DESIGN, ECONOMIC OPERATION AND PERFORMANCE OPTIMIZATION OF GRID-CONNECTED OFFSHORE WIND FARMS, PV SYSTEM AND SUBSEA PUMPED HYDRO STORAGE FOR CRITICAL LOADS.
CASE STUDY IN DENMARK

A THESIS SUBMITTED TO
THE BOARD OF GRADUATE PROGRAMS
OF
MIDDLE EAST TECHNICAL UNIVERSITY, NORTHERN CYPRUS CAMPUS

BY

NOAH ODION

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN ELECTRICAL AND ELECTRONICS ENGINEERING PROGRAM

SEPTEMBER 2022

Approval of the Board of Graduate Programs

Prof. Dr. Cumali Sabah
Chairperson

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science

Prof. Dr. Murat Fahrioğlu
Program Coordinator

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Prof. Dr. Murat Fahrioğlu
Supervisor

Examining Committee Members

Prof. Dr. Murat Fahrioğlu	METU NCC/EEE	
Asst. Prof. Dr. Canras Batunlu	METU NCC/EEE	
Asst. Prof. Dr. Mehmet Şenol	CIU/ EEE	

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Noah, Odion
Signature:

ABSTRACT

DESIGN, ECONOMIC OPERATION AND PERFORMANCE OPTIMIZATION OF GRID-CONNECTED OFFSHORE WIND FARMS, PV SYSTEM AND SUBSEA PUMPED HYDRO STORAGE FOR CRITICAL LOADS.
CASE STUDY IN DENMARK

Odion, Noah
Masters of Science, Electrical and Electronics Engineering
Supervisor: Prof. Dr. Murat Fahrioglu

September 2022, 87 Pages

Power solution obtainable from Hybrid renewable energy system is promising and clean. However, since it is weather-dependent, it cannot follow variations in demand. This inherent variability, especially in wind and solar energy, causes mismatch between energy production and demand mostly at the time of demand thereby causing grid instability and increasing the risk of blackout. The subsea pumped hydro can solve this problem by storing excess energy from wind and solar and then dispatch it when demanded. Unlike conventional Pumped hydro, it uses the sea as an upper reservoir, a hollow sphere on the sea bed as the lower reservoir and the pressure difference in the sea as the head. During pumping and charging operations, water is pumped out of the sphere. Similarly, during generating and discharging operations, water falls back into sphere and drives an integrated turbine. It can be utilized for ancillary services in electricity market to generate revenue. Existing literatures have investigated the techno-economic feasibility of this technology in various dimensions. However, this study focus on balancing the numerous offshore wind energy and solar energy in Danish energy mix. Also, it considers the economic viability of operating the subsea pumped hydro for ancillary services in the Nord Pool using scenario-based studies in understudied location.

Keywords: Pumped hydro power, Subsea energy storage, Grid balance, and Ancillary services.

ÖZ

KRITIK YÜKLER IÇIN ŞEBEKEYE BAĞLI AÇIK DENIZ RÜZGÂR SANTRALLERI, PV SISTEMI VE DENIZALTI POMPALI HIDRO DEPOLAMA TASARIM, EKONOMIK İŞLETME VE PERFORMANS OPTIMIZASYONU.
DANIMARKA'DA DENEYSEL ÇALIŞMA

Odion, Noah
Yüksek Lisans, Elektrik ve Elektronik Mühendisliği
Tez Yöneticisi: Prof. Dr. Murat Fahrioğlu

Eylül 2022, 87 sayfa

Hibrid yenilenebilir enerji sistemleri temiz bir güç çözüm sunuyor olmalarına rağmen hava durumuna bağlı oluşları yüzünden ihtiyacı karşılayamazlar. Bu doğal değişkenlik, özellikle de rüzgâr ve de güneş enerjisinde, enerji üretimi talebi ile uyuşmaz ve elektrik kesintilerine dahi sebebiyet verebilmektedir. Denizaltı pompalı hidro, rüzgâr ve güneşten gelen fazla enerjiyi depolayarak ve gerektiğinde göndererek bu sorunu çözebilir. Geleneksel Pompalı hidro'dan farklı olarak, üst rezervuar olarak denizi, alt rezervuar olarak deniz tabanındaki içi boş bir küreyi ve ana olarak denizdeki basınç farkını kullanır. Pompalama ve şarj işlemleri sırasında küreden su pompalanır. Benzer şekilde, üretim ve boşaltma işlemleri sırasında su tekrar küreye düşer ve bütünleşmiş bir türbini çalıştırır. Elektrik piyasasında yan hizmetlerde gelir elde etmek için kullanılabilir. Mevcut literatürler, bu teknolojinin ekonomik fizibilitesini farklı boyutlarda araştırmıştır. Bu çalışma, Danimarka'daki sayısız açık deniz rüzgâr enerjisi ve güneş enerjisinin dengelenmesine odaklanmaktadır. Ayrıca, Nord Havuzundaki yardımcı hizmetler için deniz altı hidro çalıştırmanın ekonomik uygulanabilirliği senaryo bazlı çalışmalar kullanılarak araştırılmıştır.

Anahtar Kelimeler: Hibrit enerji santralleri, Denizaltı enerji depolama, Şebeke dengesi ve Yan hizmetler.

I would like to dedicate this work to my parents, Mr. Michael Odion and Mrs. Philomena Odion, for their tremendous efforts towards my academic despite their limited resources.

ACKNOWLEDGEMENTS

First, I would express my gratitude to the Almighty God whose grace helped me to successfully finish my master program. Despite my challenges when I first arrived METU NCC, His grace enabled me to finish well and strong.

Secondly, my gratitude goes to Mrs Zuhal Topaloglu for her motherly and financial support towards me during difficult times in the course this graduate program.

Finally, I would like to express my deepest appreciation to my parents especially my late mum who sacrificed so much to ensure I come this far. I will take this memory with me to be my sunshine after the rain.

TABLE OF CONTENTS

CHAPTERS

6. **SCENARIO-BASED STUDIES AND CO-OPTIMIZATION OF THE SYSTEM**

CHAPTER EIGHT

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

ABBREVIATIONS	
AGC	Automatic Generation Control
ARDL	Autoregressive Distributed Lag
BESS	Battery Energy Storage System
BOS	Balance of System
CEDREN	Centre for Environmental Design of Renewable Energy
CHP	Combined heat power plant
CAES	Compressed Air Energy Storage
DA	Day Ahead
DK1	Bidding zone of Western Denmark
DK2	Bidding zone of Eastern Denmark
DNI	Direct Normal Irradiance
EU	European Union
ENTSO-E	Transmission System Operators for Electricity
FCR-N	Frequency-Controlled Normal Reserve
FSPV	Floating Solar Photovoltaic System
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiance
GTI	Global Tilted Irradiance
GWh	Gigawatt hour
HRES	Hybrid Renewable Energy System
IPBESS	The Intergovernmental Science-Policy Platform on Biodiversity
kWp	Kilowatt Peak

LCOE	Levelized Cost of Energy
MPP	Maximum Power Point
MWh	Megawatt hour
NPV	Net Present Value
OECD	Organization for Economic Co-operation and Development
PHES	Pumped Hydro Energy Storage
POC	Point of Connection
P.R	Performance Ratio
PV	Photovoltaic
PVGIS	Photovoltaic Geographic Information System
RETs	Renewable Energy Technologies
RCN	Research Council of Norway
StenSea	Stored Energy in the Sea
SINTEFF	The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology
SOLARGIS	Solar Geographic Information System
SHPS	Subsea Hydro Pumped Storage
TSO	Transmission System Operat

LIST OF SYMBOLS

SYMBOLS

A:	Swept area (m^2)
C_p:	Power coefficient
C.F	Capacity factor
E	Energy (J)
F	Force (N)
H	Height (m)
V	Volume (m^3)
ρ	Density(Kgm^{-3})
g	Acceleration due to gravity(ms^{-2})
z	Elevation head relative to datum (m)
v	Velocity(ms^{-1})
P	Pressure (Nm^{-2})
h_L	Total head losses between point
γ	Relative density (Nm^{-3})
Q	Flow rate ($m^{-3}s$)
$P_{pumping}$	Power required to pump (W)
$P_{generating}$	Power generated during turbine operation (W)
t	Time (sec)
C_{max}	Storage capacity (MWh)
ρ_{sw}	Density of sea water (kgm^{-3})
V_{inner}	Volume of water inner volume (m^3)
r_{inner}	Inner radius of sphere (m)

d	Depth (m)
P	Power (Watt)
V	Average wind speed (ms^{-1})
R	Radius (m)
Z_r	Reference height
Z_o	Surface roughness
V (z)	Wind speed at height Z
V (z_r)	Wind speed at reference height
N_p	Number of panels
PV	Photovoltaic system
P_{panel}	Maximum output power
P.R	Performance ratio
I_t	Investment expenditures
M_t	Operations and Maintenance expenditures
F	Fuel expenditure
E	Sum of all electricity generated
r	Discount rate
n	Operational lifetime (yrs.)
P_{SHS}	Power from SPH
P_w	Power from wind
P_{PV}	Power from PV
P_{DG}	Power from Diesel Generators
P_{LOAD}	Demand
C^{min}	Minimum storage capacity.

CHAPTER 1

INTRODUCTION

1.1 Background

Air pollution has increased progressively in correlation with energy demand and consumption from fossil fuels. A key component of energy transition is reducing carbon dioxide (IV) oxide emissions in order to limit global warming. Increasing concern about climate change and rising prices of fossils fuels has prompted governments to stimulate and facilitate the developments of renewables [1][2]. In the face of global climate change, further action is needed to mitigate the effects of carbon emissions and reduce carbon footprint in the energy sector on a global scale. In the wake of global energy transition, further measures are needed to reduce emissions and mitigate climate change’s effects. It is possible to reduce carbon emissions by 90% through renewable energy and energy efficiency [1].

Renewable energy sources like wind, solar, hydropower, biomass, wave and tidal etc. are natural, abundant and can be harnessed without compromising future energy needs [3]. However, they depend on weather and such factor constitute a major drawback associated with them [3]. Furthermore, obtainable power solution is not reliable. For instance, solar and wind energy fluctuate due to seasonal changes and such intermittency make Location and availability of resources are factors which determine where they are installed [4]. This means a single stand-alone renewable may pose some challenges like poor power output and high operating costs, which is why renewable energy systems, diesel generators and large-scale BESS are usually combined [3][4]. The effectiveness of a hybrid energy system is hinged on the accuracy of its underlying components and operation characteristics as surely as the individual key in a typewriter contributes to the overall efficiency of the typewriter machine. [5] Generally, integrated energy system is a combination of renewables and diesel/Petrol generator to produce electricity which is either fed into the grid or stored in battery storage like in micro grid application [3][6]. The main benefits of integrated energy system are to reduce diesel, improve electrical power production, minimize costs of operation, reduce greenhouse gas (GHG) emission, and improve overall system efficiency [6].

The hybrid energy system is a sustainable energy solution in which wind energy is complemented by solar energy and/or energy storage. It may be stand-alone or grid-connected mode [3][6]. In other words, HRES may be classified into the Island mode whereby the energy generated is consumed locally and grid-connected mode whereby the renewables are connected to the grid [3] [6]. Stand-alone renewable energy system must have a high-capacity battery storage to be able to meet the energy demands of load centres connected to it. In the case of grid-connected hybrid energy system, the total reactive power can be fed to grid. For stand-alone systems supplying local loads, if the power generated is more than the local load plus losses, the excess power from the wind turbines and PV generators is diverted to a dump or stored in the battery bank. Moreover, when the generated is less than consumer load, the deficit power needs to be supplied from storage element e.g. a battery bank or pumped hydro energy storage [7].

There are two generally accepted configurations of hybrid power plants:

- Energy systems where renewable energy systems and diesel generators are integrated with the goal of fuel reduction [6].
- Energy systems where renewable energy source produces more and the diesel generator is used as back-up supply in scenarios of low power and high load demand [6].

Also, to further increase energy consumption with minimum environmental and social impacts; to minimise the severe impact of uncertainty and randomness of wind power and photovoltaic power generations; to maintain and stabilize grid frequency, foster minimum power loss and voltage profile consistent with conventional power system, then an integrated system consisting of hydropower plant, wind turbines and PV system is necessary [8]. As a flexible system, hydropower has the ability to adjust to load variation and support the integration of wind and solar energy on the grid. Also, it has the capacity to function as a large scale energy storage system-it has remarkable potential to effectively cover the power deficit during dispatch of energy [5] [8].

1.2 Problem Description

Despite the availability of huge hydro resource in Denmark, it is almost impossible to build out hydropower dams due geological constraints. This means, there is no hydro-based flexible unit in their energy portfolio and the option left, as far as hydro power is concerned, is to explore and investigate various concepts of pumped hydro to balance their power network. In the light of this, both underground and offshore (Subsea) pumped hydro energy storage have been proposed as these can help to overcome these natural factors as discussed in details in subsequent sections.

1.3 Description of Study location

Wind turbines and coal power plants dominates the energy mix in Denmark. The share of electricity from wind power is near 30%, making Denmark the world's largest provider of wind power [6] [24]. The Danish Power exchange is part of the largest electricity market (Nord Pool) and the TSO is Energinet.dk [6] [7]. Expansion of wind energy is one of the numerous European Union (EU) environmental targets. With 2050 in sight, it anticipates being 100% carbon dioxide free by 2035, with power generated exclusively by renewable sources [7] [24]. This include a complete electrification of the transport sector and a system completely free of fossil fuels [7] [24].

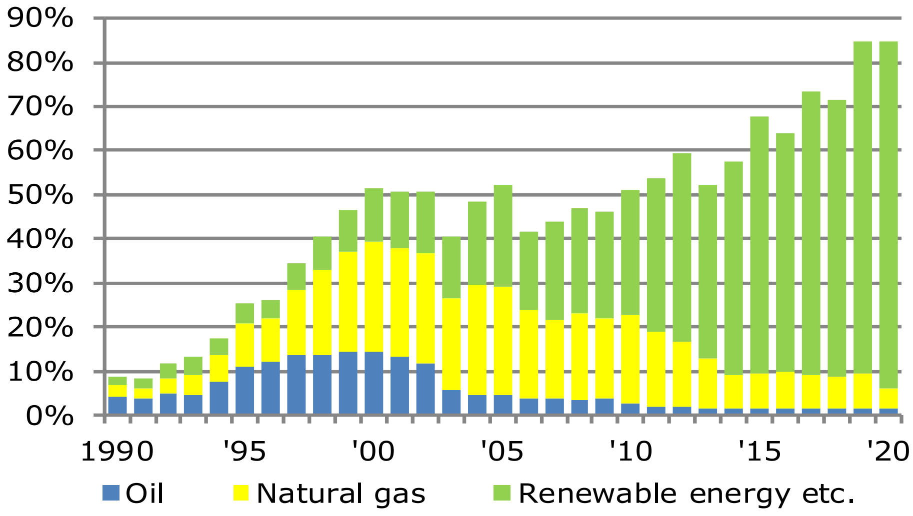


Fig1. Electricity production from fuels in Denmark (except coal)

The Danish energy sector is a good example of green transition; it has experienced a remarkable transformation from black to green, a success achieved in 45 years since the period of oil crisis in 1973 [6][7]. With national growth, it achieved an unprecedented level of electricity security of 99.996 percent with 50% renewables share [6][7]. Over the years, reduction of energy consumption and increased share of renewable energy to abate greenhouse gas and optimize cost while facilitating energy independence and national security has been the taken numerous actions of the Danish Parliament taken on the basis of a broad consensus [6] [7] [33]. Since the 1970s, policies have driven the remarkable green transition, and such feats illustrate the possibility of sustained high economic growth and reduced fossil fuel dependence through persistent and aggressive energy policies. Compared with pre-industrial Danish economy, the post-industrial Danish economy was characterized by a reduction in energy consumption and CO_2 emissions [5] [32].

The electric grid in western Denmark (DK1) is part of Synchronized grid Continental Europe whereas the eastern part (DK2) connects to Sweden. [23] In terms of connected power grids, this continental synchronous grid is the largest [6] [7]. More than 400 million customers, including most of the EU are served by this phase-locked 50Hz electricity grid [2] [3] [4]. With a production capacity of 667 GW, which went online in 2009, it provides an operating reserve margin of approximately 80 GW. The various transmission system operators operating this grid constitute the Union for the Coordination of Transmission of Electricity (UCTE), now part of the European Network of Transmission System Operators for Electricity (ENTSO-E). Among the OECD and other EU member states, the Danish economy is one of the most energy-efficient. [4][6][7]. As a result of present action, Denmark is now on its way to an energy-efficient future. 2050 is the target date for eliminating fossil fuels by the Danish government [6][7]. Renewable energy currently covers more than 40% of electricity consumption in Denmark yet, there is a challenge: with increased number of renewables, there is need for a balancing unit to help stabilize the system frequency and make it more flexible. [6][7] [4] [32].

The flexibility of a grid system is a measure of how quick it responds to load variations. Quantitatively, there is huge hydro resource and high potential for large-scale hydropower in Denmark but due to topographical restrictions, it is not feasible in such terrain. [6][7] [4]. Additionally, even though hydropower is durable, flexible and reliable, severe droughts winter and dry season often affect it capacity causing under-production, under-performance and frequent outages such as experienced in Pakistan, Brazil and Portugal etc. This is one of the reasons for large-scale deployment of floating solar photovoltaic into marine spaces near existing hydro power plants like in those countries listed above and many others. In a bid to solve this challenge, research showed pumped hydro energy storage proved the most economically feasible option among others. However, for Denmark, CEAS, underground PHS and SPHS have been investigated as the only feasible grid balancing solution relevant it need.

The techno-economic feasibility of SPHS has been investigated in part in very few literatures but not applied to locations and that is main focus of this project. [6][9] Denmark has strong links to its neighbours and this interconnection becomes increasingly important because it determines the reliability of its power supply since there is no flexible energy source like pumped hydro in their energy mix now. The countries interconnected with Denmark include Norway, Sweden, Finland, Germany, the Netherlands and the United Kingdom [7][4] [23].

The critical elements which facilitated this transition and established Danish stronghold in energy sector includes research and development, demonstration of new technologies and systems. Enterprises in the public and private sectors, coupled with a stable political and regulatory framework, have facilitated these significant innovations and breakthroughs in energy concepts and systems. The three foundations that underlie the carbon transition in Denmark include renewable energy, energy efficiency and system integration (including electrification) [13] [32].

1.4 Research Questions and Objectives

- How should SPHS be integrated with existing wind farms and PV system for balancing purpose? Is there a relationship between the optimal solution and the characteristics of the load center?

- In what ways can large-scale SPHS regulate their load, and what limitations do they have?

- To provide flexibility in operation and ancillary services to European electricity market, how should large-scale SPHS be integrated with existing wind farms and PV systems?
  - What is the relationship between the control structure and dynamic behaviour?
  - What is the correlation between component size and regulation?

- What should be most energy-efficient and cost-effective way and offshore location for SPHS installation?

Therefore, the objectives of this study is to investigate the economic viability of balancing existing offshore wind farms and PV systems in Denmark with SPHS considering CHP in future studies. Also, it investigates the economic viability of operating the proposed SPHS for ancillary services in the Nord Pool using scenario-based studies of energy flow in understudied location.

1.5 Data and Methodology

The meteorological data used in this study includes temperature, solar irradiance, precipitation of North and Baltic Sea. Several online simulation tools developed by the scientific community were utilized in designing the floating PV system and assessing the offshore wind farms in selected and studied locations. Three notable online simulation tools used in this project are Esox-Lautec weather downtime simulation tool, PVGIS and Global Atlas.

The methodology adopted in this study includes:

- Review of related and relevant literatures mostly on Denmark.
- Data collection from available sources like Nord Pool and from Danish energy website (Energinet)
- Organization of data in suitable format for analysis and simulation.
- Assessing Danish offshore wind and solar energy with GIS.
- Comparison of five (5) different offshore wind farms to determine the most feasible site for subsea energy storage.
- Mathematical modelling of subsea energy storage (Stensea)
- Technical report writing.

Also, due to wide scope of this project and limited space, some sections will be analysed in future work.

CHAPTER 2

LITERATURE REVIEW

Denmark has strong links to its neighbours and this interconnection becomes increasingly important because it determines the reliability of its power supply since there is no flexible energy source like pumped hydro in their energy mix at the moment. The countries interconnected with Denmark include Norway, Sweden, etc. Some literatures have investigated the causal link between the renewable energy consumption, CO_2 emissions and economic growth in Denmark for the period of 1972-2012 [32].

The relationship dynamics between technological innovations, energy prices, economic growth, and Danish energy consumption was investigated the same period using annual series data which span 42 years (1970-2012). In subsection on methodology, it discussed why autoregressive distributed lag (ARDL) is an appropriate method for assessing long-term relationships between the variables considered [33].

Another study focused on the need for flexible and balancing options to help manage the numerous renewables in Europe in general and Denmark in particular and how that the installation of energy storage will increase energy security and revenue in the Nord Pool. For example, various storage options such as CAES, BESS etc. relevant to the Danish power system was reviewed a team of authors [9]. The same study compared rated efficiency and system prices for different technologies [9].

Similarly, the strategies for solving the balancing problem and to enhance the integrating more renewable energy source in their energy mix has been investigated. The feasibility of including the combined heat and power (CHP) plants in balancing fluctuating wind power demonstrated [10].

The methodology adopted involves the use of the energy system analysis computer model ENERGYPLAN and a detailed assumption for the development of the Nordic market for electricity [10]. A demonstration of possible future flexible energy systems, capable of balancing production and demand as well as securing voltage and frequency requirements on the grid, has also been conducted [11].

Comparing various storage options, the potential impact of CAES technology on Western Denmark was investigated in a study. Specifically, the energy balancing effect on excess energy production was the goal of the research. [12]

Also, using the simulation modelling tool “OEMOF”, the introduction of flexible energy source into the numerous renewable resources of the Danish grid has been demonstrated. Due to topographical constraints, the conventional type of hydro power dam was not factored in the simulation modelling. Hence, two pumped hydro energy storage options such as Underground pumped hydro storage and offshore pumped hydro storage were considered and compared in the analysis [13].

A literature study in [14] also concluded that joint operation of wind farm and battery energy storage system (BESS) in DA and FRC market can results in greater profits for the wind farm owner compared to the conventional method of bidding in just one market. The same work assumed the location of the wind farm with battery energy storage system (BESS) in Eastern Denmark (DK2). Furthermore, another literature study investigated the optimal operation technique for battery energy storage systems (BESS) based on real-time electricity prices using simulation modelling to maximize profits [15] [21].

Furthermore, to enhance grid flexibility, another author [48] investigates the potential of large-scale heat pumps as thermal storage capacity for large share of renewable systems. The study aimed to evaluate whether to what extent heat pumps can serve this purpose by evaluating their technical and economic feasibility for supplying district heating and other ancillary services for power grid [48].

A new technological concept called Subsea Pumped Hydro Storage (SPHS) was evaluated in a thesis. The technology was described, its performance analysed based on a set of criteria and comparison with other forms of energy storage technologies was shown. [16] [27] Utilizing hydrostatic pressure in the ocean, the author in references [17] [27], proposed unobtrusive, safe, and economical energy storage alternative that uses water pumped out of concrete spheres to store energy which is later released through turbine.

In another similar study, subsea energy storage was analysed in terms of the cost structure, it comparison with alternative energy storage options was shown and the necessary price arbitrage for its commercial operation calculated. A sensitivity analysis was conducted to assess the impact of different cost parameters, as well as the storage depth below sea level in proportion to the number of units [18] [21] [22].

To investigate the impact of Danish large-scale wind energy on intraday electricity market, another author shows how wind forecast errors affect intraday prices relative to day-ahead prices in the context of intermittency. They also investigate cross-border exchanges in the intraday market and the causal relationships between wind generation, fossil-fuelled generation, and electricity consumption [48].

In [41], the techno-economic analysis of floating photovoltaic systems, for southern European countries. Specifically, it investigates the feasibility of co-locating 1MWp floating PV system with existing Gouvães dam that is included in the Tâmega hydroelectric complex under construction in northern of Portugal.

An optimal sizing design, power electronics topologies, control regarding optimal sizing design and power electronics topologies is reviewed in [50]. Hybrid solar and wind systems, both connected to the grid and stand-alone, are reviewed in the same paper.

The study in [51], presents a three-way analysis of the effects of wind energy production and planned cross-border energy flows on interconnectors between western Denmark and eastern Denmark, southern Norway, Stockholm, Sweden, and Germany.

The paper in [52] introduces and applies a methodology to evaluate to what extent Danish wind production has been utilized domestically by the historical Danish energy system in 2008.In the light of these findings, it is discussed how to design the future system so that it can accommodate future increases in wind power [52].

CHAPTER 3

GRID BALANCE IN EUROPE

3.1 Balancing Wind and Solar Energy in Europe

In simple terms, grid balance refers to the matching of energy generation and consumption. For this reason, the power grid requires some flexible unit, like hydropower, to manage fluctuations in wind and solar energy [30] [31]. The combination of the EU emission reduction targets and increasing energy demand will result in a greater proportion of electricity generated from renewables [30] [31].

The percentage of renewables in electricity generation in Ireland, Germany, and the United Kingdom was predicted to reach 25% by 2022, while Denmark is expected to lead with a 70% as their market share [30]. Since renewables varies with weather conditions and demand varies with human activities, then outsmarting the grid by making it intelligent system is another viable option. Power system networks must be flexible in order to produce electricity using renewable sources [30] [31].

