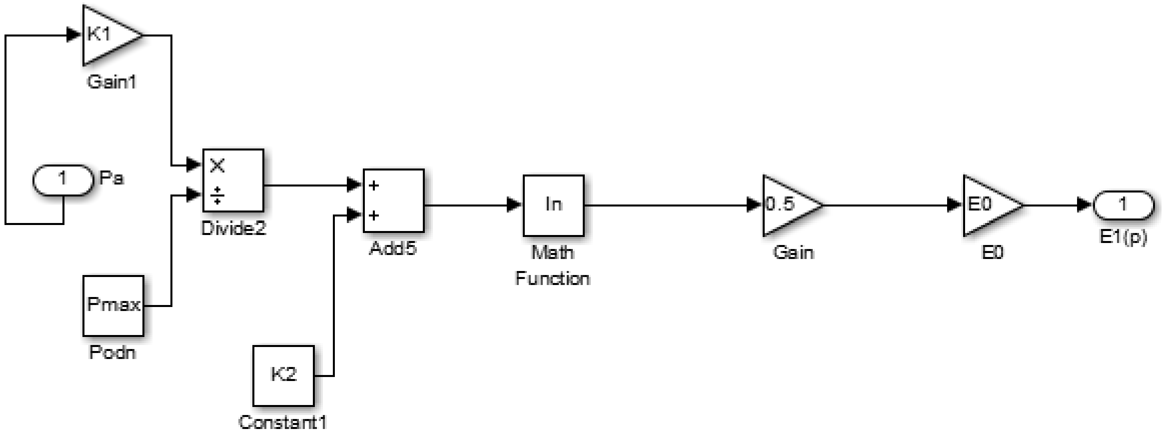


Fig. C. 2. Bulk Modulus sub-model

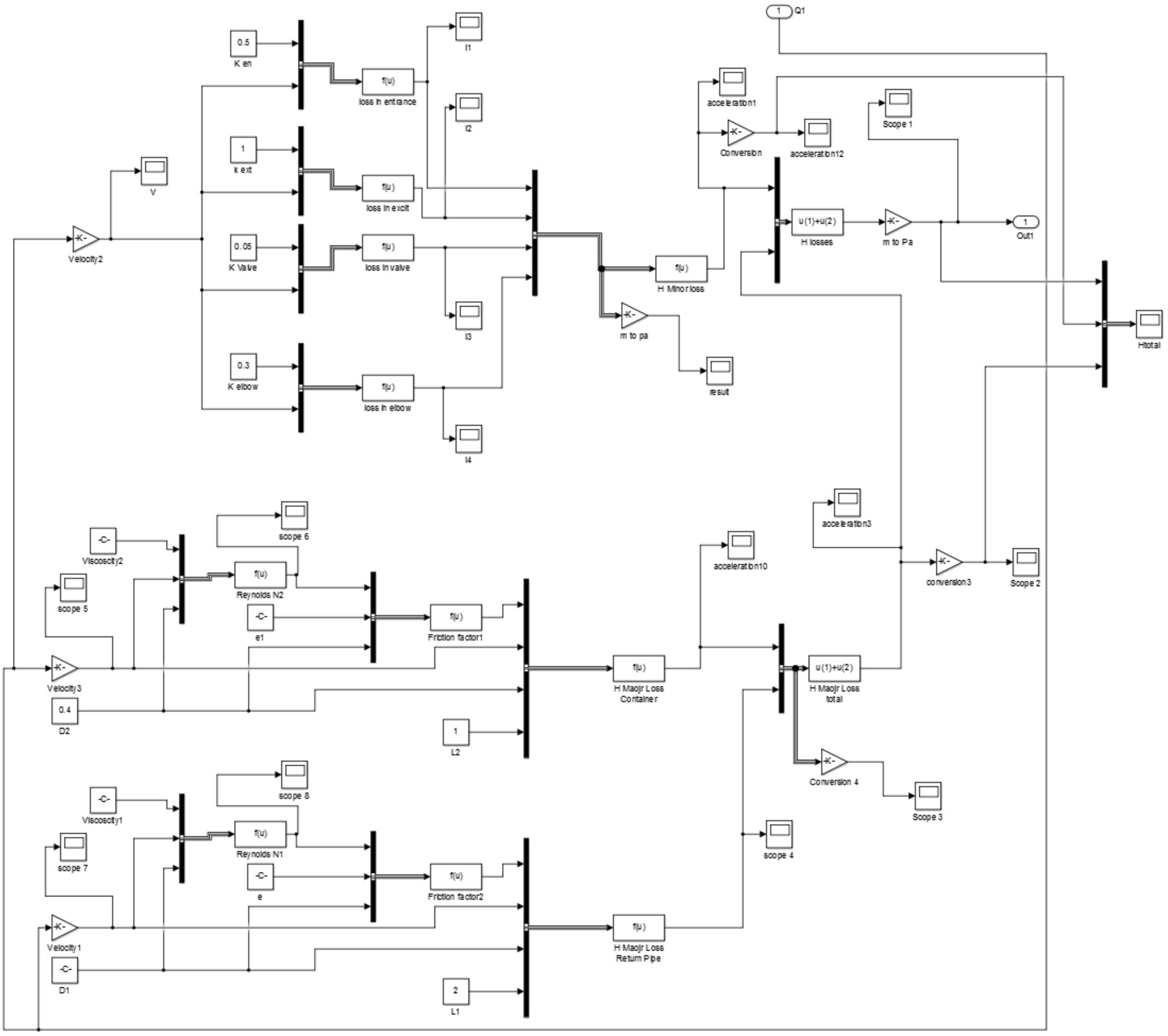


Fig. C. 3. System losses (major and minor losses)

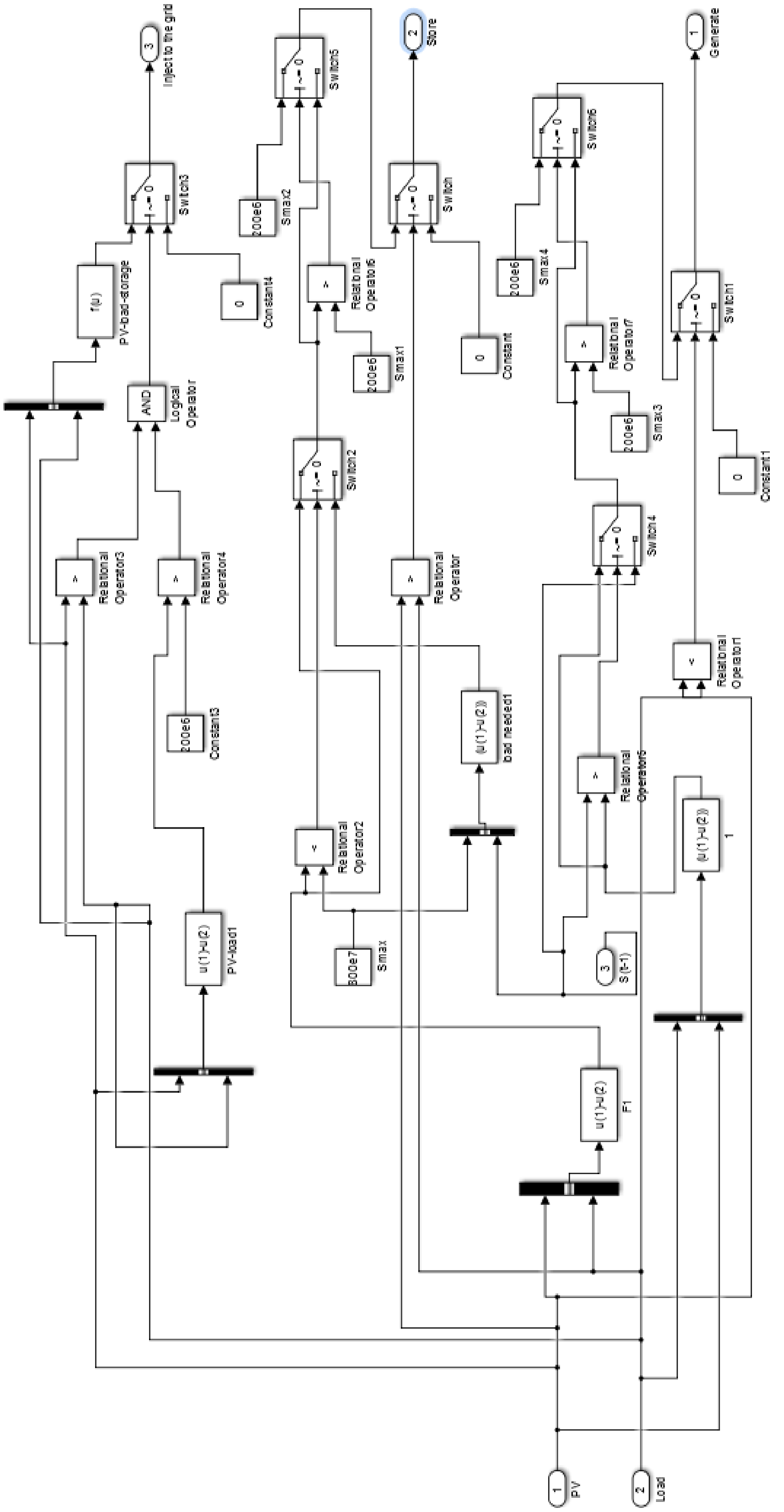


Fig. C. 4. Management system model

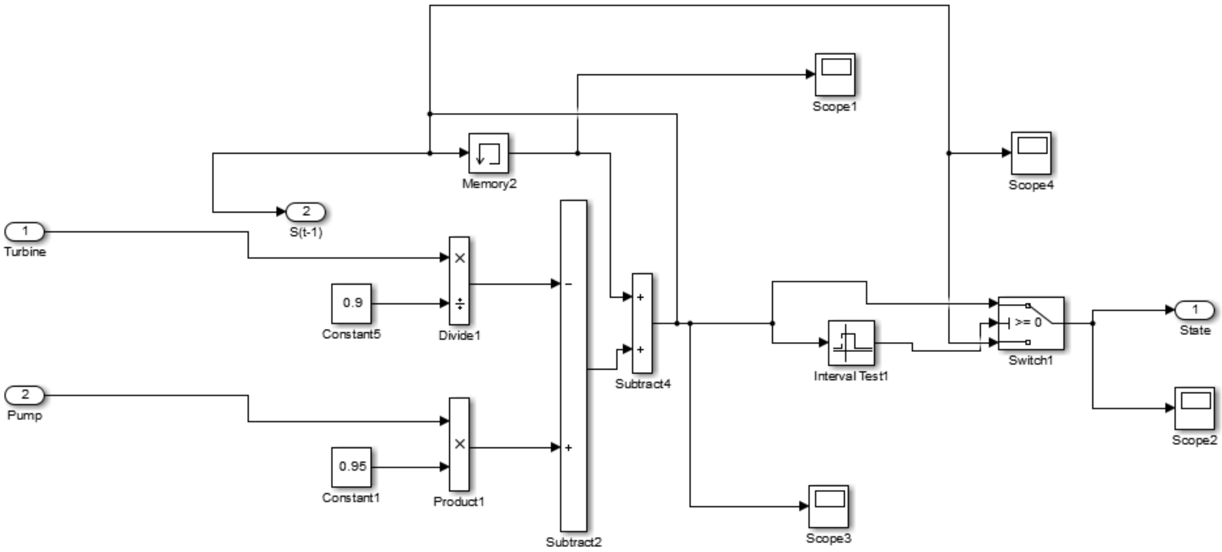


Fig. C. 5. Storage state

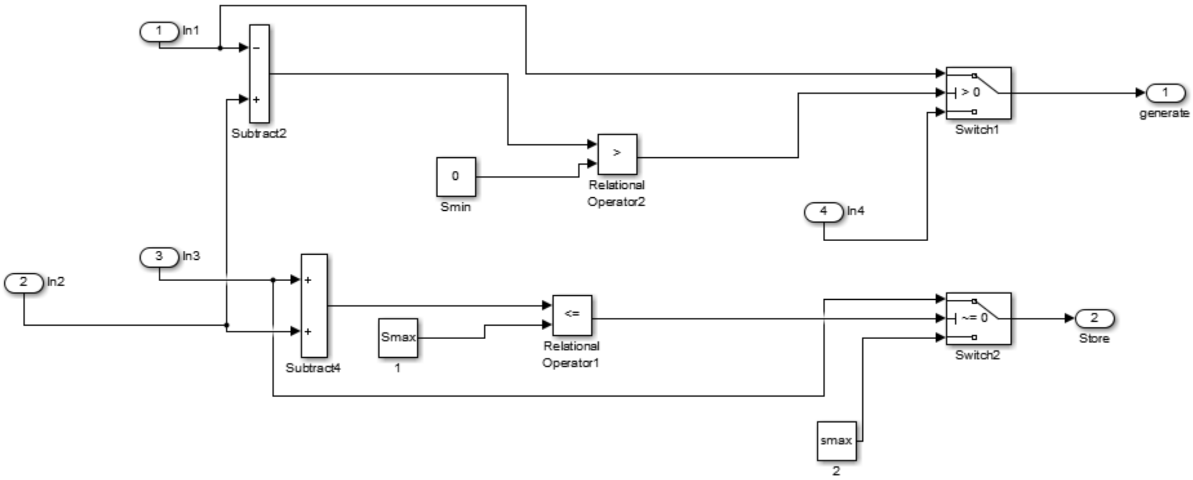


Fig. C. 6. Storage control system

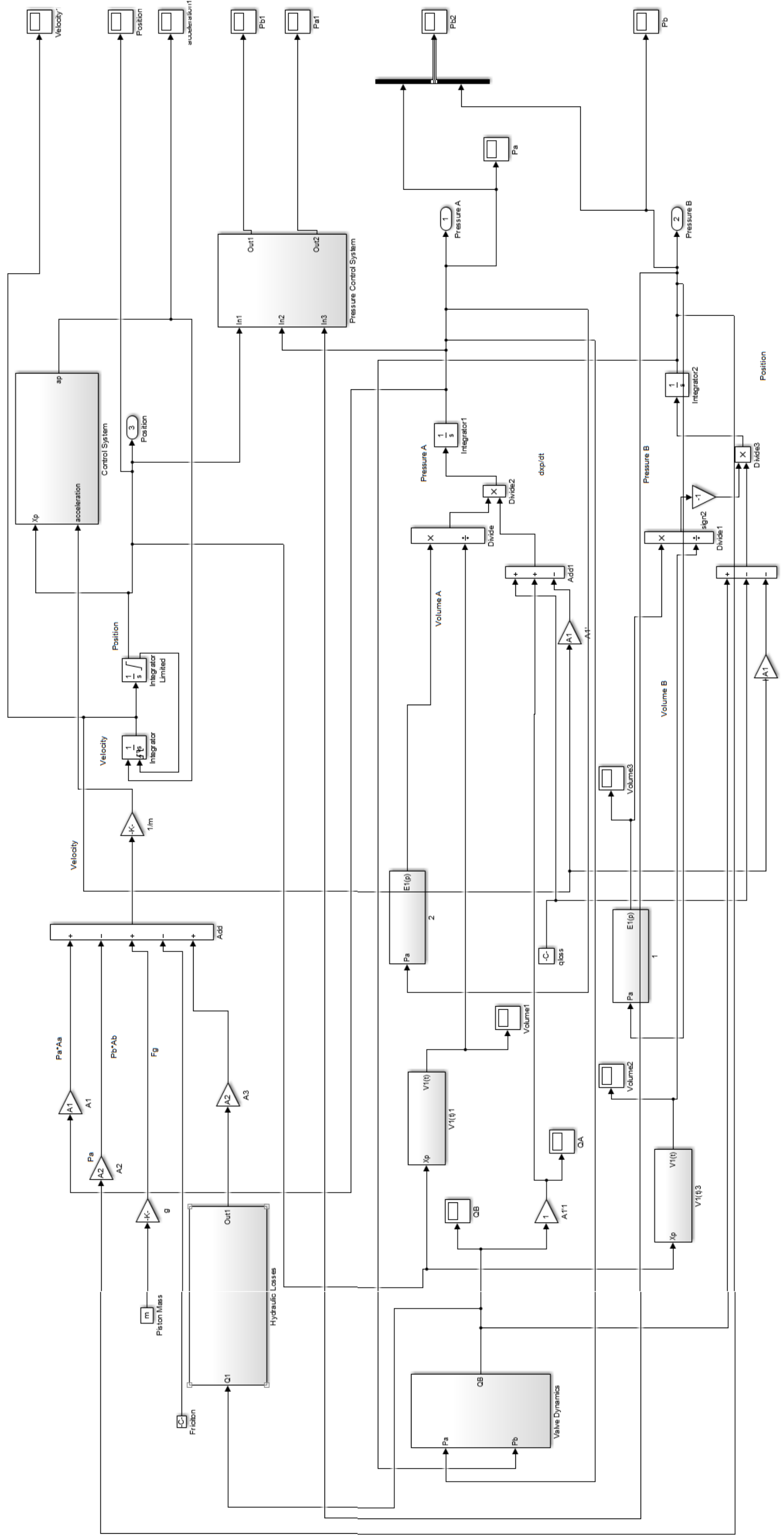


Fig. C. 7. Hydraulic Sub-model

Appendix D

Grid Code Status for Wind Farms Interconnection in Northern Africa and Spain: Descriptions and Recommendations for Northern Africa

Work done in collaboration with SINTEF and CENER

I. Introduction

Renewable energy generation has increased significantly, in the past few years, to constitute an important proportion of the total energy generation in the electric grid. The high share of these intermittent generation sources causes several issues to the utility grid. To ensure grid stability, various challenges must be addressed. Studies and experience in recent years have revealed new technical solutions needed to overcome these difficulties. Solutions include new methods and practices that should be applied in order to provide more flexibility and improve the efficiency of the electric system.

