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Techno-economic Guidelines for Choosing between BESS and Gas Turbine

School of Technology and Innovations
Master's thesis in Science
Energy Technology

Vaasa 2021

UNIVERSITY OF VAASA
School of Technology and Innovation

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Title of the Thesis:	Techno-economic Guidelines for Choosing between BESS and Gas Turbine
Degree:	Masters of Energy Technology
Programme:	Energy Technology Programme
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Evaluator:	Professor Seppo Niemi
Year:	2021 **Pages:** 141

ABSTRACT:

Goal for the thesis was to find out if it is economically and technically possible for battery storage system (BESS) to replace gas turbine (GT) which is used for peak loads. Study was made for two different sizes of GTs (25MW and 104MW) and for four different sizes of BESS'(25MW/25MWh, 25MW/100MWh, 104MW/104MWh and 104MW/416MWh) in two different countries in Belgium and in Ireland. Study answers the questions: What services GT and BESS can offer? What are the annualized costs, net present value (NPV), internal rate of return (IRR) and payback for two different sizes of GTs in Belgium and in Ireland? What are the annualized costs, NPV, IRR and payback for four different sizes of BESS' in Belgium and in Ireland? What kind of services BESS can offer to make it profitable? What are the situations when BESS can/should replace GT or not? In which scenario it is economically and technically possible to replace GT with BESS? As the background for this study different types of GTs and storages were introduced, grid structure and applications were presented, and cost structure for BESS and GT and electricity markets were described. Data for study was collected from two existing gas turbines, researches, reports, literature, and public data sources. In Belgium, different system service markets and in Ireland, system service markets and intraday market were analyzed. Analysis for different markets in Belgium and in Ireland was conducted by a rule-based Excel model and the sensitivity analysis was conducted by BESS' capital expenditures and discount rates of 0% and 4%. Results of the study showed that it is technically possible for BESS to replace GT used for peak loads, except in one four hours' case where 104MW/104MWh BESS' capacity was exceeded. In Belgium it is economical invest in the 25MW/25MWh and the 25MW/100MWh BESS' if they are offering multiple services and investment prices are 450€/kWh, 350€/MWh or 200€/kWh. If multiple services are provided by 104MW/104MWh and 104MW/416MWh BESS' with the investment price of 200€/kWh, the investment is profitable. In Ireland, it is profitable to invest in 25MW/25MWh and 104MW/104MWh BESS' even with current prices with the help of the DS3 program. But when 25MW/100MWh and 104MW/416MWh BESS' participate in the DS3 program, prices go down and multiple services are provided, it is also profitable to invest in these storages.

KEYWORDS: Peak load generation, battery storage system, gas turbine, profitability

VAASAN YLIOPISTO
Tekniikan ja innovaatiojohtamisen yksikkö

Tekijä:	Viivi Ruotsala
Tutkielman nimi:	Huippukuorman tasaamiseen tarkoitetun akkuvaraston ja kaasuturbiinin teknistaloudellinen vertailu
Tutkinto:	Energiatekniikan Diplomi-insinööri
Oppiaine:	Energiatekniikka
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Työn arvioija:	Professori Seppo Niemi
Valmistumisvuosi:	2021 **Sivumäärä:** 141

TIIVISTELMÄ:
Diplomityön tarkoituksena oli selvittää, onko taloudellisesti ja teknisesti mahdollista korvata akkuvarastolla kaasuturbiini, jota käytetään huippukuorman tasaamiseen. Tutkimus tehtiin kahdelle erikokoiselle kaasuturbiinille (25 MW ja 104 MW) ja neljälle erikokoiselle akkuvarastolle (25 MW/25 MWh, 25 MW/100 MWh, 104 MW/104 MWh ja 104 MW/416 MWh) kahdessa eri maassa, Belgiassa ja Irlannissa.

Tutkimus vastaa kysymyksiin: Mitä palveluja kaasuturbiini ja akkuvarasto pystyvät tuottamaan? Mitkä ovat kaasuturbiinien vuotuiset kustannukset, nettonykyarvo (NPV), sisäinen korko (IRR) ja takaisinmaksuaika Belgiassa ja Irlannissa? Mitkä ovat akkuvarastojen vuotuiset kustannukset, NPV, IRR ja takaisinmaksuaika Belgiassa ja Irlannissa? Mitä palveluita akkuvaraston pitäisi tuottaa, jotta se olisi kannattava? Missä tilanteessa akkuvarasto voisi korvata kaasuturbiinin? Missä tilanteessa on taloudellisesti ja teknisesti mahdollista korvata kaasuturbiini akkuvarastolla?

Taustatiedoksi erilaisia kaasuturbiineja ja akkuvarastoja esiteltiin. Sähköverkon rakennetta ja sen sovelluksia kuvailtiin, samoin akkuvaraston ja kaasuturbiinin kulurakennetta ja edelleen sähkömarkkinoiden rakenteita.

Tutkimusta varten kerättiin materiaalia ja dataa kahdesta eri kaasuturbiinilaitoksesta, tutkimuksista, raporteista, kirjallisuudesta ja avoimista tietokannoista. Neljä eri Belgian tasepalvelua analysoitiin, Irlannin markkinoista neljä eri tasepalvelua ja päivittäinen markkina analysoitiin. Analyysit eri markkinoista tehtiin sääntöpohjaisella Excel mallilla. Herkkyysanalyysi toteutettiin akkuvarastojen investointihinnoilla ja 0 % ja 4 % diskonttokoroilla.

Tutkimuksen tuloksena todettiin, että teknisesti akkuvarasto pystyy korvaamaan kaasuturbiinin kaikissa muissa tilanteissa paitsi yhdessä 104 MW/104 MWh neljän tunnin jaksossa, jossa akkuvaraston kapasiteetti ylittyy. Taloudellisessa mielessä Belgiassa on kannattavaa investoida 25 MW/25 MWh ja 25 MW/100 MWh akkuvarastoihin, jos akkuvarastoa käytetään usean palvelun tuottamiseen ja investoinnin hinta on 450 €/kWh, 350 €/kWh tai 200 €/kWh. Investointi on myös kannattava 104 MW/104 MWh ja 104 MW/416 MWh akkuvarastoille, jos investointihinta on 200 €/kWh ja akkuvarastoa käytetään usean palvelun tarjoamiseen.

Irlannissa investoiminen 25 MW/25 MWh ja 104 MW/104 MWh akkuvarastoihin on jo nyt kannattavaa, jos akkuvarasto tuottaa useita palveluja ja osallistuu DS3-ohjelmaan. Kun akkujen hinnat tulevat lähemmäs arvoa 200 €/kWh ja akkuvarasto osallistuu DS3-ohjelmaan, myös 25 MW/100 MWh ja 104 MW/416 MWh akkuvarastoista tulee kannattavia sijoituksia.

Hakusanat: Huippukuorman tasaaminen, akkuvarasto, kaasuturbiini, kannattavuus

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Abbreviations

BESS	Battery energy storage system
BM	Balancing market/balancing mechanism
CAES	Compressed air energy storage
CER	Commission for Energy Regulation
CM	Capacity market
CMU	Capacity market unit
CRU	Commission for Regulation of Utilities
DAM	Day-ahead markets
Discos	Distribution companies
DoD	Depth of discharge
DRR	Dynamic reactive response
DS3	Delivering a Secure, Sustainable Electricity System program
ENTSO-E	European Network of Transmission System Operators for Electricity
FESS	Flywheel energy storage system
FFR	Fast frequency response
FPFAPR	Fast post-fault active power recovery
FTR	Financial transmission right
FWM	Foreward markets
Gencos	Generation companies
IDA	Intraday auction market
IDM	Intraday market
IEA	International Energy Agency
IPP	Independent power producer
IRR	Internal rate of return
I-SEM	Integrated Single Electricity Market
ISO	Independent system operator
ktoe	Kilotonns of oil equivalent
kW	Kilowatt
kWh	Kilowatt-hours
MCR	Minute or tertiary control reserve
MO	Market operator
MW	Megawatt
MWh	Megawatt-hours
NIEN	Northern Ireland Networks
NPV	Net present value
PCR	Primary control reserve
PHS	Pumped hydro storage
POR	Primary operating reserve
PV	Photo voltage
RM1	Ramping margin 1 hour
RM2	Ramping margin 2 hour
RM8	Ramping margin 8 hour
RRD	Replacement reserve (De-Synchronised)
RRS	Replacement reserve (Synchronised)

SCR	Secondary control reserve
SEM	Single Electricity Market
SEMO	Single Electricity Market Operator
SIR	Synchronous inertial response
SOR	Secondary operating reserve
SONI	System Operator of Northern Ireland
SRP	Steady-state reactive power
TOR1	Tertiary operating reserve 1
TOR2	Tertiary operating reserve 2
Transco	Transmission companies
TSO	Transmission system operator
UPS	Uninterrupted power supply
URegNI	Utility Regulator Northern Ireland

1 Introduction

Grid edge solutions are an important and growing part of electric utility networks. Grid edge solutions include new technologies such as battery energy storage and distributed generation. Deployment of these new technologies are challenging traditional, more centralized approaches for ensuring a stable grid with balanced supply and demand. Traditional centralized technologies, including large gas turbines for managing peak loads, are being replaced with these new grid edge solutions. This thesis will identify situations in which gas turbines could be replaced by battery energy storage systems (BESS). The study focus is on the economic impacts of these technical solutions.

Opportunities for BESS' have been studied for example in the field of peak shaving, in hybrid power plants, BESS combined with renewable energy production or BESS as a part of the micro grid. Studies about BESS replacing open cycle gas turbines (OCGT) as a peaker power plant are not common. However, closing the gas turbine power plants have already started for example in California which have opened new markets for BESS'. It is reasonable to anticipate this trend will continue as renewable generation increases, since current OCGT technology is not suitable for operating in grids with very high penetrations of renewables due to their technical limitations. Traditional generation such as OCGT have minimum operating power constraints that prevent electrical grids from operating 100% on renewable sources, even for short periods of time. BESS do not have these limitations. This context is important for the future, but the work presented here focuses on the business case for replacing OCGT with BESS today.

BESS have potential to replace many of the services from gas turbines, and BESS are already used worldwide to provide network and market services in utility networks. For example, Hitachi ABB Power Grids has installed base over 500MW worldwide of grid edge solutions. One of the biggest projects from Hitachi ABB Power Grids is the ESCRI-SA Dalrymple BESS ("ESCRI"), a 30MW/8MWh BESS in Australia. ESCRI is used for ancillary services in addition to offering black start, regulated network services, and for securing autonomous operation of local network . (Hitachi ABB Power Grids 2020).

The goal for the thesis was to generalize conditions under which it is an economic solution to choose BESS instead of a gas turbine, with a focus on capacity market and ancillary services. There are a range of additional network and behind-the-meter services that BESS can provide, but the thesis is focused on the market services. To achieve this, the study had to

1. Determine the services that are needed in the network and list them out.

2. Calculate the annualized cost, internal rate of return (IRR), net present value (NPV) and payback for new two different sizes of GTs both in Ireland's and Belgium's markets (based on the usage data from existing GTs, reports and researches made).

3. Analyze GTs' usage data and define situation where BESS could or should replace GT.

4. Calculate annualized cost, IRR, NPV and payback for four different sizes of BESS' in Ireland and Belgium by using data from researches, reports and usage data. In addition, the work had to make a proposal of what kind of services BESS can offer to make it profitable.

5. Make a summary of the scenarios in which it is economically and technically possible to replace GT with BESS.

A sensitivity analysis had also performed with BESS CAPEX and discount rates 0% and 4%.

Thesis consists of 10 chapters. After *Introduction* Chapter 2 presents working principle for two different types of gas turbines, simple-cycle and combined cycle.

In Chapter *3,* seven different types of storages: battery storages, hydrogen-based energy storages, pumped hydro storages, compressed air storages, flywheel, supercapacitor, and thermal storages are presented.

Chapter 4 presents storage locations in the different parts of the grid and the structure of power grids. Also, market applications for BESS is introduced.

Chapter 5 includes gas turbine and battery storage cost structures and equations for net present value, internal rate of return and payback period which are used for financial analysis.

Chapter 6 present the theoretical background for electricity markets. This section includes competition models, different market types, electricity market and ancillary service market.

Chapter 7 focuses on the presenting two different markets, their energy mix, market structure and model and other special features.

Chapter 8 includes data for calculations. In this section technical information, revenue streams and usage data for GTs and BESS' are presented. Additionally, market data and background for remunerations in two different markets are introduced. Excel models and sensitivity analysis for revenues in different markets are described.

Chapter 9 results from financial analysis is presented and analyzed. Financial analysis in conducted in two different markets for four different sizes of BESS' and two different sizes of GTs.

Chapter 10 summarizes the study, describes the results and proposals for future studies.

Chapter 11 is a summary of the study.

2 Gas turbines

While amount of renewable energy generation increases more flexible energy production is needed. Gas turbines are used worldwide for power generation for both base and peak load generation. There are different types of gas turbines and most common are simple cycle also known as open cycle, and combined cycle gas turbines which are used for flexible energy generation. (Welch, et al. 2015). In second section simple cycle's and combine cycle's features and functionalities are introduced.

2.1 Simple-cycle gas turbine

Simple-cycle gas turbines are used for power generation. Simple-cycle gas turbine consists of four main components: compressor, combustion chamber, turbine, and generator shown in the Figure 1. (Poullikkas 2009)

There are three main steps for energy production with gas turbines: air compression, combustion, and energy conversion. The process for producing electricity starts when air enters to the compressor which compresses the air to higher pressure and temperature. Air is not separately heated the compression causes the rise of the air temperature. (Poullikkas 2009)

Then the compressor air enters to the combustion chamber. At the combustion chamber injected fuel and air is mixed and combustion process occurs in constant pressure. Simple-cycle gas turbine's combustion system provides all necessary phases for combustion: mixing, burning, dilution and cooling. (Poullikkas 2009)

When combustion mixture exits from the combustion chamber it enters to the turbine where the combustion mixture expands, and gases is converted to mechanical energy. (Poullikkas 2009)

Modern gas turbines can offer high efficiency from 25% to 40%. About half of the total energy produced is used to run the generator and the compressor. One of the biggest energy losses is caused by hot (400-600 °C) exhaust gases which are not utilized in simple-cycle process. (Poullikkas 2009)

Even though the efficiency is quite poor, simple-cycle gas turbines are used for reserve power and for peak loads, because of their relatively cheap investment cost. Running the simple-cycle gas turbines is rather expensive but because they run occasionally operational cost stay in reasonable level. (Huhtinen, et al. 2013)

Simple-cycle gas turbines does not operate well with part loads which is major disadvantage for the simple-cycle gas turbine. For example, with 30% load simple-cycle gas turbine can reach only 50% efficiency of its nominal efficiency. With 50% load gas turbines efficiency is only 75% of its normal efficiency. There are solutions which can be used to reach better efficiency such as inter-cooling and recuperation. (Poullikkas 2009)

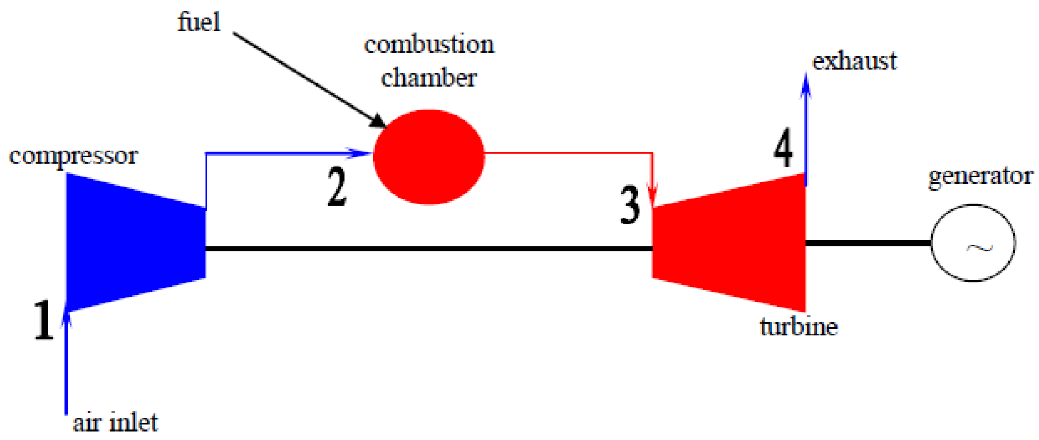

Figure 1. Simple Cycle Gas Turbine (Poullikkas 2009)

2.2 Combined cycle gas turbine

Combined cycle gas turbine consists of one or more gas turbines combined with steam turbine. Combined cycle gas turbine utilizes heat recovery from exhaust gas by producing steam to generate electricity. Efficiency for combined-cycle gas turbine which produces only electricity is 50%-58%. (Poullikkas 2009)

Simplest version of combined-cycle gas turbine consists of compressor, combustion chamber, turbine, heat recovery steam generator, steam turbine, condenser, feed water pump and two generators shown in the Figure 2. Compressor compresses the air which goes to combustion chamber. In combustion chamber injected fuel and air mixture burns. Heated air goes to the turbine, expands, and creates kinetic energy. Energy from the turbine goes to generator and transforms it to electricity. (Poullikkas 2009)

Hot exhaust gases go to heat recovery steam exchanger where hot exhaust gases heat up water in separate water circuit. Water converts to steam which runs the steam turbine. Kinetic energy from the steam turbine goes to generator which transforms steam to electricity. Hot steam from the steam turbines goes through condenser where the steam condensates to water. Condensate water is pumped back to heat recovery steam generator. (Poullikkas 2009)

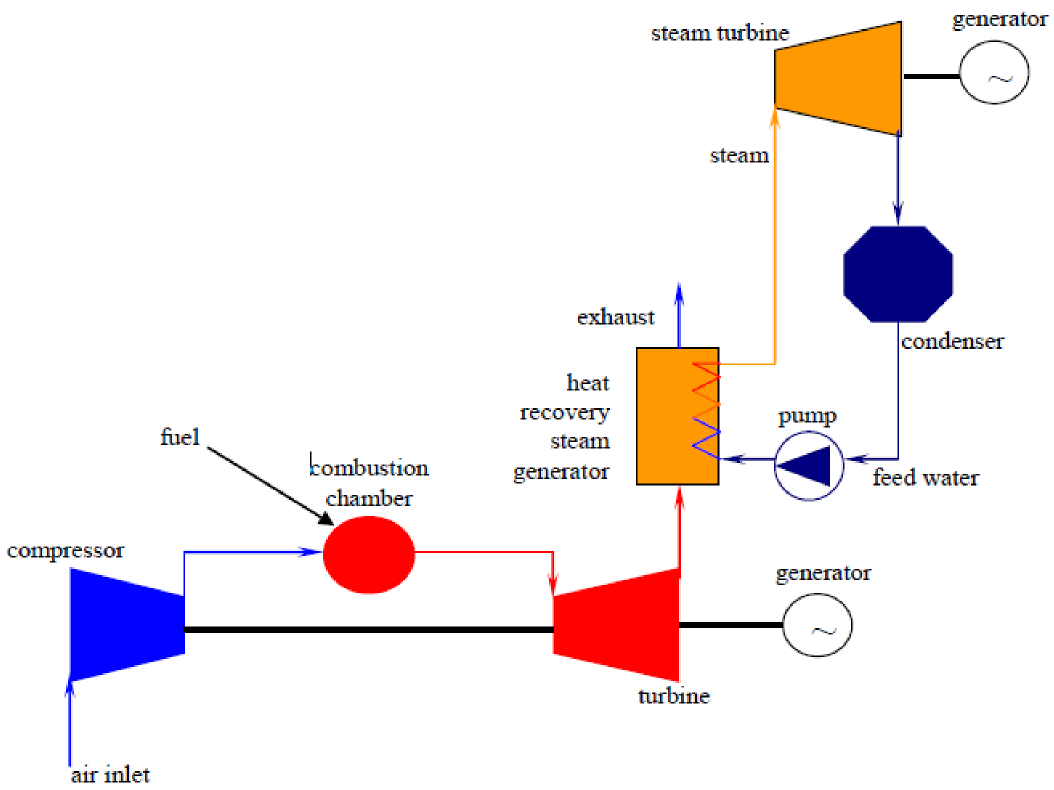

Figure 2. Combined cycle gas turbine (Poullikkas 2009)

In combined cycle gas turbines there are single, dual, or triple pressure heat recovery steam generators. Single pressure heat recovery steam generator produces 30% of the plant's output energy. By dual pressure heat recovery steam generator, the increase is 10% and by triple pressure heat recovery steam generator output energy production can reach up to 55%. (Poullikkas 2009)

There are several advantages in combined cycle gas turbine power plants such as high efficiency, low emissions (natural gas), low capital costs, short construction time and fast startup time. (Poullikkas 2009)

3 Energy storages

In third section different types of storages are introduced. There are several types of energy storages that can be grouped in four main categories electro-mechanical, electro-magnetic, electro-chemical and thermal storage shown in the Figure 3. In this section some example of each category is presented. (Sumper et al. 2016)

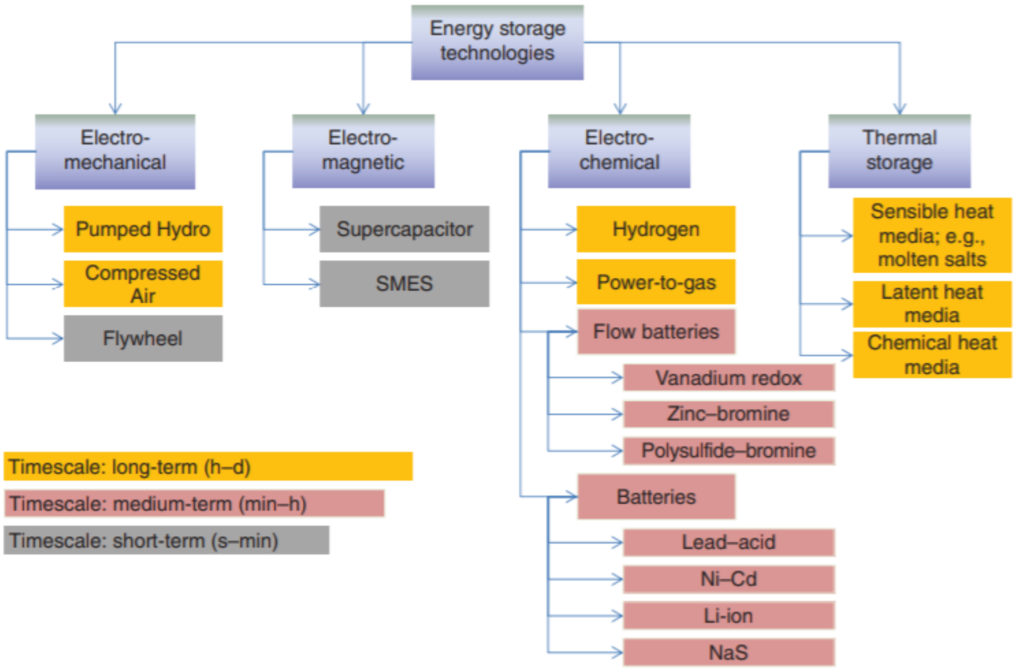

Figure 3. The catalog of storage technologies. (Sumper et al. 2016)

3.1 Battery energy storage systems

Grid-scale battery energy storage system (BESS) is an electrochemical device which is used to store excess energy from the power plant or the grid for later use. BESS is used to increase flexibility in the power system, for example to support renewable energy production. (Bowen et al. 2019)

There are several different types of battery technologies available for grid-scale BESS' such as lithium-ion and lead-acid batteries. Currently lithium-ion batteries are dominating the markets because the price for the grid-scale batteries have declined and due to technical innovations and improved manufacturing capacity. (Bowen et al. 2019)

BESS has several key characteristics which are used to describe functionalities and properties such as cycle life/lifetime, energy capacity, rated power capacity, round-trip efficiency, self-discharge, state of charge and storage duration.

- **Cycle life/lifetime** describes amount of charging and discharging cycles which BESS can provide before failure or major degradation.
- **Energy capacity** is maximum number of kilowatt-hours (kWh) or megawatt-hours (MWh) which BESS can store. (Bowen et al. 2019)
- **Rated power capacity** in kilowatts (kW) or megawatts (MW) is the maximum rate of discharge which BESS can offer when discharging is started from a fully charged rate or rated power capacity is total possible discharge capacity.
- **Round-trip efficiency** (percentage) is a ratio of the energy charged to the BESS to the energy discharged from the BESS.
- **Self-discharge** reduces energy from the BESS without being discharged by the customer or grid. Self-discharge occurs for example when battery is discharging itself by unwanted internal chemical reaction. Self-discharge is given as a percentage which describes the charge lost in a certain time period.
- **State of charge** have an influence on the BESS' ability to provide ancillary services or energy to the grid in all situations. It describes a percentage level of the charge of the BESS and it is calculated from present level of charge and range from completely discharge to fully charged.
- **Storage duration** describes the time the BESS can discharge at its power capacity before the energy capacity is depleting. Storage duration is presented in megawatt-hours (MWh). (Bowen et al. 2019)

BESS consists of battery, power management system (PMS) which controls protection circuits system (PCS) and battery management system (BMS). PCS converts AC/DC and it is used for power quality control. BESS structure in shown in the Figure 4. BMS is used to control and monitor batteries.

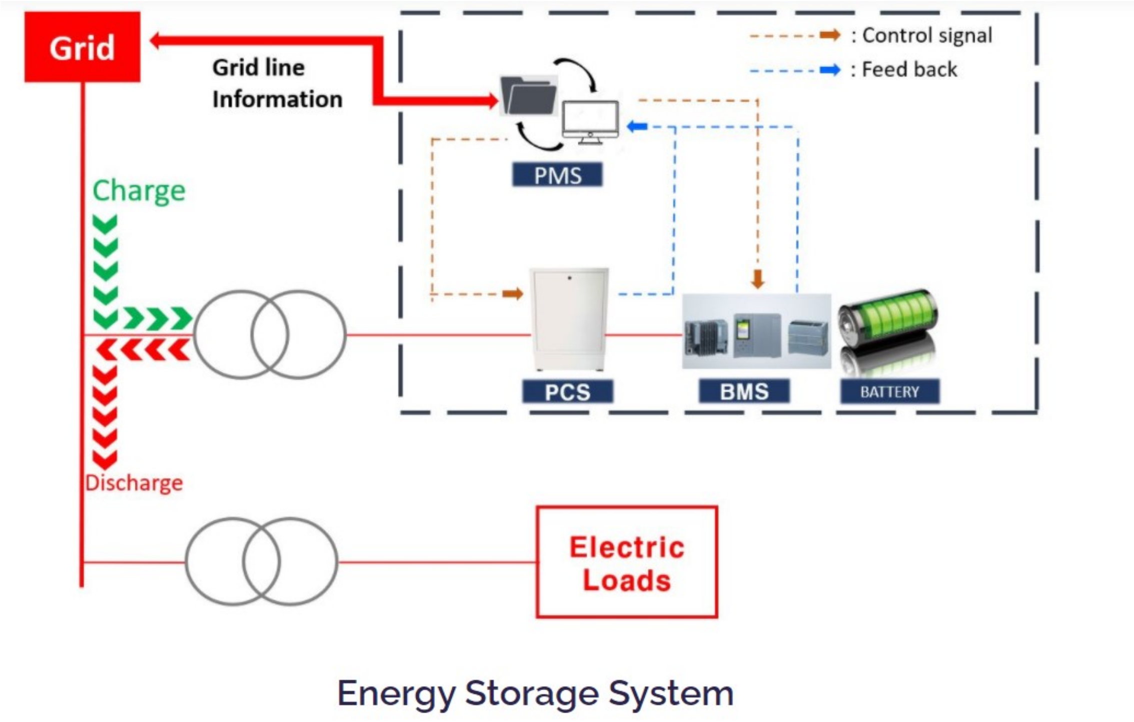

Figure 4 Structure of the BESS. (C&A Electric 2020)

3.1.1 Different types of batteries

Batteries are closed electrochemical storage systems that can perform a reversable conversion from chemical energy to electrical energy and from electrical energy to chemical energy. This operation can be performed with good efficiency, around 80-90%. (Rufer 2018)

Each battery consists of several cells installed either in parallel and/or in series. All the cells are packed into isolated and controlled container. Battery cell consists of electrodes, two pairs of electrochemically active substances, electrolyte, and separator. (Rufer 2018)

There are two types of electrodes: negative anodes and positive cathodes, which are usually made of different metals. Anodes captures electrons during oxidation reaction, and cathodes loses electrons during reduction reaction. (Sumper et al. 2016) During discharge, the cathode is positive terminal and anode is negative terminal. During charging situation is wise verse cathode is negative and anode is positive terminal. Operating principle is shown in the Figure 5. (Rufer 2018)

Electrolyte is solid or liquid substance which helps the two electrochemically active substances to keep electron balance during the redox reaction. Between anolyte and catholyte region there is electrical potential difference. Separator is needed to avoid internal short circuits by avoiding direct contact between the two regions. (Sumper et al. 2016)

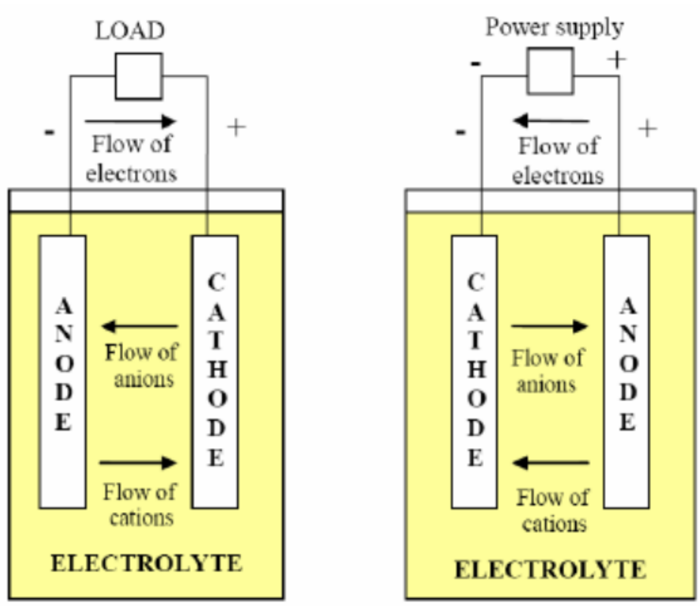

Figure 5 Chargeable battery diagram. (Poullikkas 2009)

Battery structure is made of cell that has two electrodes, which are surrounded by electrolyte. Anode negatively charged electrode is surrounded by electrochemically active substance and cathode positively charged electrode is surrounded by electrochemically active substance. These two pairs of electrochemically active substances have voltage difference. Voltage between the electrodes is maximum while battery is charged. In this state the battery has open-circuit voltage. (Sumper et al. 2016)

Electrical circuit is closed when external load is added. After closing the circuit, the battery is discharging. Electrons from the anode (negative electrode) moves to cathode (positive electrode). During this process electrical potential between two electrochemically activated substances is diminished. To charge the battery, external energy source is needed to restore the electrical potential difference between electrodes. (Sumper et al. 2016)

There are several types of batteries with different functionalities and features such as Lead-Acid, Nickel-Cadmium, Sodium-Sulphur, and Lithium-Ion batteries.

3.1.2 Lead-acid batteries

Lead-acid battery cells consists of several lead (Pb) plates that are set in parallel and immersed in electrolyte sulfuric acid (H_2SO_4). This type of batteries is widely used in non-stationary and stationary applications. Lead-acid batteries has technical problems while charging and discharging, such as sulfation and explosion risk due to hydro gas forming. Sulfation occurs when battery deprive during full-charge process and form sulfate crystals. This process decreases battery's capacity. Explosion risk is formed when charging voltage surpasses recommended level. Due to this process water in the electrolyte evaporate by forming flammable hydro gas. (Sumper et al. 2016)

Lead-acid batteries have poor cycle life only 200-1800 cycles, depending on for example temperature and depth of discharge (DoD). Its open-circuit voltage reaches up to 2.04 V. Lead-acid batteries have low power and energy densities and they need periodic water maintenance. Lead-acid batteries have important advantage which is low price (up to 270€/kWh). (Sumper et al. 2016)

3.1.3 Nickel-cadmium batteries

Nickel-cadmium (Ni-Cd) battery cells are made of nickel and cadmium hydroxide plates which are immersed in potassium hydroxide based alkaline solution. Ni-Cd batteries are used in general stationary and portable industrial applications. (Sumper et al. 2016)

Ni-Cd batteries have good cycle life from 3500 to 50 000 cycles at 10% DoD. Its open-circuit voltage is around 1.2 V. Ni-Cd batteries is low maintenance and have high ramp power rates. Ni-Cd batteries have three down sides, they are expensive, cadmium and nickel are toxic to humans and this type of batteries suffers from memory effect. Nickel and cadmium are toxic heavy metals which causes health risk to humans and EU has set 75% target in 2003 for recycling for this type of batteries. Memory effect occurs when battery is repeatedly recharged without it has been fully discharged. This causes sudden voltage drop in the cell and it is regarded as a capacity fade. Cost for Ni-Cd batteries are more than ten times compared to lead-acid batteries (Sumper et al. 2016)

3.1.4 Sodium-sulfur batteries

Sodium-sulfur (NaS) batteries have different structure than for example Ni-Cd and Lead-acid. NaS battery cell consists of electrodes which are in liquid form and electrolyte is in solid form and it acts also as a separator. Electrodes are surrounded by tube made of electrolyte. To get the electrodes to liquid state, high temperature (300-400°C) is needed. Since the cell reaction is exothermic the proper operating temperature is easy to maintain, and the needed input energy is low. For that reason, it does not affect substantially to batteries efficiency. (Sumper et al. 2016)

NaS batteries are used for stationary high-power applications. It is relatively new and promising technology with high specific power. Its open-circuit voltage is 2.075 V. NaS batteries advantages are low in self-discharge and in maintenance, it has almost 99% recyclability, energy density is 151 kWh/m^3 and it has high energy efficiency up to 85%.

Because of the structure, properties, and features of NaS batteries, they have relatively low capital costs compared to lead-acid batteries. NaS battery technology is new and for that reason it is constantly under research and development. There are some problems that reduces batteries lifetime, such as cracking of electrolytic tube and corrosion caused by sulfur. (Sumper et al. 2016)

3.1.5 Lithium-based batteries

Lithium-ion batteries consists of metal oxide cathode, carbon and lithium atom-based anode, organic electrolyte and polyethylene or polypropylene separators. Open-circuit voltage for lithium-ion batteries reaches up to 3.7 V. (Sumper et al. 2016)

Lithium-ion batteries are widely used for portable applications like electronic devises and mobile phones. This type of batteries are also promising alternative for buildings, renewable energy generation and electrical vehicles. Lithium-ion batteries have features and functionalities such as high specific energy 75-125 Wh/kg, high energy density 170-300 Wh/l and fast charging and discharging capability with high efficiency of 78%. (Sumper et al. 2016)

Challenges for lithium-ion batteries are narrow voltage and temperature range which is needed for proper operation. Lithium-ion batteries organic electrolytes are flammable which causes environmental and security risk. (Sumper et al. 2016)

3.2 Other energy storages

In addition to battery storages hydrogen based energy storage system, pumped hydro storage, compressed air energy storage, flywheel, supercapacitor and thermal storage are presented in this chapter.