As a result, different operations and reorganization of the power system is required to ensure reliability and energy supply in the future. The European Clean Energy Package (also known as the Winter Package) was presented in 2016 and it goals are related to, renewables, energy efficiency energy,electricity market etc.[30][31]. Several actions to meet the demand for flexibility were identified. Increased cross-border transmission capacity is a major strategy for increasing system flexibility. The EU mandated in 2014 that all member states interconnect at least 10% of their capacity (MW) by 2020, and possibly 15% by 2030 [30][31].

Consequently, national blackout frequencies decreases, isolated areas and countries can rely on their neighbours' electricity systems for security, and intermittent renewable energy is more easily integrated [30][31]. Furthermore, interconnection is a critical factor in achieving this goal. In the case of Norway, additional transmission lines will installed to ensure interconnections to Northern Europe [30][31].

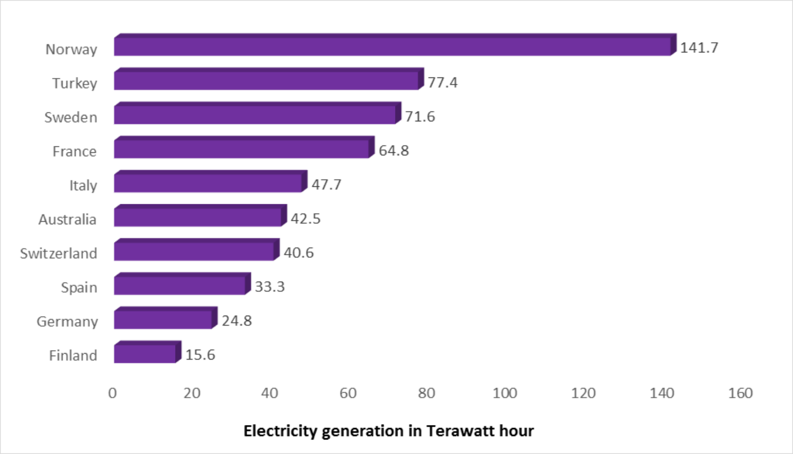


Fig 2. Total installed hydro reservoir in EU

Data source: Statista [36]

The integration of existing renewable sources of energy in a secure and cost-effective manner is a key componnent of increasing system flexibility along with more interconnected power systems, new market designs, and new national and European policies and incentives [30][31]. The new market design should increase flexibility between energy produced and consumed; consumption should adjusted to real-time prices, while generators production becomes more predictable [30].

A cross-border increase in transmission capacity and re-design of new electicity markets and policies should likely take place in combination with deployment of energy storage. This allows for the storage of electricity when there is a surplus of production and electricity prices are low and release it later when demand and prices are high [30]. Therefore, electricity storage is a critical component of balancing services, as it provides the flexibility essential to maintain balance between solar and wind generation. Storage is expected to play a significant role in the integration of renewables in the European energy system, and has been gaining attention from policy makers since the mid-2000s [30].

In Germany, the energy transition policy (Energiewende) was passed in 2010, making it the first document to define storage as a pillatr of integrating variable renewable energy[30][31]. Due to its cost-effectiveness, the German Advisory Council on Environment considered Norwegian pumped storage as a major option for balancing renewable energy production in

Northern Europe in 2011. The presence of Norwegian reservoirs accounts for 50% of the hydropower in Europe and 99% of the energy storage capacity in world [30][31].

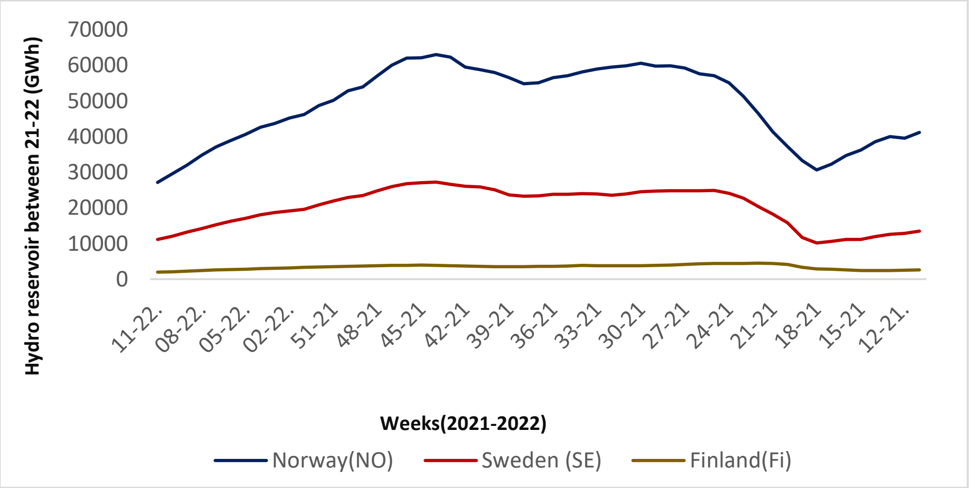


Fig 3. Comparison between Norway, Sweden and Finland’s weekly hydro reservoir [37]

Data source: Nord Pool [37]

In Norway, RCN has in recent decades set up special research programmes in partnership with an environmental design and renewable energy group (CEDREN) to investigate the advantages and drawbacks of balancing energy system of EU[30][31]. Energie21 is the name of the country's research and development, demonstration, and commercialization strategy for new energy technology. The latest updates from this concept emphasize the role of integrated energy systems, including interconnectors with European Union (EU) [30][31]. One of the first large-scale exchange projects focused on the flexibility of the existing Norwegian hydropower infrastructure. SINTEF energy research investigated the potential for large-scale energy storage for Europe [30][31]. Their study concluded that by upgrading existing hydropower plants and building new pumped storage between existing reservoirs, Norway’s hydropower capacity could increase by 20GW while adhering to current regulation and concession requirements [31]. On the other hand, previous research projects did not take into account political feasibility as well as enviromental and societal impact of such project [30][31].

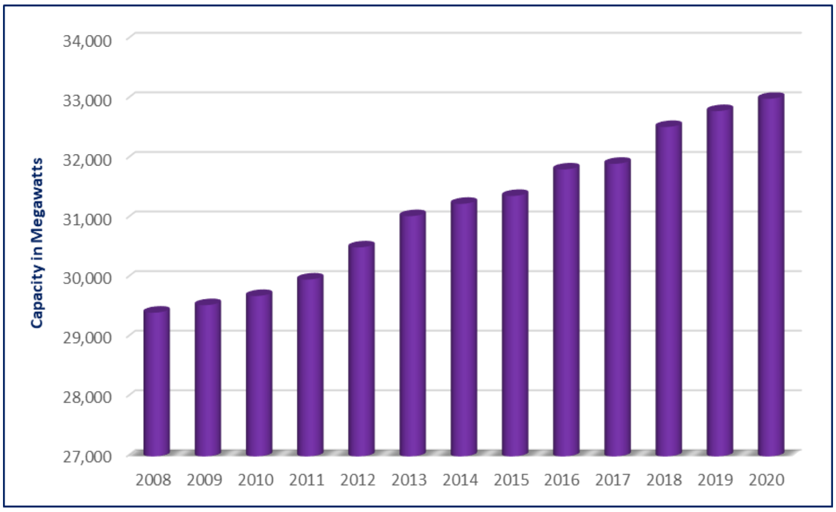


Fig 4. Annual capacity of hydro reservoir in Norway

Data source: Statista [38]

Climate-neutral energy is derived from water resources, but catchments provide other ecological services such as recreation, irrigation, biodiversity etc. Therefore, Norwegian hydropower has the potential to reduce CO_2 emissions in Europe, but this must be balanced against the potential negative impacts on local environment, communities, and other business sectors [30][31][34]. Around the world, habitat degradation and loss of habitat threatens biodiversity, and according to a recent report from IPBES, loss of biodiversity threatens humanity on par with climate change [30][31][34]. All forms of energy production (including renewables), impact the environment negatively.Consequently, for the Norwegian hydropower system to meet electricity demands, trade-offs must be made between climate-neutral energy and landscape and biodiversity preservation [30][31][34].

3.2 Energy Storage Prospects in Denmark

The development of energy storage can be classified into the following main areas:

- Electrochemical storage – batteries and hydrogen storage (in combination with fuel-cells)

- Mechanical storage – pumped hydro, compressed air and flywheels
- Electrical storage – super capacitors
- Heat storage – accumulators

The emphasis in this thesis is on the mechanical energy storage mechanism, one of the balancing measures mentioned above. Energy produced by larger thermal plants with low flexibility is traditionally collected by these units to balance loads at peak and off-peak hours [34] [35]. This is accomplished by making economically advantages trades by taking advantage of the difference in energy at difference of energy at difference times to make economically beneficial trades. Using energy storage enhances the efficiency of the electricity system, as power generating plants can run at optimal levels for longer periods despite lower demand if the storage capacity is adequate and the system can handle the loads. Intermittent energy sources cannot meet more than 15 or 20% of the electricity demand in a region if no energy storage is implemented [9] [34] [35].

When the generation of power varies by up to about 10%, balancing can usually be achieved by using spinning reserves, which means altering the operation of running plants in the system. During times of high fluctuations, however, non-spinning reserves are required. A reserve consists of plants not normally connected to the system and with short start-up times, such as gas turbines, and plants that can be offloaded. Energy storage units can be used instead of these fossil fuelled plants just to remove them from the energy mix. Storage facilities can be placed close to the location of generation in order to balance load during peak or off-peak hours, close to load to avoid transmission losses on lower voltage levels, or close to the load just so it can provide adequate power during times of peak demand.

An energy storage unit is made up of three different components: storage medium, power conversion system, and balance of plant equipment. Increasing the size of the storage units leads to a greater impact on the storage medium cost [9]. As a result, the largest types of units use water and air as a medium because they are cheap, plentiful, and have low losses. In terms of economics, the medium is usually half the price of the entire storage facility. This cost can be divided into two parts: the cost of acquiring the medium and the cost of keeping it in an energy-storing condition. The power conversion system converts alternating current to direct current and vice versa and serves as interface between the storage facility and the power grid.

The PCS for mechanical energy storage units is made up of the motor and generator train, which converts kinetic energy to electrical energy.

Power unit must be able to respond to changes in electricity production ranging from short-term (seconds) to long-term variations in order to balance wind and solar power generation (weeks). Alternatively, technologies such as electrochemical batteries, flywheels, and compressed air can handle short-term power system fluctuations by delivering high power ratings (1-1000 MW) over short and medium time periods (from minutes to days). While hydropower can also balance short-term fluctuations, it also has the advantage of being able to store large amounts of water and generate electricity over long periods of time (days to week). These characteristics enable hydropower to counteract long-term wind fluctuations. Energy storage stands out as the most important component which needs to be addressed if the future wants to rely on renewable energy.

This holds true even in the case of Denmark. As Denmark and its neighbours increase their wind production, the availability of balancing and regulating capacities abroad may be limited. There have been several proposals in literature for large scale electricity storage technologies that could be useful in stabilizing the Danish power system. These include the compressed air energy storage (CAES), the Underground pumped hydro storage and offshore pumped hydro storage. These can help eliminate the topography limitation of Denmark [9].

3.3 Operational principle for Conventional PHS

PHS is a dynamic and flexible method of storing energy as well as generating electricity. By filling and emptying reservoirs such as Dams and lakes, water can be moved between upper and lower levels. A natural water reservoir or an artificial reservoir can be used. When high levels of electricity generation are not needed or when demand is low, such as at night or on weekends, excess power can be used to pump water from the upper storage reservoir. The peak generation occurs generally during the day when there is high penetration of Renewable Energy Technologies (RETs) like solar and wind [34] [35.]

The hydro turbine is usually operated in pump mode at night when the wholesale price of electricity is low, when the demand for electricity is low, or during the time when the wholesale price of electricity is low. At times of high electricity demand or low system capacity, the stored energy in the water at the higher elevation is released to the lower reservoir through gravity. Through this simple concept, energy is transferred from the peak part of the daily load curve to the base thus flattening the load curve and by using traditional a traditional AC generator, the turbine produces electricity [34] [35].

This technology employs a similar infrastructure as conventional hydroelectric plants, the main difference being the turbine paired with a pump set. In most cases, PHS does not consume water in the process of storing energy or producing electricity. Through evaporation, reservoir, tunnel, or pipeline leaks, water can be lost and most installations do not require continuous supply of bulk water or make-up water and as a result water is considered to minimal. Accordingly, pumped hydro energy storage plants are quite often integrated into existing water infrastructure to serve additional functions, such as critical water transfer capabilities and the management of reservoirs levels to facilitate natural flow management.

Fig 5. Solar-powered pumped hydroelectric energy storage plant in Zimbabwe

Image source: Afrik21 [43]

PHES is not hundred percent efficient (100 %,), as are all energy storage systems [34]. Depending on a number of factors, its overall cycle efficiency varies but it usually falls between 70% and 80%. In both pumping and generation modes, the pump/turbine suffers the greatest loss of about 8%. To be an economically viable part of the power system, the electricity price differential between pumping and generating modes would need to cover pumping, operating and maintenance costs, and capital costs. Other project-related system benefits must also be acknowledged [34] [35].

Over time, PHS technology has been improved through the addition of reversible pump turbines, static frequency converter motor starting equipment, mechanical bearings, and high-speed automatic controls. New PHS have been built using adjustable speed machines in Japan and Germany. Ternary pumped hydro projects also use single synchronous machines connected by torque converters or clutches to a separate turbine and pump and a hydraulic bypass or short-circuit with a single synchronous machine. It offers even more operational capabilities, flexibility, and efficiency as a result of the new technology.

The following are the main design parameters that define a pumped hydro energy storage (PHES) scheme:

- The upper and lower reservoir water volumes
- Hydroelectric generation potential power defined by a water turbine rated flow and power (or mega-watt MW) capacity
- The net vertical head available which is the difference in elevation of the upper and lower water storage reservoirs.
- The potential energy available which is a function of volume and head.
- The energy storage time period in hours, which is a function of the potential energy and size of the turbine. The stored electrical energy often stated in mega-watt-hours (MWh) or giga-watt-hours (GWh)

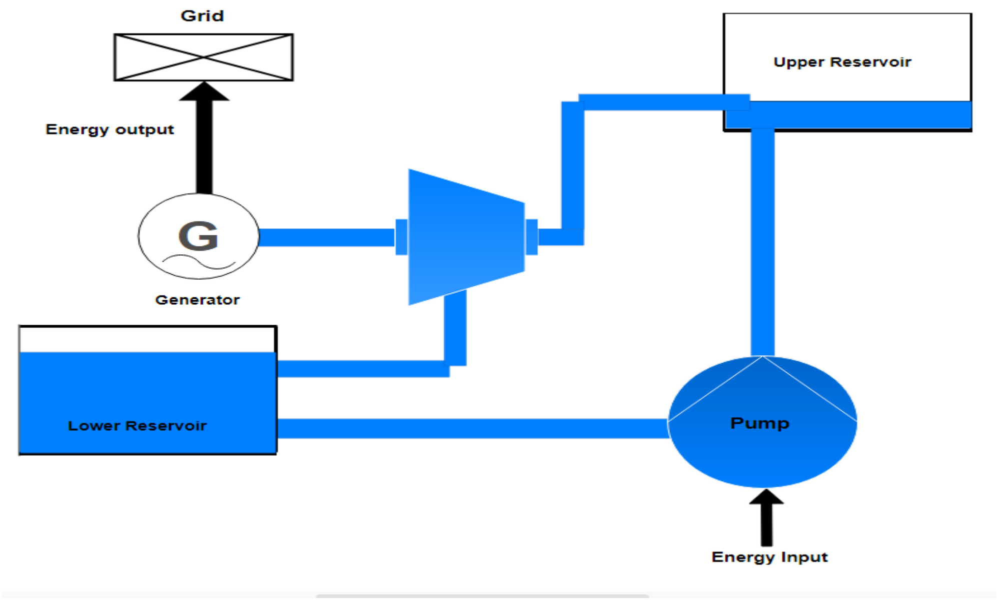


Fig 6. Architecture of pumped hydroelectric power plant

Software: Drawio

3.31 Power and Energy Equations

Basically, energy from flowing water is used in hydro projects, such as PHS. The equations for PHS include:

3.311 Energy:

Energy (E) is the product of the force of (F) and height (H). The force here is the weight of water.

$$E = F * H$$

$$E = V\ \rho\ g\ H$$

Potential, pressure, or kinetic energy can all be used to measure the energy potential of water. Depending on the speed of the water travelling, potential energy can be derived from the flow of water, pressure of water etc. A pumped storage hydropower facility that includes waterways with varying elevations and pipe diameters can be evaluated by the Bernoulli theorem. Assuming constant discharge rates, Bernoulli's equation includes that energy head at any point downstream, plus losses.

The Bernoulli equation is mathematically stated as:

$$Z_1 + \frac{(V_1{}^2)}{(2g)} + \frac{P_1}{\gamma} = Z_2 + \frac{(V_2{}^2)}{(2g)} + \frac{P_2}{\gamma} + h_L$$

3.312 Efficiencies

The efficiency of the overall project cycle, especially for pumped storage projects, is an important factor that determines whether a hydropower project will succeed. Efficiency in pumped storage hydropower projects can be calculated as the ratio between the energy output and the energy input. Energy inputs are typically captured 70 to 80% by pumping storage hydropower projects, which means that about 7 to 8 MWh of energy are recovered for every 10 MWh of energy input. Pump, turbines, and waterways are the main sources system losses.

3.313 Power

Power is a measure of the rate at which work or energy is completed

$$P = \frac{\Delta E}{\Delta t}$$

The hydraulic head (ΔH) changes with the discharge and specific weight of water, so power is the product of these three factors:

$$P = \gamma\, Q\, \Delta H$$

Where;

γ = Relative density of the fluid [Ib/ft^3; N/m^3]

Q = Rate of flow [ft^3; m^3/s]

ΔH = Change in head [ft; m]

Generally, power is measured in horsepower (HP) in imperial units and as kilowatts (kW). By multiplying the right side of the equation by time, kilowatt-hours or horsepower-hours can be calculated.

From Bernoulli equation, the change in head (ΔH) for the power equation is:

$$\Delta H = H_2 - H_1 = \left[\frac{P_2}{\gamma} + Z_2 + \frac{(V_2{}^2)}{(2g)}\right] - \left[\frac{P_1}{\gamma} + Z_1 + \frac{(V_1{}^2)}{(2g)}\right]$$

In a PHS project, H represents energy per weight applied to pump water, and during turbine operation it represents energy per weight applied by fluid. The equation required for pumping water to upper reservoir is:

$$P_{\text{pumping}} = \frac{\gamma\, Q\, \Delta H}{\eta}$$

The power generated during turbine operation is mathematically calculated as:

$$P_{\text{generating}} = \eta\, \gamma\, Q\, \Delta H$$

Generally, the amount of energy stored is proportional to the volume of water and the head between the reservoirs. Therefore, assuming a 90% of efficiency, an elevation change of 1000 feet will produce roughly 9000 MWh for power grid.

3.32 PHES for Ancillary Services

In the absence of large-scale storage of electricity at reasonable costs, a power grid operator is responsible for making sure supply and demand are constantly balanced. Power grids are always making adjustments to meet demand as it changes (actually, much more rapidly than one seconds). Power grid stability and continuous supply-demand matching require decisions to be made over a wide range of time frames. Operators of power grids use the day-ahead market to ensure there is enough supply to meet anticipated demand 24 hours in advance. It works the same way on an hour-ahead basis as the real-time market. The hour-ahead market clearing is followed by real-time dispatch, but what happens in between?

In between discrete moments when real-time markets clear, grid operators must handle fluctuations in supply and demand, referred to Ancillary services. These services are expected to become more increasingly valuable in future energy markets and any new hydro power unit must be designed to maximize revenue opportunities for ancillary services and improve power system security in the deployed region. The PHES system is designed to be based on well-established rotating machine technology. Synchronous machines have a long history and will continue to play a key role in utility grid ancillary services. This is accomplished through provision of inertia, frequency, voltage, and fault level support.

Four primary types of ancillary services include:

- Reactive power
- Frequency regulation
- Spinning and non-spinning reserves
- Black start

In this study, we focus on frequency regulation, reserve and black start.

3.321 Frequency regulation

All generators in a big power grid must spin at the same frequency, or the system may become unstable. Maintaining the frequency of a big grid at something very close to 60 Hz is critically important. In the event that the frequency of the grid deviates slightly from 60 Hz, the spinning generators will naturally exert more force on one another to return it to 60 Hz. If the deviation is really large, the grid will become unstable. To correct high or low system frequencies, power grid operators use frequency regulation.

The power grid can be likened to a bathtub with a faucet and a drain. Water level in the bathtub is similar to power grid frequency. There will be rise in water level in the bathtub if the faucet is much larger than the drain. Similarly, if supply outpaces demand in a power grid, the frequency will rise to higher than 60 Hz. This scenario is seen during sudden a spike in wind energy or decrease in energy demand like when everyone in the US turns off their television. As a result, the level of the water in the bathtub will fall if the drain is bigger than the faucet. The system frequency will fall below 60 Hz as demand exceeds supply in the power grid. Usually, this occurs when the supply suddenly drops, such as when a large generator suddenly stops working.

Generally, grid operators are able to handle over-frequency events more easily than under-frequency events. They can respond to frequency exceeding 60Hz by reducing the output of certain generators if the frequency starts increasing slowly. However, there are greater risks associated with under-frequency events due to their ability to cause a significant loss of electricity when they occur unexpectedly. During this condition, recovering the system frequency to 60 Hz involves three phases, collectively referred to as frequency control and these include:

- Primary frequency control: this automatically activated upon detecting an under-frequency event. Frequencies sensors allow generators to automatically adjust their output.
- Secondary frequency control: in the event that under-frequency event does not correct itself within ten seconds, secondary frequency control is triggered, also automatically. An automatic generation control system (AGC) is sometimes used for secondary frequency regulation.
- Tertiary frequency control: whenever primary or secondary frequency control mechanisms cannot correct an under-frequency event within a few minutes, tertiary frequency control is activated. Power grid operators typically manually adjust some power plants dispatch as part of tertiary frequency control.

Example 1:

Suppose a 100 MW generator supplies 10 MW for regulation at a regulation capability price of $ 5 per MW. The generator is dispatched to produce 60 MWh of energy through the real-time market at a price of $ 15 per MWh. Because of a frequency deviation event, the generator is asked to produce an extra 2MW of power for 10 minutes. The total revenues of this generator would be:

- Energy market revenue: 60 MWh $* \; 15\left(\frac{\$}{\mathrm{MWh}}\right) = \$\,900$
- Regulation capability: 10 MW $* \; 5\left(\frac{\$}{\mathrm{MW}}\right) \; = \; \$25$
- Regulation performance: $2\mathrm{MW} * \left(\frac{10}{60}\right)\mathrm{hr} * 15\left(\frac{\$}{\mathrm{MWh}}\right) = \$\,5$
- Total revenue: $ 900 + $ 25 + $ 5 = $ 930

3.322 Reserves and Black Start

In the event of a loss of another power plant**,** or in the event that demand exceeds what was expected, power grid operators maintain reserves as back-ups. If the frequency of a power grid falls below 60Hz, the system may be forced to use reserves in order to bring it back up to normal speed. Spinning and non-spinning reserves constitutes two quality of reserves. The spinning reserves represent a large amount of synchronous (60Hz) capacity that is not currently producing electricity. Spinning reserves are expected to be able to generate electricity for the specified time period when activated (e.g. 10minute, 30minute and 60-minute spinning reserve). A non-spinning reserve means that capacity that has not been activated but can be activated and ready to generate electricity within the specified time of activation.

As with regulations, reserves in areas where power restructuring has taken place are often raised through auctions. Unlike regulations, reserves are just a service to increase power output (there is no reserve down like regulations are down). Generators that provide reserves receive the electricity price of those reserves and, on demand, the real-time energy prices.

Example 2:

Consider the same generator in previous example produce 50 MWh in the energy market at a price of $ 15 per MWh. This generator provides 10 MW of reserve and a capability price of $ 25 per MW. At the start of an hour, the TSO tell the generator to produce 2 MW of power for the following half hour (which is 30minutes). The total revenues for this hour will be:

- Energy market revenue : $50\ \mathrm{MWh} * 15\left(\frac{\$}{\mathrm{MWh}}\right) \Rightarrow \$\,750$
- Reserve capability : $10\ \mathrm{MW} * 25\ \left(\frac{\$}{\mathrm{MW}}\right) \Rightarrow \$\,250$
- Regulation performance : $2\mathrm{MW} * \left(\frac{30}{60}\right)\mathrm{hr} * 15\left(\frac{\$}{\mathrm{MWh}}\right) \Rightarrow \$\,15$
- Total revenue: $ 750 + $ 250 + $ 15 = $ 105

CHAPTER 4

PUMPING AND GENERATION MODES OF PUMPED HYDRO ENERGY STORAGE

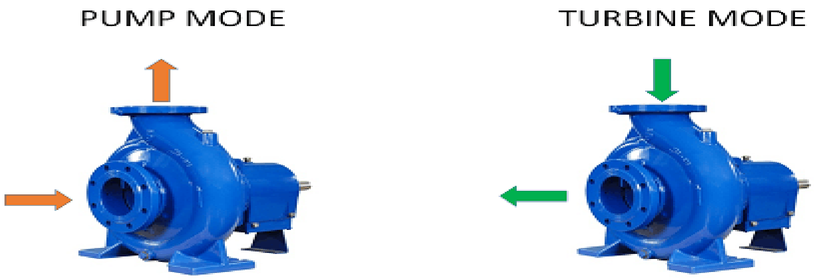


Fig 7. Pump and Generation mode of turbine (Click here for image source)

In each period (time step), the analysis in this section considers if there is excess energy in the grid is required. Provided other criteria are met, the system uses excess energy on the grid to pump water to the upper reservoir and this is referred to as pumping mode. [19] In contrast, generation mode is used when peaking power is required and it is capable of generating its own power. Below is a detailed description of the logic followed in this calculation.