However, it is not only the high share of renewable power that is calling for stricter requirements; it is also due to the advance in technology that inquires stricter requirements. An example for a technology triggered change of requirements is to have a wide range of reactive power control. For the case of wind turbines, this is made possible with the introduction of an interface between wind turbine generator and the grid via power electronics. Reactive power and voltage can be controlled more accurately and easily with modern wind turbines (full scale back-to-back converter or doubly fed electrical machine), compared to regular induction generators directly connected to the network. This new requirement can significantly support the grid voltage stability.

The integration standard of renewable energy currently exits at the national level or grid company level. Several counties are updating their grid code, or developing standards' documents, based on experiences learned from other countries. These include requirements or guidelines to meet the increasing penetration of renewable energy generation. Sometimes, grid code requirement for generators are general and applicable independently of generator types. Other times, special grid codes are made for the particular renewable energy source, e.g. wind and photovoltaic generation.

Grid codes are often similar in different countries because they have the same general objectives. Example of requirements that are included in most of the wind power plant interconnection standards are [1]:

- Voltage range for continuous operation.
- Frequency range for continuous operation.
- Low voltage ride through.
- Active power set point and ramp rate control.
- Reactive power control and voltage regulation.
- Power quality such as flicker, harmonics and voltage fluctuation.

Grid codes may be different among countries due to: the way grids are managed in each country, different features and development stages of renewable energy generation, different characteristics of the power system, as well as different grid companies. These standards may differ in their contents and particularly in the specific values of some requirements.

Grid code requirements for renewable energy plants especially large wind farms has been explored in the literature. The United States regional and federal grid code was examined in [2]. Grid code regulations for Canada, Spain, Ireland, Germany, and UK were discussed in different countries by authors in [3–7]. In [8], authors compare grid code requirements in Germany, Denmark, UK, and Ireland. Other comparative studies for different international grid codes were presented in [9-11]. The harmonization of international grid codes and the expected future trends in the regulations are also discussed in [11].

A more comprehensive comparison of grid codes for several countries was presented in [12]. These countries include Germany, Belgium, UK, Ireland, Canada, Sweden, Denmark, New Zealand, USA, Spain, and Norway. Another review of recent grid codes for different countries is studied in [13]. Authors in [14] present a review of both grid requirements and control methods, necessary for the participation of wind turbines in synthetic inertia and system frequency control. Grid code modifications for the implementation of renewable sources in insular energy systems were discussed in [15]. A major update of current grid requirement is essential for a safer shift towards sustainable energy generation. To ensure future grid stability, it is important to introduce control and regulation capabilities to renewable energy sources [15].

In this work, we extend the literature by discussing the status of grid codes in North African countries and in Spain with a focus on wind energy. Concerning grid code for other renewable systems such as PVs, only few countries have elaborated technical requirements regarding PV installation. A discussion about these requirements in Spain is presented in section 3.1. However, up to date, Morocco and Egypt have not elaborated such grid codes. As for the requirements for the solar thermal and biomass, renewable energy generators, these are considered as being similar to conventional thermal systems. This is the reason behind our focus on wind energy. Recommendations for further development of grid codes in North Africa are also proposed.

This work is structured as follows. Section II discusses the status of grid code development in Europe and North Africa. A discussion about technical grid connection requirements for generators in Spain, Morocco and Egypt is presented in section III. The different technical requirement for the interconnection of wind farm in Spain, Morocco, and Egypt are compared in section IV. Section V, explores the barriers facing North African Countries and provides recommendations on the development of grid codes for renewable energy integration in these countries. Finally, section VI provides a summary and some concluding remarks.

II. Status of development

2.1. Grid codes in Europe

Grid codes in Europe were generally developed together with the unbundling process in the energy sector; whereby previous state controlled monopolies were divided up and shared responsibilities for production, distribution and supply were defined. The amount of detail included in the codes, however, vary very much from country to country.

The process to address the special characteristics of renewable energy generation has been driven largely by the development of wind power. In the 1980s, wind power enjoyed an exceptional treatment when it comes to grid connection requirements, as it was not system relevant. However, during the 1990s wind power development gained momentum, while the old regulations still were in place, disregarding system relevance aspects of wind power. This mismatch has led to large amounts of wind power connected to the grid; following requirements which were not suitable for large scale implementation. Eventually, this resulted in a significant threat for stable grid operation, consequences of a major disturbance became even more severe due to the contribution of wind power. The Irish moratorium on grid connection of wind power, in 2003, is an example of unfortunate consequence of inadequate grid code requirements.

The rising total share of wind power and the continuously growing system relevance, have been the reasons for the extension and adaptation of grid codes to include wind power generation. Thus wind turbine manufacturers and wind power plant developers were given stricter requirements. The most relevant requirement that has evolved is that wind turbines have to stay connected to the grid during disturbances, i.e. fault ride-through capability.

Currently, the European Network of Transmission System Operators for Electricity (ENTSO-E), which is an umbrella organization for European Transmission System Operators (TSO), is developing a set of network codes that will be implemented as European Law. These network codes define a common language and format; and are a contribution towards harmonization of grid codes within Europe.

2.2. Grid code in North Africa

Grid codes for generation units in many North African countries are determined on a case-by case basis. There is therefore a need for standardized grid codes in order to simplify the grid connection planning process. Currently, the general approach is to base the requirements on European grid codes, with appropriate modifications.

The electricity sector in the North African countries differ, and reflect each nation's market structure. A summary of current national market structures, institutions and regulations are given in Table 1 for Algeria, Tunisia, Libya and Egypt. In addition a brief description follows for each mentioned country.

Table 1
Current national market structure, institutions and regulations

	Algeria	**Egypt**	**Tunisia**	**Libya**
Reform	Under way with new law passed	Limited	Limited	None
Market structure	Single buyer with unbundling	Vertically integrated under the Egyptian Electricity Holding Company	Limited	Vertically integrated
Separate regulator	Yes	Yes, but without responsibility for tariffs	No	No
Open access	No	No	No	No
Grid code/distribution code	Yes/yes	Yes/no	No/No	No/no
Private sector participation	Yes, in generation and distribution	Yes, in generation	Yes, in generation	No
Tariffs	Subsidized	Subsidized	Subsidized	Subsidized

Algeria: On February 2002, with the approval of Law no. 02-01, the Liberalization of Algeria's electric sector has begun. The law contains requirements for unbundling the former vertically integrated utility, SONELGAZ; market model and participant responsibilities and roles [16]. Algeria has developed a single-buyer market model with the transmission grid planning and operation governed by the independent system operator (ISO) that is represented by SONELGAZ/OS. Four independent power producers (IPPs) with international ownership also took part in the Algerian power market. In addition, there are four distribution companies located in separate geographic regions across the country. Renewable energy and energy efficiency has been emphasized by the government. At present, renewable energy sources represent only a small proportion of the total energy generation. Algeria plans to develop 2,570 MW of renewable generation by 2020 and 12,000 MW by 2030 [16].

Egypt: The electricity sector in Egypt is controlled by the Ministry of Electricity and Energy. This governmental organism is responsible for the development of polity and the implementation of government decrees. The Electricity Utility and Consumer Protection Regulatory Agency is responsible for supervising the electricity sector. Its role is to enhance the operational, financial, technical and practical organisms of the electricity business. A schematic of the electricity sector is illustrated in Fig. 1 [16].

The electricity sector consists of executive authorities that are in charge of a specific mechanism of the electricity sector. The daily operations of the electricity sector which consist of generating, transmitting and distributing energy are carried out by the Egyptian Electricity Holding Company (EEHC) and its partners. The generation division consists of six companies owned by the government which include hydropower plants, renewable energy system plants, and four other companies classified by geographic area, comprising Cairo, West Delta, Upper Egypt and East Delta. In addition, in the generation sector, there are three other private companies with six IPPs. The transmission activities are managed by the Electricity Transmission Company that is owned by the government and acts as a single buyer of all generation. Energy is sold by the transmission company to nine regional distribution companies that are state-owned. Hence, this country has a single-buyer market model with elements of a monopoly model under the Egyptian Electricity Holding Company.

Tunisia: The generation of electricity, transmission and distribution has been supplied, till 2002, by one state owned, vertically integrated monopoly, company known as STEG (Société Tunisienne de l'Electricité et du Gaz). In 1996, the monopoly of STEG's has been ended by the Tunisian government to support private power generation. In 2002, a combined-cycle plant producing 471 MW at Rades started operation and was the first IPP. Two years after, the second IPP has also started operation. The most important participants in Tunisia's power sector today are STEG and the two IPPs. Fig. 2 illustrates the organization of Tunisia's energy sector.

This country developed a strategy for the promotion of renewable energy sources starting 1985. Relative to its neighbours, Tunisia has been early in shaping a progressive energy management strategy. In 2009, a solar plan was implemented in Tunisia with a purpose to increase the share of renewable energy systems and energy efficiency.

Libya: The energy generation, transmission and distribution are owned and controlled by the General Electricity Company of Libya (GECOL) which is a vertically integrated monopoly. The power sector is hence governed by GECOL as it is in charge of planning, policy, and regulation. Therefore, an independent regulatory authority does not exist in Libya’s power sector. In response to the rapidly growing energy demand, Libya has launched an aggressive generation and transmission expansion plan. The country has an ambitious plan to install generation capacity of 13,000 MW by 2020 [16]. In addition, to transmit the new generation to locations with increasing demand, Libya has started several transmission projects. These plans comprise studies for the expansion of international interconnections. At this time, the power sector's main role is to guarantee secure and sufficient supply of power to every part of the country. The objectives of Libya are to reduce technical and nontechnical losses, to develop service quality and efficiency and to reinforce interconnections with nearby countries.

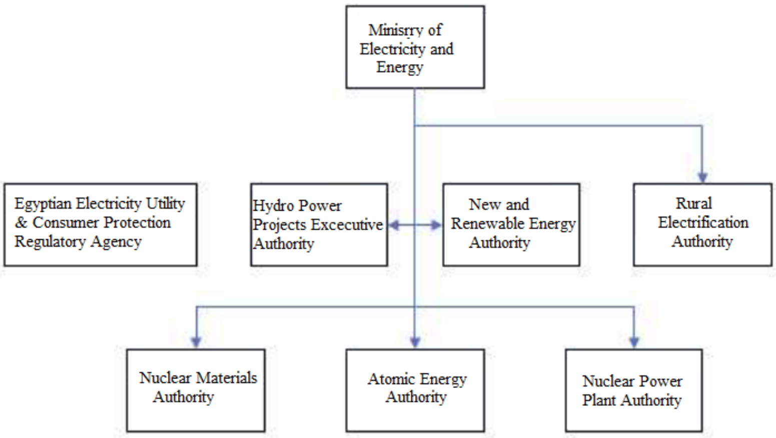


Fig. 1. Structure of Egypt’s electricity sector.

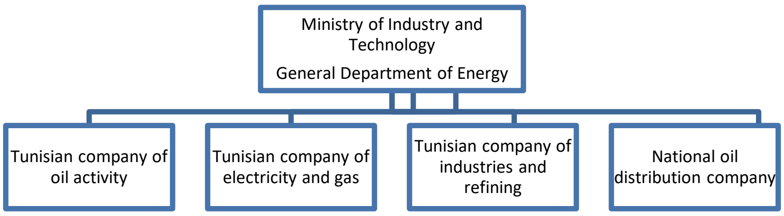


Fig. 2. Organization of Tunisia’s Energy Sector.

Morocco: The power sector of Morocco consists of private and public operators. The main players include the Office National d’Electricité (ONEE), independent power producers (IPPs), and the distributors. The principal role of ONEE is to operate and manage the transmission grid of the country, part of the distribution network, and its generators. ONEE holds power-purchase agreements (PPAs) with private producers.

Morocco's distribution sector includes both public and private companies. The electricity market activities are regulated by several ministries which include the Ministry of Interior, the Ministry of Energy and Mines, the Ministry of Economic Affairs, and the Ministry of Finance. According to Law Dahir 2-94-502, Morocco has a single-buyer market model. All generated power in Morocco is purchased by ONEE through power-purchase agreements. ONEE is also responsible for importing power from Algeria and Spain. The Moroccan power sector is organized as illustrated in Fig. 3.

To consider progress and allow for changes, Morocco has to make some regulatory and legal adjustments. Currently, Morocco does not have an independent regulatory authority. In addition, there is no published transmission tariff for making access to the transmission system. However, the country is working on a reform that will create a free market which will function in parallel with the regulated market. The Moroccan government supports renewable energy through various laws, met through a number of projects with targets relating to energy security and development [17].

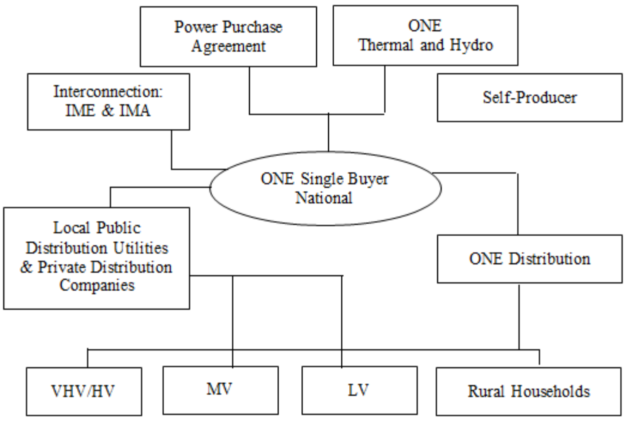


Fig. 3. The organization of the Moroccan Power Sector. IME=Interconnection Morocco–Europe; IMA=Interconnection Morocco–Algeria.

III. Grid code requirements in Spain, Morocco and Egypt

In this section, requirement for generators encountered in different grid codes will be discussed..

3.1. Spain – wind and solar power plants

The development of renewable energy technologies and green energy solutions involves both the governmental incentives towards these installations, but also the appropriate regulatory framework where the connection requirements are summarised. Generally, grid codes are demonstrated to satisfy the operational limitations and ensure the system security.

As far as the technical recommendations for special regime generation are concerned, emphasis is rather paid on wind power plants, however only few countries, like Spain Germany and Italy have elaborated technical requirements regarding PV installations. Fig. 4 shows the different limiting curves of voltage at the grid connection point for PVs in Spain, Germany and Italy, respectively. The German and Italian grid codes are stricter and more demanding since PV installations have to attend voltage dips deeper and shorter without tripping.

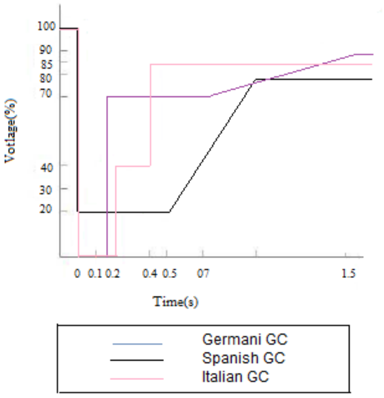


Fig. 4. Voltage limiting curves at the grid connection point for PVs.

In Spain, grid codes that concern wind power integration support that during faults, wind turbines must continue being connected permitting the protection system to clear the fault [18]. Wind power penetration at the distribution level mainly concerns local power inefficiencies. One of the major issues is to keep the steady-state nodal voltages within their acceptable limits (±5%). According to this reference point, wind integration in distribution level has to encounter the RD 436/2004 as appears in MITYC in 2004 [19,20]. “Metodología para la actualización y sistematizacióndelrégimenjurídico y económico de la actividad de producción de energíaeléctrica en régimenespecial”.

The Spanish System Operator, Red Electrica de España (REE), has numbered various technical specifications, like the Operation Procedure which was approved in October 2006 as "Requirements for response to voltage dips of production facilities under the special regime" (P.O.12.3) [21]. P.O.12.3 refers, mainly, to the acceptable voltage dips at the interconnection point with the transmission/distribution grid of a wind farm after a short circuit fault without tripping. These disturbances include both balanced and non-balanced faults; mainly due to single-phase-to-ground, two-phase to-ground and three-phase short-circuits.

However, a first draft of a new proposal, P.O.12.2, was launched in 2008 and then its updated version in 2010 under the title: "Technical requirements for wind power and photovoltaic installations and any generating facilities whose technology does not consist of a synchronous generator directly connected to the grid" [22-25]. The updated text is not only orientated to wind but also to PV power plants with a capacity greater than 10 MW and differs from the previous calls in the voltage-time characteristic according to the type of fault, while it is in effect since 2011. Additionally, this call requires for the first time a voltage controller for defining the reactive power support during voltages outside the normal operation range [26].

3.1.1. Performance under Normal Operation

3.1.2. Voltage and Frequency

According to the Spanish regulation RD 661/2007, the nominal frequency is 50 Hz and it allows a wide continuous frequency range of 48–51.5 Hz. For instance, the wind farms may stay coupled to the grid for frequencies below 48 Hz no more than 3 seconds (P.O.1.6). The disconnection time for over frequencies (>51.5 Hz) has to be agreed with the TSO. Wind Power Plants (WPPs) also need to operate with a range around the rated voltage. Fig. 5a represents the minimum periods that the plant must remain connected to the grid under variations in voltage/frequency during normal operations and/or disturbances [19].

3.1.3. Active and reactive power

The Spanish normative takes into account the participation in secondary control via power curtailments. In more details, the WPP needs to reach any set-point defined by the TSO, in addition to this; it should state the difference among the actual and the rated power when it operates in attenuated mode.