3.2.1 Hydrogen based energy storage system

Hydrogen can be produced from several different sources such as fossil fuels, water, and biomass. After hydrogen have been produced it can be stored or transported through pipelines to electricity producers. Renewable energy sources can be used in a process where electrolyzers produce hydrogen. Hydrogen can be changed to electricity by using regenerative fuel cell production process. (Sumper et al. 2016)

3.2.2 Pumped hydro storage

Pumped hydro storage (PHS) is one of the electro-mechanical storages. Its power generation is based on gravitational potential energy of water. When there is excess electricity in the grid, water is pumped to upper reserve and when energy is needed water runs through turbine unit and generates electricity to the grid. The energy stored is depending on the height of the waterfall and upper reserve water volume. Operation principle is shown in the Figure 6. Lifetime for PHS is around 30-50 years and usually round-trip efficiency is 65-75%. (Sumper et al. 2016)

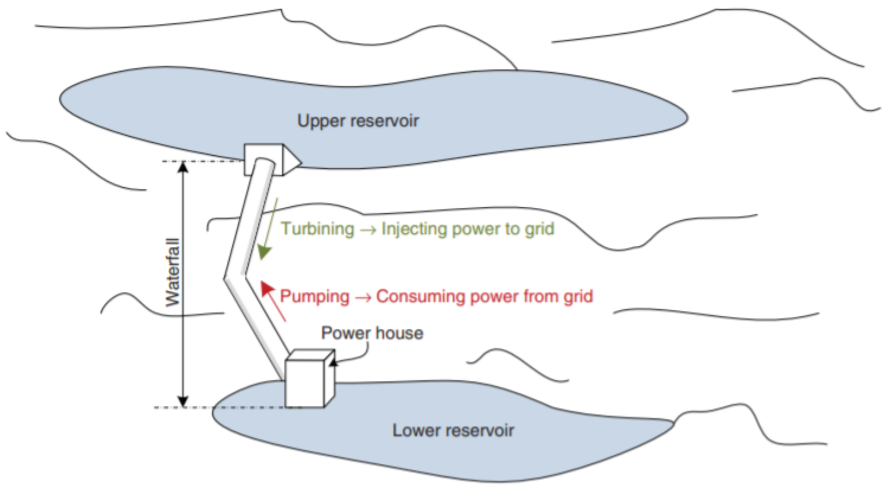

Figure 6. The operating principle of PHS. (Sumper et al. 2016)

3.2.3 Compressed air energy storage

Compressed air energy storage (CAES) is electro-mechanical storage system which is based on conventional gas turbine technology. There are several possible solutions for CAES and one of them is to store energy as compressed air in an underground storage cavern where the pressure is 40-70 bar and the temperature is near-ambient. The other option is to store the compressed air above-ground tanks. (Sumper et al. 2016)

When energy is needed compressed air is mixed with natural gas and combusted in the gas turbine unit which converts the combusted gas to rotational kinetic energy. After that kinetic energy is converted to electricity. Lifetime for CAES is approximately 40 years and energy efficiency is around 70%. (Sumper et al. 2016)

3.2.4 Flywheel energy storage system

Flywheel energy storage system (FESS) is also one of the electro-mechanical storages systems and it is based on kinetic energy in a rotating disk. Rotating disk is coupled with shaft of an electrical machine and when the machine accelerates energy is transferred to flywheel and it is stored as kinetic energy. Flywheel discharges when systems speed is reduced. (Sumper et al. 2016)

Efficiency for flywheel is around 90% and cycle life is up to 10^7 cycles. FESS have high energy and power density and it also have high ramp power rates. FESS have limitations because it can only be used as short-term storage applications and FESS is only able to absorb and inject power at full load for few minutes. (Sumper et al. 2016)

3.2.5 Supercapacitor energy storage

Supercapacitor is grouped under electro-magnetic energy storage technology. Supercapacitor consists of electrochemical cells which contains conductor electrodes, an electrolyte and membrane. Layout of supercapacitor seems similar than batteries but there is one major difference between those two because there is no chemical reaction in supercapacitor instead the energy is stored electrostatically in the cell. (Sumper et al. 2016)

Supercapacitors have high round-trip efficiency around 80% and they offer high ramp power rates, cyclability, specific power (W/kg) and power density (W/m^3). Supercapacitors have high self-discharge rates and in situations where high power and energy are needed supercapacitor offers limited applicability. (Sumper et al. 2016)

3.2.6 Thermal storages

There are number of different types of thermal storages which can be grouped under three categories: sensible heat media, latent heat media and chemical heat media. In sensible heat media thermal storage energy transfer mechanism is based on temperature variation. In latent heat media storage thermal energy is stored and released by material phase change process. Chemical heat media storage is based on exothermic chemical reaction in substance which is separated in two components. The process can be reversed by applying the heat. (Sumper et al. 2016)

4 Grid and applications

In the fourth section grid structure and different application to support and balance the grid in different situation are introduced. In order to achieve a functional and stable grid, the demand and supply need to be in balance. Frequency control is essential and the demand for it is increasing while renewable energy production increases. Storage systems offers alternative way for conventional power generation to frequency control. (Sumper et al. 2016)

4.1 Storage systems in the different parts grid

Grid balancing is needed in any point of time. To achieve grid balance demand and consumption must meet up. Supply and demand balancing of electricity is crucial for grid to operate properly. Grid does not have any storage capacity of its own but there are several options for grid balancing. When power is needed balancing can be done for example with demand-controlled biomass power generation, combined heat and power plant, flexible conventional power plant, or by discharging energy from storage system. If there is excess energy in the grid the balancing can be done by shutting down power generation, changing power to heat, gas or chemical energy, or by charging energy storage systems. (Moseley et al. 2014)

Storage systems and other solutions that are used for grid balancing can be classified by power markets, services they are providing and by the local operators of the storage systems. (Moseley et al. 2014)

Grid has different levels and different type of services for example local storage systems are in the low voltage grid, regional storage systems are in the medium voltage grid and centralize storages are in the transmission grid. Local and regional storages are relatively small and modular storages that can achieve large capacity by connecting several units. Storage solutions such as flywheel and battery need to be low maintenance and low in cost to compete with other type of storage solutions. Centralized storages such as pumped hydro power stations, also known as large-scale solutions, has high efficiency and capacity but low specific costs. (Moseley et al. 2014)

Local storage systems can provide same services than regional and centralized systems, but when small storage systems are used, they must be operated by intelligent controls and communication to be able to provide these services. Small scale storage systems can offer services that centralized storage systems are not able to provide for example uninterrupted power supply and to reduce grid loads in the grid. This kind of services can be used to support renewable energy productions such as wind or solar power generation. Large scale systems limitations could be for example transformers between the voltage levels which limits the power flow and in some cases transmission capacity could be limited. (Moseley et al. 2014)

4.2 Power grid

Role of storage systems in the future network is important. They play huge role to integrate renewable energy sources to the network. Power grid consists of transmission network and distribution network. (Moseley et al. 2014)

4.2.1 Transmission network

Transmissions systems are used to transfer large amount of energy from generation areas to load centers by using high-voltage levels which reduce energy loses. Transmissions systems are typically operated by 400 kV, 500 kV and 750 kV levels. Transmission networks have been built between countries and regions to reach system reliability and economic use of resources. (Moseley et al. 2014)

Integrating renewable energy production units to the transmission network, cause challenges. Wind and solar power are often produced in the areas where population density is low, and which causes long transmission distances. Variety in the energy production and allocated consumption causes technical constrains to transmission network. For example, thermal load of components and maximum energy load for transmission network can be exceeded. (Moseley et al. 2014)

4.2.2 Distribution network

Distribution network distributes the energy to the customer. Distribution network can be low voltage (< 1kV), medium voltage (1-36 kV) or high voltage (36 kV<). Network planning and operation ensures security aspects of the network such as sort-circuit limitation, thermal load of components and voltage level deviation. (Moseley et al. 2014)

Distribution network phases challenges caused by increasing use of renewable energy sources. Majority of installed renewable energy sources are installed in distribution network. Distributed energy production has changed the nature of the distribution network which causes challenges such as direction changes of the flow load. These changes can cause high current which can lead to high thermal load and exceed the limit of voltage deviation. (Moseley et al. 2014)

To extend the distribution network there are different options such as use of existing lines to construct parallel lines or adding transformers. Also, smart grid technology which consists of data management and communication between load, storage systems, generators and components can be used to extend the distribution network. Small scale storage systems are good addition to distribution network extensions because of their flexibility and controllability in voltage control with active and reactive power control. (Moseley et al. 2014)

4.3 Reserve power

There are four different stages of reserve qualities: instantaneous, primary, secondary, tertiary reserve, which have their own characteristics. (Moseley et al. 2014)

Instantaneous reserve is used when for example turbine is not able to replace immediately the power deficit between mechanical power input and network load. In this case kinetic energy of rotating masses such as flywheel compensate the lack of mechanical power. In this situation also BESS can be activated to provide almost instant electrical energy. (Moseley et al. 2014)

Primary reserve gets activated by decentralized speed controllers which reacts during frequency drop within several seconds. To achieve small and quick contribution from several power plants co-operation must work seamlessly. The frequency drop needs to be compensated as quickly as possible for example by increasing torque in turbines and using hydraulic and/or thermal storages. (Moseley et al. 2014)

Secondary reserve is activated in 3-5 minutes after primary reserve, by activating power plants for example by adding part load to thermal power plant and/or by activating hydro power plants. Power plants in secondary reserve are activated selectively, only in the affected subsystems. Primary reserve is deactivated after secondary level is activated. This ensures that primary reserve is available immediately when needed. (Moseley et al. 2014)

Tertiary reserve (long-time reserve) will replace the secondary reserve. Secondary reserve gives time to review economical load dispatch for tertiary reserve. Transmissions system operator ensures that right amount of energy is available to provide stable system operation. (Moseley et al. 2014)

These four different reserves are presented in the Figure 7 by network frequency and time.

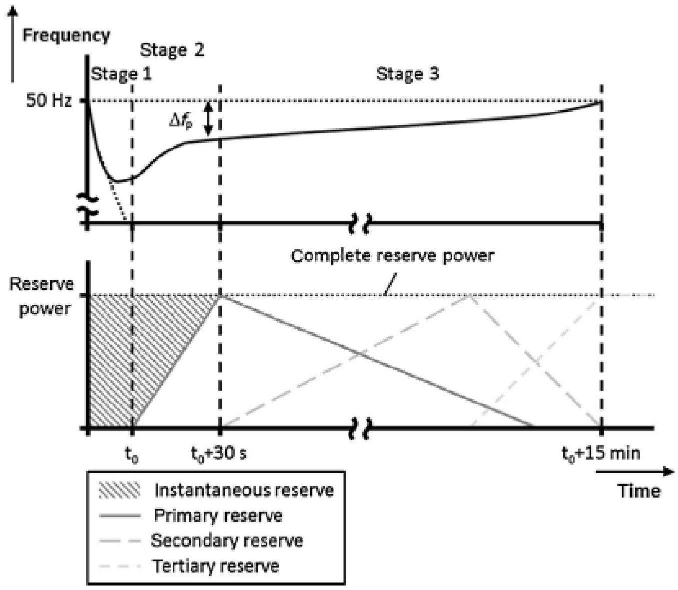

Figure 7. Fundamental network-frequency curve and reserve time domains. (Moseley et al. 2014)

4.4 Market applications for the battery storage systems

Battery storage systems can be used in different applications such as frequency control, self-supply, uninterruptible power supply, energy trading, peak shaving and in micro grids. Depending on application, market situation and sizes, services provided by BESS differs from each other. Multipurpose use of BESS' make them more profitable in the energy markets. (Moseley et al. 2014)

4.4.1 Frequency control

Frequency control is service that keeps supply and demand in balance. Frequency in Europe is 50 Hz and in US 60 Hz. The drop of frequency occurs when demand is higher than supply and rises when generation is higher than demand. Transmission system operator

(TSO) ensures that grid is stabile by activating and deactivating capacity, based on demand. Battery storage system or flexible power generation can be used as frequency control. (Moseley et al. 2014)

In many countries or regions power control markets are based on tenders in a public bidding process. European Network of Transmission System Operators for Electricity (ENTSO-E) controls frequency control power markets in Europe. There are three different markets for frequency control: Primary Control Reserve (PCR) which needs to be activated within 30 s, Secondary Control Reserve (SCR) which needs to be activated fully in 15 min and Minute or Tertiary Control Reserve (MCR) which is manually activated and MCR needs to run minimum 4 h after activation. (Moseley et al. 2014) Activation times for different reserves are presented in the Figure 8.

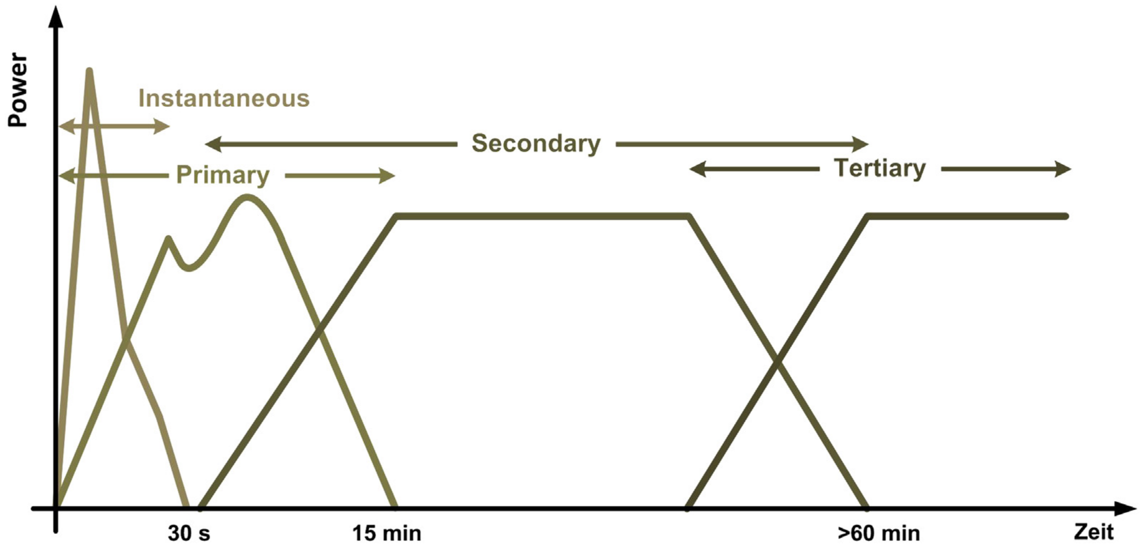

Figure 8. Activation times for different reserves. (Moseley et al. 2014)

4.4.2 Spinning reserve

Spinning reserve or instantaneous reserve is produced historically by thermal generation which provides physical resistance against frequency changes. Physical resistance is created by rotating masses which is part of the thermal power generation process. If energy is produced with system which do not have rotating masses or the mass rotation is too slow like in the wind power or PV-systems, the situation is different. These systems are connected to grid by converter which do not have inertia. Storage systems such as batteries with fast logic and quick respond time can provide instantaneous reserve also known as synthetic inertia. For these reasons converter-based solutions suits well together with the battery storage systems. (Moseley et al. 2014)

4.4.3 Primary control reserve

Primary control reserve (PCR) controls the systems frequency. It reacts automatically and it is provided as service by many different generation units. Frequency deviation in Europe is usually ±0.2 Hz from 50 Hz. (Moseley et al. 2014)

PCR markets are organized in some European countries by reserve auctions which are open for every supplier and works nondiscriminatory in a transparent way. In some countries, PCR markets are not public. In these countries TSO provides balancing services. Power plants are chosen as a part of PCR, based on generation capacity, location and power generated in the control area. (Moseley et al. 2014)

Battery storage systems can be used for frequency balancing. Electricity generation decreases by charging and increases by discharging the battery. Battery is connected to the grid by converter which balances voltage and frequency level, and changes direction and amplitude within milliseconds. (Moseley et al. 2014)

There are some concerns with the charging and discharging times because systems that are participating to PCR markets must be available all the time, ready to operate immediately, with agreed capacity and time. This issue has been considered and bidding markets will face changes which supports battery use as PCR. (Moseley et al. 2014) Other question related battery storage systems especially decentralized storage systems is that, should battery storage system owners need to pay taxes, dues, and grid fees for charging the batteries or should they be released from these burdens? (Moseley et al. 2014)

Technical challenge for battery storage systems is for example lifetime expectance which relates closely to operational conditions. However, battery storages have advantages that conventional power plant does not have for example, conventional power plant will face higher production cost if the power plant operates below their maximum rating. Another problem is that power plant is not able to refinance themselves only offering PCR services. While renewable energy production increases, that will narrow the markets from power plants so that renewable energy production combined with batteries will have good opportunity to participate to PCR markets. (Moseley et al. 2014)

4.4.4 Secondary control reserve

Secondary control reserve (SCR) is second step in the frequency control that compensates fluctuation of the load from a few minutes to several hours. Only prequalified and dedicated generation unit can provide SCR services. (Moseley et al. 2014)

Battery storage systems cannot compete directly whit conventional power generation in SCR markets. Battery storage systems do not have endless fuel supply like power plants and battery storage systems needs huge capacity to reach the demanded level. To get more capacity to battery storages is expensive and still there might be situations when battery storages are not able to meet the demands that are set for SCR. For these reasons battery storage systems are not the best solution in the SCR markets. (Moseley et al. 2014)

4.4.5 Tertiary control reserve

Tertiary control reserve (MCR) is third level of the frequency control reserve which is activated within 15 min and used maximum 4 hours at the time. MCR are paid services that are provided by prequalified and dedicated generation units. Activation of the units happens by request. (Moseley et al. 2014)

Minute reserve do not have ramp up requirements which opens the markets for conventional power generation plants. There is more competition in MCR markets because of increase of renewable energy production there are more conventional power generation units available in this sector. For these reasons and due to the same limitations of battery storage systems mentioned in SCR markets, makes it hard for battery storage systems to penetrate to these markets. (Moseley et al. 2014)

4.4.6 Uninterrupted power supply

Uninterrupted power supply (UPS) is one of the largest markets for the battery storage systems. UPS systems are used for example in data centers, hospitals, telecommunication systems, and production facilities where it is critical to avoid power interruptions. Depending of protected application UPS system needs to work even with in milliseconds. BESS suits well for UPS systems because they have ability to provide almost instant backup power. In some applications batteries are connected to other power source like diesel generator. (Moseley et al. 2014)

In UPS applications batteries are usually fully charged most of the time and discharged during disturbance. In Europe need for USP systems varies from 20 minutes to few hours per year but in some other countries where electricity grids are unstable, the need for UPS is daily. Disturbance of the power grids can be short-term interruptions from millisecond to few seconds or long-term interruptions from several seconds to several hours.

Usually batteries that are used as UPS systems are used from milliseconds to certain period. This type of applications give time for other backup systems to start or protected system to shut down safely. (Moseley et al. 2014)

Lead-acid batteries have minimal aging at maximal charge, and they have simple structure which makes them good candidate for UPS system. Lithium-ion batteries have also potential features for USP solution especially when bridging time is below 15-30 minutes and space for battery storage is limited. (Moseley et al. 2014)

4.4.7 Peak shaving

Constant power consumption is much cheaper than irregular power consumption because energy production costs for peak power plants are much higher than for base load power plants. Peak demand requires also more grid capacity and power generation which increase the costs. To lower the costs for peak consumption the volatility of the load needs to be smoothed which can be done either by storage systems or by demand side management. Peak shaving model for BESS is based on selling energy during peaks when the price is high and charging by buying energy when the price is low.
(Moseley et al. 2014)

4.4.8 Other application and markets

There are also other markets for battery storages such as island grids, micro grids, stabilizing conventional generation, and ancillary services. One of the benefits for battery storages systems is that they can be used for multiple purposes. (Moseley et al. 2014)

Island grids are usually located places such as islands, and rural areas where there is no connection to the main grid and for that reason, they are not able to participate to the electricity markets. All power generation is produced locally which is rather expensive.

In this kind of solutions battery storages can offer multiple services such as UPS and frequency control at once and lower the cost for electricity production. (Moseley et al. 2014)

Micro grid is small grid which consists for example of battery storage system, gas turbine and PV-generator. Micro grid has connection to the main grid, but it can work independently for example during major disturbance situations in the main grid. Storage systems can lower the costs and offer multiple services such as UPS, frequency control and peak shaving. (Moseley et al. 2014)

Battery storage system is great addition to conventional power generation which have limited flexibility. Batteries can be used to smoothing the load gradient which prevents the wear of thermal generation unit and if the battery is located at the same site with the power generation unit no extra grid connection is required. (Moseley et al. 2014)

Batteries can be used as ancillary services such as black start, reactive power, and voltage control. These services alone are not able to provide enough revenues to make battery services profitable. But if these services are combined with other services it is possible to make the storage system profitable. (Moseley et al. 2014)

Battery storage system can also be used for smoothing the load gradient whit renewable energy production. In this case battery is located at the renewable energy production site and it is connected to the grid through the inverter and for that reason new grid connection is not needed. (Moseley et al. 2014)

5 Cost structures and economic analysis

In the Chapter 5 cost structure for GT and BESS are introduced. Economic analysis payback, net present value (NPV) and internal rate of return (IRR) is introduced in this section. These analyses are used to describe if the energy project is profitable or not.

5.1 Gas turbine cost structure

Cost structure for GT consists of capital costs (CAPEX), variable costs, fixed operational and management (O&M) costs, efficiency, and amount of full operational hours.

Capital costs consists of costs such as gas turbine, procurement, construction services, engineering, land, spare parts, grid connection, project management and project development. (Duffy et al. 2015)

Operational costs consist of fixed and variable costs. Fixed costs include costs such as cost of capital, fixed operational and management costs, and size of fuel storage. Variable costs include costs such as fuel and unexpected repair costs. (Huhtinen, et al. 2013)

5.2 Battery storage cost structure

BESS cost structure consists mainly from CAPEX, O&M, and replacement costs. CAPEX includes battery storage system and construction costs. O&M costs consists of fixed operating and maintenance costs and variable costs includes costs such as purchased electricity. Replacement costs includes battery replacement costs. (Sumper, A. 2016)

5.3 Financial analysis

Energy projects are usually long-term projects which are costly and nearly impossible to reverse. For investors energy projects have high up-front costs and the projects are long-lived so it is crucial to have proper financial analysis to support the investors to make strategically reasonable decisions. (Duffy et al. 2015)

Financial analysis consists of several different financial metrics such as net present value (NPV), internal rate of return (IRR) and payback period (PP). These metrics are used to analyze the viability of the energy project. (Duffy et al. 2015)

Every project has several viewpoint depending on which perspective are used to perform the financial analysis. It is necessary to underline difference between public and private viewpoints. Usually financial analysis focuses on private perspective which aim is to maximize the value to the firm and its stakeholders. Public perspective which are external to the company might be ignored while private sector project costs are analyzed. However public sector considers factors such as environment, health, education, and income which causes costs for the projects. Public sector viewpoints should be considered as a part of the analysis when financial analysis is conducted. (Duffy et al. 2015)

5.3.1 Net present value

NPV is used as an indicator for the project's financial potential. (Kodukula 2006) It presents the difference between the present value of cash flow and present value of cash outflow during certain period of time. (Investopedia 2020)

NPV uses discount rate element which takes into account that money in the present is worth more than same amount in the future because of earnings from alternative investment and possible inflation. (Investopedia 2020)

To perform the calculations cash flows, number of time periods and discount rate need to be identified. NPV calculations is based on many estimations and assumptions which give room for error but still NPV calculations are widely used to evaluate investments and projects. (Investopedia 2020)

If NPV is positive project is worthy to invest and higher NPV makes the project more attractive for investors. (Kodukula 2006) If the NPV is negative the investment will result a net loss and it is not a good investment. (Investopedia 2020)

Formula for calculating NPV is presented in Equation 1. Net Present value. where

R_T = Net revenue during a single time period

i=Discount rate

t=Number of time period

$$NPV = \sum_{t=1}^{n} \left(\frac{R_t}{(1+i)^t} \right) \quad (1)$$

Equation 1. Net Present value. (Investopedia 2020)

5.3.2 Internal rate of return

IRR is a metric that is used to analyze profitability of investment. IRR is discount rate which makes the NPV cash flows equal to zero. IRR is calculated with same concept than NPV. It describes the annual rate of growth that is expected from the investment. The investment is more desirable when IRR is high. IRR is hard to calculate manually so it is often calculated for example by Excel. (Investopedia 2020)

Formula for calculating IRR is presented in Equation 2. Internal rate of return. (Investopedia 2020) where

C_t=Net cash flow during the time period

C_0=Total initial investment costs

IRR=The internal rate of return

t=The number of time period

$$0 = NPV = \sum_{t=1}^{T} \frac{C_t}{(1 + IRR)^t} - C_0 \quad (2)$$

Equation 2. Internal rate of return. (Investopedia 2020)

5.3.3 Payback period

Payback period method is used to calculate how long time it takes to repay the original investment. This method is widely used because it easily express is the investment profitable or not. Shorter payback period makes investment more attractive for investors. Limitation for this method is that it does not take into account time value of the money. For this reason, there is greater possibility for inaccuracy when long term investment is calculated. (Kodukula 2006)

Payback period formula for calculating simple payback period is presented in Equation 3. Simple payback period. . Payback is expressed in years T. *Initial capital costs* is expressed in € and *annual net revenues* is expressed €/year.

$$T = \frac{Initial\ capital\ costs}{Annual\ net\ revenues} \quad (3)$$

Equation 3. Simple payback period. (Tester et al. 2012)

6 Electricity market structure

Electricity markets consists of several functions such as vertically integrated utilities, generating companies (gencos), distribution companies (discos), retailers, market operator (MO), independent system operator (ISO), transmission companies (transco), regulator, small consumers, and large consumers. All the functions have its own role in electricity market. (Kirschen et al. 2004)

Gencos can own one or several power plants which sell and produce energy and/or services such as reserve, voltage control and regulation. Generation company can operate independently outside the traditional monopoly. In some cases, this type of power plants is called independent power producers (IPP) (Kirschen et al. 2004)

Discos operates and owns distribution network. Traditionally discos have monopoly where they sell electricity to consumers which are connected to their network. In deregulated environment distribution network development, operation and maintenance is decoupled from the energy sale for the customers. Retailers are competing with each other to perform energy sale. (Kirschen et al. 2004)

Retailers participates to the wholesale market by buying and reselling electrical energy to consumers which are not allowed or don’t want to participate in wholesale market. Retailers do not need to own distribution, or generation assets. (Kirschen et al. 2004)

MO matches the bids and offers made by buyers and electrical energy sellers. It accepts bids and offers and ensures that seller gets payment and buyer gets electricity which they have purchased. (Kirschen et al. 2004)

ISO usually just monitors and controls the power system. Its main role is to maintain the security power system. (Kirschen et al. 2004)

Transcos operate the transmission system by the instruction given by ISO. Transcos owns assets such as transformers, transmission lines, and cables. (Kirschen et al. 2004)

Regulator is the governmental body which ensures efficient and fair operation in energy sector by approving and determining rules for electricity markets. Prices for services and products provided by monopolies are also set by regulator. (Kirschen et al. 2004)

Small consumers by electricity via retailer and large consumers participates to the markets by buying electricity directly from the market. (Kirschen et al. 2004)

6.1 Competition models

In this chapter four different types of competition models are presented: monopoly, purchasing agency, wholesale competition and retail competition.

6.1.1 Monopoly

In a monopoly model there are two different types of sub models. In the first model utility integrates all functions generation, transmission, and distribution to one monopoly. In the other sub model generation and transmission is managed by one utility. Distribution network is owned by local monopoly which buys electricity from the utility. (Kirschen et al. 2004)

6.1.2 Purchasing agency

In first purchasing agency sub model integrated utility does not own all the generation capacity. Utility agency acts as a purchasing agent and buys the energy from IPPs which are connected to the network. In the second sub model utility does not own any generation capacity. Instead it purchases all the energy from IPPs. Retail and distribution activities are also separated. Discos purchases the energy from wholesale purchasing agency and sell it to consumers. Purchasing agency has monopoly towards IPPs and discos and for that reason they are regulated. (Kirschen et al. 2004) Integrated and disaggregated purchase models are presented in the Figure 9.

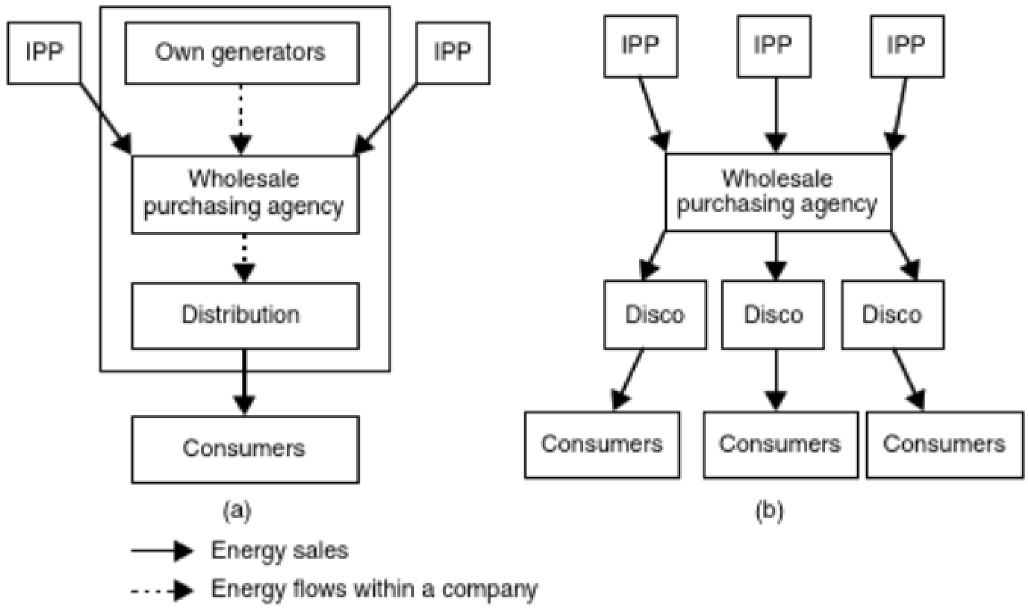

Figure 9. Purchasing agency model of electricity market (a) integrated version, (b) disaggregated version. (Kirschen et al. 2004)

6.1.3 Wholesale competition

In the wholesale competition model generation companies sell energy to the disco and consumers buys their electricity directly from them in the wholesale electricity market. Large consumers can buy electricity from wholesale market. Transmission network and the spot market are the only functions which remains centralized in wholesale market. At the retail level system is centralized because discos operate in the distribution network in several area and purchase electricity for customers in its service territory. This model is more competitive for generation companies because retail price is determined by supply and demand and for that reason retail electricity price is regulated. (Kirschen et al. 2004) Wholesale competition model is presented in Figure 10.

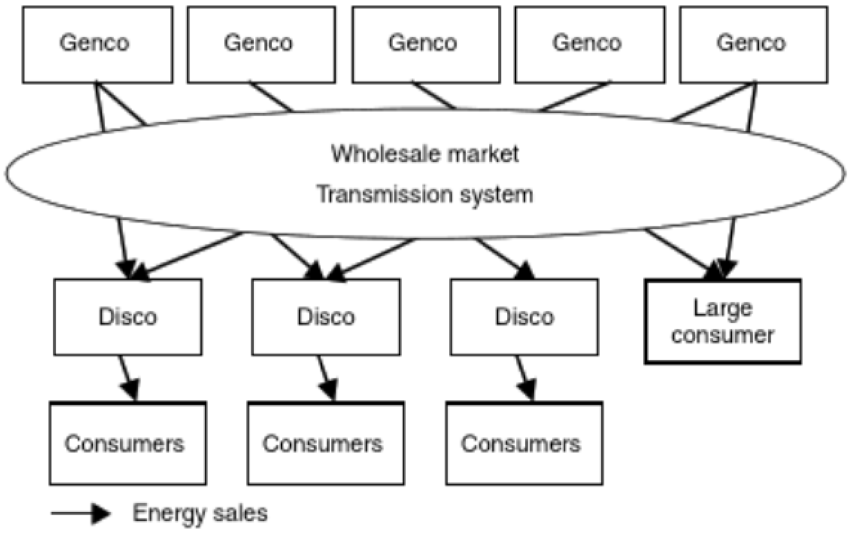

Figure 10. Wholesale competition model of electricity market. (Kirschen et al. 2004)

6.1.4 Retail competition

Retail competition model is the most competitive electricity market model. In this model consumers can choose their supplier. Small and medium consumers buy electricity from retailers, but large consumers can buy electricity also from wholesale market. Regulation in the retail price is not needed because consumers can change their retailers freely. Only transmission and distribution network provision and operation stay as monopoly and for that reason transmission and distribution network charges are regulated. (Kirschen et al. 2004) Retail competition model is presented in Figure 11.

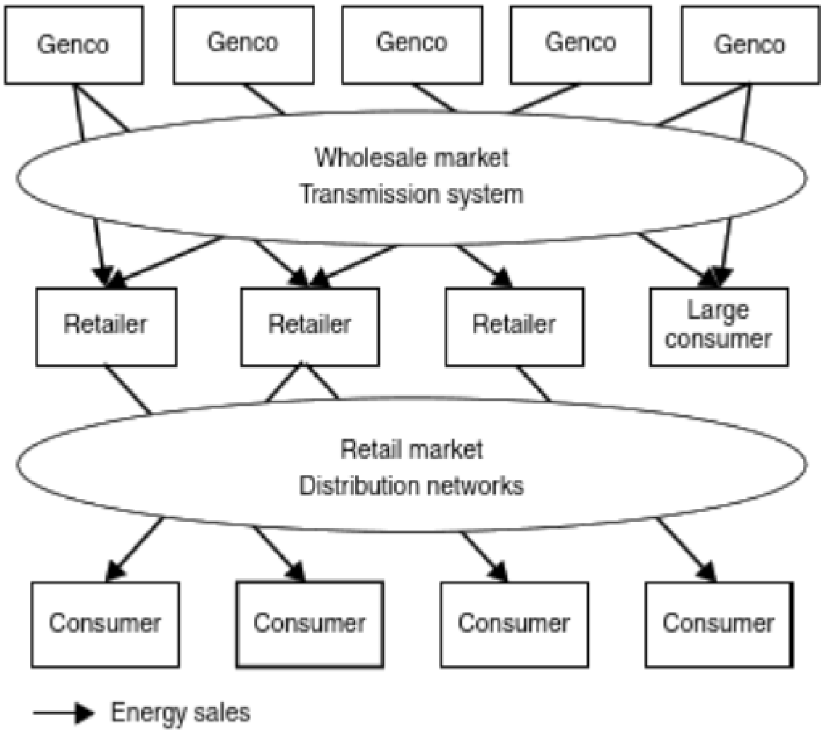

Figure 11. Retail competition model of electricity market. (Kirschen et al. 2004)

6.2 Market types

There are several different market types such as spot market, forward contracts and forward markets, future contracts and future markets, options and contracts for difference which determines when the seller and the buyer arrange the trades. These trades contain for example the date of the delivery, mode of settlement and conditions that are attached to the transaction. (Kirschen et al. 2004)

In a *spot market* transaction between buyer and seller occurs immediately "on the spot". Seller or buyer cannot back out of the deal because there are no conditions attached to the deal. (Kirschen et al. 2004)

In a *forward contract and forward* markets contract includes the quality and quantity of the goods, the date of the delivery, the date and price of the payment after delivery and penalties if seller or buyer fails to deliver their part. (Kirschen et al. 2004)

In *future contracts and future markets* parties do not need to be producers or consumers they can be parties who want to buy a contract for delivery in the future delivery date and they are planning to sell the goods at higher price later. Or sell the contract first and hope to buy one later at lower price. These contracts are called future contracts because they are not backed by physical delivery. (Kirschen et al. 2004)

Forward and future contracts are so called firm contracts which means that the delivery is unconditional. Buyers who are not capable to take full delivery must sell the excess on the spot market. And sellers who are not able to deliver the agreed quantity must purchase the missing amount from the spot market. If participants have used contract with conditional delivery also known as *option,* the contract is exercised only if participants decide it is in their interest to do so. There are two variants in options puts and calls. Puts gives the right for the holder to sell a given amount of a commodity at the contracted price. Call option gives right for the holder to buy agreed amount of commodity at exercise price. In Europe option can be used only at its expiry date. (Kirschen et al. 2004)

In some cases, consumers and producers are obligated to trade through centralized market. Because they are not able to enter into bilateral agreements they cannot use forward, future and option contracts. In this situation parties uses *contract for difference* which operate together with centralized market. Strike price and the amount of the commodity is agreed in the contract for difference. Parties participates in the centralized market and after completion of the market contract for difference is settled. If the strike price is higher than centralized market price the buyer pays the seller price between the two prices according the contract. And if the market price is lower than strike price the seller pays the buyer the difference between the prices. (Kirschen et al. 2004)

6.3 Electricity market

In electricity market trades are treated as services rather than commodities. These services are usually sold in baggage of megawatt-hours which are delivered over a specific time period. These periods are usually set as an hour, half an hour or quarter of an hour. Electricity market are changing quickly, and the price varies in different time period because it is based on electricity generation and load. (Kirschen et al. 2004)

6.3.1 Managed spot market

Spot market is also known as reserve market or balancing mechanism. Because of the nature of the electricity market it is hard to predict precisely how much energy is consumed and generated in a certain time spot and for that reason it is necessary to manage the spot market near the delivery time of the electricity. There are many variables which affects the reliability of the network such as quick changes in consumption, problems in generation and timing issues. Managed spot market works only if the producers gets fair price for selling and buying electricity. In a managed spot market offers are made freely, and they are selected by system operator. (Kirschen et al. 2004)

6.3.2 Open electricity market

Bilateral trading has two parties, seller, and buyer. Contracts are made directly between these two parties. There are three different types of trades: customized long-term contract, trading "over the counter" and electronic trading. Customized log-term contracts are used for selling large amounts of energy during long period of time. Trading "over the counter" is used for smaller amounts of energy. These amounts are usually standard periods such as certain time of week or a day. In electronic trading sellers and buyers can bid and buy energy. Sellers and buyers are anonymous, and the program checks automatically if there are matching bids and buys in the system and seals the deal. If there are no match the offer is waiting for match until the time closes. This type of trading is cheap and fast. (Kirschen et al. 2004)

Electricity pool offers a mechanism for supplier and consumer to trade energy with systematic way. Generation companies submits an offer to supply certain amount of energy at certain time, period, and price. Bids are ranked by increasing price by forming supply curve. Demand curve is established same way but using offers for specific time, amount, and price of electricity, made by consumers. Intersection of demand and supply curves shows the spot of market balances. All offers lower than the clearing price are approved, and generators are obligated to produce the quantity of energy they have offered. If the need for energy is higher the additional energy produced is receiving clearing price for every additional megawatt-hour of energy they have produced. (Kirschen et al. 2004)

6.3.3 Keeping the balance

System operator is obligated to keep the balance in electricity market. In a free market philosophy, all the parties that are willing to adjust their consumption or production to maintain the balance would be allowed to participate in the balancing market. This would be the best situation for system operator to maintain the balance and keep the prices in low level. (Kirschen et al. 2004)

Balancing services can be offered for long-term bases or for a specific time period. In a long-term contracts system operator can purchase certain amount of capacity to be available during contract time for fixed price. Contract also contains price which is payed for every MWh produced. Balancing services for certain periods are often offered after open energy market has closed. For example, units that are not fully loaded can submit bids to increase their capacity or units with full load can offer to decrease their capacity. (Kirschen et al. 2004)

6.3.4 Gate closure

Gate closure in spot market must happen in some point. Gate closure can occur for example hour, half an hour, or minutes before the real time depending on the country. Different types of unit need different type of time to be ready for deliver. When the closure is closer to real time the contracted amount is closer to real demand. (Kirschen et al. 2004)

6.4 Ancillary service market

Ancillary services are used to stabilize and secure the grid. Ancillary services include services such as regulation, load-following, and spinning-reserve. Regulation and load following are handling rapid fluctuation in a grid and for that reason units that are already operating and connected to the grid are used to provide these services. (Kirschen et al. 2004)

Different types of contracts are offered for different ancillary services. Long term contracts are used for services which quantity does not change or they have small changes for example frequency regulation, power-system stabilizer, and black-start. Spot market is needed for the ancillary services which quantity or prices changes for example daily. (Kirschen et al. 2004)

It is hard to predict the amount needed for ancillary services so system operator might want to have bigger pool of resources to make sure that they are able to meet the demand and in same time system operators are trying to avoid over paying for the services. (Kirschen et al. 2004)

7 Market study Ireland and Belgium

Ireland and Belgium were chosen for this study because they have different type of market structure and geographical locations. Ireland is an island which have ambitious goal for adding renewable energy production and in the same time they have one of the most complex energy market structures in Europe. Belgium is in the continental Europe and it have several interconnections between neighbor countries. Market structure in Belgium follows the same structure as other European countries. Comparing these two countries gives good overview of the variation in the electricity markets.