4.1 Pumping Mode

The analysis takes into account a number of variables during pumping mode to ascertain if the upper reservoir is filled with water each period. There are four major constraints that determine whether or not there is energy and if so, how much of it is available for pumping.

The constraints include:

- Unit capability – What does pump/turbine unit's capacity means (e.g. 200MW)? The study considers pumps with single and adjustable speeds separately.

- Available excess energy - Surplus energy in the power grid?
- Available water in lower reservoir – Is there enough water in the lower reservoir?
- Quantity of water available in upper reservoir –How much volume of water is available in the upper reservoir? At each time step, water can only be pumped if the upper reservoir has space. The constraints of pumping process were converted to cubic foot per second (cfs) for each one-hour period to allow for better comparison at each period (time step). The analysis considers each constraints and chooses the lowest value for further investigation. E is used for energy, and P is used for power.

4.1.1 Available Excess Energy

Therefore, the surplus energy is determined thus:

$$\mathrm{E_{pump}} = \mathrm{P_{pump}} * \mathrm{t}$$

But power generated during pumping is: $\mathrm{P_{pump}} = \frac{\gamma \mathrm{Q} \Delta \mathrm{H}}{\eta}$

Solving for volumetric flow rate (Q): $\mathrm{Q} = \frac{\eta\ \mathrm{P_{pump}}}{\gamma\ \Delta \mathrm{H}}$

Consider a situation in which the available pumping power is 1000MW, the pumping efficiency is 98%, relative density is 62.422 $\left(\frac{\mathrm{lb}}{\mathrm{ft}^3}\right)$, pumping efficiency is 98%, and 1,452.3 feet of net head. Using the equation for volumetric rate above we obtain:

To calculate the flow rate in this scenario, it is important to first refresh on the meaning of horse power (HP) and the foot-pound-second (ft-lb-s). Horse power is defined as a unit of measurement of power or the rate at which work is done usually in reference to the output of engines or motors. It is a non-metric unit of power. There are many standards and types of horse power but in this thesis we focus on mechanical horse power which is approximately 746W. In the same vein, the FPS is based on three fundamental units which are: foot (for length), the pound (for either mass or force) and the second (for time) [19].

Remember that electrical equivalent of one horsepower is 746Watts in SI unit which is equal to 550 $\left(\frac{\mathrm{ft.lb}}{\mathrm{s}}\right)$ in foot-pound-second so that the mathematical correlation between the three units is given as:

$$1\text{horse power(HP)} = 745.7\text{W} = 550 \left(\frac{\text{ft.lb}}{\text{s}}\right)$$

Also the specific weight (γ) of water equivalent to $1000\left(\frac{\text{kg}}{\text{m}^3}\right)$ is $62.422\left(\frac{\text{lb}}{\text{ft}^3}\right)$. Now let us calculate the flow rate for different scenarios using these data. From equation above

$$\text{Q} = \frac{1000\ \text{MW} * 0.98}{62.422\left(\frac{\text{lb}}{\text{ft}^3}\right) * 1{,}452.3\ \text{ft}}$$

To obtain rate of flow in cubic feet per second it is necessary to convert the given power from watt to ft-lb per second. From the mathematical relationship up there we can express Watt in terms of ft-lb/s:

$$745.7\text{W} = 550 \left(\frac{\text{ft.lb}}{\text{s}}\right)$$

Expressing watt in terms on foot pound per second:

$$1\text{Watt} = \frac{550}{745.7}\left(\frac{\text{ft.lb}}{\text{s}}\right)$$

Also, we know that $1\text{MW} = 10^6\ \text{W}$ so that $1000\text{MW} = 1000 * 10^6\ \text{W};\ 1\left(\frac{\text{m}^3}{\text{s}}\right) = 35.31467\left(\frac{\text{ft}^3}{\text{s}}\right)$

Combining all the parameters in one equation, we have the expression below:

$$\text{Q} \Rightarrow \frac{1000\text{MW} * 0.98}{62.422\left(\frac{\text{lb}}{\text{ft}^3}\right) * 1{,}452.3\ \text{ft}} * \frac{550}{745.7}\left(\frac{\text{ft.lb}}{\text{s}}\right) * \frac{1{,}000{,}000\text{W}}{1\text{MW}} = 7973.2\left(\frac{\text{ft}^3}{\text{s}}\right) \Rightarrow 225.78\left(\frac{\text{m}^3}{\text{s}}\right)$$

4.1.2 Unit Capability

Separate equations are used to calculate the unit capability of single and convertible speed units. Two separate equations are needed because of the different operational characteristics of the two types of units. The following analysis show the approach used for each type of unit:

Single Speed Units: During pumping mode the input power to these units is nearly constant. Although discharge varies depending on pumping head, the model assumes constant head, therefore discharge is considered for single speed unit.

Each speed unit is taken into account individually in this calculation. Since power input is almost constant for each unit, the analysis assumes that unit1 will turn on when excess energy will exceed the unit’s capacity. After the next interval of energy availability is reached, each subsequent unit is programmed to turn on [19].

Consider, for example, a scenario with 700 MW as available power, four (4) pump/turbine units, each with a capacity of 325000 kW (325 MW), 92% pump efficiency, and net head of 1452.3 ft. (442.66 m). Assume a Hydro Francis Turbine Generator is used in this operation.

The first step in the model is to evaluate Unit1, and whether the available is greater than the rated capacity of 325 MW. The equivalent flow for Unit1 is $2591.28\ \left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$ according to equation

$$\mathrm{Q} \Rightarrow \ \frac{325\ \mathrm{MW}\ *\ 0.98}{62.422\left(\frac{\mathrm{lb}}{\mathrm{ft}^3}\right)\ *\ 1452.3\ \mathrm{ft}}\ *\ \frac{550}{745.7}\left(\frac{\mathrm{ft.lb}}{\mathrm{s}}\right) *\ \frac{1{,}000{,}000\ \mathrm{W}}{1\ \mathrm{MW}} = 2591.28\ \left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right) \Rightarrow 73.38\ \left(\frac{\mathrm{m}^3}{\mathrm{s}}\right)$$

In the next step, Unit 2 is evaluated, which is the combined rated capacity of two units, and whether the power available is greater than 650 MW (2 * 325 MW). Then, using similar equation, the equivalent flow for Unit 2 is calculated as $2591.28\ \left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$:

$$\mathrm{Q} \Rightarrow \frac{325\mathrm{MW}\ *\ 0.98}{62.422\ \left(\frac{\mathrm{lb}}{\mathrm{ft}^3}\right) *\ 1452.3\ \mathrm{ft}} * \frac{550}{745.7}\left(\frac{\mathrm{ft.lb}}{\mathrm{s}}\right) * \frac{1{,}000{,}000\mathrm{W}}{1\mathrm{MW}} = 2591.28\ \ \left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right) \Rightarrow 73.38\ \left(\frac{\mathrm{m}^3}{\mathrm{s}}\right)$$

Approximately, the flow calculated flow rate is $73\left(\frac{\mathrm{m}^3}{\mathrm{s}}\right)$.

In the next step, unit 3 is calculated, which is the combined rated capacity of three units with total capacity of 975 MW. However, since the excess power available on the grid is 700 MW and it is less than the total capacity, subsequent units will not operate. Then, the equivalent flow of each unit is then added to obtain the cumulative flow rate of 5182.56 $\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$ since all units are considered separately i.e.

$$2591.28\ \left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right) + 2591.28\ \left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right) = 5182.56\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$$

Recall that the conversion rate from cubic foot per second to cubic metre per second is:

1Cubic foot per second = 0.0283168 Cubic metre per second

$$5182.56\ \left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right) * 0.0283168 = 146.75\left(\frac{\mathrm{m}^3}{\mathrm{s}}\right)$$

4.1.4 Adjustable Speed Unit:

Adjustable speed pumps can operate at a wider variety of power inputs when in pumping modes. The model uses similar equation to determine the flow, Q, because adjustable speed pumps can operate at variety of power inputs. After that, a sample computation for variable speed units is carried out [19].

Consider a scenario in which the available pumping power is 500 MW, efficiency is 98 %, and the resultant head is 1452.3 ft. Similarly, a limiting factor flow of $3986.6\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$ was obtained:

$$\mathrm{Q} \Rightarrow \frac{500\ \mathrm{MW} * 0.98}{62.422\left(\frac{\mathrm{lb}}{\mathrm{ft}^3}\right) * 1452.3\ \ \mathrm{ft}} * \frac{550\left(\frac{\mathrm{ft.lb}}{\mathrm{s}}\right)}{745.7\ \mathrm{W}} * \frac{1{,}000{,}000\ \mathrm{W}}{1\ \mathrm{MW}} = 3986.582\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right) \Rightarrow 112.89\left(\frac{\mathrm{m}^3}{\mathrm{s}}\right)$$

4.1.5 Available Water in the Reservoir

Lower Reservoir

At each time step, the water available in the lower reservoir is calculated using the elevation of the lower reservoir at the conclusion of the previous time step. The volume of water available (V) in the lower reservoir is translated into units of cubic feet per second for each one-hour time (t) step using the following equation:

$$\mathrm{V} = \mathrm{Q\ t}$$

Solving for Q, the new equation is: $\mathrm{Q} = \frac{\mathrm{V}}{\mathrm{t}}$

Consider the following scenario: 1000 acre-feet of water is available, and the time period is one hour (1-time step). The equivalent flow, calculated using equation is $12100.07\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$:

Recall that the conversion rate between acre foot and cubic foot per second is:

1-acre = 43560 ft^2

1-acre foot per second = 12.10007 cubic foot per second

$$\Rightarrow \frac{1000\ \mathrm{ac-ft}}{1\mathrm{hr}} * \frac{1}{3600}\left(\frac{\mathrm{hr}}{\mathrm{sec}}\right) * \frac{43{,}560\ \mathrm{ft}^2}{1\mathrm{ac}} = 12{,}100\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right) \Rightarrow 342.63\ \left(\frac{\mathrm{m}^3}{\mathrm{s}}\right)$$

Upper Reservoir

At each time step, the volume available in the upper reservoir is calculated using the elevation of the upper reservoir at the conclusion of the previous time step. Equations above are used to convert the volume available in the upper reservoir to cubic foot per second.

The model selects the minimum flow value available for pumping at each time step, then evaluates whether there is volume available in upper reservoir to receive pumped water now that Q values for each of the constraints- available excess energy, unit capability, and water available in lower reservoir- have been determined. The energy used to pump water to the upper reservoir is calculated using the power equation and the least value of Q.

For example, consider the following scenario: volumetric flow rate is $3986\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$, the pumping efficiency 98 %, the net head is $1452.3\ \mathrm{ft}$ feet, and the period is 1 hour. Using equation, the energy dispatched is calculated to be 500 Mh as shown below:

Remember that $\mathrm{E_{pump}} = \mathrm{P_{pump}} * \mathrm{t}$ and $\mathrm{P_{pump}} = \frac{\gamma\, \mathrm{Q}\, \Delta\mathrm{H}}{\eta}$

So that the combined equations becomes: $\mathrm{E_{pump}} = \frac{\gamma\ \mathrm{Q}\, \Delta\mathrm{H}}{\eta} * \mathrm{t}$

Also, converting from foot pound per second to Watt: $1\left(\frac{\mathrm{ft.lb}}{\mathrm{s}}\right) = \frac{745.7}{550}\ \mathrm{Watt}$

$$\mathrm{E_{pump}} \Rightarrow \frac{62.422\left(\frac{\mathrm{lb}}{\mathrm{ft}^3}\right) * 3986\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right) * 1452.3\ \mathrm{ft}}{0.98} * \frac{745.7\ \mathrm{Watt}}{550\left(\frac{\mathrm{ft.lb}}{\mathrm{s}}\right)} * \frac{1\ \mathrm{MW}}{1{,}000{,}000\ \mathrm{MW}} * 1\ \mathrm{hr} = 500\ \mathrm{MWh}$$

Compute the volume of water pumped to the upper reservoir. Consider a case in which the available flow is 1138.5 cubic foot per second and the time period is one hour. The volume of water pushed to the higher reservoir is 94.09 acre-feet, using equation

$$\mathrm{V} \Rightarrow 3986\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right) * \frac{3600}{1}\left(\frac{\mathrm{sec}}{\mathrm{hr}}\right) * \frac{1\ \mathrm{ac}}{43{,}560\ \mathrm{ft2}} * 1\mathrm{hr} = 329\ \mathrm{ac} - \mathrm{ft}\ (405815.5246\mathrm{m}^3)$$

Recall that $1\mathrm{acre} - \mathrm{feet} = 1233.4818375475\ \mathrm{m}^3$

The volume of water within the upper and lower stores is calculated at the conclusion of the pumping cycle for utilize amid the following time step.

4.2 Generation Mode:

When in generation mode, the model examines a variety of factors to determine if peaking power is needed, and if so, what quantity of energy is available and/or provided at each time step. The following four main constraints come into play during generation mode:

4.2.1 Required Peaking Power: what is the need for peaking power on the grid and what quantity of power is required?

Unit Capability – How large is the pump/turbine unit (e.g. 200MW)? The model considers both single speed and adjustable speed pumps separately.

Water Available in Upper Reservoir– How much water is available in the upper reservoir to operate turbines

Volume Available in Lower Reservoir – What is the quantity of water in the lower reservoir? Generating power is feasible as long as lower reservoir can contain water. The reservoir is empty at the beginning of the simulation. For better comparisons at each time step, the constraints during generation mode were all converted to cubic per seconds. Each constraint is evaluated and the minimum value is selected for further analysis. The peaking power is calculated using similar equation

$$\mathrm{E_{turbine}} = \mathrm{P_{turbine}} * \ \mathrm{t} \ \text{and} \ \mathrm{P_{turbine}} = \gamma \ \mathrm{Q} \ \Delta\mathrm{H} \ \eta$$

Solving for Q, we obtain: $\mathrm{Q} = \frac{\mathrm{P_{turbine}}}{\gamma \ \Delta\mathrm{H} \ \eta}$

Notice the difference between flow rate for turbine and that of pump. In pumping mode, the power utilized is input while in generation mode it is output. Like pumping mode, we repeat the calculations considering a scenario where the required power is 1000 MW, the efficiency of turbine is 98 %, and net head is 1,452.3ft. According to expression below, the peak constraint is 8,304 cubic foot per second:

$$\mathrm{Q} \Rightarrow \frac{1000 \ \mathrm{MW}}{62.422 \left(\frac{\mathrm{lb}}{\mathrm{ft}^3}\right) * 1452.3 \ \mathrm{ft} * 0.98} * \frac{550 \left(\frac{\mathrm{ft.lb}}{\mathrm{s}}\right)}{745.7 \ \mathrm{W}} * \frac{1000000 \ \mathrm{W}}{1 \ \mathrm{MW}} = 8304.183 \left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$$
$$\Rightarrow 235.17 \left(\frac{\mathrm{m}^3}{\mathrm{s}}\right)$$

A separate equation was used again for single and adjustable speed units to determine unit optimal capacity. These different units can operate at different efficiencies and potentially function differently, so separate equations are needed. For the purpose of this analysis, both types of units are assumed to work similarly. To maintain ideal efficiency values, single and adjustable speed units are expected to operate between 70 to 100 percent of the rated unit capacity [19].

Based on its operational principle, each unit is considered separately. The analysis assumes that Unit1 works when peaking power is required for each pump/turbine unit between 70% and 100% of the unit's capacity. The following units are then activated once each succeeding interval of optimal power is met.

For each unit, the following techniques were adopted:

Single Speed Unit: In generation fashion, single speed units can work at flows as low as 50% of the rated discharge. However, to maintain unit efficiency, the range of operation is limited to 70%. The flow Q is calculated for each unit using equation.

Again, for example, consider a scenario with 700 MW of available power, twelve (12) pump/turbine units, each with a capacity of 325 MW and 89% pump efficiency, and net head of 1452.3ft (442.66 m). It is assumed that each unit works when the needed power is between 70% to 100% of the evaluated unit capacity, and the results between 228 MW to 325 MW: Minimum range 325 MW * 70% = 227.5 MW.

Like the first calculation during pumping mode, determine whether Unit 1's peaking power requirement exceed 325 MW. Since 700 MW is greater than 325 MW, the same equation is used to calculate the volume flow rate as $2971\left(\frac{\text{ft}^3}{\text{s}}\right)$:

$$\text{Q} \Rightarrow \frac{325\text{ MW}}{62.422\left(\frac{\text{lb}}{\text{ft}^3}\right) * 1452.3\text{ ft} * 0.92} * \frac{550}{745.7}\left(\frac{\text{ft.lb}}{\text{s}}\right) * \frac{1{,}000{,}000\text{ W}}{1\text{MW}} = 2971\left(\frac{\text{ft}^3}{\text{s}}\right) \Rightarrow 84.13\left(\frac{\text{m}^3}{\text{s}}\right)$$

$$\Rightarrow 2971\ \left(\frac{\text{ft}^3}{\text{s}}\right) * 0.0283168 \Rightarrow 84.13\left(\frac{\text{m}^3}{\text{s}}\right)$$

In the next step, we determine whether Unit2 requires higher peaking power than 325 MW, the nameplate capacity for two units. Since 700 MW is greater than 650 MW, the same equation is then applied to calculate a $2971\left(\frac{\text{ft}^3}{\text{s}}\right)$ flow for unit 2:

$$\text{Q} \Rightarrow \frac{325\text{ MW}}{62.422\left(\frac{\text{lb}}{\text{ft}^3}\right) * 1452.3\text{ ft} *0.98} * \frac{550}{745.7}\left(\frac{\text{ft.lb}}{\text{s}}\right) * \frac{1{,}000{,}000\text{ W}}{1\text{MW}} = 2971\left(\frac{\text{ft}^3}{\text{s}}\right) \Rightarrow 84.129\left(\frac{\text{m}^3}{\text{s}}\right)$$

Next, Unit 3 is calculated for but the maximum power needed is less than 975 MW (3* 325 MW = 975 MW):

Three units at optimum capacity but less than 878 MW (325 MW * 2 + 325 MW * 70%) equivalent to units working at full capacity and the third Unit working at 70 %. Unit3 and beyond will not turn on. Since the units are considered independently, the streams are included from each of the working units adding up to a total flow of:

$$2971\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right) + 2971\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right) \Rightarrow 5942\ \left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right) = 168.28\left(\frac{\mathrm{m}^3}{\mathrm{s}}\right)$$

As the units are considered independently, the streams are included from the working units to get an aggregate flow of 5942 $\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$ or $168.28\left(\frac{\mathrm{m}^3}{\mathrm{s}}\right)$.

This value of volume flow rate was obtained using similar conversion as previous calculations.

Adjustable Speed Unit - An adjustable speed pump can operate at a broader range of outputs when operated in generation mode and can deliver power outputs as low as 30 % of the rated discharge. They are by and large worked inside 70 % of their evaluated capacity to keep up optimum capacity. A similar methodology to that used by single speed pumps/ turbines in generating mode can also be applied to adjustable speed pumps [19]. It assumes that Unit 1 operates at 60 to 100% of its capacity when peak power required. Once each subsequent interval of peaking power required is reached, each subsequent unit is programmed to turn on. The model calculates each unit's flow rate, Q, using similar equation

Consider, for example, another scenario where required peak power is 675 MW, 4 units, 325MW each, 92% turbine efficiency, and 1,452.3 feet (442.66 m) of net. The assumption in this calculation is one turbine per time runs when requested control is between 70 and 100% of evaluated unit capacity, which comes about in a pump turbine run of 228 to 325 MW:

Minimum range is calculated thus: $100\ \% \ \Rightarrow 325\ \mathrm{MW}$

$$70\ \% \Rightarrow \frac{0.70 * 325\ \mathrm{MW}}{100} = 228\ \mathrm{MW}$$

Modelling starts with Unit1, and determines whether peaking power required exceeds 325MW, the rated capacity of each pump/turbine unit. Equation computes an equivalent flow for Unit1 to be $2874\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$;

$$\mathrm{Q} \Rightarrow \frac{325\ \mathrm{MW}}{62.422\left(\frac{\mathrm{lb}}{\mathrm{ft}^3}\right) * 1452.3\ \mathrm{ft} * 0.92} * \frac{550}{745.7}\left(\frac{\mathrm{ft.lb}}{\mathrm{s}}\right) * \frac{1{,}000{,}000\ \mathrm{W}}{1\ \mathrm{MW}} = 2874\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$$

$$\Rightarrow 81.39\left(\frac{\mathrm{m}^3}{\mathrm{s}}\right)$$

The next calculation assesses Unit2 and decides if top control required surpasses 650 MW (2* 325 MW = 650 MW), which is the combined capacity for two units. For unit 2, an equivalent flow rate of $2874\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$ is similarly computed as shown below:

$$\mathrm{Q} \Rightarrow \frac{325\ \mathrm{MW}}{62.422\ \left(\frac{\mathrm{lb}}{\mathrm{ft}^3}\right) * \ \ 1452.3\ \mathrm{ft}\ \ * \ \ 0.92} * \frac{550}{745.7}\left(\frac{\mathrm{ft.lb}}{\mathrm{s}}\right) * \frac{1{,}000{,}000\ \mathrm{W}}{1\ \mathrm{MW}} = 2874\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$$

$$\Rightarrow 81.39\left(\frac{\mathrm{m}^3}{\mathrm{s}}\right)$$

It is again necessary to have 675 MW of peak power. Unit 9 and subsequent units will not operate because the peaking power required is greater than 975 MW i.e.

(3 * 325 MW = 975 MW), each unit operating at 100% which is the maximum attainable efficiency, and also less than 878 MW (325*2 + 325 MW* 70%) which implies two units working at 100% and the third unit working at 70%:

$$\Rightarrow (325 * 100\%)\ \mathrm{MW} + (325 * 100\%)\ \mathrm{MW} + (325 * 70\%\ ) \Rightarrow\ 878\ \mathrm{MW}$$

Also, because the units are evaluated independently, the fluxes from each unit are summed together, resulting in total flow rate of $5748\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$:

$$\Rightarrow\ 2874\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right) + 2874\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right) = 5748\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$$

The moment imperative issue worth considering is the sum of water accessible within the upper supply. Conditions utilized in previous calculations are too utilized here to change over the accessible water volume into cubic feet per unit [19]. A pumping mode time step increases the water level in the upper reservoir, whereas a generation mode time step decreases it [19]. In the same way that the pumping mode has an example case, the generation mode has one as well.

Using elevation of the lower reservoir at the conclusion of the previous time step, the volume available in the lowest reservoir is calculated at each time step. Cubic feet per second are calculated by applying above equations to the lower reservoir volume. A computation procedure similar to previous equation would be used in a hypothetical case [19].

Similarly, at each step, the calculation determines the minimum flow value that may be generated, while also evaluating whether there is space in the lower reservoir to meet the constraints- peaking power, capacity, and water. The power equation uses the minimum value of Q value to compute the energy generated.