On the other hand, the reactive power control prerequisites require wind power plants to regulate the output reactive power Q in response to grid voltage variation, also known as Automatic Voltage Regulation (AVR). In general, the reactive power requirement is usually given in three different ways:

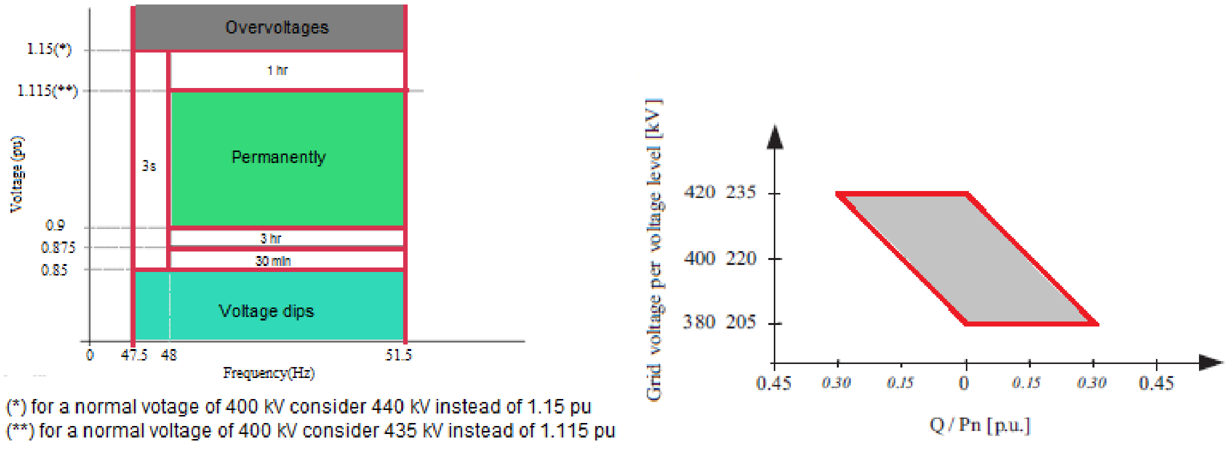
- Q control: The reactive power should be controlled independently from the active power at the point of connection.
- Power factor control: The reactive power is controlled proportionally to the active power at the point of connection.
- Voltage control: It is a function, which controls the voltage in the voltage reference point by changing the reactive power generation.

It should be stressed out that the reactive power control and voltage control functions are mutually exclusive, which means that only one of the above three functions could be activated at a time [27].

Under voltage control mode and in case the voltage is outside the range of ±5% of its nominal value, i.e. 0.95 or 1.05 pu, the installation injects/absorbs reactive power according to the voltage deviation and the reference point.

The requirements described herein concern high voltage values and are a function of the active power and transmission voltages as given beneath [28]:

- Minimum deviation of ±15 % of reactive power generation for all technical P range and nominal voltage.
- Minimum range of ±30 % of reactive power generation as a function of the voltage, as shown in Fig. 5b.



(*) for a normal votage of 400 kV consider 440 kV instead of 1.15 pu
(**) for a normal voltage of 400 kV consider 435 kV instead of 1.115 pu

Fig. 5. a) Voltage-frequency behavior, b) Voltage – reactive power correlation.

The voltage in an electrical system is regulated by all generators. The high penetration level of wind energy into the network requires an active participation from wind farms in voltage control scheme at the connection point, complying also with the TSO requirements.

The generators control the voltage through reactive power control. The direct relationship among the voltage difference and the reactive power is shown in the following equation:

$$\Delta V_{AB} = \frac{R \times P + X \times Q}{V_R} \tag{1}$$

As X>>R, the variations in reactive power affect at a higher rate the voltage drop than any variations in the active power P. This can lead to the disconnection of wind farms and may threat the system's power stability.

According to Real Decreto RD 661/200, the voltage control offers premium that ranges from -4% to 8% of 7.8441 c€/kWh to energy producers that operate for a power factor depending on the demand profile.

The RD. 436/2004 defines bonus and penalties for reactive power variable according to the time of the day (peak, medium and normal level) and expressed in percentage of the averaged price. The bonus can range from 4% to 6% if facilities maintain a unity power factor at the connection point. Table 2 represents the complement according the power factor and demand determination.

Table 2

Bonus according to power factor and load demand.

	Power Factor COS PHI	Peak	Medium	Low
Inductive	< 0,95	-4	-4	8
	<0,96 &>0,95	-3	0	6
	<0,97 &>0,96	-2	0	4
	<0,98 &>0,97	-1	0	2
	<1 &>0,98	0	2	0
	1	0	4	0
Capacitive	<1 &>0,98	0	-4	-4
	<0,98 &>0,97	2		
	<0,97 &>0,96	4		
	<0,96 &>0,95	6		
	< 0,95	8		

3.1.4. Performance under Distorted Regime

Grid disturbances like voltage sags or swells may lead to tripping of wind and PV power plants. In order to avoid this, grid codes requirements usually involve the following:

a) stay connected to the grid even if the voltage drops down to zero for up to 150 ms
b) contribute to voltage recovery by injecting reactive current
c) rise up the active power after the fault clearance

The typical features grid codes often call during fault incidents are the ones beneath:

a) Fault ride-through (FRT) capability, including both low voltage ride-through (LVRT) and high voltage ride-through (HVRT) of the system to recover to its pre-fault status, in addition to the time frame necessary for WPPs to withstand symmetrical and asymmetrical faults without disconnecting or even the conditions under which a disconnection from the grid in inevitable.
b) P and Q limitation during faults and recovery.
c) Reactive current injection (RCI) for voltage support during fault and recovery.

3.1.5. Fault ride-through capability – LVRT and HVRT control

According to Spanish P.O.12.3, WPPs and PVs need to remain connected within the area defined by the graph as is shown in Fig. 6a. The voltage drop is characterized by a voltage decay followed by a voltage recovery in two ramps with different slope. This voltage decay rises up to 20% of the nominal value for the first 0.5 seconds, followed by a voltage enhancement divided in two parts: firstly from 20% to 80% of the nominal value in the next 0.5 seconds and one from the 80% to the 95% of the nominal value in a total time of 14 seconds. Additionally, in case of a double-line-to- ground fault the voltage nadir does not drop beyond the 60% of the nominal value [26,29]. The minimum value of 0.2 pu derives from stability simulations and the maximum active power that can be lost by the Spanish power grid when a fault occurs, whereas the time interval of 0.5 s for the voltage dip complies with the general protection criteria of the Spanish electrical system. Additionally, the voltage recovery indicated above results from the under-voltage protection of non-renewable generators and is activated for voltages lower than 0.8 pu.

According to P.O.12.2, the magnitude and duration of voltage dips for single-phase, two-phase to ground and three-phase faults are depicted in Fig. 6b. The low voltage ride-through capability states that wind and PV power plants need to tolerate 0% remaining voltage dips until 150 ms without going out of operation. Furthermore, the aforementioned plants should be able to stand a voltage swell up to 130% at the connection point.

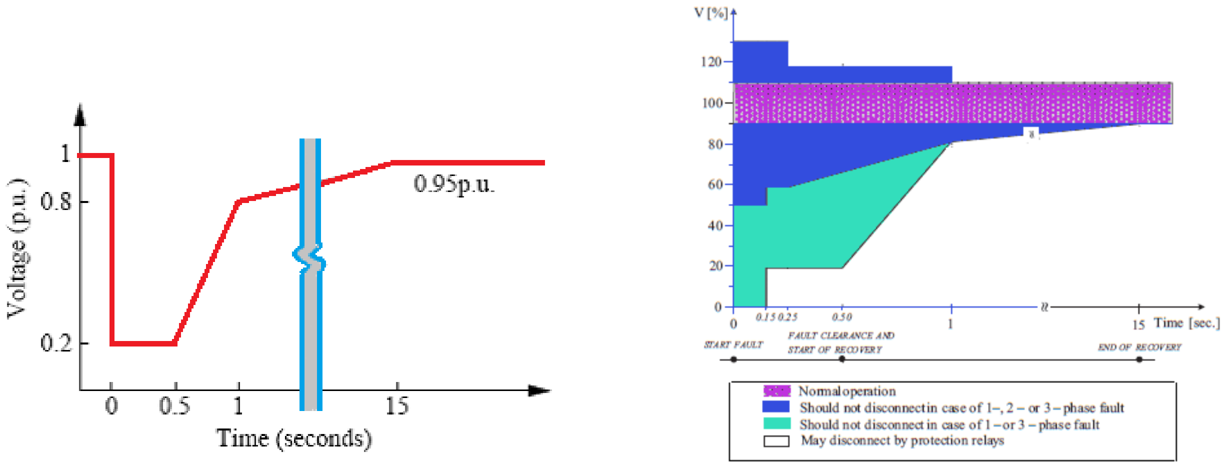


Fig. 6. a) Voltage behaviour after a short circuit incident according to P.O.12.3., b) Time-voltage profile as defined in P.O.12.2 draft. Minimum voltage dips to be supported by PV & Wind power plants without disconnection.

In the particular case of a two-phase to ground disturbance, there exists a different voltage-time curve to characterize the voltage dips. According to Fig. 6b:

- No disconnection is allowed within the blue area for one-, two- and three-phase faults.
- No disconnection is allowed within the green area for one- and three-phase faults.
- During the whole transient regime, the facility must be able to inject to the grid at least the nominal apparent current.

Fig. 7 correlates the voltage-time characteristics for the different Spanish grid code procedures. The P.O.12.2 draft entails more demanding requirements since both wind and PV farms must support deeper and longer voltage dips, but is still more relaxing in the special case of two-phase to ground faults.

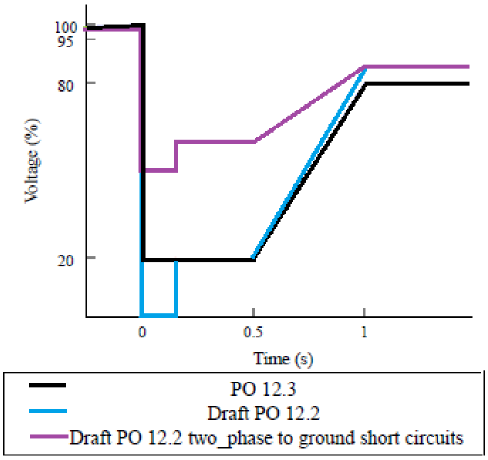


Fig. 7. Spanish grid code procedures: comparison of voltage-time limiting curves at the grid connection point.

3.1.6. P and Q requirements during faults and recovery

For both operational procedures, i.e. P.O.12.3 & P.O.12.2, the demand of active and/or reactive power is not allowed during periods of system failure and recovery following the fault clearance. All along the transient regime, the system needs to feed the grid with at least its nominal apparent power.

P.O.12.3 permits punctual consumption only when the conditions detailed in Table 3 and Table 4 are fulfilled [29].

As far as the P.O.12.2 is concerned there are some specific conditions which have to be met for the reactive and active power and are detailed below

- Momentary active or reactive power consumption (< 0.6 pu) is allowed during just the first 40 ms after the start of the fault and the first 80 ms after the clearance of balanced (three-phase) faults [22,30].
- Momentary active or reactive power consumption (< 0.4 pu) is allowed during just the first 80 ms after the start of the fault and the first 80 ms after the clearance of unbalanced (single-phase and two-phase) faults [22,30].

3.1.7. Reactive power control

Similarly to automatic voltage regulation (AVR) in conventional generators, PV and wind power plants need to supply reactive current when the voltage levels are found to be less than 0.85 pu, whereas they should not consume reactive power between 0.85 pu and the minimum voltage that allows a normal operation of the grid. The following need to be fulfilled:

a) The controller will be activated when the voltage ranges outside the normal operation limits
b) Throughout the short circuit incident, the power plant should inject/absorb reactive current according to the action of the voltage controller with minimum saturation levels defined by the curve ABCDE, as illustrated in Fig. 8a.
c) Within the operation limits of $0.85 \leq V \leq 1.15$ pu, the injected reactive current will be based on the voltage control, probably saturating the regulator limits.

Table 3
Punctual consumption during symmetrical faults.

SYMMETRICAL FAULT (THREE-PHASE)			
	During fault period of 150 ms since the fault is generated	During the first 150 ms from post-fault	
Reactive power produced per cycle (20 ms)	<60% of the nominal power	<60% of the nominal power	
Reactive current per cycle (20 ms)		Less to 1.5 times the corresponding current to registered nominal power	
Active power	Punctual consumption	Punctual consumption	Additional consumption <10% nominal power

Table 4
Punctual consumption during unsymmetrical faults.

UNSYMMETRICAL FAULT (TWO-PHASE AND SINGLE-PHASE)		
	During fault period of 150 ms since the fault is generated and during the first 150 ms from post-fault	Rest fault
Reactive power	Punctual consumptions	< to the reactive power equivalent to 40% of the nominal power registered during a period of 100 ms < 40% of the nominal power registered per cycle (20 ms)
Active power	Punctual consumptions	< to the active power equivalent to 45% of the nominal power registered during a period of 100 ms < 30% of the nominal power registered per cycle (20 ms)

3.1.8. *Active power control*

At the same time a disturbance occurs, the facility should restraint the active current injection within the grey area, as depicted in Fig. 8b. It can be easily seen that the active current limitation is a linear function of the active power that the plant was generating before the fault incident and of the voltage level.

Considering voltage levels lower than 0.5 pu, the active current can be dropped to zero. When current saturation happens, reactive current limitation given by voltage controller saturation precedes over active current limitation. For voltages higher than the normal operation, the facility will try to maintain the active power level prior to the disturbance. In addition, the gain of the active current controller should ensure a dynamic response (90% increment) in less than 40 ms for lower voltage figures of V < 0.85 pu and 250 ms for V > 0.85 pu.

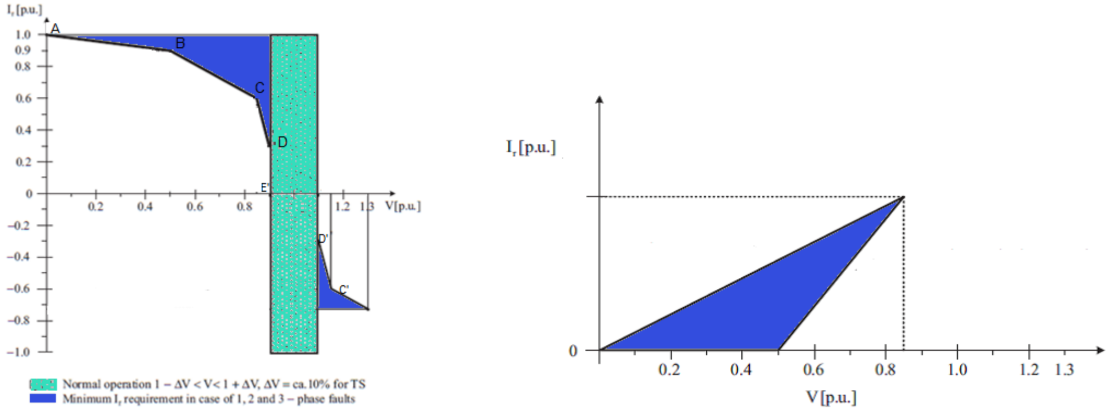


Fig. 8. a) Reactive current generation/consumption according to voltage profile, b) Active current limitation

3.2. *Morocco*

Grid codes for transmission network are concerned by the control of electrical system which includes frequency and voltage control, as well as farm behavior in abnormal network conditions. In the contrary, small production units which are connected to the distribution network, are concerned by the power quality, the contribution Pcc and the protection system. The common requirements of "Grid Code" include Fault Ride Through (FRT or LFRT) (behavior towards voltage sags), limits in terms of voltage and frequency, regulation of active power and frequency control, regulation of reactive power, in addition to power factor and voltage control. In the case of Morocco, these technical requirements are still under development. Morocco has no written down, standardised grid codes. Rules for connection are determined on a case-by-case basis in agreement with the grid owner ONEE.

3.2.1. General Requirements

The Moroccan system operator has various technical specifications in case of disturbances generated at the common connection point. According to the IEC technical report 61000-3-7, the limit values for flicker in high voltage (HV) and extra high voltage (EHV) networks are Pst = 0.8 and Plt = 0.6 [30]. Concerning harmonics, the limit values of the levels of harmonic voltages (in percent of nominal voltage) HV and EHV are presented in Table 5.

Wind Farms in Morocco must have the ability to withstand voltage unbalance. The voltage unbalance factor is given by the ratio of the negative sequence component of the voltage to the direct component. The unbalance limit value for extra high voltage is 1% [31].

Table 5

Limit values of the levels of harmonic voltages (in percent of nominal voltage) HV and EHV

Odd Order not multiple of 3		Odd ranks not multiple of 3		Even Order	
rank h	Harmonic Voltage (%)	rank h	Harmonic Voltage (%)	rank h	Harmonic Voltage (%)
5	2	3	2	2	1.5
7	2	9	1	4	1
11	1.5	15	0.3	6	0.5
13	1.5	21	0.2	8	0.4
17	1	>21	0.2	10	0.4
19	1			12	0.2
23	0.7			>12	0.2
25	0.7				
>25	0.2+0.5×25/h				
Total rate of harmonic distortion : 3% en HV -EHV					

3.2.2. Fault ride Through (FRT or LFRT)

The RE park should be strong even in case of voltage dips ranging up to 0% of V_n for some countries for a specific duration. It must at the same time contribute to the rapid restoration of P/Q to the original situation before default after voltage recovery. Some counties require an increase in reactive power during disturbance to support tension (as the case of conventional machines). These characteristic differs from one country to another according to the network and the protection system. Wind farms, in Morocco, must be able to resist voltage dips down to 20% of the nominal voltage over a time span of 600ms [32], see Fig. 9.