7.1 Belgium

Belgium's energy markets are strongly connected to the European markets and the market structure is similar as into other European countries. Market mechanism consists of generation, power markets, transmission & distribution, and retail market. (Deloitte Conceil 2015)

Belgium's market structure is based on retail competition model presented in chapter 6.1.3. Belgium's market structure is presented in Figure 12.

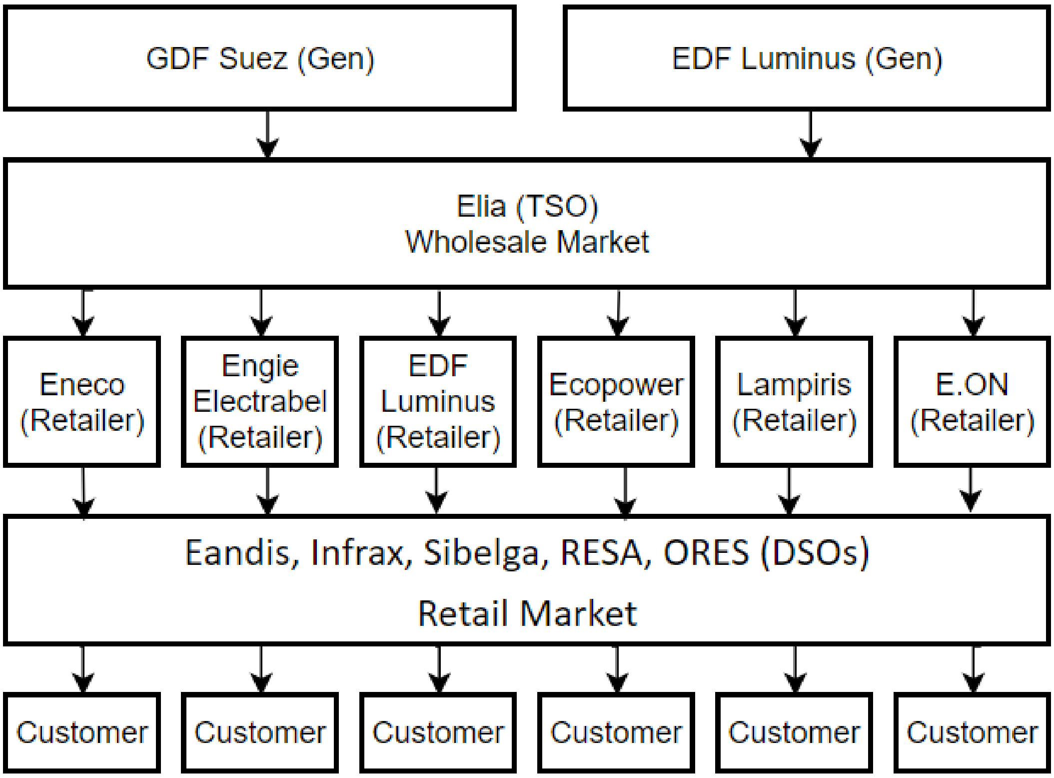

Figure 12. Electricity market model in Belgium. Modified from (Deloitte Conceil 2015)

Parties which are participating in Belgium's markets are presented in the Table 32.

Table 1. Players in Belgium's electricity markets. (next 2020)

Player	Function	Examples
Producer	Produces electricity and in some cases can provide ancillary services.	Engine Electrable and EDF Luminus
TSO	Transmits electricity through the high voltage grid (70<400 kV).	Elia
DSO	Transmits electricity through the low-voltage grid (400V-70kV).	Eandis, Infrax, Sibelga, RESA, ORES
Energy supplier	Sells the electricity to customer. Customers can choose which supplier they use.	Eneco, Engie Electrabel, EDF Luminus, Ecopower, Lampiris, E.ON

Balancing responsible party (BRP)	BRP makes balancing nominations based on the consumption and/or the production data.	Large consumers or producers are their own BRP. Supplier arranges BRP for small end-customers.
Regulator	Regulator is independent party which guards TSO, DSO, producers, and consumers which are participating the market	VREG (Vlaamse Regulering-sinstantie voor de Elektriciteits- en Gasmarkt, Flanders), CREG (Commisie for the Regulation of Electricity and Gas, federal) CWaPE (Commission Wallonne Pour l'Energie, Wallonia)
Power Exchange	Power Exchange manage transparent and anonymous energy trading platform where market participants can submit supply and demand bids. Market is cleared every 15 min.	EPEX Spot Belgium

7.1.1 Energy mix in Belgium

According to IEA the total energy production in Belgium has changed between 1990 to 2019 from 71 190 GWh per year to 93 470 GWh per year. New energy production forms have been developed and the energy mix has changed during the years. Usage of oil has stopped in 2009 and share of coal has decreased dramatically in the same time share of renewable energy production has increased. Nuclear has increased slightly and use of natural gas is five times higher than in 1990. (IEA 2019) Electricity production by source between 1990 and 2019 is presented in the Figure 13.

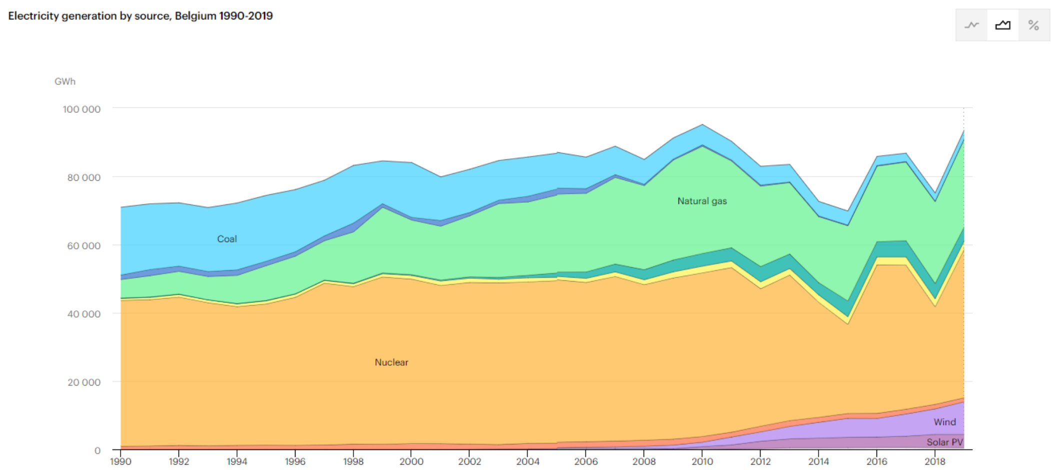

Figure 13. Electricity generation by source in Belgium in from 1990 to 2019. (IEA 2019)

In Belgium electricity generation consists of several different energy production forms such as natural gas, nuclear, wind, biofuels, coal, solar, waste and hydro. In 2019 energy generation in Belgium was dominated by nuclear. Its share was 47 % of the total energy production. Natural gas had 28 % share and wind 10 % share. Biofuels and solar had 4 % share each and coal and hydro 3% share each. Electricity generation by source in 2019 is presented in the Figure 14.

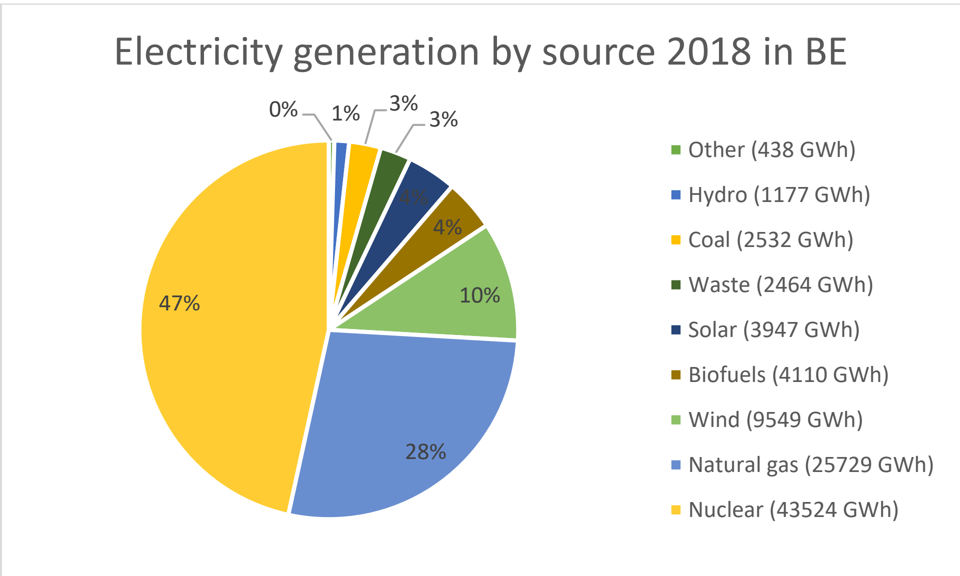

Figure 14. Electricity generation by source in Belgium 2018. Modified from (IEA 2019)

Electricity import has been variating from 1990 to 2019. Energy import has been in its lowest in 1990 (411 ktoe or 4 780 000GWh), 1998 (673 ktoe or 7 837 000GWh) and 2009 (816 ktoe or 9 490 000GWh) and its highest in 2015 (2039 ktoe or 23 714 000GWh) and 2018 (1860 ktoe or 21 632 000GWh). Electricity export has been its lowest in 2015 (233 ktoe or 2 710 000GWh) and 2018 (370 ktoe or 4 303 000 GWh) and its highest in 2019 (1254 ktoe or 14 584 000GWh). (IEA 2019) Electricity import and export between 1990 and 2019 is presented in the Figure 15.

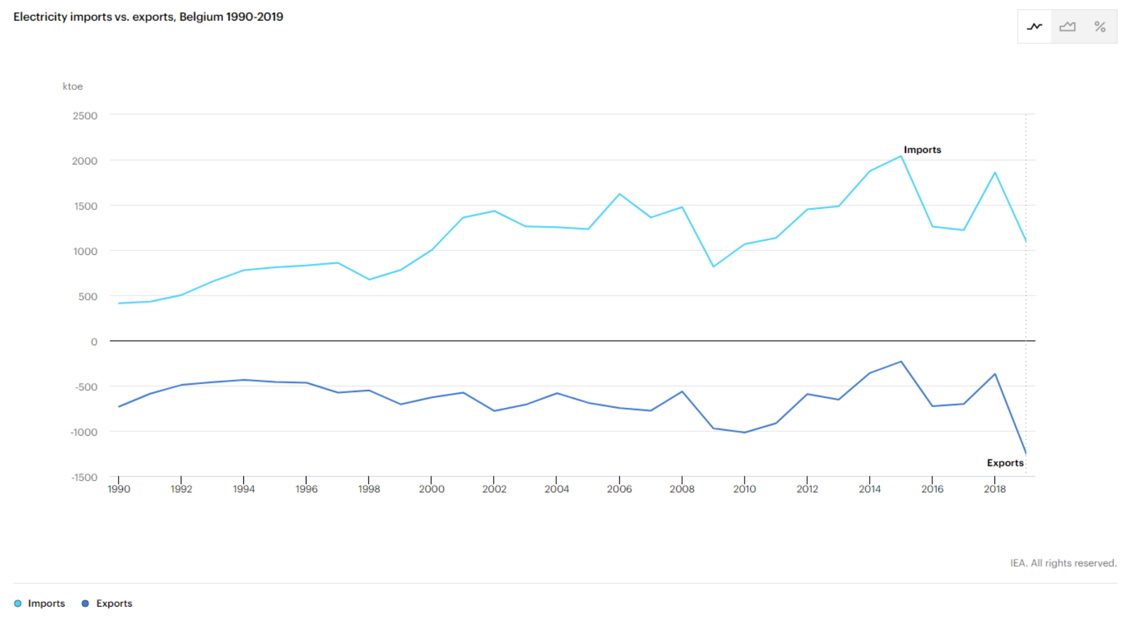

Figure 15. Belgium's electricity imports and exports from 1990 to 2019. (IEA 2019)

7.1.2 Belgium's electricity markets

Electricity market structure follows the same electricity market structure as many other European country. Basic structure consists of Future markets, Day-ahead markets, Intra-day market, and Balancing markets. (Incite 2017) Belgium market structure is presented in the Figure 16.

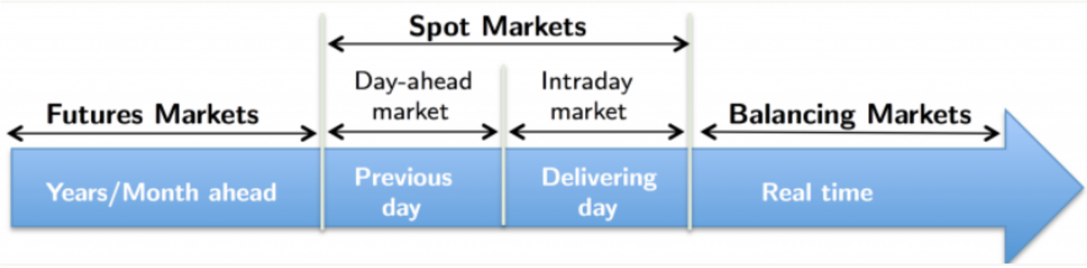

Figure 16. Type of electricity markets as a function of the time when energy is produced. (Incite 2017)

Belgium's Capacity remuneration mechanism (CRM) describes how the mechanism works and the process that involves in the capacity auction, prequalification etc. Process includes four phases pre-auction, auction, time between auction and delivery period and time during delivery period. (Elia Group 2019)

7.1.3 Prequalification and pricing

Prequalification occurs in pre-auction phase. Only Capacity market units (CMUs) which have passed prequalification phase can participate in the auction process. Prequalification process show if the generation unit can deliver the services that it is offering. There are various aspects which needs to be met such as technical, financial, and administrative aspects. (Elia Group 2019)

Power units which holds minimum amount of capacity is obligated to participate in prequalification process. Power units can participate to the prequalification process thorough aggregators portfolio if the unit is not able to meet all the requirements alone. But any capacity holder has chance to opt-out from CRM. This means that unit is not obligated to participate in the market, and they are not receiving penalties for being unavailable. (Elia Group 2019)

Usually Capacity Contract is made for 1 year but in cases where new capacity or enhanced capacity which have required large investments can be awarded for several years.

For units such as RES and energy storages which are not able to be available 100% derate factor is used to make it possible for them to participate in the markets. (Elia Group 2019)

Auction pricing have two option pay-as-bid and pay-as-clear. Pay-as-bid means that bidders who are selected are remunerated based on the bids and in pay-as-clear pricing selected bidders is awarded with same market clearing price. (Elia Group 2019)

7.1.4 Capacity product

Prequalified capacity providers are awarded with Capacity contract and they are defined as capacity products. There are obligations which the CMUs needs to meet to receive capacity remuneration. Capacity products have obligations which are grouped into three categories pre-delivery period monitoring, availability monitoring and payback obligation. (Elia Group 2019)

7.1.5 Secondary market

Secondary market offers providers a market where CMU which is not able to meet its obligation can buy capacity from other CMUs to avoid penalty. All providers participating in Secondary market needs to be prequalified as CMU. After the transfer to the other CMU the capacity obligation is fully transferred, and the original CMU is 'free' from its obligations. (Elia Group 2019)

7.1.6 Interconnections

CRM in Belgium is open to foreign CMUs through Indirect Cross-Border Participation and Direct Cross-Border Participation. France, Netherlands, UK, and Germany are in the Belgian control zone and they can participate in the CRM from the first delivery period. Direct Cross-Border Participation is possible for CMUs which are directly connected to the Belgium control zone. They have possibility to be facilitated from the first Auction. (Elia Group 2019)

7.1.7 Spot markets

Spot markets consists of day-ahead market, intraday market and intraday to real time markets. Spot and balancing markets are presented in the Figure 17.

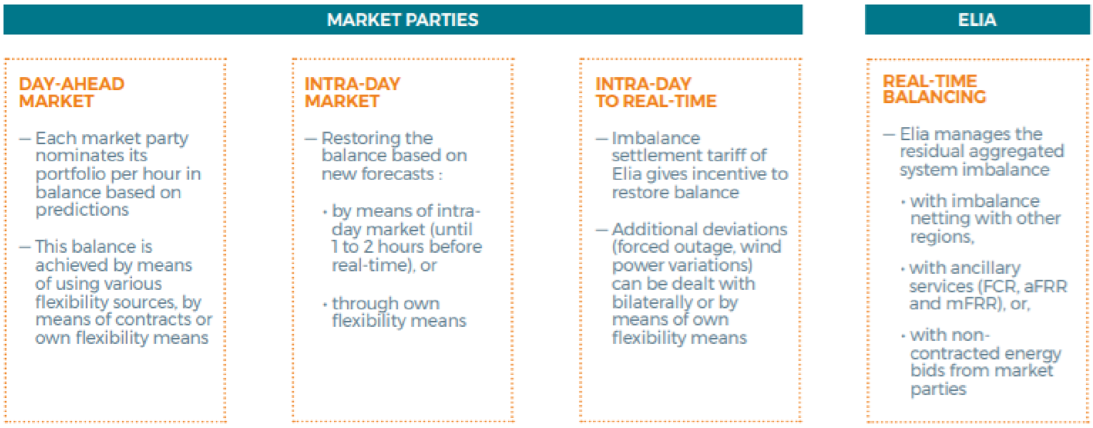

Figure 17. Belgium’s spot and balancing markets. (Elia Group 2017)

Intraday and Day-ahead markets in Belgium is operated by Belpex. Every day in DAM single hours or block of hours are exchanged through auction. Auction price is between -500€/MWh and 3000€/MWh. Gate closes at 2:00pm day before delivery time. (Frontier Economics 2016)

Intraday market operates continuously every hour in every day. In IDM auction hourly blocks and freely defined blocks are traded. Time frame for trades are from 14:00 day before until 5 minutes before delivery. Auction prices are between -9999.99€/MWh and 9999,99€/MWh. (Frontier Economics 2016)

7.1.8 Balancing market

Balancing market in Belgium consist of FCR, aFRR and mFRR markets. (Elia Group 2017) Balancing market is presented in Figure 18 by service and by time.

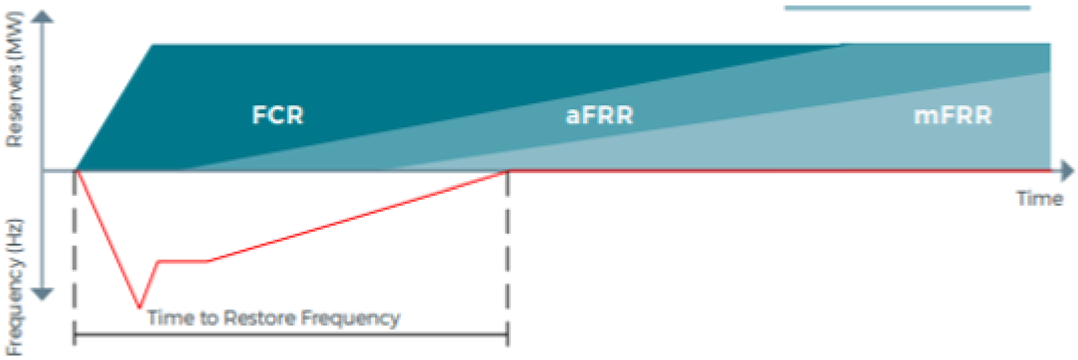

Figure 18. Belgium's balancing market presented in timeline. (Elia Group 2017)

7.1.9 Ancillary and balancing services

FCR is used in European interconnected system to frequency stabilization and preventing blackouts. Reaction time for FCR is 30 seconds. In Continental Europe there is fixed capacity of 3000 MW which is divided between TSOs. All players, all voltage levels and technologies including storages and demand response can provide FCR services. Tenders are made in daily bases and the remuneration is paid based on reservation (MW). (Economie 2019)

aFRR is used during larger imbalance to relieve FCR, it helps to stable the balance and frequency. aFRR is automatically activated maximum in 7.5 minutes. Regulatory approves yearly volumes needed. Only units with large assets and power-scheduling obligation offer aFRR services. However, market is opening for all voltage levels, all players, and all technologies in the future. Tenders are set as daily tenders and remuneration is based on activation (MWh) and reservation (MW). (Economie 2019)

mFRR is a service which is used during major imbalances and it need to be available in 15 minutes. Sizing for need is made as daily sizing planned and announced. All technologies, voltage levels and players can offer mFRR services. Units are remunerated based on activation (MWh) and reservation (MW). (Economie 2019)

7.1.10 Strategic reserve

Strategic reserve is different from balancing reserve. Strategic reserve is used to minimize risk of structural shortage in Belgium. Units which are out-of-market can be contracted by Elia. Strategic reserve units are brought to the market with consistent price required by price signal during period of structural shortage. (Elia Group 2018)

7.2 Ireland

Ireland together with Northern Ireland forms all-island Single Electricity Market (SEM). They both have own TOSs, DSOs, Market operators and Regulatory Authorities which works together to achieve reliable electricity system. (Ryan 2014) All electricity market parties in Ireland and Northern Ireland is presented in the Table 1.

Table 2. Ireland's electricity market parties. (Ryan 2014)

	Ireland	Northern Ireland
Regulatory Authority	CER	UREGNI
TSO	EirGrid	SONI
DSO	ESB Networks	NIE
Market Operator	SEMO	SEMO

EirGrid operates as TSO in Ireland. It manages, develops, and operates the electricity transmission network also known as a grid. Grid consists of substations and circuits at 400 kV, 220 kV and 110 kV. Grid is owned by ESB Networks, Transmission Asset Owner (TAO) and EirGrid. (EirGrid 2018)

In Northern Ireland SONI (System Operator of Northern Ireland) is operating as TSO. Grid is owned by SONI and Northern Ireland Networks (NIEN). Transmission network operates at 275 kV and 110 kV. There are interconnections between Ireland and Northern Ireland which goes through substations in the Tandragee and the Louth. (EirGrid 2018)

Single Electricity Market Operator SEMO consists of TSOs EirGrid and SONI. SEMO operates as a TSO in all-island transmissions system and it is regulated in Ireland by Commission for Energy Regulation CER and in Northern Ireland by Utility Regulator Northern Ireland (URegNI). (EirGrid 2018)

Irelands market model is based on wholesale competition model introduced in chapter 6.1.3. Irelands wholesale model is presented in the Figure 19.

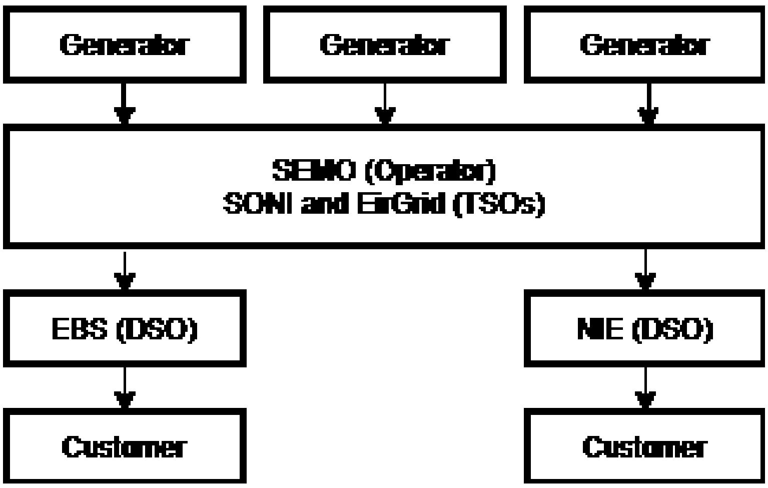

Figure 19. Ireland wholesale market model.

7.2.1 Energy mix

According to International Energy Agency (IEA) the total energy production in Ireland has changed between 1990 to 2018 from the 14 500 GWh per year to 30 900 GWh per year. New energy production forms have been developed and the mix has changed during the years. Share of coal has slightly and oil has dramatically degreased. Use of natural gas has quadruple and hydro power has stayed in the same level. In a year 2018 new energy productions forms: wind, solar, biofuels and waste has almost one third of the energy production share. (IEA 2019) Share of different energy production forms from 1990 to 2018 are presented in the Figure 20.

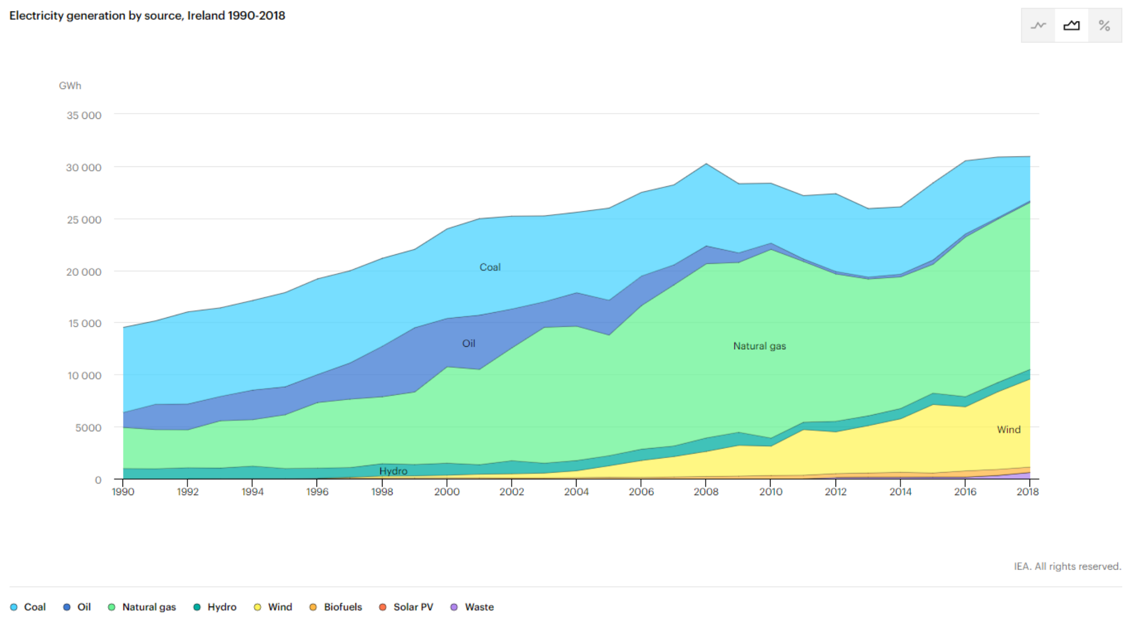

Figure 20. Electricity generation by product in Ireland from 1990 to 2018. (IEA 2019)

In 2018 Energy generation by source in Ireland is dominated by natural gas which is nearly 52 % of total energy generation. Wind has slightly over quarter 27 % share of the energy production and coal has almost 14 % share. Rest of the energy production forms have only 7% share of the total energy production. (IEA 2019) Electricity generation by source is presented in the Figure 21.

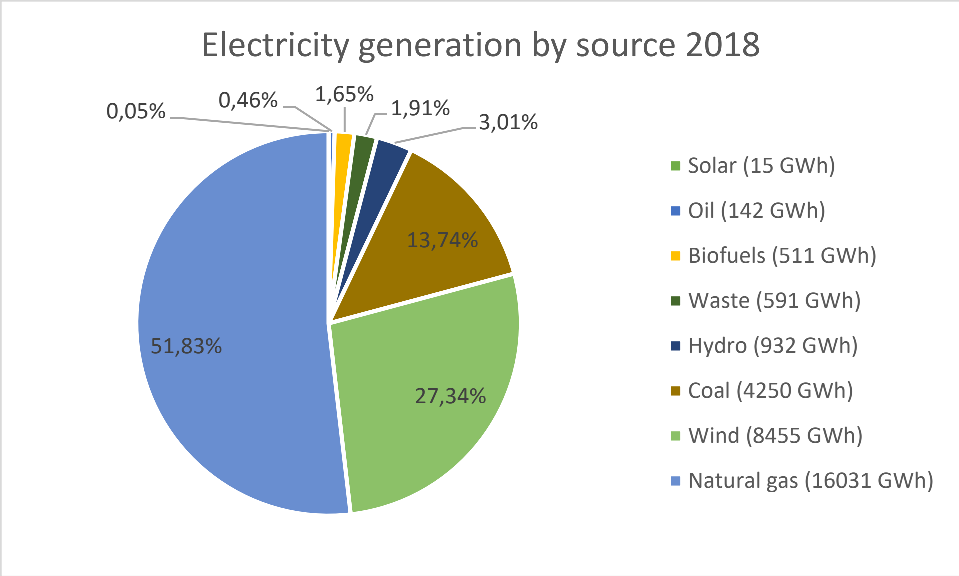

Figure 21. Ireland's electricity generation by source in the 2018. (IEA 2019)

Electricity import has been variating from the year 1995 to 2018. It has been lowest in the years 1995 (2 ktoe or 23 000GWh) and 2001 (3 ktoe or 35 000GWh) and highest in years 2005 (176 ktoe or 2 047 000GWh), 2013 (226 ktoe or 2 628 000GWh) and 2014 (245 ktoe or 2 849 000GWh). Electricity export has been its lowest in 2003 to 2006 (1 ktoe or 12 000GWh) and its highest in 2016 (136 ktoe or 1 582 000GWh) and 2017 (154 ktoe or 1 791 000GWh). In 2018 import was 139 ktoe or 1 617 000GWh and export 142 ktoe or 1 651 000GWh. (IEA 2019) Electricity export and import from 1995 to 2018 is presented in the Figure 22.

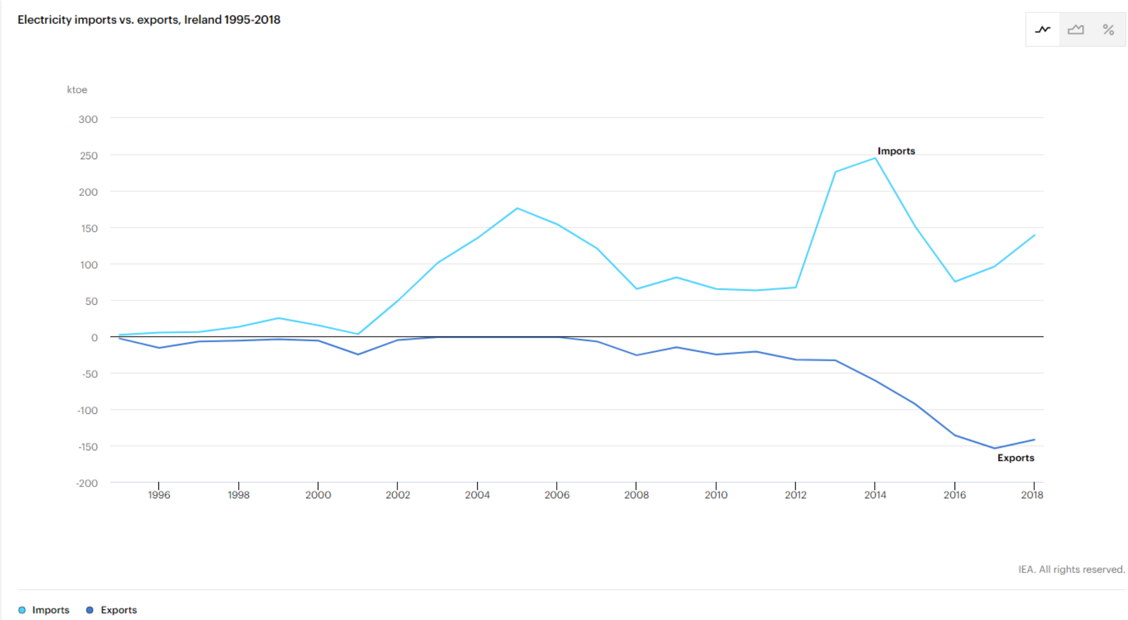

Figure 22. Ireland's electricity imports and exports from 1990 to 2018. (IEA 2019)

7.2.2 Ireland's electricity markets

Wholesale electricity market arrangement in Ireland and Northern Ireland consists of Integrated Single Electricity Markets (I-SEM) which includes auctions or multiple markets. I-SEM connects all-island electricity market to European electricity markets. I-SEM provides benefits such as participation to energy markets, maximizing interconnection in system balancing and increasing opportunities to participate in trading in different time frames. (EirGrid 2016)

I-SEM is part of European market coupling through Great Britain which connects Ireland and Northern Ireland to 38 cross-border interconnections in total of 20 countries whit 3 000 terawatts (TW) generation capacity. The main idea in market coupling is that when energy flows freely from country to county the single price stays the same and when the grid is congested the price change. (EirGrid 2016) Interconnections between European countries are shown in Figure 23.