Consider the following scenario: the available flow rate is $1195.76\left(\frac{\mathrm{ft}^3}{\mathrm{s}}\right)$, net head is 360.89feet (110m), the total energy dispatched during generation mode with 92% turbine efficiency and one hour time step is:

$$E_{\text{turbine}} \Rightarrow 62.422\left(\frac{\text{lb}}{\text{ft}^3}\right) * 1195.76\left(\frac{\text{ft}^3}{\text{s}}\right) * 360.89\ \text{ft} * \frac{745.7\ \text{Watt}}{550\left(\frac{\text{ft.lb}}{\text{s}}\right)} * \frac{1\ \text{MW}}{1{,}000{,}000\ \text{MW}} * 1\text{hr}$$

$$\Rightarrow 36.52\ \text{MWh}$$

In order to calculate the volume of water used to generate power from the energy generated, we use the same equation used above. The results of this calculation:

$$V \Rightarrow 1195.76\left(\frac{\text{ft}^3}{\text{s}}\right) * \frac{3600}{1}\left(\frac{\text{sec}}{\text{hr}}\right) * \frac{1\ \text{ac}}{43{,}560\ \text{ft}^2} * 1\text{hr} = 98.82\ \text{ac} - \text{ft}\ (121892.68\ \text{m}^3)$$

Again, recall that $1\text{acre} - \text{feet} = 1233.4818375475\text{m}^3$

Control Strategy for the proposed Hybrid Power plant

The utility-scale hybrid power plant as sustainable solutions in which wind energy is complimented solar energy and subsea pumped hydro energy storage technology as shown

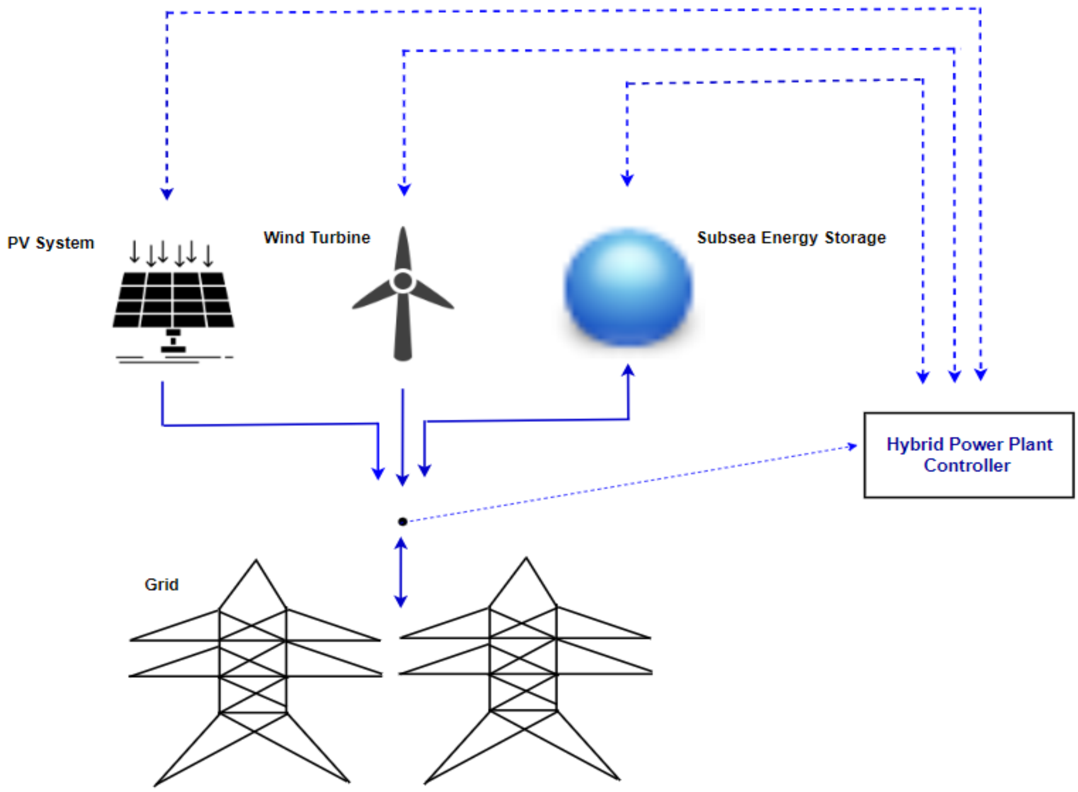


Fig 8. Control strategy for the proposed system

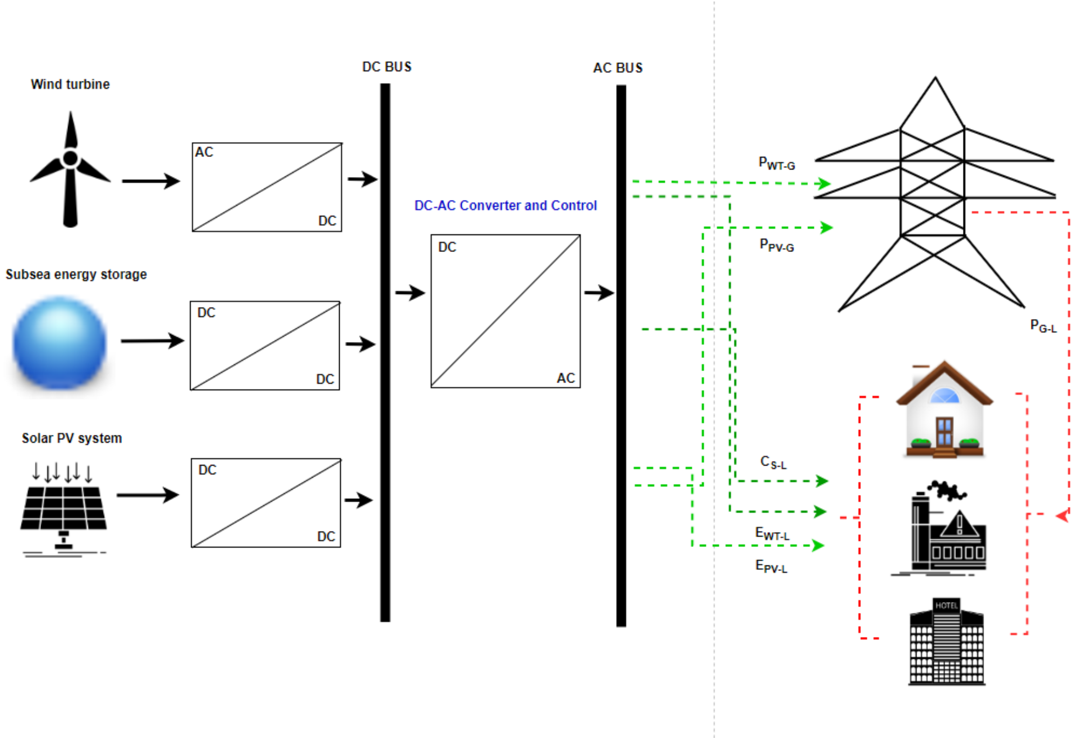


Fig 9. Architecture for the proposed system

Software: Drawio

Hybrid energy system showing integrated wind turbines, PV system and subsea energy storage system connected to critical loads. Here, for the purpose of illustration, the critical loads include factory, residential and commercial buildings. Energy is dispatched to load centre through effective control dispatch techniques. The DC-DC and DC-AC converters are used in power conversion so that the AC voltage specification of the power grid can be met.

Solar cells, for instance, generate DC power whose output varies with voltage and incident solar radiation. A high-efficiency transfer of power to the grid is crucial for taking full advantage of the power available at the cell’s output. Hence, the grid interface should deliver AC power that meets the grid specifications and draw input power that allows the solar cell to operate at its maximum power. To minimize the losses in power generation, the DC power should be converted to AC power with higher frequency [50].

CHAPTER 5

ANALYSIS OF PROPOSED HYBRID POWER PLANT

5.1 Underwater (Subsea) Energy Storage System

A variety of studies have shown that geological constraints prevent from implementing a conventional pumped hydro energy storage system. In contrast, Denmark has adequate water resources enough to generate energy from the offshore environment using CAES and other offshore energy storage technologies like the Stored Energy in Sea (StEnSea) which is the focus of this thesis. An offshore energy storage solution is a buoyant energy which is operated with the same principles with PHS. Basically, the concept of underwater storage is the same as the conventional type of PHS. The only difference is how energy is generated through pumping water in the sea [16] [17]. (See Fig.10)

In general, subsea energy storage technology is a closed vessel resting on the seabed. As a result, excess energy from floating solar PV or offshore wind turbines is then utilized to release water from the vessel, resulting in near-vacuum inside. Under the pressure generated by the seawater above, water can be allowed to flow back into the vessel to recover energy. Using the same principle as traditional pumped hydro system, the water flowing into the vessel turns a turbine, generating electricity [16] [17] [18] [26].

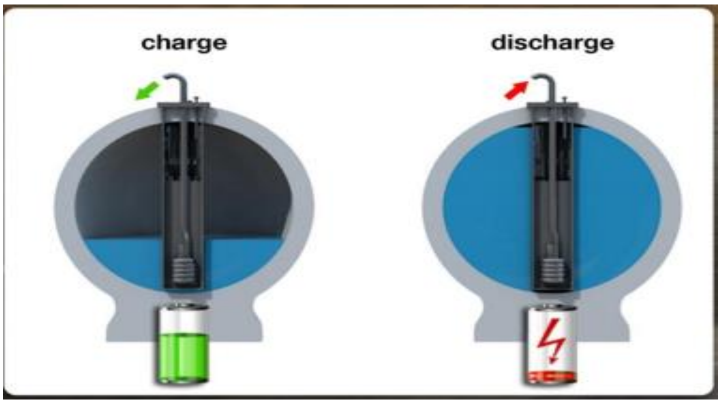


Fig10. Charge and Discharge mode of StenSea [47]

Additionally, the system is able to benefit from a great deal of pressure exerted by the sea above it. When vessels are at near-vacuum when fully charged, pressure increases by approximately 1 atmosphere per 10 metres of depth [17]. With a system designed to operate at near-vacuum, there is a huge differential to take advantage of. Some designs propose to operate at pressures in excess of 75 bar and it is expected that such systems will operate at around 80-85% efficiency, similar to pumped hydro storage [17] [26]. The underwater design also eliminates evaporation, which drains water, and therefore energy, from pumped hydro and installation is easily scalable. Electrical connections to the grid are all that underwater reservoir needs and the capacity of such an installation can easily be scaled up by adding more underwater or subsea reservoirs with the appropriate electrical infrastructure. SPHS system using deep water use the high hydrostatic pressure of the ocean to serve both as upper and lower reservoirs. In discharging process, pressure difference creates a force that drives the turbines to generate energy [16] [17] [18] [26]. Figure.11 shows SPHS connected to wind farm.

Compared to the near-surface environment, deep seas are remarkably different. The waves have no effect on the structure, but seismic forces have a significant impact on it, accelerating the structure as an additional mass of water is added. The lack of mass that often characterizes soils make them comparatively weak. One of the most important factors that should be considered during design and installation of SPHS is the depth to which the system is immersed. Using the inner volume of the sphere, the efficiency of the pumps and turbines units, as well as the depth, it is possible to calculate the total charge capacity (in megawatt hours). The maximum capacity the storage converted from joules (J) to megawatt-hour (MWh) is expressed as:

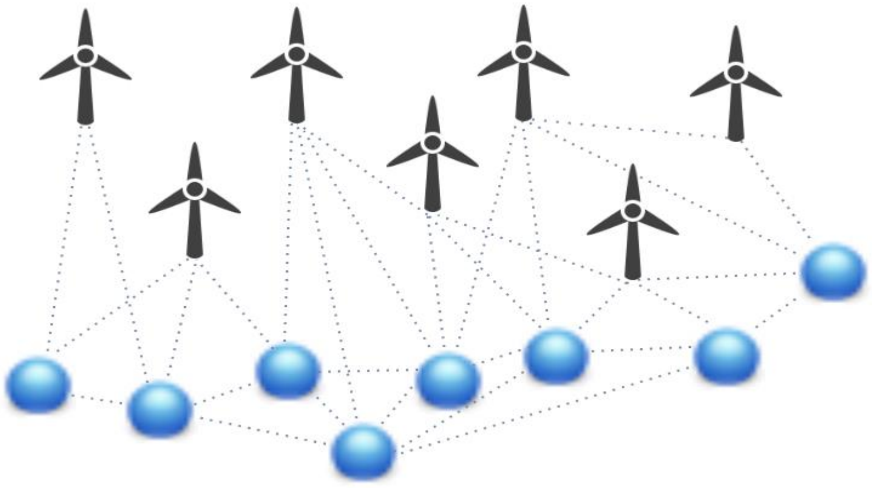


Fig 11. Subsea energy storage technology connected to offshore wind farms

Software: (Drawio)

$$\mathrm{C_{max}\,(MWh)} = \frac{\rho_{sw}\,\eta\,.\,d.\,g\,.\,V_{inner}}{3.6 * 10^{9}}$$

Recall that the conversion from megawatt hour (MWh) to joules is: $1\mathrm{MWh} = 3.6 * 10^{9}\mathrm{Joules}$

Using the available data for StenSea, and the above equation, we now calculate the capacity of the energy storage system for various depths ranging from 100-750 m. First, determine volume of the inner spherical concrete and capacity (MWh) using ocean depth of 100 m using acceleration due to gravity (9.81m/s^2), minimum efficiency (η) of 80 %:

$$V_{\mathrm{inner}} = \frac{4.\pi.\mathrm{r^3}_{\mathrm{inner}}}{3} \Rightarrow \frac{4.\pi.14.28^3}{3} \sim 12200\ \mathrm{m}^3$$

Inner diameter for StenSea is 28.6m as shown in table 5.1

We now plug in the inner volume in the next equation:

$$\mathrm{C_{max}\,(MWh)} = \frac{\rho_{sw}\,\eta\,.\,d.\,g\,.\,V_{inner}}{3.6 * 10^{9}} \Rightarrow \frac{(1000 * 0.80 * 100 * 9.81 * 12000)}{(3.6 * 10^{9})} \Rightarrow 2.616\ \mathrm{MWh}$$

Next, we repeat the calculation for the next ocean depth (d) = 150m;

$$\mathrm{C_{max}\,(MWh)} = \frac{\rho_{sw}\,\eta\,.\,d.\,g\,.\,V_{inner}}{3.6 * 10^{9}} \Rightarrow \frac{(1000 * 0.80 * 150 * 9.81 * 12000)}{(3.6 * 10^{9})} \Rightarrow 3.9240\ \mathrm{MWh}$$

Table5.1 Technical specification for StenSea

Technical Data	
Material	Concrete
Turbine capacity	5 MW/unit
Diameter (d)	28.6 m
Discharge time (hr)	4 hr
Capacity	5 MW/unit
Efficiency	73-85%
Shell thickness (t)	2.70 m
Storage volume (V)	12000 m^3/unit
Max water depth (m)	700 m
Pressure	70 bar
Unit per storage farm	5-140 units
Construction depth	750 m

Table 5.2 Comparison of Energy storage capacity (MWh) at different turbine efficiencies and different ocean depth (d)

Ocean depth (d)(m)	Cmax (MWh) @ $\eta = 73\%$	Cmax(MWh)@ $\eta = 75\%$	Cmax(MWh)@ $\eta = 80\%$	Cmax(MWh)@ $\eta = 83\%$	Cmax(MWh)@ $\eta = 85\%$
100	2.3871	2.4525	2.6160	2.7141	2.7795
150	3.5807	3.6788	3.9240	4.0712	4.1693
200	4.7742	4.9050	5.2320	5.4282	5.5590
250	5.9678	6.1313	6.5400	6.7853	6.9488
300	7.1613	7.3575	7.8480	8.1423	8.3385
350	8.3549	8.5838	9.1560	9.4994	9.7283
400	9.5484	9.8100	10.4640	10.8564	11.1180
450	10.7420	11.0363	11.7720	12.2135	12.5078
500	11.9355	12.2625	13.0800	13.5705	13.8975
550	13.1291	13.4888	14.3880	14.9276	15.2873
600	14.3226	14.7150	15.6960	16.2846	16.6770
650	15.5162	15.9413	17.0040	17.6417	18.0668
700	16.7097	17.1675	18.3120	18.9987	19.4565
750	17.9033	18.3938	19.6200	20.3558	20.8463

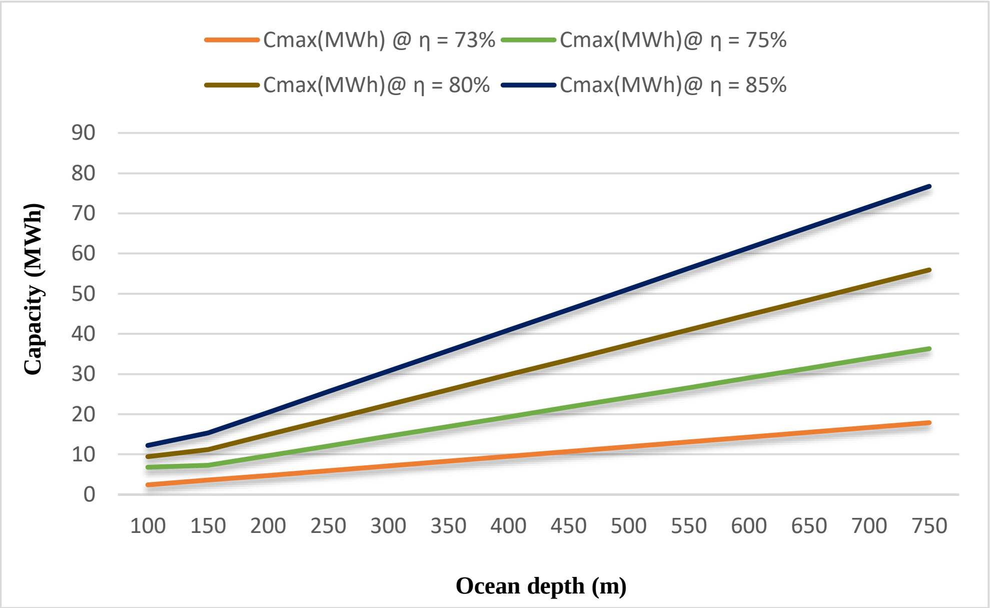


Fig.12 Energy storage capacity of subsea at different ocean depths and turbine efficiencies

From this technical analysis, we can deduce that the storage capacity of StenSea is highly dependent on pump/turbine efficiency among other factors. Also, it is scalable, efficient and economical and its market share will increase as ocean energy storage system becomes more mature. Also, it is possible in principle to build out larger shares and install at deeper ocean depths. One major parameter which determines the installation cost of this system is depth of ocean (d).

One of the world largest offshore wind farms is expected to be a capacity of 600 MW at Krieger Flak in the Baltic Sea. Also, with an approved plan to build an artificial island in the North Sea with hundreds of wind turbines generating a combined capacity of 10 GW offshore, electricity more than enough for the whole Denmark will be generated and the surplus will be sold to other nations and green hydrogen will be created from sea water.

By May 2021, there were 6203 turbines in Denmark from which 5598 are onshore while 605 are offshore bringing the total installed capacity to 6669 MW. Also, this statistic shows that there are approximately ten times more onshore turbines than offshore turbines. The table below reveals in details the total installed capacity in Denmark.

5.2 Geographic Information System (GIS)

Esox-Lautec weather downtime simulation tool

- The web-based software used here supports offshore wind power generation projects based on data from Copernicus Climate Change Service (C3S). Data and modelling tools that are easily accessible and high quality are increasingly needed as many new countries enter the offshore wind industry. Fig.11 and Table5.3 shows some offshore wind farms in the North Sea. Horns RevI, II, III accounts for large number of wind turbines in Denmark [39].

Global Atlas

- It is a web-based software used in parallel with SOLARGIS to assess mostly the photovoltaic power potential, GHI and DNI of a location understudy [42].

Temperature and Precipitation

- ClimateChart: This visualizes the climate of every place on earth by showing the temperature and precipitation [25].

PVGIS

- Solar radiation information is provided here on PV systems in Europe and the continent.

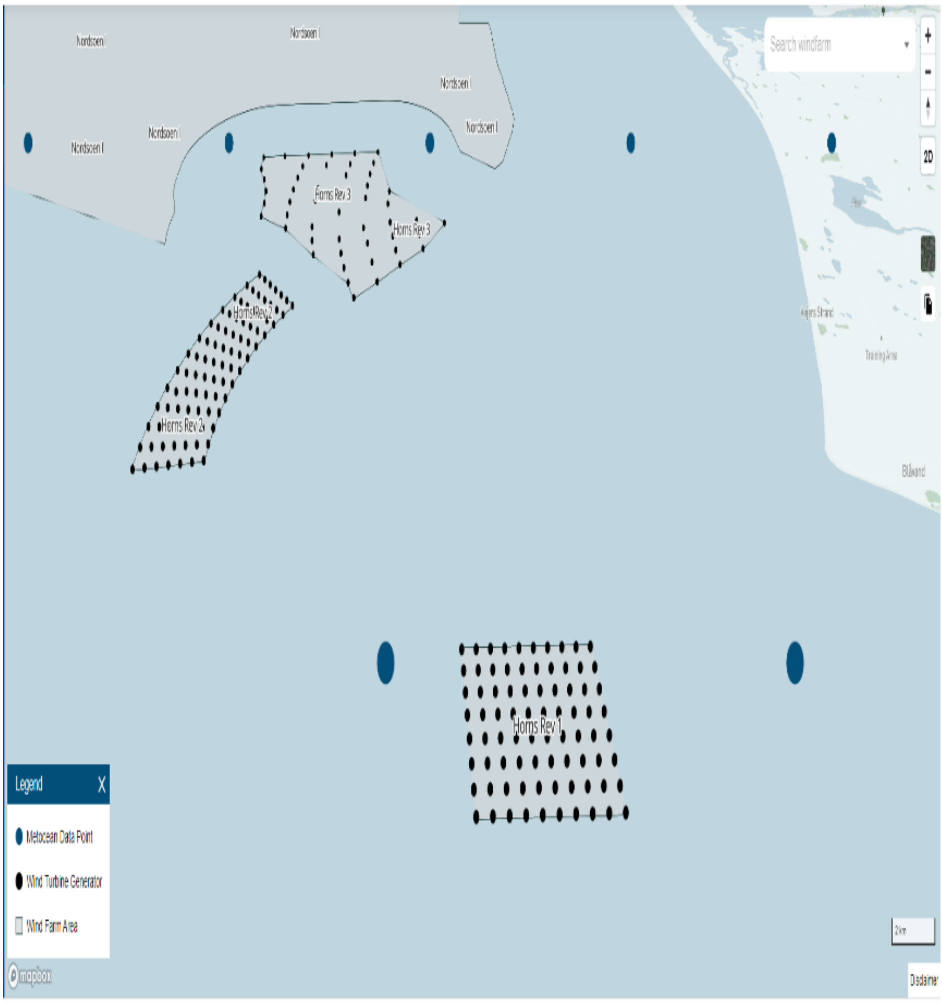


Fig13. Layout of Horns Rev I, II, III in Geographic Information System (GIS) Esox-Lautec weather downtime simulation tool [39].

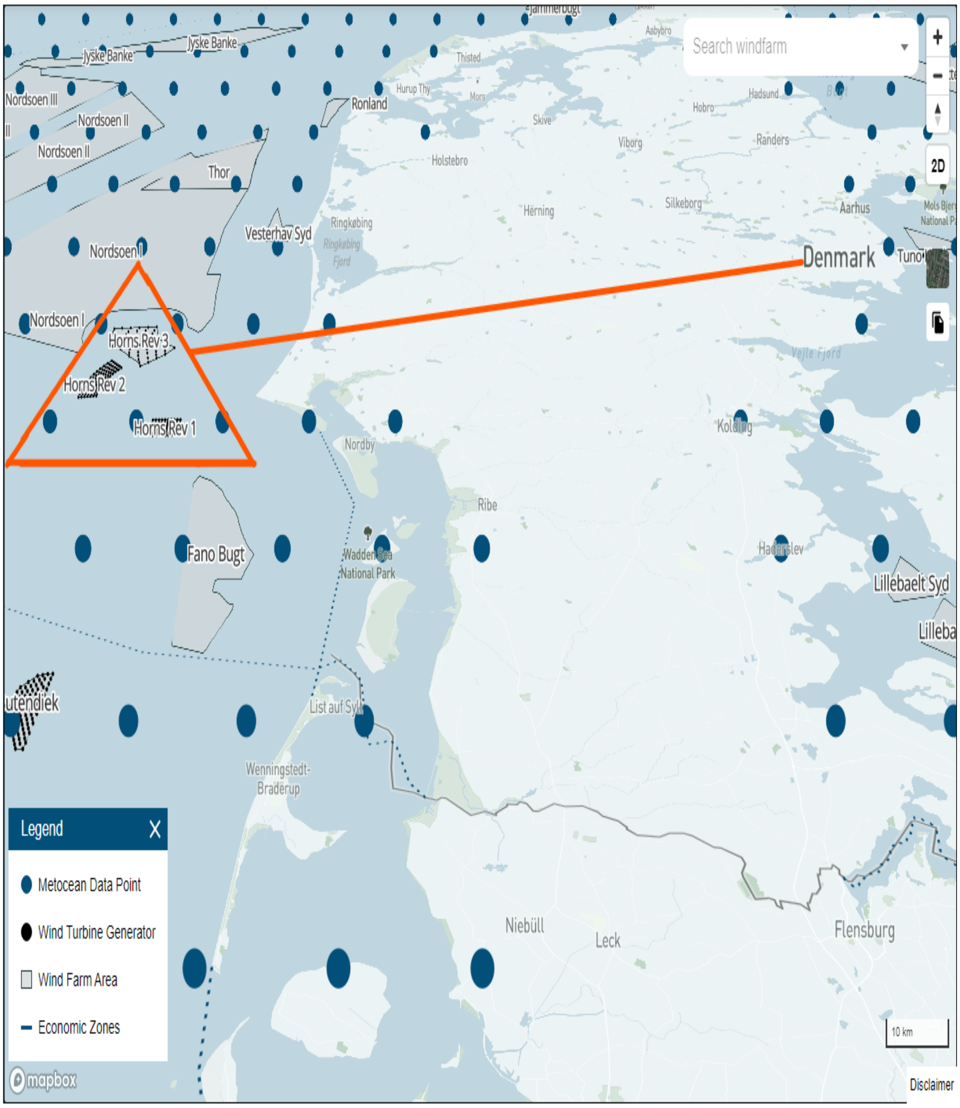
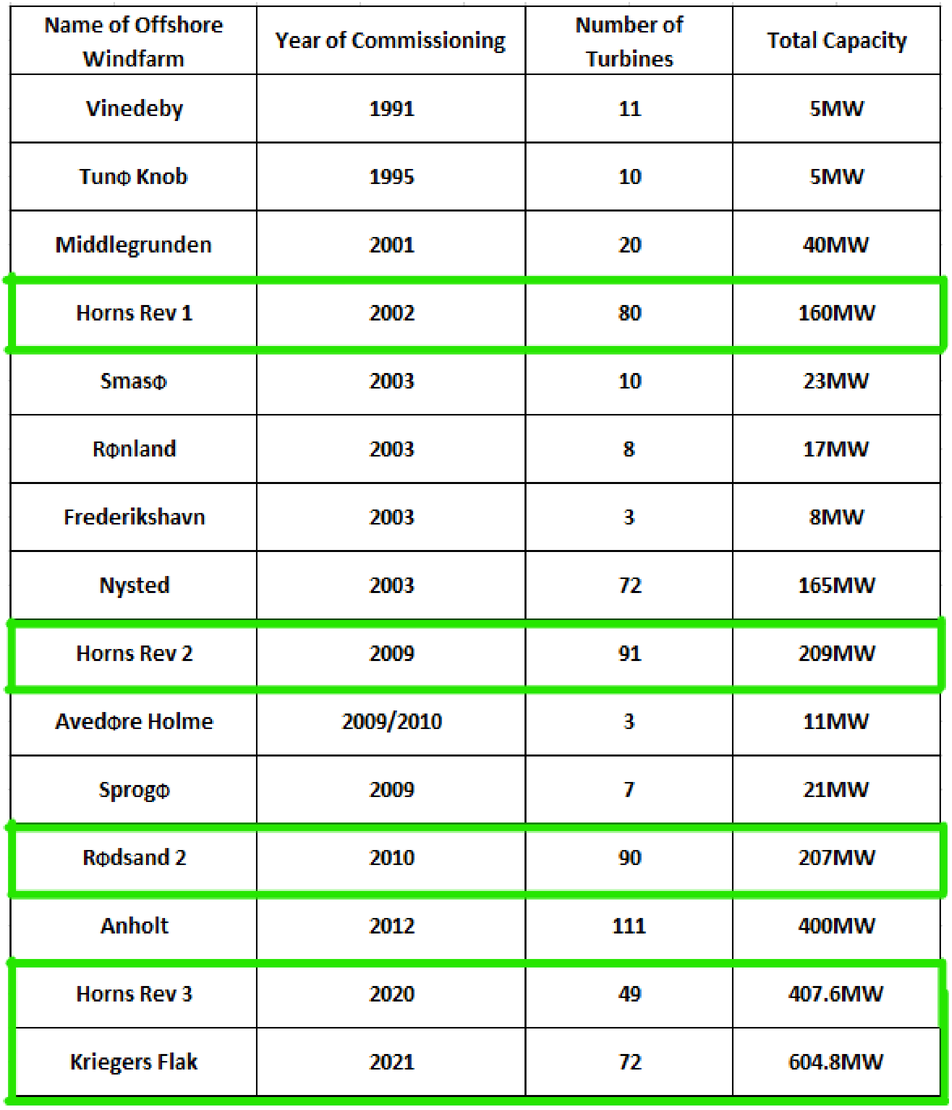


Figure 14. Distance between onshore and Horns RevI, II, III offshore wind farms

Esox-Lautec weather downtime simulation tool [39].