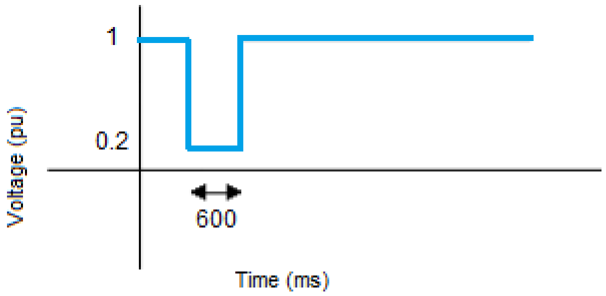


Fig. 9. Fault ride-through curve for wind power

3.2.3. Active power and frequency control

The park should have the ability to contribute to the regulation of active power according to the frequency deviation from the nominal frequency. In the case of Germany, for example, for frequency greater than 50.2 Hz, the park has to gradually reduce its power output to 40% of power available for each deviation of 1 Hz. The British code expects that the park should have a frequency control system to help primary and secondary control. For Morocco, the park must continue to provide full power regardless of frequency.

3.2.4. Reactive current Requirements during voltage dips

The supply of reactive power is important for voltage stability. Its influence on the voltage level depends very much on the power of CC network. There exist several modes of regulation which include connection point voltage, power factor, and reactive power at the connection point. The wind farm should allow the provision and uptake of reactive power. The absorption should be at least between 0 and 0.3Pn and the supply must be at least between 0 and 0.4Pn where Pn is the rated power of the farm [31].

3.2.5. Operating limits for voltage and frequency

Parks must operate continuously for variations of frequencies and voltages that remain within predefined ranges. But also, for a limited time under conditions outside the stated ranges. During small variations in frequency at the grid connection point, generators are required to remain connected and operating. The Moroccan system operator specifies this range. The normal conditions in frequency variation are 50 ± 0.1 Hz while the degraded conditions are 50 + 1 Hz / – 2.5Hz.

The wind farm must be able to resist voltage dips down to 20% of the nominal voltage over a time span of 600ms. Fig. 9 presents the Fault ride-through curve for wind power. Concerning the reactive current requirement during voltage dips, grid codes recommend that wind parks provide support for the network by the production of reactive power during failure to maintain and recover the voltage. Even the parks must go beyond 100% of their capacity in terms of production of reactive power.In addition, the wind farm must be able to resist to voltage variation depending on the network type as illustrated in Table 8 [31].

3.3. Egypt – wind power

The requirements specified in the following section are the minimum requirements that should be fulfilled by a wind farm at the grid connection point. The grid operator has the authority to disconnect a wind farm from the grid in case this later does not fulfill the requirements specified in the grid connection code. The reconnection of this wind farm should be agreed with the grid operator. For a stable and safe operation of the grid, the grid operator is authorized to change the following requirements or to provide further ones.

3.3.1. Power Quality Requirement

All wind farms should comply with the requirements presented in this section. The voltage wave-form quality must be maintained by wind farms at the grid connection point. In the event of voltage deviation from its permissible voltage range at the grid connection point, wind farm shall be capable of delivering available active power according to wind conditions when the voltage remains within the ranges stated in Table 6. Wind farm automatic disconnection from the grid is prohibited.

If required by the grid operator, a wind farm shall be able to disconnect automatically from the grid at stated voltages. Automatic disconnection settings and terms are agreed with the grid operator [33].

Table 6
Minimum time periods.

Voltage range	Time period for Operation
0.85 pu-0.90 pu	Unlimited
0.90 pu-1.10 pu	Unlimited
1.10 pu-1.15 pu	30 minutes

In the event of a frequency deviation of the grid from its allowable value, wind farm automatic disconnection from the grid should be prohibited due to the deviation within the frequency range of 47.5 Hz until 51.5 Hz [33].

According to IEEE 519, the maximum level of harmonic voltage and current distortion should be as presented in Table 7. Tables 8, 9, and 10 illustrate maximum level of Harmonic current distortion from wind farms [34]. The total distortion in Table 8 is the maximum level of harmonics current distortion of all generating equipment irrespective of the actual I_{sc}/I_L.

Table 7

Maximum level of harmonic voltage distortion.

Voltage Level	**Level of harmonic voltage distortion**	
	Odd Harmonies %	Total Harmonies %
More than 161KV	1.0	1.5
69.001- 161KV	1.5	2.5
Up to 69 KV	3.0	5.0

Table 8

Maximum level of integer harmonic current distortion in the frequency range up to 2 kHz.

Short circuit ratio	**Maximum integer harmonic current distortion as percentage of I_L**					
	Odd harmonic distortion					**Total* Distribution**
I_{sc}/I_L	**<11**	**≥ 11 to <17**	**≥ 17 to < 23**	**≥ 23 to < 35**	**≥35**	
<50	2.0	1.0	0.75	0.3	0.15	2.5
>50	3.0	1.5	1.15	0.45	0.22	3.75

Table 9

Maximum level of harmonic current distortion in the frequency range above 2 kHz

Short circuit ratio	**Maximum harmonic current distortion in the frequency range above 2 kHz as percentage of I_L**					
I_{sc}/I_L	2 kHz ≤f≤ 3 kHz	3 kHz ≤f≤ 4 kHz	4 kHz ≤f≤ 5 kHz	5 kHz ≤f≤ 6 kHz	6 kHz ≤f≤ 7 kHz	7 kHz ≤f≤ 9 kHz
<50	0.3	0.25	0.2	0.15	0.12	0.1
≥50	0.6	0.5	0.4	0.3	0.25	0.2

Table 10

Maximum level of inter-harmonic current distortion up to 2 kHz.

Short circuit ratio	**Maximum interharmonic current distortion as percentage of I_L**			
I_{sc}/I_L	**<0.5kHz**	**0.5 kHz ≤f≤ 1 kHz**	**1kHz ≤f≤ 1.5kHz**	**1.5kHz ≤f≤ 2 kHz**
<50	0.3	0.25	0.15	0.1
≥50	0.45	0.4	0.25	0.2

Here Isc is the maximum short circuit current at grid connection point, I_L represents maximum load current (fundamental frequency component) at the grid connection point and the maximum level of even harmonics is 25% of odd harmonics.

The flicker that is caused by wind farms at the grid connection point must be within the limits presented in Table 11 [35].

Table 11

Flicker Factor

Term	flicker factor
Short Term (10 minutes)	$P_{st} \leq 0.35$
Long Term (2 hours)	$P_{lt} \leq 0.25$

Concerning the voltage unbalance and fluctuations, wind farms must have the ability to withstand voltage unbalance beyond 2%. The voltage fluctuations are typically caused by the switching operations in a wind farm, such as the start and stop of wind turbine generator and because of inrush currents during wind turbine generator starting. The maximum voltage fluctuation is 5% from the voltage nominal value [33]. The voltage at the grid connection point for wind farms shall not vary for more than ±5% of nominal voltage.

If required by the grid operator, a wind farm shall be able to disconnect automatically from the grid at stated voltages. Automatic disconnection settings and terms are agreed upon with the grid operator [33].

In the event of a frequency deviation of the grid from its allowable value, wind farm automatic disconnection from the grid should be prohibited due to the deviation within the frequency range of 47.5 Hz until 51.5 Hz [33].

The frequency and the voltage limits within which the wind plant shall only connect to the grid are between or equal to 48 Hz and 50.2 Hz for the frequency, while the voltage is between or equal to 0.95 per unit 1.05 per unit.

3.3.2. *Active power control*

Because of the variations in the grid frequency or the voltage at the grid connection point, the wind plant is not permitted to reduce power output within the range 47.5 Hz up to 50.2 Hz of frequency for the time periods presented in Fig. 10a. In the case of over frequency, grid frequency ranging from 50.2 Hz to 51.5 Hz, active output power of the wind turbine generator must be reduced by 40% of the actual active output power as illustrated in Fig. 10b.

The following Equation gives the reduction of the output power [33]:

$$\Delta P = 0.4PM\frac{\Delta f}{Hz} \tag{2}$$

Where PM is the actual output power prior to the exceeding of 50.2 Hz grid frequency and Δfis the actual grid frequency minus 50.2 Hz.

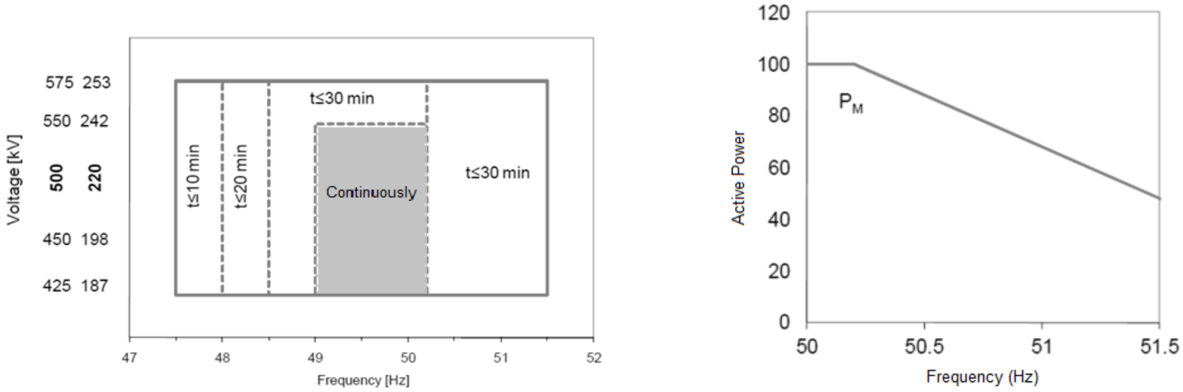


Fig. 10. a) Output power Requirements in case of grid frequency and voltage variations , b) Reduction of active power due to over frequency

The active output power of a wind farm must be reduced on request of the utility grid operator in the following cases:

- Possible risk for a safety grid operation
- Risk of overloading and bottlenecks
- Risk of islanding
- Dynamical or statistical Loss of grid stability
- Maintenance.

To reduce the active output power, the wind farm must have at the grid connection point, an input signal for a set-point value provided by the grid operator. This signal must be followed by the wind plant within one minute in the case of a reduction of active output power. The Wind plant should have the ability to decrease the active output power within steps of maximum 10% of rated power of the wind plant. In addition, the wind farm can be disconnected from the electric grid in case the output power is below 10 % of rated power. The active output power reduction must be at a rate of 20 % of rated power. The connection agreement of the wind farm agreed on with the grid operator contains more details of the technical solution of the set-point signal [33].

3.3.3. *Reactive power control*

At the grid connection point, wind plants must have the ability to regulate the reactive power within the range of 0.95 lagging to 0.95 leading at maximum active power as illustrated in Fig. 11. This requirement is applicable to wind farms with high-voltage terminals at grid connection point. Reactive power is controlled by wind plants with the following method [33]:

- Set-point control of reactive power Q
- Set-point control of power factor (cos φ)
- Fixed power factor (cos φ)
- Characteristic: power factor as a function of active power output of the wind farm, cos φ (P)
- Characteristic: reactive power as a function of voltage, Q(U)

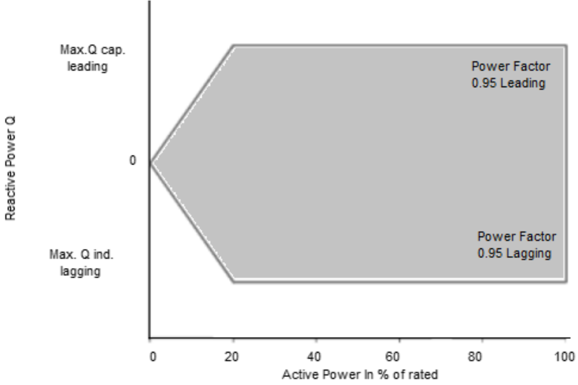


Fig. 11. P-Q Diagram,

The connection agreement determines the mode of operation of reactive power control. To control the reactive power or cos φ, the wind farm must have at the grid connection point, an input signal for a set-point value provided by the grid operator. This signal must be followed by the wind plant within one minute. With respect to reactive power capability below rated capacity of the wind plant, and when operating at an active power output below the rated capacity of the wind farm (P<Pmax), the wind plant shall be able to be operated in every possible operating point in the P-Q Diagram, presented in Fig. 11. Taking into account losses related to the transformed, the auxiliary service power and the wind plant cabling, reactive power supply at the high-voltage terminals must completely match with the P-Q Diagram, even at reduced active power output. The maximum Qcap. and Qind. are determined from the rated power of the wind plant and the power factor of 0.95, see Fig. 11 [33].

3.3.4. Temporary voltage drops

In the occurrence of short voltage drops caused by grid faults, Wind turbine generators are not allowed to disconnect from the grid. In the case of temporary voltage drops, wind generators must ride-through the grid fault without disconnecting from the grid when at least one of the three phase-to-phase voltages is above the curve presented in Fig. 12.

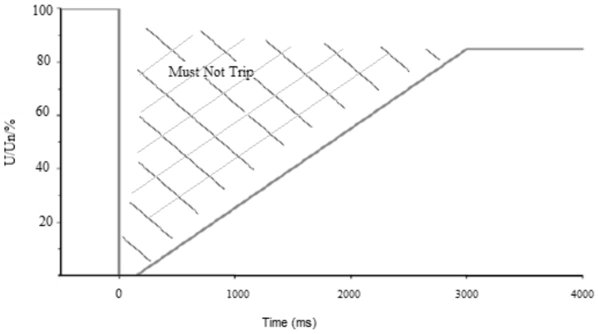


Fig. 12. Fault ride through profile for a wind farm.

The wind plant is not permitted to disconnect from the grid in case of voltage drops above the curve.

The reactive power or reactive current requirements that must be fulfilled by wind turbine generators during the temporary voltage drop are:

1) In the case of 3-phase faults, the injection of reactive current by the wind turbines must be performed according to Fig.13. The turbines must inject reactive current for the time period 150 ms until fault clearance [33].

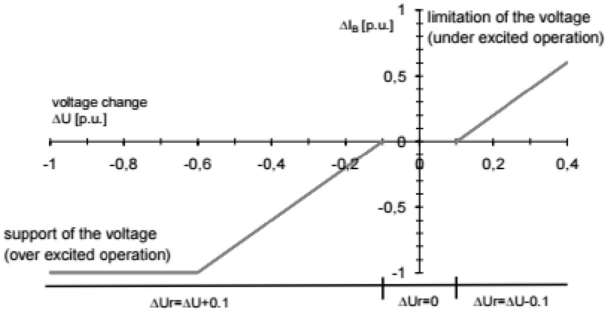


Fig. 13. Current injection during the fault

The required minimum reactive current is presented in Fig. 13 and is expressed by the ratio of the reactive current and the nominal reactive current in per unit, against the voltage drop, expressed by the ratio of the actual voltage value and its nominal value in per unit [33]

$$\frac{\Delta I_B}{I_N} = k\frac{\Delta U_r}{U_N} \tag{3}$$

$$\Delta U = U - U_0 \tag{4}$$

Here U_N represents rated voltage, I_N rated current, U voltage during fault, I_B is required reactive current change during fault U_0 pre-fault voltage, and U_r stands for relevant voltage change during the fault. The k factor ranges from 0 to 4 while its preferable setting is 2.

2) Wind turbine generators requirements for 2 phase and 1phase faults during the time period 150 ms after the fault entrance until fault clearance are:

- Consumption of reactive power below 40 % of rated power
- Consumption of active power below 30 % of rated power each grid cycle (20 ms).

The wind farm must, after fault clearance, have an active power that has same level as before the fault's occurrence. This should be reached within a time period of 10 s after fault clearance. The consumption of reactive power after fault clearance must be equal or below the reactive power consumption before the fault.

Two temporary voltage drops may occur in case of non-successful auto-reclosures as illustrated in Fig. 14. The requirements presented in Table 15 should be followed by the wind farm in order to ride-through the two successive voltage drops. The maximum allowed times, when automatic reclosing is applied, are presented in Table 12.

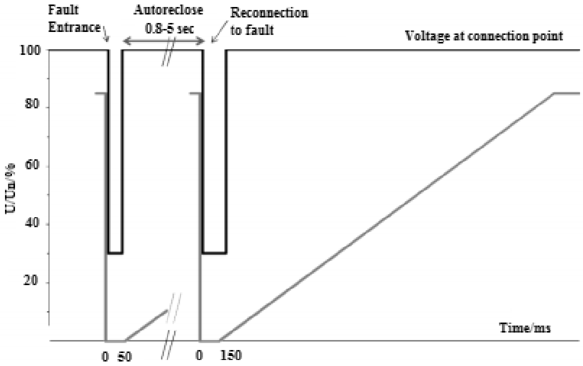


Fig. 14. Voltage drops caused by non-successful auto-reclosure

Table 12
Auto-reclosure time range

Case	500kV- Single phase Trip and reclose	500kV-Three phase Trip and reclose	220kV-Three phase Trip and reclose
Fault Occurrence	60 ms	60 ms	80 ms
Single phase trip	80 ms		
Single phase reclose after	800 ms		
Evolving fault clearance	200 ms		
Permanent fault	60:80 ms		
Three phase trip		80 ms	100 ms
Three phase reclose		5000:6000 ms	500 : 100 ms
Reclaim time	Not less than 200 sec		

3.3.5. Grid protection

The protection code specifies the grid protection techniques that should be performed by wind farms. The grid protection device in wind farm must have a setting which conforms to the grid protection setting started in the grid code see Table 13.

Table 13
Setting of the grid protection

Function	Setting range	Recommended setting	
		Level	Setting time
Overvoltage U >>	1.00 – 1.30 U_n	1.20 * U_n	≤ 3s
Undervoltage U <	0.10 – 1.00 U_n	0.80 *U_n	3s
Undervoltage U <<	0.10 – 1.00 U_n	0.30 * U_n	300 ms – 1 s
Overfrequency	50 – 52 Hz	51.5 Hz	≤ 100 ms
underfrequency	47.5 – 50 Hz	47.5 Hz	≤ 500 ms

IV. Comparison of grid codes

A comparison of the different technical requirement for the interconnection of wind farm in Spain, Morocco, and Egypt is discussed in this section. Four requirement categories are being compared which include Fault-ride through requirements, dynamic regulation during fault, requirements for reactive current supply during voltage dips, and voltage/frequency operating range.