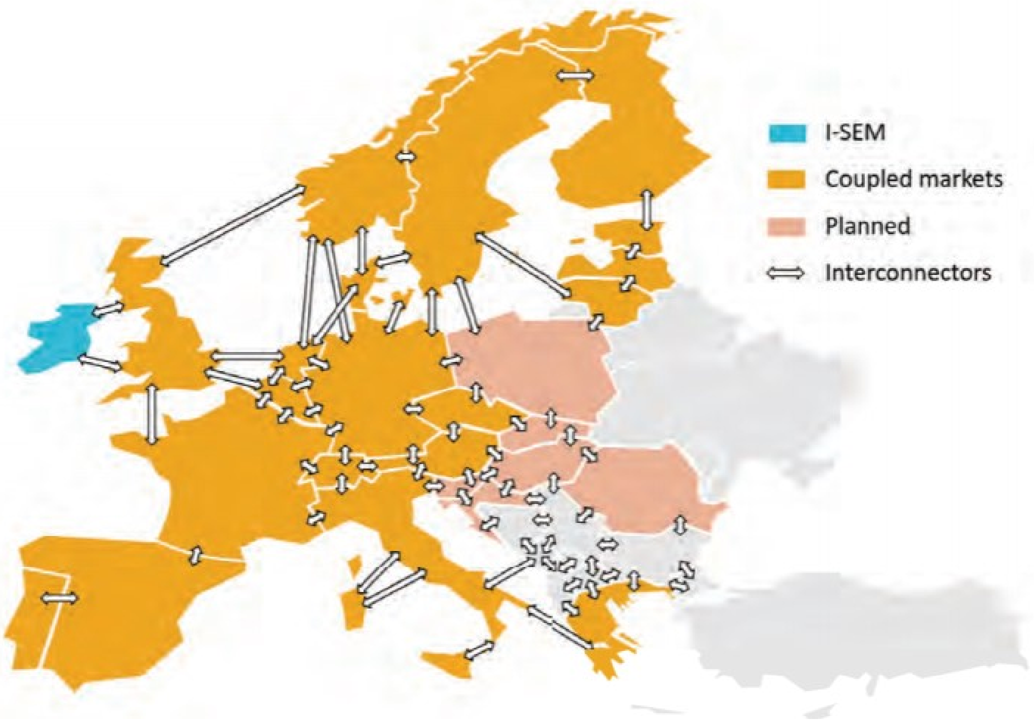

Figure 23. Interconnections in Europe in 2018. (EirGrid 2016)

I-SEM participates in Day-Ahead Market (DAM), Intraday Market (IDM), Balancing Market (BM), Forward Market (FWM), Financial Transmission Right (FTR) and Capacity Market (CM). I-SEM market structure is presented in Figure 24.

DAM closes day before and IDM operates between DAM is closed until one hour before delivery. BM operates just before or during real time, to balance demand and supply of energy. These three markets are running before the energy is delivered and this type of markets are called ex-ante or spot markets.

FEM and FTR are financial instruments in I-SEM. FWM are agreed months or years before the delivery. FWM is also known as strike price which means that certain amount of energy has been planned to deliver in agreed date. Depending on energy used in agreed date the buyer needs to receive or pay the difference between the strike price and spot price. FTR protects the holder from price difference between coupled markets which means that if the energy flows freely from country to country the price in the markets

are equal but if the interconnection is congested the price will change. But if countries are paying to interconnection owners congestion rent in the form of FTR they do not need to pay the differences in price. FTRs are purchased in the FTR auction.
Capacity providers are committed to be available to deliver energy to the grid on call. CM receive regular capacity payments which is used to fund generation capacity. (EirGrid 2016)

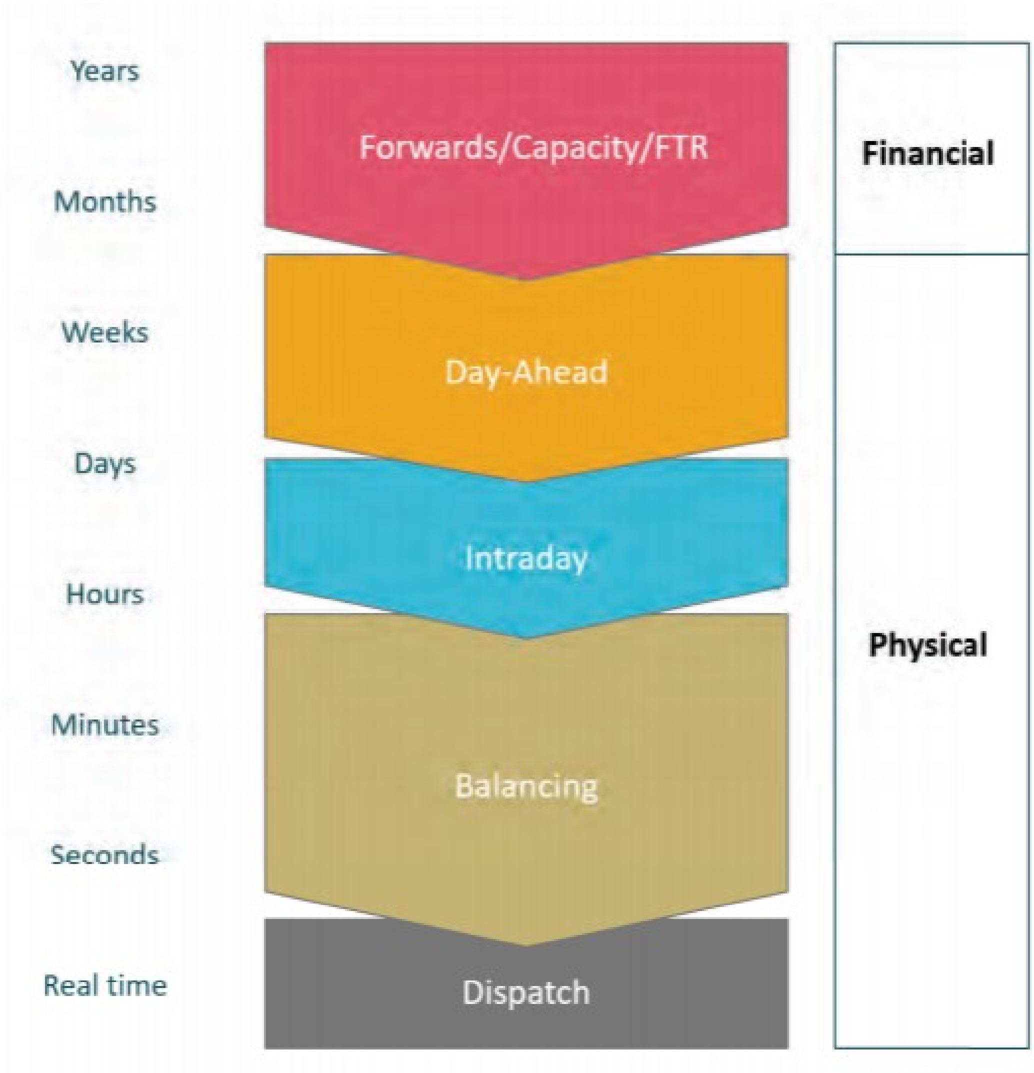

Figure 24. Market time frames in Ireland. (EirGrid 2016)

Electricity markets in Ireland are regulated by the Commission of Regulation of Utilities (CRU) which responsibilities in energy sector is divided in three areas: to regulate electricity generation, gas and electricity networks, and gas and electricity supply activities. Single Electricity Markets (SEM) is regulated by CRU in Ireland and the Utility Regulator in the Northern Ireland. Decisions in SEM are made by SEM Committee which consists of CRU, Utility Regulator, and an independent member. (Department of Communication, Climate Action & Environment 2020)

SEM is a wholesale electricity market which is operating in Ireland and Northern Ireland. Single Electricity Market Operator (SEMO) ensures that SEM provides reliable, sustainable, and competitive electricity wholesale market whit long-term social and economic benefits for both Ireland and Northern Ireland. SEMO is joined ventures together with TSOs EirGrid in Ireland and SONI on Northern Ireland. SEMO is regulated and licensed by the Utility Regulatory for Northern Ireland (UREG) and Commission for Energy Regulatory (CER) in Ireland. (SEMO 2020)

SEM consists of six different markets: two ex-ante Energy Markets, a Balancing Market, two markets for Financial Instruments and a market for Capacity Remuneration. These six markets operate independently in different timelines. (SEMO 2020)

Energy market is divided in four main categories: long term, medium term, short term, and real time markets. Long term market known as Capacity Market (CM) includes capacity trading which have been agreed up to five years before delivering date. Medium term markets consist of Forward Market (FWM) and Financial Transmission Right (FTR) auctions which are known as Financial Instruments. Medium term market agrees the electricity delivery date and capacity over a year to one month before the trading date. Short term market includes Day-Ahead (DAM) and Intraday Market (IDM) which trades energy one day ahead up to shortly before real time. Real time market known as Balancing Market (BM) occurs just before trade time or into real time. (SEMO 2020)

7.2.3 Capacity market

Capacity Market (CM) ensure that there is continuous electricity supply which meet the demand in Ireland and Northern Ireland. CM is completely auction based and power generation units that are the most efficient and have lowest cost capacity are usually chosen. Generation capacity includes storage capacity, demand side units and interconnection capacity. (SEMO 2020)

Units that are chosen for CM will get payment during the year of each MW of capacity they have sold in the auction. The units that have been chosen to the CM needs to fill the requirements of capacity and availability in the DAM, IDM and BM. Service providers are also required to pay different charges for example when the energy price exceeds the strike price. Generator units which are participating in SEM can also earn revenues from system services and energy markets. (SEMO 2020)

To ensure the energy production, CM uses de-rating. De-rating considers power unit's reliability and ability to secure the energy supply as well as consider locational constrains. Locational constrains includes limitations such as amount of power flow through interconnection. (EirGrid & SONI 2019)

7.2.4 Balancing market

Balancing market (BM) consists of before or real time balancing services, which ensures that the energy supply always meet the energy demand. TSO keeps the system balance by using the BM. TSO determines imbalance settlement price for the balancing actions. (SEMO 2020)

BM consists of balancing services offered by generator or suppliers. TSO decides which of the offered services it will use. For example, TSO could request generator to increase output to meet the demand. Generator get paid for the extra energy produced to balance the grid. TSO can also request support including services such as energy reserve or voltage regulation from non-energy balancing services. (SEMO 2020)

Balancing Market auction day is divided in 48 imbalance periods, each of them is 30 minutes. Each 30 minutes period is divided in six 5 minutes imbalance pricing periods. Trading period are aligned with Intraday electricity market trading periods. 19 days before the trading day submission window for market data is opened and it is closed 1 hour before 30 minutes imbalance settlement period. (SEMO 2020)

Participation to BM is mandatory for all generator which have export capacity over 10 MW and voluntary for units with capacity under 10 MW. Different parties such as generator, supplier, assetless trader, interconnectors and capacity market unit have different roles in BM. (SEMO 2020)

7.2.5 Day-ahead and intraday electricity market

SEMOpx is part of SEM and it provides DAM and IDM trading. SEMOpx have wide energy products and services portfolio which provides flexible approach to energy trading in a day-ahead and intraday timeframe. (SEMOpx 2020)

DAM is energy trading platform for scheduling bids, offers and interconnector flows in pan-European ex-ante market. DAM is executed as a daily auction which occurs every calendar day at 11:00. Bid for the trading can be offered in 24 one-hour trading periods in timeframe from 23:00 evening to 23:00 the following evening, this timeframe is known as Trading Day. (SEMOpx 2020)

DAM is followed by Intraday Auction Market which offers change for service providers to adjust their physical position to real time. SEMOpx IDM have three daily auctions: first intraday auction (IDA-1), second intraday auction (IDA-2) where the SEM is coupled with

Great Britain's bidding area by interconnections and the third intraday auction (IDA-3) which is local SEM auction. (SEMOpx 2020)

Instead of one-hour Trading Period which is used in DAM, IDM uses 30 minutes Trading Periods in Intraday Auction. Durations for the auctions in IDA-1 is 24 hours, in IDA-2 is 12 hours and in IDA-3 is 6 hours. (SEMOpx 2020) IDA-1, IDA-2 and IDA-3 schedules are presented in the Table 3Table 1.

Table 3. Schedules for IDA-1, IDA-2 and IDA-3. (SEMOpx 2020)

Auction	Auction Start Time	Trading Periods	Auction Duration
IDA-1	17:30	23:00-23:00	24 hours
IDA-2	08:00	11:00-23:00	12 hours
IDA-3	14:00	17:00-23:00	6 hours

Exchange Members can participate in local price matching market called Intraday Continuous Market which adjusts Exchange Members' physical position closer to real time. Intraday Continuous Market is open every day of the year and trading occur from 23:00 to 23:00 in following day. Trading day consist of 48 half hour trading periods. Simple order is an offer to sell or bid to by energy in a half hour trading period. Block Order is made of a two, four, eight, or 24 hour duration blocks as a bid to buy or an offer to sell electricity. (SEMOpx 2020)

There are different types of order conditions for Simple Order or Block Order such as Immediate or cancel, fill or kill, good till date, good for session and iceberg, which are used in the Intraday Continuous Market. There are also 22 pre-defined Block Order with different timeframes and durations, that are available for trading in the Intraday Continuous Market. (SEMOpx 2020)

7.2.6 DS3 delivering a secure, sustainable electricity system

Delivering a Secure Electricity System (DS3) program was established to ensure that the electricity system operates in a safe, efficient, and secure manner while the amount of renewable energy production increases in Ireland and Northern Ireland. TSOs EirGrid and SONI make sure that the electricity supply and power flow from generator to consumers works seamlessly. (EirGrid & SONI 2016)

Energy generations consists of two different generation types synchronous and non-synchronous generation. Synchronous generation is produced mostly by fossil fuels such as gas, oil and coal which can generate same amount of electricity all the time. For that reason, synchronous electricity generation is predictable, reliable, and easy to bring to the grid. (EirGrid 2020)

Non-synchronous generation is in many cases produced by renewables such as solar and wind. These energy production forms do not produce same amount of energy all the time, because they are depending on the available energy such as sun light and wind. For these reasons non-synchronous energy is less reliable and more difficult to bring into the grid. DS3 program's aim is to support to add amount of non-synchronous generation to the power system in secure and safe manner. (EirGrid 2020)

DS3 program consists of three main pillars System Policies, System Performance and System Tools. Main pillars are presented in the Figure 25. System Policies pillar is used for policy control to ensure that the DS3 program follows correct level of regulations. The System Tools pillars is used to control actions through the program. System Performance pillar includes managing and monitoring all the units that are connected to all-islands electricity system. (Gaffney, et al. 2019)

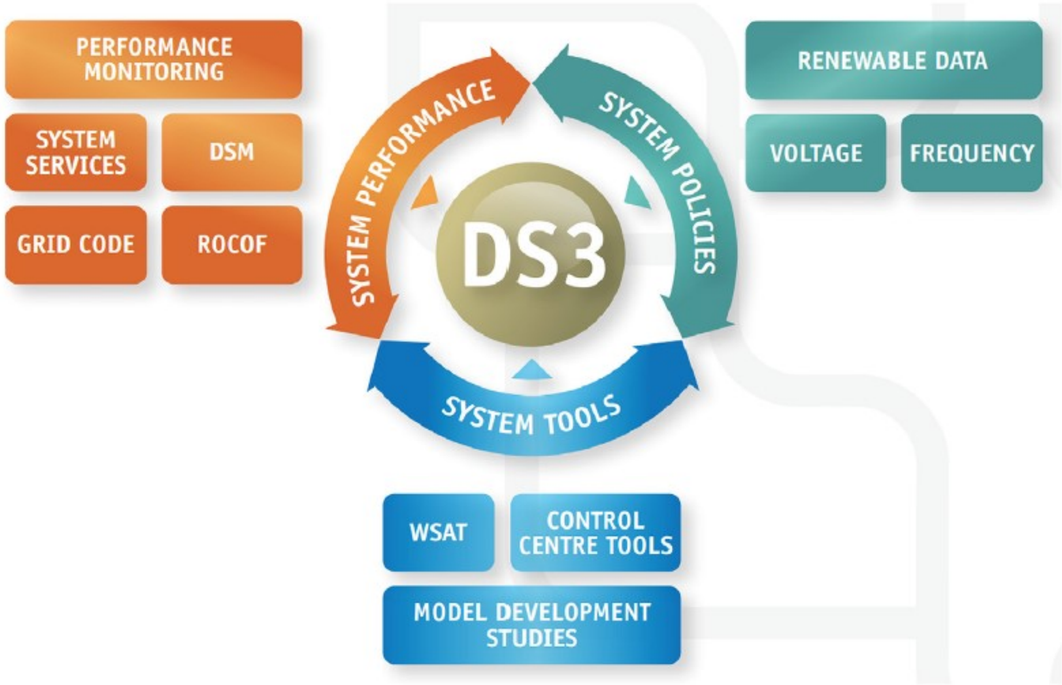

Figure 25. Main pillars for DS3 program. (Gaffney, et al. 2019)

DS3 program doubles Ancillary Services products from seven to fourteen products by using these three pillars. These new fourteen services products forms work stream called System Services. (Gaffney, et al. 2019)

7.2.7 System services

System services consists of 14 service products that can be grouped in two main categories Frequency Control Services and Voltage Control Services. Frequency Control Services consists of Inertia Response, Reserve and Ramping. Voltage Control Service contains Transient Voltage Response, Voltage Regulation and Network. System services are divided under these categories. System services are presented in the Table 4. (SEM Committee 2014)

Table 4. System services in Ireland. (Gaffney, et al. 2019)

Category	System Service		Unit	Definition	New or existing
Voltage Control	Steady-state Reactive Power	SSRP	MVArh	MVar capability (% of capacity that capability is provided)	Existing
	Dynamic Reactive Response	DRP	MWh	MVar capability during large (>30%) voltage dip	New
Inertia Response	Synchronous Inertial Response	SIR	MWs^2h	Stored kinetic energy	New
	Fast-Post Active Power Recovery	FPFAPR	MWh	Active power >90% within 250ms of voltage >90%	New
	Fast Frequency Response	FFR	MWh	MW delivered between 2-10s	New
Reserve	Primary Operating Reserve	POR	MWh	MW delivered between 5-15s	Existing
	Secondary Operating Reserve	SOR	MWh	MW delivered between 15-90s	Existing
	Tertiary Operating Reserve 1	TOR1	MWh	MW delivered between 90-5min	Existing
	Tertiary Operating Reserve 2	TOR2	MWh	MW delivered between 5-20min	Existing
	Replacement Reserve, De-Synchronized	RRD	MWh	MW delivered between 20min-1hour	Existing
	Replacement Reserve, Synchronized	RRS	MWh	MW delivered between 20min-1hour	Existing
Ramping	Ramping Margin 1 hour	RM1	MWh	The increased MW output that can be delivered with a good degree of certainty for the given time horizon.	New
	Ramping Margin 3 hours	RM3	MWh		New
	Ramping Margin 8 hours	RM8	MWh		New

Frequency control services are presented in the timeline in the Figure 26. Voltage system control services are presented in the timeline in the Figure 27.

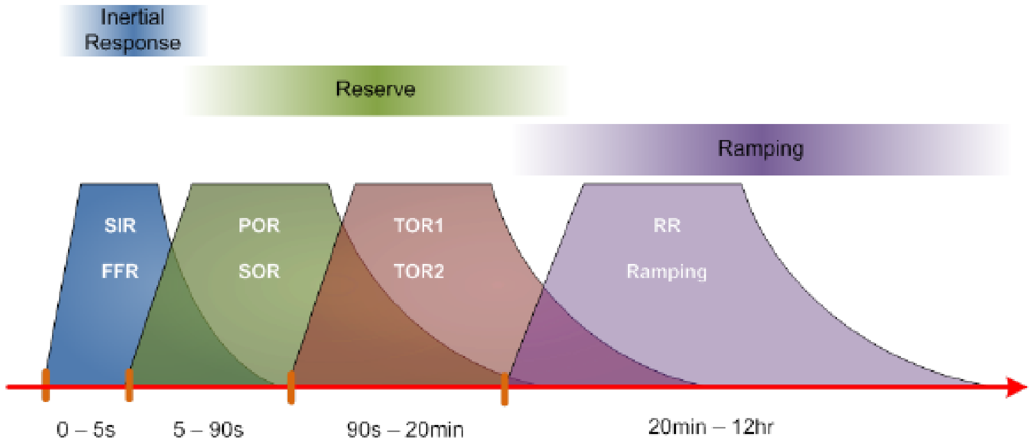

Figure 26. Frequency control services. (SEM Committee 2014)

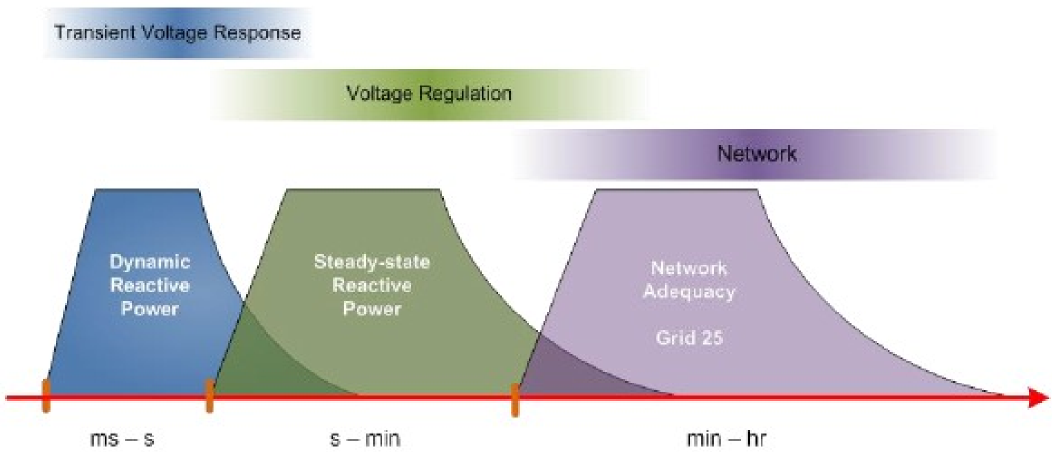

Figure 27. Voltage control services. (SEM Committee 2014)

Synchronous Inertial Response (**SIR**) is activated automatically when there is frequency imbalance in the grid. If the unit is available, it will provide the service. SIR is most likely more valuable at high wind and during nighttime. SIR services can be provided by conventional, new, and enhanced units. (SEM Committee 2014)

Fast Frequency Response (**FFR**) responses automatically when there is frequency disturbance in the grid. FFR units are not synchronous but they need to be available to provide service. To provide FFR service units might need to operate inefficient level and the operating levels is controlled by control systems. FFR service value depends on system conditions and FFR units have mostly the same requirements than SIR, but it is not able to replace SIR units because of lack of spinning inertia. Wind and conventional units can provide FFR service. (SEM Committee 2014)

Fast Post Fault Active Power Recovery (**FPFAPR**) responses automatically in the event of fault in the situation where the service is available (unit is exporting at the time). Synchronous units and some wind farms can provide FPFAPR service. The FPFAPR service value is depending on number of synchronous units and system conditions. (SEM Committee 2014)

Operating Reserve consists of primary (**POR**), secondary (**SOR**) and tertiary (**TOR1**, **TOR2**) operating reserve products also known as standard ancillary service products. Operating reserve services are used in most electricity systems. All units approved as operating reserve products needs to be capable to provide reserve power to TSO. There for the value of operating reserve services come from energy being available and ready to export in short notice. (SEM Committee 2014)

There are two different types of Replacement Reserve: synchronized (**RRS**) or not synchronized (**RRD**) which are used to replace the reserve provided by POR, SOR and TOR. Value and requirements of the reserve for the RRS and RRD will vary over time because it depends on system and market conditions of the balancing market. Existing and enhanced conventional units are capable to provide replacement reserve services. (SEM Committee 2014)

Ramping Margin services (**RM1**, **RM3** and **RM8**) are ready to generate from TSO’s request if for example wind is forced to drop out for few hours. Ramping products value and ramping requirements will vary based on market and system conditions. Peaking units can provide these services. (SEM Committee 2014)

Dynamic Reactive Reserve (**DRR**) is automatically provided by connected generators when voltage drop occurs due to a fault. DRR service is more valuable during high wind but it is related to scarcities in a given time and location. Conventional generation units are usually able to provide DRR services. (SEM Committee 2014)

Steady-State Reactive Power (**SRP**) is needed during normal system operation and it is dispatched by TSO. Requirements for SRP depends on demand and generation-mix. SRP service provide lagging or leading MVars depending on TSOs request. Conventional and some wind power units can provide this service. (SEM Committee 2014)

7.2.8 Entering the system service market

Previously system service providers have been mostly conventional power generation units. The current situation where the amount of renewable energy generation units is increasing there is a need for new system service providers. To enter the system service market, power generation units need to demonstrate their capability by passing Qualification Trial Process. This process gives chance for technologies which have similar characteristics than previous system service providers. (EirGrid & SONI 2017) List of services which GT and BESS can provide is presented in the Table 5.

Remuneration for system services is based on real time availability, not installed capacity. According to SEM Committee's decision paper SEM-14-108 scalars for performance, scarcity, products, and volume should be implemented to incentivize reliability, flexibility, performance, and value for the money. Payment for the generation unit consists of tariff, scalars, and availability volume. (EirGrid & SONI 2017)

Table 5. System services which GT and BESS can provide (EirGrid & SONI 2020)

System Service	GT	BESS
SIR	X	-
FFR	X	X

POR	X	X
SOR	X	X
TOR1	X	X
TOR2	X	X
RRD	X	X
RRS	X	X
RM1	X	X
RM3	X	X
RM8	X	X
FPFAPR	X	X
SRP	X	X
DRP	X	X

7.3 Summary of Ireland’s and Belgium’s electricity markets

Ireland’s and Belgium’s markets differs from each other. European commission have listed differences between Ireland’s and Belgium’s battery storage strategies in areas such as permitting, energy markets and capacity mechanisms, ancillary services, grid aspect, involvement of TSO and DSO, and best practices. (European Commission 2020)

Permitting

In Ireland energy storages applies the same standard permitting rules as power generation plants. In Belgium for stationary batteries permit or notification is needed if the capacity for the unit is higher than 10000Vah. (European Commission 2020)

Energy markets and capacity mechanisms

In Ireland energy storages are able to participate in the electricity markets, including balancing and intraday market and energy storages are able to participate in the Irish Capacity Remuneration Mechanism but duration of the storage effects on the derate factors. (European Commission 2020)

In Belgium storages are allowed to participate in balancing and spot electricity markets directly or via aggregator. Loop block orders in the EPEX energy exchange, supports storages to participating the markets. New CRM provides storages to participate in the markets directly or indirectly. (European Commission 2020)

Ancillary Services

In Ireland storages can contract to ancillary service markets under both grid code and DS3 program. In Belgium batteries are able to provide FCR, aFRR/mFRR, black start and voltage control services. Ancillary services are provided either via aggregator or directly. (European Commission 2020)

Grid Aspect

In Ireland Storages are paying double tariff, connection and access charges. Network code is same which is used for wind generation. TSO is planning to change the network code to support storage's characteristics and ability to provide grid stability. There is no metering for energy storages at the moment. (European Commission 2020)

In Belgium storages are paying double charges if they are directly connected to the low voltage or medium voltage distribution grid. (European Commission 2020)

Involvement of TSO and DSO

In Ireland TSO and DSO do not own energy storages at the moment. In Belgium in Wallonia (<70kV) the DSOs are allowed operate and own storages, but they are only allowed to use them if market fails to meet the demand. At federal level (<70kV) TSOs are not allowed to operate and own storage systems. (European Commission 2020)

Best practices

In Ireland battery storages are needed to provide services such as FFR to support the increasing number of renewables. Public service obligation levy is only used for on-site consumption of the storages. (European Commission 2020)

In Belgium National Investment Pact which for private sector foster partnership between public and private sectors whit in six strategic sectors, including energy storages. Permitting or notification requirement for storage unit is depending on storage capacity. CRM design which provides possibility for storage units to participate in the market directly or via aggregator. Specific tariff for storages provided by regulatory framework. Storages are exempted form taxes and the obligation to submit green certificates. (European Commission 2020)

Summary of BESS and GT participation in markets in Ireland and Belgium are presented in the Table 6.

Table 6. Summary of BESS and GT participation in different electricity markets.

	IRELAND		BELGIUM	
	BESS	GT	BESS	GT
Capacity Market	Yes	Yes	Yes	Yes
Arbitrage	Yes	-	-	-
Voltage Control	Yes	Yes	Yes	Yes
Frequency Reserve	Yes	-	Yes	Yes
Inertia	-	Yes	-	-
Black Start	-	Yes	Yes	Yes

(EirGrid & SONI 2020), (Elia Group 2019), (European Commission 2020), (Elia Group 2019), (Oureilidis, et al. 2020), (Borgan et al. 2019)

8 BESS' features and functionalities compared to gas turbines

In this chapter features and functionalities of open cycle gas turbine and battery storages are presented and compared.

8.1 Open cycle gas turbine

In this study two different sizes 25 MW and 104 MW peaker OCGTs was chosen. Investment costs, operational costs and revenues for new GTs was calculated in both Ireland and in Belgium based on literature, researches, and publicly available IDA and balancing price data. Usage data was collected from two existing OCGT power units located in different countries. Technical information for GTs is presented in the Table 7 and total run hours, number of starts and capacity produced by GTs is presented in the Table 8.

Table 7. Technical information for 25MW and 104 MW GTs. (Hitachi ABB Power Grids 2020), (Ålands Karftnät 2020)

	25 MW	**104 MW**
Min capacity (MW)	5	5
Max capacity (MW)	25	104
Ramp-up time, full load (min)	15	20
Availability (%)	98	98
Heat Rate (GJ/GWh)	10 000	12 457

Table 8. Total run hours, number of starts and capacity produced by GTs. (Hitachi ABB Power Grids 2020), (Ålands Karftnät 2020)

	25 MW	**104 MW**
Total run hours	13	68
Number of starts per year	8	29
Total capacity produced MWh	43	582

Revenue streams for GTs is described in the Figure 28Figure 1. GTs which are used for peak loads gets most of the revenues by capacity payments, for being available and other remuneration such as tariffs. Revenues from selling energy in IDA are relatively small. In this study IDA prices (2019) from Ireland and Belgium were used to calculate electricity market revenues. (Entso-e 2021)

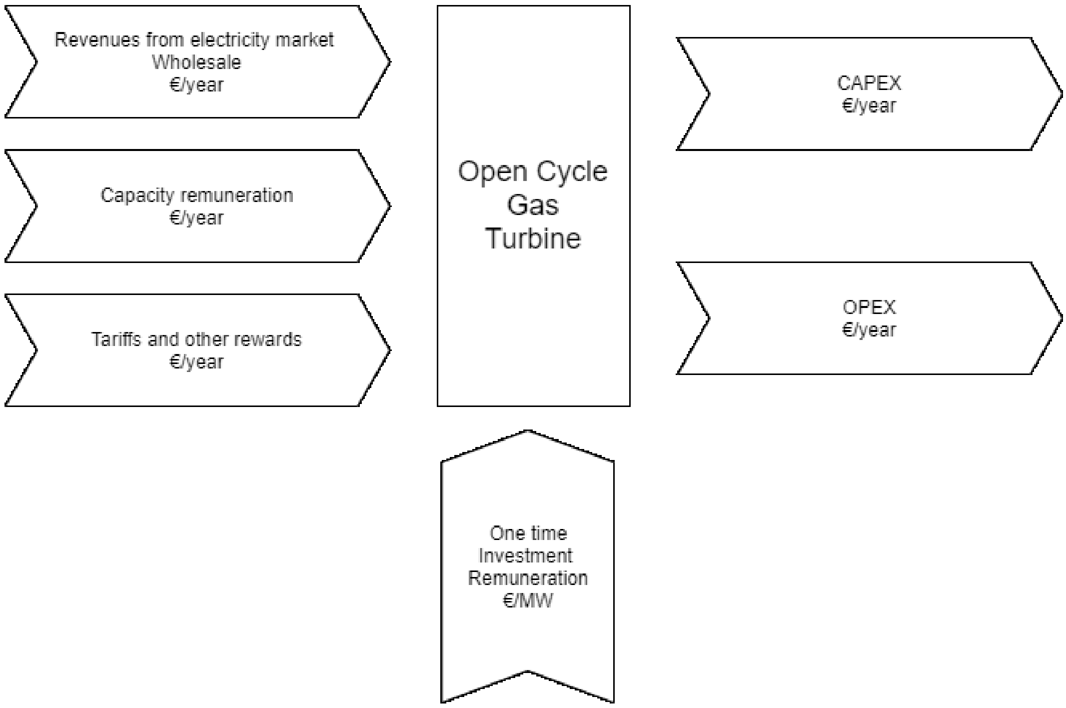

Figure 28. Revenue streams flow chart for GT.

Data for calculating capacity remuneration, tariffs and other rewards are presented in Table 9 Table 9. Capacity remuneration, tariffs and other rewards. (EirGrid & SONI 2018), and data for calculating costs for CO_2, fuel price and start-up costs are presented in Table 10.

Table 9. Capacity remuneration, tariffs and other rewards. (EirGrid & SONI 2018), (Frontier Economics 2019), (SEM Committee 2018), (EirGrid & SONI 2019)

IRELAND	
DS3	
Tariff RR (€/MWh)	0.56
Tariff RM3 (€/MWh)	0.16
Tariff RM8 (€/MWh)	0.14
DS3 Capacity payment per year (€/MW)	16 100
Other	
Capacity payment per year (€/MW)	40 650
New capacity investment (€/MW)	300 000

Table 10. Fuel price, CO_2 and start-up costs for GTs. (European Comission 2019), (Perez Linkenheil et al. 2017)

	IRELAND	BELGIUM
CO_2 (€/MWh)	27	27
Average fuel price (€/t)*	456	357
Start-up costs (€/MW)	44	44

*Taxes included

OCGT CAPEX and annual fixed OPEX in Ireland is based on PÖYRYS' report *COST OF NEW ENTRANT PEAKING PLANT AND COMBINED CYCLE PLANT IN I -SEM : A report to the Utility Regulator and the Commission for Regulation of Utilities* (PÖYRY 2018). CAPEX and fixed OPEX in Belgium is based on FICHTNER's report *Cost of Capacity for Calibration of the Belgian Capacity Remuneration Mechanism (CRM)* (FICHTNER 2020). Values are presented in the Table 11.

Table 11. OCGT CAPEX and annualized fixed OPEX. (PÖYRY 2018), (FICHTNER 2020)

	Ireland	Belgium
CAPEX		
EPC Contract price €/MW	506 100 €/MW	410 000 €/MW
Filling fuel tank % of EPC	Depends on consumption. 3.5 day for full load.	0.5%
Other % of EPC	18%	20.4%
Fixed OPEX €		
Operating costs % of EPC or €/MW	0.8%	14 400 €/MW
Incurrence % of EPC	0.6%	0.5%
Maintenance % of EPC	0.5%	0.5%

Land, water connection, electrical connection costs and interests during construction are excluded from CAPEX calculations because these values vary depending on construction site.

8.2 Battery energy storage system

In this study four different sizes Lit-ion BESS' was chosen based on sizes of the OCGTs. Investment costs, operational costs and revenues for new BESS' was collected and calculated in both Ireland and in Belgium based on literature, researches and publicly available IDA and BM price data. Same usage data from OCGTs was used.

Technical data for BESS' is presented in the Table 12. Two different power sizes and discharge duration were chosen.

Table 12. Technical data for BESS'

Size	**BESS1**	**BESS2**	**BESS3**	**BESS4**
Power (MW)	25	25	104	104
Energy (MWh)	25	100	104	416
Discharge duration (h)	1	4	1	4

Same usage data and IDA prices for capacity market was used than for GTs. Total run hours, number of starts and capacity produced by GTs is presented in the Table 8.