Table 5.3 Offshore wind farm profile in Denmark



Name of Offshore Windfarm	Year of Commissioning	Number of Turbines	Total Capacity
Vinedeby	1991	11	5MW
Tunφ Knob	1995	10	5MW
Middlegrunden	2001	20	40MW
Horns Rev 1	2002	80	160MW
Smasφ	2003	10	23MW
Rφnland	2003	8	17MW
Frederikshavn	2003	3	8MW
Nysted	2003	72	165MW
Horns Rev 2	2009	91	209MW
Avedφre Holme	2009/2010	3	11MW
Sprogφ	2009	7	21MW
Rφdsand 2	2010	90	207MW
Anholt	2012	111	400MW
Horns Rev 3	2020	49	407.6MW
Kriegers Flak	2021	72	604.8MW

Assessing Danish Wind Power

The fundamental equation for calculating the mechanical power of a wind turbine is:

$$P = \frac{1}{2} C_p (\lambda, \beta) AV^3$$

Where ρ is the air density (kg/m^3), C_p is power coefficient, A is the swept area of the rotor blades (m^2), V is average wind speed (m/s), and λ is the tip speed ratio. The theoretical maximum value of the power coefficient C_p is 0.593, also known as Betz's constant. This constant is mathematically proved later in this study.

The Tip Speed Ratio (TSR) describes the relationship between the rotating speed of the blade tip and the wind speed in a wind turbine. Mathematically,

$$\lambda = \frac{R\omega}{V}$$

Where R is the radius of turbine (m), ω is angular speed (rad/s), V is average wind speed (m/s).

A direct measurement of wind speed at a particular height is not always possible due to various factors. Thus, the data at any height can be extrapolated or interpolated in order to determine the wind speed at any particular height. At lower altitudes, the wind velocity is measured at a lower height, which is prone to error due to vegetation, shading, and obstacles. For Denmark, it is important to use the data already provided in Nord Pool for analysis to avoid re-inventing the wheel.

The equation below relates turbine hub height and wind speed:

$$V(z) \text{ In} \left(\frac{z}{z_o}\right) = V(z_r) \text{ In} \left(\frac{z}{z_o}\right)$$

Z_r is the reference height (m), Z is the height at which wind speed is to be calculated, Z_o is the surface roughness (0.1-0.25 in the case of crop land), V (z) (m/s) is the wind speed at height z, and V (z_r) is the wind speed at reference height z (m/s).

Capacity factor (CF)

In electrical energy terms, net cf is the ratio between the actual production and maximum output over a period of time. This ratio can be applied to any electricity producing installation, whether it generates electricity via fossil fuel or renewable energy. Any class of such installation can also be defined by defining the average capacity factor, which helps to compare the performance of different energy systems.

Mathematically, it is expressed as:

$$\text{Capacity factor} \Rightarrow \frac{\text{Actual Annual Energy Production(MWh)}}{\text{Nameplate Capacity(MW)} * \text{T(hrs)}}$$

Nameplate capacity is the maximum rating of the wind farm. Time T is simply the product of total number of hours per day and the amount of days in a year as a whole i.e. $365 \text{ days} * 24 \left(\frac{\text{hours}}{\text{day}}\right) \Rightarrow 8760 \text{ hrs}$. In the light of this, we can express capacity in terms of the total time:

$$\text{Capacity factor} = \frac{\text{Actual Annual Energy Production(MWh)}}{\text{Maximum plant rating(MW} * 365 \text{ days} * 24 \left(\frac{\text{hours}}{\text{day}}\right)}$$

Another way of expressing capacity factor is:

$$\text{Capacity factor} = \frac{\text{Actual Annual Energy Production (MWh)}}{\text{Maximum plant rating(MW)} * 8760 \text{ hrs}}$$

Capacity factor is always less than availability or uptime at any time. Reduced uptime can be caused, for example, by reliability issues and unscheduled maintenance. Furthermore, the design, location and type of electricity produced, as well as the fuel used or, in the case of renewable energy, the local weather conditions, are important factors. Regulatory constraints and market forces can also affect the capacity factor, potentially affecting both its fuel purchase and electricity salt. Typically, the capacity factor is computed over an annual time frame, averaging out most temporal fluctuations. Nevertheless, seasonal changes can be determined by calculating it for a month. Alternatively, it can be calculated for the duration of the power source’s operational life and its decommissioning life. It can also be expressed as full load hours.

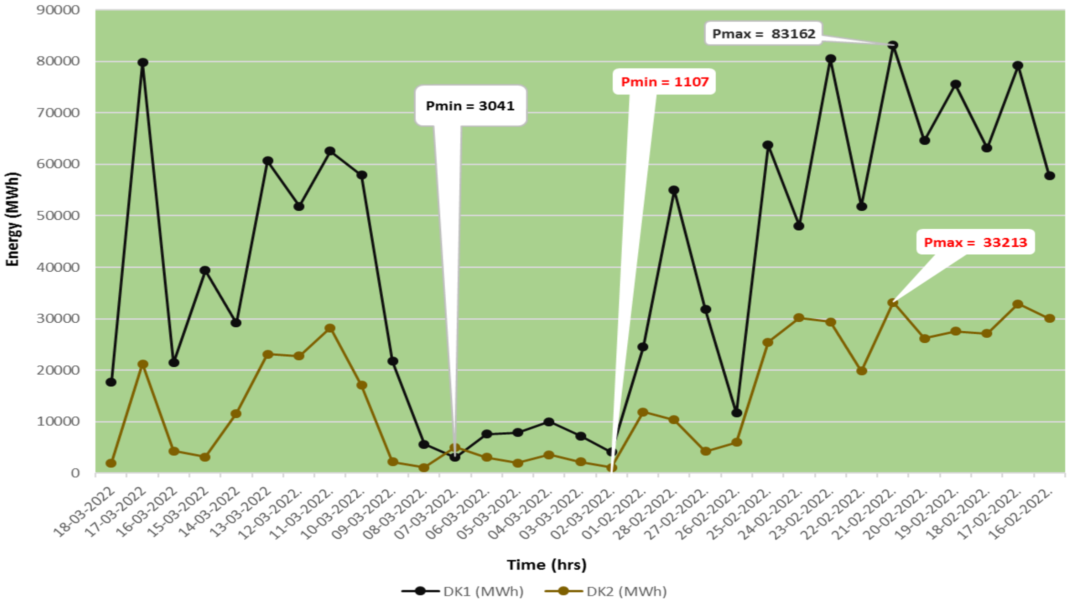


Fig.15 Daily wind energy production in Western (DK1) and Eastern (DK2) Denmark (February 2022 - March 2022)

Data source: Nord Pool [40]

Example 1:

Consider Horns Rev2 for classical illustration. Its nameplate capacity is 209.3MW. Between 2013 (year of commissioning) and January 2017, it produced 6416 GWh and an average yearly production of 875 GWh/year. Calculate its capacity factor based on this data:

$$\Rightarrow \quad \frac{875{,}000 \ \ (\text{MWh})}{365 \text{ days} * 24 \left(\frac{\text{hours}}{\text{day}}\right) * 209.3 \text{ MW}} = 0.477(\sim 48\%)$$

The capacity factor (CF) for Horns Rev 2 based on this data is 47.7%. Such value is a reflection of high wind resource in the offshore environment in the North Sea. Table5.4 shows the total installed capacity, annual energy production, of some of the offshore wind power production in Denmark in 2013. The capacity factors are calculated as shown below. From the table, we can see that Horns Rev2 has the highest capacity factor.

Calculate few capacity factors for selected location using available information in table 5.4.

Horns Rev1

$$\Rightarrow \frac{615396325\ (\mathrm{kWh})}{365\ \mathrm{days} * \ 24\left(\frac{\mathrm{hours}}{\mathrm{day}}\right) * \ 160000\ \mathrm{kW}} = 0.4391(\sim 43.91\%)$$

Smaso

$$\Rightarrow \frac{77612801\ (\mathrm{kWh})}{365\ \mathrm{days} * \ 24\left(\frac{\mathrm{hours}}{\mathrm{day}}\right) * \ 23000\ \mathrm{kW}} = 0.3853(\sim 38.53\%)$$

Roland

$$\Rightarrow \frac{62778739\ (\mathrm{kWh})}{365\ \mathrm{days} * \ 24\left(\frac{\mathrm{hours}}{\mathrm{day}}\right) * \ 17000\ \mathrm{kW}} = 0.4216\ (\sim 42.16\%)$$

Frederikshavn

$$\Rightarrow \frac{21849069\ (\mathrm{kWh})}{365\ \mathrm{days} * \ 24\left(\frac{\mathrm{hours}}{\mathrm{day}}\right) * 8000\mathrm{kW}} = 0.311853\ (\sim 31.18\%)$$

Fig16. Comparison of capacity factors

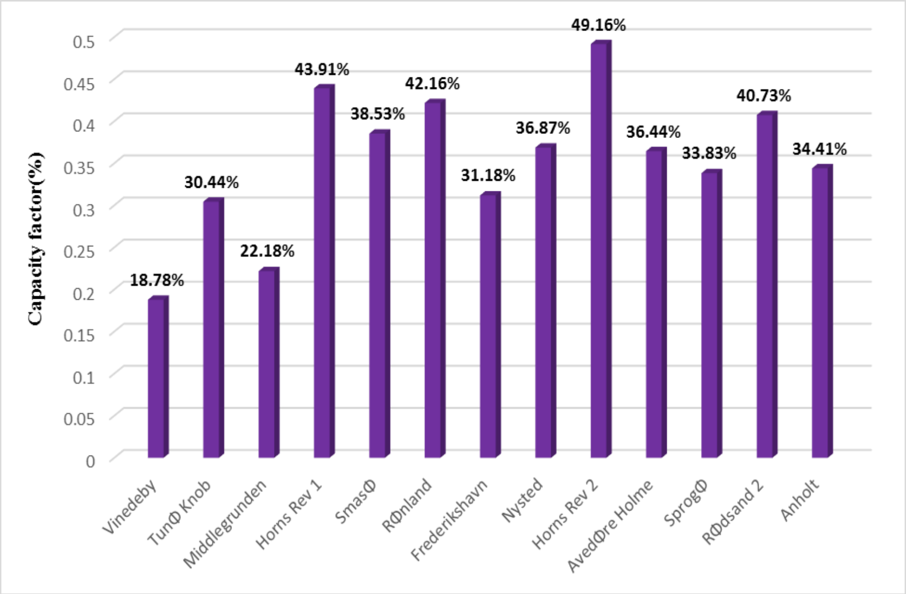


Table 5.4 Capacity factors of Danish offshore wind farms (2013)

Offshore Windfarms in Denmark	Total Installed Capacity	Production 2013 (kWh)	Capacity Factors
Vinedeby	5MW	8,227,484	18.78%
TunΦ Knob	5MW	13,334,401	30.44%
Middlegrunden	40MW	77,714,701	22.18%
Horns Rev 1	160MW	615,396,325	43.91%
SmasΦ	23MW	77,612,801	38.53%
RΦnland	17MW	62,778,739	42.16%
Frederikshavn	8MW	21,849,069	31.18%
Nysted	165MW	532,868,598	36.87%
Horns Rev 2	209MW	900,055,183	49.16%
AvedΦre Holme	11MW	35,109,531	36.44%
SprogΦ	21MW	62,226,853	33.83%
RΦdsand 2	207MW	738,511,986	40.73%
Anholt	400MW	1,205,398,737	34.41%

From figure 14, we clearly see that both Horns Rev 1 & 2 have the highest capacity factors in 2013 partly due to the high level of wind resource in the North Sea. Note that Horns Rev III project has been commissioned but not operational at this time. Also, the hub heights and swept areas of these turbines selected for this projects may also have contributed to this high value. It is, generally, the unavailability of renewable energy sources, such as solar, wind, and hydroelectricity, that results in low capacity factor. Furthermore, the plant may be able to produce electricity, but required fuel (wind, sunlight or water) may not be available and this can limit capacity factor. Hence, availability factor affects capacity factor.

Providing water for fish downstream and preventing water levels from getting too high or too low can also affect hydroelectric plant production. Despite their low availability factors, solar, wind, and hydroelectric plants can produce electricity almost always if fuel is available. Variability in wind farms is caused by the inherent variability of wind resource. There are three major factors that determine a wind farm's capacity factor: wind availability, turbine swept area, and generator size. Also, it is affected by transmission lines capacity and the demand for electricity. Wind farms typically have capacity factors between 25 and 45%. Figure 13 shows daily production of wind energy from Western (DK1) and Eastern (DK2) Denmark to the Nord Pool from February 2022 to March 2022.

5.3 Assessing Danish Solar Energy

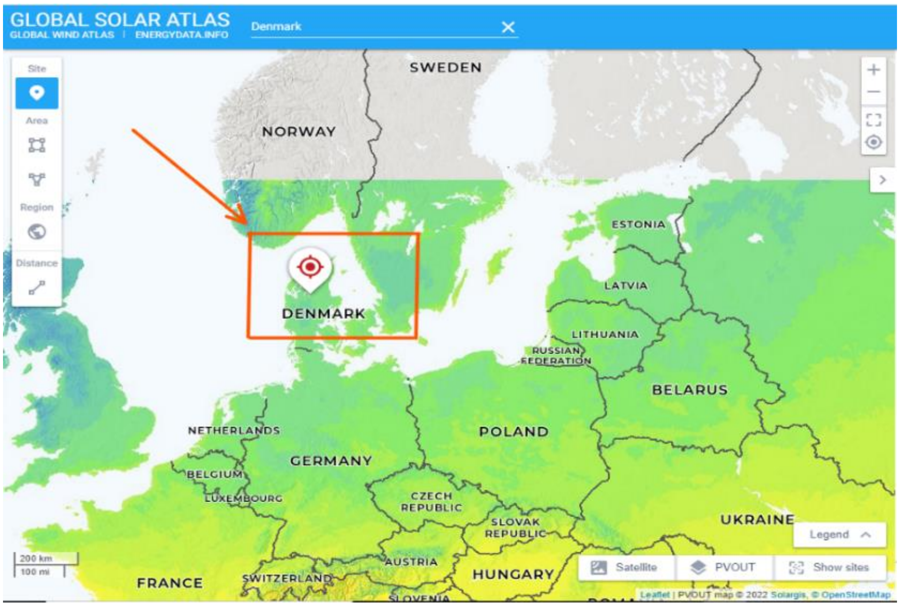


Figure 17. Online solar simulator (Global wind and solar Atlas) showing solar resource in Denmark

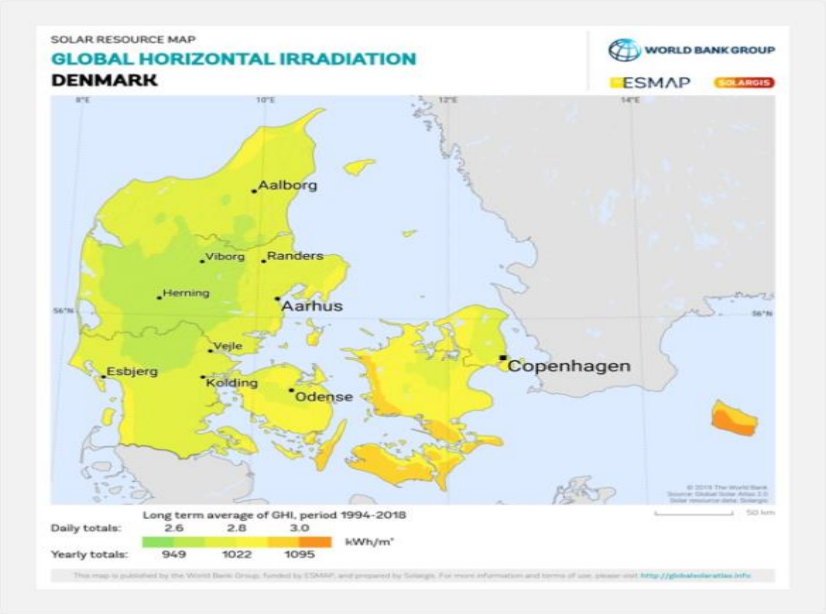


Figure 18. Global horizontal irradiation map [42]

Source: Solargis

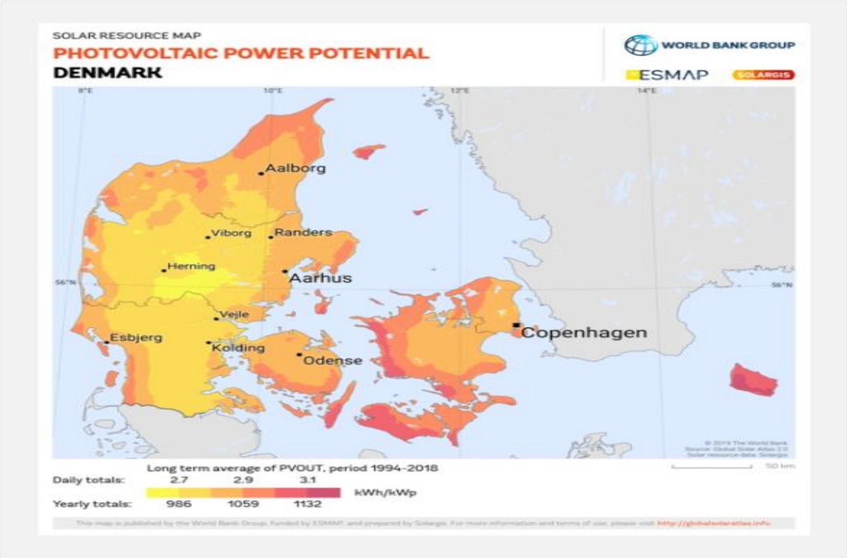
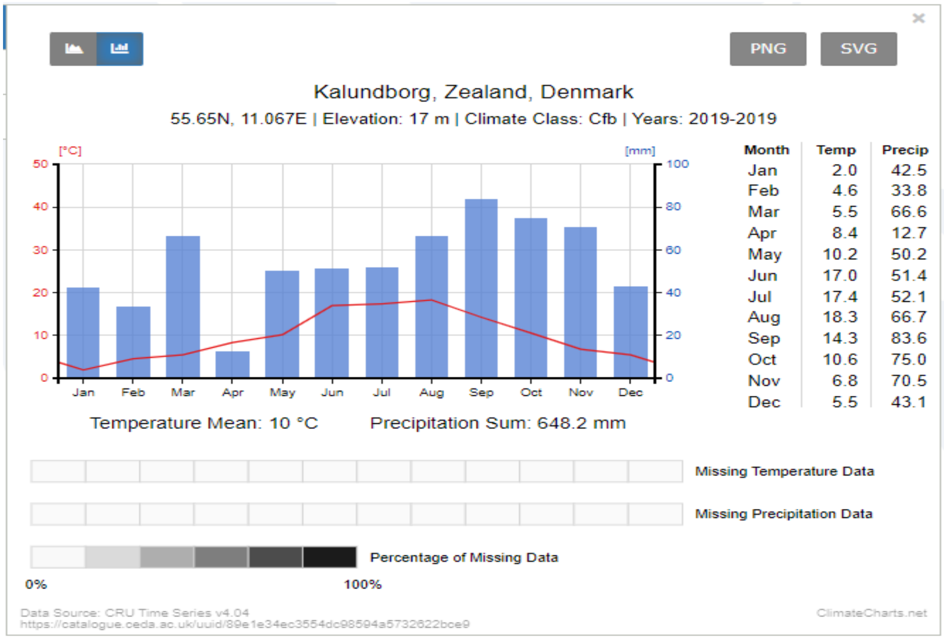


Figure 19. Global PV power potential map [42]

Source: Solargis



Kalundborg, Zealand, Denmark

55.65N, 11.067E | Elevation: 17 m | Climate Class: Cfb | Years: 2019-2019

Month	Temp	Precip
Jan	2.0	42.5
Feb	4.6	33.8
Mar	5.5	66.6
Apr	8.4	12.7
May	10.2	50.2
Jun	17.0	51.4
Jul	17.4	52.1
Aug	18.3	66.7
Sep	14.3	83.6
Oct	10.6	75.0
Nov	6.8	70.5
Dec	5.5	43.1

Temperature Mean: 10 °C Precipitation Sum: 648.2 mm

Data Source: CRU Time Series v4.04
https://catalogue.ceda.ac.uk/uuid/89e1e34ec3554dc98594a5732622bce9

Figure 20. Temperature and Precipitation profile of Zealand, Denmark from ClimateChart application [25]

5.3.1 Grid Requirements- Tolerance to grid Voltage and Frequency Deviations

Synthetic inertia through inverter is the key connection between the renewable energy storage system and the grid. One of the methods of synchronising renewables to the grid is by using inverters. However, the inverters must follow certain technical requirements- before they are permitted to feed into the power supply grid. To maintain the power grid's stability, these requirement which are, codes and standards, must be followed.The main PV inverter grid code requirements includes:

- Tolerance to grid deviations and response to abnormal grid conditions
- Power quality requirements
- Prevention of stand-alone operation

The underlying fact with which we are dealing is the fact that renewable power sources do not provide electrical power oscillating at norminal frequency (50Hz). Solar panels provide continous DC power, and the frequency with which wind turbines operate will depend on their rotational speed or they may output DC power as well. A PV plant must be able to withstand voltage and frequency deviations at the point of connection (POC) under normal and abnormal operating condition without reducing the active. In Denmark, the requirements for normal operating conditions for PV plants less than11kWp include:

- Normal operating voltage:

$$85\% < \frac{U}{U_N} < 110\%$$

- Normal operating frequency range:

$$49\text{Hz} < \frac{U}{U_N} < 51\text{ Hz}$$

5.3.2 Conversion Efficiency

- **Losses in a converter**
  - Inductor, capacitor and wire losses
  - Switch conductor losses
  - Switch turn-on turn-off losses
  - Body diode losses
  - Transformer losses
  - Control circuit power consumption

$$\eta_{\text{conv-inv}} = \frac{P_{\text{AC}}}{P_{\text{DC-in}}} \quad \text{and} \quad \eta_{\text{conv-DC/DC}} = \frac{P_{\text{DC-out}}}{P_{\text{DC-in}}}$$

- The conversion efficiency of power converters can vary with input voltage as well as operating temperature

- The power output of the inverter is derated above a threshold operating temperature

- PV converters are designed and dimensioned to operate with the highest efficiency at the norminal input power and voltage.

Where $\eta_{\text{conv-inv}}$ and $\eta_{\text{conv-DC/DC}}$ are converters efficiencies and P_{AC} $P_{\text{DC-in}}$ $P_{\text{DC-out}}$ are AC and DC power input and output in converter circuit.

