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TESI DI LAUREA MAGISTRALE

DEVELOPMENT OF AN ENERGY MODEL TO STUDY THE RELEVANCE OF LONG-TERM ENERGY STORAGE WITHIN THE BELGIAN ELECTRICITY ZONE POWERED WITH 100% RENEWABLES

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La testa che spicca fuori dall'acqua non vede il proprio corpo sommerso.
E' la punta dell'iceberg, l'iceberg intero, il resto è andato disperso.

— *La punta dell'iceberg - Eugenio in Via Di Gioia*

Summary

The University of Liège, in particular the Chemical Engineering Department, is involved in several research projects to improve the process of methanol production in a catalytic reactor from CO_2 capture and water electrolysis. The present work illustrates how this technology can be applied in a 100% renewable by 2050 context with the purpose of studying the economic viability using it as long-term energy storage. The Python model utilised was already developed in 2015 using wind power and power-to-methanol as only technologies. In order to obtain a more realistic model, other RES technologies (photovoltaic and Biomass) and short-term storage (battery and pumped-hydro) have been implemented. Defining a possible base case in 2050, some simulations have been performed obtaining an electricity cost equal to 142.1 eur/MWh. A correspondent power generation mix in which the installed capacity of onshore wind energy is over the maximum Belgian potential has also been computed. Assuming an increase of the biomass power capacity up to 2 GW, a new power generation mix closer to the reality has been found (11.51 GW offshore, 24.72 GW solar PV, 10.51 GW onshore, 2 GW biomass) at the expense of a higher total electricity cost equal to 149.7 eur/MWh. Moreover, the effects of Power To Methanol parameters on the electricity cost are quantified and discussed. Interesting are the results regarding the operation of the energy storage technologies during the whole period. A comparison with another model given by Montefiore Institute researchers gave attractive results that validated the ones shown with the present model. In a future work, the use of another type of optimization problem is suggested to have more robustness and lower computation time (flaws in the present model).

Sommario

L' Università di Liegi, in particolare il dipartimento di ingegneria chimica, è coinvolta in diversi studi di ricerca per migliorare il processo di produzione di metanolo partendo dalla cattura di CO_2 e dall'elettrolisi dell'acqua. Con l'obiettivo di studiare la fattibilità economica, il presente lavoro mostra in che modo questa tecnologia può essere usata come stoccaggio di energia a lungo termine nel 2050 in un contesto 100% rinnovabile. Il modello Python utilizzato, già sviluppato nel 2015, prevedeva l'uso dell'eolico e di power-to-methanol come uniche tecnologie. Al fine di ottenere un modello più realistico, altre fonti energetiche rinnovabili (fotovoltaico e biomassa) e accumuli a breve termine (batterie e stazioni di pompaggio) sono state implementate. Dopo aver definito un scenario base nel 2050, alcune simulazioni sono state effettuate ottenendo un costo dell' energia elettrica pari a 142.1 eur/MWh. Inoltre, un mix energetico in cui la potenza installata dell'eolico onshore supera il massimo potenziale previsto per il Belgio è stato ottenuto. Assumendo un aumento della potenza installata degli impianti a biomassa a 2 GW, il nuovo mix energetico si è avvicinato ad una possibile realtà (11.51 GW di eolico offshore, 24.72 GW di solare fotovoltaico, 10.51 GW di eolico onshore e 2 GW di biomassa) a scapito di un costo dell'energia elettrica di 149.7 eur/MWh, più alto del caso precedente. In aggiunta, l'influenza dei parametri che si riferiscono alla tecnologia power-to-methanol è stata quantificata e discussa attraverso un'analisi di sensibilità. Interessanti sono i risultati riguardanti il funzionamento dello stoccaggio di energia durante l'intero periodo. Il confronto con un altro modello fornito dai ricercatori dell'Istituto Monfefiore ha confermato i risultati ottenuti nel modello attuale. In un futuro, l'uso di un altro problema di ottimizzazione è consigliato per ottenere più robustezza e minore tempo di calcolo (punti deboli del modello qui presentato).

Résumé

L'Université de Liège, en particulier le Chemical Engineering, prend part à plusieurs projets pour améliorer le procesus de production de méthanol dans un réacteur catalytique à partir de la capture de CO_2 et de l'électrolyse de l'eau. Ce travail montre comment cette technologie peut être appliquée dans un contexte 100% renouvelable en 2050. Son objectif est d'étudier la viabilité économique l'utilisant comme stockage à long-terme. Le modèle Python utilisé était déjà développé en 2015 en utilisant l'énergie éolienne et le power-to-methanol comme seules technologies. Avec l'objectif d'obtenir un modèle plus réaliste, des autres énergies renouvelables (photovoltaïque et biomasse) et stockage d'énergie à court terme (batteries et hydraulique par pompage) ont été implémentées. Définissant un cas possible en 2050, des simulations ont été réalisées obtenant un coût d'électricité égal à 142.1 eur/MWh et un mix de production d'électricité correspondant pout lequel la puissance installée des éoliennes est plus grande que le potentiel maximal en Belgique. En assumant une augmentation de la capacité énergique dérivée de la biomasse jusqu'à 2 GW, un nouveau mix de production d'électricité plus proche de la réalité a été trouvé (11.51 GW offshore, 24.72 GW photovoltaïque, 10.51 GW onshore, 2 GW biomasse) au détriment d'un coût d'électricité égal à 149.7 eur/MWh. De plus, les effets des paramètres de P2Meth sur le coût d'électricité ont été quantifiés et soulevés. Intéressants sont les résultats qui concernent l'opération des technologies de stockage pendant toute la période. Une comparaison avec un autre modèle développé par les chercheurs de l'Institut Montefiore donne des résultats intéressants qui valident ceux montrés dans le modèle actuel. Dans un futur travail, l'utilisation d'une autre typologie de problème d'optimisation est conseillée pour avoir plus de robustesse et un temps de calcul réduit (défauts du modèle actuel).

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Chapter 1

Introduction

1.1 Background

Climate change is a serious issue in Europe. The current changes in our planet's climate are giving instability in all forms to the world. The last two decades have been the warmest years on record. The trend of the temperature is clear and an immediate and strong climate action is necessary.[44]

On 28 November 2018, a long-term vision for a modern, competitive, prosperous and climate-neutral economy by 2050 was presented by the European Commission. The strategy, called "*A clean Planet for All*, shows the way of investing into realistic technological solutions, empowering citizens and aligning actions in different fields such as finance, research and industrial policy with the purpose of leading Europe to climate neutrality. In line with the Paris Agreement, developed in 2015 during the COP21, the Commission's vision for a climate-neutral future covers all EU policies set earlier. The objective is to keep the global temperature increase to well below 2.0 °C and pursue efforts to keep it to 1.5 °C" [67](FIG: 1.1).

Contrary to the Paris Agreement, the purpose of this long-term strategy is not to set targets, but to provide a vision and a direction inspiring researchers, entrepreneurs, stakeholders and citizens to develop a new business and create new jobs. Each Member State, in relation to its own resources, can contribute to the modernization of the economy and improve the quality of life in Europe.
The long-term vision presented by the European Commission requires joint action in seven strategic areas. Carbon capture and storage represents a strategy to reduce greenhouse gas emissions by 80% to 95% in 2050 compared to their 1990 level. [68] The actual energy system is not yet ready to produce electricity with zero-emissions due to the high difficulty of the integration in large scale of intermittent energy sources such as wind and solar energy. Nowadays Oil, natural gas and coal still constitute the principal energy sources producing worldwide more than 35 Gton of CO_2 every year and other air pollutants such as NO_x, SO_x and heavy metals. Therefore, sustainable sources as wind, solar, geothermal, biomass and hydropower will be the

solutions which will follow the purpose of replacing fossil fuels and consequently reducing greenhouse gas emissions. [43]

With the growth of renewable technologies, electricity systems will require greater flexibility and, in order to obtain zero-emissions, electricity will need to be stored over days, weeks or months. It is only possible to drive an electricity decarbonisation transforming the whole energy sector with the implementation of new energy storage systems and new control technologies.
The conventional technologies for electricity storage, such as batteries and pumped hydroelectric, can't provide an inter-seasonal service due to the low energy density (<1 MJ/kg). A possible solution is the use of chemical energy carriers with high storage density. Methanol can be one of the most promising candidates to store renewable energies thanks to its high energy density equal to 19.7 MJ/kg.[43]
Methanol is not the only candidate to provide storage service to the electrical grid; hydrogen, produced from the surplus of renewable energies can be stored at industrial scale and could play an important role in the energy transition [69]. With respect to methanol, hydrogen presents several disadvantages due to safety issues and the high cost to store and transport it.

Methanol is one of the most flexible chemical energy carriers and it can be made from a wide array of feedstocks. In some countries, such as Iceland, Netherlands and Canada, the small scale production of ultra-low carbon intensity renewable methanol is already underway; the CO_2 is captured from the air and then combined with renewable hydrogen produced via electrolysis into methanol [70]. Methanol is a colorless liquid with a boiling point equal to 64.96 °C, easy to store and to transport, safer and with a cleaner combustion than gasoline[6].Moreover methanol can be a desirable choice as a transportation fuel because of the ease to distribute it, its large availability and its efficient combustion.[71]

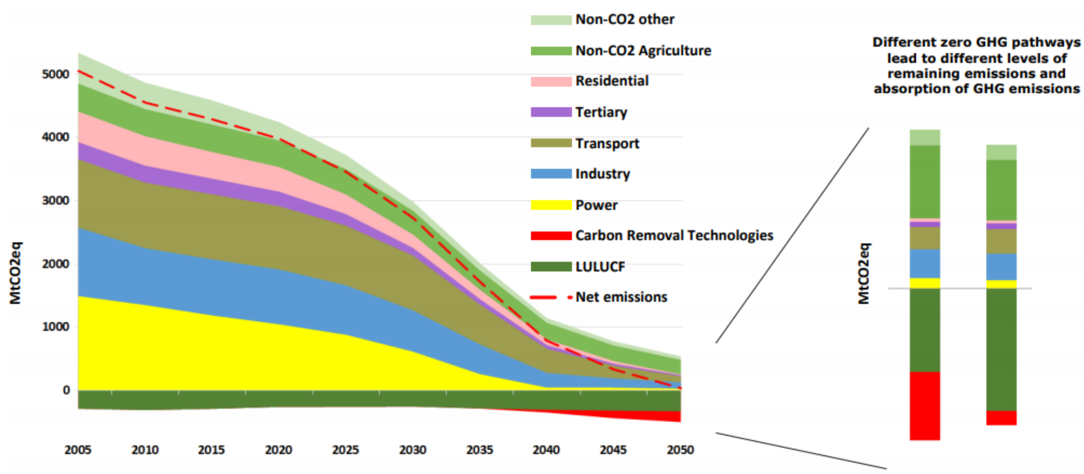


FIG: 1.1. GHG emissions trajectory in a 1.5 °C scenario [44]

1.2 Aim of the thesis

The present work has been developed during the Erasmus Programme at the University of Liège from February to June 2019, thanks to Dr. Léonard Grégoire in the Chemical Engineering Department. The aim of the thesis is a development of an energy model to study the relevance of long-term energy storage within the Belgian electricity zone powered with 100% renewables.
The main objective of the work was to implement an existing model written in Python developed in 2015 by Léonard Grégoire and other researchers in which only the presence of wind technology and Power to Methanol energy storage has been considered. The purpose of the model is to study the influence of Power to Fuel (P2F) energy storage on the electricity cost in an electricity zone powered with 100% renewables assumed to be in 2050. The implemented model, with respect to the previous one, appears more realistic thanks to the presence of other renewable sources and short-term energy storage and using five-years period historical data.

The energy system concerned, presents a *"communist"* centralised state system in which the person that sells the electricity is the same as who buys it. In the actual system, with the purpose of increasing the competitiveness, the energy is bought and sold through different step and thus different people take part in the process. In our model, the storage units do not have to pay for the electricity absorbed (different from the reality) giving a service for the stability of the energy system in the area selected. In addition, the electricity zone does not present interaction with neighbouring countries.

The work has been divided in several parts due to the progressive implementation of the Python code with the different energy sources and storages. Starting from the implementation of Pumped-storage hydroelectricity, proceeding with biomass, the distinction between onshore and offshore wind energy, solar energy and finally battery.
In order to obtain useful parameters for the creation of the model, a technical and economical analysis for each technology has been done using literature and projecting them by 2050. Moreover, for solar and wind energy and for the Belgian consumption it has been necessary to download and analyse historical data referred to the period 2013-2018 with 15 minutes resolution to get an idea of what could be the variation of both demand and generation under realistic conditions.
Several simulations have been done in order to study the total electricity cost of the system, the cost of each technology, the installed capacity, the quantity of energy produced and the trend of the energy level of each energy storage during the period. According to the maximum potential in Belgium regarding RES, upper bounds have been defined using constraints with the purpose to obtain a model more realistic.
At the end of the work, a sensibility analysis has been done in order to take into account the margin of error presents in several parameters due to the high uncertainty on the estimation of a possible scenario in 2050.

Chapter 2

State of art and implementation of RES

2.1 Overall view of wind energy technology

2.1.1 Role of wind energy in the electric power system

The penetration of the wind in the world's energy is one of the most significant developments of the late 20th century. Over the last 25 years, wind turbines have matured and are now cost competitive in many countries with the traditional energy source mainly as a result of the improvement in aerodynamics, computer science and power electronics. [18]

Wind has an annual very high economic impact and it is globally competing in the clean energy economy; it is a clean fuel source and it does not pollute the air like traditional power plants. It can be built on existing farms or ranches; farmers can continue to work the land due to the fact that wind turbines only use a faction of the land; the wind power plant owners make rent payments to the farmer. One of the problems could be the noise and aesthetic pollution although wind parks have relatively small influence on the environment compared to the traditional power plants. [59]

The impacts of wind power on the power system can be categorized in short and long term effects. The prior effects are connected to the operation in time-scale minutes to hours, the latter ones are related to the contribution of the wind generation providing adequacy in the system.[60]
One of the critical issues is how to manage the stability of wind power output in grid-connected systems; several solutions have been studied and, for example, a Control Centre for Renewable Energies that operates under the grid system operator and manages the wind power output with a control system based on wind power forecast has been introduced in Spain. [19]

2.1.2 Situation worldwide

According to preliminary statistics published by WWEA, the overall capacity of wind turbines installed worldwide by the end of 2018 reached 600 GW and, as it is shown in FIG 2.1, from 2007 to 2017 the cumulative installed wind capacity increased at a compound rate of 10-15% with a total installed wind capacity in 2017 of 539 GW. [20]
China has the larger share (almost 197 GW) followed by United States and Germany (90 GW and 55 GW) in the end of 2017 due to policy changes which drove to a rush of installations in 2015 [12].

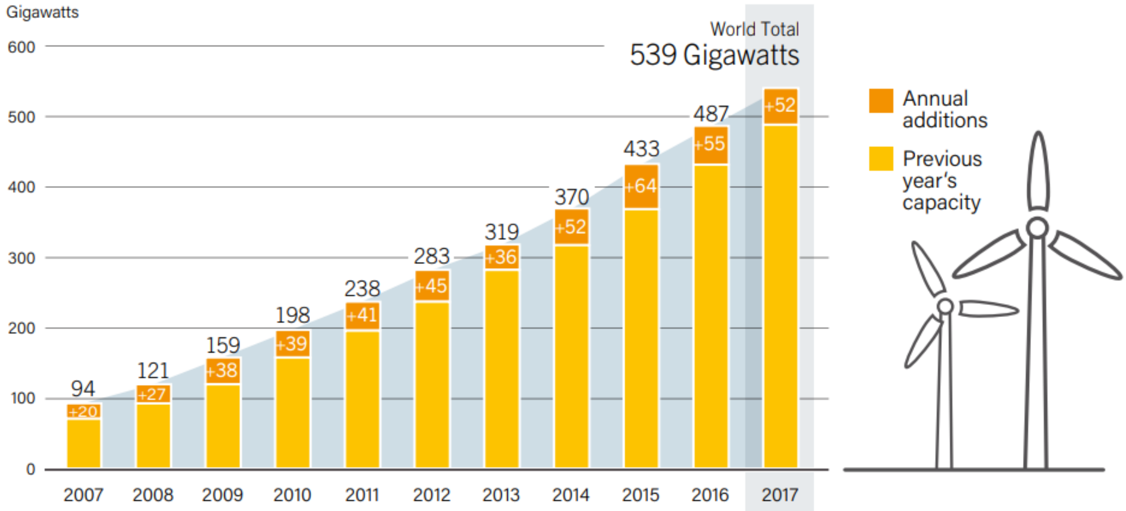


FIG: 2.1. Wind Power Global Capacity and Annual Additions, 2007-2017 [20]

The growth during the last decade in Belgium, the control area chosen in the present work, is very strong and in 2015 an annual production of 5574 GWh was reached with 3600 GW of installed wind capacity[56]. Belgium has the smallest ”Exclusive Economic Zone” in the North Sea compared to neighbouring countries. Wind turbines could be installed offshore but the limit of available space for additional wind development presents strong constraints in the future. Furthermore, public acceptance and other criteria (e.g. aviation routes, land-use) are factors that can limit the onshore wind's development together with the high population density and therefore the available space.
In the adequacy scenario for Belgium 2050 [7], a maximum amount of 9 GW of wind capacity installed onshore and 8 GW of offshore wind have been assumed; these assumptions depend on how the above constraints would evolve according to geopolitical decisions.

2.1.3 Technology Overview

Wind is a form of solar energy and it is cause by a combination of three events: the sun heats the atmosphere, the earth's surface is irregular and the earth rotates. A wind turbine transforms energy of the wind into electricity using the rotation of the rotor blades thanks to the aerodynamic force. In the moment the wind flows across the blade, a difference of pressure is created between the two sides of the blade. This variation creates a force divided in two components: lift and drag. If the force of the lift is stronger than the drag, the rotor turns. This last one is connected to the generator creating in this ways electricity. [57] Wind turbines can be divided in two basic groups:

- Horizontal-Axis Turbines: they operate "upwind" and the blades face into the wind; they are the most common in the market
- Vertical-Axis Turbines: they are omnidirectional. Therefore, they do not need to be adjusted to point into the wind to operate

Since there are stronger and more consistent winds out in the ocean, wind farms can be based onshore (on land) or offshore (sea); due to different geographic, political and technology issues, several are the advantages and disadvantages of each type.
The size and type of wind turbines installed in the EU varies between countries: for onshore wind turbines the average is 2.7 MW and for offshore application it can vary significantly from 2 MW in France to 6 MW in UK. For 2030-2050, the average size of wind turbines in offshore application could grow to sizes of 10 MW up to 20 MW. [21]

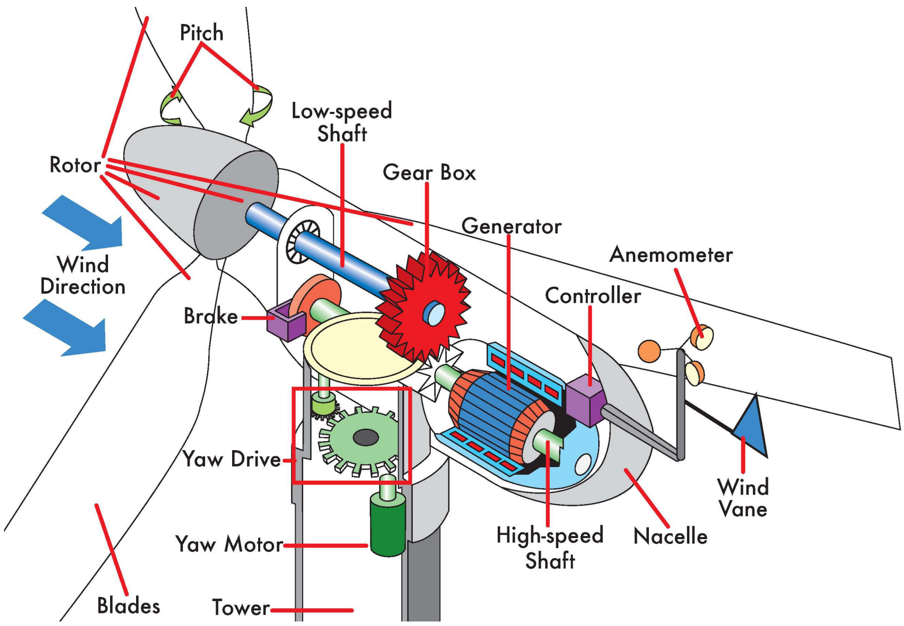


FIG: 2.2. A visual representation of the machinery components [52]

2.2 Implementation in the model of wind energy

2.2.1 Technical analysis

In the previous model [6], the only presence of wind energy in order to achieve the goal of 100% renewables has been considered . In the present work the decision was to improve the model distinguishing onshore and offshore production due to the fact that the two types of technology have different economical costs and different capacity factor.
From the website of ELIA [53], the Belgian Transmission System Operator, the historical wind-power generation data from the 1st January 2013 to 31st August 2018 concerning onshore and offshore wind generation have been downloaded. Using this data, the capacity factor has been computed in each time with the ratio of the real production and the total capacity installed in each period. It has also been used in the model in order to calculate the production in relation to the chosen wind capacity installed in the model.
For each technology it has been necessary to make economic and technical assumptions.

First of all no market competitiveness is considered in the model, so it can be viewed as describing a state-controlled electricity zone without interaction with neighbouring zones.
No geographical distinction has been taken into consideration to simplify the model; the considered zone is considered as a *"copper plate"* with no limitations due to electricity transmission and distribution. In this model, an average wind capacity factor has been supposed dividing onshore and offshore area. Due to the improvement of the technologies, the capacity factor will increase from an average 23% / 34% in 2013 to 45% / 48% in 2050 respectively for onshore and offshore wind. [22] In the present work it has been assumed equal to the historical wind-capacity factor data given by ELIA taking into account that new wind farms could be built in location with lower wind speeds.

One size of wind turbine for onshore and one size for offshore has been chosen. The type of wind turbine does not influence the final results. It only changes the optimum number of wind turbine and not the optimum wind power needed to satisfy the demand. For this reason the type of technology has been taken freely.
As already mentioned,several types of wind turbines with many different characteristics are present in the market. An onshore wind turbine with a power of 5 MW and an offshore wind turbine with a power of 10 MW have been assumed.
The efficiency of the wind turbines has not been chosen as they are not needed in the model; historical capacity factor data are used to take into account the variability of the generation.

2.2.2 Economical analysis

With the purpose of analysing the influence of these technologies in the model, it has been necessary to make economical assumptions projected in 2050.
Between 2008 and 2017, there was an improvement of wind power technologies in several aspects such as higher hub heights, larger areas swept by blades, better power control. In that moment, the large presence of wind turbines in the market caused the investment cost to fall.
It is possible to categorize the total installed costs of a wind project in 5 major costs: [12]

- Civil works: preparation of the site
- Turbine cost: rotor blades, gearbox, power converter, tower, transformer and nacelle
- Grid connection: transformers and substation to connect the wind park to the local distribution or transmission network
- Planning and project costs: it depends of the location and the complexity of the project
- Land: it is usually rented through long-term contracts

Current onshore wind energy is a mature technology but it is expected that capital costs will drop further in projection to 2050. However, this will happen at a moderate rate. A reference CAPEX cost of 1100 euro/kW has been assumed. Concerning the Fixed O&M , a reference annual cost equal to 1.7% of the CAPEX cost has also been assumed. The projected lifetime for 2050 is not very different with respect to the actual one and it has been estimated equal to 25 years with a discount rate of 7% [12].
Since offshore wind is a less mature technology than onshore wind, several technological improvements and a lower CAPEX are expected in 2050. A reference CAPEX cost of 2280 euro/kW and a Fixed O&M equal to 2.3% of the CAPEX cost have been considered. In this case the projected lifetime is expected to increase; for this reason a value of 30 years with a discount rate of 7% has been taken into consideration [12].

The tables presented below (TAB: 2.1 and TAB: 2.2) displays a summary of the assumptions applied to the present work relating to onshore and offshore wind turbines.

Power Capacity	CAPEX	Fixed O&M	Discount rate	Lifetime
MW	*eur/kW*	*%CAPEX/year*	*%*	*years*
5	1100	1,7	7	25

Table 2.1. Summary of the technical/economical assumptions for onshore wind technology

Power Capacity	CAPEX	Fixed O&M	Discount rate	Lifetime
MW	*eur/kW*	*%CAPEX/year*	*%*	*years*
10	2280	2,3	7	30

Table 2.2. Summary of the technical/economical assumptions for offshore wind technology

2.2.3 Model building

The presence of wind technology in the model plays an important role for the generation of electricity. One of the features implemented regarding wind energy in the actual model and different from the previous one, is the differentiation between onshore and offshore wind energy production. It was necessary for each technology to make assumptions and to define technical and control parameters in order to implement the Python code.

First of all, historical data for onshore and offshore wind energy have been uploaded in Python. The capacity factor in each time-step has been calculated computing the ratio between the measured energy production and the total installed capacity in each period.
In order to compute the wind energy production for both technologies in the instant i, the following formulation has been used:

$$E_{wind,off/onshore}(t_i) = n_{wind,off/onshore} \times P_{wind,off/onshore} \times CF_{wind,off/onshore}(t_i) \quad (2.1)$$

In which:

- $E_{wind,off/onshore}(t_i)$ = energy production in a certain instant i from off/onshore wind turbines
- $n_{wind,off/onshore}$ = number of off/onshore wind turbines
- $P_{wind,off/onshore}$ = nominal power of one off/onshore wind turbine
- $CF_{wind,off/onshore}(t_i)$ = capacity factor in a certain instant i of offshore wind turbines

An important role is played by $n_{wind,off/onshore}$, one of the variable parameters chosen by the optimization problem in order to satisfy all the constraints and minimize the total cost of electricity of the system. For physical reasons, one of the constraints set the generated power from the wind turbines to be higher than zero in order to produce energy and not to absorb it.
In order to control and obtain interesting values regarding the presence of wind energy in the model, several parameters for each technology have been used. It is possible to divide them in three main categories:

1. TECHNICAL PARAMETERS
   - Nominal power of onshore and offshore wind turbine [*p_offwm*] and [*p_onwm*]
   - CAPEX [*capex_offwm*] and [*capex_onwm*], Fixed O$M [*fixed_om_offwm*] and [*fixed_om_onwm*], annuity factor [*annuity_cst_offwm*] and [*annuity_cst_onwm*]
   - Lifetime [*life_offwm*] and [*life_onwm*]
2. MODEL VARIABLES
   - Capacity factor [*cfoff(t)*] and *cfon(t)*]
   - Percentage of energy served [*perc_off*] and [*perc_on*]
   - Quantity of energy served [*serv_offwm(t)*] and [*serv_onwm(t)*]
   - LCOE cost [*cost_offwm*] and [*cost_onwm*]
3. OPTIMIZATION VARIABLES
   - Number of wind turbines [*n_offwm*] and [*n_onwm*]

In case of surplus of energy (spread > 0, difference between energy production and consumption) or rather the quantity of energy served directly from a technology in a certain instant i is smaller than the energy production of that technology in the same instant. Thus, part of the energy generated is not directly used to serve the demand but to be stored or curtailed if the capacity of the the energy storage system is not sufficient. Therefore, it is necessary to define how much energy of the total generated by a given technology is directly used; in order to do so, the total energy production is multiplied by a weighted coefficient that takes into account the ratio between the energy generated from a certain technology and the total energy generated.
Due to the task given to biomass energy as base-load production unit, it has not been included in the total energy generated. The formulations 2.2 and 2.3 show how the energy served for each technology at a certain instant i has been calculated:

$$\%_{wind,off/onshore}(t_i) = \frac{E_{wind,off/onshore}(t_i)}{E_{wind,off/onshore}(t_i) + E_{wind,off/onshore}(t_i) + E_{solar}(t_i)} \quad (2.2)$$

$$E_{served,wind,off/onshore}(t_i) = E_{wind,off/onshore}(t_i) \times \%_{wind,off/onshore}(t_i) \quad (2.3)$$

2.3 Overall view of solar technology

2.3.1 Role of PV system in the electric power system

In the last five years, photovoltaic energy has grown at an average annual rate of 60% and it is quickly becoming an essential part of the energy mix in some countries. This growth has been driven by a reduction in the cost of the PV modules, an increment of the efficiency, an improvement of the power electronics and the reliability.
Nowadays it has become usual to see small PV systems installed on the roofs of houses or big farms next to the road in the countryside. 99% of these PV systems are connected to the grid and for this there is no need for batteries. All the surplus energy generated and not used is directly injected to the grid.
In the future 30% of the solar energy capacity is projected to be installed on rooftoops and the left 70% will be installed in large ground-mounted systems known as utility-scale solar projects.[30]
Solar PV installations combined with batteries can provide electricity in zones where the power transmission line is not available, particularly in developing countries with a large availability of solar irradiation.