Based on GT usage data duration and energy produced is grouped for time slots from 1 hour to 5 hours. In a Table 13 and a Table 14 is presented the duration, number of period and if the BESS can deliver needed capacity.

Table 13. BESS' capability to replace 25MW GT.

		BESS can exceed the required capacity	
Duration	Number of periods	25MW/25MWh	25MW/100MWh
1h	5	yes	yes
2h	2	yes	yes
3h	1	yes	yes

Table 14. BESS' capability to replace 104MW GT.

		BESS can exceed the required capacity	
Duration	Number of periods	104MW/104MWh	104MW/416MWh
1h	6	yes	yes
2h	13	yes	yes
3h	5	yes	yes
4h	4	no	yes
5h	1	yes	yes

Revenue streams for BESS' is described in the Figure 29. BESS' that are used for peak loads gets most of the revenues by capacity payments, for being available and other remuneration such as tariffs. If BESS' are used in multiple purposes for example ancillary services revenues are much higher. In wholesale market revenues are relatively small but additional revenues from ancillary services makes BESS' more profitable.

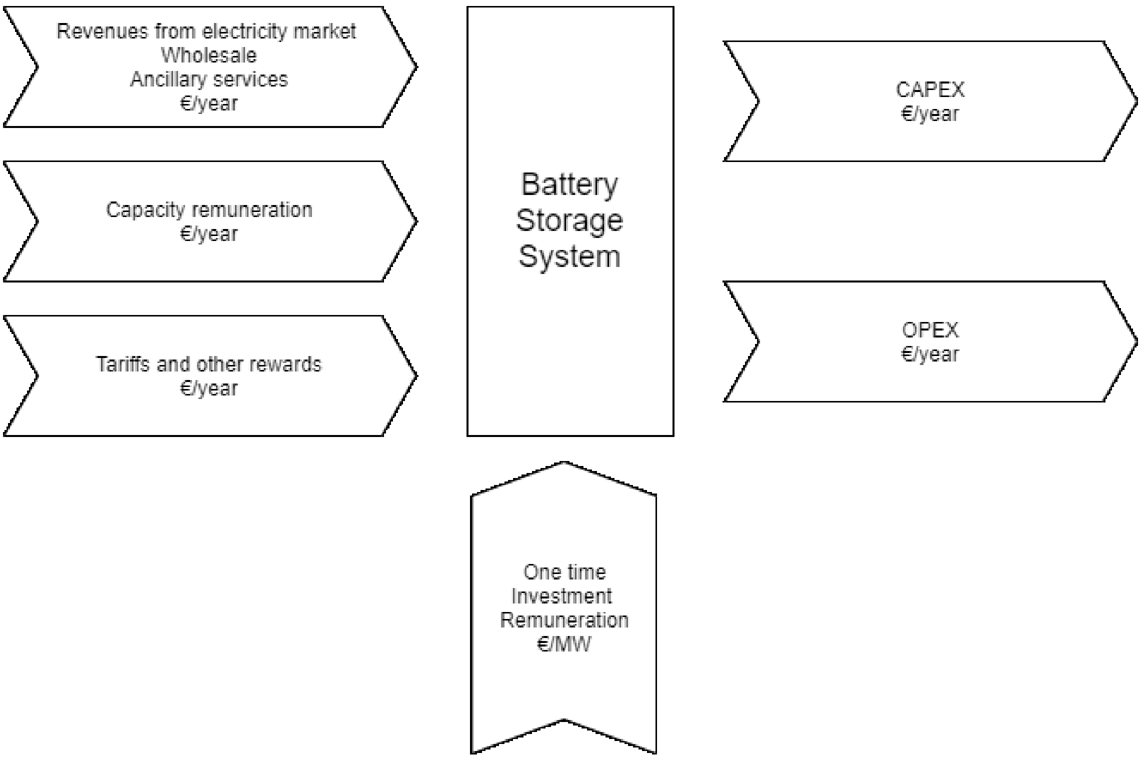

Figure 29. Flow chart of BESS' revenue stream.

Data for calculating capacity remuneration, tariffs and other rewards in Ireland are presented in Table 15.

Table 15. Capacity remuneration, tariffs and other rewards for BESS' in Ireland. (EirGrid & SONI 2018), (Frontier Economics 2019), (SEM Committee 2018), (EirGrid & SONI 2019)

IRELAND	
DS3	
Tariff FFR (€/MWh)	2.16
Tariff POR (€/MWh)	3.24
Tariff SOR (€/MWh)	1.69
Tariff TOR1 (€/MWh)	1.55
Tariff TOR2 (€/MWh)	1.24
Tariff RR (€/MWh)	0.5
Tariff RM3 (€/MWh)	0.16
Tariff RM8 (€/MWh)	0.14
Tariff RRD (€/MWh)	0.56
DS3 Capacity payment per year (€/MW)	16 100
Other	
Capacity payment per year (€/MW)	40 650
New capacity investment (€/MW)	300 000

In Ireland units which are part of DS3 program gets payments for example for ancillary services FFR-RM8 based on scalars, tariffs and available volume presented in Figure 30.

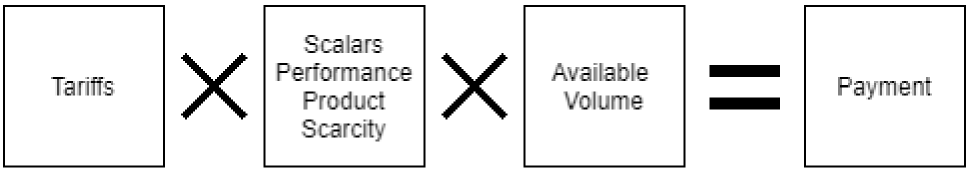

Figure 30. DS3 program payments: System Service Regulated Tariffs, Scalars and Volumes (EirGrid & SONI 2017).

In this study Performance, Product and Temporal Scarcity Scalar is used. These scalars are listed in the Table 16, Table 17 and Table 18.

Table 16. Performance Scalar. (EirGrid & SONI 2018)

Performance Scalar	
Availability %	**Scalar in %**
<60	0
60<70	25
70<80	50
80<90	70
90<95	85
95<100	100

Table 17. Product scalar (EirGrid & SONI 2018)

Product scalar	
Reaction time (ms)	**Scalar**
150	3
300	2.57
300<	0

Temporal Scarcity Scalars are calculated based on publicly available SNSP: Northern Ireland 60 days data (EirGrid 2020) by using method in research *Stacking Battery Energy Storage Revenues with Enhanced Service Provision* (Borgan et al. 2019) Values for Temporal Scarcity Scalar is presented in Table 18.

Table 18. Temporal scarcity scalar

Temporal Scarcity Scalar						
SNSP Level %	**POR-TOR2**	**POR-TOR2 % per 60 days**	**FFR**	**FRR % per 60 days**	**DRR**	**DRR % per 60 days**
<50	1	53.8	0	53.8	1	69.1
50<60	1	15.2	1	15.2		
60<70	4.7	30.9	4.7	30.9	6.2	30.9
>70	6.3	0	6.3	0	8.5	0
Temporary Scarcity Scalar	**2.14**		**1.61**			**2.61**

Electricity prices for 2019 in Ireland and in Belgium is used in this study. In Ireland 136.4€/MWh and in Belgium 80.2€/MWh. Prices includes taxes. (eurostat Statistics Explaned 2020)

CAPEX for BESS' is collected from three different reports *Electrochemical Energy Storage: Lithium-Ion Battery* EASE (2020), *Energy Transition in Belgium – Choices and Costs* (EnergyVille 2017) and EU's database *Database of the European energy storage technologies and facilities* (EU 2020). Values chosen to calculate current prices for BESS is presented in the Table 19.

Table 19. Current CAPEX and fixed OPEX prices for BESS'. EASE (2020), (EnergyVille 2017), (EU 2020)

CAPEX and fixed OPEX for BESS	
CAPEX 1 hour BESS (€/kWh)	700
CAPEX 4 hours BESS (€/kWh)	500
Fixed OPEX (% of CAPEX)	1.4
Fixed OPEX (€/kW)	5

8.3 Equations for BESS' state of charge in the symmetric electricity markets

Battery storage level was calculated by using rule-based MS Excel model. Battery storage state of charge (SOC) was calculated by Equation 5 which is used for symmetric load and arbitrage load.

$$E_{d,max}(t) = BSL_b(t) \times \eta \quad (4)$$

Equation 4. Maximum discharge energy. (Forsberg 2018)

$E_{d,max}(t)$ (MWh) is the maximum energy that can be discharged. $BSL_b(t)$ (MWh) is battery storage level before discharging. Discharge efficiency is η.

Battery storage level after charging is presented in Equation 5.

$$BSL_a = \begin{cases} BSL_b(t) + \eta \times D(t) & , D(t) \geq 0 \ \wedge \ BSL_a(t) < BSL_{max}(t) \\ BSL_{max}(t) & , D(t) \geq 0 \wedge \ BSL_a(t) \geq BSL_{max}(t) \\ BSL_b(t) - \frac{|D(t)|}{\eta} & , D(t) < 0 \ \wedge \ |D(t)| < E_{d,max}(t) \\ 0 & , else \end{cases} \quad (5)$$

Equation 5. Battery storage level. (Forsberg 2018)

D(t) (MWh) requested symmetric electricity.

BSL_a (MWh) is battery storage level after discharging or charging. (Forsberg 2018)

8.4 Market data for Belgium and Ireland

In this study two different markets Ireland and Belgium was studied. In Belgium's markets FCR, aFRR, mFRR Flex and mFRR Standard was studied. In Ireland FFR, POR, SOR, TOR1 and RRD and capacity IDA was chosen. Ancillary services in Belgium and Ireland are presented in Table 20

Table 20. Ancillary services in Belgium and in Ireland. (Moseley et al. 2014), (next 2020)

EU general	Belgium	Ireland
Spinning reserve (Instant)	R1 (primary reserve) FCR (Instant)	SIR (kinetic energy) FFR (2-10s) POR (5-15s)
Primary Reserve (30sec-15min)	R2 (secondary reserve) aFRR (30s-15min)	SOR (15-90s) TOR1 (90s-15min) TOR2 (5-20min)
Secondary Reserve (15min-1hours)	R3 (tertiary reserve) mFRR (15min-hours)	RRD (20min-1h) RRS (20min-1h)
Tertiary Reserve (<4 hours)		RM1 (1h) RM3 (3 hours) RM8 (8 hours)

More information about market data, prices, loads and frequency for Belgium and Ireland are listed in a Table 37 which can be found from Appendices 1.

8.5 Revenue streams

Revenue streams for BESS' are calculated with simple rule-based MS Excel models. Model is based for BESS power and capacity, load, prices and market structures.

In Belgium FCR, aFRR and mFRR and in Ireland DRR and FFR-TOR1 have different types of models because market structure for these services differs from each other.

8.5.1 Belgium frequency containment reserve

Frequency containment reserve (FCR) market is symmetric, and BESS can earn revenues from both charging and discharging. Revenues are paid based on power charged and discharged €/MW. Sold energy is calculated by using requested load, SOC and by converting capacity in to sold energy. Equation 5 is used to calculate SOC.

Sensitivity analysis is performed by changing minimum energy price €/MWh from 5 to 150 €/MWh in 10€/MWh steps.

Assumption: BESS is participating to FCR market as much as it can, and it always wins in the market auction. BESS is only charged when requested capacity is negative.

BESS1, BESS2 and BESS3 earns the most €/year when all the price (€/MWh) above zero is accepted. BESS4 earns the most when the price (€/MWh) is above 10€/MWh). Results from sensitivity analysis for FCR is presented in the Table 38 in Appendices 2. Highest yearly revenues for BESS1 is 1 100 000€ per year, BESS2 is 1 440 000€ per year, BESS3 is 1 940 000€ per year and BESS4 is 1 510 000€.

8.5.2 Belgium automatic frequency restoration

Belgium's automatic frequency restoration (aFRR) market consist of two different markets aFRR+ and aFRR-. BESS can earn revenues from both discharging in aFRR+ and charging in aFRR- markets. Revenues are based on energy charged and discharged €/MWh. Sold energy is calculated by using requested load, SOC and by converting capacity in to sold energy. Equation 5 is used to calculate SOC.

In this Excel based model SOC is based on requested load and energy price. Model decides requested load based on SOC and revenues. Sensitivity analysis is conducted by changing minimum price for charging and discharging. For charging from 0€/MWh to 20€/MWh in every 5€/MWh steps. For discharging from 0€ to 80€/MWh in every 10€/MWh steps.

Assumptions: Assumption: BESS is participating to aFRR market as much as it can, and it always wins in market auction. BESS is only charged when requested capacity is negative.

BESS1, BESS2 and BESS3 earns the most when minimum charging price is above 0€/MWh, 20€/MWh and/or 40€/MWh and discharging prices (€/MWh) are above zero without limitations.

BESS4 earns the most when charging and discharging prices (€/MWh) are above zero without limitations.

Highest revenues for BESS1 is 800 000€ per year, for BESS2 around 1 360 000€ per year, for BESS3 around 2 850 000 € per year, and for BESS4 7 530 000€ per year. Results from sensitivity analysis for aFRR are presented in Table 39, Table 40, Table 41 and Table 42 Appendices 3-6.

8.5.3 Belgium frequency restoration via manual activation mFRR

There are two different types of frequency restoration service via manual activation (mFRRs), mFRR Standard and mFRR Flex. They both have own markets with different pricing and loads. In this study these markets are studied separately. During discharging revenues are payed according the pricing €/MWh. Charging costs for the BESS owner is calculated with 80.2 €/MWh which is EU price for electricity in Belgium in the year 2019.

In this Excel based model SOC is based on load and energy price. Model decides requested load based on SOC and revenues. Sensitivity analysis is conducted by changing the minimum price €/MWh for discharging and by reducing charging costs €/MWh. For discharging the minimum price sensitivity analysis is conducted from 0 €/MWh to 1000 €/MWh in every 200 €/MWh steps.

Assumptions: Assumption: BESS is participating to mFRR market as much as it can, and it always wins in the market auction. BESS is only charged when requested capacity is zero or BESS's SOC is 5%.

mFRR Flex market

BESS1-BESS4 earn their highest revenues when market price is not limited. Highest revenues for BESS1 is 160 000€ per year, BESS2 it is 295 000€ per year, BESS3 it is 610 000€ per year and BESS4 it is 860 000€ per year. Results from sensitivity analysis for mFRR Flex are presented in Table 43, Table 44, Table 45 and Table 46 in Appendices 7-10.

mFRR Standard

BESS1-BESS4 earn their highest revenues when price is limited from 0€/MWh to 200€/MWh. Highest revenues for BESS1 is 800 000€ per year, BESS2 it is1 750 000€ per year, BESS3 it is 2 940 000 € per year and BESS4 it is 5 230 000€ per year. Results from sensitivity analysis for mFRR Standard are presented in Table 47, Table 48, Table 49 and Table 50 in Appendices 11-14.

8.5.4 Belgium summary of revenue streams

Summary of the highest revenues in different markets in Belgium is presented in the Table 21. These values are used in the financial calculations.

Table 21. Summary of highest revenues in different markets in Belgium.

	BESS1	BESS2	BESS3	BESS4	GT 25MW	GT 104MW
FCR €/year	1 100 000	1 440 000	1 940 000	1 510 000	-	-
aFRR €/year	800 000	1 357 500	2 852 500	7 530 000	-	-
mFRR Stan €/year	800 000	1 750 000	2 940 000	5 230 000	130 000	5 870 000
mFRR Flex €/year	160 000	295 000	610 000	860 000	1 500 000	34 180 000

8.5.5 Ireland system services

System services form FFR to TOR1 is handled as one entity. FFR-TOR1 market is symmetric and BESS can earn revenues from both charging and discharging. Revenues are paid based on energy charged and discharged €/MW. Sold energy is calculated by using requested load, SOC and by converting capacity in to sold energy. Equation 5 is used to calculate SOC.

Sensitivity analysis is performed by changing minimum energy price €/MW from 0 to 150 €/MW in 50€/MW steps.

Assumption: BESS is participating to FFR-TOR1 market as much as it can, and it always wins in market auction. BESS is only charged when requested capacity is negative.

BESS earns revenue also via DS3 program. Additional award €/MWh is based on Scalars presented in Table 15, Table 16, Table 17, Table 18 and capacity reward €/MW per year.

All the BESS' earn the most €/year when all the prices €/MW above zero is accepted. Highest revenues with DS3 program for BESS1 are 1 430 000€ per year, BESS2 they are

2 550 000 € per year, BESS3 they are 1 810 000€ per year and BESS4 they are 2 560 000€ per year. Results from sensitivity analysis for FFR-TOR1 with DS3 program is presented in the Table 51 in the Appendices 15. Highest revenues without DS3 program for BESS1 are 1 100 000€ per year, BESS2 they are 1 940 000 € per year, BESS3 they are 1 410 000€ per year and BESS4 they are 1 940 000€ per year. Results from sensitivity analysis for FFR-TOR1 without DS3 program is presented in the Table 52 in the Appendices 16.

8.5.6 Ireland intraday auction market IDA

In IDA BESS earns revenue by discharging €/MWh. Charging costs for the BESS owner is calculated with 130.2 €/MWh which is EU price for electricity in Ireland in the year 2019.

In this Excel based model SOC is based on load and energy price. Model decides requested load based on SOC and revenues. Sensitivity analysis is conducted by changing the minimum price €/MWh for discharging and by reducing charging costs €/MWh from the revenues. For discharging the minimum price sensitivity analysis is conducted from 0 €/MWh to 150€/MWh in every 50 €/MWh steps.

Assumptions: BESS is participating to IDA as much as it can, and it always wins in the market auction. BESS is only charged when requested capacity is zero or BESS's SOC is 5%.

BESS1 earns its biggest revenue 109 000 € per year when IDA price is above 150€/MWh. BESS2 earns its biggest revenue 432 000€ per year when IDA price is above 100€/MWh. BESS3 earns its biggest revenue 414 000€ per year when IDA price is above 150€/MWh. BESS4 earns its biggest revenue 9 291 000€ per year when IDA price is above 50€/MWh. Results from sensitivity analysis are presented in Table 53, Table 54, Table 55 and Table 56 in the Appendices 17-20.

8.5.7 Ireland Summary of revenue streams

Summary of the highest revenues in different markets in Ireland is presented in the Table 22. These values are used in financial calculations.

Table 22. Summary of highest revenues in different markets in Ireland.

	BESS1	BESS2	BESS3	BESS4	GT 25MW	GT 104MW
FFR-TOR1+DS3 €	1 430 000	2 550 000	1 810 000	2 560 000	-	-
IDA+DS3 €	109 000	432 000	414 000	9 291 000	1 430 000	8 180 000

9 Financial analysis for OCGTs and BESS’

In this comparison analysis two different sizes of gas turbines and four different sizes of BESS’ are compared as an investment in two different countries in Ireland and in Belgium. For each BESS and GT annualized costs, NPV and discounted payback with discount rate 4% is calculated, as well as IRR and simple payback. Each GT and BESS is analyzed separately.

Detailed calculation results of GTs are presented in the Table 57 and Table 58, in the Appendices 21 and 22. Detailed calculation results for BESS’ in Belgium are presented in the Table 59, Table 60, Table 61 and Table 62 in the Appendices 23-26. Detailed calculation results with DS3 program for BESS’ in Ireland are presented in Table 63, Table 64, Table 65 and Table 66 in the Appendices 27-30. Detailed calculations for BESS’ in Ireland without DS3 program is presented in the Table 67, Table 68, Table 69 and Table 70 in the Appendices 31-34.

Profitability for storages are calculated with different scenarios.

1. All storages are calculated with two different CAPEX for one-hour BESS 450€/kWh and 200€/kWh and for four hours BESS 350€/kWh and 200€/kWh.
2. Revenues for BESS’ are calculated by two cases
    a. Case1 minimum revenues (one service only)
    b. Case2 potential revenues (sum of all services)

Sum of all services is not accurate because in this model services are not co-optimized in the dispatch. A more robust dispatch optimization would prioritize the services in same time to optimize the use of BESS and maximize the revenues. This could be done for example by machine learning. In these calculations the individual services give the contribution from each service, whereas the sum of all services gives the maximum potential which could be achieved by combining different services. Real revenues for BESS’ are somewhere between the highest individual revenue (called the “minimum” revenue in this work) and sum of all services.

9.1 Financial analysis in Belgium

Profitability for each GT and BESS is analyzed separately by using key figures: Net CAPEX, OPEX, Revenues, IRR, NPV, Simple Payback, Discounted Payback, Annualized Costs and Annualized Profits. Each GT and BESS has its own key figure table.

Minimum revenue has been chosen from four different markets FCR, aFRR, mFRR Flex and mFRR Standard by using rule-based Excel models. The most profitable of these individual markets is used in the financial analysis, although there is likely higher revenue possible through improved dispatch optimization that combines revenue from the various services.

9.1.1 Open cycle gas turbines 25MW and 104MW in Belgium

Revenues for 25MW and 104MW GTs have been calculated with in two different markets mFRR Flex and mFRR Standard. For 25MW and 104MW GTs mFRR Flex market is the most profitable. The most optimistic key figures are presented in the Table 23. Detailed calculations can be found from Appendices 21.

Revenues highly differs between 25MW and 104MW because the use of 104MW GT managed to hit the market during the highest prices. Because of that yearly revenues for 104 MW GT might be much lower. 25 MW GT’s revenues are lower but still in reasonable level.

In this study GTs earn their revenues from mFRR Flex market. IRR for 104MW GT is high 55%. It seems good for investors point of view but compared to GT’s running hours IRR is rather high. IRR for 25 MW GT is 14% which is more reasonable for this type of gas turbine power plant.

NPV is positive for both 25MW GT and 104MW GT which indicates that investors could consider investing in these projects.

For payback period the effect for discount rate is rather small. For 104MW GT the payback is too optimistic but for 25MW GT payback period from 6 to 7 years is reasonable.

Annualized revenues for both GTs with 0% and 4% discount rate are positive and they are earning revenues every year.

Calculations for 25MW and 104MW GTs shows that to achieve more reliable results more data is needed. In this case one year of data was used. 104MW GT was hitting the market during high prices and 25MW GT was hitting the market during low prices. Longer time period smoothens out these peaks and gives more reliable results. One reason for these results is that data for GTs is collected from two different countries which means that for example seasonal changes are different and demand for energy is different during the day.

Table 23. Key figures for 25MW and 104MW GTs in Belgium.

Ireland GTs	25MW	104MW
Net CAPEX €	6 200 000	51 550 000
OPEX €/year	461 000	2 800 000
Revenues €/year	1 500 000	34 180 000
IRR %	14 %	55 %
NPV €	4 590 000	240 720 000
Simple Payback, (Discount Rate 0%)	6	2
Discounted Payback, (Discount Rate 4%)	7	2
Annualized Costs €/year (Discount Rate 0%)	-870 000	-6 240 000
Annualized Costs €/year (Discount Rate 4%)	-1 020 000	-7 440 000
Annualized Profit €/year, (Discount Rate 0%)	630 000	27 940 000
Annualized Profit €/year, (Discount Rate 4%)	480 000	26 740 000

9.1.2 Battery storage 25MW/25MWh in Belgium

CAPEX for BESS1 is calculated with two different values 450€/kWh and 200€/kWh. Actual revenues for BESS1 is calculated based on FCR revenues and potential revenues are calculated based on sum of FCR, aFRR and mFRR Standard. Key figures for BESS1 is presented in the Table 24. Belgium BESS1 25MW/25MWh key figures. and more detailed calculations are presented in Appendices 22.

Case 1

IRR and NPV for Case 1 is too low for 450€/kWh BESS. IRR does not reach to 10% and NPV is negative. Payback period is too long around and above 15 years. Annualized revenues are positive but still in this case investment is not viable.

For 200€/kWh BESS IRR is over 10% and NPV is positive. Payback is from 6 to 7 years which is in considerable level for investors. Annualized revenues are same than for 450€/kWh BESS but because of the reduced investment costs revenues are in a good level. Based on this investment BESS1 is good investment.

Case 2

Results calculated by potential revenues for 450€/kWh and 200€/kWh BESS are both in good level. For 450€/kWh BESS IRR is over 10% and NPV is positive. Payback is 6 years and annualized revenues are in good level. 200€/kWh BESS results are even better with IRR over 40% and high NPV. Payback is 3 years and annualized revenues are higher than for 450€/kWh BESS. Based on this both are profitable investments.

These cases are calculated by 3-, 4-, 5- and 12-months data which makes the calculations inaccurate. To get more accurate results more data is needed. Also sum of the revenues needs to be calculated by more accurate method.

Table 24. Belgium BESS1 25MW/25MWh key figures.

Belgium BESS1 (25MW/25MWh)	450€/kWh		200€/kWh	
	Case1	Case2	Case1	Case2
Net CAPEX €	11 250 000		5 000 000	
OPEX €/year	180 000		180 000	
Revenues €/year	1 100 000	2 700 000	1 100 000	2 700 000
IRR %	2%	17%	16%	42%
NPV €	-1 470 000	11 120 000	4 540 000	17 130 000
Simple Payback, (Discount Rate 0%)	13	6	6	3
Discounted Payback, (Discount Rate 4%)	15<	6	7	3
Annualized Costs €/year (Discount Rate 0%)	-930 000		-510 000	
Annualized Costs €/year (Discount Rate 4%)	-1 190 000		-630 000	
Annualized Profit €/year, (Discount Rate 0%)	920 000	1 230 000	920 000	1 650 000
Annualized Profit €/year, (Discount Rate 4%)	920 000	970 000	920 000	1 530 000

From technical point of view BESS1 can replace 25MW GT when the usage data from GT is used.

BESS1 acts differently in different markets. BESS1 SOC levels in FCR, aFRR, mFRR Flex and mFRR Standard markets are presented in the Figure 31, Figure 32, Figure 33 and Figure 34. In FCR and aFRR market BESS1 uses its whole capacity, SOC from 5% to 95% and it actively varies all the time. In mFRR Flex market BESS1 is fully charged almost all the time. In the mFRR Standard market BESS1 is fully charged less than half of the time and when discharging the demand is high and SOC decreases rapidly. BESS1 is used for its full capacity, SOC from 5% to 95%. Based on the way that BESS1 acts in different markets with its full capacity tells that it does not have great potential for provide combination on different services. In case to achieve higher revenues BESS1 needs to be used strategically and in a smart way to combine different markets.

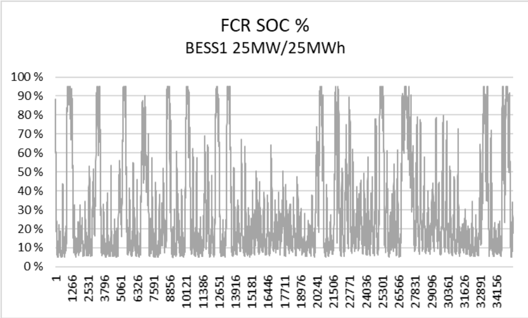

Figure 31. BESS1 FCR SOC %.

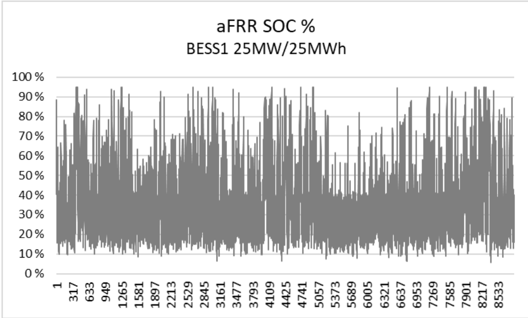

Figure 32. BESS1 aFRR SOC %.

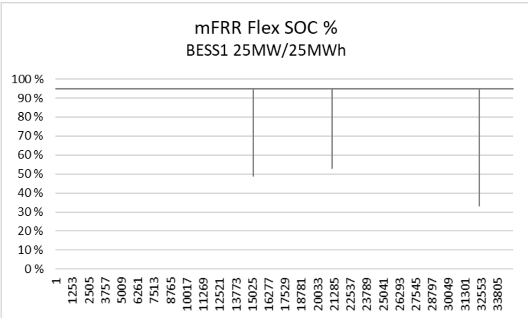

Figure 33. BESS1 mFRR Flex SOC %.

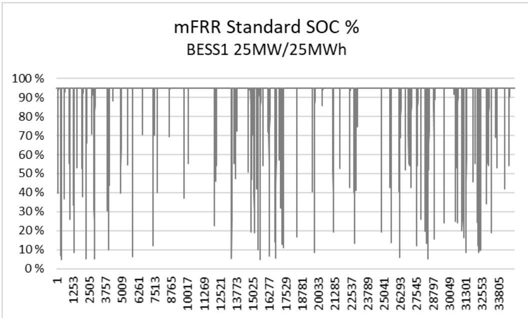

Figure 34. BESS1 mFRR Standard SOC %.

9.1.3 Battery storage 25MW/100MWh in Belgium

CAPEX for BESS2 is calculated with two different values 350€/kWh and 200€/kWh. Actual revenues for BESS2 is calculated based on mFRR Standard revenues and potential revenues are calculated based on sum of FCR, aFRR and mFRR Standard. Key figures for BESS2 is presented in Table 25 and more detailed calculations are presented in Appendices 23.

Case 1

IRR and NPV for Case 1 is too low for 350€/kWh BESS. IRR does not reach 10% and NPV is negative. Payback period is too long around and above 15 years. Annualized revenues are negative. In this case investment is not viable.

For 200€/kWh BESS IRR is barely over 10% and NPV is positive. Payback is from 8 to 9 years. Annualized revenues for discount rate 0% are relatively small under 100 000€/year and with derate of 4% annualized revenues are negative. In this case 200€/kWh BESS is not a good investment.

Case 2

Results calculated by potential revenues for 350€/kWh and 200€/kWh BESS are both in good level. For 350€/kWh BESS IRR is over 20% and NPV is positive. Payback is from 3 to 6 years. For 350€/kWh BESS annualized revenues for 4% discount rate are relatively low but for 0% discount rate revenues are in good level.

200€/kWh BESS' results are even better with IRR over 30% and high NPV. Payback is 3. Annualized revenues are in good level for 200€/kWh. Both 350€/kWh and 200€/kWh BESS' are good investments.

These cases are calculated by 3-, 4-, 5- and 12-months data which makes the calculations inaccurate. To get more accurate results more data is needed. Also sum of the revenues needs to be calculated by more accurate method. By these calculations biggest revenues are earned in mFRR Standard market. At the moment this market might exclude batteries because resources which are participating in this market needs to be available all the time and if battery is used it needs time to charge. mFRR Flex market gives 8 hours recovery time for resources, but mFRR Flex market is less used than mFRR Standard market, so the revenues are much lower.

Table 25. Belgium BESS2 25MW/100MWh key figures.

Belgium BESS2 (25MW/100MWh)	**350€/kWh**		**200€/kWh**	
	Case1	Case2	Case1	Case2
Net CAPEX €	35 000 000		20 000 000	
OPEX €/year	175 000		175 000	
Revenues €/year	1 750 000	4 548 000	1 750 000	4 548 000
IRR %	3%	21%	11%	35%

NPV €	-830 000	24 030 000	5 180 000	30 040 000
Simple Payback, (Discount Rate 0%)	12	5	8	3
Discounted Payback, (Discount Rate 4%)	15<	5	9	3
Annualized Costs €/year (Discount Rate 0%)	-2 510 000		-1 510 000	
Annualized Costs €/year (Discount Rate 4%)	-3 320 000		-1 970 000	
Annualized Profit €/year, (Discount Rate 0%)	-935 000	1 512 500	65 000	2 512 500
Annualized Profit €/year, (Discount Rate 4%)	-1 745 000	702 500	-395 000	2 052 500

From technical point of view BESS2 can replace 25MW GT when the usage data from GT is used.

BESS2 acts differently in different markets. BESS2 SOC levels in FCR, aFRR, mFRR Flex and mFRR Standard markets are presented in the Figure 35, Figure 36, Figure 37 and Figure 38. In FCR market BESS2 uses it whole capacity, SOC from 5% to 95% and it actively varies all the time. But the full SOC is rare and the variation happens mostly between 5% and 10%. aFRR market BESS2 uses only its capacity between SOC 5% to 25% in most of the time and it actively varies between these SOCs. In mFRR Flex market BESS2 is fully charged almost all the time. In mFRR Standard market BESS2 uses its full capacity but over half of the time it is fully charged and during demand it is strongly discharged. Based on this BESS2 has potential to provide several services but if it is used for one service only one-hour BESS is better option.

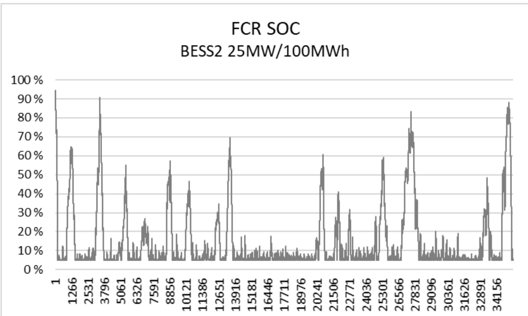

Figure 35. BESS2 FCR SOC %

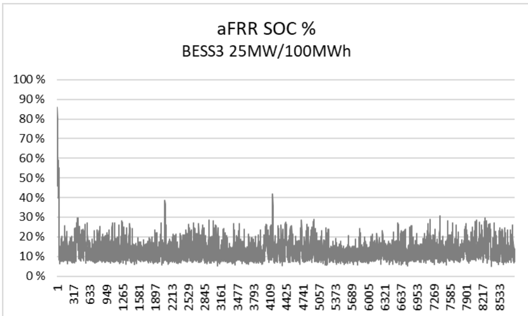

Figure 36. BESS2 aFRR SOC %

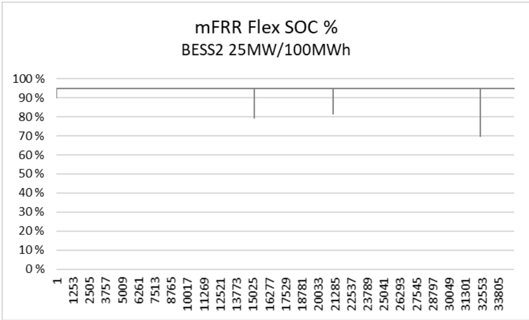

Figure 37. BESS2 mFRR Flex SOC %

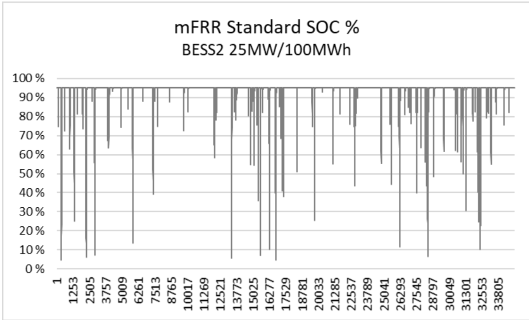

Figure 38. BESS2 mFRR Standard SOC %

9.1.4 Battery storage 104MW/104MWh in Belgium

CAPEX for BESS3 is calculated with two different values 450€/kWh and 200€/kWh. Actual revenues for BESS3 is calculated based on mFRR Standard revenues and potential revenues are calculated based on sum of FCR, aFRR and mFRR Standard. Key figures for BESS3 is presented in Table 26 and more detailed calculations are presented in Appendices 24.

Case 1

IRR and NPV for Case 1 is too low for 450€/kWh BESS. IRR and NPV are negative. Payback period is too long over 15 years. Annualized revenues are negative so in this case investment is not viable.

For 200€/kWh BESS3 IRR is barely over 10% and NPV is positive. Payback is from 10 to 12 years. Annualized revenues for derate 0% is relatively small bit over 100 000€/year and with derate of 4% annualized revenues are negative. In this case 200€/kWh BESS is not a good investment.

Case 2

Results calculated by potential revenues for 450€/kWh and 200€/kWh BESS3 are both in good level. For 350€/kWh BESS3 IRR is under 10% and NPV is positive. Payback is from 9 to 11 years. For 350€/kWh BESS3 annualized revenues for 4% discount rate are relatively low but for 0% discount rate revenues are in good level. This is not a good investment.