4.1. Fault-ride through requirements

The Spanish grid requirements does not permit wind farms to absorb reactive power during and after three phase faults, as well as in the period of voltage recovery after fault clearance. However, the absorption of reactive power can be allowed during a duration of 150 ms after the beginning of the fault, and a duration of 150 ms after clearance of the fault (only if 60% of rated power is not being exceeded). In addition, the active power must not be absorbed by wind farms during the fault and in voltage recovery period after the clearance. Nevertheless, during a period of 150 ms after the beginning of the fault, and a period of 150 ms after fault clearance, the absorption of active power is permitted. The consumption of active power is allowed with a maximum of 10% of rated power during three-phase faults.

Wind farms in Spain must be able to resist voltage dips down to 20% of the nominal voltage over a time span of 500 ms. Similar characteristics can be observed in the requirement governing wind farms connection in

Morocco. The minimum voltage level during faults is 20%. However, wind farms are obliged to remain connected for faults duration of 600 ms. The Egyptian grid code requirement is more demanding as it requires wind farms to remain connected during voltage dips down to 0%. It stipulates that wind farms must remain connected to the electric grid for faults duration of 150 ms. During the fault, the maximum voltage sag duration is 3 s. However, if the fault continues longer than the standard clearing time, disconnection of wind turbines is allowable. Table 14 presents a comparison of LVRT characteristics in different grid codes.

Table 14
LVRT characteristics in different grid codes

Country	**Fault Duration (ms)**	**Min Voltage level (% of Vnom)**	**Voltage restoration**
Spain	500	20	1
Morocco	600	20	Not Available
Egypt	150	0	3

4.2. *Dynamic regulation during fault*

The requirement for capacitive current injection for the Egyptian grid code during faults was shown in Fig. 13. According to this grid code, capacitive reactive current must be supplied by wind farms during three phase faults between 10-60% drop in grid voltage and after the origin of the voltage dip with 150 ms. This supply should be performed with a specific rate of the rated current for each voltage drop of 1%. On the other hand, Spain requires maximum reactive current injection during three phase faults. However, for two and one phase faults, the maximum permitted consumption of reactive power is 40% of the rated power after the fault entrance by a 150 ms period. In addition, the maximum consumption of active power in each grid cycle is 30% of the wind turbine rated power. Concerning Morocco, there is a lack of such relevant information in the Moroccan interconnection requirements.

4.3. *Requirements for reactive current supply during voltage dips:*

The Spanish grid code stipulates that wind farms must stop absorbing reactive power within 100 ms of voltage drop, and are required to inject reactive power within 150 ms of grid recovery. According to the Egyptian grid code, the reactive power must be regulated by wind farms at the grid connection point within the range of 0.95 lagging to 0.95 leading at maximum active power. The absorption in the Moroccan connection requirements should be at least between 0 and 0.3 of the wind farm rated power and the supply must be at least between 0 and 0.4 of the rated power.

4.4. *Voltage and frequency operating Range*

The nominal frequency according to the Spanish grid code requirements is 50 Hz and it permits a large continuous frequency range of 48–51.5 Hz. Below frequencies of 48 Hz, for example, wind farms must not stay coupled to the grid for more than 3 seconds. On the other hand, the normal conditions of frequency variation for wind farm connected to the Moroccan grid are 50 ± 0.1 Hz, while the degraded frequency conditions are 50 + 1 Hz /-2.5Hz.

Compared to other countries, Egypt specifies in its grid code that in the occurrence of grid frequency deviation from its allowable value, wind farm automatic disconnection from the grid should be forbidden because of the deviation within the frequency range of 47.5 Hz until 51.5 Hz. Wind plants should only be connected to the grid within a frequency between or equal to 48 Hz and 50.2 Hz, and a voltage between or equal to 0.95 per unit 1.05 per unit.

Another important difference lies in the withstand voltage unbalance required by the Egyptian and the Moroccan grid requirement. Whereas, wind farms in Morocco must have the ability to withstand voltage unbalance of 1% for the extra high voltage, Egypt requires wind farms to withstand a voltage unbalance beyond 2%.In addition, according to the Egyptian grid code, the voltage at the point of common coupling should not change more than ±5% of its nominal value. In the event of over frequency, the active power supplied by wind turbine generator has to be decreased by 40% of the actual output.

V. Recommendations on the development of grid codes for renewable energy in Northern Africa

5.1. Barriers facing North African Countries

This section discusses important technological, economic, regulatory and institutional barriers preventing the emergence of a regional market in North Africa. Collective measures to remove these are summarised below in Table 15.

Table 15
Summary of challenges facing North African Countries with recommendations

Challenges	Recommendations
Regulations:	
-Lack of standards and norms -Non-harmonized regulations -Low third-party access to the grid -Low capacity of the electrical grids	-Harmonize electric grid codes -Establish a coherent regional regulatory framework (conditions for electricity trade, regulation, etc.)
Technical	
-Weak interconnection capacity -Organization and management of interconnections	-Strengthen existing inter connections and extend to countries not yet connected (e.g. Mauritania)
Institutional	
-Low command of technologies -Lack of competence	-Strengthen the regional capabilities for integration of RE in electrical networks (regional plan for connecting RE to the grid) -Adopt a common negotiating position with the EU
Economic	
-Management of price distortions in the sector -Fossil fuel subsidies	-Gradual reduction of subsidies -Communication and public awareness -Financing mechanisms to be implemented

5.1.1. Physical Infrastructure Barriers

The majority of North African countries are facing challenges due to rapidly increasing power demand. The lack of generating capacity creates insufficient reserve margin that might lead to critical system operations. Even though there is a significant increase in installed capacity, available capacity to meet the peak demand and maintain an adequate reserve margin remains the key component. Hence, during peak demand, systems are under huge pressure because they run under very small reserve margins which are negative in most countries. This issue could lead to unstable system performance and ineffective operations.
Possible implications caused by insufficient generation capacity are summarized below:

- Reliability risk: This is a system security issue. It occurs when the system is unable to meet the demand or when it does not securely handle unexpected disturbances. Therefore, to maintain the security of supply at the national level, operators of power grids in North African countries could be required to disconnect cross-border interconnections and to apply load shedding actions.
- Stability Risk: operators have to maintain system synchronism by controlling voltage and frequency and hence maintaining stability of the synchronized power grids. Consequently, they have to achieve both active and reactive power equilibrium in order to maintain frequency and voltage respectively. The lack of adequate reserve margin, in most North African countries, leads to imbalance between the demand and the generation; which creates non-equilibrium in active power and thus results in deviation from standard frequency. Even if Egypt has a synchronized system, the share of surplus power to boost spinning reserve is limited because of the deficiency of available generating capacity. In addition, rigorous frequency control would be required to maintain the standard frequency of the system due to the lack of generating capacity.
- Low system inertia: Some North African power grids have very low system inertia. The synchronization to high inertia system in these power grids is very complex. This issue would involve some major reinforcement to secondary frequency control at the generation side before full synchronization of the entire North African power grids.

5.1.2. Transmission Network Access

Transmission operation is managed as part of a vertically integrated system, under a ministry in most of the power grids in North African countries. Third party access to power grids has been blocked by the lack of regulatory rules and the organizational attachment of the transmission. Consequently, to attract market players such as industrial consumers, IPPs, and traders would necessitate transparent and non-discriminatory market rules. The organizational inflexibility barrier contributes to the slow development of North African countries' electricity market. The development of the market and the synchronization process would be facilitated by the independence of the transmission, with well-defined responsibilities and decision-making authority over system operations.

5.1.3. Non-binding Trading Arrangements

The trading arrangements currently used between the system operators of the synchronized power grids are bilateral. Agreements do not include binding articles for trading electricity in bulk amounts. Most of them appear to limit electricity trade to exchanges during emergency operations. Therefore, the current trading arrangements of North African countries limit the attractiveness of electricity trade.

5.2. Recommendations

This section summarizes recommendations towards the development of North African grid codes. Those that are suitable for each country's specific conditions and for the integration of renewable energy.

5.2.1. The need for grid codes

In the past, and in many countries still, the electricity sector has been a vertically integrated and state-owned monopoly including power generation, distribution and supply. In this situation, the specification of power plant and equipment connected to the grid was selected according to need and cost-benefit analyses. Specifications included location, fuel type, control systems and other technical details.

With the splitting up of state-owned monopolies into multiple companies with a separation of roles and responsibilities (unbundling) and the introduction of competition through market liberalisation, many different companies become active in the sector, including power generation companies. This has led to a need to specify general rules and requirements, i.e. grid codes: In an unbundled electricity sector, grid codes are needed to clarify the distribution of responsibilities, and to ensure the safe, secure and economic operation of the grid.

Grid code requirements for generators are particularly important with increasing renewable energy integration. Renewable generation changes fundamentally the power system; and it is important that critical issues are anticipated and avoided in a timely fashion. Ireland is an example where wind power was allowed to develop with inadequate connection requirements, leading to an abrupt stop in 2003 of wind integration due to system stability concerns. To release this moratorium a grid code for wind was developed. Moreover, renewable generation is often made up of more and smaller plants, making it inefficient to specify requirements on a case-by-case basis.

5.2.2. Education

Proper understanding of what is needed and what is possible is essential in any development process. For grid codes, this involves cross-disciplinary education where all actors achieve a certain level of understanding of the power system and each other's concerns. This includes generation technologies, operational strategies, economics, laws, regulations, and other fields. For example, system operators should learn about technical capabilities and limitations of renewable energy. Universities have an important role to play in this, producing graduates with high expertise in the relevant disciplines. But expertise in each area is not sufficient in itself. It is crucial that this expertise is brought together and shared amongst all grid code stakeholders.

5.2.3. Stakeholder involvement

This point is a continuation of the one above on education. In order to arrive at best decisions with good compromises, it is important that the views of all stakeholders are shared and discussed. This may happen in multiple ways. Formal discussions and negotiations are only a part of it. To facilitate this process, there should be one or more forums or working groups; where everyone are brought together to share views and ideas. Informal meetings can be very efficient in order to explore new ideas.

Standardisation agencies with experience in developing national standards, such as e.g. IMANOR in Morocco, may have a natural role in this. A standardisation committee tasked with writing a national standard for grid connection may be a good basis for a national grid code.

5.2.4. Governance

How the development and maintenance of grid codes should be governed is a question that needs to be answered. There should be a well-defined, transparent and open process, involving relevant stakeholders as pointed out above. The grid codes will have cost impacts on users and stakeholders that will affect customers' energy bills. The costs may also determine the competitiveness of different market actors, such as generators. In order to balance different interests, good governance of the grid code development process is important.

Guiding principles could be:

- A code Panel should represent all stakeholders with independent chair.
- Any stakeholder should be able to raise a modification.
- Informal workshops are a good way to test challenges, ideas or proposals for changes to the Code.
- Working groups with experts should be appointed where appropriate.
- Changes should be consulted on.
- Consultation should be meaningful and take account of responses.
- The National or Regional / EU Regulator should have final decision, if industry does not agree on a change.
- Changes should not be implemented retrospectively.
- Changes should allow sufficient notice period for new requirements to be designed, specified, contracted and delivered.
- There must be an option for exemptions.

5.2.5. Standardisation

Standardisation of codes means the existence of well-documented and predictable grid codes that apply to all within a country or region. Power generation from wind and solar energy is typically made of small generating units, i.e. wind turbines or photovoltaic arrays. A wind turbine is not generally custom-made for a particular installation. The application of standard solutions and economy of scale is important for the minimisation of manufacturing costs. This means that when manufacturers design their generating units and systems, they must anticipate and account for different conditions, including different grid connection requirements. In order to allow for designs that can fit in different markets, it is critical that the grid connection requirements are known i.e. well documented and not subject to sudden changes. Predictability is probably more important than similarity, although it helps that grid codes are formulated using the same nomenclature and that the requirements are largely the same. Predictable, standard requirements helps the supply industry to know what is needed, and therefore helps the creation of a healthy supply chain that can provide components at minimal costs, suitable for a big market.

Standardisation of requirements moreover contributes to a level playing field, where different developers and technologies can compete without unfair bias.

5.2.6. Harmonisation

Harmonisation of codes means that grid codes in different countries or regions are formulated with the same technical definitions and are largely the same, in terms of scope and structure. Specific requirements may be different, as appropriate for each individual power system. Harmonisation of grid codes is another step from standardisation within a single area.

In Europe, there is an on-going effort to harmonise grid codes to support a well-functioning single electricity market. This process is driven by the ENTSO-E umbrella organisation for European TSOs. These so-called Network Codes provides a structuring of codes, definitions and basic requirements that can be readily adopted by North African countries. This will help in the communication and transfer of knowledge and technology. Although not members of ENTOS-E, it is therefore recommended that North African countries align with this process.

5.2.7. Grid code vs. market solutions

Codes are not the only option to achieve a safe, secure and economic operation of the grid. It should also be investigated of what can be achieved through market-based solutions, i.e. an ancillary services market. A market enables actors to participate on a paid-for basis, earning revenue by supporting grid stability. As in markets, in general, it allocates resources in an efficient way, allowing generators and other facilities to benefit from their individual strengths in terms of controllability and flexibility. However, this requires that the ancillary services market is well designed and that there is a sufficient number of potential participants and competition that it will actually function. This is probably easier in already well-established liberalised electricity markets than in newly markets.

The main difference is that grid codes demands universal technical capabilities, whereas ancillary services markets pays for technical capabilities on a voluntary basis. Codes put the same requirements on all generators, disregarding the extra costs it puts on different types of generators and whether all requirements are needed in all locations. A market that is more flexible, may ask for different capabilities in different areas, and may change more rapidly over time as needs change.

The recommendation here is that market solutions should be considered as an alternative to strict grid codes. Grid codes are clearly important and for many requirements the only viable way to ensure that those will be satisfied, but for less universally needed capabilities, codes may be inefficient, raising the costs of electricity supply unnecessarily, and hindering renewable energy integration. For example, need for reactive power support is locally dependent and it is better to pay for this where it is needed, than requiring the capability to do so from all generators everywhere in the grid.

5.2.8. Scope and structure

Different countries have grid codes with different scopes, and when developing new codes it is a relevant question how much they should include. For example, should they also cover electricity market design and market rules? In order to simplify communication and facilitate harmonisation with Europe, it is recommended for new grid codes being developed in North Africa that the structure of the ENTSO-E Network Codes already adopted.

5.2.9. What should be included in the code

The *required* behaviour of generators and other facilities connected to the grid should be something less than the *desired* behaviour. Although it may be tempting to add requirements or make requirements stricter for the sake of improved system safety and security, there is a balance due to the costs of imposing too many requirements. Requirements that have little benefit should not be included in the code. In general, before defining requirements, it is important to learn about what is really needed. Too many standard requirements are inefficient, giving an unnecessarily costly power system.

It is always an option to leave things out of the code, and instead impose additional requirements on a case-by-case basis when needed. This is against several of the recommendations made above, but is worth keeping in mind as a counterweight to the temptation of including ever more requirements in the codes. Grid codes are not good at any cost.

5.2.10. Room for exemptions

In order to allow innovations, it must be possible to be exempted from grid code requirements in certain circumstances. This is highly important for example for demo projects testing new technology in full scale. A reasonable condition for being granted exception is that the facility is relatively small and poses no risk to system stability.

VI. Conclusion

This document has given an overview of grid codes including their historical context and current status of development in Europe and North Africa. Particular emphasis in the report has been on what is relevant for renewable energy generation such as fault ride through, voltage control, reactive power control, and frequency regulation. Typical grid code technical requirements were introduced and more details given for what is presently the situation in Spain, Morocco and Egypt. Spain has elaborated technical requirements regarding PV installations and well established grid code for wind energy installations.

Europe is in a process of harmonisation of grid codes to facilitate closer integration of electricity markets. As part of this process, ENTSO-E has published wide-ranging network codes that will be legally binding in the EU. These codes affect particularly cross-border network and market issues. This has implications also for North African countries which has or will have connections to European countries.

As North African countries have ambitions to integrate new renewable plants with several thousands of MW, they are in a clear need to develop grid codes or standardised rules for connections, with the aim to ensure safe, secure and economic operation of the grid, taking into account the special characteristics of fluctuating renewable energy sources and new technologies for grid connection. This will help Arab countries move gradually from the current status of their electricity markets; to an integrated regional market that will enable efficient and open participation by all market players in cross-border trade.

Finally, this report has proposed a number of recommendations for the further development of grid codes suitable for renewable energy integration in Northern African countries. Among the main recommendations for the North African countries are those proposed for transitional market design, that will go a long way toward meeting these countries' objectives relating to reliability, sustainability, and security of supply; without the need for significant national power sector reform. Others are directly related to the mini road map of what should be done in North Africa, in Morocco and Egypt to develop grid codes.

References

[55] International Electrotechnical Commission. "Grid integration of large-capacity Renewable Energy sources and use of large-capacity Electrical Energy Storage". 2012

[56] Zavadil RM, Smith CJ. Status of wind-related US national and regional grid code activities. In: Proceeding of IEEE power engineering society general meeting. 2005; 2: 1258-1261

[57] Bernard S, Beaulied, Trudel G. Hydro-Quebec grid code for wind farm interconnection. In: Proceedings of IEEE power engineering society general meeting. 2005:2:1248-1252.