2.3.2 Situation worldwide

In the next years solar PV dominates renewable capacity growth and in the next six years 575 GW of new capacity is expected. As it is possible to perceive in FIG: 2.3, utility-scale projects represent 55% of the growth. [61]
As the growth in China and Japan has increased in recent years, together they achieve about 88 GW of solar installation between 2014 and 2016. At the end of 2016 China reached the 27% of cumulative installed capacity globally. The yearly installations in Europe reached a historical maximum value of 22 GW in 2011 with an expected addition in the following years up to 8 GW. [12]

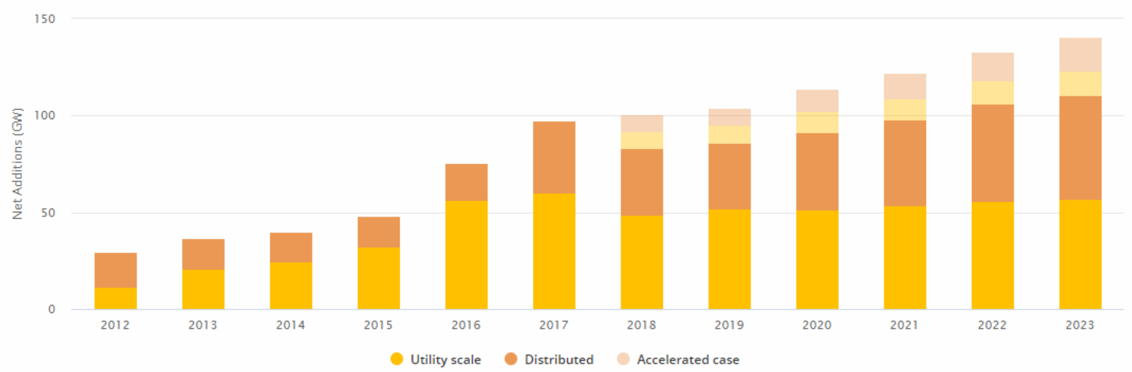


FIG: 2.3. Net solar PV capacity additions 2012-2023 [61]

In Belgium the solar installations were mainly installed between 2008 and 2012.

In the next years a constant growth of the installed solar capacity is expected. In one studio performed by ELIA [7], three scenarios (FIG: 2.4) for 2040 have been proposed starting from 2020:

- The "Base Case" scenario assumes a growth around 100 MW/year reaching 6 GW in 2040;
- The "Large Scale RES" scenario assumes a growth around 300 MW/year reaching 10 GW in 2040;
- The "Decental" scenario assumes a growth around 600 MW/year reaching 18 GW in 2040;

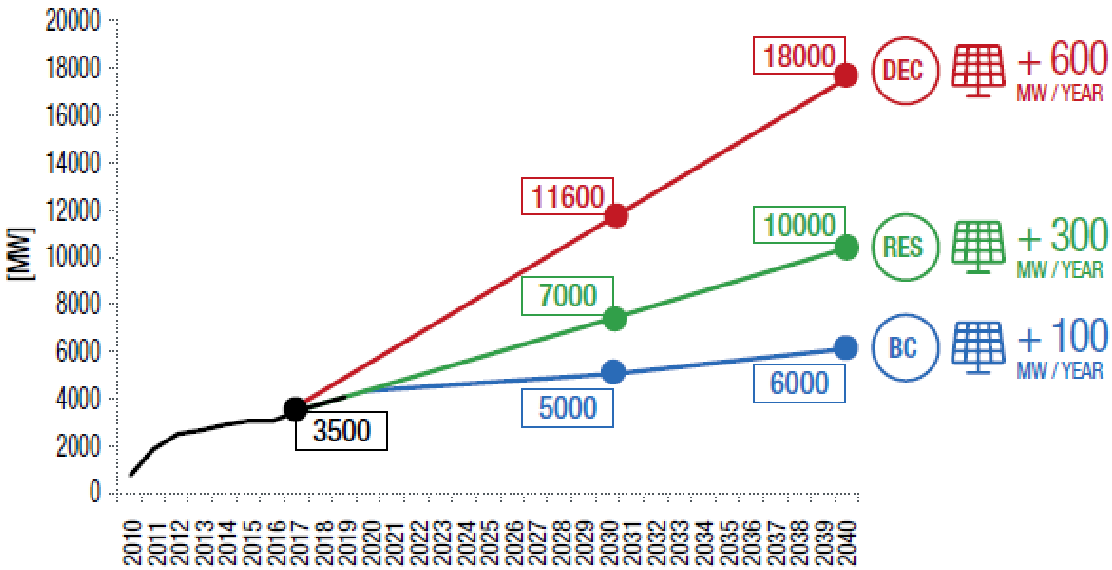


FIG: 2.4. Installed solar capacity per scenario in Belgium [7]

2.3.3 Technology overview

A photovoltaic module (or panel) is made of long chains of PV cells in order to boost the power output available from only one cell (usually 1-2 W). Thanks to this modularity, it is possible to build PV systems from small to large scale.
The photovoltaic system consists of several components including solar panels able to absorb and convert sunlight into electricity, an inverter to change electricity current from DC to AC, support of the panels, cables and other electrical components. In the case of a residential photovoltaic system it is possible to integrate a battery system in order to improve the performance.
The PV system, thanks to the silent operation due to the absence of moving parts and zero environmental emission, is suitable to be installed everywhere as long as the average sunlight radiation is sufficient. Moreover the invested energy for its

manufacturing and installation is recovered within 0.5 and 2 years.
The size of the panel in residential and commercial market is different: 99 x 164 cm made of 60 cells (residential) and 99 x 196 cm made of 72 cells (commercial). The nominal power of a single module depends on the surface and on the electrical efficiency of the module; usually the range is between 150-350 W.[31] The electrical efficiency depends mainly on the type of photovoltaic technology used and it varies within 10% for Amorphous Silicon (A-Si) and 20-22% for mono-crystalline silicon (mono-Si). In the market, crystalline is used (mono or poly) because of its high efficiency and its low cost.

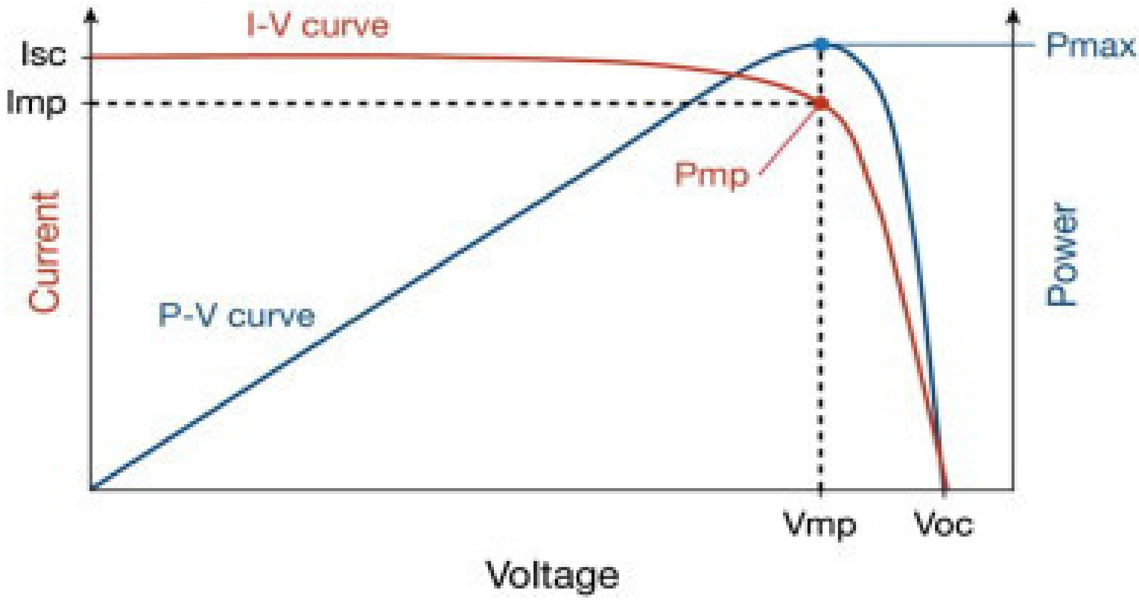


FIG: 2.5. Characteristic curves of a typical PV module in certain solar irradiance and temperature. [32]

Each photovoltaic module is characterized with a curve (FIG: 2.5) that defines the relation between voltage and current in a certain condition. This electric characteristic changes in relation to the type of technology, the solar irradiation and the temperature; it provides the information needed to operate as close as possible to its maximum peak power value. [31]
A very interesting characteristic is the lifetime of a solar module; solar industry usually guarantees 25-30 years of lifetime in which, at the end, the photovoltaic module decreases the efficiency. Nonetheless, it is still able to produce electricity with a lower output.
Different leaders in this sector guarantee after 25 years that the PV module will produce 92% of their original output and that 99 out of 100 solar modules are projected to produce 70% of their original output after 40 years lifetime when proper maintenance is carried out. [47]

2.4 Implementation in the model of PV system

2.4.1 Technical analysis

In order to implement the previous model [6] and have a varied energy mix, it has been decided to consider solar energy, in particular photovoltaic energy. In the same ways that has been done with wind energy, the historical power generation data from the 1st January 2013 to 31st August 2018 concerning solar generation have been downloaded from the website of ELIA [53]. Thanks of these data, the capacity factor has been computed in each time with the ratio of the real production and the total capacity installed in each period and it has been used in the model in order to calculate the production in relation to the solar capacity installed.
With the purpose of implementing solar technology in the model, it has been necessary to make some assumptions.

No geographical distinctions have been considered in order to simplify the model and an average capacity factor in all the control area has been supposed. Due to the technology improvements in the future, the average capacity factor will increase from 13% in 2013 to 17% in 2050[22]. In the present work it has been assumed equal to the capacity factor computed from the the historical data.

The choice of the size of the PV system is arbitrary and it has been decided to set 5 MW that corresponds to a solar park of medium dimension. This assumption doesn't influence the final results changing only the optimum number of PV system and not the optimum total power capacity required from solar technologies to satisfy the demand.
Because of the efficiency is not needed in the model, it has not been chosen.

2.4.2 Economical analysis

The price of solar PV modules decreased by 80% from the end of 2010 and the end of 2016, a period over which 87% of the cumulative global capacity installed occurred. In recent years the cost reduction is more modest with an average price in 2016 13% lower than in 2015 [12]. The slowing down of the growth rate it is due to changes in the legal system in several countries in Europe.
In 2013, thanks to the low cost and the high maturity, crystalline Si technology dominated the market with more than 85% of new PV systems installed becoming the technology expected to be predominant in the next future [22].

In order to study the economical influence of this technology in the model, it has been necessary to define some economic parameters.
From country to country, PV system prices vary significantly depending on market maturity, market size and the competition between the installer. In the present work the presence of both residential and commercial PV system has been taken into

account considering the difference costs of the two technologies. As said previously, in the future the utility-scale projects represent 55% of the growth. For this type of systems an average CAPEX cost in 2050 equal to 760 eur/kW has been estimated. Concerning the Fixed O&M, a reference annual cost equal to 2% of the CAPEX cost has been assumed . For commercial solar PV system an average CAPEX cost in 2050 equal to 520 eur/kW has been estimated with a reference Fixed O&M cost equal to 1.7% of the CAPEX cost for year. Regarding the lifetime an average value of 25 years for both technologies has been used with a discount rate of 7% [22].
In order to obtain a single value for each parameters, a weighted arithmetic mean base on the quantity of PV expected has been done:

$$\text{CAPEX} = 0.55 \times 760 + 0.45 \times 520 = 650 \text{ eur/KW} \tag{2.4}$$

$$\text{Fixed O\&M} = 0.55 \times 2 + 0.45 \times 1.7 = 1.85\% \text{ CAPEX/year} \tag{2.5}$$

In the following table (TAB: 2.3) all the assumptions have been summarized.

Power Capacity	CAPEX	Fixed O&M	Discount rate	Lifetime
MW	*eur/kW*	*%CAPEX/year*	*%*	*years*
5	650	1,85	7	30

Table 2.3. Summary of the technical/economical assumptions for solar PV technology

2.4.3 Model building

The presence of solar technology gives a further implementation to the model with the purpose of increasing and defining better an optimum Belgian energy mix in 2050. To write the python code, it has been necessary make some assumptions and define technical and control parameters.

Historical data for solar energy in Belgium have been uploaded in Python and, calculating the ratio between the measured energy production and the total installed capacity in each period, the capacity factor in each time step has been computed. The following formulation represents the way used in the model to compute the solar energy production in the instant i:

$$E_{solar}(t_i) = n_{solar} \times P_{solar} \times CF_{solar}(t_i) \tag{2.6}$$

In which:

- $E_{solar}(t_i)$ = energy production in a certain instant i from solar energy
- n_{solar} = number of solar park
- P_{solar} = nominal power of a average solar park

- $CF_{solar}(t_i)$ = capacity factor in a certain instant i of solar energy

An important role is played by n_{solar}, one of the optimization variable used in the optimization problem with the purpose to minimize the total cost of electricity of the system respecting all the constraints. The generated power from solar energy is set to be higher than zero to obtain always a production of energy and not an absorption.

The presence of solar energy in the model is defined by three main types of parameters:

1. TECHNICAL PARAMETERS
   - Nominal power of an average solar park [*p_pv*]
   - CAPEX [*capex_pv*], Fixed O$M [*fixed_om_pv*], Annuity factor [*annuity_cst_pv*]
   - Lifetime [*life_pv*]
2. MODEL VARIABLES
   - Capacity factor [*cfpv(t)*]
   - Percentage of energy served [*perc_pv(t)*]
   - Quantity of energy served [*serv_pv(t)*]
   - LCOE cost [*cost_pv*]
3. OPTIMIZATION VARIABLES
   - Number of solar park [*n_pv*]

In case of spread > 0 (surplus of energy), the quantity of the solar energy production in a certain instant i is different from the quantity of served directly in that instant. As a matter of fact, part of the energy generated is not served for the demand but it is stored. With the purpose to define the energy directly served to the consumption, a weighted coefficient that take into account the ratio between the energy generated from solar energy and the total from RES has been defined.
Biomass energy has been defined as base-load production unit and for this reason it has not been included in the total energy generated. The following formulations show how the solar energy served at a certain instant i has been computed:

$$\%_{solar}(t_i) = \frac{E_{solar}(t_i)}{E_{solar}(t_i) + E_{wind,onshore}(t_i) + E_{wind,offshore}(t_i)} \tag{2.7}$$

$$E_{served,solar}(t_i) = E_{solar}(t_i) \times \%_{solar}(t_i) \tag{2.8}$$

2.5 Overall view of Biomass power plant

2.5.1 Role of Biomass in the electric power system

In order to avoid dangerous climate change, Europe is striving for zero carbon electricity production by 2050; several are the options explored and biomass could be taken in consideration [11]. Biomass is a renewable energy source used for many centuries and still nowadays is very important in several developing countries. Under UE legislation it is possible to consider that the amount of carbon emitted, through the use of the fuel, is the same of the amount of CO_2 absorbed by the plants to produce the same quantity of biomass: this process is called ”carbon cycle”. For this reason biomass source can be classified as renewable source [10].
Nowadays in the market mainly 5 different types of feedstocks used as fuel are present: wood from forestry or wood processing, agricultural crops, food and industrial waste, residues from agricultural harvesting and by-products from manufacturing processes[11].
It is possible to convert the biomass in order to produce three types of energy vectors:[10]

- Heat: the combustion of solid biomass and biogas generates heat. The systems can be from small to industrial scale;
- Electricity: combined cycle power plants can produce heat and electricity through co-generation;
- Transport fuels: using energy crops is possible to derive biofuels;

The use of biomass has many advantages over conventional energy sources and as well as over other renewable energies; the increasing of the production of biomass energy could have several consequences mainly related to socio-economic and environmental issues[13]. The utilization of the biomass as energy source for domestic heating generates pollution emitting in the air pollutants such as the PM 2.5, PM 10, CO, dioxins and furans.
The combustion of biomass in large-scale power plants is different and, thanks to the new technology, it is possible to capture and remove most of the pollutants. Due to the difficult control of temperature in the combustion chamber and time needed by the fuel to burn completely, the production of the electricity for industrial power plants represents a constant base-load for the electric grid.

2.5.2 Situation worldwide

The world's population continues to grow and today, in 2019, the population is twice than 1960 and in 2050 is projected to increase further to 9 billion. Because of this trend, the percentage of the global energy used in cities will increase significantly. Due to the wide availability of by-product of many industrial and agricultural process, biomass represents a renewable energy source with high growth potential [14]. But in the reality the growth of biomass is very slow; in 2018 the generation grew by only 2% with a similar rate of 2016 and 2017. In the key European countries like Germany and Italy, the growth has slowed and in others like Poland and Finland has even fallen slightly. A few large projects are still existing thanks to the possibility to the reconversion of the old coal power plant [15].

One of the most restriction of biomass is the pollution caused from particulates. As the following graph shown (FIG 2.6), it is possible to notice that the growth of biomass power plants in Europe projected to 2030 is much lower than the growth of the other types of renewable sources like wind and solar energy.

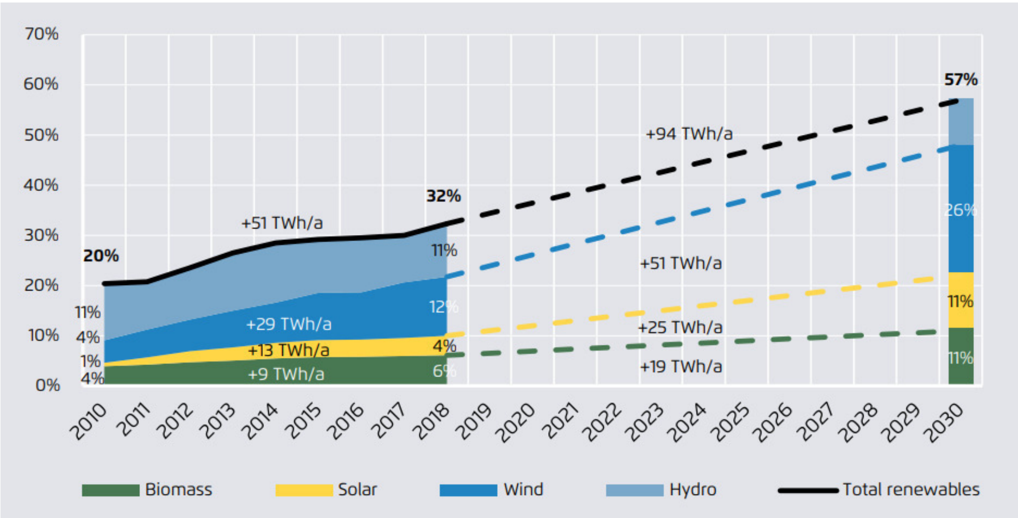


FIG: 2.6. 2030 projection of renewable electricity share in European Commission's Long Term Strategy [15]

2.5.3 Technology Overview

In order to study the power generation from biomass source, it is essential to consider the three components that characterize the process:

- Biomass feedstocks: different properties and varieties of the fuels impact the power generation;
- Biomass conversion: in this process the biomass feedstocks are transformed into the energy used then converted in heat and/or electricity;
- Power generation technologies: several are the existing solution in the market; they depend of the type of the fuel input and the type of the conversion;

The power generation from biomass power plant can be achieved using different type of feedstocks and power generation technologies and the process can be direct (e.g. gasification) or include intermediate conversion processes. Mainly it is possible to classify the conversion process in two main categories: Thermo-Chemical process and Bio-Chemical process. Moreover the first one can be categorized in other three processes: Combustion, gasification and Pyrolysis.
Direct combustion of biomass is a mature and commercially available technology and can be applied for a wide range of scales (from a few MW to 100 MW). In the world the most important process is the combustion route in which two are the main components: the biomass-fired boiler (stoker and fluidised bed) and the steam turbine. The first is used to produce steam and the second is used to convert the steam to generate electricity.
It is very interesting the use of combined heat and power (CHP) biomass plants for the simultaneous production of electricity and heat from one source of energy. These systems can achieve high overall efficiency and the provided heat of stream can be utilized for industrial use or for space/water heating in residential buildings (directly or through a district heating network) [16].

The chemical composition of feedstocks is highly dependent on the plant species and for this usually it is very heterogeneous. It is important to take into account the ash content, the density, the particle size and the moisture content because they could create critical problems during the operation of the power plant.[12]
The moisture content of biomass can vary from 10% to 60%; higher is the percentage and lower is the energy value of the feedstock. Related to this problem is that the transportation costs increases and then in general the total fuel cost on an energy basis. Energy density is an important parameter and its improving can reduce transportation costs and improve also the combustion efficiency.
Another important consideration is the ash content. It can be formed during the combustion process and then deposit inside of the combustion chamber and gasifier decreasing the performance and increasing the maintenance costs.
The density and the size of the biomass is also important because they have effect on the rate of heating and drying during the process [16].

2.6 Implementation in the model of Biomass power plant

2.6.1 Technical analysis

In order to implement the model and to have a more realistic projection in 2050 of the control area that has been taken in consideration, the biomass power plants has been adapted for the present work.

As said previously, the growth of biomass in the future is slow; in one of the prevision that have been done by ELIA [7], the Belgian Transmission System Operator (TSO), the biomass installed capacity forecasted by the regions for 2020 is assumed to remain constant in the future. To reach the national renewables target of 13% by 2020, three power biomass plants have been scheduled to operate in Belgium with a total installed capacity of 900 MW.
In the present work, a total installed capacity of 900 MW has been considered. It has not been decided to set an optimization problem finding the optimum number of biomass power plants in the system because it would not have been realistic in the projection for 2050 in Belgium as said previously [7].
The role of the biomass power plants in the system corresponds to an unit that is set as "must run" and so it operates in baseload operation constantly during the year. Due to the fact that the power plants needs maintenance, the plants have to shut-off for a certain period (usually 1 months). To simplify the implementation in the model and considering a capacity factor of 85%, a baseload installed capacity of 750 MW constant during the simulation has been chosen .[17] For a further simplicity, it has been assumed that it exists only one power plant in operation with a constant power capacity of 750 MW.

Since the power plants existing in Belgium use mainly wood pellets as feedstock, it has been assumed that all plants will use this type of fuel. The assumed net electrical efficiency has been assumed to 35%, value given from "3E" [17] and assumed as average for large scale biomass in Belgium. This value is coherent with literature values [16] in which they assumed the net electrical efficiency to average 35% and varies between 31% for wood gasifiers and 36% for stoker/CFC/BFB and AD systems. In the present work, the thermal generation of the power plants has not been taken into account.

2.6.2 Economical analysis

The type of technology, the region and the type of feedstock used vary significantly the cost of biomass power generation equipment[16]. For power plants powered by wood pellets and for Belgium country, it has been decided to assume a CAPEX cost of 800 eur/kW [17] derived from a weight average of values for Belgium.
Fixed Operation and maintenance cost (Fixed O&M) for biomass power plants has typical range from 1% and 6% of the initial CAPEX per year [16]. In this model an average value of 5% given from assumptions for standard large scale biomass plants in Belgium has been assumed [17]. Fixed O&M costs consist of scheduled maintenance, insurance, routine component/equipment replacement.
The discount rate used to represent the average cost of capital for biomass power generation is assumed to be 10% [16]. The value is slightly higher than the ones used for the other technologies due to an expected lower growth of the technology in the energy system. The economic life of this type of power plants is usually 20-30 years; an operation period of 30 years has been assumed [17].

Unlike other renewable source like wind, solar and hydro, biomass electricity generation requires fuel and then an additional cost. The feedstock has to be produced, collected, transported and stored in order to be always available close to the power plants. The cost of the fuel represents from 40% to 50% of the total cost of electricity produced and it varies depending of the type of the feedstock used.
Price of biomass fuel are difficult to obtain due to several chemical properties and geopolitics reason. In order to make a reasonable assumption, different prices in literature have been compared . In the first source [16], the cost of industrial wood pellets in Europe is estimated equal to 9.8-11.1 USD/GJ. With the appropriate conversions (current exchange rate: 1 USD = 0.89 eur) it is possible to obtain a value of 0.031-0.035 eur/kWh. The second source [17] assumed a market price wood pellets cost of 189.5 USD/ton. Assuming an average high heating value of 5.10 kWh/kg [58] and the same current exchange rate defined previously, it is possible to obtain a pellet price of 0.033 eur/kWh. In this present work, an average pellet total cost of 0.033 eur/kWh (primary energy) has been assumed taking into account the feedstock and transport costs.
The table presented below (TAB 2.4) gives a summary of the assumptions applied to the present work relating to the biomass power plants.

Power Capacity	CAPEX	Fixed O&M	Fuel cost	Discount rate	Lifetime	Efficiency
GW	*eur/kW*	*%CAPEX/year*	*eur/kWh*	*%*	*years*	*%*
0,75	800	5	0,033	10	30	35

Table 2.4. Summary of the technical/economical assumptions for biomass technology

2.6.3 Model building

In the previous model, wind source has been considered the only one technology for the generation of electricity. One of the main problem of wind and solar energy is that are source of energy not continuously available for conversion into electricity. The presence of biomass in the system guarantees a certain quantity of electricity delivered in the electrical grid. In the present model, due to technological reason, it has been chosen to use biomass power plants in baseload operation during the year. Therefore the power plants run without interruption with a constant power of 750 MW. The capacity in the control area has been assumed fixed due to slow growth of biomass in Belgium and following the prevision that have been done by ELIA for 2050 [7].
In order to control and obtain interesting values regarding the influence of biomass power plants in the model, several parameters have been used. It is possible to divide them in two main categories:

1. TECHNICAL PARAMETERS
    - Constant power capacity generation [*p_bio*]
    - Efficiency [*eff_bio*]
    - CAPEX [*capex_bio*], Fixed O&M [*fom_bio*] and Annuity factor [*annuity_cst_bio*]
    - Fuel cost [*fuel_bio*]
    - Lifetime [*life_bio*]
2. MODEL VARIABLES
    - Quantity of energy served [*serv_bio(t)*]
    - LCOE cost [*cost_bio*]

Chapter 3

State of art and implementation of energy storage

3.1 Overall view of the technology P2Meth

3.1.1 Role of P2Meth in the electric power system

The increasing of the energy demand, the energy security, the sustainability need and the energy cost competitiveness have guided to a new energy transition. The use of the surplus of electricity deriving from renewable energies to produce low carbon methanol could be a solution to overcome the challenges due to the intermittency of renewable energies [23]. Different candidates have been proposed to match the generation of the electricity with the consumption at any point in time but most of them are not economically attractive yet without subsidies.
One of the solutions consists in the use of liquid fuels such as methanol thanks to the high energy density and the easy and cheap way to storage and transport. For these reasons they can be suitable for long-term energy storage [6]. Moreover, the available surplus of electricity in the grid can be used to produce methanol as fuel for transport for existing internal combustion engine vehicles in order to help the de-carbonization in both electricity and transportation sector [23].

3.1.2 Situation worldwide

Nowadays methanol (or MeOH) is used for different chemicals uses with several new transformations in emerging sector. With an average annual growth rate of about 10%, global methanol installed production capacity grows every year since 2009.
There are several plants in Europe even if China dominates the MeOH capacity production and consumption. The main use is chemical but, with an accounting in total for 37% of the world MeOH demand, it is used also in direct fuel application [24].
The transition of this type of fuel as stationary long-term energy storage is not easy because current storage technologies are more convenient and more economically

attractive [6]. The industrial scale production of renewable methanol is already underway in different countries using different kinds of sources like geothemal power in Iceland, municipal solid waste in Canada and biogas in Netherlands.