200€/kWh BESS' results are better with IRR over 20% and high NPV. Annualized revenues are in good level. Payback is from 4 to 5 years. 200€/kWh BESS is good investment.

These cases are calculated by 3-, 4-, 5- and 12-months data which makes the calculations inaccurate. To get more accurate results more data is needed. Also sum of the revenues needs to be calculated by more accurate method. By these calculations biggest revenues are earned in mFRR Standard market. At the moment this market might exclude batteries because resources which are participating in this market needs to be available all the time. If battery is used it needs time to charge. mFRR Flex market gives 8-hour recovery time for resources, but mFRR Flex market is less used than mFRR Standard market. In mFRR Flex market revenues are rather small compared to mFRR Standard market.

Table 26. Belgium BESS3 104MW/104MWh key figures.

Belgium BESS3 (104MW/104MWh)	**450€/kWh**		**200€/kWh**	
	Case1	Case2	Case1	Case2
Net CAPEX €	46 800 000		20 800 000	
OPEX €/year	710 000		710 000	
Revenues €/year	2 940 000	7 730 000	2 940 000	7 730 000
IRR %	-5%	8%	5%	26%
NPV €	-22 350 000	11 880 000	2 650 000	36 880 000
Simple Payback, (Discount Rate 0%)	15<	9	10	4
Discounted Payback, (Discount Rate 4%)	15<	11	12	5
Annualized Costs €/year (Discount Rate 0%)	-3 830 000		-2 100 000	
Annualized Costs €/year (Discount Rate 4%)	-4 920 000		-2 580 000	
Annualized Profit €/year, (Discount Rate 0%)	-1 600 000	1 770 000	130 000	3 500 000
Annualized Profit €/year, (Discount Rate 4%)	-2 690 000	680 000	-350 000	3 020 000

From technical point of view BESS3 can replace 104MW GT except in one 4-hour case where 104MWh capacity was exceeded.

BESS acts differently in different markets. BESS3 SOC levels in FCR, aFRR, mFRR Flex and mFRR Standard markets are presented in the Figure 39, Figure 40, Figure 41 and Figure

42. In aFRR market BESS3 uses it whole capacity, SOC from 5% to 95% and it actively vary all the time. In FCR Market BESS3 uses its whole capacity but full SOC is rare and the variation happens mostly between 5% and 30%. In mFRR Flex market BESS3 is fully charged almost all the time. In mFRR Standard market BESS3 uses its full capacity but below half of the time it is fully charged and during demand it is strongly discharged. Based on this information BESS3 have capacity to provide several services.

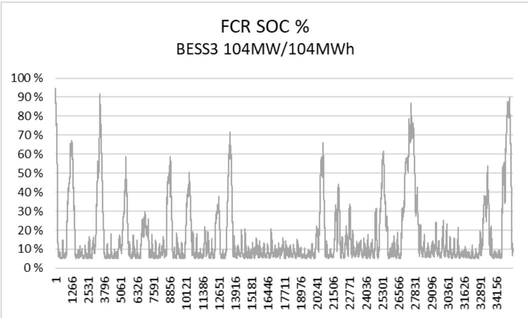

Figure 39. BESS3 FCR SOC %

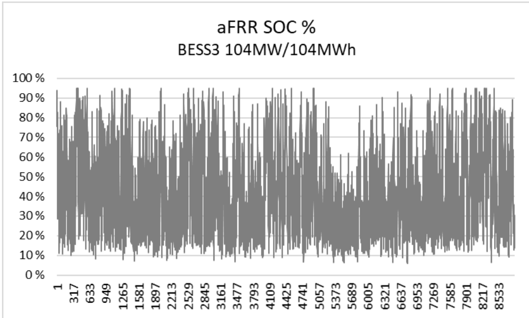

Figure 40. BESS3 aFRR SOC %

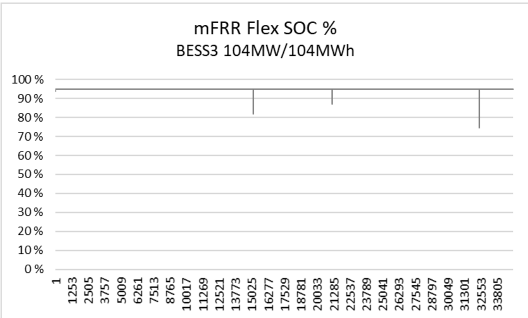

Figure 41. BESS3 mFRR Flex SOC %

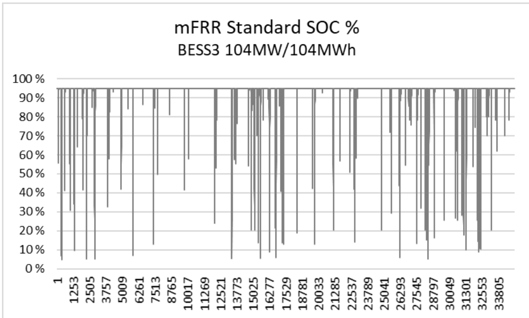

Figure 42. BESS3 mFRR Standard SOC %

9.1.5 Battery storage 140MW/416MWh in Belgium

CAPEX for BESS4 is calculated with two different values 350€/kWh and 200€/kWh. Actual revenues for BESS4 is calculated based on aFRR revenues and potential revenues are calculated based on sum of FCR, aFRR and mFRR Standard. Key figures for BESS4 is presented in Table 27 and more detailed calculations are presented in Table 61 Appendices 25.

Case 1

IRR and NPV for Case 1 is too low for 350€/kWh BESS. IRR and NPV are negative. Payback period is over 15 years. Annualized revenues are negative so in this case investment is not profitable.

For 200€/kWh BESS4 IRR is just 2% and NPV is negative. Payback is around and over 15 year. Annualized revenues for derate 0% is relatively small for this size investment and with derate of 4% annualized revenues are negative. In this case 200€/kWh BESS is not a good investment.

Case 2

Results calculated by potential revenues for 350€/kWh and 200€/kWh BESS' are both in good level. For 350€/kWh BESS4 IRR is just 2% and NPV is negative. Payback is from 12 to over 15 years. For 350€/kWh BESS annualized revenues for 4% discount rate are negative and for 0% discount rate revenues rather low for this size of investment. Based on this this is not a good investment.

Annualized revenues are in better level for 200€/kWh BESS. IRR for 200€/kWh BESS is 11% and NPV is in reasonable level. Payback is from 7 to 9 years and annualized revenues are higher than for 350€/kWh BESS. 200€/kWh BESS might be viable investment.

Table 27. Belgium BESS4 104MW/416MWh key figures.

Belgium BESS4 (104MW/416MWh)	**350€/kWh**		**200€/kWh**	
	Case1	Case2	Case1	Case2
Net CAPEX €	145 600 000		83 200 000	
OPEX €/year	710 000		710 000	
Revenues €/year	7 530 000	14 270 000	7 530 000	14 270 000
IRR %	-5%	2%	2%	11%
NPV €	-70 730 000	-16 700 000	-10 730 000	43 300 000
Simple Payback, (Discount Rate 0%)	15<	12	13	7
Discounted Payback, (Discount Rate 4%)	15<	15<	15<	9

Annualized Costs €/year (Discount Rate 0%)	-10 420 000		-6 260 000	
Annualized Costs €/year (Discount Rate 4%)	-13 810 000		-8 190 000	
Annualized Profit €/year, (Discount Rate 0%)	-3 600 000	1 720 000	560 000	5 880 000
Annualized Profit €/year, (Discount Rate 4%)	-6 990 000	-1 670 000	-1 370 000	3 950 000

For technical point of view BESS4 can replace 104MW GT.

BESS4 acts differently in different markets. BESS4 SOC levels in FCR, aFRR, mFRR Flex and mFRR Standard markets are presented in the Figure 43, Figure 44, Figure 45 and Figure 46. In aFRR market BESS4 uses it whole capacity, SOC from 5% to 95% and it actively varies all the time. In FCR Market BESS4 does not use its whole capacity and full SOC is rare and the variation happens mostly between 5% and 20%. In mFRR Flex market BESS4 is fully charged almost all the time. In mFRR Standard market BESS4 rarely uses its full capacity but below half of the time it is fully charged and during demand it is strongly discharged. Based on this information BESS4 has capacity to provide several services. Even if the BESS4 offers several services it seems to be too big for this market. It is too expensive and only small amount of its capacity is used.

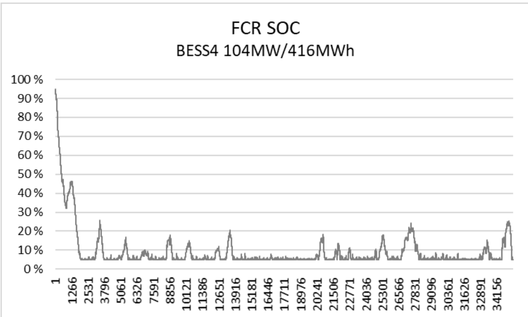

Figure 43. BESS4 FCR SOC %

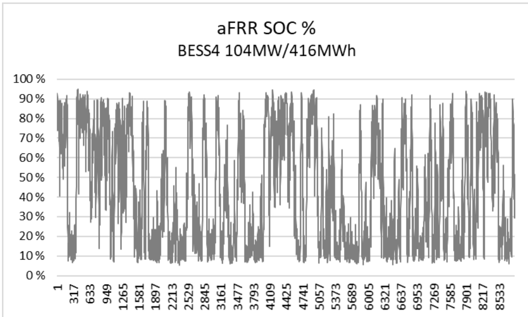

Figure 44. BESS4 aFRR SOC %

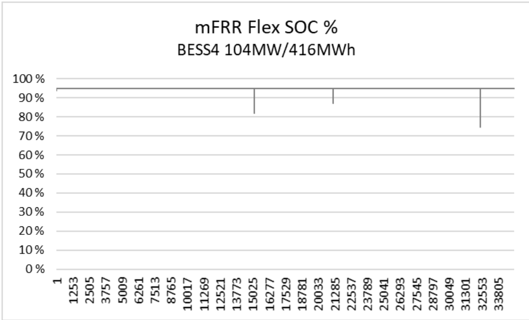

Figure 45. BESS4 mFRR Flex SOC %

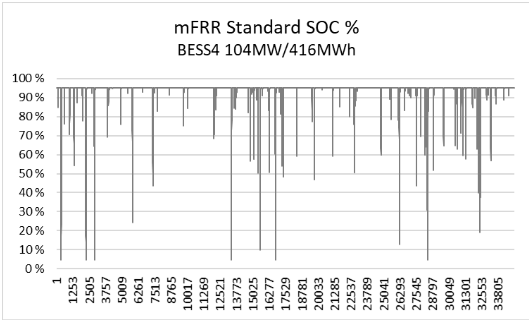

Figure 46. BESS4 mFRR Standard SOC %

9.2 Financial analysis in Ireland

Profitability for each GT and BESS is analyzed separately by using key figures: Net CAPEX, OPEX, Revenues, IRR, NPV, Simple Payback, Discounted Payback 4%, Annualized Costs and Annualized Profits. Each GT and BESS has its own key figure table.

Minimum revenue has been chosen from two different markets FFR-TOR1 and IDA by using rule-based Excel models. Most profitable market is used in the financial analysis.

Each BESS and GT is analyzed separately, and detailed calculations are presented in Appendices 22, 27-30. In Ireland there is a DS3 program which supports new fast acting power generation units and storages entering the market. In this section all the calculations are made by using revenues and rewards from DS3 program. Calculations without DS3 program can be found in Appendices 22, 31-34.

9.2.1 Gas turbine 25MW and 104MW in Ireland

Revenues for 25MW and 104MW GTs have been calculated based on IDA, capacity reservation payments and DS3 rewards. The most optimistic key figures are presented in the Table 28. Most of the revenues comes from capacity payments and only small amount is from IDA.

IRR for 25MW GT is low only 5% but NPV is positive and payback is between 10 and 14 years. Annualized revenues are positive. 25MW GT is not so viable investment because of low IRR and long payback.

IRR for 104MW GT is 16% and NPV is positive. Payback is between 6 and 7 years. Annualized revenues are positive, and they are in reasonable level. Based on these results 104MW GT would be worth to invest.

To get more reliable results more data is needed. In this case one year of data was used. 104MW is used more than 25MW GT during the year and that effects the results. Other reason which effects the results is that data for GTs is collected from two different countries which means that for example seasonal changes are different and demand for energy is different during the day.

Table 28. Key figures for 25MW and 104MW GTs in Ireland.

Ireland GTs	25MW	104MW
Net CAPEX €	7 590 000	31 760 000
OPEX €/year	671 000	2 500 000
Revenues €/year	1 430 000	8 180 000
IRR %	5%	16%
NPV €	410 000	27 150 000
Simple Payback, (Discount Rate 0%)	10	6
Discounted Payback, (Discount Rate 4%)	14	7
Annualized Costs €/year (Discount Rate 0%)	-1 180 000	-4 620 000
Annualized Costs €/year (Discount Rate 4%)	-1 350 000	-5 360 000
Annualized Profit €/year, (Discount Rate 0%)	250 000	3 560 000
Annualized Profit €/year, (Discount Rate 4%)	80 000	2 820 000

9.2.2 Battery storage 25MW/25MWh in Ireland

CAPEX for BESS1 is calculated with two different values 450€/kWh and 200€/kWh. Actual revenues for BESS1 is calculated based on IDA+DS3 revenues and potential revenues are calculated based on sum of IDA+DS3 and FFR-TOR1+DS3. Key figures for BESS1 is presented in Table 29 and more detailed calculations are presented in Appendices 27.

Case 1
CAPEX for 450€/kWh BESS is relatively low because of the DS3 program reward for new investment. Revenues are in good level. IRR is almost 40% and NPV is high. Payback is only 4 years and annualized revenues are in good level. 450€/kWh BESS is worth to invest.

CAPEX for 200€/kWh BESS is 0€ because of the reward from the DS3 program. This is not reasonable result because every investment cost something. Because of this IRR is 0% and payback is 0. NPV and annualized revenues are high.

Case 2
CAPEX for 450€/MWh BESS1 is relatively low because of the DS3 program reward for new investment. Revenues are in good level. IRR is over 70% and NPV is high. Payback is only 2 years and annualized revenues are in good level. 450€/MWh BESS is worth to invest.

CAPEX for 200€/kWh BESS is 0€ because of the reward from the DS3 program. This is not reasonable result because every investment cost something. Because of this IRR is 0% and payback is 0. NPV and annualized revenues are high.

DS3 program is temporary program which helps storage systems to enter the market and, in the future, it is not needed if the prices sink near to 200€/kWh. Without the program payback for BESS1 is 2 to 4 years and IRR is between 27% and 46%. Also annualized revenues are in good level. More detailed calculations without DS3 program can be found from Appendices 31. For these reason 200€/kWh is a good investment even without the DS3 program.

Data for IDA is for one year and for FFR-TOR1 it is for 4 months. To get more accurate results more data is needed. High peaks and low prices smoothen out when larger amount of data is used. Also effect of seasonal variation can be seen better.

Table 29. Ireland BESS1 25MW/25MWh key figures.

Ireland BESS1 (25MW/25MWh)	450€/kWh		200€/kWh	
	Case1	Case2	Case1	Case2
Net CAPEX €	3 750 000		0	
OPEX €/year	210 000		210 000	
Revenues €/year	1 620 000	3 210 000	1 620 000	3 210 000
IRR %	37%	74%	-	-
NPV €	10 720 000	24 730 000	14 320 000	28 340 000
Simple Payback, (Discount Rate 0%)	4	2	0	0
Discounted Payback, (Discount Rate 4%)	4	2	0	0
Annualized Costs €/year (Discount Rate 0%)	-460 000		-210 000	
Annualized Costs €/year (Discount Rate 4%)	-550 000		-210 000	
Annualized Profit €/year, (Discount Rate 0%)	1 160 000	2 750 000	1 410 000	3 000 000
Annualized Profit €/year, (Discount Rate 4%)	1 070 000	2 660 000	1 410 000	3 000 000

For technical point of view BESS1 can replace 25MW GT.

BESS1 acts differently in different markets. BESS1 SOC levels in FFR-TOR1 and IDA markets are presented in the Figure 47 and Figure 48. In FFR-TOR1 market BESS1 uses its whole capacity, SOC from 5% to 95% and it actively varies all the time. In IDA market BESS1 is used for its whole capacity SOC from 5% to 95%. It is full over half of the time but when charged or discharged the change is rapid. Based on the way the BESS1 acts in different markets with its full capacity tells that it does not have great potential for provide combination of different services. In case to achieve higher revenues BESS1 needs to be used strategically and in a smart way to combine different markets. It is noteworthy that in IDA most of the revenues comes from capacity payments and revenues for selling the energy is low. Main issue in this market is that charging the BESS from the grid is expensive and revenues are low. Extra revenues are hard to earn if BESS participates only in IDA.

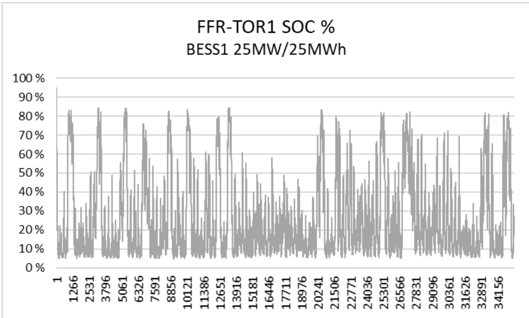

Figure 47. BESS1 FFR-TOR1 SOC %

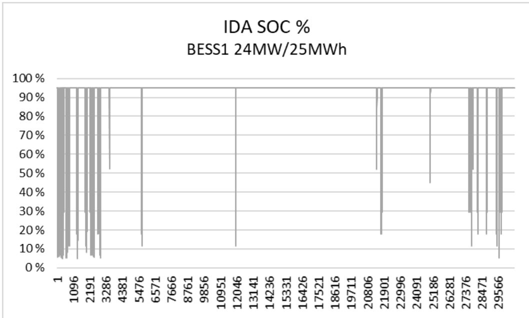

Figure 48. BESS1 IDA SOC %

9.2.3 Battery storage 25MW/100MWh in Ireland

CAPEX for BESS2 is calculated with two different values 350€/kWh and 200€/kWh. Actual revenues for BESS2 is calculated based on FFR-TOR1+DS3 revenues and potential revenues are calculated based on sum of IDA+DS3 and FFR-TOR1+DS3. Key figures for BESS2 is presented in the Table 30 and more detailed calculations are presented in the Appendices 28.

Case 1

Revenues for 350€/kWh BESS is low. IRR is only 3% and NPV is negative. Payback is high from 10 to over 15 years. Annualized revenues are low. Even with reward from DS3 program this is not profitable investment.

CAPEX for 200€/kWh BESS2 is lower and that effects IRR and NPV positively. IRR is 18% and NPV is positive and in good level. Payback is from 5 to 6 years. Annualized revenues are positive. With these results BESS2 is worth to invest.

Case 2

For 350€/kWh BESS2 revenues are in acceptable level but not create. IRR is over 12% and NPV is positive. Payback is from 7 to 8 years and annualized revenues are in good level. Based on this information 350€/kWh BESS might be worth to investment.

For 200€/kWh BESS IRR is over 30% and NPV is high. Payback is 2 years and annualized revenues are also high. For investor this is a good investment. Even without DS3 program this 200€/kWh BESS would be good investment with 15% IRR, positive NPV and from 5 to 6 years payback. Detailed calculation can be found from Appendices 32.

Data for IDA is for one year and for FFR-TOR1 it is for 4 months. To get more accurate results more data is needed. High peaks and low prices smoothen out when larger amount of data is used. Also effect of seasonal variation can be seen better.

Table 30. Ireland BESS2 25MW/100MWh key figures.

Ireland BESS2 (25MW/100MWh)	**350€/kWh**		**200€/kWh**	
	Case1	Case2	Case1	Case2
Net CAPEX €	27 500 000		12 500 000	
OPEX €/year	210 000		210 000	
Revenues €/year	2 710 000	4 650 000	2 710 000	4 650 000
IRR %	3%	12%	18%	33%
NPV €	-1 050 000	16 520 000	13 370 000	30 940 000
Simple Payback, (Discount Rate 0%)	11	7	5	2
Discounted Payback, (Discount Rate 4%)	15<	8	6	2
Annualized Costs €/year (Discount Rate 0%)	-2 040 000		-1 040 000	
Annualized Costs €/year (Discount Rate 4%)	-2 680 000		-1 330 000	
Annualized Profit €/year, (Discount Rate 0%)	670 000	2 610 000	1 670 000	3 610 000
Annualized Profit €/year, (Discount Rate 4%)	30 000	1 970 000	1 380 000	3 320 000

From technical point of view BESS2 can replace 25MW GT.

BESS2 acts differently in different markets. BESS2 SOC levels in FFR-TOR1 and IDA markets are presented in the Figure 49 and Figure 50. In FFR-TOR1 market BESS2 does not use its whole capacity, SOC is most of the time from 5% to 15% and it varies all the time.

In IDA BESS2 is used for its whole capacity SOC from 5% to 95%. It is less than half of the time empty but when charging or discharged the change is rapid. Based on the way that BESS2 acts in different markets it has potential to provide different services. It is note-worthy that in IDA most of the revenues comes from capacity payments and revenues for selling the energy is low. Main issue in this market is that charging the BESS from the grid is expensive and revenues from sold energy are low. Extra revenues are hard to earn if the BESS participates only in IDA.

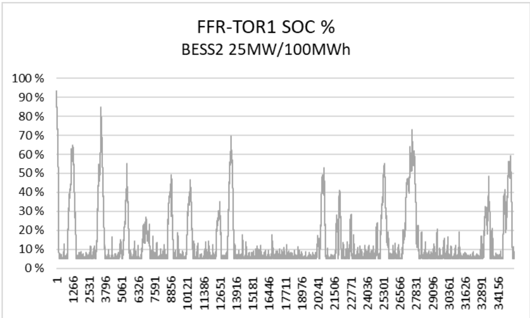

Figure 49. BESS2 FFR-TOR1 SOC %

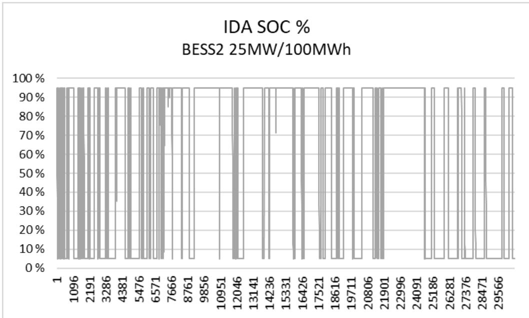

Figure 50. BESS2 IDA SOC %

9.2.4 Battery storage 104MW/104MWh in Ireland

CAPEX for BESS3 is calculated with two different values 450€/kWh and 200€/kWh. Actual revenues for BESS3 is calculated based on IDA+DS3 revenues and potential revenues are calculated based on sum of IDA+DS3 and FFR-TOR1+DS3. Key figures for BESS3 is presented in Table 31 and more detailed calculations is presented in Appendices 29.

Case 1

CAPEX for 450€/MWh storage is relatively low because of the DS3 program reward for new investment. Compared to investment revenues are in good level. IRR is almost 40% and NPV is high. Also, payback is only 3 years and annualized revenues are in good level. 450€/MWh BESS is worth to invest.

CAPEX for 200€/kWh BESS is 0€ because of the reward from the DS3 program. This is not reasonable result because every investment cost something. When CAPEX is zero IRR and payback is also zero. NPV and annualized revenues are high. Even without DS3 program IRR is 27%, NPV is positive and payback is 4 years. Based on this 200€/kWh is a good investment even without the DS3 program. More detailed calculations without DS3 program can be found in Appendices 33.

Case 2

For 450€/kWh BESS revenues are high. IRR is almost 50%, and NVP is positive. Payback is 3 years and annualized costs are in good level. Based on this information 450€/kWh BESS is worth to invest.

CAPEX for 200€/kWh BESS is 0€ because of the reward from the DS3 program. This is not reasonable result because every investment costs. Because of this IRR is 0% and payback is 0. NPV and annualized revenues are high. Even without DS3 program 200€/kWh BESS would be good investment with 35% IRR, positive NPV and 3 years payback.

DS3 program is temporary program which helps storage systems to enter the market and, in the future, it is not needed if the prices sink near to 200€/kWh. More detailed calculations without DS3 program can be found in Appendices 33. For these reason 200€/kWh is a good investment even without the DS3 program

Data for IDA is for one year and for FFR-TOR1 it is for 4 months. To get more accurate results more data is needed. High peaks and low prices smoothen out when larger amount of data is used. Also effect of seasonal variation can be seen better.

Table 31. Ireland BESS3 104MW/104MWh key figures.

Ireland BESS3 (104MW/104MWh)	**450€/kWh**		**200€/kWh**	
	Case1	Case2	Case1	Case2
Net CAPEX €	15 600 000		-	
OPEX €/year	850 000		850 000	
Revenues €/year	6 283 000	8 763 000	6 283 000	8 763 000

IRR %	37%	48%	-	-
NPV €	44 320 000	59 320 000	60 870 000	75 870 000
Simple Payback, (Discount Rate 0%)	3	3	0	0
Discounted Payback, (Discount Rate 4%)	3	3	0	0
Annualized Costs €/year (Discount Rate 0%)	-1 890 000		-850 000	
Annualized Costs €/year (Discount Rate 4%)	-2 250 000		-850 000	
Annualized Profit €/year, (Discount Rate 0%)	4 393 000	6 873 000	5 433 000	7 913 000
Annualized Profit €/year, (Discount Rate 4%)	4 033 000	6 513 000	5 433 000	7 913 000

For technical point of view BESS3 can replace 104MW GT except in one 4-hour case where BESS' capacity is exceeded.

BESS3 acts differently in different markets. BESS3 SOC levels in FFR-TOR1 and IDA markets are presented in the Figure 51 and Figure 52. In FFR-TOR1 market BESS3 does not use its whole capacity, in some cases SOC is from 5% to 95% but mainly SOC from 5% to 30% is used. SOC actively vary all the time. In IDA Market BESS3 is used for its whole capacity, SOC from 5% to 95%. BESS3 is used less than half of the time. If BESS is strategically used revenues could get higher by combining different markets. In IDA most of the revenues comes from capacity payments and revenues for selling the energy is low. Main issue in this market is that charging the BESS from the grid is expensive and revenues are low. Extra revenue is hard to earn.

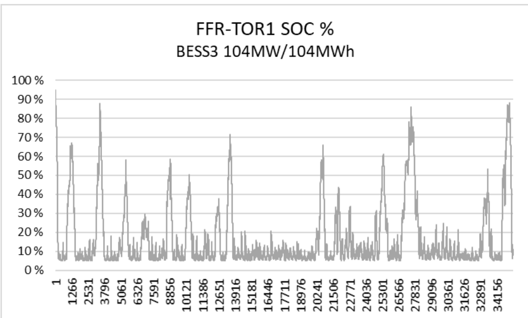

Figure 51. BESS3 FFR-TOR1 SOC %

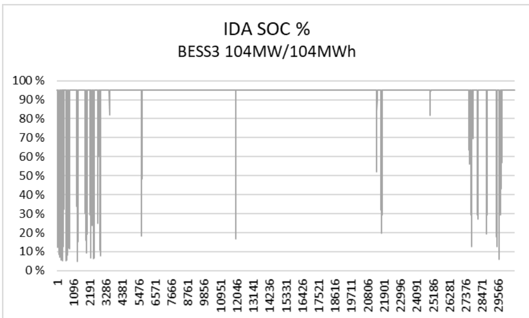

Figure 52. BESS3 IDA SOC %

9.2.5 Battery storage 104MW/416MWh in Ireland

CAPEX for BESS4 is calculated with two different values 350€/kWh and 200€/kWh. Actual revenues for BESS4 is calculated based on IDA+DS3 revenues and potential revenues are calculated based on sum of IDA+DS3 and FFR-TOR1+DS3. Key figures for BESS4 is presented in Table 32 and more detailed calculations are presented in Appendices 30.

Case 1

For BESS4 investment cost by 350€/kWh price is high. Even the revenues are high it is not enough to reach appropriate level in IRR and NPV. IRR is below 10% and even with positive NPV the payback is between 11 and 14 years. Annualized revenues are too low. In this case BESS is not a good investment.

200€/kWh BESS' investment costs are lower which makes IRR and NPV higher. IRR is 13% and NPV is in good level. Payback is between 7 and 8 years. Annualized revenues are in good level. Based on these figures 200€/kWh BESS is worth to invest.

Case 2

For BESS4 investment cost by 350€/kWh price is high. Even the revenues are high it is not enough to reach appropriate level in IRR and NPV. IRR is below 10% and even with positive NPV the payback is between 9 and 12 years. Annualized revenues are too low. In this case BESS is not a good investment.

200€/kWh BESS' investment costs are lower which makes IRR and NPV higher. IRR is 17% and NPV is in good level. Payback is between 6 and 7 years. Annualized revenues are in good level. Based on these figures 200€/kWh BESS is worth to invest.

Data for IDA is one year and for FFR-TOR1 it is for 4 months. To get more accurate results more data is needed. High peaks and low prices smoothen out when larger amount of data is used. Also effect of seasonal variation can be seen better.

Table 32. Ireland BESS4 104MW/416MWh key figures.

Ireland BESS4 (104MW/416MWh)	350€/kWh		200€/kWh	
	Case1	Case2	Case1	Case2
Net CAPEX €	152 880 000		90 480 000	
OPEX €/year	850 000		850 000	
Revenues €/year	15 510 000	18 730 000	15 510 000	18 730 000
IRR %	4%	7%	13%	17%
NPV €	1 900 000	25 970 000	61 900 000	85 970 000
Simple Payback, (Discount Rate 0%)	11	9	7	6
Discounted Payback, (Discount Rate 4%)	14	12	8	7
Annualized Costs €/year (Discount Rate 0%)	-11 040 000		-6 880 000	
Annualized Costs €/year (Discount Rate 4%)	-14 600 000		-8 990 000	
Annualized Profit €/year, (Discount Rate 0%)	4 470 000	7 690 000	8 630 000	11 850 000
Annualized Profit €/year, (Discount Rate 4%)	910 000	4 130 000	6 520 000	9 740 000

From technical point of view BESS4 can replace 104MW GT.

BESS4 acts differently in different markets. BESS4 SOC levels in FFR-TOR1 and IDA markets are presented in the Figure 53 and Figure 54. In FFR-TOR1 market BESS4 does not use its whole capacity, SOC from 5% to 25% is used. SOC actively vary all the time. In IDA Market BESS4 is used for its whole capacity SOC from 5% to 95%. It is used actively all the time with its whole capacity. If BESS4 is used actively in IDA market, there is no room for other services but if it is strategically used revenues could get higher by combining different markets. In IDA most of the revenues comes from capacity payments and revenues for selling the energy is low. Main issue in this market is that charging the BESS from the grid is expensive and revenues from sold energy are low. Extra revenues are hard to earn. Based on this information BESS4 might be too big for these markets compared to investment and earned revenues.

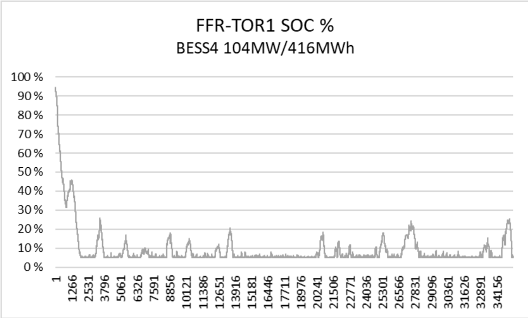

Figure 53. BESS4 FFR-TOR1 SOC %

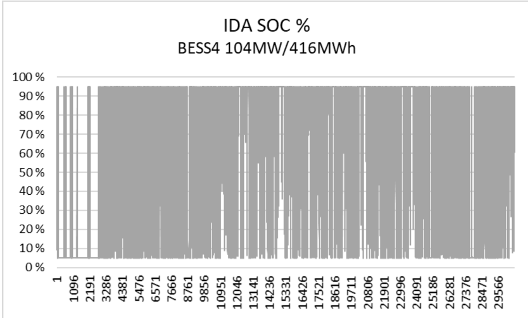

Figure 54. BESS4 IDA SOC %

9.3 Summary of Belgium’s and Ireland’s financial analysis

In Belgium’s markets investing in the BESS’ is more expensive than in Ireland’s markets. With current prices investing in large BESS is not reasonable but after prices goes down BESS1 and BESS2 will become more reasonable investment in Belgium. Instead in Ireland DS3 program makes BESS’ worth to invest already. After the prices goes down the DS3 program is not needed.

Biggest difference between these two markets is caused by the location and structure of the markets. Ireland needs to be more self-sufficient than Belgium because of its location. Belgium have several interconnections to other European countries and it also participates in European electricity markets. For these reasons Belgium does not need as much storage capacity and fast acting reserve or ancillary services as Ireland. In Ireland number of interconnections is smaller and the electricity market structure differs from other European countries. Also amount of renewable energy production has increased rapidly and it is still increasing and the need for the storages and fast acting reserve in Ireland is higher than in continental Europe.

9.3.1 Belgium summary of annualized revenues and simple payback

Annualized revenues (0% discount rate) and payback period (0% discount rate) in years are presented in the Figure 55, Figure 56, Figure 57, Figure 58, Figure 59 and Figure 60.

In the Table 33 is presented if the BESS is worth to invest or not. Case1 presents the minimum revenues and Case2 potential revenues.

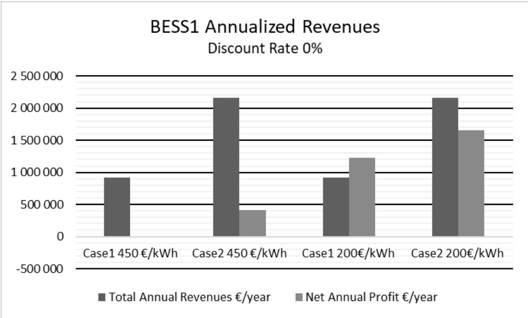

Figure 55. BE BESS1 Annualized Revenues

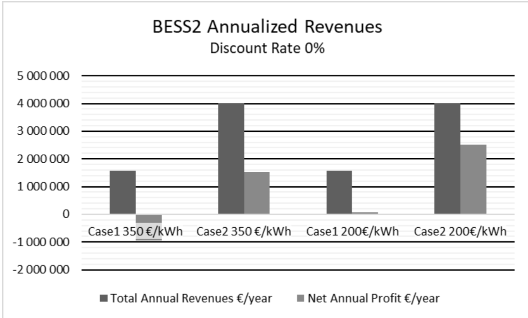

Figure 56. BE BESS2 Annualized Revenues

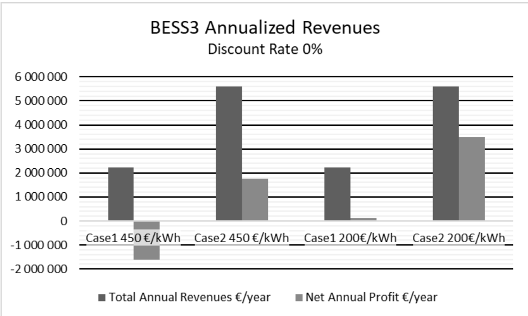

Figure 57. BE BESS3 Annualized Revenues

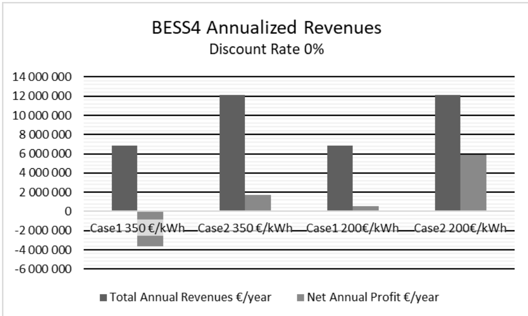

Figure 59. BE BESS4 Annualized Revenues

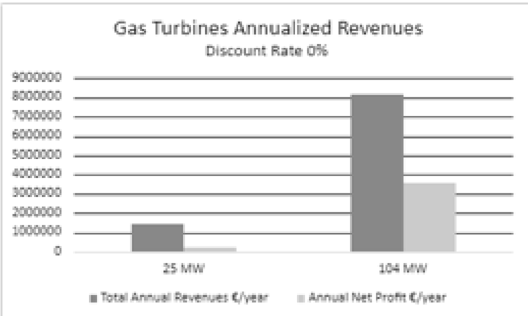

Figure 58. BE GTs Annualized Revenues

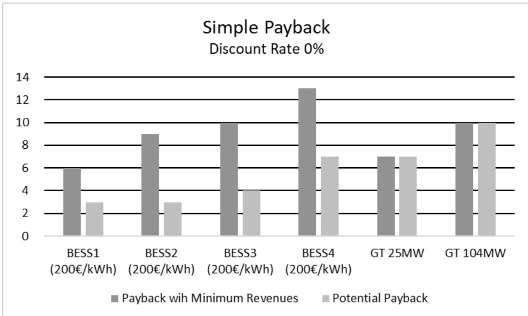

Figure 60. BE Simple Payback

Table 33. Is the BESS viable investment in Belgium?