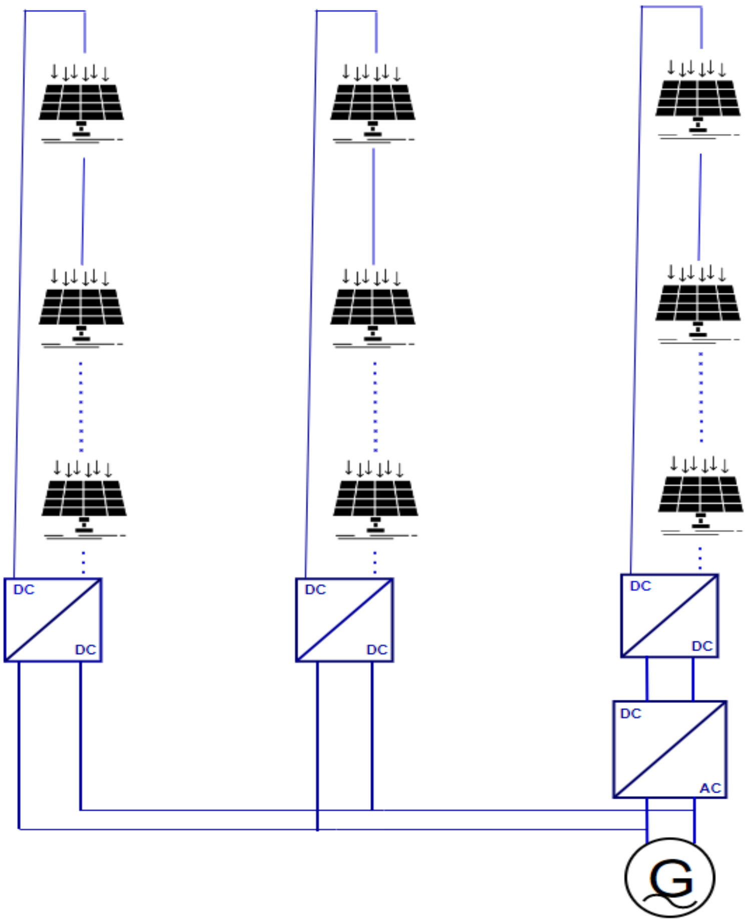


Figure 21. Multi-string inverter connected to the grid

Software : Drawio

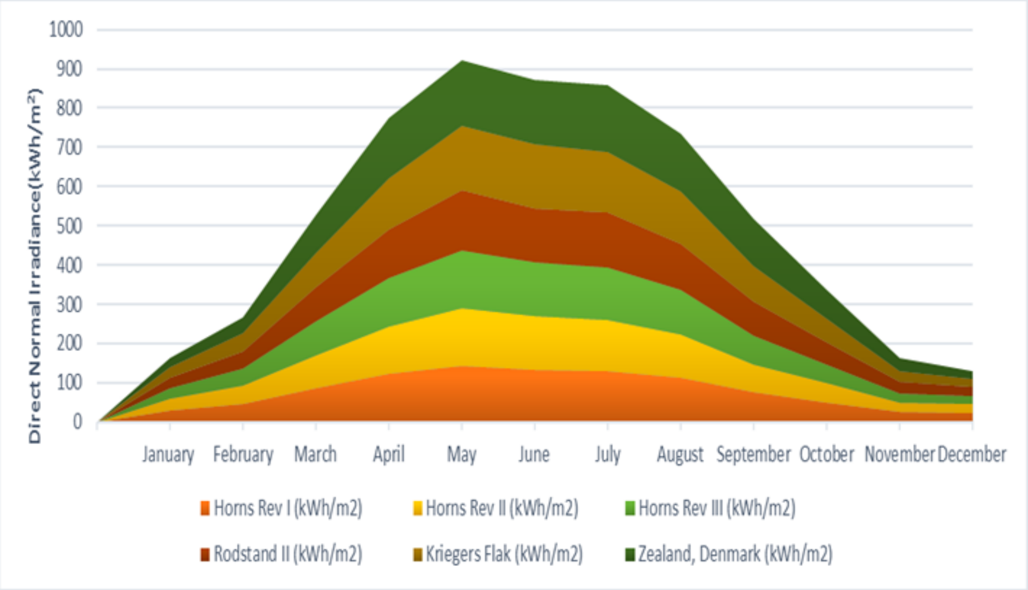


Figure 22. Comparison between Direct Normal Irradiance (DNI) of selected locations in Denmark (Global Atlas)

The solar irradiance chart shows that Zealand has the highest sun hours annually compared to other selected locations. Justifiably so, this location is home to some of the biggest power plants in Denmark such as Wirsol Lechenborg Solar PV park which is a grount-mounted 60MW solar project occupying a large area of land. Also, there is a 25MW bioenergy project called the Koge CHP plant in same Zealand. Since most of the energy systems are in this location, then it makes economic sense to either use exisitng PV systems or ramp it up.

Renewable generation is not dispatchable in the sense that a system operator such as Energinet cannot schedule wind and solar due to their low ramp rates so they are not flexible. Operational flexibility is determined by the plants ramp rate and minimum run time. Ramp rate is how fast the plant can increase or decrease its power output as measured in megawatts per hour or percent capacity per unit time. Minimum run time is the shortest amount of time that the plant can run once it is brought online.

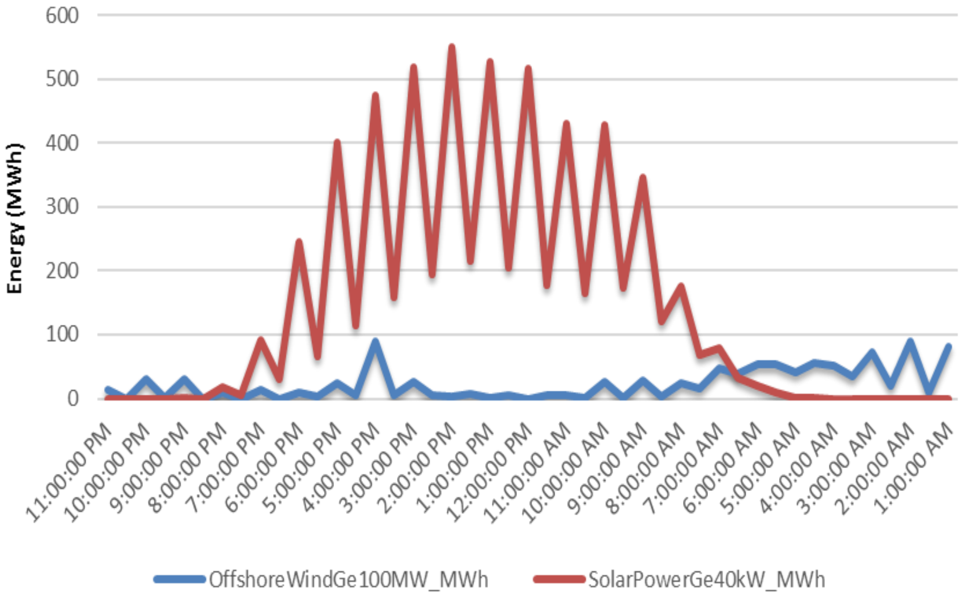


Figure 23. High solar energy and low wind energy

Data source: Energinet

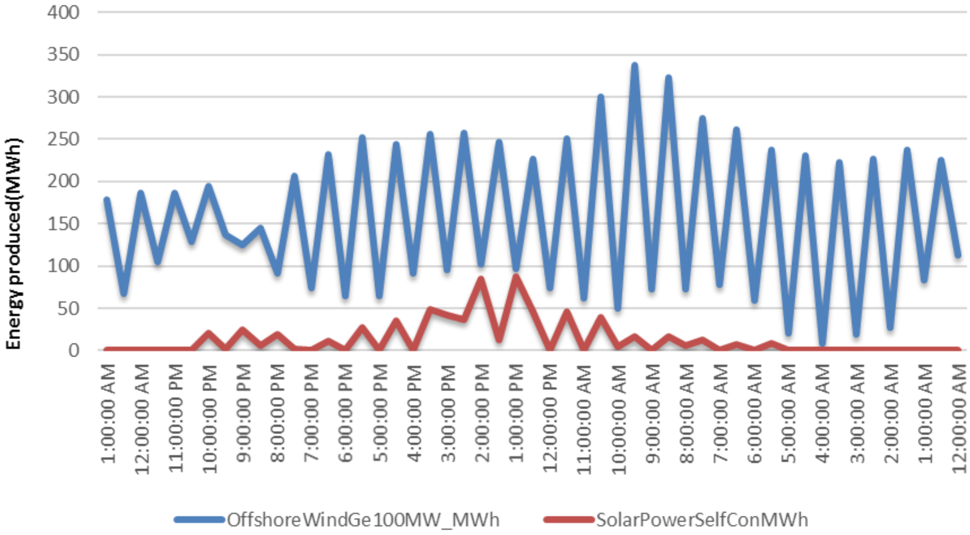


Figure 24. High wind energy and low solar energy

Data source: Energinet

Figure 22 and 23 are chart showing wind and solar energy production in Denmark. The offshore wind energy is from power plant ≥ 100 MW. The Solar power plant is ≥ 40 kW

5.3.5 Economic Analysis for SPHS

In evaluating economic viability of the proposed floating PV system, three major indices used are:

- Levelized cost of energy (LCOE)
- Net present value (NPV)
- Balance of system (BOS)

In this study, only LCOE is considered due to time and space. LCOE and NPV are time-dependent value of money economic methodologies. In many countries around thw world, solar power is becoming competitive with conventional energy sources, meaning the LCOE from solar PV is cheaper than ever. Solar photovoltaic has significantly reduced in price over the last few years, resulting in the growth of this industry. Solar prices are constantly falling, so developers are exploring ways to increase solar plant efficiency in order to maximize profits.

A complex and highly technical process is required to convert solar radiation into electrical power. By itself, a solar array cannot produce a safe, reliable and usable electric output, even if it has photovoltaic modules forming the core. There are variety of devices that transmit energy through a solar plant, which are configured according to a wire network and other electrical hardware. It is often referred to as balance of system (BOS). A BOS cost is the total upfront cost of a PV system, excluding module costs.

Moreover, they can be divided into hard cost and soft costs. Battery/energy storage systems, wires, supports racks, inverters, switches, and land are considered hard costs. Soft cost include planning, permission, customer acquisition, insurance, and installation labour are considered soft costs. There are considereable differences in these costs across regions, technologies, and markets segments, and they are strongly influenced by local conditions and regulatory environments. The BOS cost for residential solar systems is higher than that of large commercial installations. A canal-top PV system and a floating system will have more expensive installation costs. Economies of scale, however, result in lower BOS costs for utility-scale systems.

Table 5.92 Cost Target for Stensea [47]

Construction Target Cost			
Concreting costs (including formwork and reinforcement)	225 (€/m^3)	2065 (T€/piece)	413 (€/kW)
Installation per unit		1500 (T€/piece)	300 (€/kW)
Pump-turbine plus electro-mechanical equipment		2625 (T€/piece)	525 (€/kW)
STENSEA Target costs per kW installed power			1238 (€/kW)
Economic useful lifetime		Units	
Construction	20	Years	
Machinery	7 - 20.	Years	
Repair and maintenance		Units	
Construction	1.5%	% of investment	
Machinery	3%	% of investment	
Insurance	0.5%	% of investment	

Calculate LCOE:

$$\mathrm{LCOE} = \frac{\mathrm{Initial\ cost(\$)} + \mathrm{O\&M}\left(\frac{\$}{\mathrm{yr}}\right) * \mathrm{PVAF(yrs)}}{\mathrm{Annual\ Energy\ Output(kWh)} * \mathrm{PVAF(yrs)}}$$

For energy storage installation cost $\left(\frac{\$}{\mathrm{kWh}}\right)$:

$$\Rightarrow \mathrm{Cost\ of\ storage}\left(\frac{\$}{\mathrm{kWh}}\right) + \frac{\mathrm{other\ components(\$)such\ as\ storage\ inverter\ and\ labour}}{\mathrm{storage\ system\ size(kW)} * \mathrm{Duration\ (hours)}}$$

Also LCOE can be calculated using the expression:

$$\mathrm{LCOE} = \frac{\sum \frac{\mathrm{I_t + M_t + F_t}}{(1+\mathrm{r})^{\mathrm{t}}}}{\sum \frac{\mathrm{E_t}}{(1+\mathrm{r})^{\mathrm{t}}}}$$

Where

I is the intial cost of investment expenditures

M is the maintenance and operations expenditiures

F is the fuel expenditures (for blackstart generators)

E is the sum of all electricity generated by the power plant

Discount rate of the project is r

Power plant operational lifetime n

Example: Suppose fifty (50) SPHS are deployed into the North Sea for ancillary purpose. Calculate the LCOE using information in table 5.92

From table 5.92, n =20yrs, O&M = 5% of total investment (construction, machinery and insurance), assume zero inflation and 2% discount.

$$\mathrm{LCOE} = \frac{\text{Initial cost(\$)} + \text{O\&M}\left(\frac{\$}{\mathrm{yr}}\right) * \text{PVAF(yrs)}}{\text{Annual Energy Output(kWh)} * \text{PVAF(yrs)}}$$

PVAF: $1 - \frac{(1+\mathrm{r})^{-\mathrm{n}}}{\mathrm{r}} \Rightarrow 1 - \frac{(1+0.02)^{-20}}{0.02} \Rightarrow 16.35\ \text{yrs}$

Annual energy output (AEP) at 85% turbine efficiency:

$$\Rightarrow 50 * 5\ \mathrm{MW} * 4\left(\frac{\mathrm{hrs}}{\mathrm{day}}\right) * 85\% * 8760\left(\frac{\mathrm{days}}{\mathrm{year}}\right) = 7446000000\ \mathrm{kWh}$$

Initial cost: $1238\left(\frac{€}{\mathrm{kW}}\right) * 50 * 5000\ \mathrm{W} = €\ 309500000$

O &M $5\% * €\ 309500000 = €\ 15475000$

LCOE $5\% * €\ 309500000 = €\ 15475000$

$$\Rightarrow \frac{€\ 309500000 + [€\ 15475000 * 16.35(\mathrm{yrs})]}{7446000000\ \mathrm{kWh} * 16.35(\mathrm{yrs})}$$

LCOE

$$\Rightarrow \frac{€\ 309500000\ + [\ €\ 15475000 * 16.35\ (\text{yrs})]}{7446000000\ \text{kWh} * 16.35(\text{yrs})} \Leftrightarrow 0.0046\left(\frac{€}{\text{kWh}}\right)$$

For 60 subsea storage

$$\Rightarrow \frac{€\ 371400000\ + [€\ 18570000 * 16.35(\text{yrs})]}{8935200000\ \text{kWh} *\ 16.35(\text{yrs})} \Leftrightarrow\ 0.00462\left(\frac{€}{\text{kWh}}\right)$$

Now suppose turbine efficiency drops from 85% to 80% and 60 subsea storage are deployed, let us calculate the cost of energy:

$$\Rightarrow 60 * 5\ \text{MW} * 4\left(\frac{\text{hrs}}{\text{day}}\right) *\ 80\ \% * 8760\left(\frac{\text{days}}{\text{year}}\right) = 8409600000\ \text{kWh}$$

$$\Rightarrow \frac{€\ 371400000\ + [\ €\ 18570000 * 16.35(\text{yrs})]}{8409600000\ \text{kWh} * 16.35(\text{yrs})}$$

$$\Leftrightarrow 0.004909\left(\frac{€}{\text{kWh}}\right) \sim\ 0.005\left(\frac{€}{\text{kWh}}\right)$$

Based on this efficiency, costs etc. we can conclude that LCOE for this technology varies with country (location), and the number of storage system operational per time. Note that all data used for calculation here were obtained from previous studies on StenSea as properly cited in references.

CHAPTER 6

SCENARIO-BASED STUDIES AND CO-OPTIMIZATION OF THE SYSTEM

6.1 Co-optimization of the proposed System

We investigate an optimal bidding strategy for existing for wind farms and SPHS operating together in the DA and FCR-N markets [15][20]. Some literatures have investigated the feasibility of wind farms and the conventional PHS. However, it is vital to study the complimentary operations of offshore wind farms and SPHS with a specific location as a case study. The Danish transmission system operator (TSO) is responsible for system balance through the reserve and balancing markets. Two regulatory zones (DK1 and DK2) exist in Denmark. DK2 is part of the Nordic power system and DK1 is part of the continental European power system (German load frequency control block). It is assumed that the ancillary service from each bidding zones (DK1 and DK2) in Denmark are different. Also, it is assumed that subsea energy storage system is installed in DK1 and generates revenue through participation in DA market and FCR-N [15][20]. In this optimization method, maximization of energy from wind farms, PV system and SPHS is considered [15] [20][21].

Objective functions:

$$E = \text{Max} \sum_{t=t_o}^{T} (P_{PV}(t) + P_w(t) + P_{SPHS}(t)).\Delta t$$

But SPHS capacity is denoted by C_{max} which equals the product of power (P_{SHS}) and time (t) of dispatch of the energy. We now substitiute C_{max} for $P_{SHS}\Delta t$ in the equation since $C_{max} = P_{SHS}\Delta t$

$$E = \text{Max} \sum_{t=t_o}^{T} (P_{PV}(t).\Delta t + C_{max}(t) + +P_w(t).\Delta t)$$

Next, minimization of energy produced by diesel generator in time interval is considered. This is due to the greenhouse emission reduction target of this study.

$$E = \text{Min} \sum_{t=t_o}^{T} P_{DG}(t).\Delta t$$

6.1.1 Equality constraints :

The load demand must be equal to or less than sum of the power produced by the generators and the wind turbines [15][20]. The diesel generator is assumed to be used for black-start as wind turbines may not suitable for black due to the intermittent nature of wind.

$$P_{DG}(t) + P_{PV}(t) + P_w(t) + P_{SPH}(t) = P_{LOAD}(t)$$

6.1.2 Upper and Lower Limits (constraints)

The major constraints is matching the maxium power delivered to the grid with the grid's capacity [15][20]. The maximum and minimum operating powers of the generators is put into consideration and these parmeters are obtainable from manufacturer's technical datasheet. In this case study, C^{max} is 85% and C^{min} is 80% of rated value. So the boundary is mathematically expressed as:

$$C^{min} \leq C(t) \leq C^{max}$$

Discharge mode of storage system:

$$C^d(t) = C(t-1) - \left(\frac{P^d{}_{SPH}(t).\Delta t}{\eta_d}\right)$$

Charge mode of storage system

$$C^c(t) = C(t-1) + (P^c{}_{SPH}(t)\Delta t * \eta_C)$$

Where $C(t-1)$ is the capacity at time t-1(kWh), η_d and η_C are the disharge and charge efficiencies respectively.

Power discharged by storage system

$$P^d{}_{SPH}(t) = P_{LOAD}(t) - P_{DG}(t) - P_{PV}(t) - P_w(t)$$

Power charge into storage system

$$P^c{}_{SPH}(t) = P_{DG}(t) + P_{PV}(t) - P_w(t) - P_{LOAD}(t)$$

$P_w(t)\Delta t$ and $P_{load}(t)\Delta t$ are the wind energy and energy demand from load centres respctively

Suppose the maximum power of diesel generator (P^{max}) is 85% of rated value and minimum power (P^{min}) is 25% of rated value, then the boundary equation is given as:

$$P_{DG}^{min} \leq P_{DG}(t) \leq P_{DG}^{max}$$

The power produced by the diesel generator must be positive:

$$P_{DG}(t) \geq 0$$

Similarly, the boundary equations for the wind farm is given as:

$$P_{w}^{min} \leq P_{w}(t) \leq P_{w}^{max}$$

Power produced by the wind farm must be positive:

$$P_{w}(t) \geq 0$$

Finally, the boundary equations for the PV system is given as:

$$P_{pv}^{min} \leq P_{pv}(t) \leq P_{pv}^{max}$$

$$P_{pv}(t) \geq 0$$

Assumptions made in this analysis

- The area occupied by subsea energy storage is approximately the same with the offshore wind farms.
- The distance between subsea energy storage from the offshore wind farms is not long so that the installation cost of subsea cables is minimized.
- The diesel generator is used for black start by restoring the system back into normal operation in case of shut down. However, that can be avoided if, for instance, the entire system is made smart**.**

6.2 SPHS for Ancillary Service

6.2.1 Balancing Energy and Balancing Capacity Markets

Balancing markets help to maintain the operational balance between production and consumption of electricity in a power system[53]. It is also known as a regulating power market. For a financial compensation, reserve providers are required to provide up-regulating bids, which correspond to accepted capacity bids, to the balancing energy market. In Denmark, participation in the balancing energy market requires a contract with Energinet[51][53].

Denmark and other neighbouring countries procure ancillary services from electricity generators and power consumers for a variety of purposes, which require different different requirements for the supply of each. Regulations for grid connection by Energinet as well as ENTSO-E Continental Europe Handbook regulate these requirements.

Suppliers of ancillary services are required to meet slighltly different requirements if they provide services in eastern Denmark (DK2) or western Denmark (DK1), which is east of the Great Belt. Consequently, these tender conditions are divided into subsections that describe the conditions applicable to DK1 and DK2.

During normal operation or during disturbances, the TSOs activate bids on the balancing energy market. A manual activation is performed from main control grid center.In exchange for financial compensation, a reserve provider whose capacity bid is accepted on the balancing capacity market must give up regulating energy bids [51][53]. To maintain adequate manual frequency restoration reserve for Energinet and its leased power plants, the balancing capacity market is used[53].

Balancing energy bids should include the following information about adjustable capacity:

- power (MW)
- price (€/MWh)
- production/Consumption
- transmission area in which the bid resource is located
- the name of the balancing resource, e.g power plant, type of production, etc.

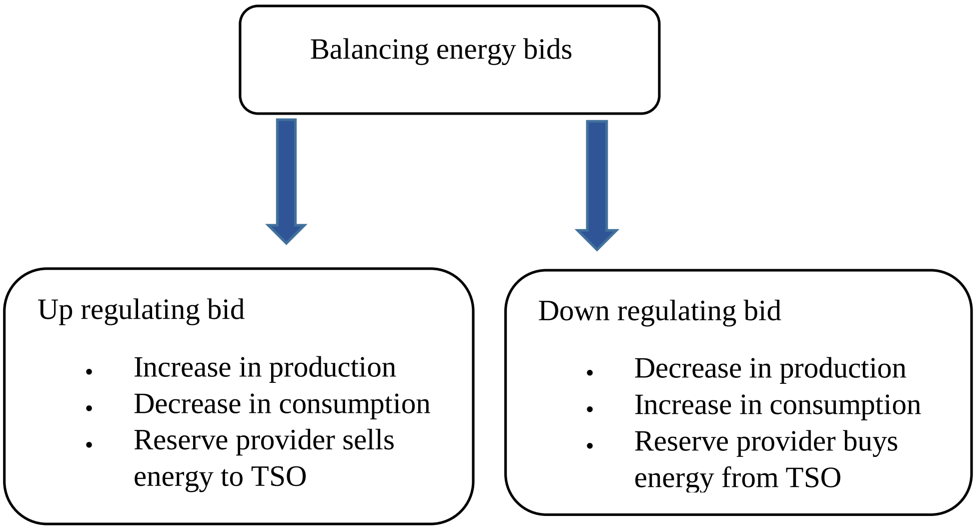


Figure 25. Frequency Regulation types

Upregulating or downregulating bids are ways of balancing energy bids. For upregulation, the resource owner sells energy to the concerned TSO either to produce more or consume less. In the case of downregulation, resource owners either reduce production or increase consumption to purchase energy from the TSO. We now demonstrate this concept with proposed SPHS and some data from Nord Pool as scenario-based studies [51][53].

6.2.2 Technical Conditions for Frequency Regulation in Denmark

Balancing authorities and independent system operators must ensure that supply (generation) and demand (load) are perfectly balanced in real-time to prevent equipment damage and disruptions in energy supply. Synchronous generators must maintain a frequency relatively close to 50Hz. In Denmark, power frequency control must be supplied at a frequency deviation of up to +/- 200mHz relative to the reference frequency of 50Hz. This will normally mean in the 49.8-50.2 Hz range. A deadband of +/-20mHz is permitted. It is essential that the reserve be supplied linearly at a frequency deviations of between 20 and 200Hz at a minimum. A frequency deviation of +/-200mHz is required for the second half of the activated reserve while the first half must be supplied within 15 seconds.

Table 6.1 Tender conditions for delivering Ancillary services in DK1 and DK2

Western Denmark (DK1)	Eastern Denmark (DK2)
Primary Reserve, FCR	Fast Frequency Reserve, FFR
aFRR supply capability	Frequency-controlled disturbance operation reserve
Secondary reserve, aFRR	Frequency-controlled normal operation reserve
Manual reserves, mfRR	aFRR Supply capability
Properties required to maintain power system stability	Manual reserves, mFRR
	Properties required to maintain power system stability

Except for FFR and FCR-D are the only reserves for which bids are invited as upward regulation reserves and downward regulation reserves.

Primary reserve, DK1 (FCR)

If the frequency deviates from 50Hz, the primary reserve regulation must restore the balance between generation and demand, stabilizing the frequency at a fairly close level. Generation and demand units automatically regulate capabilites by responding to grid frequency deviations via control equipment. A sufficient amount of primary reserves must be available within the synchronous area of ENTSO-E RG Continental Europe. The share of Energinet in continental grid is determined annually based on generation in western Denmark. As part of this grid, Energinet is responsible for supplying a propotionate share of the +/-3,000 MW requirements. As long as the manual and automatic regulating reserves can take over, the regulation must be able to be maintained until they can take on the task; however, it needs to be possible for at least 15 minutes.

6.2.3 Compensation for Frequency Regulation

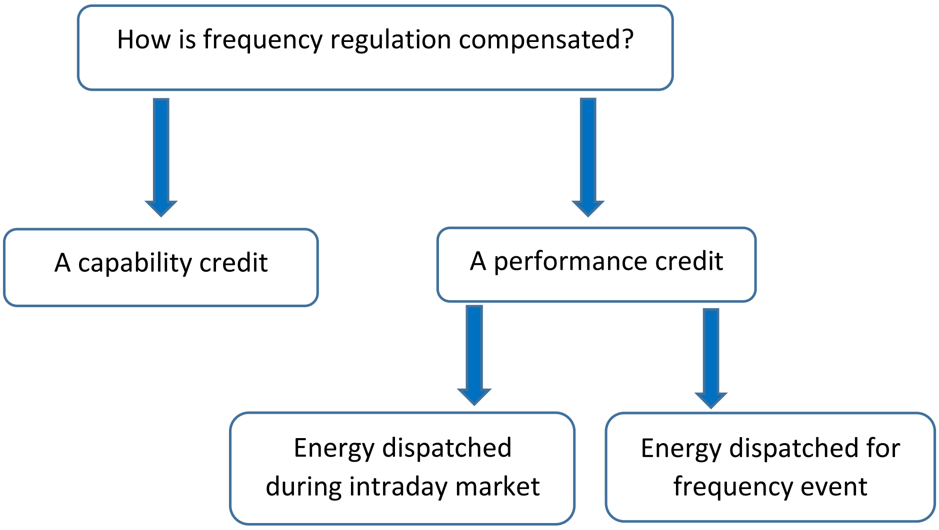


Figure 26. Compensation for frequency regulation

Capability credit is the €/MW payment for the grid operator to reserve some energy for future use. It is comparable to the capacity payment from capacity demand response programs. In this section, capability credit is called reguation capability (RC).