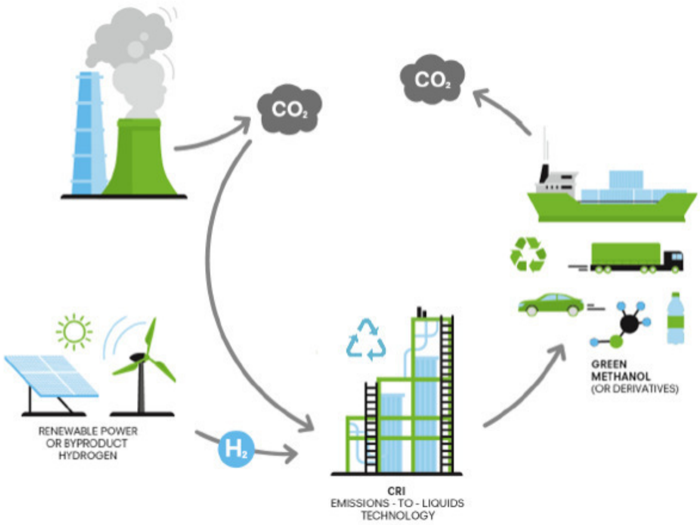


FIG: 3.1. Scheme of the power-to-fuel process using methanol [54]

3.1.3 Technology overview

Pathways for the production of Methanol

Methanol (CH_3OH or $MeOH$) is a chemical liquid used in many products and it could be produced in different ways from different sources. Renewable methanol, often called bio-methanol, is produced using hydrogen produced from renewable electricity.
There are mainly two main pathways to produce renewable methanol:

- Biomass pathway: through fermentation or gasification of organic matter in order to produce synthesis gas (syngas) that is processed in a reactor and transformed into bio-methanol;
- Electro-fuel pathway: the renewable energy is used to obtain hydrogen from water electrolyse; CO_2 is captured from the atmosphere or from flue gas and it reacts then with the hydrogen

The FIG 3.2 shows graphically the two different pathways for the production of methanol from different feedstocks.

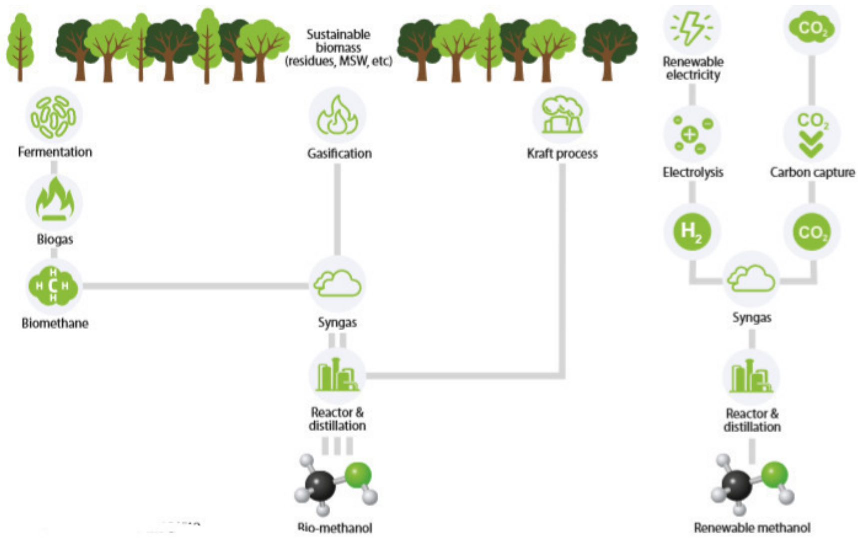


FIG: 3.2. Renewable methanol production processes from different feedstocks [25]

Hydrogen production

The production of hydrogen can be done with various technical processes and from a large number of primary energy sources. One of the promising ways is the electrolysis, a process that use electricity to split water into hydrogen and oxygen [50]. This process is well known and for more than a century has been used [26] and it may offer great opportunities with variable power generation, main characteristic of the renewable energies technologies. When there is a surplus of electricity generation, it is possible to use it and produce clean hydrogen through electrolysis.
This process requires the use of a unit called electrolyzer, a technology well-suited for small-scale and large-scale in distributed hydrogen production. [50]

There are three technologies that can be considered for hydrogen production through electrolysis: Alkaline Electrolysis Cells (AEC), Proton Exchange Membrane Electrolysis Cells (PEM-EC) and Solid Oxide Electrolysis Cells (SOEC).

The Alkaline electrolysis is the most mature technology available for power to fuel application; it uses an alkaline solution as electrolyte material in order to transfer electrons through hydroxide anions. The energy efficiency varies between 64% and 66% and it depends of the capacity of the electrolyzer and the pressure of the hydrogen delivered. Currently it is the cheapest technology with a long lifetime.

PEM electrolysis is a more recent technology than AEC and it is currently used for small application and under demonstration for larger scales. Thanks to the higher compactness and suitability for stack pressurization, several developments of this technology in the future could reduce the investments costs below the alkaline technology. PEM electrolyzers manufacturers are investing a lot for the development of this technology for power-to-gas applications.

Solid Oxide Electrolyzer Cells operates at 700-800°C to reduce the electrical input needed for the electrolysis reaction. It is very interesting for its high efficiency of the electrolysis process (80-90%) and for the possible use as a fuel cell in a "reverse" mode. This feature can be very interesting in the power-to-fuel applications avoiding the investments costs for an independent fuel cell. Moreover the coupling of SOEC electrolyzer with the methanol reactor allows a heat recovery saving energy and improving the total efficiency of the system [29]. The cost of the technology has not been confirmed yet due to the early stage of development of this technology [26].

For AEC and PEM electrolyzer the start-up time can be:

- 10 to 40 minutes for cold start-up (it depends on the initial temperature)
- few seconds for standby start-up (auxiliaries ready to run)

The following table (TAB:3.1) summarizes the main characteristics of the different types of electrolyzers in the market given the main advantages and disadvantages.

Alkaline	PEM	SOEC
Mature	mature	Not mature
Low installation cost	High installation cost	High installation cost
Long lifetime	Short lifetime	Short lifetime
Slow on/off switch	Quick on/off switch	Slow on/off switch
Other advantages: Well established and known technology	Other advantages: • Highly pure product • High current density and voltage effiency • Highly pressured product	Other advantages: • Inexpensive catalyst (nickel) • Solid electrolyte • Lower critical energy demand Other disadvantages: • Low stability of the electrolyte and catalyst • Need for high temperature

Table 3.1. Choice of the electrolyzer technology

CO_2 **Capture**

To reach the goal of the reduction of CO_2 emissions, it is needed a combination between renewable energies, CCS and energy efficiency. To meet the target set by the International Energy Agency (IEA) by 2050 to keep temperature rises to no more than 2°C, CCS will eventually deliver 17% of the necessary reduction.
The CO_2 emitted by industries represents around 40% of the global CO_2 emissions among which electricity production, oil and gas and cement manufacture emit continuously a big amount of CO_2 that can be captured at source, transported and then stored safely or directly used.
Three main existing capture technologies can be used to large-scale industrial processes from emitting sources: post-combustion, pre-combustion and oxyfiring.

Moreover, CO_2 can be directly removed from air (FIG 3.3) with the use of a solid sorbent heated to 100 °C when it is saturated of CO_2. At this point, the carbon dioxide is then released from the sorbent and it is collected and concentrated. This CO_2, instead of being stored, can be directly combined with hydrogen to product clean methanol.
The are several companies that nowadays are trying to build large-scale plants in order to capture directly the CO_2 from the air. Near Zurich, in Switzerland, on 31th May 2017, the first commercial direct air capture using technology patented has been inaugurated by the Swiss company ClimeWorks. [49]

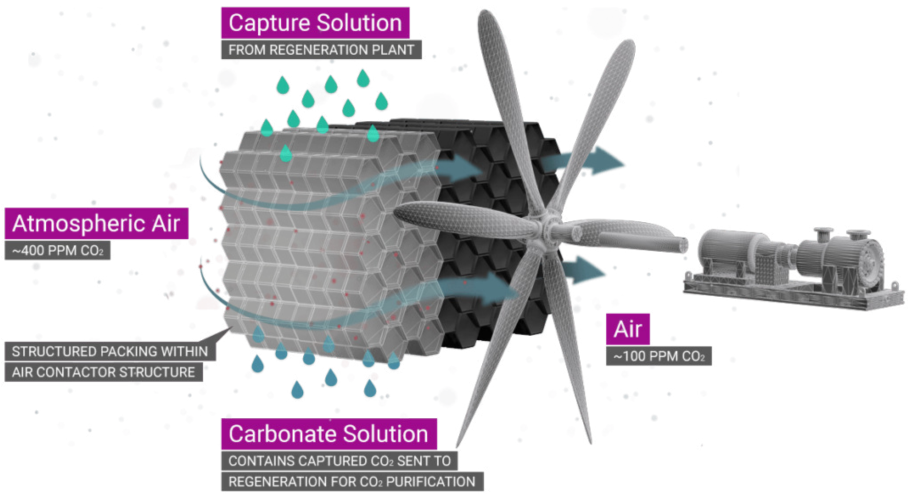


FIG: 3.3. Direct air capture (DAC) with stream of pure compressed CO_2 as output. [51]

Methanol synthesis

Nowadays two type of reactors used in different working conditions are present in market for the synthesis of methanol: adiabatic and isothermal. The adiabatic system is made up of a series of fixed bed reactors and systems of removal of the heat. The cost of this kind of reactor is low and the production capacity is very high but, due to the adiabatic process, the high equilibrium temperatures implies low conversion for each cycle.
The isothermal reactor is cooled in continuous using water or gas. In order to obtain a good reaction rate the reactor has to work at 240°C-260°C with a high recycle ratio. The installation cost of this reactor is much higher than the adiabatic one and the size is limited. [38]

Fuel Cell

Direct Methanol Fuel Cell (DMFC) and Reformed Methanol Fuel cell (RMFC) are two types of fuell cells that, for their operation, use polymer electrolyte membrane. Each technology has pro and cons but RMFC has many desirable features with respect to the other such as: higher efficiency, smaller cell stacks, no water management, better operation at low temperatures.
This type of technology has reached an advanced stage of development and it is also available for large scale systems (up to 8 MW). [63]

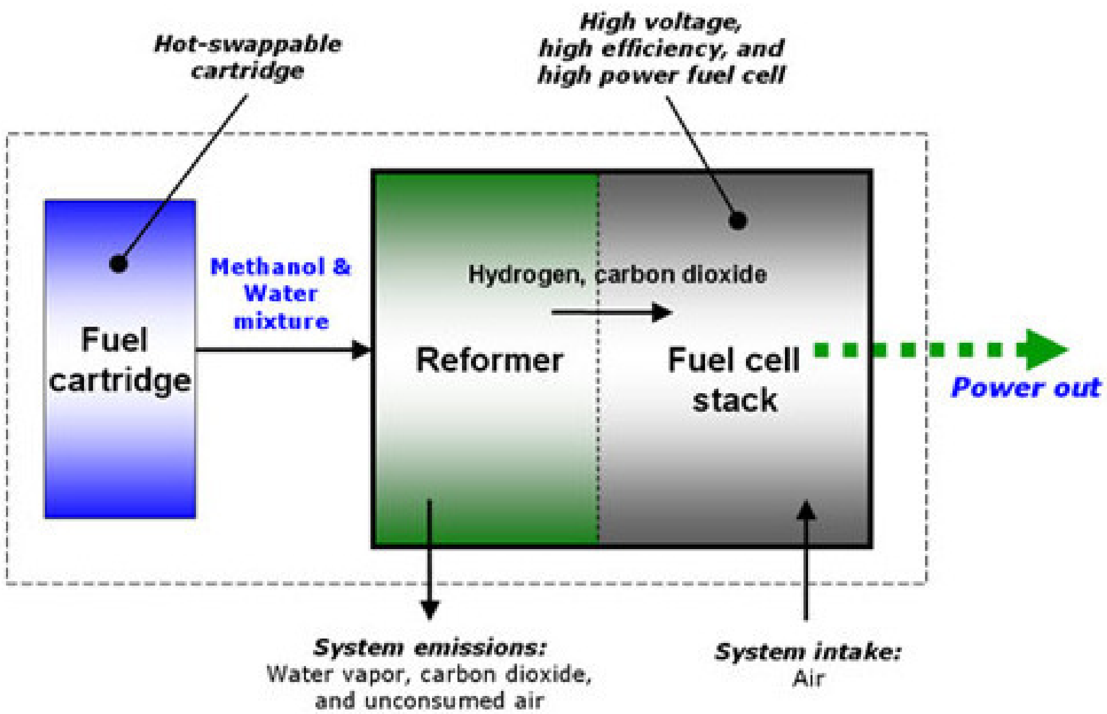


FIG: 3.4. Operation principle of RMFC [62]

3.2 Implementation in the model of P2Meth

3.2.1 Technical analysis

The technical assumptions regarding Power to Methanol that have been taken into account in the actual model are very similar to those in the previous work [6]. As shown previously, in order to convert the surplus of electricity from renewable sources into fuel and also to convert it again into electricity several technologies are needed. For each intermediate step, numerous are the technologies available in the market and therefore it has been necessary to make some technical choices.
Before starting the description, for all the technologies no ramp-up and ramp-down has been considered.

Production of Hydrogen

It has been decided to use an electrolyzer in order to split water into hydrogen and oxygen using electricity from the surplus of renewable energies; various are the types of electrolyzer that can be used to carry out this process. In the present work an alkaline electrolyzer has been utilized for the following reasons:

- Mature and well known technology
- Low installation cost
- Long lifetime

For Power to Methanol at large scale application, this type of electrolyzer typically operates with pressurized hydrogen at 10-15 bar and an operating temperature of 60-80 °C. A maximum electricity input of 10 MW with a correspondent hydrogen output capacity of 6.9 MWHHV has been chosen. After the purification unit (deoxidiser and dryer) the H_2 reaches a purity higher than 99.999%.
The efficiency of the technology depends of the pressurization of hydrogen. At current stage, the energy efficiency is about 66% but in 2050 could reach 69% with the improvements of the technology. Therefore, in the present work an electrolyzer efficiency (kWhHHV-H2/kWhe) of 69% has been assumed [26].

Capture of CO_2

Regarding the capture of CO_2, different technologies can be considered and several different industrial sources can be evaluated. In the present work the capture of CO_2 from high-purity sources has been considered with a corresponding cost defined in the next section [27].

Methanol synthesis

For the methanol synthesis a reactor with the same size of the Alkaline electrolyzer (10 MW) has been considered . In order to carry out the reaction, it is necessary to provide a certain quantity of hydrogen and carbon dioxide to obtain one kg of methanol. For this reactor, the consumptions are equal to the stechiometric ratios: 0.19 kgH2/kgMeOH and 1.38 kgCO2/kgMeOH. The values adopted in this section are provided by ENEA in the following source [26]. With a capacity of 10 MW the corresponding consume is equal to 1.23 ton of CO_2/h; converting this value per unit of energy, the consumption is equal to 0.123 tonCO_2/MWh. The methanol synthesis efficiency is considered to remain constant in the future at a fixed value of 75.5% (MWhHHV-MeOH out/MWhHHV-H2 in).

Fuel Cell

Regarding the fuel cell technology, a Reformed Methanol Fuel Cell has been used due to the high efficiency and the advanced stage of development. Moreover it is suitable for large scale application and therefore it has been possible to assumed a 10 MW RMFC system. A value of efficiency of 70% has been considered because of a possible improvement of the technology by 2050 with an actual value of 60%[39].

Storage

In the present work, due to the relative ease of storing methanol at room temperature and due to the high availability of tanks, an infinite capacity of the storage has been considered [6].

3.2.2 Economical analysis

Definitions of the terminology

With the purpose of studying the economical influence of Power to Methanol technology in the present work, it is necessary to make some assumptions. The total cost of this technology has been calculated with the sum of the costs of the single technologies involved in the process and projected by 2050. First of all, it is necessary to define some economical parameters defined in the study ”Potential of power-to-gas” conducted by ENEA in 2016: [26]

$$\text{Total CAPEX} = \text{Installed CAPEX} + \text{Project CAPEX} \tag{3.1}$$

With

$$\text{Installed CAPEX} = \text{Factory gate cost} + \text{Additional costs} \tag{3.2}$$

and

$$\text{Project CAPEX} = 0.3 \times \text{Installed CAPEX} \tag{3.3}$$

Installed CAPEX includes the factory gate cost of equipments and additional costs comprising transport, installation, civil work, balance of plant and commissioning costs.

Alkaline electrolyzer

[26] As said previously, for the production of hydrogen the use of an alkaline electrolyzer with an electricity capacity of 10 MW and with a delivered pressurized hydrogen at 10 bar have been assumed. The total installed CAPEX estimated to be in 2050 (including balance of plant, transport, installation and commissioning) is 500 eur/kW assuming 50% decrease from the current cost (Equation: 3.4).
In order to obtain a hydrogen purity higher than 99.999%, it is necessary a purification unit that generally represents from 10 to 20% of the factory gate of the electrolyzer (in the total installed CAPEX has been already assumed). The cost of the water, source of the hydrogen, has been neglected. The annual Fixed Operational and Maintenance has been considered equal to 1.5% of the CAPEX cost (Equation: 3.5). The lifetime of the electrolyzer has been assumed equal to 25 years with a discount rate of 7% [26]. Using the definitions previously explained:

$$\text{Total CAPEX} = 500 + 0.3 \times 500 = 650 \text{ eur/kW} \tag{3.4}$$

$$\text{FO\&M} = 1.5\% \times 650 = 9.75 \text{ eur/(kW year)} \tag{3.5}$$

3.2.3 CO_2 cost

The estimated price of CO_2 in 2050 is very uncertain and for this reason three different literature sources have been used .
In the first source [28] there are present several costs depending of the type of plants; an average value of 40 euro/ton has been taken.
In the second source [27] an average cost of CO_2 from high-purity sources equal to 26 $/ton has been taken, with a value varying between 3.9 and 74$/ton.
In the last source [26] the price of CO_2 has been set at a price between 80 and 120 eur/ton assuming capture of CO_2 from industrial and fossil power plants and including CO_2 pressurization at 70 bar and transportation.
Considering a consumption of 8.6 ton of CO_2 per hour in case of a power capacity of 10 MW [26], it corresponds to a consume of 0.123 ton of CO_2 per MWh producted. The table below (TAB: 3.2) gives a summary of all the assumption and the computations:

	FIRST SOURCE		SECOND SOURCE		THIRD SOURCE	
CONSUME	COSTS					
tonco2/MWh	eur/tonco2	eur/MWh	eur/tonco2	eur/MWh	eur/tonco2	eur/MWh
0,123	40	4,92	26,6	3,27	100	12,3

Table 3.2. Table summarizing the assumption taken in different sources. [28] [27] [26]

In the present model an average price of CO_2 equal to 40 eur/ton (4.92 eur/MWh of energy stored) has been taken into consideration.

Methanol synthesis

Regarding the methanol synthesis, as said previously, a methanol reactor with power capacity of 10 MW has been considered. The source used for this technology [26] estimates a specific factory gate cost of the methanol reactor in 2050 equal to 700 eur/kW (current value is equal to 1500 eur/kW). In addition to this value it is necessary to take into consideration the additional cost (eq: 3.6) of the methanol reactor and the project cost (eq: 3.8). Additional costs (transport, civil work, isntallation, balance of plant and commissioning costs) equal to 50% of the cost of the methanol reactor have been assumed. Using the definitions explained, the total CAPEX has been computed (eq: 3.9). Moreover it was necessary to consider a Fixed O&M cost of the reactor; it has been assumed equal to 7.5% (eq: 3.10).
The lifetime of the methanol reactor has been assumed equal to 20 years with a discount rate of 7%.

$$\text{Additional cost} = 50\% \times 700 = 350 \text{ eur/kW} \tag{3.6}$$

$$\text{Installed capacity} = 350 + 700 = 1050 \text{ eur/kW} \tag{3.7}$$

$$\text{Project CAPEX} = 0.3 \times 1050 = 315 \text{ eur/kW} \tag{3.8}$$

$$\textbf{Total CAPEX} = \mathbf{1050 + 315 = 1365} \ \ \textbf{eur/kW} \tag{3.9}$$

$$\text{FO\&M} = 1.5\% \times 650 = 9.75 \text{ eur/(kW year)} \tag{3.10}$$

Fuel cell

As explained before, the conversion from the methanol stored to electricity has been done with a Reformed Methanol Fuel Cell. A projected CAPEX costs in 2050 equal to 500 eur/kW has been assumed for this technology (actual cost = 1000 eur/kW) with a Fixed O&M costs equal to 20 eur/kW for year. Regarding the lifetime, a value of 20 years with an annual discount rate of 7% have been assumed . [39]

Storage

Because of the relative ease of storing methanol and the investment much lower than the cost of converting electricity into fuel (and back), the cost of keeping energy stored over time has been considered as negligible, which is one of the great advantages of methanol storage. [6]

Technology	Costs			Efficiency	Lifetime
	CAPEX	FOM	Fuel cost		
	eur/kW	*eur/(kW year)*	*eur/MWh*	*%*	*years*
Alkaline Electrolyzer	650	9,75	-	69	25
CO2 cost	-	-	4,92	-	-
Methanol synthesis	1365	9,75	-	75,5	20
Fuel cell	500	20	-	70	20
Storage	0	0	-	-	-
TOTAL	**2500**	**40**	**4,92**	**35**	**20**

Table 3.3. Table summarizing the assumption in the different components

3.2.4 Model building

As cited before, power to methanol technology requires several components in order to convert electricity into fuel and then fuel into electricity. In the python model, this technology has been summarized in only one technology (such as a ”black box”) gathering together all the components.
The presence of a long-term storage guarantees several advantages in case of a system with high penetration of intermittent renewable energies. In order to implement Power to Methanol technology in the actual model it has been necessary to make assumptions.

The round trip efficiency has been multiplied directly in the conversion from electricity to methanol without having any losses during the process to convert the fuel into electricity.
When there is surplus/needs of electricity it has been decided to use P2F as last candidate to store/release energy; it means that the energy is stored/released in first step with a short term energy storage (PHES and battery) and then with this technology. This decision has been taken because of:

- High investment cost of the technology
- Low round trip efficiency
- Long term role in the energy system

In order to implement this technology in the python code, several parameters have been used. It is possible to divide them in three main categories:

1. TECHNICAL PARAMETERS

    - Power capacity in absorbing and releasing electricity [*p_in_max_m*] and [*p_out_max_m*]
    - Maximum and minimum energy capacity [*st_max_m*] and [*st_min_m*]
    - Round Trip Efficiency [*RTE_m*]
    - CAPEX [*capex_st_m*, Fixed O&M [*fixed_om_st_b*], Annuity factor [*annuity_cst_st_m*].
    - Life time [*life_st_m*]

2. CONTROL VARIABLES

    - Energy level available in the storage [*level_m(t)*]
    - Initial energy level available [*level_m0* (equal to *st_max_m/2*]
    - Quantity of stored energy including losses through RTE [*st_in_m(t)*]
    - Quantity of served energy neglecting losses losses[*serv_st_m(t)*]
    - LCOE cost [*cost_st_m*]

3. CONTROL VARIABLES

    - Number of P2F units [*n_st_m*]

3.3 Overall view of PHES

3.3.1 Role of hydropower in the electric power system

Pumped Hydro Energy Storage (PHES) is the most mature, reliable and cost-effective renewable energy storage technology available playing an important role in several countries.
PHES has no equal in ”load following” capability in which it can meet load fluctuations minute-by-minute; even though other conventional thermal power plants can respond to load fluctuations, their response times are not as fast. PHES plants, due to these characteristics, can be used to reduce the frequency of start-ups and shut-downs of conventional thermal plants maintaining in this ways the balance between supply and demand.

Besides the grid flexibility and security services, PHES can be used to store energy over time; when a dam is present, it is possible to meet system peaks and, depending on the size of the reservoir, energy can be stored over days, weeks, months, seasons or even years.
The significant flexibility gives to hydropower a position in the future energy mix as complement to variable renewable sources. When the sun shines or the wind blows, reservoir level increases providing in this way energy when the solar and wind generation decrease.
Key characteristics of this technology are the quick start up and the efficient operation even when used only for a few hours. Another advantage, in contrast with thermal power, hydropower can operate efficiently at partial loads.

Hydropower is the only large-scale and cost-efficient storage technology available today but several aspects have to take into consideration during the design. In addition to an economic assessment, social and environmental assessments must be done to avoid negative impacts on local populations, ecosystems and biodiversity [1].

3.3.2 Situation worldwide

Worldwide, PHES is considered to have a great development potential because of its high-efficiency, large-scale energy storage capacity, long life-time and low self-discharge. In the last decade, after the liberalization of the electricity markets, the increasing entry of renewable energy sources has again turned the public attention towards PHES as a mature and large scale energy storage technology well-suited to support the integration of green energy production and grid stability [2].
In 2017 China, Japan and United States were the countries with the highest energy storage power capacity provided by pumped hydro storage. As shown in FIG: 3.5, pumped hydro storage represents the largest source of today's electricity storage accounting for 96% of the total energy storage of all types estimated in 2017. In the energy transition, hydropower looks to become an even more strategic player. The

International Renewable Energy National Agency (IRENA) conducted a strategic map until 2030, and pumped hydro capacity could be doubled to 325 GW from the 150 GW installed in 2014.[3]

	Electro-mechanical	Electro-chemical	Thermal Storage	Pumped hydro storage	Grand Total
China		0.1	0.1	32.0	**32.1**
Japan		0.3		28.3	**28.5**
United States	0.2	0.7	0.8	22.6	**24.2**
Spain	0.0	0.0	1.1	8.0	**9.1**
Germany	0.9	0.1	0.0	6.5	**7.6**
Italy		0.1	0.0	7.1	**7.1**
India		0.0	0.2	6.8	**7.0**
Switzerland	0.0	0.0		6.4	**6.4**
France	0.0	0.0	0.0	5.8	**5.8**
Republic ofKorea		0.4		4.7	**5.1**
Grand Total	**1.1**	**1.6**	**2.3**	**128.1**	**133.1**

FIG: 3.5. Stationary energy storage power capacity [GW] by technology type and country, operational by mid-2017 [3]

3.3.3 Technology Overview

The principle of Pumped Hydro Energy Storage (PHES) is to store electrical energy by utilizing the potential energy of the water. The annual generation is proportional to the head and flow of water. Conventional PHES systems use two water reservoirs at different elevation and as it is shown in the FIG 3.6, they can work in two different modes:

- Turbining mode: the potential energy of the flowing water is converted in mechanical energy in a turbine that drives a generator to produce electricity.
- Pumping mode: the water from the lower reservoir is pumped to the upper reservoir consuming electricity of the grid.

When the electrical demand is low, the excess of generation capacity is used to pump the water into the upper reservoir. On contrary, when there is higher demand, the water is released back into the lower reservoir generating electricity (usually using Francis turbines). Environmental impacts caused by the construction are serious issues and many proposed projects have been deleted for the potential impact on the ecosystem, landscape and wildlife.

The efficiency varies quite significantly (due to the long history and long lifetime); the RTE (Round Trip Efficiency) can be over 80% in some recent PHES plants.
The construction of the plant typically takes many years therefore the capital investment in civil construction is very high but the operation and maintenance costs are low. Only after decades of operation there is a return of the investments. The lifetime of the electro-mechanical equipment is typically 40-50 years but the plants (civil construction) may have lifetime of a hundred years [5].