Viable investment in Belgium

	Case1 (Minimum Revenues)			Case2 (Potential Revenues)		
	450€/kWh	350€/kWh	200€/kWh	450kWh/€	350€/kWh	200€/kWh
BESS1 (25MW/25MWh)	No	-	**Yes**	**Yes**	**-**	**Yes**
BESS2 (25MW/100MWh)	-	No	No	**-**	**Yes**	**Yes**
BESS3 (104MW/104MWh)	No	-	No	No	-	**Yes**
BESS4 (104MW/416MWh)	-	No	No	-	No	**Yes**

9.3.2 Belgium summary of annualized revenues and discounted payback

Annualized revenues (4% discount rate) and payback period (4% discount rate) in years are presented in the Figure 61, Figure 62, Figure 63, Figure 64, Figure 65 and Figure 66. In the Table 34 is presented if the BESS is worth to invest or not. Case1 presents the minimum revenues and Case2 the potential revenues.

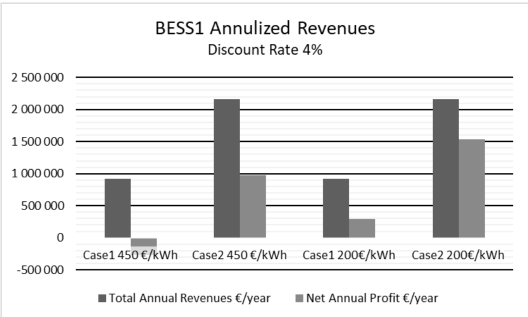

Figure 61. BE BESS1 Annualized Revenues (Discount rate 4%)

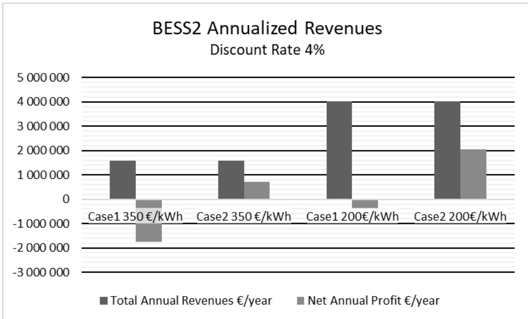

Figure 62. BE BESS2 Annualized Revenues (Discount rate 4%)

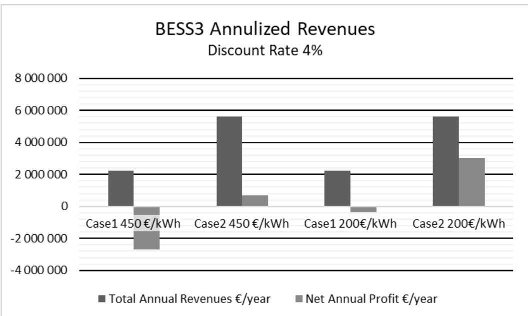

Figure 63. BE BESS Annualized Revenues (Discount rate 4%)

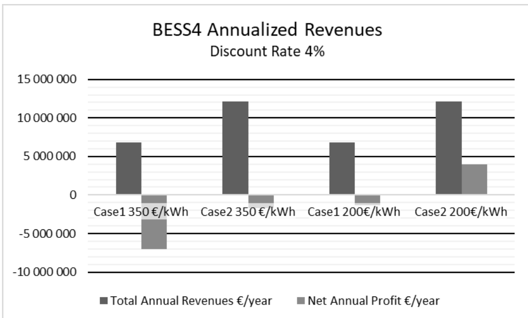

Figure 64. BE BESS4 Annualized Revenues (Discount rate 4%)

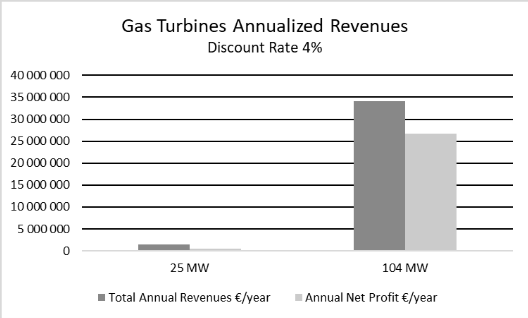

Figure 65. BE GTs Annualized Revenues (Discount rate 4%)

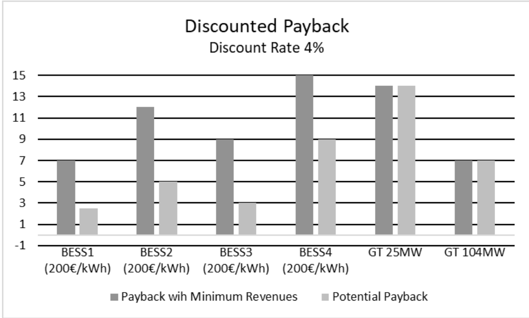

Figure 66. BE Discounted Payback (Discount rate 4%)

Table 34. Is BESS viable investment with discount rate 4% in Belgium?

Viable investment in Belgium						
	Case1 (Minimum Revenues)			**Case2 (Potential Revenues)**		
	450€/kWh	350€/kWh	200€/kWh	450€/kWh	350€/kWh	200€/kWh
BESS1 (25MW/25MWh)	No	-	**Yes**	**Yes**	**-**	**Yes**
BESS2 (25MW/100MWh)	-	No	No	**-**	**Yes**	**Yes**
BESS3 (104MW/104MWh)	No	-	No	No	-	**Yes**
BESS4 (104MW/416MWh)	-	No	No	-	No	**Yes**

9.3.3 Ireland summary of annualized revenues and simple payback

Annualized revenues (0% discount rate) and payback period (0% discount rate) in years are presented in the Figure 67, Figure 68, Figure 69, Figure 70, Figure 71 and Figure 72. In the Table 35 is presented if the BESS is worth to invest or not. Case1 presents the minimum revenues and Case2 the potential revenues.

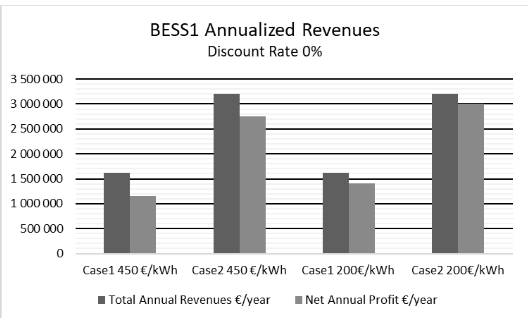

Figure 67. IE BESS1 Annualized Revenues

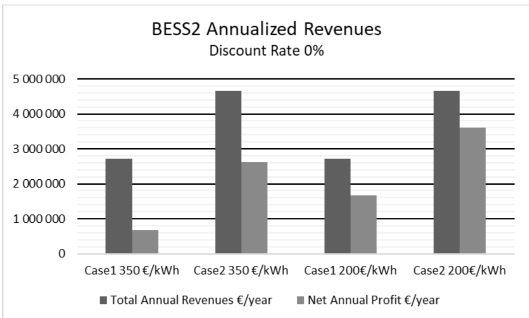

Figure 68. IE BESS2 Annualized Revenues

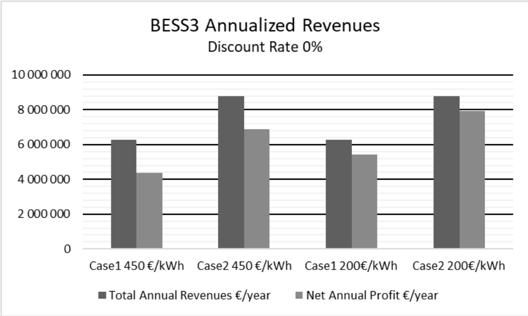

Figure 69. IE BESS3 Annualized Revenues

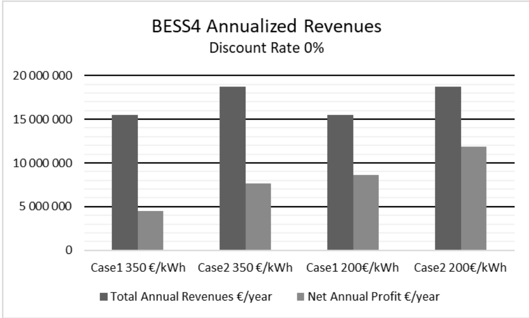

Figure 70. IE BESS4 Annualized Revenues

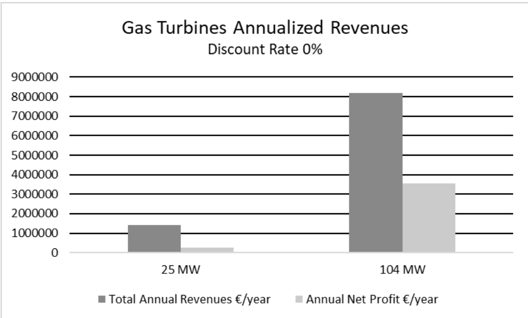

Figure 71. IE GTs Annualized Revenues

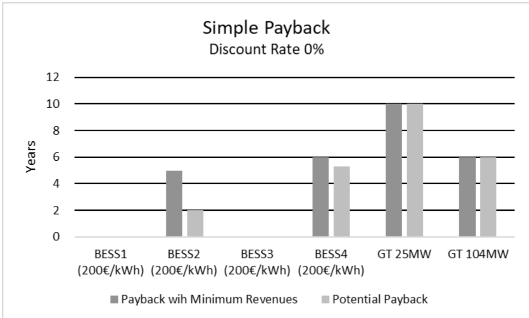

Figure 72. IE Simple Payback

Table 35. Is BESS viable investment in Ireland?

Viable investment in Ireland						
	Case1 (Minimum Revenues)			**Case2 (Potential Revenues)**		
	450€/kWh	350€/kWh	200€/kWh	450kWh/€	350€/kWh	200€/kWh
BESS1 (25MW/25MWh)	**Yes**	**-**	**Yes**	**Yes**	**-**	**Yes**
BESS2 (25MW/100MWh)	-	No	**Yes**	**-**	**Yes**	**Yes**
BESS3 (104MW/104MWh)	**Yes**	**-**	**Yes**	**Yes**	**-**	**Yes**
BESS4 (104MW/416MWh)	-	No	**Yes**	-	No	**Yes**

9.3.4 Ireland summary of annualized revenues and discounted payback

Annualized revenues (4% discount rate) and payback period (4% discount rate) in years are presented in the Figure 73, Figure 74, Figure 75, Figure 76, Figure 77 and Figure 78. In the Table 36 is presented if the BESS is worth to invest or not. Case1 presents the minimum revenues and Case2 the potential revenues.

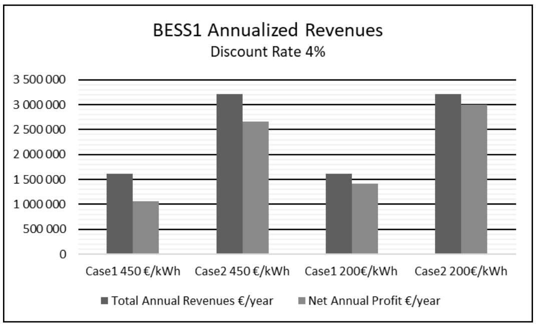

Figure 73. IE BESS1 Annualized Revenues (Discount rate 4%)

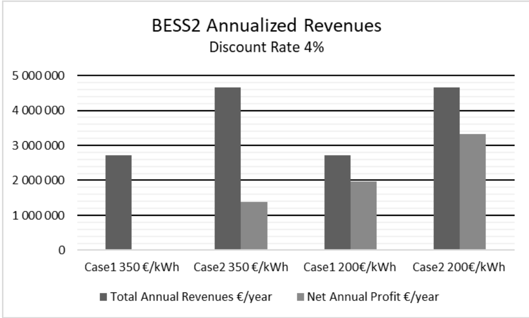

Figure 74. IE BESS2 Annualized Revenues (Discount rate 4%)

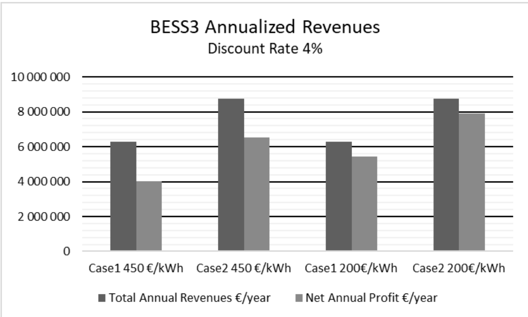

Figure 75. IE BESS3 Annualized Revenues (Discount rate 4%)

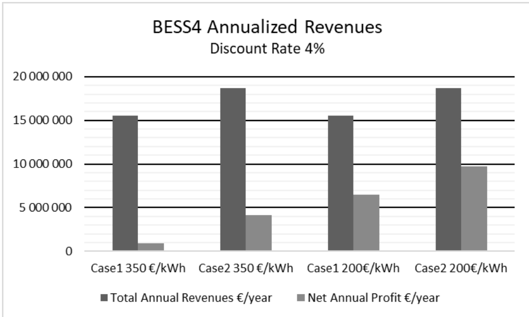

Figure 76. IE BESS4 Annualized Revenues (Discount rate 4%)

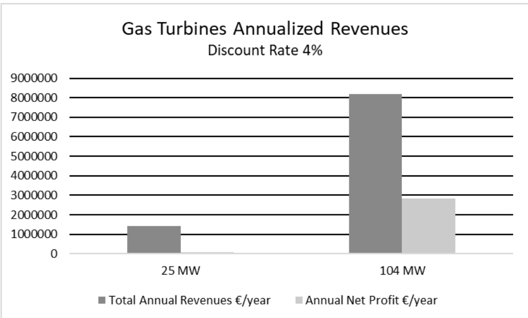

Figure 77. IE GTs Annualized Revenues (Discount rate 4%)

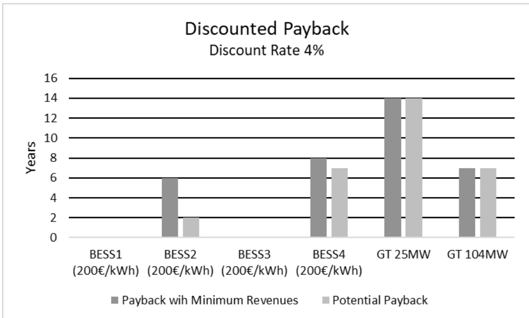

Figure 78. IE Discounted Payback (Discount rate 4%)

Table 36. Is BESS viable investment with discount rate 4% in Ireland?

Viable investment in Ireland						
	Case1 (Minimum Revenues)			**Case2 (Potential Revenues)**		
	450€/kWh	350€/kWh	200€/kWh	450kWh/€	350€/kWh	200€/kWh
BESS1 (25MW/25MWh)	**Yes**	**-**	**Yes**	**Yes**	**-**	**Yes**
BESS2 (25MW/100MWh)	-	No	**Yes**	**-**	**Yes**	**Yes**

BESS3 (104MW/104MWh)	**Yes**	**-**	**Yes**	**Yes**	**-**	**Yes**
BESS4 (104MW/416MWh)	-	No	**Yes**	-	No	**Yes**

10 Conclusions

The goal for the thesis was to generalize conditions under which it is an economic solution to choose a battery storage system instead of a gas turbine. Based on the conducted study, the following answers could be given to the set six research questions:

1. What services GT and BESS can offer?

BESS can technically provide same services than GT with certain limitations, but it depends on the country if it is allowed to provide them.

- Participating in the capacity market, voltage control and black start are possible for both GT and BESS in both Ireland and in Belgium.
- In Ireland, BESS can participate in arbitrage, but in Belgium's market this information was not found so the assumption is that it is not possible to participate in this market. GTs are not able to participate in this market because of the technical limitations.
- Participating in the frequency reserve market for BESS in Ireland and for GT and BESS in Belgium is allowed. Information for GT's participation in this market in Ireland was not found so the assumption is that it is not allowed to participate in this market.
- Information for inertia was only found for GT in Ireland so assumption is that it is not possible for GT to participate in this market in Belgium. BESS is not able to produce synthetic inertia, so they are not able to participate in this market.
- Some markets need to be reorganized to support the use of BESS'. Ireland has already started by creating DS3 program.

2. What are the annualized costs, net present value (NPV), internal rate of return (IRR) and payback for two different sizes of GTs in Belgium and in Ireland?

Data for calculating the CAPEX and fixed OPEX was collected from reports and studies. Variable costs were calculated based on usage data and fuel prices.

In Belgium annualized costs were calculated by discount rates 0% and 4%. For 25MW and 104MW, GTs proved to have positive annualized profit with both discount rates 0% and 4%. NPV, IRR and simple payback and discounted payback are in good level. Both GTs are viable investments. The results of the 104MW GT are extremely high because it managed to hit the markets when the electricity price was highest.

Based on the results of annualized costs for 25MW GT and 104MW GT in Ireland, the annualized costs for both were positive. But for 25MW GT, NPV, IRR and payback are not in good level. For these reasons, 25MW GT is not a good investment. Instead, 104 MW GT would be a good investment based on these calculations.

To get more reliable results more data is needed. One year is too short to get reliable results.

3. In which situations BESS could or should replace GT?

Two different sizes of GTs 25MW and 104MW and four different sizes of BESS' were studied: BESS1 (25MW/25MWh), BESS2 (25MW/100MWh), BESS3 (104MW/104MWh) and BESS4 (104MW/416MWh). Usage data from two different GTs was collected. Based on the data, BESS1 and BESS2 were compared to 25MW GTs data and BESS3 and BESS4 were compared to 104MW data.

Based on the results, 25MW GT can be replaced with both BESS1 and BESS2.

GT of 104MW can be replaced with BESS4. In one four-hour time period BESS3's capacity was exceeded and in that one case this BESS is not able to replace 104MW GT. In all the other cases it was able to replace 104MW GT.

4. What kind of services BESS can offer to make it profitable?

Electricity markets are different in Belgium and in Ireland. For that reason, BESS' are providing different services and they are participating in different markets in different countries.

In Belgium, studied markets consist of fast acting ancillary service markets

- FCR, Frequency containment reserve
- aFFR, Automatic frequency restoration
- mFRR Flex, Flexible frequency restoration via manual activation
- mFRR Standard, Standard frequency restoration via manual activation

In Ireland investigated markets consist of

- FFR, Fast frequency response
- POR, Primary operating reserve
- SOR, Secondary operating reserve
- TOR1, TOR2, Tertiary operating reserve 1 and 2
- RRD, Replacement reserve, de-synchronized
- RRS, Replacement reserve, synchronized
- RM1,RM3 and RM3, Ramping margin 1, 3 and 8 hours
- IDA, Intraday auction

In Ireland BESS' also get revenues and rewards from DS3 program which supports storages and fast acting reserve to enter the market. Services from FFR to TOR1 are ancillary services which reacts from seconds to 20 minutes. In this study, IDA includes RRD service which reacts between 20 minutes to one hour.

FCR in Belgium matches FFR and POR in Ireland, aFRR in Belgium matches SOR, TOR1 and TOR2 in Ireland. mFRR markets in Belgium matches Ireland's RRD, RRS and RM1, RM3 and RM8.

5. What are the annualized costs, net present value (NPV), internal rate of return (IRR) and payback for four different sizes of BESS’ in Belgium and in Ireland?

NPV, IRR, payback and annualized costs were calculated for two different prices for four different size of batteries. Each market was studied separately with rule-based Excel model. Annualized costs were calculated by using 0% and 4% discount rates.

Belgium

Based on results in Belgium BESS1 is viable investment all the cases except when investment price is 450€/kWh and only one service is provided. In the viable cases, NPV is positive, IRR is over 16%, payback is under 7 years and annualized profit are positive, for both 0% and 4% discount rates.

BESS2 is viable investment with all investment prices while it provides multiple services. NPV is positive, payback is under 9 years, IRR is over 11% and annualized profit are positive with both discount rates.

BESS3 is viable investment only if it provides multiple services and the investment price is 200€/kWh. In this case NPV is positive, IRR is 26%, payback is under 5 years and annualized profit is positive with both discount rates.

BESS4 is viable investment only when investment price is 200€/kWh and it is offering multiple services. In this case NPV is positive, IRR is 11%, payback is under 9 years and annualized costs are positive with both discount rates.

Ireland

In Ireland BESS1 is viable investment with all investment prices and while it provides one or multiple services. NPV is positive, IRR is over 37%, payback is under 4 years and annualized profits are positive with both 0% and 4% discount rates.

BESS2 is viable investment in all cases except when investment price is 350€/kWh and only one service is provided. In the other cases NPV is positive, IRR is over 12%, payback is under 8 years and annualized profits are positive with both discount rates.

BESS3 is viable investment with all investment prices while it provides one or multiple services. In these cases, NPV is positive, IRR is over 37%, payback is 3 years and annualized profits are positive with both discount rates.

BESS4 is viable investment only if investment price is 200€/kWh. In these cases, NPV is positive, IRR is over 13%, payback is under 8 years and annualized profits are positive with both discount rates.

6. In which scenarios it is economically and technically possible to replace GT with BESS?

Belgium

In Belgium the BESS is worth to invest with 0% discount rate. In general, if only one service is provided by the BESS, only BESS1 with investment costs of 200€/kWh is worth to invest. In case several services are provided, BESS1 and BESS2 are worth to invest by both investment prices 450€/kWh or 350€/kWh and 200€/kWh. BESS3 and BESS4 are worth to invest when several services are offered if the investment price is 200€/kWh.

If discount rate is 4% BESS1 is worth to invest in all cases except if only one service is provided, and investment price is 450€/kWh. For BESS2 it is worth to invest if several services are provided. BESS3 and BESS4 are worth to invest if investment price is 200€/kWh and several services are provided. At current prices, 700€/kWh BESS' are too expensive to invest.

When prices go down in Belgium, BESS' have potential to replace GTs which are used for peak loads. Results from this study shows that BESS1, BESS2 and BESS4 can technically replace 25MW and 104MW GTs and BESS3 failed only in one case. When BESS’ are used for multiple purposes, they will be viable investments and interesting possibility to support the grid.

Ireland

In Ireland BESS’ are worth to invest with 0% and 4% discount rates. Ireland’s market is more favorable for BESS’. With the help of DS3 program even if only one service is provided, BESS1 and BESS3 are profitable with both investment prices 350€/kWh and 200€/kWh. Additionally, BESS2 and BESS4 are worth to invest if price is 200€/kWh. When discount rate is 0% and BESS1 offers one service or several services or BESS2 and BESS3 offers several services, DS3 program is not needed if the price is 200€/kWh.

At current prices, 700€/kWh BESS1 and BESS3 are worth to invest if they are participating to DS3 program. BESS2 and BESS4 are not worth to invest at the current prices.

In Ireland BESS’ have potential to replace GTs which are used for peak loads. Results from this study shows that BESS1, BESS2 and BESS4 can technically replace 25MW and 104MW GTs and BESS3 failed only in one case. As an investment BESS1 and BESS3 would be viable with the help of DS3 program which makes it possible for them to enter the markets with current prices. But when prices go down also BESS2 and BESS4 are able to enter the electricity markets in Ireland. When the prices reach to 200€/kWh DS3 program is not needed.

Future topics

For future study instead of summing up different markets more detailed and complex model should be made. This model should take into account combination of different markets load, prices, SOC and aging of the battery storage to achieve more accurate results. Future modeling should also incorporate the potential for additional revenue from network and behind-the-meter services.

11 Summary

Goal for the thesis was to find out if it is economically and technically possible for battery storage system (BESS) to replace gas turbine (GT) which is used for peak loads. Study was made for two different sizes of GTs (25MW and 104MW) and for four different sizes (25MW/25MWh, 25MW/100MWh, 104MW/104MWh and 104MW/416MWh) of BESS' in two different countries in Belgium and in Ireland.

Study answers the questions: What services GT and BESS can offer? What are the annualized costs, net present value (NPV), internal rate of return (IRR) and payback for two different sizes of GTs in Belgium and in Ireland? What are the annualized costs, NPV, IRR and payback for four different sizes BESS' in Belgium and in Ireland? What kind of services BESS can offer to make it profitable? What are the situations when BESS can/should replace GT or not? In which scenario it is economically and technically possible to replace GT with BESS?

As a background for this study data was collected from two existing GTs, researches, reports, and literature. Electricity markets in Belgium and in Ireland were studied. Based on that, rule-based Excel models were created to determine potential revenues for BESS'. The sensitivity analysis was conducted by BESS' capital expenditures and discount rates of 0% and 4%. Technical features for GTs and BESS' were compared and NVP, IRR, payback and annualized profit were calculated with 0% and 4% discount rates.

Results of the study showed that it is technically possible for BESS to replace GT used for peak loads, except in one four-hours' case where 104MW/104MWh BESS' capacity was exceeded.

Electricity markets in Belgium and Ireland are different. Because of the location and market structure Ireland needs more fast acting services than Belgium. Ireland supports batteries to enter the market and this can be noticed in the results of this study.

After calculations analysis were made for NVP, IRR, payback and annualized profits for all BESS', with two different prices and discount rates of 0% and 4% in Belgium and in Ireland. The results show that in Belgium it is economical to invest in the 25MW/25MWh and the 25MW/100MWh BESS' if investment prices are 450€/kWh, 350€/MWh or 200€/kWh and they are offering multiple services. If the investment price is 200€/kWh and multiple services are provided 104MW/104MWh and 104MW/416MWh BESS' are profitable investments.

In Ireland, the DS3 program makes it profitable to invest in the 25MW/25MWh and the 104MW/104MWh BESS' even with current prices. Investing in the 25MW/100MWh and the 104MW/416MWh BESS' will be profitable when multiple services are provided, and investment prices are 350€/kWh and 200€/kWh.

Overall, this study shows that BESS' are and will be potential solutions for replacing GTs which are used for peak loads. In addition, they are able to provide additional services to support the grid which makes them interesting options for investors.

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Appendices

ANNEX 1

Table 37. Market data, prices, load and frequency for Belgium and Ireland.

Country	Market area	Time interval	Amount of data months	Year	Source
BE	FCR	5 min (capacity sold) 1 hour (reservation)	4 5	2020	(Entso-e 2021), Elia Group (2021)
BE	aFRR	15 min	3	2020	(Entso-e 2021), Elia Group (2021)
BE	mFRR Flex and Standard	15 min	12	2019	Elia Group (2021)
BE	DAM	1 hour	12	2019	(Entso-e 2021)
IE	FFR-TOR1	5 min	4	2020	SEMO (2021)
IE	IDA, DRR	30 min	12	2019	SEMOpx (2021)
IE	DAM	1 hour	12	2019	(Entso-e 2021)

ANNEX 2

Table 38. Sensitivity analysis for BESS in Belgium's FCR market.

Min price €/MWh	BESS1	BESS2	BESS3	BESS4
0	**1 100 000**	**1 440 000**	**1 940 000**	1 480 000
10	1 040 000	1 390 000	1 830 000	**1 510 000**
20	1 040 000	1 390 000	1 830 000	1 510 000
30	1 040 000	1 390 000	1 830 000	1 510 000
40	1 040 000	1 390 000	1 830 000	1 510 000
50	1 030 000	1 380 000	1 820 000	1 500 000
60	1 000 000	1 310 000	1 750 000	1 450 000
70	940 000	1 240 000	1 660 000	1 390 000
80	880 000	1 160 000	1 480 000	1 300 000
90	830 000	1 110 000	1 390 000	1 240 000
100	740 000	980 000	1 220 000	1 110 000

ANNEX 3

Table 39. BESS1 aFRR sensitivity analysis.

BESS1 25MW/25MWh aFRR sensitivity analysis (€/year)			
	Min charging price €/MWh		
Min discharging price €/MWh	**0**	**10**	**20**
0	**800 000**	635 000	2 500
20	**800 000**	635 000	2 500
40	**800 000**	635 000	2 500
60	637 500	507 500	2 500
80	65 000	57 500	2 500
100	37 500	30 000	2 500

ANNEX 4

Table 40. BESS2 aFRR sensitivity analysis.

BESS2 25MW/100MWh aFRR sensitivity analysis (€/year)			
	Min charging price €/MWh		
Min discharging price €/MWh	**0**	**10**	**20**
0	**1 357 500**	1 090 000	7 500
20	**1 357 500**	1 090 000	7 500
40	**1 355 000**	1 087 500	7 500
60	1 070 000	862 500	5 000
80	50 000	50 000	7 500
100	7 500	7 500	5 000

ANNEX 5

Table 41. BESS3 aFRR sensitivity analysis.

BESS3 104MW/104MWh aFRR sensitivity analysis (€/year)			
	Min charging price €/MWh		
Min discharging price €/MWh	**0**	**10**	**20**
0	**2 852 500**	2 277 500	12 500
20	**2 852 500**	2 277 500	12 500
40	**2 852 500**	2 277 500	12 500
60	2 247 500	1 795 000	12 500
80	165 000	152 500	12 500
100	65 000	52 500	12 500

ANNEX 6

Table 42. BESS4 aFRR sensitivity analysis.

BESS4 104MW/416MWh aFRR sensitivity analysis (€/year)			
	Min charging price €/MWh		
Min discharging price €/MWh	**0**	**10**	**20**
0	**7 530 000**	6 012 500	30 000
20	7 525 000	6 012 500	30 000
40	7 520 000	6 020 000	30 000
60	5 057 500	4 092 500	25 000
80	190 000	192 500	32 500
100	20 000	22 500	20 000

ANNEX 7

Table 43. BESS1 mFRR Flex sensitivity analysis.

BESS1 25MW/25MWh mFRR Flex sensitivity analysis			
mFRR Flex Price €/MWh	Discharging Revenues €/year	Charge cost €/year	Total €/year
0 €	160 000	3 000	**160 000**
1 000 €	160 000	3 000	160 000
3 000 €	150 000	2 000	150 000

ANNEX 8

Table 44. BESS2 mFRR Flex sensitivity analysis.

BESS2 25MW/100MWh mFRR Flex sensitivity analysis			
mFRR Flex Price €/MWh	Discharging Revenues €/year	Charge cost €/year	Total €/year
0 €	300 000	5 000	**295 000**
1 000 €	300 000	5 000	295 000
3 000 €	290 000	4 000	286 000

ANNEX 9

Table 45. BESS3 mFRR Flex sensitivity analysis.

BESS3 104MW/104MWh mFRR Flex sensitivity analysis			
mFRR Flex Price €/MWh	Discharging Revenues €/year	Charge cost €/year	Total €/year
0 €	620 000	11 000	**610 000**

1 000 €	620 000	11 000	610 000
3 000 €	590 000	9 000	580 000

ANNEX 10

Table 46. BESS4 mFRR Flex sensitivity analysis.

BESS4 104MW/416MWh mFRR Flex sensitivity analysis			
mFRR Flex Price €/MWh	Discharging Revenues €/year	Charge cost €/year	Total €/year
0 €	870 000	14 000	**860 000**
1 000 €	870 000	14 000	860 000
3 000 €	840 000	13 000	830 000

ANNEX 11

Table 47. BESS1 mFRR Standard sensitivity analysis.

BESS1 25MW/25MWh mFRR Standard sensitivity analysis			
mFRR Standard Price €/MWh	Discharging Revenues €/year	Charge cost €/year	Total €/year
0	930 000	130 000	**800 000**
200	930 000	130 000	**800 000**
400	450 000	30 000	420 000
600	400 000	20 000	380 000
800	400 000	20 000	380 000
1000	190 000	0	190 000

ANNEX 12

Table 48. BESS2 mFRR Standard sensitivity analysis.

BESS2 25MW/100MWh mFRR Standard sensitivity analysis			
mFRR Standard Price €/MWh	Discharging Revenues €/year	Charge cost €/year	Total €/year
- €	2 050 000	300 000	**1 750 000**
200 €	2 050 000	300 000	**1 750 000**
400 €	940 000	70 000	870 000
600 €	850 000	60 000	790 000
800 €	830 000	50 000	780 000
1 000 €	270 000	0	270 000

ANNEX 13

Table 49. BESS3 mFRR Standard sensitivity analysis.

BESS3 104MW/104MWh mFRR Standard sensitivity analysis			
mFRR Standard Price €/MWh	Discharging Revenues €/year	Charge cost €/year	Total €/year
- €	3 430 000	490 000	**2 940 000**
200 €	3 430 000	490 000	**2 940 000**
400 €	1 640 000	120 000	1 520 000
600 €	1 460 000	90 000	1 370 000
800 €	1 450 000	90 000	1 360 000
1 000 €	550 000	0	550 000

ANNEX 14

Table 50. BESS4 mFRR Standard sensitivity analysis.

BESS4 104MW/416MWh mFRR Standard sensitivity analysis			
mFRR Standard Price €/MWh	Discharging Revenues €/year	Charge cost €/year	Total €/year
- €	6 160 000	930 000	**5 230 000**
200 €	6 160 000	930 000	**5 230 000**
400 €	2 790 000	240 000	2 550 000
600 €	2 520 000	190 000	2 330 000
800 €	2 460 000	180 000	2 280 000
1 000 €	550 000	0	550 000

ANNEX 15

Table 51. FFR-TOR1 sensitivity analysis with DS3 program.

FFR-TOR1 Revenues €/year with DS3				
Min price €/MW	BESS1	BESS2	BESS3	BESS4
0	**1 430 000**	**2 550 000**	**1 810 000**	**2 560 000**
50	1 140 000	2 010 000	1 490 000	2 020 000
100	800 000	1 310 000	1 060 000	1 320 000
150	440 000	580 000	580 000	580 000

ANNEX 16

Table 52. FFR-TOR1 sensitivity analysis without DS3 program.

FFR-TOR1 Revenues €/year without DS3

Min price €/MW	BESS1	BESS2	BESS3	BESS4
0	**1 100 000**	**1 940 000**	**1 410 000**	**1 940 000**
50	1 030 000	1 810 000	1 350 000	1 820 000
100	740 000	1 210 000	990 000	1 220 000
150	430 000	560 000	550 000	560 000

ANNEX 17

Table 53. BESS1 IDA sensitivity analysis.

BESS1 25MW/25MWh IDA sensitivity analysis				
IDA Price €/MWh	Discharging Revenues €/ year	Charging Cost €	DS3 € per year	Total €
0	30 000	-142 000	1 000	-111 000
50	1 530 000	-3 221 000	32 000	-1 659 000
100	660 000	-666 000	7 000	1 000
150	**330 000**	**-223 000**	**2 000**	**109 000**

ANNEX 18

Table 54. BESS2 IDA sensitivity analysis.

BESS2 25MW/100MWh IDA sensitivity analysis				
IDA Price €/MWh	Discharging Revenues €/year	Charging cost €/year	DS3 €/year	Total €/year
0	30 000	-13 000	1 000	18 000
50	540 000	-206 000	11 000	345 000
100	**580 000**	**-154 000**	**6 000**	**432 000**
150	440 000	-72 000	3 000	371 000

ANNEX 19

Table 55. BESS3 IDA sensitivity analysis.

BESS3 104MW/104MWh IDA sensitivity analysis				
IDA Price €/MWh	Discharging Revenues €/year	Charging cost €/year	DS3 €/year	Total €/year
0	110 000	-588 000	6 000	-472 000
50	6 250 000	-13 148 000	131 000	-6 767 000
100	2 490 000	-2 490 000	25 000	25 000
150	**1 200 000**	**-794 000**	**8 000**	**414 000**

ANNEX 20

Table 56. BESS4 IDA sensitivity analysis.