A perfromance credit is the €/MW payment for the frequency regulation service actually delivered. This is comparable to the energy payment from capacity demand response programs. Performance credit in this section consist of energy market revenue (EMR) and regulation performance (RP).

The total revenue for ancillary services as discussed in chapter 3.0 is expressed thus:

$$\text{Total Revenue } (€) = \text{EMR} + \text{RC} + \text{RP}$$

Where EMR is energy market revenue, RC is regulation capability, and RP is regulation performance.

The information in the following tables indicate danish wind energy real-time data. The assumption here is that SPHS is used for balancing purpose during the Nord Pool Intraday market. So, the 6th column of each table in all scenarios indicates energy supplied by SPHS for regulation within 24hrs as demanded during frequency events.

Scenario 1

Table 6.2 Nord Pool Intraday, Regulating bids, Regulating volumes and prices (12/4/2021)

12/4/2021	Nord Pool Intraday (MWh)		Regulating Bids (DK1) (MW)		Regulating Volumes (MWh)		Regulating Prices (EUR/MWh)	
Periods	Buy	Sell	Up	Down	Up	Down	Up	Down
00 - 01	5.0	607.8	636	2033	0	0	20.82	20.82
01 - 02.	20.0	500.0	705	2116	0	0	41.86	34.61
02 - 03.	48.8	627.0	682	2272	0	0	41.73	34.61
03 - 04.	33.8	595.0	636	2352	0	0	41.15	34.0
04 - 05.	23.8	580.0	639	2340	0	0	41.52	34.000
05 - 06.	2.0	603.0	642	2385	0	0	37.97	37.97
06 - 07.	0.0	550.1	626	2509	0	0	41.62	41.62
07 - 08.	15.8	195.0	528	2529	21	0	100.00	54.16
08 - 09.	12.9	0.00	478	2411	147	0	100.00	63.31
09 - 10.	151.0	150.0	492	2532	10	0	73.00	63.2
10 - 11.	95.0	437.7	633	2682	0	0	50.12	50.12
11 - 12.	178.5	585.0	533	2882	0	0	48.12	48.12
12 - 13.	99.0	735.0	565	2844	0	0	45.57	45.57
13 - 14.	95.0	736.0	599	2713	0	0	40.26	40.26
14 - 15.	104.4	714.4	543	2892	0	0	39.09	39.09
15 - 16.	0.0	643.0	582	2846	0	0	38.94	38.94
16 - 17.	80.0	771.0	586	2997	0	0	40.71	40.71
17 - 18.	50.0	740.7	549	3066	0	0	44.7	44.7
18 - 19.	20.0	723.5	532	3075	0	0	46.07	39.06
19 - 20.	85.0	686.0	520	2881	0	0	50.04	50.04
20 - 21.	3.0	618.2	481	2541	4	0	49.44	46.95
21- 22.	80.2	620.2	612	2523	0	0	55.12	55.12
22 - 23.	95.0	653.2	693	2350	0	0	39.51	39.51
23 - 00.	131.5	647.5	690	2352	0	0	37.38	37.38

The information in table 6.1 & 6.2 are Nord Pool data for Denmark on the dates indicated. In this section, we investigate the techno-economic feasibility of SPHS for bids balancing using this data. The performance index considered are as follows:

$$\textbf{Energy market revenue}(\textbf{EMR}) \Rightarrow \text{Energy dispatched in real} - \text{time} * \text{ real time price}$$

The focus in this scenario are the green spots in table 6.1. Energy dispatch during intraday market includes the periods of 7.00 -10.00am, and 8.00 - 9pm. Average day-ahead price on this day (12 - 4 -2021) from Nord Pool is € 44.58 and system price is € 40.58.

Assuming SPHS is utilized for ancillary services,

Total energy dispatched during these higlighted periods:

15.8 + 12.9 +151.0 + 3.0 = 182.7 MWh

$$\text{Energy market revenue}(\text{EMR}) = 182.7 \text{ MWh} * \ 40.58 \left(\frac{€}{\text{MWh}}\right) \Rightarrow € \ 7413.966$$

$\textbf{Regulation capability (RC)} \; \Rightarrow$

$$\text{Power supplied for regulation (MW)} * \text{ Regulation capability price } \left(\frac{€}{\text{MWh}}\right) * \text{Time (hr)}$$

$$528 \text{ MW} * 100\left(\frac{€}{\text{MWh}}\right) * 1\text{hr} \; = \; € \, 52800$$

$$478 \text{ MW} * 100\left(\frac{€}{\text{MWh}}\right) * 1\text{hr} = \; € \, 47800$$

$$492 \text{ MW} * 73\left(\frac{€}{\text{MWh}}\right) * 1\text{hr} = \; € \, 35916$$

$$481\text{MW} * 49.44\left(\frac{€}{\text{MWh}}\right) * 1\text{hr} = € \, 23780.64$$

€ 52800 + € 47800 + € 35916 + € 23780.64 = €160296.64

$\textbf{Regulation performance (RP)} \; \Rightarrow$

$$\text{Regulation volume (MWh)} * \text{ System price } \left(\frac{€}{\text{MWh}}\right)$$

$$(21 \; + 147 \; + 10 + \; 4) \text{ MWh} * \; 40.58\left(\frac{€}{\text{MWh}}\right) \Leftrightarrow 182 \text{ MWh} * \; 40.58\left(\frac{€}{\text{MWh}}\right)$$

$$\Rightarrow \; € \, 7385.56$$

Total revenue : € 7413.966 + € 160296.64 + € 7385.56 = € 175096.166

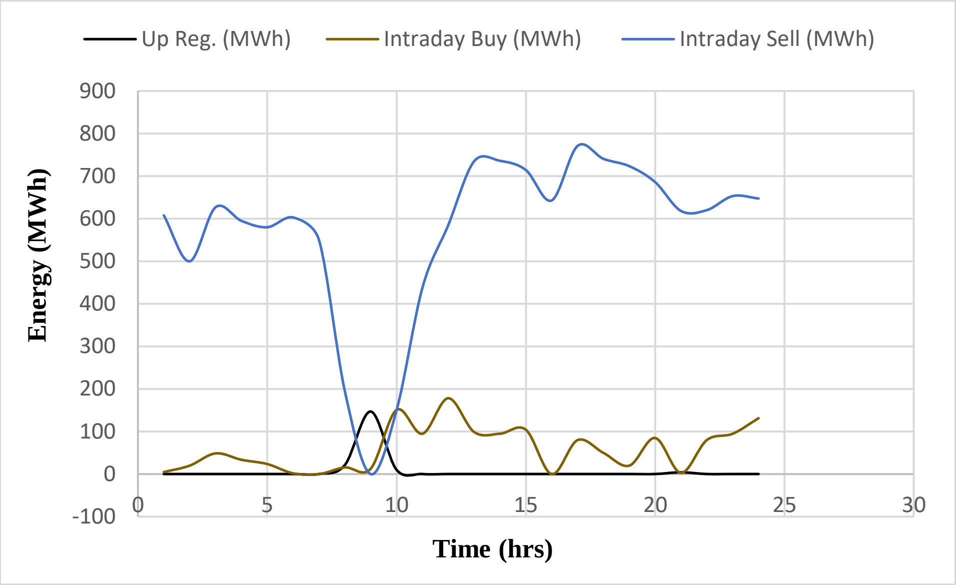


Figure27 Upward regulation bid in Denmark (12/04/2021)

Data source : Nord Pool [44]

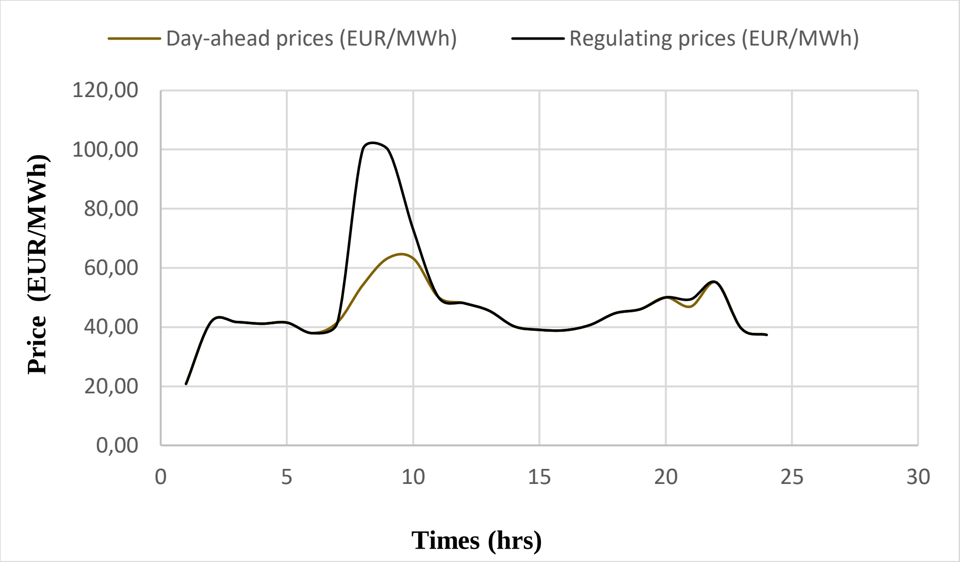


Figure28 Day-ahead and regulating prices (12/04/2021)

Data source : Nord Pool [44][45]

Scenario 2

The same procedure is applied in this section.

$$\textbf{Energy market revenue}(\textbf{EMR}) \Rightarrow \text{Energy dispatched in real} - \text{time} * \text{ real time price}$$

Similarly, like the first scenario, the focus are the green spots in table 6.2. Energy dispatch during intraday market includes the periods of 6.00-10.00am, and 13.00-17:00pm. Average day-ahead price on this day(14/4/2021) from Nord Pool is €67.62 while system price is €45.22.

Total energy dispatched during these higlighted periods (See coulumn for Nord Pool Intraday under Buy):

$$(51.0 + 188.4 + 184.5 + 148.7 + 55.6 + 50.0 + 159.1 + 69.6)\text{MWh} = 906.9\text{MWh}$$

$$\text{Energy market revenue(EMR)} = 906.9\text{MWh} * 45.22\left(\frac{€}{\text{MWh}}\right) \Rightarrow € \, 41010.018$$

Table 6.3 Nord Pool Intraday, Regulating bids, Regulating volumes and prices (14/4/2021)

14/4/2021	Nord Pool Intraday (MWh)		Regulating Bids (DK1) (MW)		Regulating Volumes (MWh)		Regulating Prices (EUR/MWh)	
Periods	Buy	Sell	Up	Down	Up	Down	Up	Down
00 - 01	55.2	479.5	606	1716	0	0	44.23	19.00
01 - 02.	32.1	520.9	581	1747	0	-18	44.19	19.00
02 - 03.	79.9	297.0	785	1527	0	-15	44.34	19.00
03 - 04.	52.5	217.7	875	1341	0	0	45.15	45.15
04 - 05.	21.3	20.0	1047	1211	0	0	51.49	51.49
05 - 06.	67.5	20.0	981	1246	0	0	52.08	52.08
06 - 07.	51.0	0.0	516	1653	91	0	96.33	76.32
07 - 08.	188.4	0.0	447	1709	237	0	200.00	118.52
08 - 09.	184.5	0.00	471	1644	296	0	200.00	125.00
09 - 10.	148.7	30.0	484	1489	80	0	115.00	75.54
10 - 11.	130.0	109.6	662	1248	0	0	62.62	62.62
11 - 12.	45.9	60.2	766	1127	0	0	62.08	62.08
12 - 13.	30.0	339.0	658	1192	0	0	58.29	58.29
13 - 14.	55.6	335.4	717	1130	43	0	80.68	54.90
14 - 15.	50.0	185.2	950	929	2	0	59.00	50.62
15 - 16.	159.1	149.3	900	902	10	0	59.00	51.52
16 - 17.	69.6	195.0	905	1056	3	0	53.79	50.78
17 - 18.	75.6	205.0	591	1427	0	-24	61.32	37.00
18 - 19.	79.5	2.0	396	1679	0	-55	73.19	38.64
19 - 20.	173.0	0.0	394	1716	0	-55	97.45	41.34
20 - 21.	139.5	7.5	413	1695	0	0	100.00	100.00
21- 22.	16.0	5.0	419	1653	0	0	85.62	85.62
22 - 23.	9.5	32.5	419	1558	0	0	75.66	49.00
23 - 00.	15.8	365.7	474	1478	0	0	62.05	62.05

Regulation Capability (RC) (See coulumn for Upward regulation bids)

$$\text{Power required for regulation (MW)} * \text{ Regulation prices } \left(\frac{€}{\text{MWh}}\right) * \text{Time (hr)}$$

$$516 \text{ MW} * 96.33 \left(\frac{€}{\text{MWh}}\right) * 1\text{hr} = € 49706.28$$

$$447 \text{ MW} * 200 \left(\frac{€}{\text{MWh}}\right) * 1\text{hr} = € 89400$$

$$471 \text{ MW} * 200 \left(\frac{€}{\text{MWh}}\right) * 1\text{hr} = € 94200$$

$$484 \text{ MW} * 115 \left(\frac{€}{\text{MWh}}\right) * 1\text{hr} = € 55660$$

$$717 \text{ MW} * 80.68 \left(\frac{€}{\text{MWh}}\right) * 1\text{hr} = € 57847.56$$

$$950 \text{ MW} * 59 \left(\frac{€}{\text{MWh}}\right) * 1\text{hr} = € 56050$$

$$900 \text{ MW} * 59 \left(\frac{€}{\text{MWh}}\right) * 1\text{hr} = € 53100$$

$$905 \text{ MW} * 53.79 \left(\frac{€}{\text{MWh}}\right) * 1\text{hr} = € 48679.95$$

€ 49706.28 + € 89400 + € 94200+ € 55660 + € 57847.56 + € 56050 + € 53100 + € 48679.95 = € 504643.79

$\textbf{Regulation performance (RP)} \Rightarrow$

$$\text{Regulation volume (MWh)} * \text{ System price } \left(\frac{€}{\text{MWh}}\right)$$

(See column for Upward regulating volumes in table 6.2)

$$(91 + 237 + 269 + 80 + 43 + 2 + 10 + 3) \text{ MWh} * 45.22 \left(\frac{€}{\text{MWh}}\right)$$

$$\Leftrightarrow 762 \text{ MWh} * 45.22 \left(\frac{€}{\text{MWh}}\right) = € 34457.64$$

Total revenue : € 41010.018 + € 504643.79 + € 34457.67 = € 580110.658

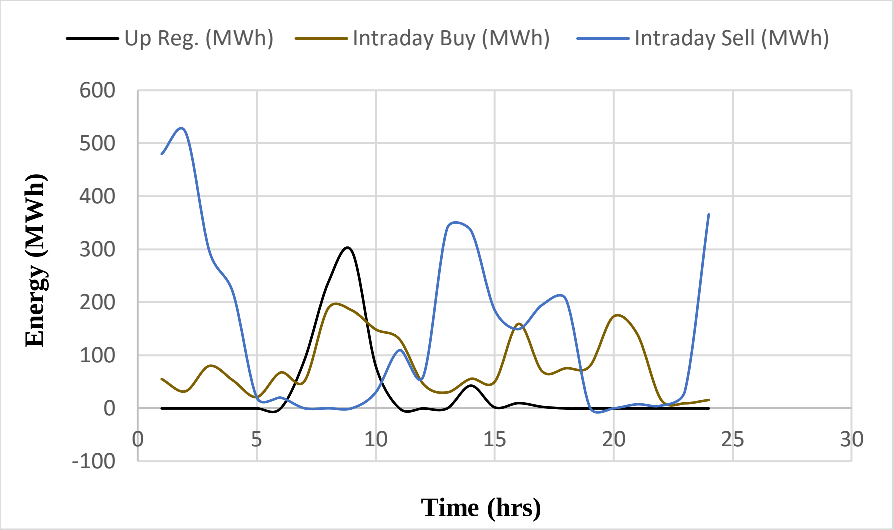


Figure29 Upward regulation bid in Denmark (14/04/2021)

Data source : Nord Pool [44][45]

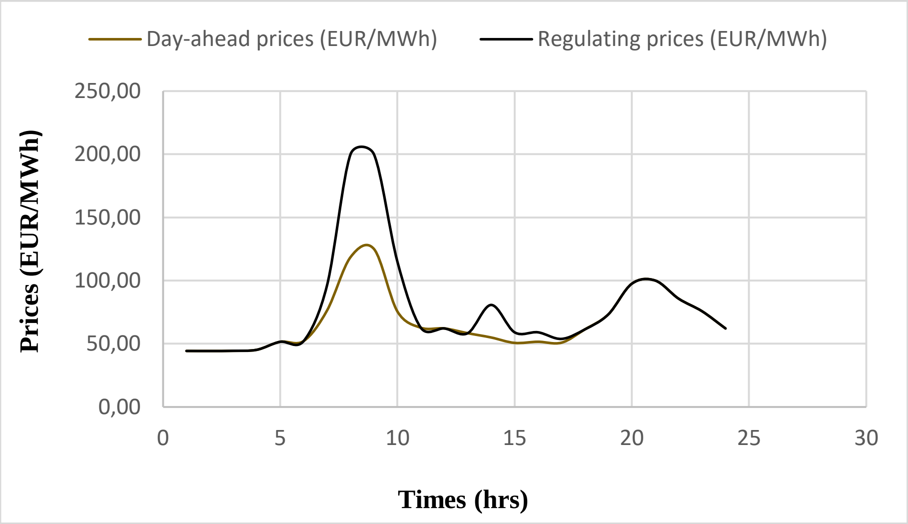


Figure 30 Day-ahead and regulating prices (14/04/2021)

Data source : Nord Pool [44][45]

Scenario3

Table 6.4 Nord Pool Intraday, Regulating bids, Regulating volumes and prices (18/4/2021)

18/4/2021	Nord Pool Intraday (MWh)		Regulating Bids (DK1) (MW)		Regulating Volumes (MWh)		Regulating Prices (EUR/MWh)	
Periods	Buy	Sell	Up	Down	Up	Down	Up	Down
00 - 01	54.0	50.0	903	1347	0	0	64.48	64.48
01 - 02.	71.5	122.8	944	1382	0	0	62.55	62.55
02 - 03.	59.0	50.0	1012	1286	0	0	62.17	62.17
03 - 04.	69.0	115.0	919	1376	68	0	62.23	62.10
04 - 05.	61.5	50.0	951	1291	0	0	61.02	61.02
05 - 06.	59.0	167.5	927	1326	41	0	60.7	60.57
06 - 07.	61.7	80.0	934	1355	0	0	60.54	60.54
07 - 08.	17.2	167.4	814	1487	0	-126	62.62	43.00
08 - 09.	94.5	285.7	757	1474	0	-74	64.52	45.00
09 - 10.	90.8	123.3	893	1302	0	0	63.57	63.57
10 - 11.	37.2	68.3	883	1223	0	0	59.91	59.91
11 - 12.	21,1	0.0	960	1053	0	-3	55.56	43.00
12 - 13.	65.2	20.0	981	1028	0	-49	55	38.00
13 - 14.	43.3	0.0	1181	830	0	-5	50.7	38.00
14 - 15.	43.8	0.0	1133	833	0	0	48.68	37.00
15 - 16.	29.0	0.0	1146	881	0	0	48.14	37.00
16 - 17.	52.8	100.0	1046	976	0	0	49.54	37.00
17 - 18.	37.8	0.0	872	1107	0	0	54.55	41.00
18 - 19.	89.7	255.6	600	1366	0	0	64.99	43.50
19 - 20.	4.0	0.0	536	1463	0	0	76.08	76.08
20 - 21.	35.7	32.0	502	1471	49	0	94.34	80.93
21- 22.	49.6	37.0	520	1522	52	0	94.13	79.17
22 - 23.	59.0	0.0	559	1476	0	0	72.88	72.88
23 - 00.	30.0	29.0	826	1153	0	-18	52.83	45.00

In this scenario**,** average price for wind production in Denmark is 61.38 (€/MWh), system price is 43.34 (€/MWh)

Energy market revenue (EMR)

Total energy dispatched during these higlighted periods (See coulumn for Nord Pool Intraday under Buy):

$$(69 + 59 + \ 35.7 + 49.6)\ \text{MWh} \ = \ 213.3\ \text{MWh}$$

$$\text{Energy market revenue (EMR)} = 213.3\text{MWh} * \ 43.34\left(\frac{€}{\text{MWh}}\right) \Rightarrow €\ 9244.422$$

Regulation Capability (RC) (See coulumn for Upward regulation bids)

$$\text{Power required for regulation (MW)} * \ \text{Regulation capability price} \ \left(\frac{€}{\text{MWh}}\right) * \text{Time (hr)}$$

$$919\ \text{MW} \ * 62.23\left(\frac{€}{\text{MWh}}\right) * 1\text{hr} \ \Rightarrow \ €\ 57189.37$$

$$927\ \mathrm{MW} * 60.7\left(\frac{€}{\mathrm{MWh}}\right) \Rightarrow €\ 56268.9$$

$$502\ \mathrm{MW} * 94.34\ \left(\frac{€}{\mathrm{MWh}}\right) * 1\mathrm{hr} \Rightarrow €\ 47358.68$$

$$520\ \mathrm{MW} *\ 94.13\ \left(\frac{€}{\mathrm{MWh}}\right) * 1(\mathrm{hr}) \Rightarrow\ €\ 48947.6$$

Regulation Performance (RP)

$$\text{Regulation volume(MWh)} * \text{System price}\left(\frac{€}{\mathrm{MWh}}\right)$$

$$(68 + 41 + 49 + 52)\ (\mathrm{MWh}) * 43.34\left(\frac{€}{\mathrm{MWh}}\right)\ \Rightarrow €\ 9101.4$$

Total revenue : € 9244.422 + € 209764.55 + € 9101.4 = € 228110.372

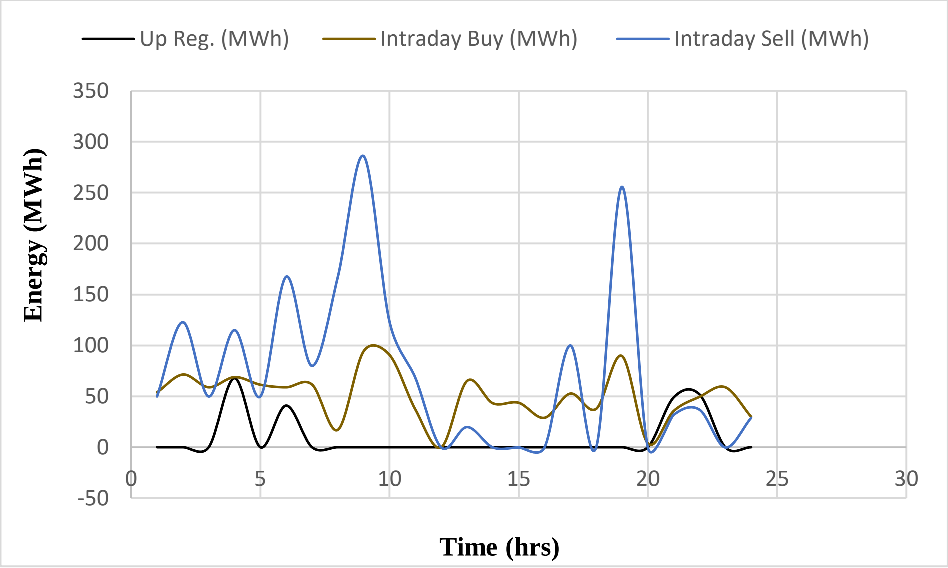


Figure31 Up regulation bid in Denmark (18/04/2021)

Data source : Nord Pool [44][45]

Scenario 4

In this scenario, we investigate the viability of SPHS using dataset for wind (onshore and offshore), solar and other energy systems in Denmark as hybrid operation.