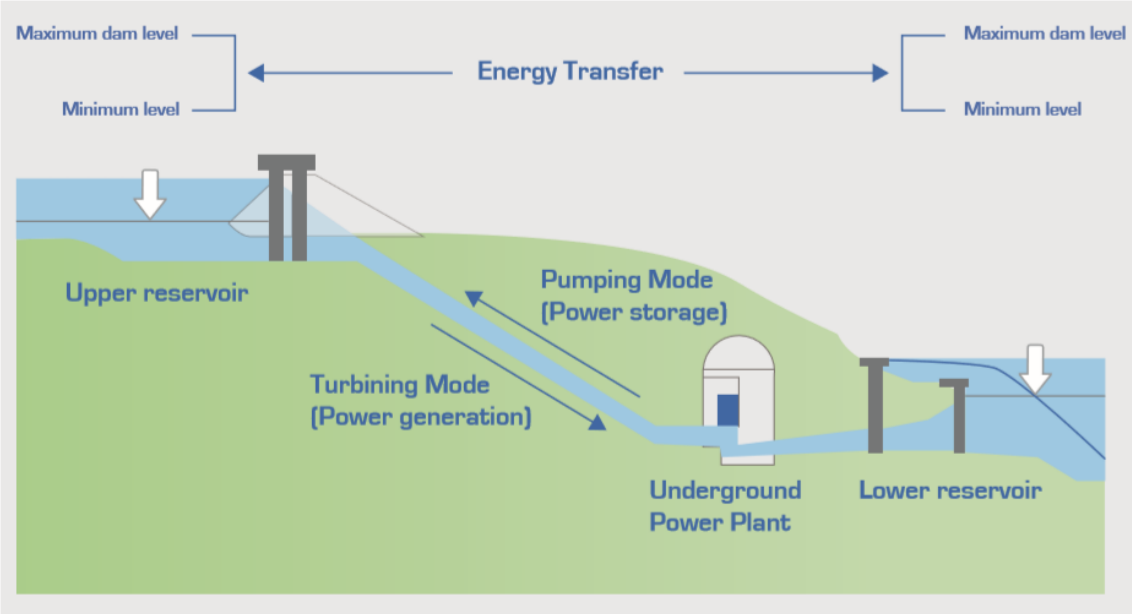


FIG: 3.6. Schematic of pumped hydro storage system [4]

In the electric power system, hydropower plants play an important role through their large reservoirs. The technical challenges of maintaining grid stability is a crucial issue and this technology have a positive impact nowadays and even more important in the future. The benefits from pumped storage hydropower in the power system will depend on the overall mix of existing generating plants and the transmission network. However, its value will tend to increase as the penetration of variable renewables for electricity generation grows.

3.4 Implementation in the model of PHES

3.4.1 Technical analysis

In the previous work [6], power-to-fuel technology has been selected such as the only storage. Various are the options for storing energy and especially during the last few years this field has attracted increasing attention.
Electricity storage will play a crucial role in the energy transition and as variable renewables grow rapidly, electricity system requires greater flexibility; electricity has to be stored over hours, days, weeks and months and electricity storage is only way to help the decarbonization providing this essential service.
Flexibility of the service is very important to allow grid operators to react in case of changes of demand or supply and to have a quickly restore of the system [3]. As it has been explained previously, the electricity zone has been taken in consideration is Belgium. In the present work, it has been proposed to study an integration of a Pumped Hydro Energy Storage (PHES) on the actual model taking advantage of the existing plant in the above-mentioned area [6].

PHES is a commercially mature technology and it dominates both the total installed energy storage power capacity (in GWh) and power capacity (in GW) [3]. The current installed capacity in Belgium is 1.3 GW with a dispatchable reservoir volume of 5.3 GWh. Moreover the unit is responsible for ancillary services reserving 0.5 GWh.
Considering the ”Large Scale RES” scenario defined by Elia, in 2030 and 2040 a new unit of 600 MW was considered increasing proportionally the total reservoir up to 7.7 GWh. Due to the limited energy capacity, nowadays the pumped-storage units in Belgium usually follow daily cycles; during the night the reservoirs are filled in order to be able to compensate the peak demand during the day. This way of working could differ in the future due to the high penetration of renewable energies [7].

The existing pumped hydro energy storage in Belgium is located in Trois-Ponts, Province de Liège; as the FIG 3.7 shows, the unit is composed by one lower reservoir and two upper reservoirs known as Coo I and Coo II (2.3 and 2.7 GWh respectively). Each upper lagoon has a depth of 28 m and a water volume of 4 million of m^3 for Coo I and 4.5 million of m^3 for Coo II; the lower lagoon contains 8.5 million of m^3 of water with a correspondent energy density of 0,58 kWh/m^3. Between the two upper reservoirs there is not communication and they are connected to the engine room through separate pipelines. The difference of height (called ’head’) between the engine room and the upper reservoir is around 250 m.

The power station is located underground and contains the plant’s six generators [8]. Traditional turbines are replaced with pump-turbines that are able to invert the direction of the flow. The Coo I reservoir powers three Francis pump-turbines with a power of 158 MW each one; the Coo II powers three 230 MW Francis pump-turbines. In order to have an efficient operation, they are placed in parallel and they work in full load operation and an automatic control decides the best combination of pump-turbines [9].

In this work any constraints regarding partial-load operation has not been assumed and therefore the presence of only one ideal Francis pump-turbine with a power of 1200 MW (and 1800 MW for the scenario 2050) has been supposed. It can work with constant efficiency also in partial-load operation.
In the reality, the power capacity in pumping operation is lower than the power capacity in turbining mode and for this reason the times of the charge and of the discharge are different. In the present model this difference is neglected and considering the two powers are considered equal.
Another factor that has not been considered is the influence of the quantity of the water in the reservoir on the global efficiency. A constant efficiency has been assumed even if the level changes.
In order to consider all these factors without having a dynamic model, a constant global efficiency (or RTE: round trip efficiency) of 75% has been considered [7].

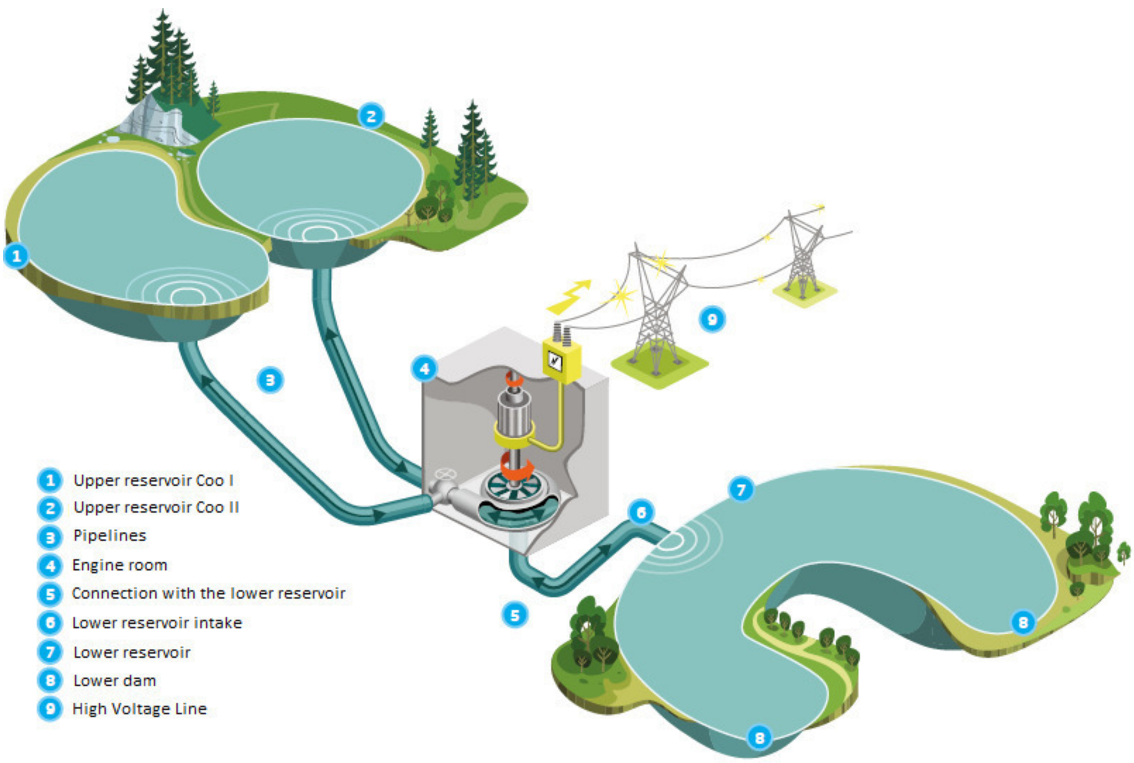


FIG: 3.7. Scheme of the "Centrale de Coo Trois-Ponts" [8]

3.4.2 Economical analysis

Thanks to the decades of operating experience, traditional PHES plants are well understood and are a mature technology. In terms of cost, structure and transformation efficiency, no major technology improvements are planned. In the period to 2050, technological and economic features of PHES plants are therefore assumed to remain in general unchanged [3].
Hydropower is a capital-intensive technology and due to the huge civil engineering works required it takes long time for the development and construction. The major cost components are:

- The civil works for the hydropower plant construction and the project development costs;
- The cost related to electro-mechanical equipment

During the development of the project, it is important to include planning and feasibility assessments, environmental impact analysis, biodiversity mitigation measures, water quality control and several others factors.
Regarding the electro-mechanical equipment for the project it is necessary to include turbines, generators, transformers, cabling and control systems. As these types of equipments are mature and well-defined technology, these costs tend to vary significantly less than the civil engineering costs.
Depending on the site, the total investment costs vary significantly; the total installed costs for large-scale hydropower projects typically range from a low 800 euro/kW to around 3000 euro/kW. The capital cost adopted in the present work is 1600 euro/kW [1].

PHES usually requires little maintenance and the operation costs are low; typical values range from 1% to 4% of the CAPEX costs[1]. In the present model, a cost of 5 eur/MWh has been adopted [9].
For hydropower plants, economic lifetime is very long and can be at least 40 years with 80 years as upper bond. For this work, a lifetime of 60 years with a discount rate equal to 7% have been selected.
The table presented below (TAB: 3.4) gives a summary of the assumptions applied to the present work relating to the pumped hydro energy storage. As it is shown, a power capacity and a reservoir energy capacity respectively of 1.8 GW and 7.7 GWh have been assumed. They correspond to the scenario for 2050 given by ELIA [7].

Power Capacity	Reservoir energy capacity	CAPEX	Uvar	Discount rate	Lifetime	RTE
GW	*GWh*	*eur/kW*	*eur/MWh*	*%*	*years*	*%*
1,2 (1,8)	5,3 (7,7)	1600	5	7	60	75

Table 3.4. Summary of the technical/economical assumptions for PHES technology

3.4.3 Model building

In the previous model, power to fuel technology was considered as the only type of storage. The presence of an intraday electricity storage together with an inter-seasonal storage gives several advantages in case of system with high penetration of renewable energies such as solar and wind [6]. In order to implement the model with PHES technology it is necessary to make assumptions.

When there is a surplus/needs of electricity it has been decided to use PHES as first candidate to store/release energy. This decision has been taken for several reasons such as:

- There is no optimization of PHES energy capacity (fixed value)
- The response is fast and it is adapted for short-term storage
- The global efficiency is higher than the one of P2F technology
- The cost of the system is lower than the one of P2F technology

All these assumptions have been taken into account during the implementation in the python code. In addition, In this model a single efficiency in pumping mode equal to the round trip efficiency has been considered without having any conversion losses during the discharge operation.
To control and obtain interesting values regarding the presence of PHES, several parameters have been used. It is possible to divide them in two main categories:

1. TECHNICAL PARAMETERS
    - Power capacity in pumping and turbining operation [*p_in_max_h*] and [*p_out_max_h*]
    - Maximum and minimum capacity in the lower and upper reservoirs [*st_max_hu*], [*st_min_hu*] and [*st_max_hb*], [*st_min_hb*]
    - Round Trip Efficiency [*RTE_h*]
    - CAPEX [*capex_st_b*, Variable cost [*u_var*], Annuity factor [*annuity_cst_st_h*].
    - Life time [*life_st_h*]
2. CONTROL PARAMETERS
    - Level of the energy capacity in the upper and lower reservoir [*level_hu(t)*] and [*level_hb(t)*]
    - Initial energy level available of the upper and lower reservoir [*level_h0*](equal to *st_max_hb/2* and *st_max_hu/2*)
    - Quantity of stored energy [*st_in_hu(t)*] and [*st_in_hb(t)*]
    - Quantity of served energy [*serv_st_hu(t)*] and [*serv_st_hb(t)*]
    - LCOE cost [*cost_st_h*]

3.5 Overall view of battery energy storage

3.5.1 Role of battery storage in the electric power system

The role of electricity storage in the next phase of the energy transition is dominant and plays a crucial role together with solar and wind power generation. In order to avoid the risk of a catastrophic climate change, governments are taking several urgent decisions with the purpose to create a sustainable energy system decreasing drastically the greenhouse gas emissions.
The rapidly improvement of batteries systems and other technologies will permit to have great flexibility of the system with high shares of renewable electricity. The electric grid requires different ancillary services; the demand and supply need to be balanced in each instant maintaining constant voltage and frequency.

The need of energy storage will be crucial in order to smooth supply fluctuations over days due to the high variability of solar and wind energy [3]. The main-use case for battery storage in the future is to provide electricity time-shift services to increase the self-consumption and avoid peak demand charges in the residential and commercial sectors with rooftop PV panels. Electricity storage will make possible the creation of 100% renewable mini-grids using effective solar home system.
The FIG: 3.8 shows the effects that a battery energy system can provide in utility scale in short-term period.

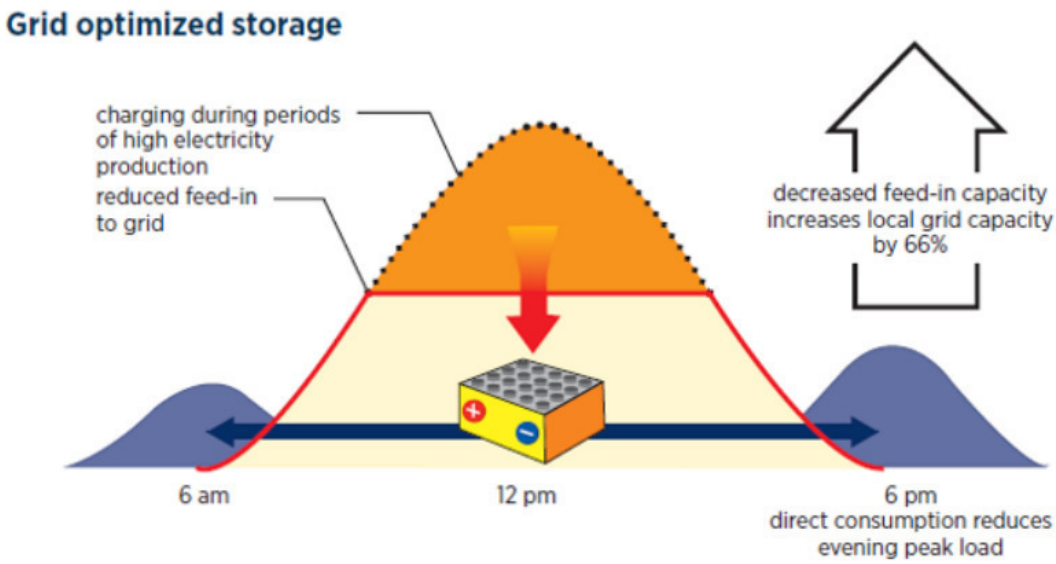


FIG: 3.8. Battery storage shaving peaks while increasing self-consumption[33]

3.5.2 Situation worldwide

Over the last few years, battery storage has grown significantly especially in Europe, South Korea and US. The predominant investment is in lithium-ion batteries in which project developers are continuously improving the design and the technology. For this reason the cost has been coming down in both residential and commercial and industrial market [34].

The global energy storage market will grow over the next years and $620 billion in investment have been estimated. The capital cost of an utility-scale lithium-ion battery storage system will decrease by more than 50%. Thanks to the penetration of this type of storage, the technology will be more and more evident in both vehicle and electricity sector.
China, U.S, India, Germany, Japan, Australia, France, U.K and South Korea will be the leading countries in the battery energy market; also in developing countries (e.g. Africa) the growth of the battery will permit the creation of isolated grids in areas without power grid [46].

This energy market is very varied and, due to cost and performance, some technologies have more development than others. The lithium-ion deep discharge cycle life, power and energy density, and other attributes have risen their markets with a consequent cost reduction. Lead-acid market batteries have been used in large installation for supply shift, smoothing and frequency response. Flow batteries are a promising longer-term battery storage solution (more than four hours) and due to the ability to handle large energy capacity, it is expected to be improved in the next decades becoming an interesting solution [35].
As it is possible to notice in the FIG: 3.9, the presence of battery storage nowadays is very small and it will take time in order to have a significant growth. In Belgium, the total installed capacity of stationary batteries for 2040 has been computed [7] in relation to the percentage of installed solar capacity. Different scenarios have been defined by ELIA and it has been considered in the Large Scale RES scenario an installed capacity equal to the 10% of installed PV capacity in 2040.

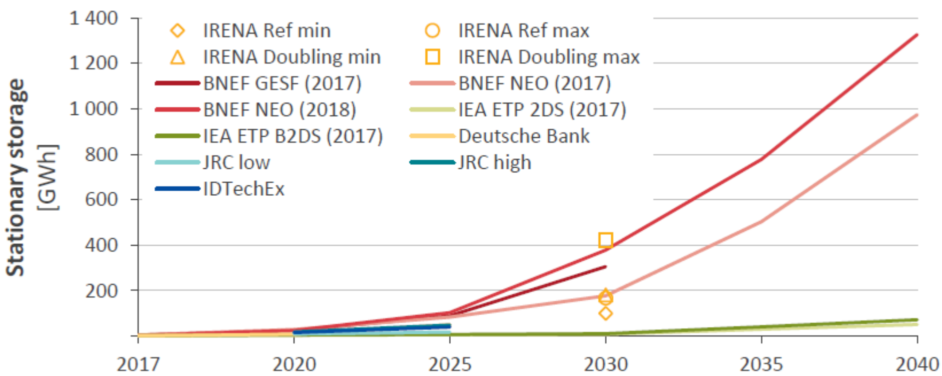


FIG: 3.9. Projections of total stationary storage installed [37]

3.5.3 Technology Overview

Battery are widely used in energy and transport sector in order to reduce the GHGs emissions; the operation principle and the properties of the different technologies are similar and for this, in this section only lithium-ion batteries have been explained.
A battery is a device able to convert electric energy in chemical energy in its active materials and then transform again the chemical energy into electricity when it is needed. As the other type of batteries, it is possible to characterize lithium-ion technology with several key parameters. The most important ones are reported below (TAB: 3.5).

Property	Unit of measures	Value
Nominal cell voltage	V	2,5 to 4,2
Specific energy	Wh/kg	100 to 158
Energy density	Wh/l	245 to 430
Specific power	W/kg	700 to 1300
Power density	W/l	2000 to 3000
Cycle life at 100%	-	Up to 3000
Self-discharge rate	% month	2 to 10
Operating temperature	°C	-40 to 65
Memory effect	-	No

Table 3.5. Summary of the Li-ion battery properties [36]

Thanks to the high energy density, Li-ion batteries are suitable for applications in which weight and volume are important in the design; therefore the long life-time and the low discharge rate made it applicable for a wide type of operations (stationary and electric vehicle uses).
There are present also some disadvantages due to abuse or abnormal battery usage conditions. The most significant issues are related to the safety and they can be divided in: mechanical abuse (strong impact of the cell), electro-chemical abuse (overcharge or short-circuit), thermal abuse (not controlled temperature) [36].

Batteries used in stationary storage applications can be also divided in two main categories: batteries more suited to store energy and others to supply power. For grid-scale stationary storage system usually the energy-designed battery is used. In the present model, due to the daily-term storage use, the power capacity has more influence on the operation. Moreover, the presence of Power to Methanol technologies used for long-term storage ensures an enormous storage capacity due to the fact that methanol is a liquid fuel easy and cheap to store at ambient temperature.
It is possible to define the C-rate parameter that represents the time needed to charge completely the battery with the nominal power. In case of power-designed batteries this ratio is lower than 1 and common values can be 0.5, 0.25, 0.1 [37].

3.6 Implementation in the model of battery energy storage

3.6.1 Technical analysis

The presence of battery energy storage in the present work represents an additional implementation with the purpose of creating a model with different technologies that will be part of the energy system in 2050. As said previously, the main role is to provide a short-term energy storage to the system together with pumped hydro energy storage; power to methanol technology will be used for long-term uses. In order to implement this technology in the model, several assumptions have been done.

During the implementation it has been decided to use battery energy storage as second choice. It means that the energy is preferably stored and released from pumped hydro energy storage and then from battery energy system; the last choice will be Power to Methanol due to its role as long-term technology. In the same ways of PHES, battery energy storage is not subject to optimization and therefore it has been necessary to set an installed power capacity. This decision has been taken considering a possible battery market in Belgium by 2050. In the present work a power installed capacity of 5 GW has been considered.

Nowadays different types of batteries are suitable for stationary uses and each one presents pro and cons with a possible improvements by 2050. In this model, as said previously, Li-ion battery has been considered due to the excellent properties, low cost and several improvements planned for the future.nIn base of the material utilized with the lithium, it is possible to identify different technologies that differs from some properties and the cost. In the present work, LFP lithium-ion battery has been chosen due to its really good properties. In the FIG: 3.10 the properties of the four main categories of Li-ion batteries in 2016 and projected to 2030 have been summarized.

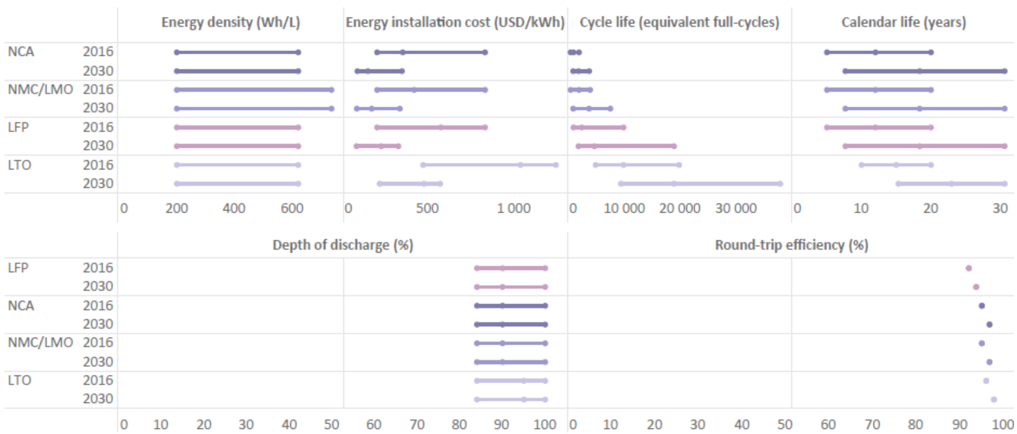


FIG: 3.10. Summary of the different types of Li-ion battery properties [3]

Due to the short-term usage of this storage and the needs to have an high input/output power capacity absorbing/releasing quickly energy variations, a power-designed battery with a C-rate equal to 0.5 has been chosen. This factor allows the calculation of the energy capacity that will be equal to 2.5 GWh. Moreover an equal charge and discharge power capacity has been assumed to simplify the model. In order to provide more information, other parameters estimated by 2050 have been assumed:

- Lifetime = 20 years and Cycle life = 20'000 equivalent full-cycles
- Depth of discharge = 100%
- Round trip efficiency = 97%

3.6.2 Economical analysis

The improvements in performance and installed cost reductions can improve the competitiveness of Li-ion battery system in the market. The first priority in the market is the reduction of the installed costs. To achieve this, there are two possible avenues: manufacturing perspective (e.g. economy of scale) and technology perspective (e.g. higher energy density that reduces materials use). In terms of cost reductions, a significant reduction is expected thanks to the improvement of the cathode technology with a resulting increase of the efficiency, energy density and lifetime. The labour costs are very location dependent and they are difficult to estimate; a decrease of these costs is expected due to the increasing of the automation in the market.

An installed CAPEX cost of 140 eur/kW has been considered in the present work [22]. In order to maintain the correct operational condition in the battery room, fixed operation and maintenance have been taken into account. A cost of 1.4% of the CAPEX costs per year with an annual discount rate equal to 7% have been assumed. The following table (TAB: 3.6) summarized all the technical and economical assumption that have been done in the present work:

Power Capacity	Energy Capacity	C-rate	Depth of discharge	RTE
GW	*GWh*	-	*%*	*%*
5	2,5	0,5	100	97

CAPEX	Fixed O&M	Discount rate	Lifetime	Cycle life
eur/kW	*% CAPEX/year*	*%*	*years*	-
140	1,4	7	20	20000

Table 3.6. Summary of the technical/economical assumptions for Li-ion battery

3.6.3 Model building

After that all the technical and economical parameters have been assumed, in order to implement the python code and obtain interesting results, it has been necessary to define technical and control parameters:

1. TECHNICAL PARAMETERS
    - Power capacity [*p_st_b_max*]
    - Maximum and minimum capacity of the battery [*st_max_b*] and [*st_min_b*]
    - Round Trip Efficiency [*RTE_b*]
    - Lifetime [*life_b*] and Cycle life [*cycle_life*]
    - CAPEX cost [*capex_st_b*], Fixed O&M cost [*fixed_om_st_b*] and Annuity factor [*annuity_cst_st_b*]
2. MODEL VARIABLES
    - Level of the energy stored in the battery [*level_b(t)*]
    - Initial energy level available [*level_b0*](equal to *st_max_b/2*)
    - Quantity of absorbed and served energy [*st_in_b(t)*] and [*serv_st_b(t)*]
    - LCOE cost [*cost_st_b*]
    - Counter ON/OFF [*counter_b(t)*] and binary variable [*onoff_b(t)*]

With the purpose to know the number of ON/OFF that at the end of the period have been done from the battery technology, a binary variable has been implemented in the model. This variable assumes a value equal to 0 when the battery is in discharge operation and equal to 1 when is in charge operation. Every time that the binary variable changes the value from 0 to 1 or from 1 to 0, a counter is implemented by one. In order to know the number of a complete ON/OFF cycle (ON to OFF + OFF to ON) it is necessary to divide the obtained value of the variable *counter_b* by 2.

The depth discharge of the battery has been assumed equal to 100% and for this reason no variable has been defined in the model. Moreover, a round trip efficiency without considering the single losses during charge and discharge has been considered . The RTE has been multiplied directly in charging mode without having any conversion during the discharge operation.

Chapter 4

Historical Data analysis

4.1 Introduction

The Belgian power grid is part of an interconnected network and, to maintain the balance between production and consumption, a series of balancing mechanisms can be activated from the Transmission System Operator. With the purpose of ensuring that the European electricity market is transparent, different institutions publish details and data regarding the electricity market of the each European country. ELIA, the Belgian TSO, provides on the website the possibility to download all the information about the electricity market in Belgium.

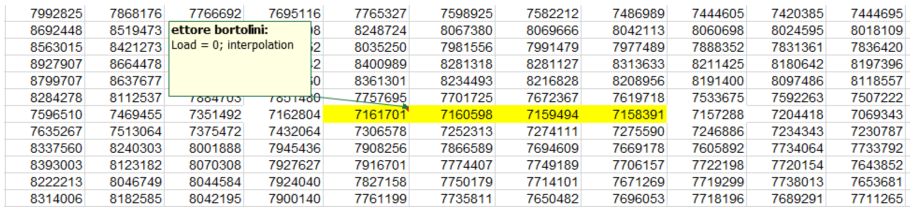
In the present work, a period from the 1st January 2013 to 31st August 2018 has been considered in order to create a model similar to the reality; the following data have been downloaded:

- Consumption data
- Offshore and Onshore wind data generation with the corresponding power capacities installed.
- Solar data generation with the corresponding power capacity installed.

ELIA's website provides data month per month and for this reason it has been necessary to join them together. Moreover each group of data has been ordered in different sheets of an Excel file in order to be readable from Python.

4.2 Common data errors

In the data downloaded and ordered, several mistakes and mismatching between consumption and production have been found. Therefore, it has been necessary to correct them and sometimes also make some assumptions.
The first typology of errors founded and corrected concerns the load historical data. Several values were equal to zero and due to the fact that, it is impossible that in a certain period in a country the demand is equal to zero, it has been necessary to correct them. In order to do it, two approaches have been followed. When the series of data was not too long (from 1 to 8 consecutive values), it has been decided to interpolate between the first and the last value of the series and create a certain continuity in the decreasing/increasing of the load in that period (e.g. FIG: 4.1).
If the series of zero-values was long (more than 8 consecutive values), the forecast values predicted for that period, also available on ELIA website, have been replaced as real demand values .