[58] Morales A, Robe X, Amenedo JLR, Arnaltes S, Zubiaur R, Torbado Z. Advanced grid requirements for the integration of wind farms into the Spanish transmission system. IET Renew Power Gener 2007;2(1):47–59

[59] Dudurych IM, Holly M, Power M. Integration of wind power generation in the Irish grid. In: Proceedings of IEEE power engineering society general meeting. 2006. 10.1109/PES.2006.1709436

[60] Erlich I, Winter W, Dittrich A. Advanced grid requirements for the integration of wind turbines into the German transmission system. In: Proceedings of IEEE power engineering society general meeting. 2006. 10.1109/PES.2006.1709340

[61] SKM, New generation technologies and GB grid codes; December 2004. Available at: http://www.ofgem.gov.uk/.

[62] Jauch C, Matevosyan J, Ackermann T, Bolik S. International comparison of requirements for connection of wind turbines to power systems.Wind Energy Jul 2005;8(8):295–306.

[63] Christiansen W, Johnsen DT. Analysis of requirements in selected grid codes. Technical Report, Section of Electric Power Engineering, Technical University of Denmark (DTU); 2006.

[64] de Alegrıa IM, Andreu J, Martın JL, Ibanez P, Villate JL, Camblong H. Connection requirements for wind farms: a survey on technical requirements and regulation. Renew Sust Energy Rev 2007;11:1858–72

[65] Mohseni M , Islam S. Review of international grid codes for wind power integration: Diversity, technology and a case for global standard. Renewable Sustainable Energy Rev. 2012;16: 3876–3890.

[66] Tsili M, Papathanassiou S. A review of grid code technical requirements for wind farms. IET Renew Power Gener 2009;3(September (3)):308–32

[67] Liu X, Xu Z, Wong KP. Recent advancement on technical requirements for grid. J Mod Power Syst Clean Energy 2013;1(3):216–22

[68] González F , Hau M, Sumper A , Bellmunt O. Participation of wind power plants in system frequency control: Review of grid code requirements and control methods . Renew Sust Energy Rev 2014;34: 551–564

[69] Rodrigues E, Osorio G, Godina R, Bizuayehu A, Rojas J, Catalao J. Grid code reinforcements for deeper renewable generation in insular energy systems. Renew Sust Energy Rev 2016;53: 163–177

[70] World Bank. "Middle East and North Africa Integration of Electricity Networks in the Arab World -Regional Market Structure and Design", December 2013

[71] World Bank. "Tapping a Hidden Resource—Energy Efficiency on the Middle East and North Africa", February 2009

[72] R. B. Alderfer, M. M. Eldridge, and T. J. Starrs, "Making Connections: Case Studies of Interconnection Barriers and their Impact on Distributed Power Projects," NREL Report SR-200-28053, July 2000.

[73] P. Bousseau, F. Fesquet, and et al., "Solutions for the grid integration of wind farms - a Survey," in Wind Energy vol. 9: Wiley Interscience, December 2005, pp. 13-25.

[74] R. Villafáfila, A. Sumper, and e. al, "On wind power integration into electrical power system: Spain vs. Denmark," Institute of Energy Technology (IET) and Aalborg University (AAU).

[75] BOE nº 254. "Resolución de 4 de octubre de 2006, de la secretara general de energía, por la que se aprueba el procedimiento de operación 12.3 requisitos de respuesta frente a huecos de tensión de las instalaciones eólicas". 24 of October 2006.

[76] T. García-Sánchez, E. Gómez-Lázaro and A. Molina-García, "A Review and Discussion of the Grid-Code Requirements for Renewable Energy Sources in Spain," International Conference on Renewable Energies and Power Quality (ICREPQ'14), Cordoba, Spain April 2014.

[77] Royal Decree 1565/2010, November 19, "Por el que se regulan y modifican determinados aspectos relativos a la actividad de producción de energía eléctrica en régimen especial".

[78] P.O.12.2 "Technical requirements for wind power and photovoltaic installations and any generating facilities whose technology does not consist on a synchronous generator directly connected to the grid". Offprint form the O.P. 12.2 outline. October 2008.

[79] Annex of P.O.12.2, 'Restricted to the Technical Requirements of Wind Power and Photovoltaic Facilities (draft)' Red Electrica, October 2008, www.ree.es (translated into English by Spanish Wind Association AEE in www.aeolica.es).

[80] REE, "El sistema eléctrico español 2005," June 2006.

[81] T. Orłowska-Kowalska et al., Advanced and Intelligent Control in Power Electronics and Drives, Studies in Computational Intelligence 531, DOI: 10.1007/978-3-319-03401-0_2, Springer International Publishing Switzerland 2014.

[82] Resolución P.O.7.4, 'Servicio Complementario de Control de Tensión de la Red de Transporte'. Red Electrica, March 2000, www.ree.es.

[83] E. Gomez, J. Fuentes, A. Molina-Garcia, F. Ruz, F. Jimenez, "Field tests of wind turbines submitted to real voltage dips under the new Spanish grid code requirements", Wind Energy 10 (5) (2007) 483–495.

[84] R. Teodorescu and M. Liserre, Grid converters for photovoltaic and wind power systems vol. 29: Wiley-IEEE press, 2011.

[85] EL FIGEL, "Conditions De Raccordement Des Eoliennes & Parcs Solaires A Base De PV Au Reseau De Transport National", ONEE.

[86] P. Bousseau, F. Fesquet, and et al., "Solutions for the grid integration of wind farms - a Survey," in Wind Energy vol. 9: Wiley Interscience, December 2005, pp. 13-25.)

[87] Wind Farm Grid Connection Code in addition to the Egyptian Transmission Grid Code (ETGC). March 2014.Available at : http://www.nrea.gov.eg/

[88] IEEE Std 519-1992. IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

[89] IEC/TR 61000-3-7 ed2.0 . Electromagnetic compatibility (EMC) - Part 3-7: Limits - Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems.

Appendix E

French Summary

La consommation d'énergie a considérablement augmenté ces dernières années à cause du développement industriel croissant et l'amélioration du niveau de vie. Plusieurs pays accordent actuellement plus d'attention au développement des énergies renouvelables et au renforcement du contrôle et de la gestion de l'énergie. Le développement des systèmes d'énergie renouvelable est provoqué par les préoccupations croissantes concernant le changement climatique et la sécurité énergétique. Les systèmes d'énergie renouvelable sont des ressources potentielles propres, caractérisées par une génération d'énergie intermittente. La fiabilité du réseau électrique est confrontée à des difficultés à surmonter à cause de la variabilité de ces sources d'énergie. L'intégration des énergies renouvelables sur les réseaux électriques constitue un défi pour les gestionnaires de réseaux et nécessite une adaptation des infrastructures pour la gestion du système électrique. Le stockage d'énergie est considéré une solution à l'intégration des énergies renouvelables.

Les systèmes de stockage d'énergie offrent des avantages techniques et économiques. Ils permettent une flexibilité pour faire correspondre la demande à l'approvisionnement énergétique en termes de quand et où l'énergie est nécessaire. Par conséquent, le stockage d'énergie réduit l'intermittence des systèmes d'énergie renouvelable et améliore la fiabilité du réseau électrique en offrant de multiples services.

La Station de Transfert d'Energie par Pompage (STEP) est le système de stockage le plus populaire en raison de ses mérites distingués. Cependant, le développement de ce système est limité en raison de ses conditions géographiques spécifiques. Afin d'améliorer ce système de stockage, un concept nouveau, connu sous le nom, stockage de l'énergie par gravitation "Gravity Energy Storage", est en cours de développement. Cette technologie est basée sur l'idée d'utiliser la technologie de stockage hydraulique approuvée de manière innovante.

Ce travail a exploré la modélisation des technologies de stockage d'énergie utilisées pour résoudre les problèmes de variabilité liés à la production des énergies renouvelables. Une attention particulière a été accordée au stockage de l'énergie par Gravity Energy Storage. Un certain nombre d'approches de modélisation sont présentées afin de déterminer la faisabilité du système et sa viabilité économique. Ce système a été évalué sur le plan technique et économique. Un dimensionnement optimal de cette technologie est également proposé. En outre, les diffèrent risque d'investissement associés au stockage d'énergie par cette technologie sont discutés. Des études de faisabilité, rentabilité et développement du système ont été menées dans le but de répondre aux différentes questions de cette thèse.

Le stockage de l'énergie par gravitation est un concept de stockage innovant qui fait actuellement l'objet de plusieurs enquêtes. Ce système est considéré comme une alternative au stockage hydraulique (STEP) car il utilise un potentiel gravitationnel pour stocker de l'énergie. Ce système élimine les limitations géologiques et le besoins d'eau confrontés par les stations de transfert d'énergie par pompage car il peut être mise en œuvre partout. Cette technologie se compose d'un grand piston, d'un réservoir rempli d'eau et d'une conduite de retour. La conduite de retour est relié à la centrale composée d'une pompe / turbine réversible et d'un moteur / générateur. Pendant le mode de chargement, un excès d'énergie est transmis au moteur qui tourne la pompe. Ce dernier force l'eau à traverser la conduite de retour et élève le piston. En mode de décharge, l'énergie est produite par le mouvement du piston vers le bas qui force l'eau à s'écouler à travers la pompe / turbine réversible.

Le stockage d'énergie par gravitation est encore dans la phase de démonstration et de recherche puisqu'il n'y a pas encore de projet opérationnel pour déterminer les caractéristiques, l'applicabilité et la viabilité du système. Des recherches supplémentaires sont donc nécessaires pour étudier la réalisation d'une telle technologie de stockage. Ce rapport résume les principales réalisations du travail de recherche de doctorat présenté, et fournit des conclusions majeures.

Les différentes études menées ont montré qu'il existe certainement un potentiel de développement de ce système étudié. Un certain nombre d'aspects ont été étudiés et expliqués pour réaliser une étude globale du système. Bien que certaines facettes aient besoin d'une enquête plus approfondie, les conclusions clés suivantes ont été obtenues:

Des études de conception, construction et dimensionnent du système "Gravity Energy Storage" ont été présentées. La méthodologie de conception proposée a pour objectif de maximiser la capacité de stockage et de minimiser les coûts de construction. Un modèle de conception optimal non linéaire a ensuite été proposé pour minimiser le coût du système tout en satisfaisant toutes les contraintes. Les résultats obtenus montrent qu'il est plus économique d'augmenter la hauteur du réservoir que son diamètre pour une capacité de stockage spécifique. En outre, une enquête sur le matériel de construction de stockage a également été menée. On a constaté que le minerai de fer est un matériau optimal qui pourrait être utilisé pour construire le piston en raison de sa densité élevée et son coût inférieur par rapport aux matériaux étudiés. En ce qui concerne la construction du réservoir, le béton armé serait le meilleur candidat. Finalement, le troisième chapitre a présenté une méthodologie pour dimensionner et exploiter de manière optimale les systèmes de stockage lorsqu'ils sont couplés aux parcs éoliens. Un modèle de stockage détaillé a été développé en utilisant la conception technique du système, l'économie et les caractéristiques du marché de l'énergie. Le stockage de l'énergie par gravitation a été décrit par ses paramètres de performance qui incluent l'efficacité de charge/décharge de stockage, la capacité du système et la période de déchargement. Ces paramètres ont été utilisés pour identifier les revenus obtenus par le système on offrant le service d'arbitrage. Le but de cette approche proposée est de maximiser le profit du propriétaire. Les résultats de cette étude montrent qu'un bon dimensionnement du stockage de l'énergie peut augmenter les revenus obtenus en chargent et déchargent le stockage de manière optimale tout en profitant de la fluctuation des prix de l'énergie.

Une étude économique a été réalisée pour calculer le coût du système. LCOE est une méthodologie pratique qui mesure la compétitivité globale des différentes technologies de stockage. Par conséquent, cette méthodologie a été utilisée pour déterminer si le système étudié est une option de stockage viable. Le LCOE est calculé en tenant compte des coûts prévus au cours de la durée de vie du système, y compris la construction, la maintenance et l'exploitation, divisés par la puissance de production attendue (kWh) durant son cycle de vie. Le calcul prend en compte la valeur temporelle de l'argent avec un taux d'actualisation approprié pendant la durée de vie du système. Dans ce travail, une estimation des coûts d'investissement, ainsi que les coûts d'exploitation et d'entretien, a permis de déterminer le LCOE du système. En outre, une comparaison avec d'autres systèmes de stockage a été menée. Les résultats obtenus à partir de cette étude révèlent que le stockage gravitaire a un LCOE très attractif par rapport à d'autres technologies de stockage. Par conséquent, le stockage par gravitation peut être considéré comme une technologie compétitive au système hydraulique (STEP).

Un modèle de stockage d'énergie a été proposé pour évaluer les revenus potentiels maximaux. Ceux-ci pourraient être générés par, le système de stockage, en participant à la fois aux marchés de l'énergie du jour d’avant et en temps réel, ainsi que le marché de la régulation. Le modèle d'optimisation détermine les quantités d'énergie optimales qui devraient être offertes au marché de la régulation; En plus de la quantité optimale d'énergie qui devrait être vendue et achetée sur les marchés du jour d’avant et en temps réel. Les résultats du modèle démontrent que des revenus potentiels élevés pourraient être générés par une participation au marché des services de régulation. Cependant, la participation à ces trois marchés entraîne un bénéfice négatif généré par le système.

Des avantages supplémentaires pourraient être pris en compte par le stockage d'énergie en exécutant d'autres services au réseau électrique. Sur la base de l'évaluation des coûts présentée, le stockage gravitaire n'est pas rentable s’il ne participe que dans un nombre limité d'applications. Par conséquent, même si le stockage par gravitation est capable d'augmenter les revenus, il doit exécuter de multiples fonctions pour justifier économiquement son fonctionnement.

Une analyse coûts-bénéfices a été effectuée dans ce travail pour déterminer la viabilité économique du stockage de l'énergie. Les modèles proposés ont été utilisés pour identifier les économies maximales pouvant être obtenues grâce à l'utilisation du stockage d'énergie. Quatre scénarios ont été simulés pour une application résidentielle à petite échelle. Des études de cas basées sur le stockage par gravitation ont été effectuées pour déterminer la rentabilité de ce système de stockage. Les résultats obtenus révèlent que la valeur actuelle nette du stockage d'énergie est la même pour les trois premiers scénarios. Cependant, il est constaté que le premier scénario (stockage d'énergie qui est connecté au réseau électrique et qui ne fournit pas d'énergie à la charge) est le cas le plus optimal pour le système de stockage résidentiel.

En outre, les résultats des calculs de la valeur actuelle nette (VAN) révèlent que le stockage par gravitation n'est pas considéré rentable pour les applications résidentielles, sauf s'il est utilisé comme système autonome. Cependant, pour une application à grande échelle, cette technologie a été prouvée comme une option de stockage viable.

Une étude de risque nous a permis de montrer si ce système innovant serait plus viable que d'autres options de stockage compétitives. Ces différents risques sont liés à la construction et au fonctionnement du système. Étant donné que la plupart des concepts semblables au stockage hydroélectrique traditionnel sont considérés comme risqués, il est crucial d'effectuer une analyse des risques pour le système de stockage par gravitation tout en évaluant sa rentabilité. L'une des techniques réalisées dans ce travail est l'analyse de sensibilité. Cette analyse effectuée a démontré que le projet est considéré comme économiquement solide, avec une VAN positive pour chacune des variables simulées. Cependant, il y a une possibilité d'obtenir une VAN négative pour les cas étudiés. En ce qui concerne l'évaluation des risques économiques, il a été démontré qu'au-dessus d'une augmentation de 18% du coût d'investissement du projet, ce dernier ne serait pas considéré comme économiquement viable. En outre, le risque d'achèvement du projet n'est pas considéré comme un risque potentiel puisque le VAN du projet atteint une valeur nulle avec un délai de plus de 30 ans. Un délai tellement élevé ne devrait pas être attendu. L'impact du risque politique a également été évalué dans cette étude. On a enquêté sur trois scénarios de cas qui incluent une diminution des prix de l'énergie, une diminution des revenus provenant du support du système transmission et distribution (T&D deferral) et une combinaison des deux scénarios précèdent. Les résultats démontrent qu'une réduction des revenus, reçue de l'arbitrage et du support du système T&D, à un impact significatif sur la VAN du projet. En ce qui concerne le risque financier, une augmentation de 3% du taux d'actualisation met en évidence la vulnérabilité économique d'un tel projet caractérisé par un coût d'investissement important.

La modélisation dynamique d'un système hybride composé d'une installation photovoltaïque et d'un système de stockage par gravitation a été développée. Une connexion au réseau électrique a été utilisée pour échanger l'énergie entre le système hybride et la charge énergétique résidentielle. Le stockage gravitaire a été utilisé pour équilibrer l'énergie et répondre à la demande grâce à la décharge et à la conservation de l'excès d'énergie du système photovoltaïque. Des modèles mathématiques détaillés des différents composants du système ont été développés par Matlab/Simulink.

Une étude de cas a été faite pour étudier la performance du système hybride et la précision des modèles développés. Les résultats obtenus démontrent que le modèle présenté est capable de faire face à la demande selon la stratégie de gestion proposée. La modélisation dynamique des composantes mécaniques du système a permis de faire une enquête sur la réaction du système face à la demande d'énergie. L'effet de la variation de charge sur les paramètres du générateur a également été étudié. On a observé que des oscillations se sont produites dans le courant du stator du générateur, la tension d'excitation et la puissance générée lors de la modification de la charge. En outre, il a été démontré qu'aucune oscillation ne se produit dans la tension du terminal et de faibles oscillations sont observées lorsque le système approche son état stationnaire. Ces systèmes utilisent des équipements mécaniques similaires tels que les centrales hydroélectriques. Le modèle développé est capable de montrer le comportement réel de la turbine hydroélectrique et du générateur synchrone.