BESS4 104MW/416MWh IDA sensitivity analysis				
IDA Price €/MWh	Discharging Revenues €/year	Charging cost €/year	DS3 €/year	Total €/year
0	480 000	-256 000	18 000	242 000
50	**15 580 000**	**-6 603 000**	**314 000**	**9 291 000**
100	5 180 000	-1 424 000	49 000	3 805 000
150	1 950 000	-463 000	13 000	1 500 000

ANNEX 21

Table 57. Calculations for GTs in Belgium.

BELGIUM Calculations for GTs	**25MW**	**104MW**
CAPEX €		
EPC Contract price	5 130 000	42 640 000
Filling fuel tank	80 000	640 000
Other	990 000	8 270 000
Total CAPEX	**6 200 000**	**51 550 000**
OPEX		
Fixed O&M €/year		
Operating costs	360 000	1 500 000
Incurrence	30 000	210 000
Maintenance	30 000	210 000
Total Fixed O&M	**420 000**	**1 920 000**
Variable O&M €/year		
Fuel	30 000	730 000
CO2	1 000	20 000
Other	10 000	130 000
Total Variable O&M	**41 000**	**880 000**
Total OPEX	**461 000**	**2 800 000**
Revenues €/year		
mFRR flex	**1 500 000**	**34 180 000**
mFRR standard	130 000	5 870 000
Total €/year	**1 500 000**	**31 380 000**
Net Revenue €/year	**1 039 000**	**28 580 000**
NPV		
mFRR flex	4 590 000 €	10 050 000 €
mFRR standard	-4 640 000 €	240 720 000 €
IRR		

mFRR flex	14 %	7 %
mFRR standard	-13 %	55 %
Simple Payback (years)		
mFRR flex	6	9
mFRR standard	48	2
Discounted Payback (years), discount rate 4%		
mFRR flex	7	12
mFRR standard	15<	2
Annualized Costs Discount Rate 0%	25 MW	104 MW
Total Annual Revenues €/year	1 500 000	34 180 000
Annualized Costs €/year	-870 000	-6 240 000
Annual Net Profit €/year	630 000	27 940 000
Annualized Costs Discount Rate 4%	25 MW	104 MW
Total Annual Revenues €/year	1 500 000	34 180 000
Annualized Costs €/year	-1 020 000	-7 440 000
Annual Net Profit €/year	480 000	26 740 000

ANNEX 22

Table 58. Calculations for GTs in Ireland.

IRELAND	**With DS3 Program**		**Without DS3 Program**	
	25MW	**104MW**	**25MW**	**104MW**
CAPEX €				
EPC Contract price	12 650 000	52 630 000	12 650 000	52 630 000
Filling fuel tank	170 000	900 000	170 000	900 000
Other	2 270 000	9 430 000	2 270 000	9 430 000
Total CAPEX	**15 090 000**	**62 960 000**	15 090 000	62 960 000
Award for new investment	7 500 000	31 200 000		
Total CAPEX after award for investment	**7 590 000**	**31 760 000**	**15 090 000**	**62 960 000**
OPEX				
Fixed O&M €/year				
Operating costs	490 000	840 000	490 000	840 000
Incurrence	80 000	320 000	80 000	320 000
Maintenance	60 000	260 000	60 000	260 000
Total Fixed O&M	**630 000**	**1 420 000**	630 000	1 420 000
Variable O&M €/year				
Fuel	30 000	930 000	30 000	930 000
CO2	1 000	20 000	1 000	20 000
Other	10 000	130 000	10 000	130 000
Total Variable O&M	**41 000**	**1 080 000**	41 000	1 080 000

Total OPEX	**671 000**	**2 500 000**	671 000	2 500 000
Revenues €/year				
Capacity reservation and other remuneration	1 430 000	8 150 000	1 020 000	4 230 000
IDA €/year	2 000	30 000	2 000	30 000
Total	**1 430 000**	**8 180 000**	**1 020 000**	**4 260 000**
Net Revenue	**759 000**	**5 680 000**	**349 000**	**1 760 000**
NPV				
IDA	410 000	27 150 000	-10 960 000 €	-42 660 000 €
IRR				
IDA	5 %	16 %	-12 %	-11 %
Simple Payback, years				
IDA	10	6	44	36
Discounted Payback, Discount Rate 4%				
IDA	14	7	15<	15<
Annualized Costs, Discount Rate 0%				
Total Annual Revenues €/year	1430000	8180000	1 020 000	4 260 000
Annualized Costs €/year	-1180000	-4620000	-1 680 000	-6 700 000
Annual Net Profit €/year	250000	3560000	-660 000	-2 440 000
Annualized Costs, Discount Rate 4%				
Total Annual Revenues €/year	1430000	8180000	1 020 000	4 260 000
Annualized Costs €/year	-1350000	-5360000	-2 030 000	-8 160 000
Annual Net Profit €/year	80000	2820000	-1 010 000	-3 900 000

ANNEX 23

Table 59. Belgium BESS1 25MW/25MWh detailed calculation results.

Belgium 25MW/25MWh			
Investment Cost €/kWh	700 €/kWh	450 €/kWh	200€/kWh
Total Capex €	17 500 000	11 250 000	5 000 000
Opex €/Year	180 000	180 000	180 000
Revenues €/Year			
Capacity sold FCR	1 100 000	1 100 000	1 100 000
aFRR capacity sold	800 000	800 000	800 000
mFRR Standard sold	800 000	800 000	800 000
mFRR Flex sold	160 000	160 000	160 000
Net Revenues €/Year			
Capacity sold FCR	920 000	920 000	920 000
aFRR capacity sold	620 000	620 000	620 000

mFRR Standard sold	620 000	620 000	620 000
mFRR Flex sold	-20 000	-20 000	-20 000
FCR+aFRR+mFRR stan	2 160 000	2 160 000	2 160 000
NPV	700€/kWh	450€/kWh	200€/kWh
FCR	-7 480 000	-1 470 000	**4 540 000**
aFRR	-10 530 000	-4 520 000	**1 490 000**
mFRR stand	-10 530 000	-4 520 000	**1 490 000**
mFRR Flex	-17 030 000	-11 020 000	-5 010 000
FCR+aFRR+mFRR stan	5 110 000	11 120 000	17 130 000
IRR			
FCR	-4 %	2 %	**16 %**
aFRR	-8 %	-3 %	**8 %**
mFRR stand	-8 %	-3 %	**8 %**
mFRR Flex	NA	NA	NA
FCR+aFRR+mFRR stan	8 %	17 %	43 %
Simple Payback			
FCR	19	**12**	**5**
aFRR	28	18	**8**
mFRR stand	28	18	**8**
mFRR Flex	-875	-563	-250
FCR+aFRR+mFRR stan	9	6	3
Discounted Payback 4%			
FCR	15<	**15<**	**7**
aFRR	15<	15<	10
mFRR stand	15<	15<	10
mFRR Flex	NA	NA	NA
FCR+aFRR+mFRR stan	10	**6**	**3**
Annualized Costs Discount Rate 0%			
Total Annual Revenues €/year	920 000	920 000	920 000
Total Potential Annual Revenues €/year	2 160 000	2 160 000	2 160 000
Annualized Costs €/year	-1 350 000	-930 000	-510 000
Net Annual Profit €/year	-430 000	-10 000	410 000
Net Annual Profit €/year	810 000	1 230 000	1 650 000
Annualized Costs Discount Rate 4%			
Total Annual Revenues €/year	920 000	920 000	920 000
Total Potential Annual Revenues €/year	2 160 000	2 160 000	2 160 000
Annualized Costs €/year	-1 750 000	-1 190 000	-630 000
Net Annual Profit €/year	-830 000	-270 000	290 000
Net Annual Profit €/year	410 000	970 000	1 530 000

ANNEX 24

Table 60. Belgium BESS2 25MW/100MWh detailed calculation results.

Belgium 25MW/100MWh			
Investment Cost €/kWh	500 €/kWh	350 €/kWh	200€/kWh
Total Capex €	50 000 000	35 000 000	20 000 000
Opex €/Year	175 000	175 000	175 000
Revenues			
Capacity sold FCR	1 440 000	1 440 000	1 440 000
aFRR capacity sold	1 357 500	1 357 500	1 357 500
mFRR Standard sold	1 750 000	1 750 000	1 750 000
mFRR Flex sold	300 000	300 000	300 000
Net Revenues €/Year			
Capacity sold FCR	1 265 000	1 265 000	1 265 000
aFRR capacity sold	1 182 500	1 182 500	1 182 500
mFRR Standard sold	1 575 000	1 575 000	1 575 000
mFRR Flex sold	125 000	125 000	125 000
FCR+aFRR+mFRR stan	4 022 500	4 022 500	4 022 500
NPV			
FCR	-35 230 000	-3 980 000	2 030 000
aFRR	-36 070 000	-4 820 000	1 190 000
mFRR stand	-32 080 000	-830 000	5 180 000
mFRR Flex	-46 810 000	-15 560 000	-9 550 000
FCR+aFRR+mFRR stan	-7 220 000	24 030 000	30 040 000
IRR			
FCR	-12 %	0 %	7 %
aFRR	-12 %	-1 %	6 %
mFRR stand	-9 %	3 %	11 %
mFRR Flex	-29 %	-22 %	-19 %
FCR+aFRR+mFRR stan	2 %	21 %	35 %
Simple Payback			
FCR	40	14	9
aFRR	42	15	10
mFRR stand	32	**11**	**7**
mFRR Flex	400	140	90
FCR+aFRR+mFRR stan	13	**5**	**3**
Discounted Payback 4%			
FCR	15<	15<	15<
aFRR	15<	15<	13
mFRR stand	15<	**15<**	**9**
mFRR Flex	15<	15<	15<
FCR+aFRR+mFRR stan	15<	**5**	**3**

Annualized Costs Discount Rate 0%			
Total Annual Revenues €/year	1 575 000	1 575 000	1 575 000
Total Potential Annual Revenues €/year	4 022 500	4 022 500	4 022 500
Annualized Costs €/year	-3 510 000	-2 510 000	-1 510 000
Net Annual Profit €/year	-1 935 000	-935 000	65 000
Net Annual Profit €/year	512 500	1 512 500	2 512 500
Annualized Costs Discount Rate 4%			
Total Annual Revenues €/year	1 575 000	1 575 000	1 575 000
Total Potential Annual Revenues €/year	4 022 500	4 022 500	4 022 500
Annualized Costs €/year	-4 670 000	-3 320 000	-1 970 000
Net Annual Profit €/year	-3 095 000	-1 745 000	-395 000
Net Annual Profit €/year	-647 500	702 500	2 052 500

ANNEX 25

Table 61. Belgium BESS3 104MW/104MWh detailed calculation results.

Belgium 104MW/104MWh			
Investment Cost €/kWh	700 €/kWh	450 €/kWh	200€/kWh
Total Capex €	72 800 000 €	46 800 000	20 800 000
Opex €/Year	710 000 €	710 000	710 000
Revenues			
Capacity sold FCR	1 940 000	1 940 000	1 940 000
aFRR capacity sold	2 850 000	2 850 000	2 850 000
mFRR Standard sold	2 940 000	2 940 000	2 940 000
mFRR Flex sold	620 000	620 000	620 000
Net Revenues €/Year			
Capacity sold FCR	1 230 000	1 230 000	1 230 000
aFRR capacity sold	2 140 000	2 140 000	2 140 000
mFRR Standard sold	2 230 000	2 230 000	2 230 000
mFRR Flex sold	- 90 000	-90 000	-90 000
FCR+aFRR+mFRR stan	5 600 000	5 600 000	5 600 000
NPV			
FCR	- 57 510 000	-32 510 000	-7 510 000
aFRR	- 48 260 000	-23 260 000	1 740 000
mFRR stand	- 47 350 000	-22 350 000	2 650 000
mFRR Flex	- 70 910 000	-45 910 000	-20 910 000
FCR+aFRR+mFRR stan	-13 120 000	11 880 000	36 880 000
IRR			
FCR	-15 %	-11 %	-2 %
aFRR	-10 %	-5 %	**5 %**

mFRR stand	-10 %	-5 %	**6 %**
mFRR Flex	NA	NA	NA
FCR+aFRR+mFRR stan	1 %	8 %	26 %
Simple Payback			
FCR	59	38	17
aFRR	34	22	10
mFRR stand	33	21	**9**
mFRR Flex	-809	-520	-231
FCR+aFRR+mFRR stan	13	**9**	**4**
Discounted Payback 4%			
FCR	15<	15<	15<
aFRR	15<	15<	13
mFRR stand	15<	**15<**	**12**
mFRR Flex	15<	15<	15<
FCR+aFRR+mFRR stan	15<	**11**	**5**
Annualized Costs Discount Rate 0%			
Total Annual Revenues €/year	2 230 000	2 230 000	2 230 000
Total Potential annual Revenues €/year	5 600 000	5 600 000	5 600 000
Annualized Costs €/year	- 5 560 000	-3 830 000	-2 100 000
Net Annual Profit €/year	- 3 330 000	-1 600 000	130 000
Net Annual Profit €/year	40 000	1 770 000	3 500 000
Annualized Costs Discount Rate 4%			
Total Annual Revenues €/year	2 230 000	2 230 000	2 230 000
Total Potential annual Revenues €/year	5 600 000	5 600 000	5 600 000
Annualized Costs €/year	- 7 260 000	-4 920 000	-2 580 000
Net Annual Profit €/year	- 5 030 000	-2 690 000	-350 000
Net Annual Profit €/year	- 1 660 000	680 000	3 020 000

ANNEX 26

Table 62. Belgium BESS4 104MW/416MWh detailed calculation results.

Belgium 104MW/416MWh			
Investment Cost €/kWh	700 €/kWh	350 €/kWh	200€/kWh
Total Capex €	208 000 000	145 600 000	83 200 000
Opex €/Year	710 000	710 000	710 000
Revenues €/Year			
Capacity sold FCR	1 510 000	1 510 000	1 510 000
aFRR capacity sold	7 530 000	7 530 000	7 530 000
mFRR Standard sold	5 230 000	5 230 000	5 230 000
mFRR Flex sold	870 000	870 000	870 000
Net Revenues €/Year			

Capacity sold FCR	800 000	800 000	800 000
aFRR capacity sold	6 820 000	6 820 000	6 820 000
mFRR Standard sold	4 520 000	4 520 000	4 520 000
mFRR Flex sold	160 000	160 000	160 000
FCR+aFRR+mFRR stan	12 140 000	12 140 000	12 140 000
NPV			
FCR	-191 870 000	-131 870 000	-71 870 000
aFRR	-130 730 000	-70 730 000	-10 730 000
mFRR stand	-154 090 000	-94 090 000	-34 090 000
mFRR Flex	-198 370 000	-138 370 000	-78 370 000
FCR+aFRR+mFRR stan	-76 700 000	-16 700 000	43 300 000
IRR			
FCR	-26 %	-24 %	-20 %
aFRR	-9 %	-5 %	2 %
mFRR stand	-13 %	-10 %	-3 %
mFRR Flex	NA	NA	NA
FCR+aFRR+mFRR stan	-3 %	2 %	11 %
Simple Payback			
FCR	260	182	104
aFRR	30	21	12
mFRR stand	46	32	18
mFRR Flex	1 300	910	520
FCR+aFRR+mFRR stan	18	12	7
Discounted Payback 4%			
FCR	15<	15<	15<
aFRR	15<	**15<**	**15<**
mFRR stand	15<	15<	15<
mFRR Flex	15<	15<	15<
FCR+aFRR+mFRR stan	15<	**15<**	**9**
Annualized Costs Discount rate 0%			
Total Annual Revenues €/year	6 820 000	6 820 000	6 820 000
Total Potential annual Revenues €/year	12 140 000	12 140 000	12 140 000
Annualized Costs €/year	-14 580 000	-10 420 000	-6 260 000
Net Annual Profit €/year	-7 760 000	-3 600 000	560 000
Net Annual Profit €/year	-2 440 000	1 720 000	5 880 000
Annualized Costs Discount Rate 4%			
Total Annual Revenues €/year	6 820 000	6 820 000	6 820 000
Total Potential annual Revenues €/year	12 140 000	12 140 000	12 140 000
Annualized Costs €/year	-19 420 000	-13 810 000	-8 190 000
Net Annual Profit €/year	-12 600 000	-6 990 000	-1 370 000
Net Annual Profit €/year	-7 280 000	-1 670 000	3 950 000

ANNEX 27

Table 63. Ireland BESS1 25MW/25MWh detailed calculation results with DS3 Program.

Ireland 25MW/25MWh			
Investment Cost €/kWh	**700 €/kWh**	**450 €/kWh**	**200€/kWh**
CAPEX €	17 500 000	11 250 000	5 000 000
Award for new investment €	-7 500 000	-7 500 000	-7 500 000
Total Capex €	**10 000 000**	**3 750 000**	**0**
Opex €/Year	210 000	210 000	210 000
Revenues			
FFR-TOR1 Total revenue	1 590 000	1 590 000	1 590 000
IDA sold	1 620 000	1 620 000	1 620 000
FFR-TOR1+IDA	3 210 000	3 210 000	3 210 000
Net Revenues €/Year			
FFR-TOR1	1 380 000	1 380 000	1 380 000
IDA	1 410 000	1 410 000	1 410 000
FFR-TOR1+IDA	2 790 000	2 790 000	2 790 000
NPV			
FFR-TOR1	4 400 000	10 410 000	14 020 000
IDA sold	4 710 000	10 720 000	14 320 000
FFR-TOR1+IDA	18 720 000	24 730 000	28 340 000
IRR			
FFR-TOR1	10 %	36 %	NA
IDA sold	11 %	37 %	NA
FFR-TOR1+IDA	27 %	74 %	NA
Simple Payback			
FFR-TOR1	**7**	**3**	**0**
IDA sold	**7**	**3**	**0**
FFR-TOR1+IDA	4	1	0
Discounted Payback 4%			
FFR-TOR1	**9**	**3**	**0**
IDA sold	**9**	**4**	**0**
FFR-TOR1+IDA	4	2	0
Annualized Costs Discount Rate 0%		Case1 450 €/kWh	Case1 200€/kWh
Total Annual Revenues €/year	1 620 000	1 620 000	1 620 000
Total Potential Annual Revenues €/year	3 210 000	3 210 000	3 210 000
Annualized Costs €/year	-880 000	-460 000	-210 000
Net Annual Profit €/year	740 000	1 160 000	1 410 000
Net Annual Profit €/year	2 330 000	2 750 000	3 000 000
Annualized Costs Discount Rate 4%		450 €/kWh	200€/kWh
Total Annual Revenues €/year	1 620 000	1 620 000	1 620 000
Total Potential Annual Revenues €/year	3 210 000	3 210 000	3 210 000

Annualized Costs €/year	-1 110 000	-550 000	-210 000
Net Annual Profit €/year	510 000	1 070 000	1 410 000
Net Annual Profit €/year	2 100 000	2 660 000	3 000 000

ANNEX 28

Table 64. Ireland BESS2 25MW/100MWh detailed calculation results with DS3 Program.

Ireland 25MW/100MWh			
Investment Cost €/kWh	500 €/kWh	350 €/kWh	200€/kWh
Total Capex €	50 000 000	35 000 000	20 000 000
Award for new investment €	-7 500 000	-7 500 000	-7 500 000
Total Capex €	**42 500 000**	**27 500 000**	**12 500 000**
Opex €/Year	210 000	210 000	210 000
Revenues			
FFR-TOR1	2 710 000	2 710 000	2 710 000
IDA	1 940 000	1 940 000	1 940 000
FFR-TOR1+IDA	4 650 000	4 650 000	4 650 000
Net Revenues €/Year			
FFR-TOR1	2 500 000	2 500 000	2 500 000
IDA	1 730 000	1 730 000	1 730 000
FFR-TOR1+IDA	4 230 000	4 230 000	4 230 000
NPV			
FFR-TOR1	-15 470 000	-1 050 000	13 370 000
IDA	-23 290 000	-8 870 000	5 550 000
FFR-TOR1+IDA	2 100 000	16 520 000	30 940 000
IRR			
FFR-TOR1	-2 %	**3 %**	**18 %**
IDA	-7 %	-2 %	**10 %**
FFR-TOR1+IDA	5 %	12 %	33 %
Simple Payback			
FFR-TOR1	17	**11**	**5**
IDA	25	16	**7**
FFR-TOR1+IDA	10	7	3
Discounted Payback 4%			
FFR-TOR1	**15<**	**15<**	**6**
IDA sold	**15<**	**15<**	**9**
FFR-TOR1+IDA	14	8	2
Annualized Costs Discount Rate 0%			
Total Annual Revenues €/year	2 710 000	2 710 000	2 710 000
Total Potential Annual Revenues €/year	4 650 000	4 650 000	4 650 000
Annualized Costs €/year	-3 040 000	-2 040 000	-1 040 000

Net Annual Profit €/year	-330 000	670 000	1 670 000
Net Annual Profit €/year	1 610 000	2 610 000	3 610 000
Annualized Costs Discount Rate 4%			
Total Annual Revenues €/year	2 710 000	2 710 000	2 710 000
Total Potential Annual Revenues €/year	4 650 000	4 650 000	4 650 000
Annualized Costs €/year	-4 030 000	-2 680 000	-1 330 000
Net Annual Profit €/year	-1 320 000	30 000	1 380 000
Net Annual Profit €/year	620 000	1 970 000	3 320 000

ANNEX 29

Table 65. Ireland BESS3 104MW/104MWh detailed calculation results with DS3 Program.

Ireland 104MW/104MWh			
Investment Cost €/kWh	700 €/kWh	450 €/kWh	200€/kWh
Total Capex €	72 800 000	46 800 000	20 800 000
Award for new investment €	-31 200 000	-31 200 000	-31 200 000
Total Capex €	41 600 000	15 600 000	0
Opex €/Year	850 000	850 000	850 000
Revenues			
FFR-TOR1	2 480 000	2 480 000	2 480 000
IDA	6 693 000	6 283 000	6 283 000
FFR-TOR1+IDA	9 173 000	8 763 000	8 763 000
Net Revenues €/Year			
FFR-TOR1	1 630 000	1 630 000	1 630 000
IDA	5 843 000	5 433 000	5 433 000
FFR-TOR1+IDA	7 473 000	7 063 000	7 063 000
NPV			
FFR-TOR1	-23 444 336	1 555 664	16 555 664
IDA	19 320 000	44 320 000	59 320 000
FFR-TOR1+IDA	35 870 000	60 870 000	75 870 000
IRR			
FFR-TOR1	-7 %	6 %	-
IDA	37 %	37 %	-
FFR-TOR1+IDA	16 %	48 %	-
Simple Payback			
FFR-TOR1	26	**10**	**0**
IDA	**7**	**3**	**0**
FFR-TOR1+IDA	6	2	0
Discounted Payback 4%			
FFR-TOR1	15<	13	0

IDA sold	9	**3**	**0**
FFR-TOR1+IDA	7	**3**	**0**
Annualized Costs Discount Rate 0%			
Total Annual Revenues €/year	6 693 000	6 283 000	6 283 000
Total Potential Annual Revenues €/year	9 173 000	8 763 000	8 763 000
Annualized Costs €/year	-3 620 000	-1 890 000	-850 000
Net Annual Profit €/year	3 073 000	4 393 000	5 433 000
Net Annual Profit €/year	5 553 000	6 873 000	7 913 000
Annualized Costs Discount Rate 4%			
Total Annual Revenues €/year	6 693 000	6 283 000	6 283 000
Total Potential Annual Revenues €/year	9 173 000	8 763 000	8 763 000
Annualized Costs €/year	-4 590 000	-2 250 000	-850 000
Net Annual Profit €/year	2 103 000	4 033 000	5 433 000
Net Annual Profit €/year	4 583 000	6 513 000	7 913 000

ANNEX 30

Table 66. Ireland BESS4 104MW/416MWh detailed calculation results with DS3 Program.

Ireland 104MW/416MWh			
Investment Cost €/kWh	500 €/kWh	350 €/kWh	200€/kWh
Total Capex €	246 480 000	184 080 000	121 680 000
Award for new investment €	-31 200 000	-31 200 000	-31 200 000
Total Capex €	215 280 000	152 880 000	90 480 000
Opex €/Year	850 000	850 000	850 000
Revenues			
FFR-TOR1	3 220 000	3 220 000	3 220 000
IDA	15 510 000	15 510 000	15 510 000
FFR-TOR1+IDA	18 730 000	18 730 000	18 730 000
Net Revenues €/Year			
FFR-TOR1	2 370 000	2 370 000	2 370 000
IDA	14 660 000	14 660 000	14 660 000
FFR-TOR1+IDA	17 030 000	17 030 000	17 030 000
NPV			
FFR-TOR1	-182 930 000	-122 930 000	-62 930 000
IDA	-58 100 000	1 900 000	61 900 000
FFR-TOR1+IDA	-34 030 000	25 970 000	85 970 000
IRR			
FFR-TOR1	-19 %	-16 %	-11 %
IDA	-1 %	4 %	13 %
FFR-TOR1+IDA	1 %	7 %	17 %
Simple Payback			
FFR-TOR1	15	10	6

IDA	15	**10**	**6**
FFR-TOR1+IDA	13	9	5
Discounted Payback 4%			
FFR-TOR1	15<	15<	15<
IDA sold	15<	**14**	**8**
FFR-TOR1+IDA	15<	**12**	**7**
Annualized Costs Discount Rate 0%			
Total Annual Revenues €/year	15 510 000	15 510 000	15 510 000
Total Potential annual Revenues €/year	18 730 000	18 730 000	18 730 000
Annualized Costs €/year	-15 200 000	-11 040 000	-6 880 000
Net Annual Profit €/year	310 000	4 470 000	8 630 000
Net Annual Profit €/year	3 530 000	7 690 000	11 850 000
Annualized Costs Discount Rate 4%			
Total Annual Revenues €/year	15 510 000	15 510 000	15 510 000
Total Potential annual Revenues €/year	18 730 000	18 730 000	18 730 000
Annualized Costs €/year	-20 210 000	-14 600 000	-8 990 000
Net Annual Profit €/year	-4 700 000	910 000	6 520 000
Net Annual Profit €/year	-1 480 000	4 130 000	9 740 000

ANNEX 31

Table 67. Ireland BESS1 25MW/25MWh detailed calculation results without DS3 Program

Ireland 25MW/25MWh			
Investment Cost €/kWh	**700 €/kWh**	**450 €/kWh**	**200€/kWh**
Total Capex €	17 500 000	11 250 000	5 000 000
Total Capex €	**17 500 000**	**11 250 000**	**5 000 000**
Opex €/Year	205 000	205 000	205 000
Revenues			
FFR-TOR1	1 100 000	1 100 000	1 100 000
IDA	1 620 000	1 620 000	1 620 000
FFR-TOR1+IDA	2 720 000	2 720 000	2 720 000
Net Revenues €/Year			
FFR-TOR1	895 000	895 000	895 000
IDA	1 415 000	1 415 000	1 415 000
FFR-TOR1+IDA	2 310 000	2 310 000	2 310 000
NPV			
FFR-TOR1	-7 740 000	-1 730 000	4 280 000
IDA	-2 450 000	3 550 000	9 560 000
FFR-TOR1+IDA	6 640 000	12 650 000	18 650 000
IRR			

FFR-TOR1	-4 %	1 %	16 %
IDA	2 %	9 %	27 %
FFR-TOR1+IDA	9 %	19 %	46 %
Simple Payback			
FFR-TOR1	20	13	**6**
IDA	12	**8**	**4**
FFR-TOR1+IDA	8	5	2
Discounted Payback 4%			
FFR-TOR1	15<	15<	7
IDA sold	15<	**4**	**4**
FFR-TOR1+IDA	10	**6**	**3**
Annualized Costs discount rate 0%			
Total Annual Revenues €/year	1 620 000	1 620 000	1 620 000
Total Potential Annual Revenues €/year	2 720 000	2 720 000	2 720 000
Annualized Costs €/year	-1 370 000	-960 000	-540 000
Net Annual Profit €/year	250 000	660 000	1 080 000
Net Annual Profit €/year	1 350 000	1 760 000	2 180 000
Annualized Costs discount rate 4%			
Total Annual Revenues €/year	1 620 000	1 620 000	1 620 000
Total Potential Annual Revenues €/year	2 720 000	2 720 000	2 720 000
Annualized Costs €/year	-1 780 000	-1 220 000	-650 000
Net Annual Profit €/year	-160 000	400 000	970 000
Net Annual Profit €/year	940 000	1 500 000	2 070 000

ANNEX 32

Table 68. Ireland BESS2 25MW/100MWh detailed calculation results without DS3 Program

Ireland 25MW/100MWh			
Investment Cost €/kWh	500 €/kWh	350 €/kWh	200€/kWh
Total Capex €	50 000 000	35 000 000	20 000 000
Total Capex €	**50 000 000**	**35 000 000**	**20 000 000**
Opex €/Year	205 000	205 000	205 000
Revenues			
FFR-TOR1	1 940 000	1 940 000	1 940 000
IDA	1 940 000	1 940 000	1 940 000
FFR-TOR1+IDA	3 880 000	3 880 000	3 880 000
Net Revenues €/Year			
FFR-TOR1	1 735 000	1 735 000	1 735 000
IDA	1 735 000	1 735 000	1 735 000
FFR-TOR1+IDA	3 470 000	3 470 000	3 470 000

NPV			
FFR-TOR1	-30 450 000	-16 030 000	-1 610 000
IDA	-30 450 000	-16 030 000	-1 610 000
FFR-TOR1+IDA	-12 830 000	1 590 000	16 010 000
IRR			
FFR-TOR1	-8 %	-5 %	3 %
IDA	-8 %	-5 %	3 %
FFR-TOR1+IDA	0 %	5 %	15 %
Simple Payback			
FFR-TOR1	29	20	12
IDA	29	21	12
FFR-TOR1+IDA	14	10	6
Discounted Payback 0%			
FFR-TOR1	15<	15<	12
IDA sold	15<	15<	12
FFR-TOR1+IDA	15<	11	5
Discounted Payback 4%			
FFR-TOR1	15<	15<	15<
IDA sold	15<	15<	15<
FFR-TOR1+IDA	15<	**14**	**6**
Annualized Costs discount rate 0%			
Total Annual Revenues €/year	1 940 000	1 940 000	1 940 000
Total Potential Annual Revenues €/year	0	0	0
Annualized Costs €/year	-3 540 000	-2 540 000	-1 540 000
Net Annual Profit €/year	-1 600 000	-600 000	400 000
Net Annual Profit €/year	-3 540 000	-2 540 000	-1 540 000
Annualized Costs discount rate 4%			
Total Annual Revenues €/year	1 940 000	1 940 000	1 940 000
Total Potential Annual Revenues €/year	0	0	0
Annualized Costs €/year	-4 700 000	-3 350 000	-2 000 000
Net Annual Profit €/year	-2 760 000	-1 410 000	-60 000
Net Annual Profit €/year	-4 700 000	-3 350 000	-2 000 000

ANNEX 33

Table 69. Ireland BESS3 104MW/104MWh detailed calculation results without DS3 Program

Ireland 104MW/104MWh			
Investment Cost €/kWh	700 €/kWh	450 €/kWh	200€/kWh
Total Capex €	72 800 000	46 800 000	20 800 000
Total Capex €	72 800 000	46 800 000	20 800 000

Opex €/Year	850 000	850 000	850 000
Revenues			
FFR-TOR1	2 480 000	2 480 000	2 480 000
IDA	6 690 000	6 690 000	6 690 000
FFR-TOR1+IDA	9 170 000	9 170 000	9 170 000
Net Revenues €/Year			
FFR-TOR1	1 630 000	1 630 000	1 630 000
IDA	5 840 000	5 840 000	5 840 000
FFR-TOR1+IDA	7 470 000	7 470 000	7 470 000
NPV			
FFR-TOR1	-53 440 000	-28 440 000	-3 440 000
IDA	-10 680 000	14 320 000	39 320 000
FFR-TOR1+IDA	5 870 000	30 870 000	55 870 000
IRR			
FFR-TOR1	-13 %	-8 %	1 %
IDA	2 %	8 %	27 %
FFR-TOR1+IDA	5 %	13 %	35 %
Simple Payback			
FFR-TOR1	45	29	13
IDA	13	**9**	**4**
FFR-TOR1+IDA	10	7	3
Discounted Payback 0%			
FFR-TOR1	15<	15<	13
IDA sold	13	9	4
FFR-TOR1+IDA	10	7	3
Discounted Payback 4%			
FFR-TOR1	15<	15<	15<
IDA sold	15<	10	**4**
FFR-TOR1+IDA	13	**8**	**4**
Annualized Costs discount rate 0%			
Total Annual Revenues €/year	6 690 000	6 690 000	6 690 000
Total Potential Annual Revenues €/year	9 170 000	9 170 000	9 170 000
Annualized Costs €/year	-5 700 000	-3 970 000	-2 240 000
Net Annual Profit €/year	990 000	2 720 000	4 450 000
Net Annual Profit €/year	3 470 000	5 200 000	6 930 000
Annualized Costs discount rate 4%			
Total Annual Revenues €/year	6 690 000	6 690 000	6 690 000
Total Potential Annual Revenues €/year	9 170 000	9 170 000	9 170 000
Annualized Costs €/year	-7 400 000	-5 060 000	-2 720 000
Net Annual Profit €/year	-710 000	1 630 000	3 970 000
Net Annual Profit €/year	1 770 000	4 110 000	6 450 000

ANNEX 34

Table 70. Ireland BESS4 104MW/416MWh detailed calculation results without DS3 Program.

Ireland 104MW/416MWh			
Investment Cost €/kWh	500 €/kWh	350 €/kWh	200€/kWh
Total Capex €	246 480 000	184 080 000	121 680 000
Total Capex €	246 480 000	184 080 000	121 680 000
Opex €/Year	850 000	850 000	850 000
Revenues			
FFR-TOR1	1 940 000	1 940 000	1 940 000
IDA	15 380 000	15 380 000	15 380 000
FFR-TOR1+IDA	17 320 000	17 320 000	17 320 000
Net Revenues €/Year			
FFR-TOR1	1 090 000	1 090 000	1 090 000
IDA	14 530 000	14 530 000	14 530 000
FFR-TOR1+IDA	15 620 000	15 620 000	15 620 000
NPV			
FFR-TOR1	-225 930 000	-165 930 000	-105 930 000
IDA	-89 420 000	-29 420 000	30 580 000
FFR-TOR1+IDA	-78 350 000	-18 350 000	41 650 000
IRR			
FFR-TOR1	-25 %	-23 %	-20 %
IDA	-2 %	1 %	8 %
FFR-TOR1+IDA	-2 %	2 %	9 %
Simple Payback			
FFR-TOR1	226	169	112
IDA	17	13	**9**
FFR-TOR1+IDA	16	12	8
Discounted Payback 0%			
FFR-TOR1	15<	15<	15<
IDA sold	15<	13	9
FFR-TOR1+IDA	15<	12	8
Discounted Payback 4%			
FFR-TOR1	15<	15<	15<
IDA sold	15<	15<	**11**
FFR-TOR1+IDA	15<	15<	**10**
Annualized Costs discount rate 0%			
Total Annual Revenues €/year	15 380 000	15 380 000	15 380 000
Total Potential Annual Revenues €/year	17 320 000	17 320 000	17 320 000
Annualized Costs €/year	-17 280 000	-13 120 000	-8 960 000
Net Annual Profit €/year	-1 900 000	2 260 000	6 420 000
Net Annual Profit €/year	40 000	4 200 000	8 360 000

Annualized Costs discount rate 4%			
Total Annual Revenues €/year	15 380 000	15 380 000	15 380 000
Total Potential Annual Revenues €/year	17 320 000	17 320 000	17 320 000
Annualized Costs €/year	-23 020 000	-17 410 000	-11 790 000
Net Annual Profit €/year	-7 640 000	-2 030 000	3 590 000
Net Annual Profit €/year	-5 700 000	-90 000	5 530 000