7992825	7868176	7766692	7695116	7765327	7598925	7582212	7486989	7444605	7420385	7444695
8692448	8519473	[illegible]	[illegible]	8248724	8067380	8069666	8042113	8060698	8024595	8018109
8563015	8421273	[illegible]	[illegible]	8035250	7981556	7991479	7977489	7888352	7831361	7836420
8927907	8664478	[illegible]	[illegible]	8400989	8281318	8281127	8313633	8211425	8180642	8197396
8799707	8637677	[illegible]	[illegible]	8361301	8234493	8216828	8208956	8191400	8097486	8118557
8284278	8112537	[illegible]	[illegible]	7757695	7701725	7672367	7619718	7533675	7592263	7507222
7596510	7469455	7351492	7162804	7161701	7160598	7159494	7158391	7157288	7204418	7069343
7635267	7513064	7375472	7432064	7306578	7252313	7274111	7275590	7246886	7234343	7230787
8337560	8240303	8001888	7945436	7908256	7866589	7694609	7669178	7605892	7734064	7733792
8393003	8123182	8070308	7927627	7916701	7774407	7749189	7706157	7722198	7720154	7643852
8222213	8046749	8044584	7924040	7827158	7750179	7714101	7671269	7719299	7738013	7653681
8314006	8182585	8042195	7900140	7761199	7735811	7650482	7696053	7718196	7689291	7711265

FIG: 4.1. Example of load data error

The second typology of errors found regards both load and production historical data. Every year, several regions in the world use daylight saving time to adjust the clocks forward one hour close to the start of spring and adjust them backward in the autumn to standard time. This effect causes a lost hour in the spring and an extra hour in the fall. Because of this, it has been necessary to add one hour of data in the spring and remove one hour in the fall in order not to count this effect and to have a certain continuity. In this case, the series of consecutive values to correct are always four. An interpolation method has been used between the first and the last value of the series creating a certain continuity of the load in that periods. The example shown in FIG: 4.1 can also be applied to this typology of mistake.

The third and last typology of errors concerns only the production historical data. It has been noticed that several times the capacity factor computed in the data-sheet was higher than 1, physically impossible. This error means that the electricity production in a certain instant is higher than the correspondent total capacity installed. This mistakes can be attributed to a not correct measurement of the production or to a not correct estimation of the installed capacity in that period. In this case, the series of consecutive incorrect values can be not too long (from 1 to 8 values) or very long. In the first case interpolation has been adopted as method; in the second case the forecast values predicted for that period have been replaced as real production values.

4.3 Electricity consumption

In order to obtain a real electricity zone and consider the variability of the demand, historical data for Belgium in the period 2013-2018 have been downloaded and analysed. After correcting the mistakes found with the methods explained previously, some calculations have been done.
The FIG: 4.2 represents the trend of the Belgium electricity load in the period chosen. The average value has been calculated and it is equal to 8.9 GW, varying from a minimum of 5.4 GW up to a maximum of 13.4 GW.
It is possible to notice that the electricity load does not vary too much and therefore there is a sort of repetition each year with a presence of maximum and minimum peaks. The Belgian electricity load estimated for 2050 can present a variation due to three main factors [7]:

1. Rise of the consumption due to economic growth, increased population and energy efficiency;
2. Additional electrification (heat pump and electric vehicles)
3. Thermo-sensitivity of the consumption

In the present work, the electricity consumption projection by 2050 does not present any variations with respect to the historical period taken into account.

In the FIG: 4.3 it is possible to appreciate better the variation of the electricity load in a reference year (2017). It is evident that during winter season the electricity load is higher than the others period of the year, surely due to the low temperature and therefore the larger use of the heating system.
It is also possible to notice the presence of an intra-day variation due to the different consumption profiles during night and during the day (FIG: 4.4). This profile in 2050 can be different due to two phenomenons: demand shedding and the demand shifting.
In the first case, the consumers are load shedding and they can reduce part of their consumption when the prices reach a certain level called "activation price". In the second case the consumption can be moved to another moment of the day in order to optimize the consumption profile in relation if the electricity price.
In the present work, these future phenomenons have been neglected.

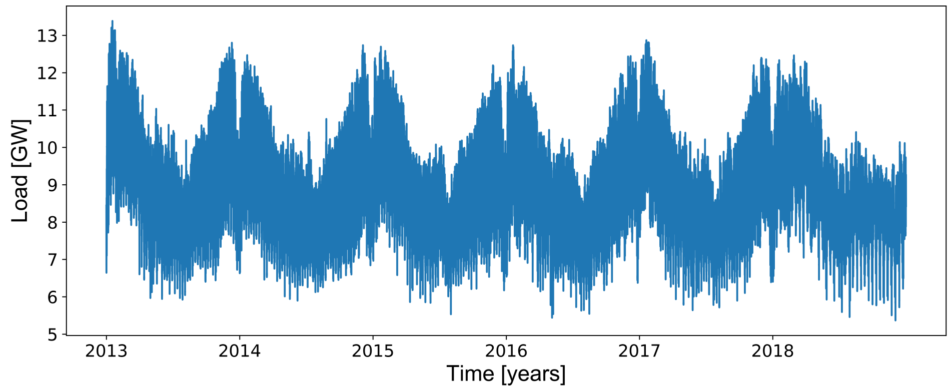


FIG: 4.2. Historical electricity load in Belgium, 2013-2018

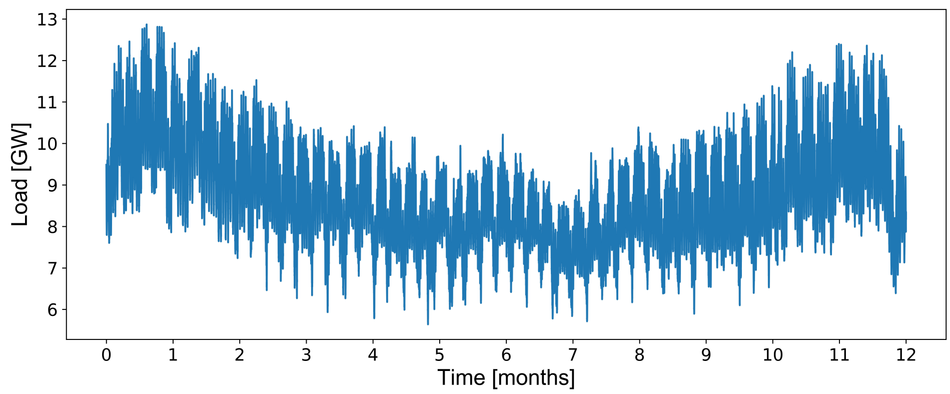


FIG: 4.3. Annual electricity load in Belgium (2017)

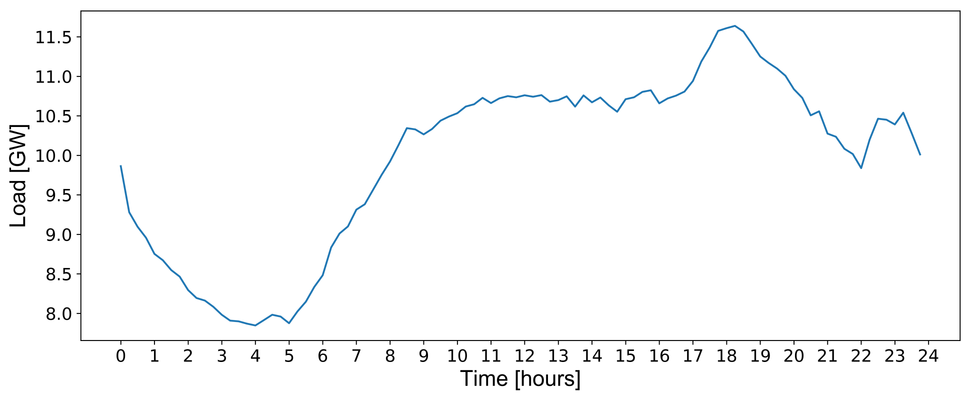


FIG: 4.4. Daily electricity load in Belgium - Thursday 3rd January 2013

4.4 Renewable energies data

In the present work renewable energies have an important role in the electricity generation. Solar and wind energy are intermittent sources, and for this the use of historical data in the control area taken into account has been necessary.
For each technology, the data referred to the period 2013-2018 have been downloaded, corrected and analysed. The purpose of this section is to obtain general informations about the electricity production and make assumptions useful in the actual model.

The FIG: 4.5 shows the high intermittent electricity production of onshore energy due to the variability of the wind speed during the year. The average capacity factor has been calculated with a result of 0.21, varying between a minimum capacity factor of 0.2% and a maximum of 93% . The growth of the production is related to the increasing of the installed capacity; it is possible to notice it from FIG: 4.8 in which it is shown the trend of the installed capacity in Belgium in the whole period.

The FIG: 4.6 shows a different trend respect to onshore energy production. The wind speed on the ocean is less variable than on land and so, as the figure shows, the electricity production of offshore energy is more constant. In the same ways as onshore wind energy, the average capacity factor has been calculated. In this case is equal to 0.38, higher than the other one because of the lower variability of the production and the higher wind speed. It varies between from a minimum capacity factor of 0.4% to a maximum of 98.6%
It is possible to notice from FIG: 4.9 the increasing of the capacity in the period 2013-2018. It is evident the similarity between the growth of the production and the growth of the installed capacity.

The trend of solar energy production is completely different from the trend of wind energy because of the different type of energy source. In FIG: 4.7 is evident the alternation of the seasons and therefore the higher production during summer and the lower production during winter. Moreover it is possible to notice the daily solar production trend due to the alternation of the night and the day. The growth of the production is low and it is possible to see from FIG: 4.10; from 2013 to 2017 big investments on the installed capacity have not been done except in 2018 in which there was a new installation of 400 MW.
Also with this technology, the average capacity factor has been calculated. The value obtained is 0.12 varying from minimum capacity factor of 0% to a maximum of 84.1% .

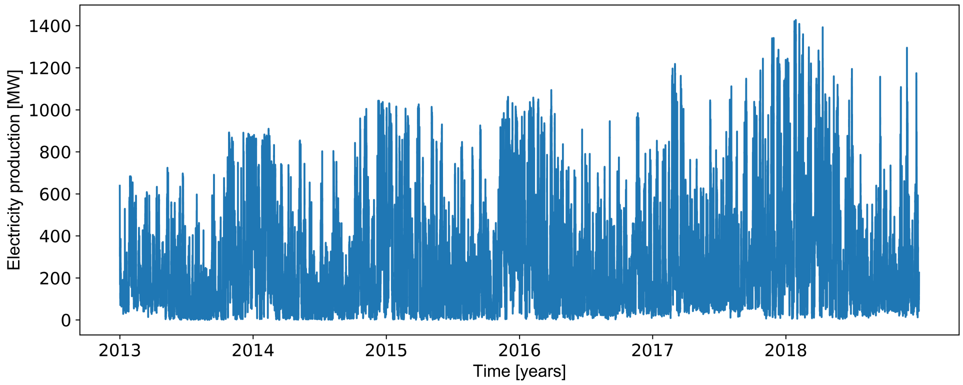


FIG: 4.5. Historical electricity production of onshore wind energy in Belgium, 2013-2018

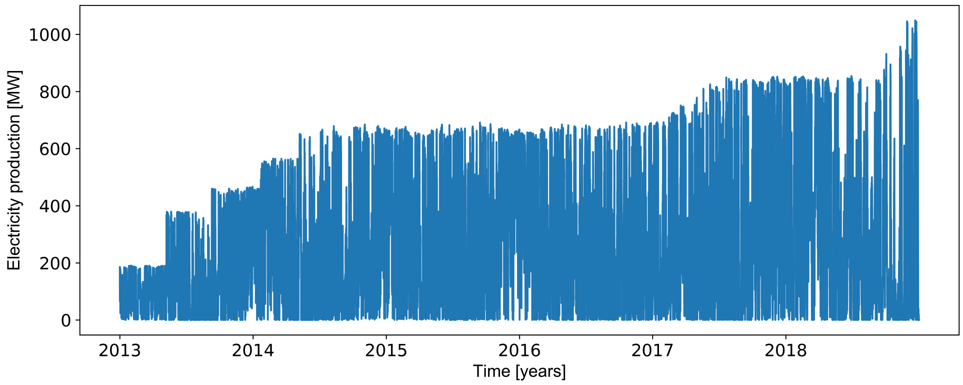


FIG: 4.6. Historical electricity production of offshore wind energy in Belgium, 2013-2018

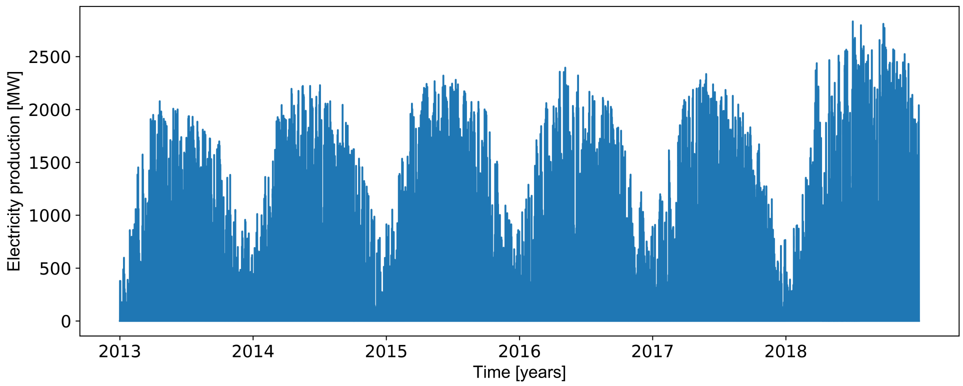


FIG: 4.7. Historical electricity production of solar energy in Belgium, 2013-2018

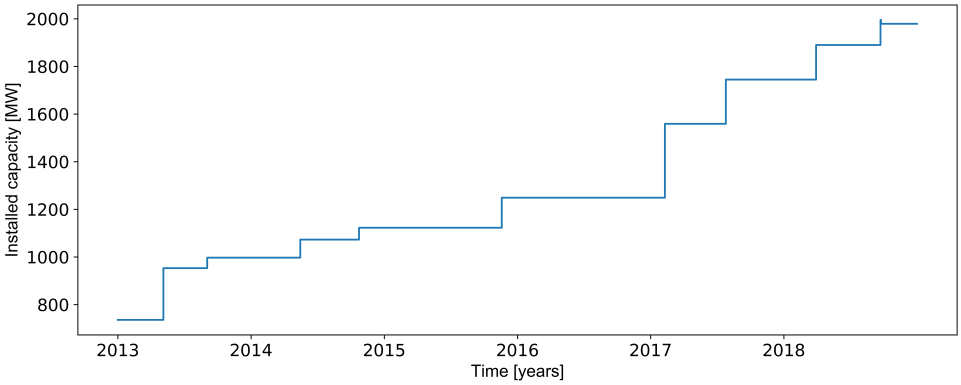


FIG: 4.8. Historical installed capacity of onshore wind energy in Belgium, 2013-2018

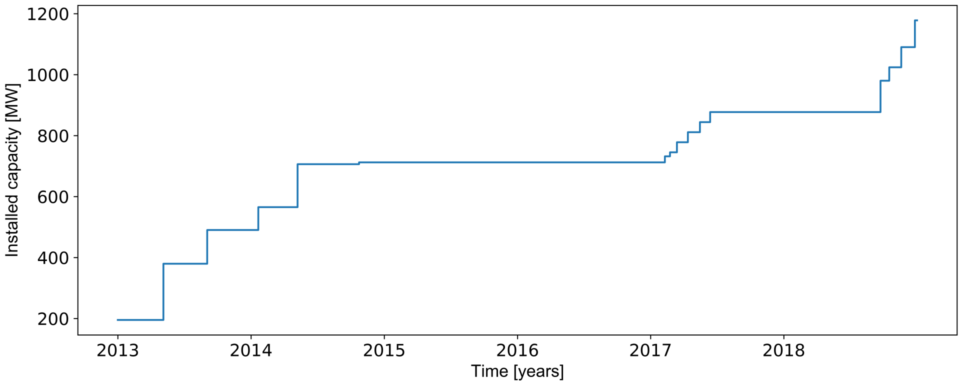


FIG: 4.9. Historical installed capacity of offshore wind energy in Belgium, 2013-2018

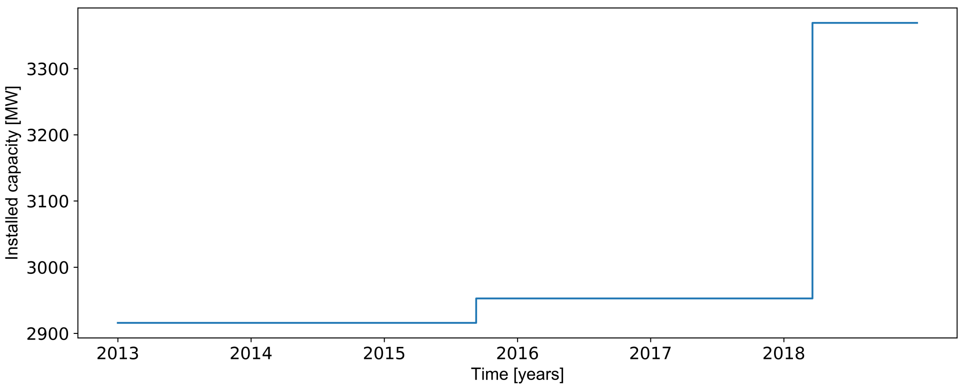


FIG: 4.10. Historical installed capacity of solar energy in Belgium, 2013-2018

Chapter 5

Simulations and results

5.1 Introduction

In the first part of this section, the results obtained from the previous model have been illustrated in order to compare them with the new ones obtained in the present work. In the second part, several simulations have been represented in different scenarios and with different assumptions.
After importing all the required historical data, defining all the technical and economical variables, describing the optimization problem specifying constraints and variables needed for the solution, several simulations with Python 3.7 have been ran on a PC with i7 processor and 8GB of RAM.
The output defined at the end of this function can be grouped in these categories:

- Number of windmills (offshore and onshore), solar park and unit of P2F system
- Total installed power for each technology
- LCOE of each technology and total LCOE
- Served energy for each technology
- Storage level at the end of the simulation
- Counter ON/OFF for methanol and battery technologies
- LOLH (Loss of load hours) parameter

All these results have been analysed and commented in the next sections.

5.2 Previous model

5.2.1 Assumptions

In a work conducted in 2015 called ”Electricity storage with liquid fuels in a zone powered by 100% variable renewable” [6] an electricity zone with 100% renewable is simulated with the purpose to determine the optimal sizing of generation and storage capacities in a certain zone. In this model the electricity is generated solely from wind energy sources and stored using power-to-fuel storage technology that combines water electrolysis, CO_2 capture and methanol synthesis.
The purpose of the work is the same of the present work, namely to evaluate the economic viability of P2F technology and obtaining the levelized electricity cost projection by 2050.

In the table below (TAB: 5.1) are summarized the economic and technical assumptions of the previous model referred to wind power and storage unit.

Variable	Unit of measure	Wind power unit	Storage unit
Net unit capacity	*MW*	5	0,25
Capex Costs	*eur/kW*	1100	856
Fixed O&M costs	*%CAPEX per year*	1,7	3
Opex costs	*eur/kWh*	0	$6\ 10^{-3}$
Lifetime	*years*	25	20
Interest rate	*%*	7	7

Table 5.1. Summary of the assumption takes in the previous model

The period taken into consideration in the historical data of Belgium is three years with 15-minutes resolution; the efficiency of the process has been considered equal to 50% and the cost of CO_2 capture are included in the operational cost.

5.2.2 Results

Based on these assumptions, the optimization problem leads to an optimum installed wind capacity of 44.6 GW and 13.5 GW of storage power capacity. The share of electricity that it is directly served by wind is equal to 74.6% with a resulting electricity cost equal to 83.4 eur/MWh. The curtailment rate of wind power is 13.3%.
It is possible to notice from these results a necessary overcapacity of windmills in order to satisfy completely the demand; this type of design leads to an electricity cost that is almost twice than the current average electricity price in the Belgian market (45.1 eur/MWh).
With the increasing of the storage capacity it is possible to decrease the curtailment

but with a resulting higher average cost of electricity. This case can be considered if the excess of methanol production can be valorized for other uses than electricity generation such as for transport application (neglected in the model). Moreover the evolution of the storage has been represented and it is shown below in FIG: 5.1.

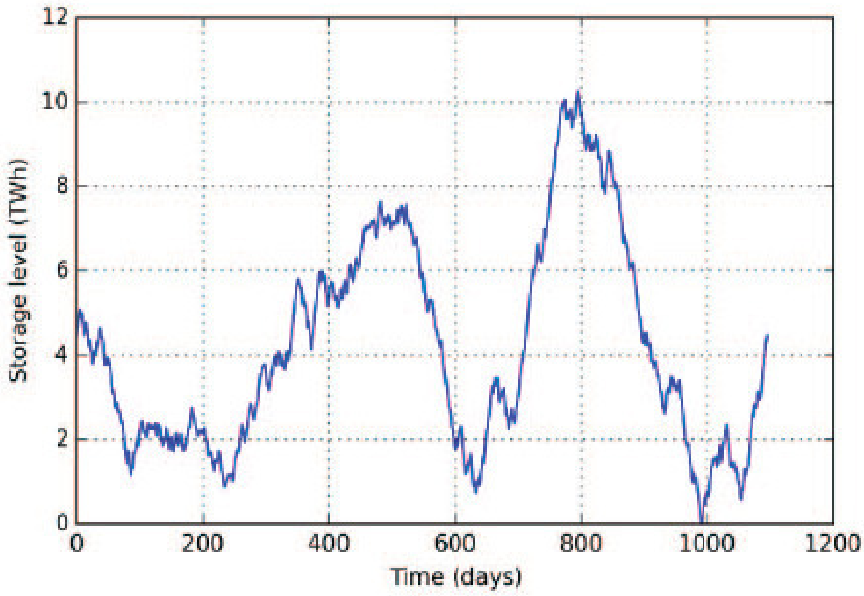


FIG: 5.1. Evolution of storage level in the previous model

5.3 Base case

5.3.1 Assumptions

In this section of the present work the results of the base case model are presented. All the assumptions taken into account have been already discussed in the previous chapters. All the assumed technical and economic parameters are shown in Table: 5.2 and 5.3. The purpose of this case is to obtain information about the order of magnitude of the different installed capacity of renewable energies and storage needed to satisfy completely the demand in each instant. Moreover, the cost of each technology and the total cost of the energy system have been computed with the purpose to elaborate an economical analysis.

Variable	Unit of measure	Offshore wind	Onshore wind	Solar PV	Biomass
Net unit capacity	*MW / MWh*	5	5	3	750
Capex Costs	*eur/kW*	2280	1100	650	800
Fixed O&M costs	*%CAPEX per year*	2,3	1,7	1,85	5
Fuel cost	*eur/kWh*	-	-	-	0,033
Lifetime	*years*	30	25	30	30
Efficiency / RTE	*%*	-	-	-	35
Interest rate	*%*	7	7	7	10
Optimization variable	*YES/NO*	YES	YES	YES	NO

Table 5.2. Summary of the technical assumptions for RES technologies

Variable	Unit of measure	PHES	Battery	P2F
Net unit capacity	*MW / MWh*	1800 / 7700	5000 / 2500	0,25*
Capex Costs	*eur/kW*	1600	140	2500
Fixed O&M costs	*%CAPEX per year*	-	1,4	1,6
Fuel cost	*eur/kWh*	-	-	0,00492 (CO2)
u_var	*eur/kWh*	0,005	-	-
Lifetime	*years*	60	20	20
Efficiency / RTE	*%*	75	97	35
Interest rate	*%*	7	7	7
Optimization variable	*YES/NO*	NO	NO	YES

Table 5.3. Summary of the technical assumptions for energy storage technologies

*Assumption of infinite methanol energy storage capacity

5.3.2 Power generation mix

Renewable energy sources

The results obtained from the base case simulation regarding the power generation mix of renewable energy sources are shown in FIG: 5.2
It is evident that wind energy source, with 40.74 GW of installed capacity, due to the lower cost of the technology and the higher average capacity factor represents the 63.3% of the power generation mix in the base case. Biomass source represents only 1.2% of the total mix due to the lower installed capacity projected to be present in 2050 in Belgium.
The presence of solar energy in the model, despite the low average capacity factor in Belgium, represents 35.5% of the power generation mix with an installed capacity of 22.8 GW.
The total installed capacity obtained is equal to 64.33 GW, very high with respect to the actual value (June 2019) in Belgium is equal 22.57 GW [64]. The large percentage of intermittent sources such as wind and solar energy implies a high value of installed capacity in order to satisfy the demand also when the total capacity factor of the three technologies is low due to weather conditions.
Comparing these values with the Belgian maximum potentials equal to 8 GW for offshore wind, 9 GW for onshore wind and 40 GW for phovoltaic [7], it is possible to notice that wind installed capacity is much larger than the realistic potentiality. This result shows the difficulty for an area like Belgium to satisfy the own demand without interconnection or the use of traditional sources (e.g. gas power plants). An increasing of the installed storage capacity can reduce the production power capacity but with a resulting rise of the total electricity costs.

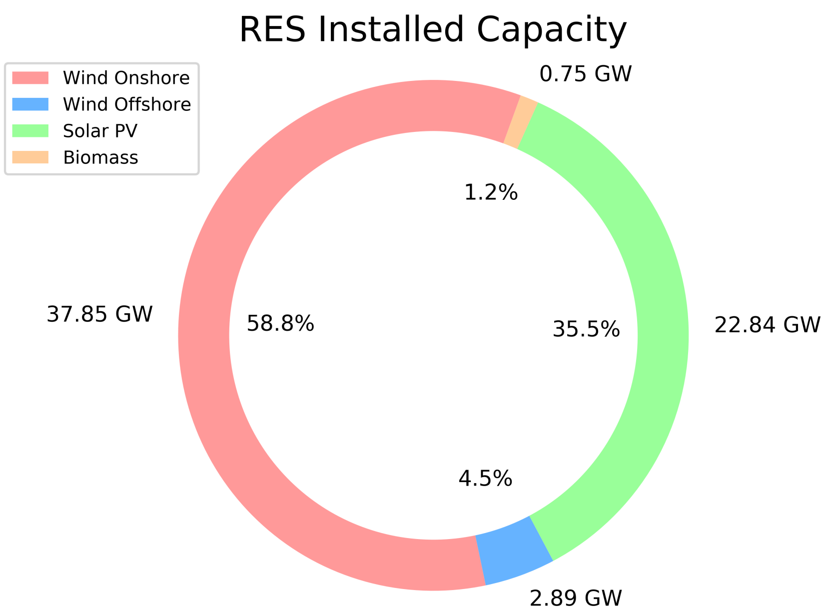


FIG: 5.2. Power generation mix - base case

Energy storage

The FIG: 5.3 shows the installed capacity needed from the energy system in order to supply/absorb the lack/surplus of energy due to the high variability in the production.
As said previously, in the present model battery and PHES power capacity have been fixed respectively to 5 GW and 1.8 GW. The optimum total storage capacity needed to satisfy completely the demand with the power generation mix shown in FIG: 5.2 is equal to 19.63 GW, of which 12.83 GW of P2F technology.
Currently the only Belgian energy storage is the Pumped Hydro Energy Storage plant in Trois-Ponts with a power capacity equal to 1.3 GW and it represents approximately 10% of the typical demand ($\sim$ 10 GW).