Table 6.5 Regulating power, Balancing power prices (upward and downward regulation)

Data source: Energinet [55]

Hour TC	Hour DK	Regulating power-downward regulation	Regulating power-upward regulation	Balancing power price-up regulation (DKK)	Balancing power price-up regulation (EUR)	Balancing power price-down regulation(DKK)	Balancing power price-down regulation(EUR)	Price for balancing power for consumption (DKK)	Price for balancing power for consumption (EUR)
23:00 Z	1:00	0	72.8	5399.78	726.06	4090.41	550	5399.78	726.06
22:00 Z	0:00	0	0	4326.9	581.8	4326.9	581.8	4326.9	581.8
21:00Z	23:00	0	0	4462.19	599.99	4462.19	599.99	4462.19	599.99
20:00Z	22:00	0	0	4789.49	644	4789.49	644	4789.49	644
19:00Z	21:00	0	0	5271.64	708.83	5271.64	708.83	5271.64	708.83
18:00Z	20:00	0	146.5	6000.1	806.78	5734	771	6000.1	806.78
17:00Z	19:00	0	124	6024.05	810	5912.12	794.95	6024.05	810
16:00Z	18:00	0	0	5307.49	713.65	5307.49	713.65	5307.49	713.65
15:00Z	17:00	0	53.3	5000.04	672.31	4820.36	648.15	5000.04	672.31
14:00Z	16:00	-4.7	0	4495.21	604.43	3789.2	509.5	3789.2	509.5
13:00Z	15:00	-4.7	0	4259.82	572.78	3577.25	481	3577.25	481
12:00Z	14:00	-1.8	0	4088.99	549.81	3123.58	420	3123.58	420
11:00Z	13:00	0	0	3855.84	518.46	3855.84	518.46	3855.84	518.46
10:00Z	12:00	0	0	3857.7	518.71	3857.7	518.71	3857.7	518.71
09:00Z	11:00	0	0	4100.82	551.4	4100.82	551.4	4100.82	551.4
08:00Z	10:00	0	0	4566.45	614.01	4566.45	614.01	4566.45	614.01
07:00Z	9:00	0	58.8	5200.09	699.21	4760.49	640.1	5200.09	699.21
06:00Z	08:00	0	0	5057.23	680	5057.23	680	5057.23	680
05:00Z	7:00	0	0	4969.54	668.21	4969.54	668.21	4969.54	668.21
04:00Z	6:00	0	0	4670.13	627.95	4670.13	627.95	4670.13	627.95
03:00Z	5:00	0	59.8	5382.97	723.8	3949.25	531.02	5382.97	723.8
02:00Z	4:00	0	0	3743.24	503.32	3743.24	503.32	3743.24	503.32
01:00Z	3:00	0	0	3722.79	500.57	2818.66	379	2818.66	379
00:00Z	2:00	0	0	3770.61	507	2818.66	379	2818.66	379

Definition of terms

Regulating power – downward regulation: the actual amount of energy down-regulated

Regulating power – upward regulation: the actual amount of energy up-reglated.

Suppose the total revenue for this scenario is calculated thus:

$$\text{Total revenue} \Rightarrow$$

$$\text{Upward regulating power (MWh)} * \text{ Balancing power price} - \text{up regulation}\left(\frac{€}{\text{MWh}}\right) +$$

$$\text{Upward regulating power (MWh)} * \text{ Price for balancing power consumption } \left(\frac{€}{\text{MWh}}\right)$$

The focus here are the green spots beginning from upward regulation in third column (See Table 6.4)

(146.5 * 806.78) + (146.5 * 806.78) = € 236386.54

(124 * 810) + (124 * 810) = € 200880

(53.3 * 672.31) + (53.3* 672.31) = € 71668.246

(58.8 * 699.21) + (58.8 * 699.21) = € 82227.096

(59.8* 723.8) + (59.8* 723.8) = € 43283.24

Total revenue = € 634445.122

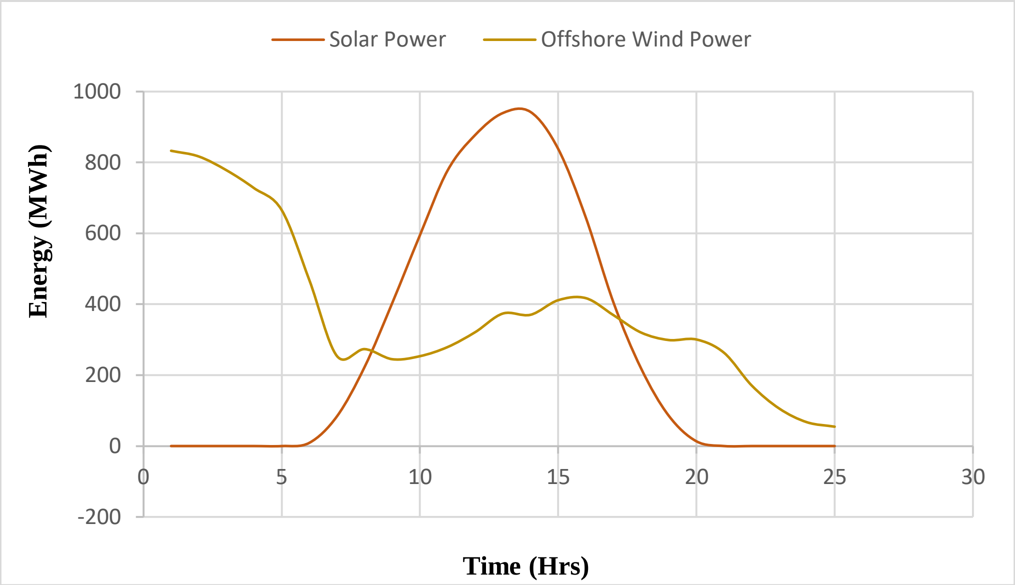


Figure32 Hybrid operation of wind and solar energy in Denmark

Data source : Energinet [54]

The data in this chart represents the overall balance of production of electricity in an area [54]. Other energy systems operational at the time of demand include Biomass, Fossil hard coal, Fossil oil, Hydro power, Other renewable, Waste etc. Data represents the overall balance of consumption, production, import and export of electricity in an area [54]. The figure shows the variation of energy from Onshore, offshore wind farms and solar PV system in Denmark on 23, August 2022 [54]. From Figure 31, between 5 a.m and 10 p.m, there is a sharp decline in offshore wind energy while the PV system increased simultaneously. In same vein, Figure 32 shows mismatch between balancing power price for upward regulation and price of balancing power for consumption the same day[55]. Due to frequency event, money was paid to balance energy deficit at the time of demand between 8:00 a.m and 14:00 pm.

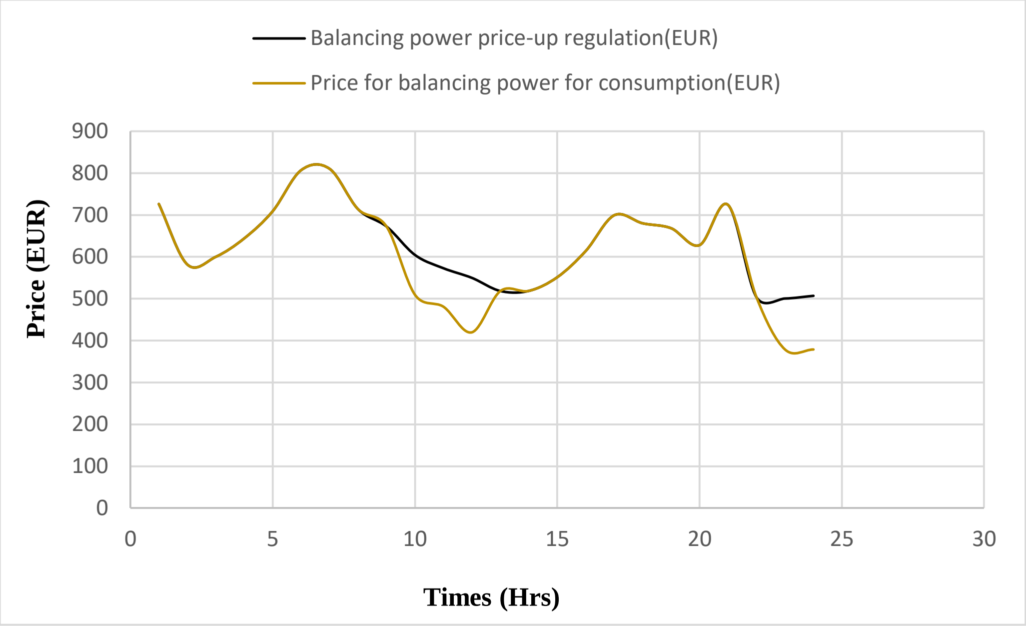


Figure 33 Price for balancing power for upward regulation and consumption

Data source : Energinet [55]

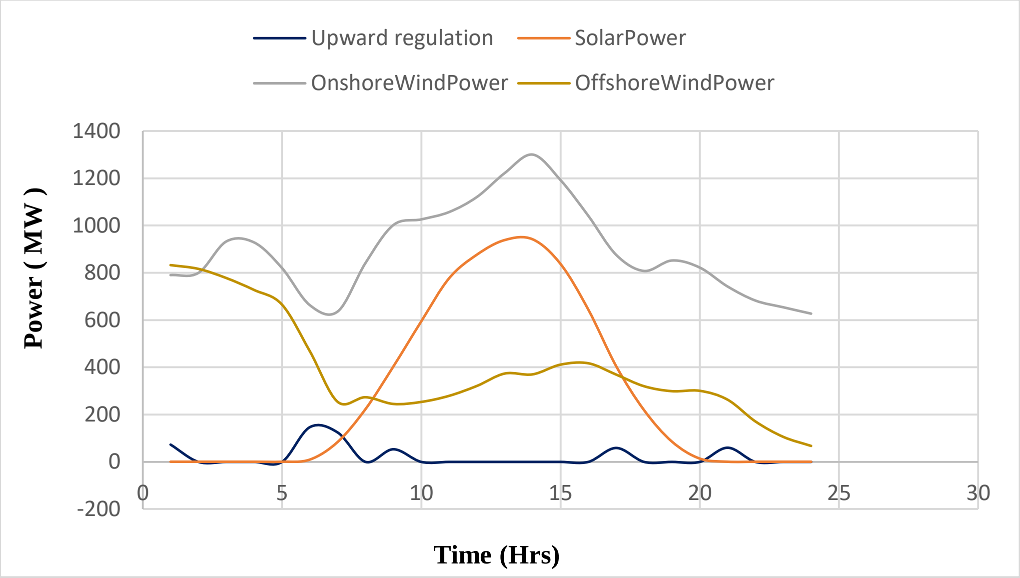


Figure 34 Regulated hybrid operation of wind and solar energy in Denmark

Data source : Energinet [54]

Calculate the number of SPHS required for frequency regulation

The energy dispatchable from one SPHS is 17 MWh (at 85% turbine efficiency) (See table 5.1). The total energy required for frequency regulation (upward regulation) from table 6.5 is:

(146.5 + 124 + 53.3 + 58.8 + 59.8) MWh = 442.4 MWh

Total number of storage system required for this scenario is 26.02. In case of contigencies, 28 SPHS will be sufficient.

CHAPTER 7

RESULTS AND DISCUSSION

This understaking investigates the feasibility of using subsea energy storage for balancing existing offshore wind farms in Denmark and also to expose the need for more innovations on this concept, especially, considering the numerous offshore wind turbines that will surround the on-going energy Island project in understudied location. Furthermore, with those scenarios studies and real-time data, it shows that it could participate in ancillary service for revenue generation.

Existing ground-mount PV system in selected location in Denmark has more energy yield than estimated floating PV system. Therefore, utilizing existing ground-mount PV system and CHP plant, most of which are sited in Zealand, is more cost-efective and capable of ramping up production capacity than installing new floating PV system. However, an optimization problem is created because hybrid power plant such as this has many constraints. Also, excess energy wind and solar can be utilized to fill the subsea energy storage system so that there is little need for diesel-generator and such concept will further reduce the carbon foot-print in Denmark.

Another important factor is the fact that one conventional PHS can be used to meet baseload and it can scale time for as long as weeks and months unlike SPHS. To this end, depending on demand and number of wind turbines, many SPHS per wind farm are required to achieve a utility scale storage capacity (MWh). So, an integrated system comprising all energy systems in Denmark plus SPHS is possible.

Considering scenario1, we can determine the number of SPHS required for ancillary services. For example, to calculate the number of SPHS needed for regulation capability with highest demand of 528 MW, several SPHS will be required unlike the conventional type of pumped hydro energy storage. Remember that megawatt for one SPHS is 17 MWh (20 MWh * 85%) (See table 5.1) so that 32 SPHS (approx) will be operational at the time of demand.

Similarly, Like the first scenario, to determine the number of SPHS needed for frequency event with regulation capability 516 MW (06 - 07a.m), several SPHS will be needed. Again, remember that megawatt-hour for one SPHS is approximately 17 MWh (at turbine efficiency of 85%) so that 30 SPHS (approx) will be operational in the sea to match the regulating bids for 1hr at the time of demand. In the same vein, for 30 mins (0.5 hr), 16 SPHS (approx) are required to match the same demand. Additionally, 18 SPHS are required to match the regulating volume 296 MWh between 08 - 09 a.m (See table 6.3), for instance, at the time of demand.

Figure 33 shows mismatch in prices during real time market. Maintaining balance between consumption and production in the electricity system and fulfilling contracts with e.g Sweden or Norway may require an up or down regulation of production and consumption in the Danish electricity system (east or west). To this end, a so-called regulating power is established as a common market for the Nordic countries. Market players who participate in the regulating power market forward their bids on how much capacity they can provide and what prices they require.

Figure 32 and 34 shows data representing the overall balance of consumption, production, import and export of electricity in the understudied location. Production is divided into main production types considering other energy systems as earlier discussed.Total number of storage system required for this scenario is 26.02. To avoid contigencies, 28 SPHS will be sufficient.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATION

Subsea energy storage is feasible in denmark and using load-forecasting and optimization strategy, it can be utilized for ancillary service in Nord Pool to generate revenue. Excess energy from wind and solar can help to charge it at low energy demand and then dispatched at peak demand. However, there are on-going research to improve its storage capacity and as shown in the analysis.

The goal of the modelling is to optimize the generation and transmission schedule on an hour by hour basis, so as to ensure good reliability while mimimizing supply cost. If not enough generation or transmission is scheduled, supply will not meet demand and if too much generation, and or transmission, is scheduled, more input energy to the power plant will be spent electrifying the grid than necessary possibly reducing grid reliability and for sure bringing about unnecessary wasted operation cost.

In conclusion, there are plants that need to be run in order to maintain system frequency and voltage requirements. The prices received by these plants when they need to run are regulated but the plants are dispatched even if these regulated prices are higher than those being offered by other plants. Similarly, higher cost plants may be dispatched to head off lower cost plants. If the higher cost plants have faster ramp rates and can be used to meet rising or falling demand more effectively than slower cost plants. So plant ramp rate in addition to the selling price for its available capacity also affects dispatch order.

REFERENCES

[1] Niels I. Meyer “Renewable energy policy in Denmark” Department of Civil Engineering, Technical University of Denmark, 2800 Lyngby, Denmark E-mail: nim@byg.dtu.dk

[2] Adam Jones (211163250) York University Prepared for ENVS 6599: Energy Storage in Denmark Submitted to Prof. Mark Winfield. Energy Transition in Denmark

[3] Mohd Mustafa et al. “Hybrid Renewable Power Generation for Modeling and Controlling the Battery Storage Photovoltaic System” Hindawi International Journal of Photoenergy Volume 2022, Article ID 9491808, 12 pages https://doi.org/10.1155/2022/9491808

[4] Salisu Muhammad Lawan et al. “A Review of Hybrid Renewable Energy Systems Based on Wind and Solar Energy: Modeling, Design and Optimization”

[5] Ajai Gupta “Modelling of hybrid energy systemdPart I: Problem formulation and model development” Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand 247667, India

[6] Peter Sorknæs et al. “Facilitating energy storage to allow high penetration of intermittent Renewable Energies” https://www.store-project.eu/documents/target-country-results/en_GB/energy-needs-in denmark-executive-summary

[7] The Danish Energy Agency Danish Energy Agency “The security of electricity supply in Denmark” Tel: +45 3392 6700, website: www.ens.dk/en

[8] Jiawei Wang “A review of Danish integrated multi-energy system flexibility options for high wind power penetration” Center for Electric Power and Energy, CEE, Department of Electrical Engineering, Technical University of Denmark, Copenhagen, Denmark Clean Energy, 2017, Vol. 1, No. 1, 23–35, doi: 10.1093/ce/zkx002 Advance Access Publication Date: 24 November 2017 Homepage: https://academic.oup.com/ce

[9] Claus Krog Ekman et al. “Prospects for large scale electricity storage in Denmark” Energy Conversion and Management 51 (2010) 1140–1147

[10] Henrik Lund et al. “Integrated Energy Systems and Local Energy Markets” Energy Policy 34 (2006) 1152–1160 www.elsevier.com/locate/enpol

[11] Henrik Lund (2005) “Electric grid stability and the design of sustainable energy systems, International Journal of Sustainable Energy”, 24:1, 45-54, DOI: 10.1080/14786450512331325910

[12] Georges Salgi “System behaviour of compressed-air energy-storage in Denmark with a high penetration of renewable energy sources” Applied Energy 85 (2008) 182–189 www.elsevier.com/locate/apenergy

[13] Parag Rajan Patil et al. “Energy System Modelling of Denmark Using OEMOF” HOCHSCHULE NORDHAUSEN FEBRUARY 2020

[14] Peng Houm et al. “Cooperation of Offshore Wind Farm with Battery Storage in Multiple Electricity Markets” Center of Electrical Engineering Technical University of Denmark Lyngby, Denmark

[15] Weihao Hu et al. “Optimal Operation Strategy of Battery Energy Storage System to Real-Time Electricity Price in Denmark” Student Member, IEEE, Zhe Chen, Senior Member, IEEE, and Birgitte Bak-Jensen, Member, IEEE

[16] John Almen and Johan Falk “Subsea Pumped Hydro Storage” (A Technology Assessment) Master’s Thesis within the Sustainable Energy Systems Programme Department of Energy and Environment Division of Energy Technology CHALMERS UNIVERSITY OF TECHNOLOGY Göteborg, Sweden 2013 Master’s Thesis T2013-387

[17] Alexander H. Slocum et al. “Ocean Renewable Energy Storage (ORES) System: Analysis of an Undersea Energy Storage Concept” Member IEEE

[18] Henning Hahn et al. “Techno-economic assessment of a subsea energy storage technology for power balancing services” Energy 133 (2017) 121e127 Fraunhofer Institute for Wind Energy and Energy System Technology (IWES), Division Energy Process Technology, Konigstor 59, D-34119, Kassel, Germany

[19] Brandi A. Antal. “Pumped Storage Hydropower: A Technical Review” B.S., University of Colorado – Boulder, 2004. In partial fulfilment of the requirements for the degree of Masters of Science in the area of Hydrologic and Hydraulic Engineering

[20] Traoré, A., Elgothamy, H. and Zohdy, M.A. (2018) Optimal Sizing of Solar/Wind Hybrid Off-Grid Microgrids Using an Enhanced Genetic Algorithm. Journal of Power and Energy Engineering, 6, 64-77. https://doi.org/10.4236/jpee.2018.65004

[21] Gea-Bermúdez, J., Das, K., Pade, L-L., Koivisto, M., & Kanellas, P. (2019). NSON-DK Day-Ahead market operation analysis in the North Sea region towards 2050. Technical University of Denmark.

[22] C.J Ponsioen “Selection and design of energy storage for the integration of offshore wind energy in the future Dutch electricity system”. Offshore Wind + Energy Storage http://repository.tudelft.nl/

[23] Energinet Report “Technical Issues Related to New Transmission Lines in Denmark” More information in ENTSO-E grid codes: https://www.entsoe.eu/network_codes/. West Coast Line from German border to Endrup and Endrup-Idomlund

[24] Peter Meibom, Klaus Baggesen Hilger, Henrik Madsen, and Dorthe Vinther “Energy Comes Together in Denmark” 1540-7977/13/$31.00©2013IEEE

[25] Laura Zepner, Pierre Karrasch, Felix Wiemann & Lars Bernard (2020) ClimateCharts.net – an interactive climate analysis web platform, International Journal of Digital Earth, DOI: 10.1080/17538947.2020.1829112

[26] PRAJWAL HONNANAYAKANAHALLI RAMAKRISHNA "Modelling, Simulation and Optimization of a submerged Renewable Storage System Integrated to a Floating Wind Farm" A feasibility case study on the Swedish side of the Baltic Sea, based on the geographical and wind conditions

[27] M. Puchta*, J. Bard, C. Dick, D. Hau, B. Krautkremer, F. Thalemann, H. Hahn "Development and testing of a novel offshore pumped storage concept for storing energy at sea-Stensea" http://dx.doi.org/10.1016/j.est.2017.06.004 2352-152X/© 2017 Published by Elsevier Ltd.

[28] MD Mehedi Hasan "Design 50MW large scale PV power plant considering Bangladeshi climate" ELEKTRO-MFE 21012 Thesis Master's 15 credits September 2021

[29] Solomon Netsanet (M.Sc.) Getnet Tadesse (M.Sc.) Ashamo Erengo (PhD) "A Study of Wind and Solar Resource Potentials for Hybrid Application in Wachemo University"

[30] Julie Charmasson, etal. "Roadmap for large-scale balancing and energy storage from Norwegian hydropower". Opportunities, challenges and needs until 2050.Centre for Environmental Design and Renewable Energy (CEDREN)

[31] Christer Ersdal Munthe "The likelihood of a Norwegian Pumped-Storage that can support intermittent Power dispatch from Solar and Wind" Master thesis in Energy, Environment and Society

[32] Viktoras Kulionis "The relationship between renewable energy consumption, CO2 emissions and economic growth in Denmark" viktoras.kulionis.563@student.lu.se. Lund University June 2013

[33] Md. Wahid Murad etal. "Dynamics of Technological Innovation, Energy Consumption, Energy Price and Economic Growth in Denmark" Publishedonline27 June2018in WileyOnlineLibrary (wileyonlinelibrary.com). DOI10.1002/ep.12905

[34] Gesine Bökenkamp "The Role of Norwegian Hydro Storage in Future Renewable Electricity Supply Systems in Germany: Analysis with a Simulation Model". A thesis submitted in fulfilment of the requirements for the degree of Dr. rer. pol.

[35] NHA National Hydropower Association "2018 Pumped Storage Report" https://www.hydro.org/wp-content/uploads/2018/04/2018-NHA-Pumped-Storage-Report.pdf

[36] International Hydropower Association; 2020 "Generation of hydropower in Europe in 2022, by country (Terawatt hours)". https://www.statista.com/statistics/690039/hydropower-generation-europe/Europe;

[37] Nord Pool Hydroreservoir. https://www.nordpoolgroup.com/en/Market-data1/Power-system-data/hydro-reservoir1/ALL/Hourly/?view=table

[38] International Hydropower Association; 2020 "Hydropower capacity in Norway from 2008 to 2021(in megawatts)" https://www.statista.com/statistics/864396/total-hydropower-capacity-in-norway/

[39] Lautec Esox "Weather downtown simulation tool". https://esox.lautec.com/

[40] Power system data (Wind power) https://www.nordpoolgroup.com/en/Market-data1/Power-system-data/Production1/Wind-Power/DK/Hourly2/?view=table

[41] J. Baptista1, 2, P. Vargas1 and J. R. Ferreira3 “A techno-economic analysis of floating photovoltaic systems, for southern European countries” https://doi.org/10.24084/repqj19.214 5

[42] Solar resource maps and GIS data for 200+ countries and regions. https://solargis.com/maps-and-gis-data/download/denmark. © 2020 The World Bank, Source: Global Solar Atlas 2.0, Solar resource data: Solargis.

[43] Afrika21 News on the Green Economy, the Environment and Sustainable Development in Africa. https://www.afrik21.africa/en/zimbabwe-solar-powered-pumped-hydroelectric-energy-storage-plant-by-ngonyezi/

[44]Volume of regulating bids (Nord Pool). https://www.nordpoolgroup.com/en/Market-data1/Regulating-Power1/Regulating-Volumes1/DK/Hourly/?view=table

[45] Volume of regulating bids (Nord Pool). https://www.nordpoolgroup.com/en/Market-data1/Regulating-Power1/Volume-of-Regulating-Power-Bids/

[46] E.C.M. Ruijgrok PhD et al. “Cost Evaluation of North Sea Offshore Wind Post 2030” On behalf of the North Sea Wind Power Hub Consortium. 4 February 2019. https://northseawindpowerhub.eu/sites/northseawindpowerhub.eu/files/media/document/Cost-Evaluation-of-North-Sea-Offshore-Wind-1.pdf

[47] Dr. Andreas Garg Christoph Lay Robert Füllmann “The feasibility of an Underwater Pumped Hydro” StenSea (Stored in the Sea)

[48] Wiebke Meesenburg “Heat pumps supplying district heating and ancillary services for the power system” DTU Mechanical Engineering, Nils Koppels Allé 403, 2800 Kgs. Lyngby, Denmark www.dtu.dk

[49] Fatih Karanfil and Yuanjing Li (2017). “The Role of Continuous Intraday Electricity Markets: The Integration of Large-Share Wind Power Generation in Denmark” The Energy Journal, Vol. 38, No. 2 (MARCH 2017), pp. 107-130. International Association for Energy Economics. https://www.jstor.org/stable/44203659

[50] Rashid Al Badwawi, Mohammad Abusara & Tapas Mallick (2015) A Review of Hybrid Solar PV and Wind Energy System, Smart Science, 3:3, 127-138. https://doi.org/10.1080/23080477.2015.11665647

[51] Elizabeth A. Unger, Gudmundur F. Ulfarsson, Sigurdur M. Gardarsson, Thorolfur Matthiasson, The effect of wind energy production on cross-border electricity pricing: The case of western Denmark in the Nord Pool market, Economic Analysis and Policy, Volume 58, 2018, Pages 121-130, ISSN 0313-5926, https: //doi.org/10.1016/j.eap.2018.01.006. (https://www.sciencedirect.com/science/article/pii/S0313592617302011)

[52] Henrik Lund. et al. (2013). System and market integration of wind power in Denmark,Energy Strategy Reviews, Volume 1, Issue 3,2013,Pages 143-156,ISSN 2211-467X,https://doi.org/10.1016/j.esr.2012.12.003.(https://www.sciencedirect.com/science/article/pii/S2211467X12000478)

[53] Brendan KirbyEric Hirst. “Real-Time Performance Metrics for Generators Providing the Regulation Ancillary Service” © 2001, Elsevier Science Inc., 1040-6190/01/$–see front matter PII S1040-6190(01)00185-3

[54] ENERGI DATA SERVICE. Electricity Balance Non-violated.

https://www.energidataservice.dk/tso-electricity/ElectricityBalanceNonv

[55] ENERGI DATA SERVICE Real-time market. https://www.energidataservice.dk/tso-electricity/RealtimeMarket