Cette étude a aussi proposé un modèle mathématique pour les composants hydrauliques du système de stockage par gravitation. Ce modèle a été développé par Matlab/Simulink; En tenant compte des caractéristiques et des exigences du système. Une étude de cas a été effectuée pour enquêter sur les performances de ce système. Le modèle Simulink développé fonctionne comme un système virtuel du “Gravity Energy Storage”. Le comportement du système par rapport au temps a été obtenu sans tester physiquement ces composants. Les résultats révèlent la dynamique du système qui inclut l'identification des paramètres cruciaux. Ces paramètres sont le temps de décharge du système et les caractéristiques de mouvement du piston, ainsi que la pression, le volume et le débit du système. Les résultats de la simulation numérique indiquent que le temps de déchargement du stockage est d'environ 368 s. Les paramètres critiques du système sont déterminés, notamment le débit et la pression qui sont égaux à $3{,}4 \times 10^{-4}$ m^3/s et 43,1 kPa. Les résultats obtenus à partir de l'étude de cas simulée sont comparés aux résultats expérimentaux d'autres chercheurs et évalués. Les pourcentages d'erreurs obtenues concernant la pression et le temps de décharge du système sont de 3,4% et de 6,2%. La différence entre les résultats obtenus à partir des modèles expérimentaux et simulés pourrait être due aux paramètres d'entrée dérivés et estimés, ou due à l’approximation des pertes du système.

Une analyse de sensibilité a également été réalisée dans ce travail pour évaluer la réponse du système aux changements de différents paramètres utilisés. Il est important de mener une telle étude parce que certains paramètres d'entrée ont été estimés. Divers scénarios avec une augmentation et une diminution de 20% et 40% des paramètres estimés ont été étudiés pour évaluer leurs impacts sur le débit du système et la pression. L'effet sur le débit est proportionnel à la variation du coefficient de décharge de la valve, module d'élasticité volumique, et des pertes hydrauliques. En ce qui concerne la pression du système, on constate que la masse du piston a un impact significatif sur la pression. Les résultats de cette analyse démontrent qu'il est essentiel d'estimer correctement les valeurs des paramètres utilisés, en particulier ceux liés aux pertes du système, y compris les pertes hydrauliques et les pertes de charge.

Les résultats obtenus montrent que l'efficacité du système dépend du type de matériau d'étanchéité utilisé. En outre, les pertes d'énergie hydraulique pourraient être réduites en concevant de manière optimale le système de conduite et en sélectionnant correctement les dimensions de la valve hydraulique et la pompe. La capacité d'énergie du système de stockage pourrait également être améliorée en dimensionnant de manière optimale le piston car ce dernier à un impact significatif sur la pression du système. Ces considérations de conception se traduiront par un stockage d'énergie plus rentable avec moins de pertes d'énergie et une maintenance réduite du système.

Un concept nouveau a été proposé dans ce travail pour améliorer la capacité de stockage de cette technologie. Ce système est basé sur l'ajout d'air comprimé au stockage d'énergie par gravitation. Ce nouveau concept est introduit et étudié. Des approches de modélisation sont présentées afin de déterminer la faisabilité du système. Les résultats de cette étude démontrent que l'utilisation d'air comprimé améliore considérablement la capacité de stockage du système. Par conséquent, une quantité intéressante d'énergie pourrait être ajoutée avec la combinaison d'air comprimé et de stockage d'énergie par gravitation. Pour maximiser la capacité de stockage, il est optimal d'utiliser un rapport air-eau égal à 1. En d'autres termes, le volume d'air dans le réservoir devrait être dominant et égal à la moitié du volume de ce dernier. Le stockage d'énergie par gravitation et l'air comprimé démontre de bonnes perspectives. Une quantité relativement importante d'énergie pourrait être stockée avec la combinaison d'air comprimé et le stockage d'énergie par gravitation.

En plus des obstacles économiques et techniques confrontés par les développeurs des systèmes de stockage d'énergie, il existe également des défis associés aux politiques et aux marchés d'énergie qui entraînent une plus grande réticence face au développement des systèmes de stockage de l'énergie. Ce rapport aboutit à une discussion sur la prise en compte de la politique et les perspectives d'avenir. L'intérêt pour le stockage de l'énergie a été alimenté par le développement croissant de la production intermittente d'énergie renouvelable. Cependant, le déploiement de systèmes de stockage d'énergie a été restreint par leurs coûts d'investissement relativement élevés par rapport aux ressources génératrices traditionnelles. De plus, le développement du stockage de l'énergie fait face à d'autres barrières qui suggèrent l'intervention politiques. Il est encore complexe de déterminer la valeur réelle du stockage de l'énergie, ce qui entraîne une difficulté à reconnaître les avantages du système.

Bien que les questions techniques et économiques soient considérées comme les principaux défis pour le développement des systèmes de stockage de l'énergie, les problèmes reliés à la politique et au marché d'énergie représentent des obstacles importants au développement du stockage d'énergie. Ces derniers obstacles incluent l'évaluation incomplète et inexacte des bénéfices offerts par les systèmes de stockage d'énergie, le traitement réglementaire, le manque d'exigence et la standardisation, ainsi que le risque de développement. En outre, les marchés actuels ne sont pas entièrement développés pour tous les services auxiliaires. Les économies d'émissions qui peuvent être évitées par le projet de stockage d'énergie ne sont pas aussi pris en considération. Par conséquent, la valeur réelle du système de stockage d'énergie n'est pas reflétée et peut être insuffisante pour justifier son investissement.

Le développement du stockage de l'énergie fait face à l'incapacité de quantifier les flux de valeurs des services multiples fournis par ce dernier au réseau électrique. La valeur réelle du système de stockage d'énergie n'est pas basée uniquement sur la différence entre l'achat d'énergie à bas prix et la vente à des prix plus élevés. Il est plutôt associé à tous les services qu'ils fournissent, y compris les services auxiliaires, la régulation, et le support du système de transmission et de distribution, etc. Le stockage d'énergie apporte d'autres avantages tels que des émissions faibles ou nulles, une réponse rapide et une capacité bidirectionnelle de réserve.

Le risque de développement des systèmes du stockage d'énergie est augmenté par l'incertitude et l'incapacité de refléter la valeur réelle de ces systèmes. Les nouveaux investisseurs sont découragés par ce risque. Des approches d'évaluation raisonnablement plus compliquées nécessaires pour refléter la prudence en matière de stockage d'énergie aux régulateurs décourageraient les fournisseurs d'électricité. La dépendance à l'égard des prix du marché dans les marchés émergents pour les nouveaux services augmente l'incertitude pour la récupération des coûts d'investissement du système. La variabilité des prix de l'énergie ajoute plus d'incertitude au recouvrement des coûts du système. La valeur du système de stockage d'énergie peut être principalement basée sur la participation à l''arbitrages énergétiques et aux services auxiliaires, ainsi qu'à la réduction des émissions de gaz à effet de serre. La dépendance à ces sources de revenus ajoute des risques au développent des projets de stockage d'énergie. En outre, le traitement réglementaire actuel du stockage accroît le risque de déploiement des nouveaux systèmes de stockage d'énergie. Ces derniers souffrent d'un manque d'incitations sur les marchés réglementés.

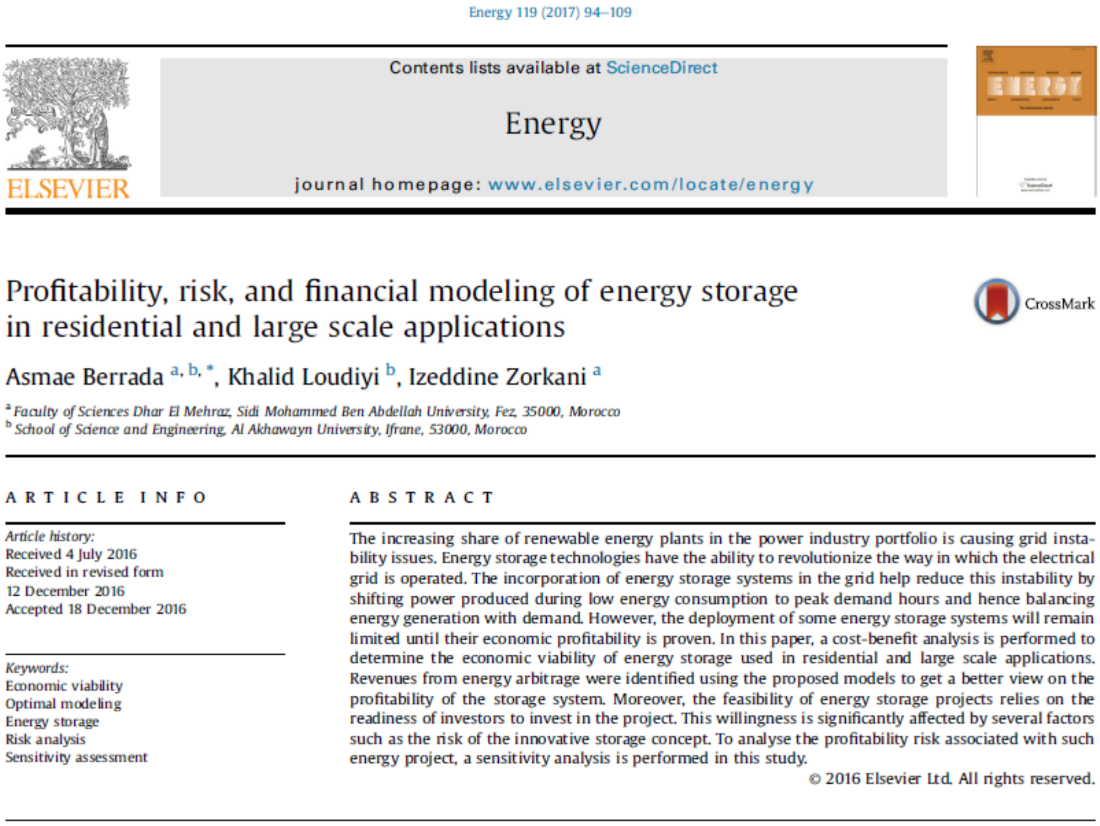
Bien que les risques réglementaires et les risques associé au marché d'énergie soient des défis importants, les risques technologiques sont également considérés comme un problème important pour le déploiement des systèmes de stockage. Un certain nombre de technologies de stockage semblent être technologiquement viables, mais elles souffrent de la réticence des développeurs qui entraînent un retard de développement de ces systèmes.

L'adoption des systèmes de stockage d'énergie est confrontée à un défi majeur associé à l'acceptation de l'industrie. Les exigences établies par les organismes de réglementation ont tendance à créer un degré élevé de prudence concernant la mise en œuvre de nouvelles technologies.

La difficulté des marchés de l'énergie à valoriser tous les différents avantages des systèmes de stockage d'énergie et les risques d'investissement élevés présentent un besoin d'intervention politique. Plusieurs politiques ont été exécutées pour soutenir d'autres technologies de production d'énergie à des fins diverses telles que "Feed in Tarrifs", les exigences réglementaires, les crédits d'impôt pour la production et d'autres. Des politiques similaires sont nécessaires pour obtenir les avantages économiques et environnementaux complets offerts par l'utilisation des systèmes de stockage d'énergie.

Avec la part croissante des sources d'énergie renouvelables dans la production électrique, il y aura une demande croissante pour les services offerts par les systèmes de stockage d'énergie. Même si le stockage d'énergie n'est pas le seul fournisseur de ces services, il y a en fait une importance accrue donnée à leur développement. Ce dernier est supporté par des politiques qui mettent à disposition des incitations pour développer des systèmes de stockage d'énergie. Une intégration standardisée de l'énergie est également nécessaire et mérite un développement. En outre, le stockage d'énergie peut devenir économique si les politiques sont adoptées. Ces politiques et ces normes attireraient les investisseurs et apporteraient leur soutien à la mise en œuvre de systèmes prometteurs de stockage d'énergie qui sont encore en phase de développement.

Appendix F



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Profitability, risk, and financial modeling of energy storage in residential and large scale applications

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Economic viability
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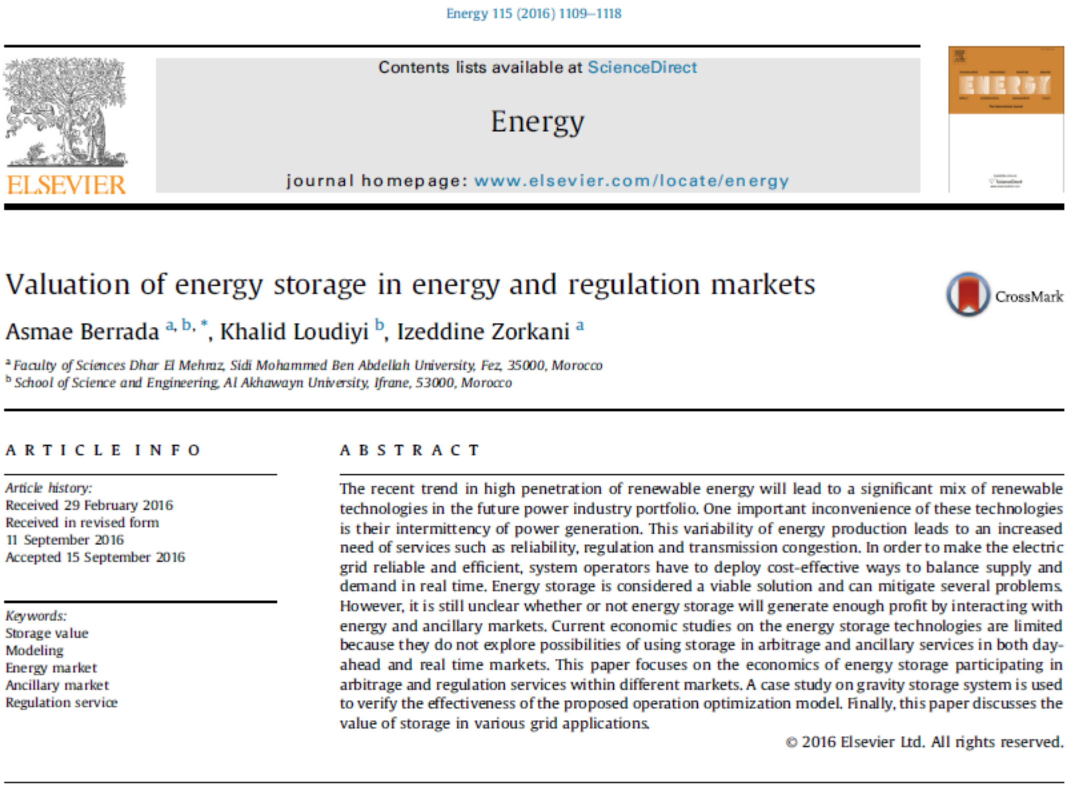
ABSTRACT

The increasing share of renewable energy plants in the power industry portfolio is causing grid instability issues. Energy storage technologies have the ability to revolutionize the way in which the electrical grid is operated. The incorporation of energy storage systems in the grid help reduce this instability by shifting power produced during low energy consumption to peak demand hours and hence balancing energy generation with demand. However, the deployment of some energy storage systems will remain limited until their economic profitability is proven. In this paper, a cost-benefit analysis is performed to determine the economic viability of energy storage used in residential and large scale applications. Revenues from energy arbitrage were identified using the proposed models to get a better view on the profitability of the storage system. Moreover, the feasibility of energy storage projects relies on the readiness of investors to invest in the project. This willingness is significantly affected by several factors such as the risk of the innovative storage concept. To analyse the profitability risk associated with such energy project, a sensitivity analysis is performed in this study.



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Valuation of energy storage in energy and regulation markets

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Modeling
Energy market
Ancillary market
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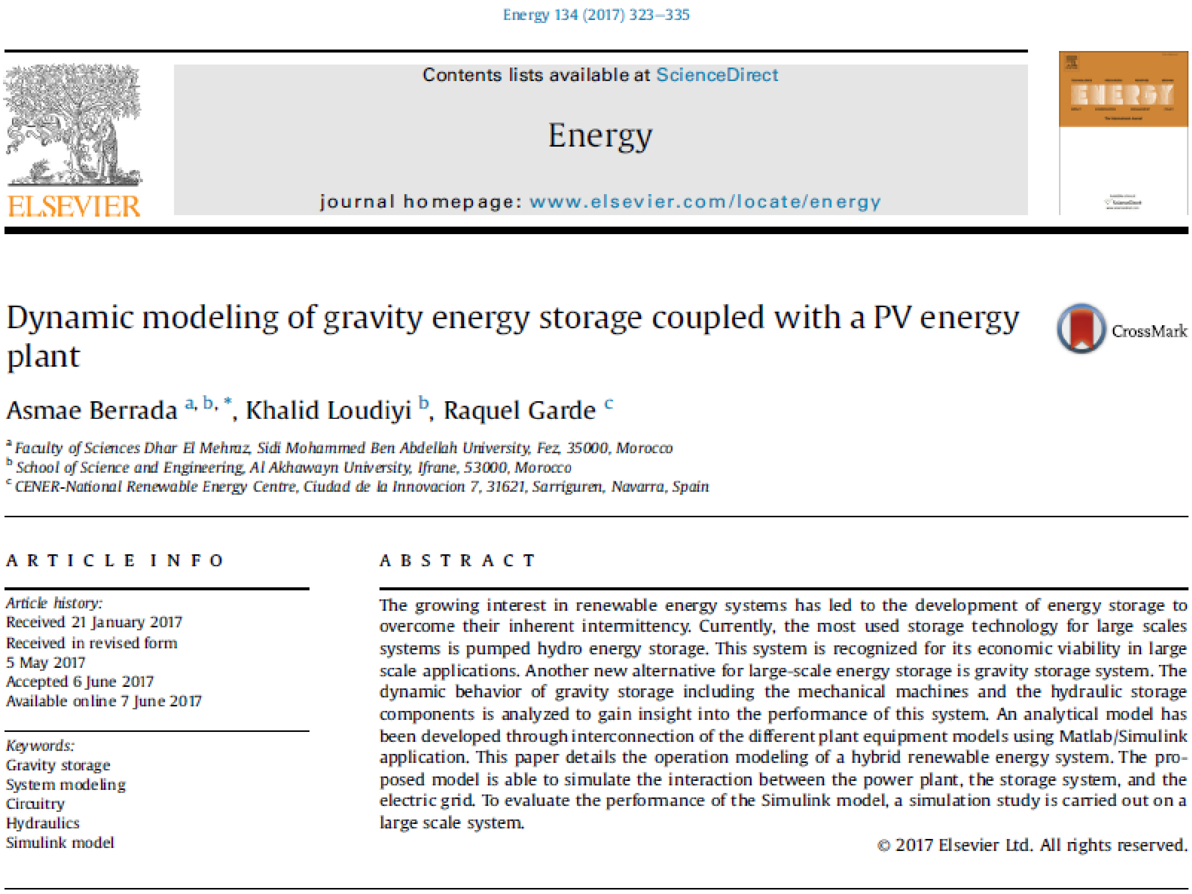
ABSTRACT

The recent trend in high penetration of renewable energy will lead to a significant mix of renewable technologies in the future power industry portfolio. One important inconvenience of these technologies is their intermittency of power generation. This variability of energy production leads to an increased need of services such as reliability, regulation and transmission congestion. In order to make the electric grid reliable and efficient, system operators have to deploy cost-effective ways to balance supply and demand in real time. Energy storage is considered a viable solution and can mitigate several problems. However, it is still unclear whether or not energy storage will generate enough profit by interacting with energy and ancillary markets. Current economic studies on the energy storage technologies are limited because they do not explore possibilities of using storage in arbitrage and ancillary services in both day-ahead and real time markets. This paper focuses on the economics of energy storage participating in arbitrage and regulation services within different markets. A case study on gravity storage system is used to verify the effectiveness of the proposed operation optimization model. Finally, this paper discusses the value of storage in various grid applications.