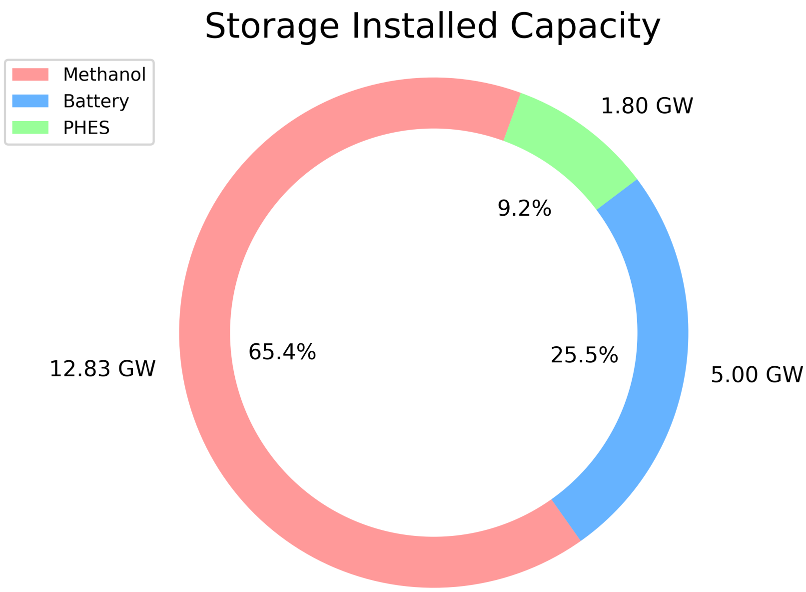


FIG: 5.3. Power energy storage mix - base case

5.3.3 Energy production and directly served mix

The figures represented in this section (FIG: 5.4, 5.5, 5.6) show in what percentage the energy is supplied from the different sources diversifying the energy produced and the energy directly served to satisfy the demand. The energy values shown in the ring charts are equal to an average annual amount. These values have been computed as the ratio between the total energy produced/served in the whole period taken into consideration and the number of years ($\sim$ 5.66 years).

It is possible to notice a sharp rise of the biomass percentage with respect to the installed power capacity due to the constant base-load operation and therefore the high capacity factor.
The amount of wind energy produced is dominant in this energy mix (73.5% in total) due to the higher capacity factor and installed capacity. Because of the large seasonal and daily variability, despite solar energy represents the 25.5% of the total installed power capacity (FIG: 5.2), it serves only the 20.5% of the total energy produced from renewable sources.

Regarding the energy served by storage units, it is possible to notice the prevalence of methanol capacity in the mix due to the restricted energy capacity of battery and PHES and the absence of an upper bound of the methanol storage capacity.
The quantity of energy served by battery energy storage is quite small because of the energy capacity assumed (2.5 GWh); it corresponds only to 1/3 of the energy served by PHES (energy capacity of 7.7 GWh - 3 times than the one of battery storage).

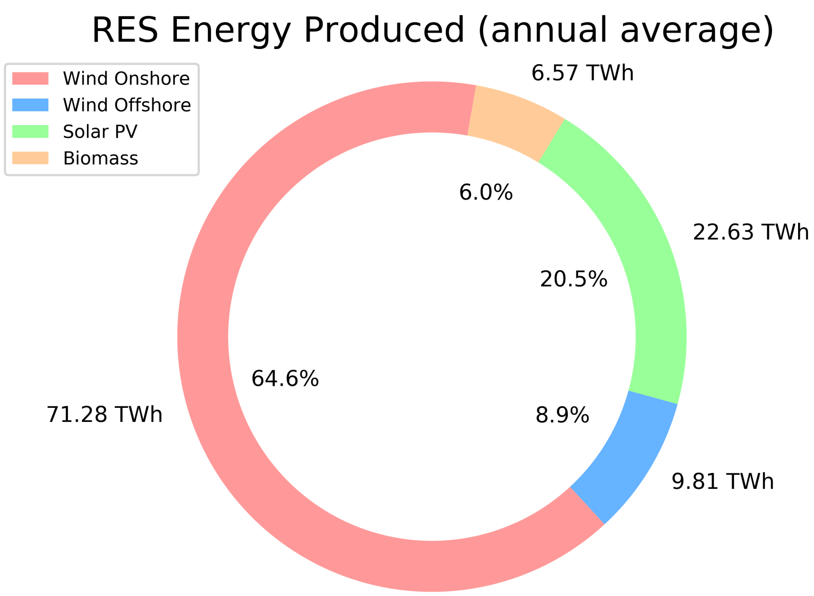


FIG: 5.4. RES - energy production mix - base case

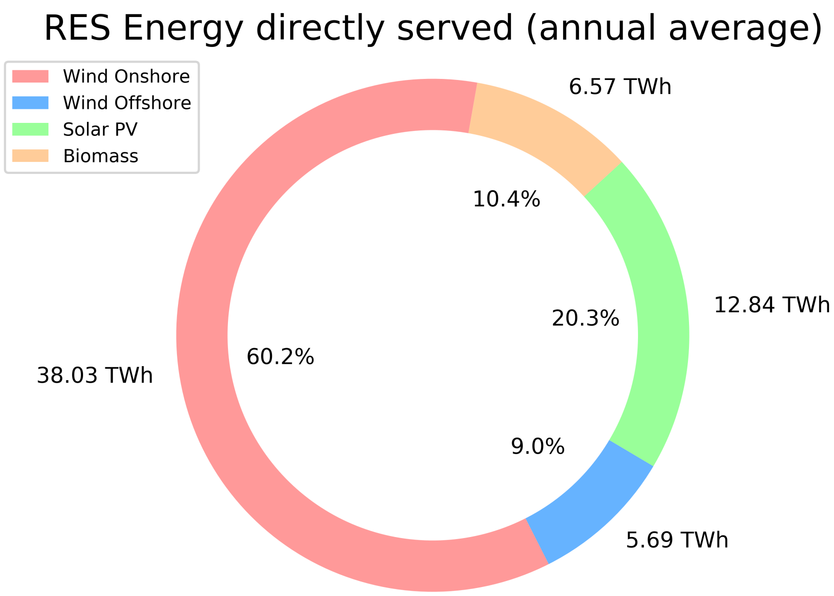


FIG: 5.5. RES - energy directly served mix - base case

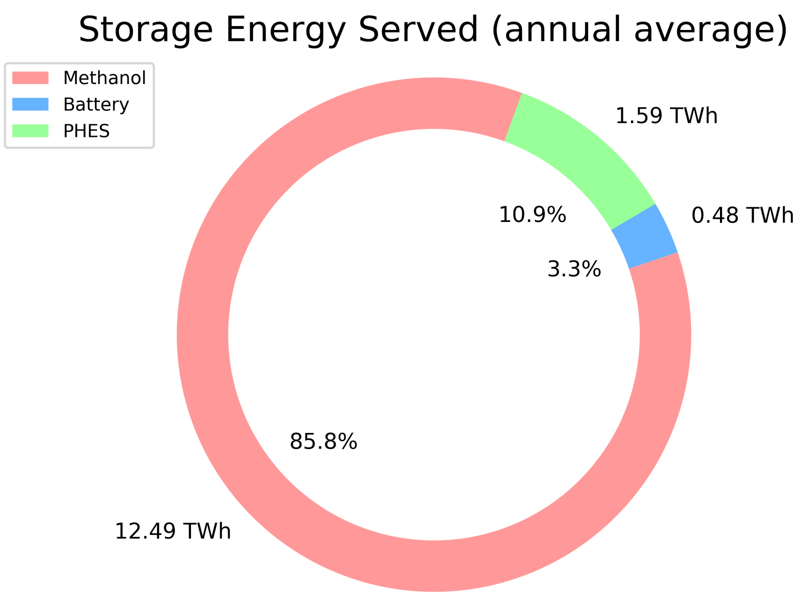


FIG: 5.6. Storage - energy served mix - base case

5.3.4 Evolution of the renewable energies production and Belgian consumption

After elaborating and obtaining interesting results looking at the percentage of the installed capacity and the energy served from the renewable energy sources and from the storage technologies, it has been decided to compare the energy production with the consumption.

Annual representation

The FIG: 5.7 shows in green color the total energy production from renewable energy sources. It is possible to observe the big variability of the production from a minimum of 0.80 GW to a maximum of 43.4 GW. The minimum is very close to the installed capacity of biomass set in the model (0.75 GW) and it means that there are moments in the year in which both wind and solar sources are not available. In these moments energy storage needs to supply the lack of energy that sometimes is close to the whole demand.
The trend of the energy consumption is represented with red color and, as it is possible to observe, it has the same behaviour every year with a variability from winter to summer seasons. The maximum value along the period is equal to 13.4 GW with a minimum equal to 5.36 GW.

It is interesting to compare the installed capacity of methanol storage with the maximum consumption; as the FIG: 5.2 shows, the methanol power installed capacity is equal to 12.83 GW, a value very close to the maximum consumption. This result can be explained by the high variability of the renewable energy sources and the necessity of the system to be able to satisfy completely the demand.

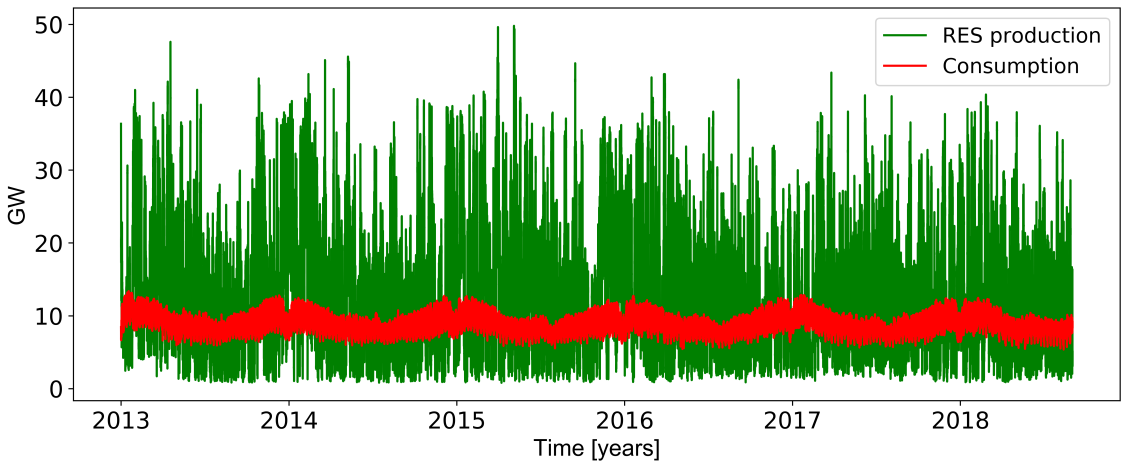


FIG: 5.7. Trend of RES production and consumption - base case

Weekly representation

In the following figure (FIG: 5.8) it has been decided to represent the trend of the RES production and the consumption in one week with the purpose of observing the intraday variability of the different energy sources.
As the figure shows, the daily variability of solar energy is evident due to the day alternating with night(red color) and the constant base-load operation of biomass power plant(blue color).
With purple colors, it is possible to observe the operation of the energy storage technology in order to satisfy completely the demand in each instant. The energy served by batteries is more difficult to notice on the graph it because of the smaller energy capacity with respect to the power capacity and therefore the ease to charge and discharge rapidly.
It is possible to notice that, during the evening hours, when the sun is about to set, PHES and battery storage are able to satisfy completely the demand without the help of P2Meth storage. After some hours they are empty and P2Meth technology starts to supply energy to the grid for all the night and for the first hours in the morning. This type of intra-day operation of P2Meth can be avoided adding more capacity to battery energy storage with the purpose of covering completely the short variations.

In some moments of the week, for example at the end of the 6th day, it is possible to notice a decreasing of the solar energy due to the future sunset and the enough capacity of PHES and battery to cover the lack of energy without the help of P2Meth technology.

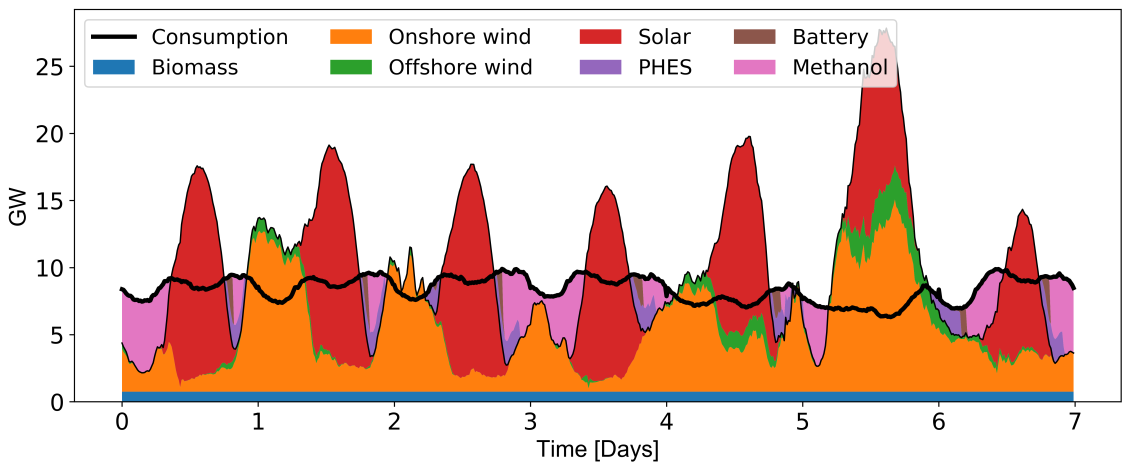


FIG: 5.8. Trend of a typical summer week of RES production, consumption and storage energy served - base case

5.3.5 Evolution of storage level

After analysing the evolution of the renewable energy production and Belgian consumption in the whole period and in a selected summer week, it has been decided to observe in what ways the energy storage reacts to this high variability of renewable energies in order to satisfy in each instant the demand and to store the energy surplus.

Methanol level

The FIG: 5.9 represents the evolution of the methanol storage level in the whole period. The initial level of the storage has been fixed at a certain level with the purpose to obtain an evolution in which the minimum value reached corresponds to an empty storage without having negative values.
Thanks to the absence of constraints regarding an upper bound in the energy capacity of the storage, it is possible to notice that the curve presents two peaks close to 8 TWh, value extremely high respect to the battery and PHES capacity (2.5 GWh and 7.7 GWh). Assuming an energy density equal to 17.85 MJ/L (around 5 kWh/L) it is possible to compute the volume necessary to store 8 TWh of methanol at ambient temperature. The resulting value is equal to 1.6 million of m^3.
In the present work it has not been considered the cost of the storage thanks to ease of store methanol due to optimal properties like: liquid fuel, higher autoignition temperature and higher explosive limit in the air respect to diesel fuel. This big amount of methanol can be stored in 32 large-scale atmospheric tanks (50000 m^3 for each one) present in the control area.
This value seems very large but, comparing it with the annual gasoline and diesel consumption in Belgium in 2015 [45], it is possible to notice a similar amount of fuel used (1.8 million of m^3 of gasoline and 8.33 million of m^3 of diesel). Thanks to this comparison, it is possible to affirm that the necessary volume is very big but not that unrealistic.

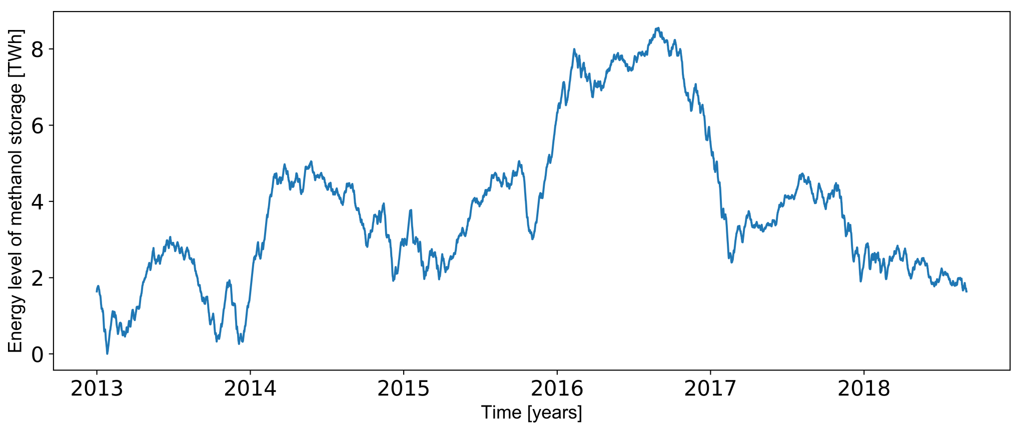


FIG: 5.9. Evolution of the methanol level during the whole period - base case

A comparison has been done calculating the volume necessary to store the same

quantity of energy in PHES and Li-ion battery. Considering an energy density of 0.5 kWh/m^3 and 300 Wh/l respectively for PHES and Li-ion battery, values of 16000 million of m^3 and 26.6 million of m^3 have been obtained.
The energy capacity required for PHES is 1800 times bigger than the actual installed capacity in Belgium, value extremely high and infeasible. Regarding battery energy storage, the obtained value is 16 times bigger than the volume required by methanol storage. These results show the importance of the high energy density of methanol. It is possible to notice in the year 2016-2017 a high request of methanol storage probably because of a low availability of wind and solar energy in the first months of the year. This result leads to an oversize of the energy storage that it is totally utilized only in that period.

Battery and PHES level

The FIG: 5.10 represent the annual evolution of PHES and battery energy storage in the first year of the simulation. It has not been chosen to show the whole period due to thick trend of these technologies and therefore a lack of clarity.
It is possible to notice that the evolution of the energy level is similar due to the limited energy capacity imposed (7.7 GWh for PHES and 2.5 GWh for battery storage). Because of the role of these energy storage systems in the model, the trend of the energy level is intensive and fast due to the intraday mode of operation.

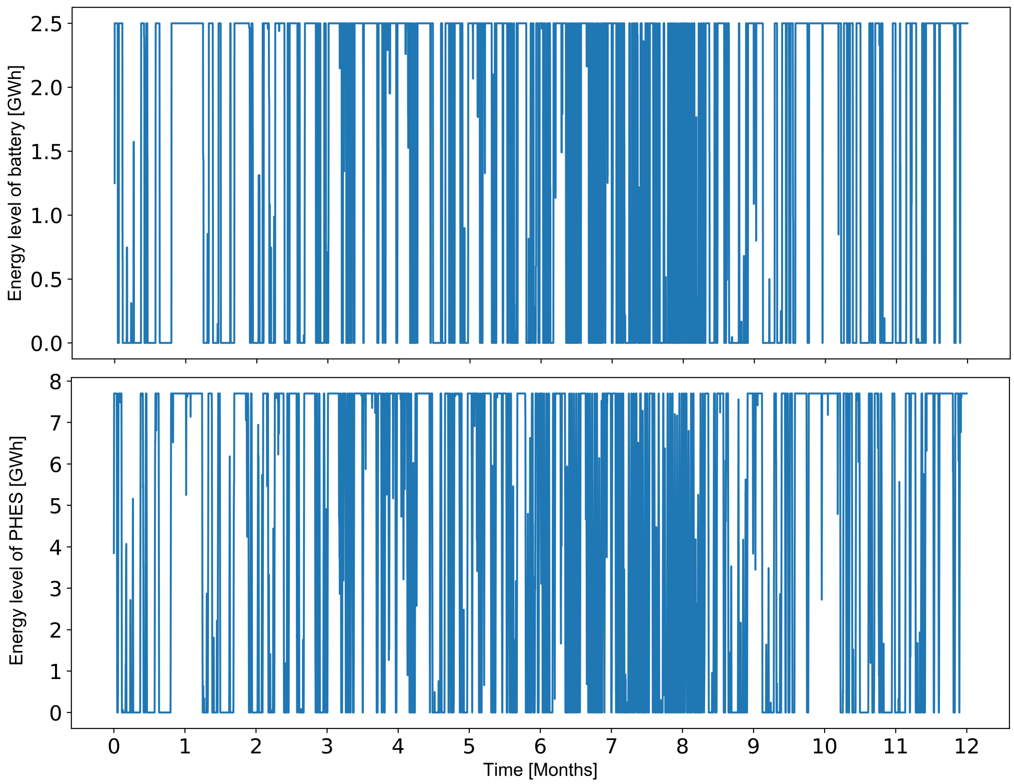


FIG: 5.10. Evolution of the PHES and battery level during one year -base case

Storage evolution in one selected week

With the purpose to analyse with more details the evolution of the energy level in the three different energy storage technologies (FIG: 5.11), it has been decided to show the trend in a selected summer week. In the graph below, it is possible to notice a difference between the intraday trends of battery and PHES level and the long-term trend of methanol level. Due to the different roles in the system, the operation of the short-term technologies is faster in charge and discharge mode with steep trend. Completely different is the operation of the methanol energy storage that, due to the long-term operation, presents small variation of the energy level during the week. It is possible to appreciate a daily charge/discharge operation in the first days of the week probably because of the effect of the alternation between day and night on the solar energy. The trend of methanol energy level gives important information about desired ramp-up and ramp-down of the energy input/output of the technology that has been neglected in the present work.

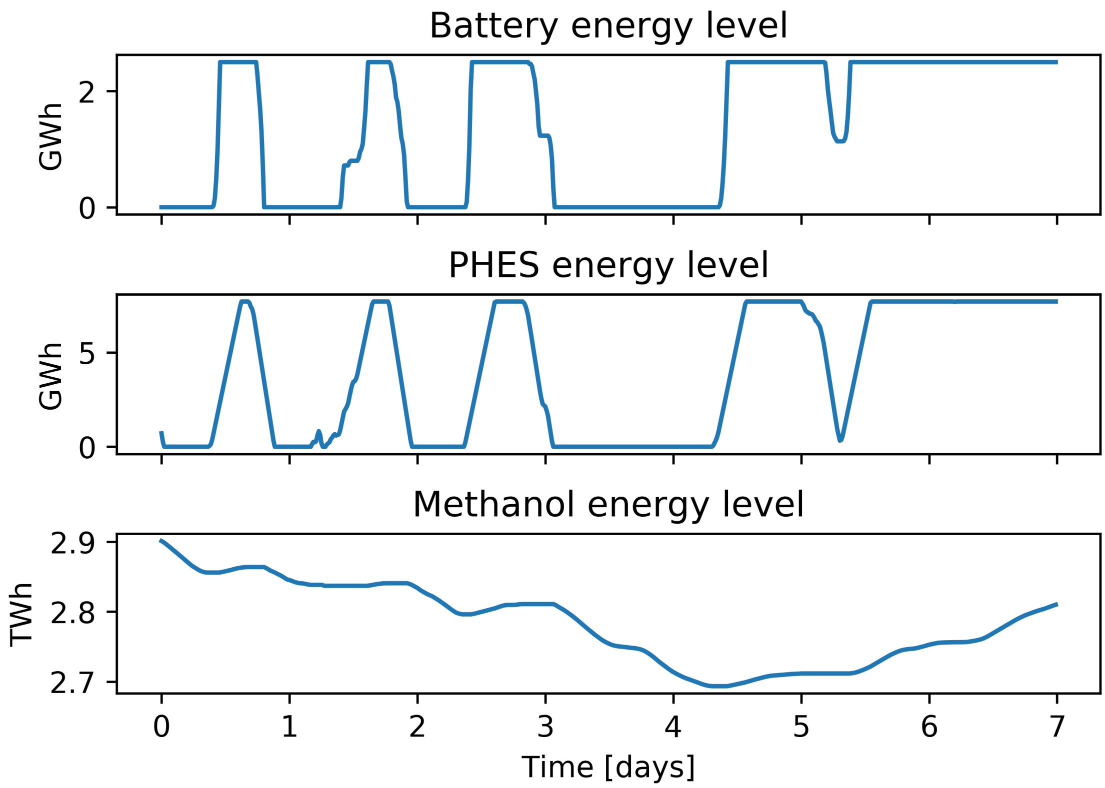


FIG: 5.11. Evolution of the storage levels during one week - base case

Moreover two parameters called *counter_m* and *counter_b* have been calculated with the purpose of giving an indication regarding the number of cycle ON/OFF of methanol and battery energy storage. In the base case simulation, 3000 and 3900 cycles respectively for methanol and battery technology have been counted along the whole period analysed. In order to obtain a specific parameter, these numbers have been divided by 2 obtaining the number of complete cycles (ON/OFF + OFF/ON) and also divided by the number of the years considered (5,66 years) obtaining in this way a specific quantity. A value of 265 and 344 complete cycles for year have been obtained respectively for methanol and battery storage. The value referred to battery technology can be compared with the expected life cycle equal to 20000 after 20 years. With the type of operation in the present model (almost one complete cycle for day), after 20 years of operation a total of 6880 cycles are performed.
The increase of the battery energy capacity can lead to a lower number of cycles especially for P2Meth storage that sometimes follows very short ON/OFF cycles. This decrease would be good for the lifetime of the technology.

5.3.6 Economical analysis

After analysing all the technical parameters obtained from the base case simulation and obtaining interesting results from the evolution of some of the parameters, the electricity cost for each technology and the total one have been investigated. The use of the levelized cost of electricity (LCOE) allows a comparison between different electricity technologies and giving an idea of the average minimum price at which electricity must be sold over the lifetime of the project.

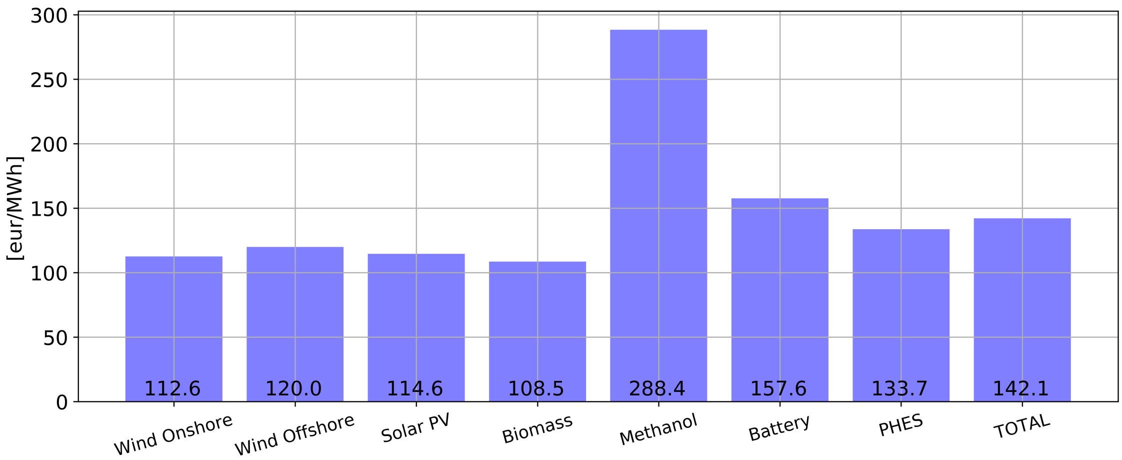


FIG: 5.12. Levelized Cost Of Electricity for each technology - base case

The FIG: 5.12 shows the results of the simulation in the base case. It is possible to observe that the LCOE cost for the production units varies from 108.5 eur/MWh of biomass to 120.0 eur/MWh for offshore wind source. The prices are higher than the average ones [40] because of the only presence of renewable energy in the energy system and the consequent necessity to store the energy when there is a surplus respect to the demand. The LCOE cost is calculated with the ratio between the total cost of the system and the total energy directly served; as it is possible to compute from FIG: 5.4 and 5.5, the ratio between the energy directly served and the total energy production is around 50-60% except for biomass that is equal to 100% due to the base-load operation and the role assumed in the system; the lower is the percentage and higher it will be the LCOE.

The costs of the energy storage are higher due to the high investment costs and the efficiency (especially for Power to Methanol technology). Due to the maturity of the technology, PHES is the cheapest energy storage with a LCOE cost equal to 133.7 eur/MWh. The obtained total electricity cost of the system in the base case is equal to 142.1 eur/MWh, more than three times of the actual cost of electricity [66] (40 eur/MWh) due to the necessary overcapacity of the system to achieve 100% demand coverage with only renewable energies and storage.

5.3.7 Comparison of the results with the previous model

The implementation that it has been done in the present work brought to a representation of Belgium more detailed with an varied energy mix and a configuration closer to the reality with lower supply variability(and thus a smaller need for storage) thanks to the different time profiles of the renewable energy sources.

It is possible to notice this effect comparing the maximum level of energy stored in the previous model with the actual one. The first system needs a maximum energy storage capacity of 10 TWh, the second one an energy storage capacity of 8 TWh. Moreover, the peak storage capacity of 10 TWh required in the initial model is obtained in 2014. while at the same period in the new model configuration, the required storage capacity is equal to about 4-5 TWh. Regarding the RES installed capacity, the comparison between the two models shows a installed wind and storage capacities of 44.6 GW and 13.5 GW respectively in the previous model and a total installed capacity of 64.3 GW and 19.63 GW in the actual model. The reason of this difference can be conferred to a scarcity of wind and solar energy availability in the first months of 2016 (considered only in the actual model) visible in FIG: 5.9 in which the energy level of methanol storage increases steeply with a consequent oversize of the system.

The electricity costs discussed in both models present big difference mainly for the economical assumptions done for the methanol storage. In the previous work a CAPEX cost for a storage unit equal to 856 eur/kW has been assumed using the investment cost for the electrolyser equal to 280 eur/kW, 576 eur/kW for the methanol synthesis and 26 eur/ton of CO_2. These values are very different from the ones assumed in our model: 650 eur/kW for the electrolyzer, 1365 eur/kW for the methanol synthesis, 500 eur/kW for the fuel cell and 40 eur/ton of CO_2. Moreover, the Power to Methanol round trip efficiency estimated in the present work is equal to 35% in comparison with the RTE considered equal to 50%. Because of this enormous and difficult estimation of a no-mature technology by 2050, a margin of error is present. A sensibility study with the economical parameters and the efficiency has been done and presented in chapter 7.

The estimations in the previous model regarding wind power technology present differences mainly due to the no distinction between onshore and offshore. The CAPEX cost utilized in the previous model is equal to the one for onshore technology (1100 eur/kW) without considering the presence of offshore technology in the total capacity factor. The no-distinction between the two technologies and the use of capacity factors referring to both sources, led t to an underestimation of the cost. In the present work, the distinction between onshore and offshore technologies in terms of capacity factor and cost parameters has brought to an estimation more realistic and precise.

Chapter 6

Others simulations

6.1 Introduction

After analysing the previous model done in 2015 and comparing it with the results given by the simulations of the present work in the base case, with the purpose of analysing the influence of some technologies on the energy system, it has been decided to vary some parameters and run other simulations.
The margin of errors present in this work can be very high because of the long term forecast of a possible situation in Belgium by 2050. For this reason, this chapter and the next one about sensibility analysis are very important to test the robustness of the model in case of variation of assumptions and parameters.
In this section, for each simulation only the main results have been presented and discussed. Below are listed the different cases that have been elaborated:

- Upper bounds on wind and solar installed capacity
- Increase of the biomass power capacity
- Increase of the biomass power capacity and upper bounds RES potential

6.2 Upper bounds on wind and solar installed capacity

In the base case simulation analysed in the previous chapter a total renewable energy installed capacity of 64.33 GW has been obtained. This value is very high respect to the actual value equal to 10 GW and it is composed by 22.84 GW of solar energy, 37.85 GW of wind onshore energy and 2.89 GW of wind offshore energy.
These values have been compared with the Belgian maximum potential provided by an Elia document [7]. The upper bounds that refer to the offshore wind installed capacity of 8 GW together with 9 GW for onshore wind and 40 GW for photovoltaic have been assumed .
It is clear that the optimum installed capacity in the base case for onshore wind

energy is much larger than the Belgian availability. With the purpose of obtaining results more realistic taking into account these limits, three new constraints have been set in the python model.

```
# Constraint functions: must all be >=0
c1 = lambda x: np.asarray([opticost(x)[27]-0.1]) #(1.0*float(a)/365.0)
...
...
c7 = lambda x: np.asarray([8-opticost(x)[4]]) #total onshore power
    installed
c8 = lambda x: np.asarray([9-opticost(x)[5]]) #total offshore power
    installed
c9 = lambda x: np.asarray([40-opticost(x)[6]]) #total PV power installed
constraints = np.asarray([c1, c2, c3, c4, c5, c6, c7, c8, c9])
```

The addition of these constraints brought the simulation to reach the convergence without the respect of them because of an infeasibility of the optimization problem.

With this result it has been possible to demonstrate the impossibility for Belgium to satisfy completely the demand using only renewable energy sources and without interconnection due to a scarce wind energy potential. Probably, with an increasing of the offshore wind capacity and thus an increasing of the total energy cost of the energy system, the onshore installed capacity can decrease obtaining values closer to the reality. With the purpose of finding a realistic situation, in the next simulation it has been decided to increase the biomass power capacity.

6.3 Increase of the biomass power capacity

6.3.1 Assumptions

In the base case analysed in the present work, a constant power capacity of 0.75 GW has been considered in order to provide a base load operation to the energy system. The limitation of the installed capacity derives from the prevision assumed by Elia [7] regarding the control area taken into account.
With the results given from the previous simulation it has been possible to demonstrate the impossibility of Belgium to have an power generation mix obtained in the base case. With the purpose of reducing the number of wind turbines used coming closed to the maximum potential available, the power capacity of biomass technology has been increased up to 2 GW. In the following simulation all the parameters and the assumptions have remained unchanged except for the power capacity of biomass.

6.3.2 Main results

The results given from the current simulation assuming a power capacity of biomass technology equal to 2 GW have been analysed in a similar way of the base case. Regarding the new power generation mix, a total installed capacity of RES equal to 56.45 GW and for energy storage equal to 18.71 GW have been obtained . These results have been compared with the ones of the base case obtaining a lower RES power capacity (-13.9%) and a lower storage power capacity (-4.9%) (in the base case respectively equal to 64.33 GW and 19.63 GW). It is possible to observe from these results the effect of base load plants in the energy system that lead to a lower use of the storage system due the non existing variability on the operation.

The optimization problem provides a power generation mix different in which onshore wind energy represents the 53.4% of the total mix and almost the absence of offshore wind energy (3.8%); this result doesn't respect again the maximum potential available for onshore wind energy.
It has been decided to run another simulation keeping the power capacity of biomass power plant to 2 GW and defining one more time constraints related to the maximum potential in Belgium of onshore and offshore wind energy. This simulation is shown and explained in the following section. As a result, the percentage of energy served to satisfy the demand (only RES) on the total (RES + storage) has been computed to be equal to 83.4% with respect to 81.2% of the base case. This result further underlines the importance of a production unit that works in base load operation in the energy system.

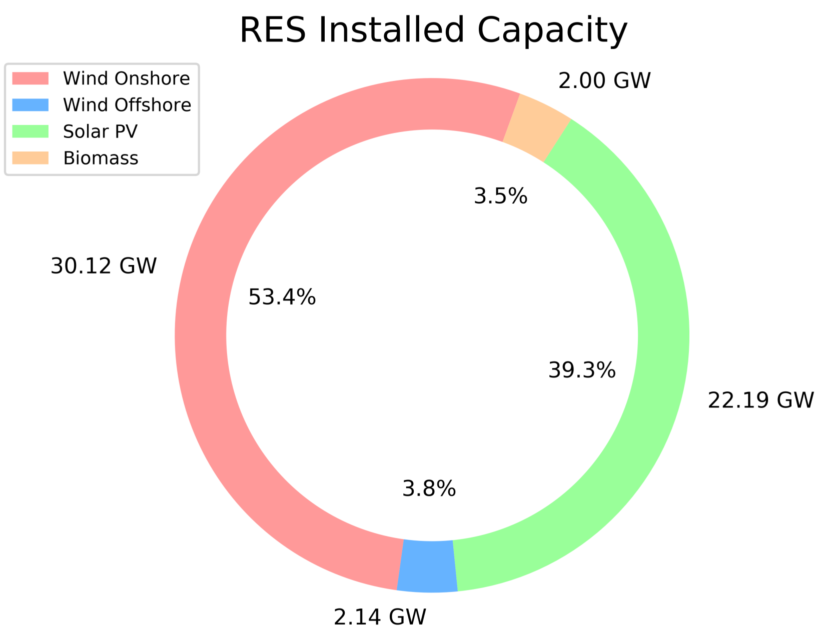


FIG: 6.1. RES installed capacity - biomass scenario case

Regarding the total electricity cost of the system, the electricity costs have been calculated in the same explained in the previous section 5.3.6. It is possible to notice in FIG: 6.2 a slightly decrease of the price from 142.1 to 140 eur/MWh) due to the lower necessity to store energy and therefore a lower need to use expensive technology.
Moreover the costs of the renewable energy sources present a lower price except for methanol due to operation of the energy system.

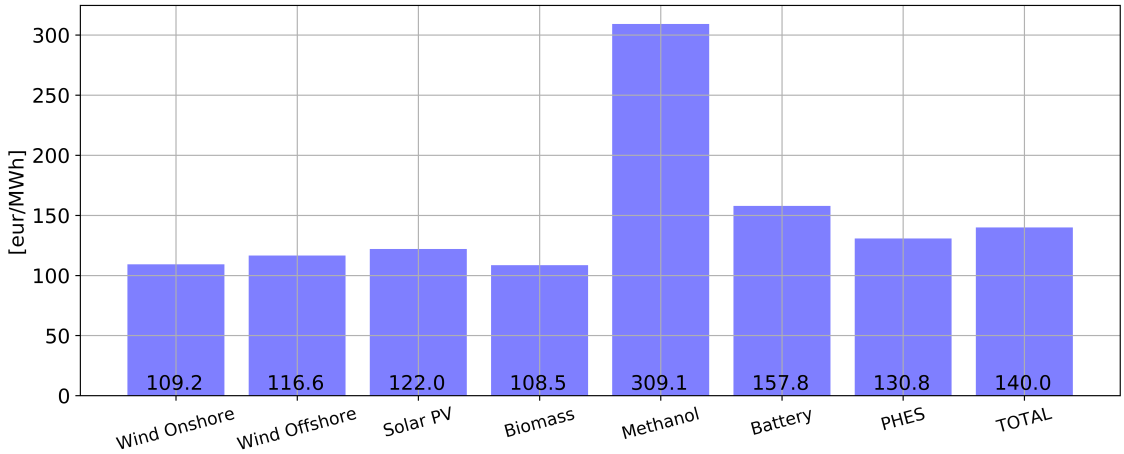


FIG: 6.2. Levelized Cost Of Electricity for each technology - biomass scenario case

6.4 Increase biomass capacity - upper bounds RES potentials

6.4.1 Assumptions

In the previous simulation the influence of a possible upgrade of biomass power capacity has been analysed on the energy system studied. The optimization problem provided a power generation with a large presence of onshore wind energy (30.12 GW) and a small quantity of offshore wind energy (2.14 GW). This power generation mix does not respect the maximum potential available in Belgium and therefore it has been decided to run a simulation with the constraints imposed in the simulation presented in 6.2 keeping the upgrade of biomass power capacity up to 2 GW.
In the previous attempt the simulation reaches the convergence without the respect of the constraints imposed due to an infeasibility of the optimization problem. In this case the larger installed capacity of biomass can bring the system to an optimum solution.
The implementation of the new constraints in the model has already been explained in the section 6.2.

6.4.2 Main results

The presence of the constraints in the section 6.2 did not have no influence on the results due to an infeasibility of the optimization problem. In the actual simulation, the convergence has been reached one more time without respecting the constraints but, in the same way, the results obtained are interesting and discussed.

The power generation mix obtained, thanks to the presence of the constraints and the higher biomass power capacity, is more homogeneous and it looks alike to the reality. As it is possible to see in FIG: 6.4, the installed capacity of onshore wind energy is equal to 10.51 GW and for offshore wind energy is equal to 11.51 GW. Both energy sources don't respect completely the constraints but they are located near to the maximum Belgian energy wind potential. The installed capacity of solar PV is equal to 24.72 GW respecting the constraints imposed of 40 GW. The total RES installed capacity is equal to 48.74 GW (-14% than the previous case in the section 6.3) but with a higher energy storage capacity equal to 20.86 GW (+11%).

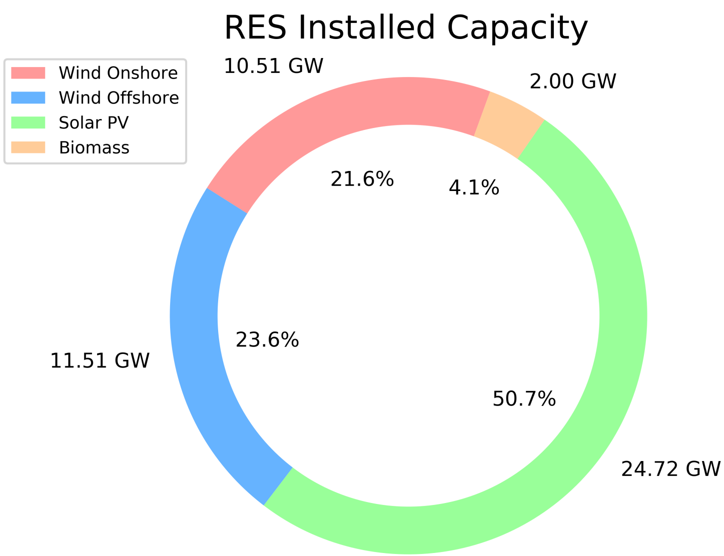


FIG: 6.3. RES installed capacity - biomass scenario case with constraints

Regarding the economical analysis in this case, it is possible to notice in FIG: 6.4 a higher total electricity cost to the base case equal to 149.7 eur/MWh (+5.3%) due to the higher presence of energy storage in the system and lower number of RES capacity. The price of P2Meth technology presents a further rise of the price with respect to the base case (+15.6%) reaching the value of 341.5 eur/MWH.
The solution just presented can be an optimum compromise to respect the maximum potential of RES in Belgium at the expense to have a higher total cost of the system.

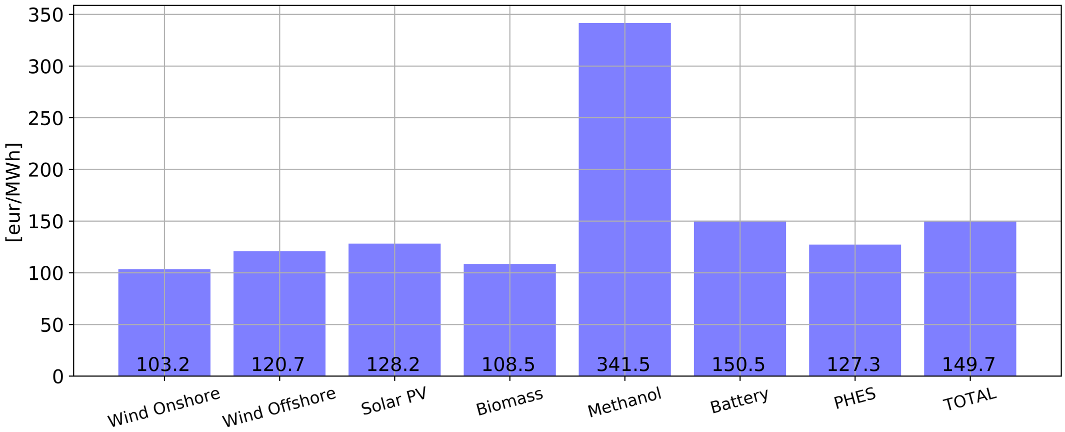


FIG: 6.4. Levelized Cost Of Electricity for each technology - biomass scenario case with constraints

6.5 Conclusions and comparison of the results with the base case

The purpose of the chapter just presented was to analyse the model imposing new constraints and new assumptions in order to create an energy system closer to the reality. It has been discovered from the section 6.2 that it is not possible for Belgium to completely satisfy the demand using renewable energy sources using a base load power plants of 0.75 GW and taking into account all the constraints referred to the maximum potential in Belgium.

In order to create a model similar to the reality and taking into account these constraints, it has been decided to increase the installed capacity of biomass energy up to 2 GW with the purpose of obtaining a higher base load operation and less needs of wind and solar energy.
These new assumptions lead the energy system to reach a new power generation mix in which onshore and offshore wind energy have an installed power capacity higher than the maximum potential assumed by Elia [7] but with values close to it.
It is possible to affirm that this energy mix in this situation can correspond to the reality due to the fact that also the potential estimated by Elia can be affected by uncertainty.

The new energy system leads to a higher total electricity cost of the system mainly due to the higher presence of Power to Methanol installed capacity (+11%) which is the most expensive technology in the energy mixed proposed.
In addition, the assumptions done for the new installed capacity of biomass energy can be justified and reported to the reality when thinking of the presence of other base load plants such as waste to energy units.

Chapter 7

Sensitivity analysis

7.1 Overview

Sensitivity analysis is the study of how an uncertainty in an input parameter influences the output of a certain model. This procedure addresses the questions: "how sure are we of the assumptions?" and "will the results of the study change if we use other assumptions?".
Sensitivity analysis is typically performed with the purpose to check the robustness of the results, searching errors in the model and understanding the relationships between input and output variables.[41]

In the present work it has been necessary to perform a sensibility analysis because of the large quantity of parameters utilized in the model and the high margin of errors due to an inaccurate estimation of the parameters projected by 2050. Several literature sources have been consulted in order to make an average and wide evaluation of the different assumptions. Despite this research, the margin of errors relative to certain parameters can be large and for this reason a deep sensitivity analysis has been performed.

The purpose of this section is to analyse mainly the influence of the assumptions related to Power to Methanol technology on the total electricity cost of the system. With this purpose, the following sensibility analyses have been carried out:

- Influence of P2Meth Round Trip Efficiency
- Influence of P2Meth lifetime
- Influence of P2Meth CAPEX cost
- Influence of CO2 cost
- Influence of the initial guess

7.2 Influence of P2Meth Round Trip Efficiency

7.2.1 Introduction

The first sensibility analysis performed regards the influence of the Round Trip Efficiency of Power to Methanol technology on the results. It has been decided to perform it due to the high uncertainly regarding the evolution of this technology in the future. In the present model it has been considered this energy storage as an only one "black box" that contains different components and for each component an efficiency by 2050 has been estimated .
This estimation could include imprecision due to a non accurate estimation of the maturity of the technology projected in 2050. With the purpose of analysing the influence of the maturity of the technology and therefore the influence of the efficiency on the model, a sensibility study varying the RTE from 20% to 45% with a 5% increment has been performed and discussed in this section.

7.2.2 Results

The sensibility study regarding the influence of the round trip efficiency of Power to Methanol technology is shown in FIG:7.1 in which it is possible to observe a big influence in both costs.
In the base case an efficiency equal to 35% has been assumed obtaining a total electricity cost equal to 142.1 eur/MWh and a P2Meth cost equal to 288.4 eur/MWh. In case of mature technology it has been assumed a maximum RTE equal to 45% with a corresponding results of 131.4 eur/MWh (-6.5%) and 245.3 eur/MWh (-20.4%) respectively for the total electricity cost and the P2Meth cost. In case of low maturity of the system a value of 20% has been assumed for this sensibility study with a corresponding results of 167.2 eur/MWh (+14.1%) and of 404.2 eur/MWh (+30.8%) respectively for the total electricity cost and the P2Meth cost.

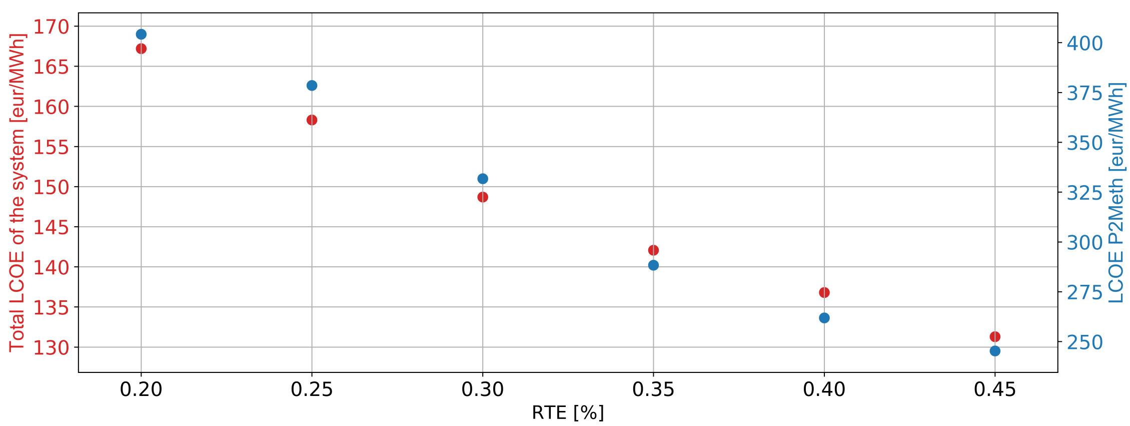


FIG: 7.1. Sensitivity analysis varying the P2Meth Round Trip Efficiency

7.3 Influence of P2Meth Lifetime

7.3.1 Introduction

In this section the influence of the Power to Methanol technology has been analysed with the purpose to obtain how this uncertainty conditions the output in the present model.
Like the round trip efficiency, the valuation of the lifetime by 2050 could present a margin of error due to an inaccurate estimation of the future maturity of the technology. The lifetime assumed in the present work has been estimated equal to 20 years but a sensibility study varying the parameters from 15 to 25 years with a 2.5 years increment has been performed and discussed in this section. It has not been possible to make simulation with values equal to 10 years due to infeasibility of the optimization problem.
The implementation in the code of this sensibility study corresponds to the procedure applied in the previous section 7.2.

7.3.2 Results

The sensibility study regarding the influence of the lifetime of Power to Methanol technology is shown in FIG: 7.2. It is possible to notice a not very marked decrease of the total cost of electricity with a more relevant influence on the cost of P2Meth technology. In the base case, a lifetime equal to 20 years has been assumed with an electricity cost of the system equal to 142.1 eur/MWh with a correspondent P2M costs of 288.4 eur/MWh. In case of high maturity of the technology and of the materials used, supposing a lifetime equal to 25 years, a total electricity cost equal to 139.2 eur/MWh (-2.1%) and a P2Meth cost of 262.8 eur/MWh (-8.9%) have been obtained. In the contrary case, assuming a lifetime equal to 15 years a total electricity cost equal to 148.4 eur/MWh (+ 4.3%) and a P2Meth cost of 327.5 eur/MWh (+13.5%) have been obtained.

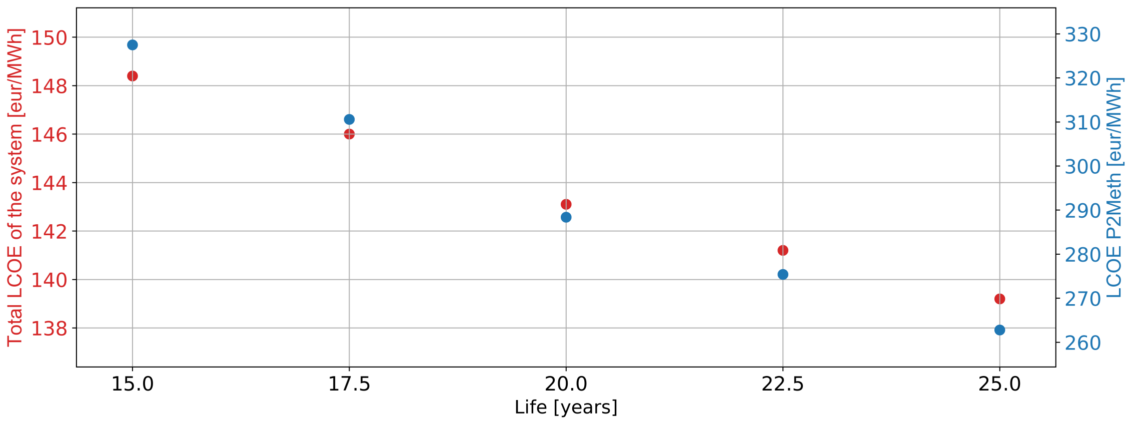


FIG: 7.2. Sensitivity analysis varying the P2Meth lifetime

7.4 Influence of P2Meth CAPEX cost and CO2 cost

7.4.1 Introduction

In this section the influence of the economical assumptions done in the present model on the results has been analysed.
The right prediction in a long term vision of parameters such as the investment cost and the cost of CO2 can present a large margin of error due to three main factors: economy of scale, choice of the technology used and the maturity of it. In the estimation, using different literature sources these factors have been considered. In order to study the influence of these parameters on the total costs of the system, sensibility studies varying from 1500 eur/kW to 3500 eur/kW (500 eur/kW step) and from 20 eur/ton of CO2 to 100 eur/ton of CO2 (20 eur/ton of CO2 step) have been performed and analysed separately in this section.

7.4.2 Results

CAPEX cost

The sensibility study regarding the influence of the CAPEX costs of Power to Methanol technology is shown in FIG: 7.3. It is possible to notice that the investment cost of this technology influence deeply the results obtained in the different simulations. In the base the electricity cost of the system is equal to 142.1 eur/MWh with a correspondent P2M costs of 288.4 eur/MWh. In case of high maturity of the technology and advanced economy of scale, supposing a CAPEX costs equal to 1500 eur/kW, a total electricity cost equal to 125.0 eur/MWh (-12%) and a P2Meth cost of 182.5 eur/MWh (-36%) have been obtained. In the contrary case, assuming an investment cost equal to 3500 eur/kW a total electricity cost equal to 159.3 eur/MWh (+ 10.3%) and a P2Meth cost of 385.4 eur/MWh (+33.5%) have been obtained.

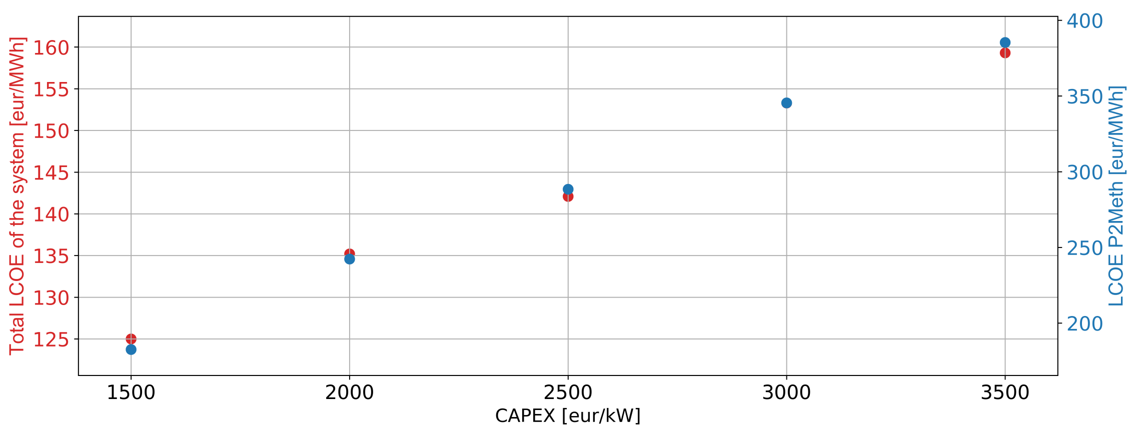


FIG: 7.3. Sensitivity analysis varying the P2Meth CAPEX cost

CO2 cost

The sensibility study regarding the influence of the CO2 costs of Power to Methanol technology is shown in FIG: 7.4. CO2 capture is a process that can be performed in different way and with different sources. The study regarding this parameter refers mainly to the type of capture utilized (from air or flue gas).
In the base case a CO2 cost equal to 40 eur/ton of CO2 a total electricity cost equal to 142.1 eur/MWh and a P2Meth cost equal to 288.4 eur/MWh have been obtained. In this case, the trend is not linear and the optimization problem, depending on the CO2 cost assumed, finds a minimum electricity cost of the system in the range between 142.1 and 144.4 eur/MWh. Also the cost of P2Meth technology is not influenced strongly with a variation between 288.4 and 298.3 eur/MWh.
From these results it is possible to affirm that the maturity of the CO2 capture systems does not influence deeply the results in the presented energy system.