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Dynamic modeling of gravity energy storage coupled with a PV energy plant

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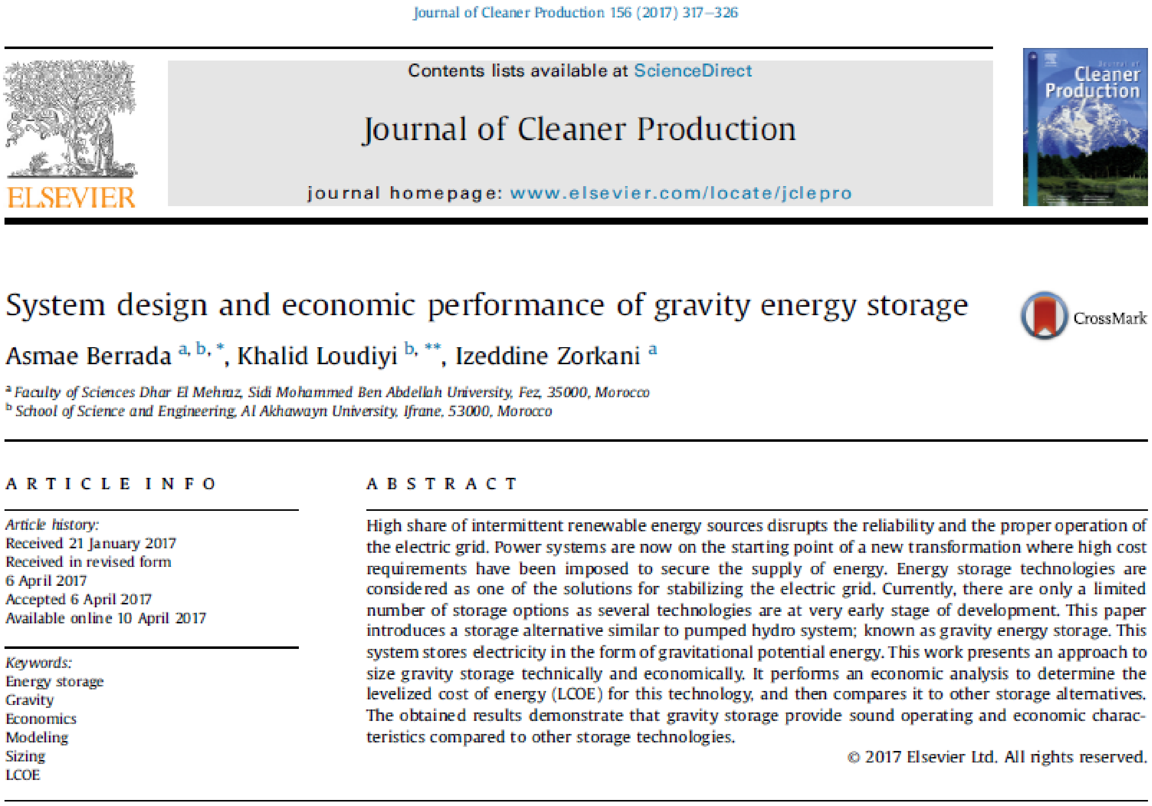
ABSTRACT

The growing interest in renewable energy systems has led to the development of energy storage to overcome their inherent intermittency. Currently, the most used storage technology for large scales systems is pumped hydro energy storage. This system is recognized for its economic viability in large scale applications. Another new alternative for large-scale energy storage is gravity storage system. The dynamic behavior of gravity storage including the mechanical machines and the hydraulic storage components is analyzed to gain insight into the performance of this system. An analytical model has been developed through interconnection of the different plant equipment models using Matlab/Simulink application. This paper details the operation modeling of a hybrid renewable energy system. The proposed model is able to simulate the interaction between the power plant, the storage system, and the electric grid. To evaluate the performance of the Simulink model, a simulation study is carried out on a large scale system.



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System design and economic performance of gravity energy storage

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Energy storage
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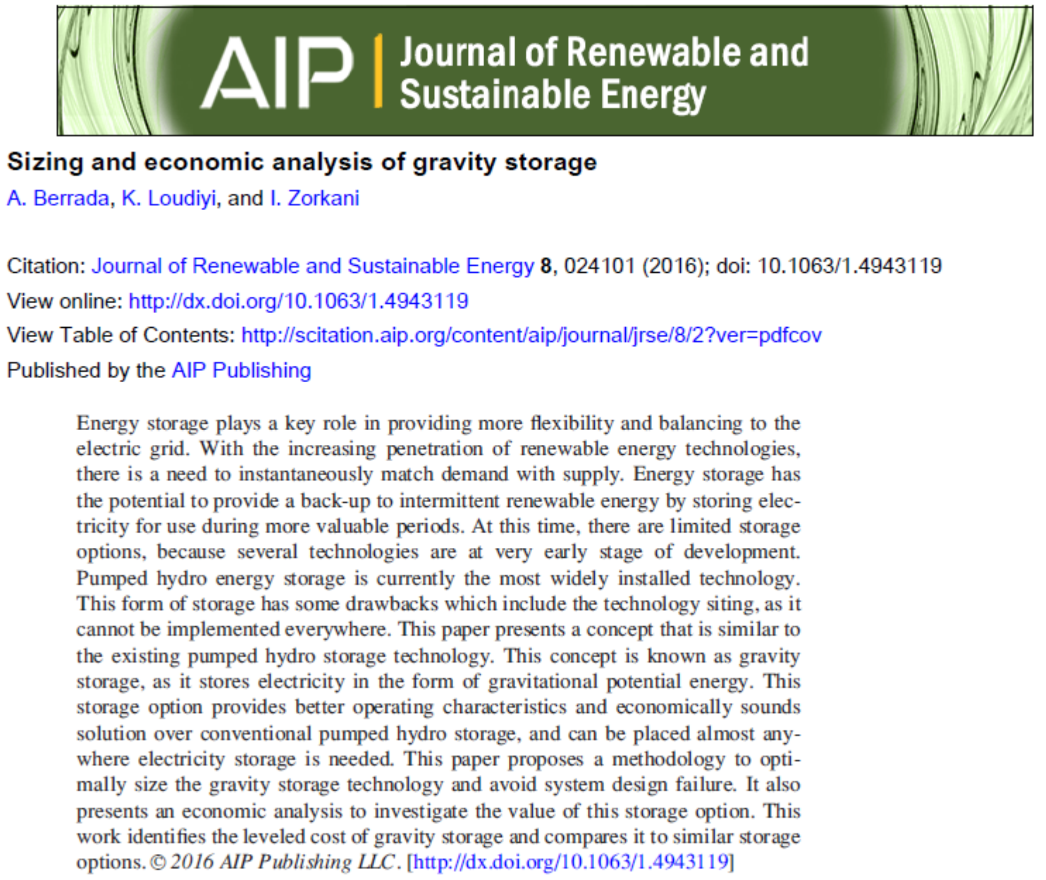
ABSTRACT

High share of intermittent renewable energy sources disrupts the reliability and the proper operation of the electric grid. Power systems are now on the starting point of a new transformation where high cost requirements have been imposed to secure the supply of energy. Energy storage technologies are considered as one of the solutions for stabilizing the electric grid. Currently, there are only a limited number of storage options as several technologies are at very early stage of development. This paper introduces a storage alternative similar to pumped hydro system; known as gravity energy storage. This system stores electricity in the form of gravitational potential energy. This work presents an approach to size gravity storage technically and economically. It performs an economic analysis to determine the levelized cost of energy (LCOE) for this technology, and then compares it to other storage alternatives. The obtained results demonstrate that gravity storage provide sound operating and economic characteristics compared to other storage technologies.



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Sizing and economic analysis of gravity storage

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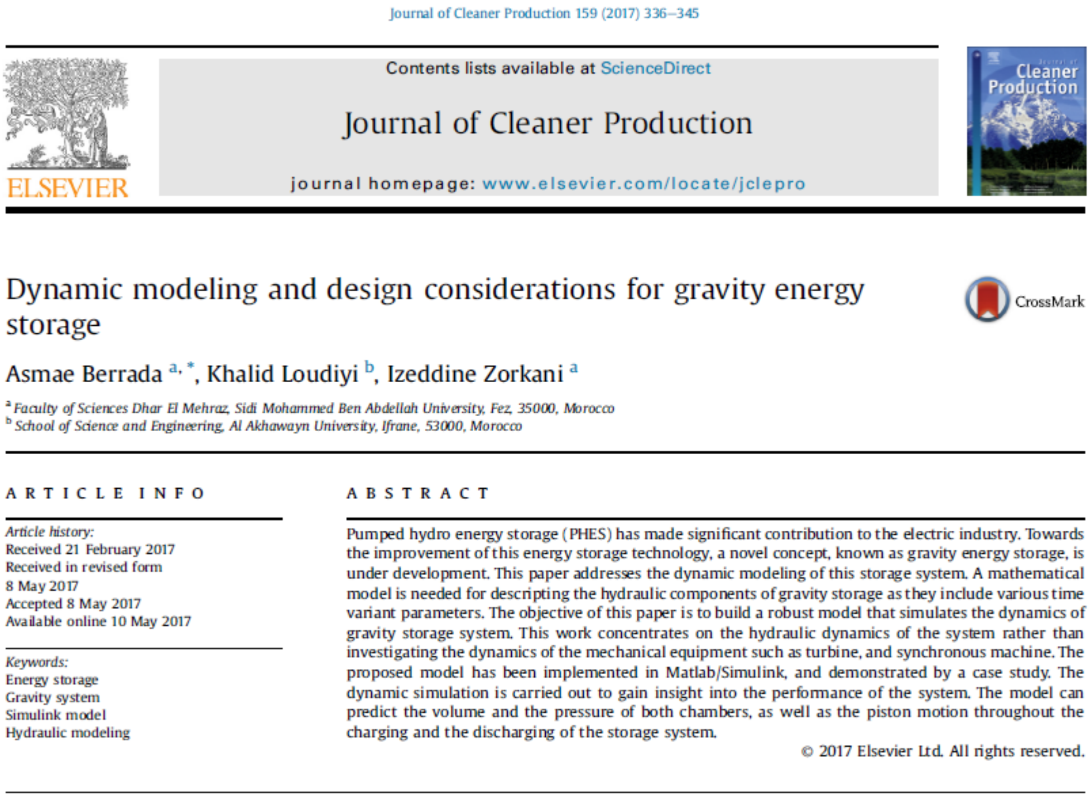
Energy storage plays a key role in providing more flexibility and balancing to the electric grid. With the increasing penetration of renewable energy technologies, there is a need to instantaneously match demand with supply. Energy storage has the potential to provide a back-up to intermittent renewable energy by storing electricity for use during more valuable periods. At this time, there are limited storage options, because several technologies are at very early stage of development. Pumped hydro energy storage is currently the most widely installed technology. This form of storage has some drawbacks which include the technology siting, as it cannot be implemented everywhere. This paper presents a concept that is similar to the existing pumped hydro storage technology. This concept is known as gravity storage, as it stores electricity in the form of gravitational potential energy. This storage option provides better operating characteristics and economically sounds solution over conventional pumped hydro storage, and can be placed almost anywhere electricity storage is needed. This paper proposes a methodology to optimally size the gravity storage technology and avoid system design failure. It also presents an economic analysis to investigate the value of this storage option. This work identifies the leveled cost of gravity storage and compares it to similar storage options. © *2016 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4943119]



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Dynamic modeling and design considerations for gravity energy storage

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Gravity system
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ABSTRACT

Pumped hydro energy storage (PHES) has made significant contribution to the electric industry. Towards the improvement of this energy storage technology, a novel concept, known as gravity energy storage, is under development. This paper addresses the dynamic modeling of this storage system. A mathematical model is needed for descripting the hydraulic components of gravity storage as they include various time variant parameters. The objective of this paper is to build a robust model that simulates the dynamics of gravity storage system. This work concentrates on the hydraulic dynamics of the system rather than investigating the dynamics of the mechanical equipment such as turbine, and synchronous machine. The proposed model has been implemented in Matlab/Simulink, and demonstrated by a case study. The dynamic simulation is carried out to gain insight into the performance of the system. The model can predict the volume and the pressure of both chambers, as well as the piston motion throughout the charging and the discharging of the storage system.

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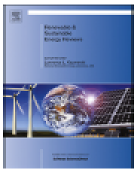

Operation, sizing, and economic evaluation of storage for solar and wind power plants

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ABSTRACT

Renewable energy sources have a huge potential to reduce greenhouse gas emissions and decrease the dependence on fossil fuels in the energy sector. However, the energy output of these sources is variable and raises concerns regarding the electric grid reliability. Therefore, the deployment of energy storage would play a key role in enabling the integration of these sources in the electric grid. This paper proposes methods for determining the optimal operation and sizing of energy storage systems. The main purpose of the operation strategy is to maximize the revenues of the renewable farm. The sizing model, on the other hand, has a purpose to minimize the cost of the hybrid system while meeting the service requirement. Both methods were formulated as non-linear programming optimization models. To verify the effectiveness of these methods; case studies have been presented. Finally, this paper proposes an economical analysis to determine the cost added by the storage to each KWh of stored energy.

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Grid code status for wind farms interconnection in Northern Africa and Spain: Descriptions and recommendations for Northern Africa

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ABSTRACT

Electricity production from renewable energy sources is increasing as costs are going down and concerns of climate change are driving political targets to shift away from fossil fuels. The fast expansion of renewable energy into the electric grid, from being negligible to becoming important for system stability, has implications for grid planning and operation. In this situation, grid operators need to ensure that the grid continues to operate in a safe, secure and economic way. To achieve this, grid codes have been introduced as common rules that regulate these responsibilities; and define standardized and transparent requirements for any facility connected to the grid. This paper gives a review of the status of grid codes in Northern Africa and Europe. It describes technical grid connection requirements particularly relevant for renewable energy integration with a focus on wind energy in general and more in-depth for Spain, Morocco and Egypt. Challenges regarding grid code standardisation and grid code compliance of renewable energy are addressed, and recommendations for further development of grid codes in North Africa are made, building on experiences from Europe.

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TOWARD AN IMPROVEMENT OF GRAVITY ENERGY STORAGE USING COMPRESSED AIR

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Abstract

The use of energy storage has received increasing attention due to the rapid growth of renewable energy generation. Among all energy storage systems, pumped hydro energy storage and compressed air are mature and large scale commercialized technologies. Combining the working principles of these two systems, a new concept is proposed in this paper, known as, compressed air gravity energy storage system. The feasibility of such technology has been analyzed in this paper by modelling the system components. In addition, its characteristics have been explored to investigate the optimal design of such system. The energy production of this technology has been compared to that of gravity energy storage without the incorporation of compressed air. The obtained results demonstrate that the use of compressed air significantly improves the system storage capacity. Therefore, compressed air gravity storage could be considered an attractive solution to the integration of large-scale intermittent renewable energy.

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EXPERIMENTAL VALIDATION OF GRAVITY ENERGY STORAGE HYDRAULIC MODELING

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Abstract

Energy storage is widely believed as a solution to the high integration of renewable energy technologies. As more renewable energy systems are deployed, there will be an increasing need for more energy storage. So far, pumped hydro storage (PHS) is considered the most significantly used storage technology. Investors are looking for systems able to overcome PHS drawbacks. As an alternative to PHS, gravity energy storage is a system that is currently under development. This technology is based on PHS working principle. The modeling and simulation of this system is the subject of this paper. This work focuses on the hydraulic dynamics of the system. Since gravity energy storage requires complex fluid and structural systems, a mathematical model has been developed using Simulink to investigate the system performance. The proposed model has been validated experimentally. The results obtained from the performed simulation allow for the identification of important parameters such as duty cycle time, piston position, chambers pressure and volume, as well as quantification of the system power and capacity. It is demonstrated that the simulated model can successfully mimic the operation of a real model with relatively small errors.