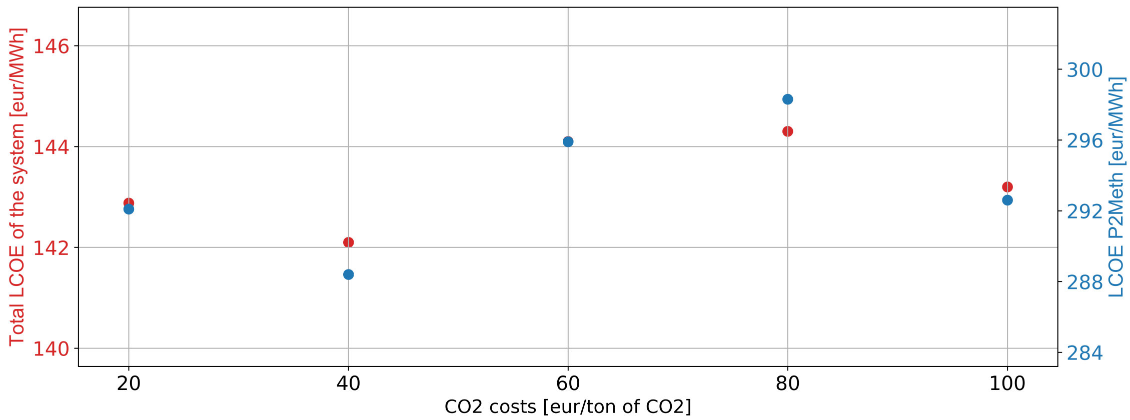


FIG: 7.4. Sensitivity analysis varying the cost of CO2 per ton

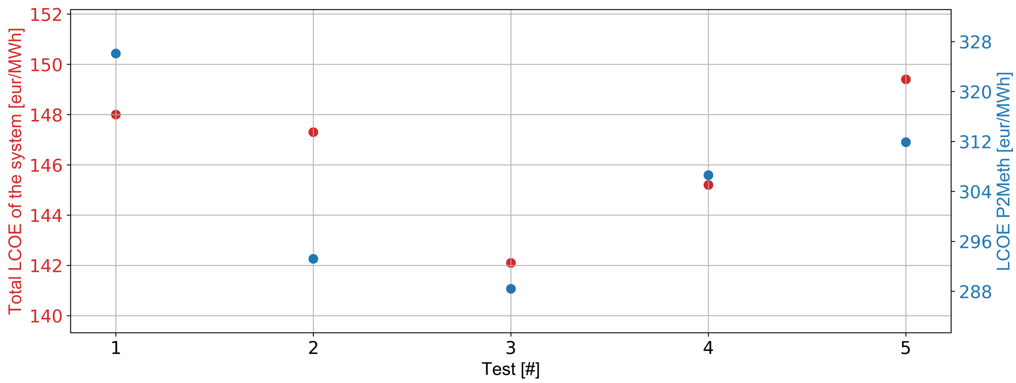
7.5 Influence of the initial guesses

7.5.1 Introduction

During the elaboration of the model and the running of the simulations a certain influence of the initial guesses on the final results has been noticed. Because of this problem, all the simulations have been performed starting from the same initial values in order to not influence the results obtained in the previous chapters.
The influence of the initial guesses leads to a low robustness of the model that it has been discovered also in the previous work in 2015 [6]. For this reason simulations starting from different ranges of initial guesses have been performed with the purpose of studying what is the influence of this set of parameters on the result.

7.5.2 Results

During the simulations done to study the influence on the results several issues have been discovered. For certain set of initial values, the optimization problem is not able to reach the convergence respecting all the constraints. Moreover, as it is possible to notice in FIG: 7.5, the influence on the total electricity cost of the system and the cost of P2Meth technology is not negligible.
These results show the instability and the low robustness of the model probably due to an incorrect way to write the optimization problem. It is possible to affirm that the order of magnitude of the total electricity cost is confirmed and it can varies from 142 to 148 eur/MWh in the base case. In all the simulations done with the purpose to study the system, the following set of initial guesses has been used : [n_onwm=4000,n_offwm=3500,n_pv=2300,n_st_m=55000].



# TEST	#1	#2	#3	#4	#5
n_onwm	2500	3600	4000	3000	2800
n_offwm	2000	1800	3500	2200	3000
n_pv	4000	4000	2300	3500	3400
n_st_m	65000	58000	55000	62000	60000

FIG: 7.5. Sensitivity analysis varying the initial guess

7.6 Summary of the results

In this section, with the purpose to deduce conclusions about the influence of the different parameters assumed for Power to Methanol technology, a briefly summary is presented with the use of two tornado charts.
The first figure (FIG: 7.6) gives an overall view of the total electricity cost obtained varying the parameters presented in the previous sections. It is possible to notice that lifetime, CO_2 cost and the initial guess have a slightly influence on the results with a range between -5% and +2%. A big influence is due to the CAPEX cost and the RTE: the first that refers to an influence of a future economy of scale and the second one regards the technical maturity of the components.
More highlighted is the sensitivity analysis regarding the cost of P2Meth. Because of the direct influence of the parameters on the results, the range is wide respect to the previous analysis. Also in this case, CAPEX cost and RTE mainly influence the results with a range between -40% and +35%. These results give high variability and high margin of errors on the evaluation of the technology projected by 2050.

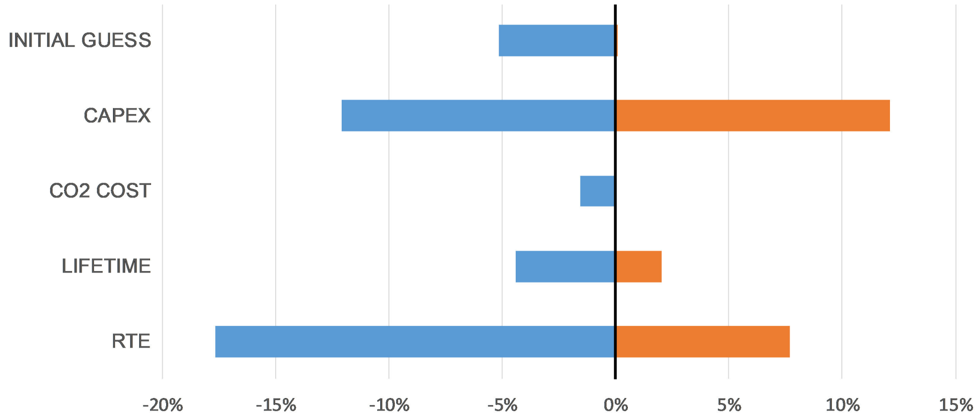


FIG: 7.6. Summary of the sensitivity analysis for the total electricity cost

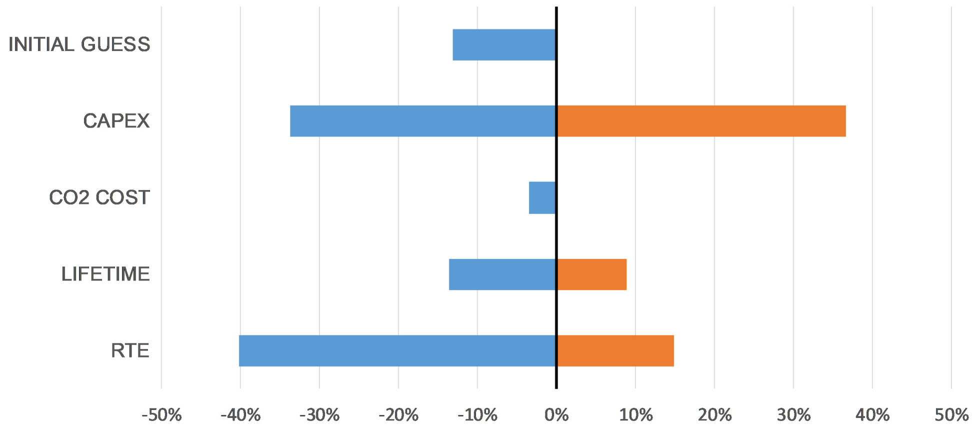


FIG: 7.7. Summary of the sensitivity analysis for the P2Meth cost

Chapter 8

Comparison with a different developed model

8.1 Introduction

Thanks to an interaction and a discussion with researchers of the Montefiore Institute (department of electrical engineering and computer science in the University of Liege), it has been recognized that the optimization problem utilized it is not the best way to deal with this type of problem. Moreover, a work elaborated in that department very similar to the model proposed in the present work but with another method of optimization more appropriate has been discovered. This model has been presented and explained in the following source: [42].

With the purpose of comparing the actual model presented in the actual work and the one given from Montefiore researchers, it has been decided to adapt the second model to the first one. The main difference between the two models is the way to formulate the optimization problem. In our model the problem has been defined thanks to the use of if/else statements; in their model everything has been formulated using mathematical formulation. The model is written on Python using Pyomo, an open-source optimization modelling language with a diverse set of optimization capabilities, and Gurobi, a mathematical programming solver.

Due to lack of time, a complete analysis of the model have not been done. However, the most important results are shown in the following two sections comparing them to the ones obtained in the present work.
In the first part of the chapter, a description of the model is presented giving informations regarding the difference between the structures and the assumptions of the models. The second one is focussed on the results and the comparison of them.

The aim of the next section is to give overall view of the model without going into details. All the explanations are specified in the original article published [42].

8.2 Description of the model

The model developed by the researchers in Montefiore Institute presents a structure completely different from the one developed in the actual work.
The code is written in Python using the Pyomo package and it is divided in several files, each of them with a specific task. The model proposes an energy system composed by solar PV, on/off shore wind, combined heat and power, waste, biomass, batteries, pumped-hydro storage, electrolysis, methanation, hydrogen and methane storage.
The problem is formulated on an optimization horizon of five years with 1 hour period. In the model that I developed, the optimization horizon is around 6 years with 15 minutes period. To match and compare the two problems, the historical data of consumption, on/offshore wind and solar energy have been transformed in 1 hour period with an arithmetic mean as shown in the equation 8.1 below:

$$cf_{1hour}(t) = \frac{cf_{15min}(t) + cf_{15min}(t+1) + cf_{15min}(t+2) + cf_{15min}(t+3)}{4} \qquad (8.1)$$

From the master Python file (*test_script.py*), it is possible to run the simulations joining all the actions performed in each of the files. The results are then available in a specific folder called *Output*. Due to some modifications done on the code, this option can not be performed and it is not presented.

To run the simulation, two key elements are needed: *draft_data_class* and *draft_opti*. With the first file, it is possible to access in a folder called *Data* and upload all the data present in the excel files. Each of these files refers to a different category of parameters (capacities, costs, efficiencies, load) with a user-friendly structure (e.g. FIG: 8.1). In order to compare the two models, all the parameters presents in these files, except for the historical data of wind, solar and consumption, have been modified and adapted. Moreover, the annuity factor computed in this model presents a different formulation. Therefore, the function that regards this parameter has been modified.

	won	woff	pv	H2	ccgt	disp	NK	PH	batt
CAPEX	1100,0000	2280,0000	650,0000	750,0000	850,0000	800,0000	0,0000	1600,0000	2500,0000
FOM	18,7000	52,4400	12,0000	30,0000	21,0000	40,0000	0,0000	0,0000	40,0000
VOM	0,0000	0,0000	0,0000	0,0050	0,0030	0,0000	0,0090	0,0050	0,0000
OPEX	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
FUEL	0,0000	0,0000	0,0000	0,0000	0,0300	0,0330	0,0035	0,0000	0,0049
CO2	0,0000	0,0000	0,0000	0,0000	0,0700	0,0000	0,0000	0,0000	0,0000
ANNUITY	0,07	0,07	0,07	FALSO	FALSO	0,1	FALSO	0,07	0,07

FIG: 8.1. Example of an user friendly Excel file

The second file contains the whole optimization problem. In the first part of the code, the parameters and the variables are initialized in the following way:

```
### Time dependent parameters ###
model.gamma_W_on = Param(model.T, initialize=data.gamma_W_on)
### Time no dependent parameters ###
model.kappa_W_on_max = Param(initialize=data.kappa_W_on_max)
### Operational variables ###
model.P_W_on = Var(model.T, within=NonNegativeReals)
### Sizing variables ###
model.K_W_on = Var(within=NonNegativeReals)
```

In the second part, all the constraints are defined. Instead of using *if/else* statements, the operation of each technology is characterized by a mathematical formulation. As the following example shows, each of these assign a rule and therefore a constraint to the problem.

```
def solar_PV_power_output_definition_rule(model, t):
    return model.P_S[t] == model.gamma_S[t] * model.K_S
model.solar_PV_power_output_definition = Constraint(model.T,
    rule=solar_PV_power_output_definition_rule)
```

With the purpose of comparing the two models, some of these rules have been deleted because they were not congruent with the hypotheses assumed in our model (e.g. upper bound limit).

```
def solar_PV_sizing_upper_bound_rule(model):
    return model.K_S <= model.kappa_S_max - model.kappa_S_0
model.solar_PV_sizing_upper_bound =
    Constraint(rule=solar_PV_sizing_upper_bound_rule)
```

At the end of the code, the objective function is defined but in different way. The aim the research conducted by the Montefiore researchers was to find the minimum cost of the energy system [eur]. In contrary, the objective in the present work was to obtain the minimum electricity cost of the energy system [eur/MWh]. With the purpose of obtaining the same formulation, the ratio between the cost of the energy system and the total energy consumption in the whole period has been performed.

The proposed model appears different in many assumptions and technologies used. For this reason, several modifications have been done like eliminating the parameters useless for the comparison (e.g. H_2, CHP, upper bounds limit) and adjusting the code accordingly. Because of lack of time, the presence of battery energy storage has not been considered in both model.

8.3 Results and comparison

Before starting the simulations, with the purpose of validating the two historical data taken into account in the two models, a check of the average capacity factor and of the average load consumption has been performed.
As it is possible to notice in the TAB: 8.1, the capacity factors of wind and solar energy are very similar. It is possible to affirm that the results can not be affected significantly by them.
Regarding the consumption, in the Pyomo model an average value of 10.3 GW has been computed from the historical data. In the present model, the data from ELIA have an average value of 8.81 GW (-15%). It is possible to observe this slight discrepancy in the FIG: 8.2. The reason can be attributed to an assumption of the growth of the demand with the purpose of studying different scenarios. It could lead the optimization problem to obtain different results. However, the goal of the comparison is to compare orders of magnitudes of the results, in order to validate them. Light differences between the models are expected.

	Parameter	Present model	Pyomo model
AVERAGE	*CF onshore wind [-]*	0,2313	0,2407
	CF offshore wind [-]	0,3842	0,3844
	CF solar PV [-]	0,1116	0,1106
	Load [GW]	8,81	10,3

Table 8.1. Comparison between the two models

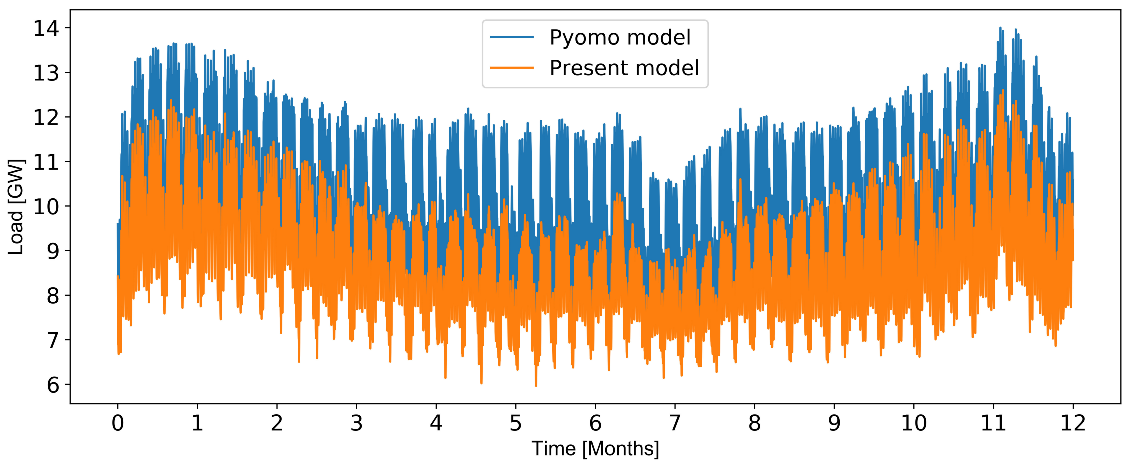


FIG: 8.2. Comparison between the consumption in the two models

One of the results presented in this section regards the behaviour of Power to Methanol energy storage during the whole year. In order to show it, a graph comprising the two trends has been performed and shown in the FIG: 8.3.
The trend observed is very similar in the operation mode, with a present value evolution more pronounced in the first part with respect to the other curve. In the last part of the year, the curves present almost the same behaviour.
The maximum energy level reached in the two curves is different with values equal to 5.24 TWh and 3.59 TWh respectively for the present and Pyomo model. The reason of the discordance just presented has not been identified.

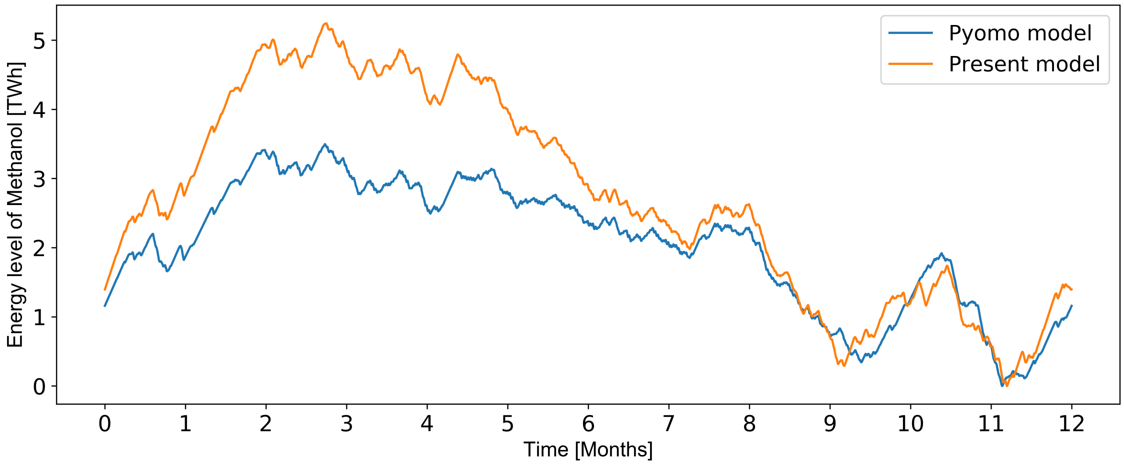


FIG: 8.3. Comparison between the methanol energy level in the two models

Important parameters to compare are the installed power capacity of the different technologies present in the energy system. Starting from Power to Methanol technology, values equal to 13.73 GW and 10.20 GW respectively for the present and Pyomo model have been obtained. The difference is not significant with an order of magnitude congruent.
Because of the different evolution of the methanol energy storage and its installed capacity, it is probable that also the installed capacities obtained are different. For this reason, the purpose of this analysis is to confirm the order of magnitude of the different results obtained.
The installed power capacities of renewable energy sources are shown in FIG: 8.4. Values of 49.1 GW and 75.02 GW have been obtained as the total respectively for the present and Pyomo model. Also in this case, the order of magnitude is similar and the difference of the two values comes from the fact that the P2Meth installed power capacity in the Pyomo model is lower and thus the energy system needs more RES to satisfy completely the demand. Moreover, the consumption in the Pyomo model is higher and can be influence in this way the result.

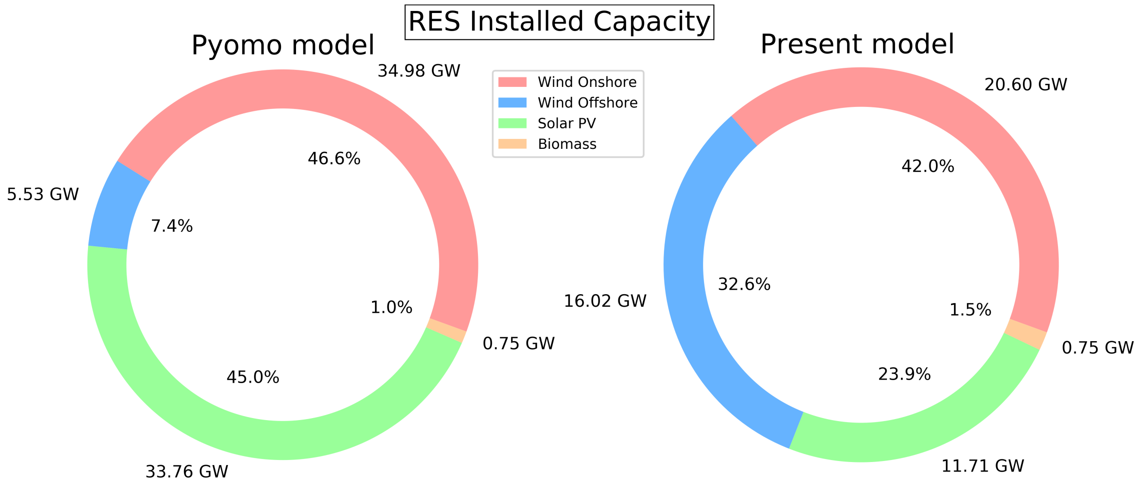


FIG: 8.4. Comparison between the installed RES power capacity in the two models

The last and most important result compared is the total electricity cost of the system. Results of 150.9 eur/MWh and 124.67 eur/MWh have been obtained respectively for the present and Pyomo model. In this case, the difference is not negligible and the following suppositions could explain it:

- The smaller presence of P2Meth installed power capacity leads to a lower total electricity cost of the system (expensive energy storage technology)
- Better use of the energy storage technologies due to the absence of operational constriction. The pyomo model does not impose the use of PHES as first energy storage but chooses the best combination in each instant.
- The discrepancy of the historical data (especially for the consumption)
- Difference between the two models not noticed due to lack of time

In conclusion, it is possible to affirm the validity of the present model developed. The order of magnitude of all the results obtained in both model are congruent except for the total electricity cost of the system that can be affected by several factors. In a future work, an analysis more detailed of the Pyomo model could be done with the purpose to obtain an optimization problem more robust and fast.

Chapter 9

Conclusion

This study presents an implementation of an existing energy model developed in 2015 with the purpose to study the influence of Power to Methanol, a long-term energy storage technology, in a zone powered with 100% renewables. The model, written in Python, included only wind energy source and Power to Methanol technology such as energy storage. The aim of the thesis is to create a model more similar to the reality, with a wide energy mix and short-term energy storage in order to analyse the electricity cost of the system projected to 2050. The technologies presents in the model are: onshore wind, offshore wind, solar PV, biomass, hydro pumped-storage, battery and power to methanol.

The first part of the work has been the updating of all the technical and economical parameters used in the previous model and the research of the new ones regarding the implemented technologies and projected by 2050. In the previous model, an under estimation of the technical and economical parameters regarding power to methanol technologies has been done; a literature research had been done finding more realistic and precise values estimated to be in 2050.

After the implementation of the model writing the Python code, several simulations have been performed. It has been decided to define a "base case" model and then to analyse it deeply. The power generation mix obtained presents a high share of onshore wind energy (37.85 GW / 58.8%) and solar PV energy (22.84 GW / 35.5%); the presence of offshore wind energy is not large (2.89 GW / 4.5%) due to the higher costs. The installed capacity of biomass has been set at 0.75 GW (1.2% of the total installed capacity).
Moreover, to satisfy in every moment the demand and store the surplus of energy, the energy system needs 19 GW of storage installed capacity (of which 12.83 GW / 53.4% of P2Meth). The obtained storage energy served shows the importance of the energy capacity of P2Meth due to the small installed capacity set for battery and PHES (resp. 2.5 GWh and 7.7 GWh).

Interesting results have been provided analysing the energy level of the three energy storage technology. The intra-day/short-term operation of battery and PHES is clearly different to the seasonal/long-term operation of Power to Methanol storage. The energy capacity of P2Meth has around 8 TWh with a correspondent methanol storage value of 1,6 million of m^3.
Moreover the number of ON/OFF cycle for battery and P2Meth has been calculated obtaining an operation during the period congruent with the maximum life cycle of the technologies.

The resulting total electricity cost is equal to 142.1 eur/MWh, higher than the one obtained in the previous model especially because of the different economical assumptions. The cost for each component has been computed achieving a minimum cost of 108.5 eur/MWh for biomass and a maximum cost equal to 288.4 eur/MWh for power to methanol technology. PHES has proved to be the cheapest energy storage technology due to the high maturity, efficiency and lifetime.

The installed capacity of onshore wind energy exceeds the maximum potential in Belgium and therefore the power generation mix it is not feasible in the control area chosen. The implementation of constraints in the model and the increasing of the biomass installed capacity up to 2 GW have allowed to obtain a power generation mix composed by 11.51 GW of offshore wind, 10.51 GW of onshore wind, 24.72 GW of solar PV and 2 GW of biomass. This result leads to a realistic model in which wind energy exceeds not too much the Belgian wind potential. With this configuration a total electricity cost equal to 149.1 eur/MWh has been obtained.

Due to the high margin of error in the estimation of the technical and economical parameters projected by 2050, a sensibility analysis varying the parameters referred to Power to Methanol technology has been performed. Moreover, during the running of the simulation a certain influence of the initial guess on the results has been noticed. For this reason, a sensibility study assuming different sets of initial guess has been done obtaining a limited variability of the total electricity cost of the system in the range 142 - 148 eur/MWh.

During the month of May, a discussion with researchers of the Montefiore Institute has exposed the wrong choice of the optimization problem for this type of work and the related robustness. A similar model developed by them with a different optimization method (using Pyomo and Gurobi) was given to me with the purpose to validate the results obtained in the present work. Several modifications have been done in order to match the assumptions done and then compare the two models. Interesting results with similar order of magnitude have been obtained despite the total electricity cost presents a discrepancy. With this procedure it was possible to affirm the consistency of the results shown in the actual work.
The Pyomo model appeared more robust and more fast than the actual one. With an optimization horizon of 1 year, the present model takes around 3 minutes to reach

the convergence. The other takes around 20 seconds. In case of a wider horizon (e.g. 5 years), in the actual work the time to compute the optimization problem was very long, around 1 hours and 15 minutes (because of the long chain of *if/else* statements in the *for* loop). The same type of test was not done with the other model due to lack of time but probably the convergence could be reached faster.

The purpose of replacing completely fossil fuels with a consequent reduction of greenhouse gas emissions requires a transformation of the whole energy sector. The study of the long-term energy storage is very important to obtain flexibility and safety in the energy system. As result of this work, methanol can be a promising candidate. However, research must be done, as well as several improvements. Although the cost of the technology is very high, the ease to store and transport it could make it a desirable choice.
Currently, the application is not feasible due to the lower round trip efficiency and the high costs. There are several projects around the world with have the purpose of obtaining large-scale plants and reducing the costs. Beside the necessity of having energy storage, large investments must be taken in the installation of RES and in the reinforcement of the power grid.

In a future work it can be interesting to perform an accurate analysis of the Pyomo model, transposing carefully all the assumptions on it with an implementation of the new constraints regarding technical operations of the technologies (e.g. ramp-up and ramp-down).
In addition, in the present model a centralised state has been considered. This energy system differs from the reality in several aspects. A future work can be the consideration of an energy system more similar to the reality adding for example interconnection and the electricity costs paid by the storage units.

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Appendix A

Code implementation

A.1 Import historical data

In order to obtain a energy system similar to the reality, the first necessary step during the creation of the python model was to import the historical data. They have been saved in an Excel file called *"historical_data.xls"* and divided by categories in different Excel sheets called *"OnShoreWind"*, *"OffShoreWind"*, *"Solar"* and *"Eliaload18"*. For each sheet, the data are ordered by columns (in case of the historical data production) and by rows (in case of historical data consumption).
The following procedure has been done with the purpose of importing them on Python:

1. Identification of the excel file

```
#Opening file 'Datos' where is all the information until year 2018
datos=pd.ExcelFile('historical_data.xls')
```

   From this point, the procedure to upload the data is the same for all the production units and for the consumption. The following procedure is referred to the historical data of onshore wind.

2. Identification of the excel sheet

```
#All the data information from the first sheet "OnShoreWind"
OnShoreWind=datos.parse('OnShoreWind')
```

3. Creation of the matrix

```
#Making a matrix with all the data
matriz_OnShoreWind=OnShoreWind.values.tolist()

#Generating an empty matrix to fullfit it with the data we want to.
matriz_onwindgen=np.empty((56732,4))
matriz_onwindcap=np.empty((56732,4))
```

4. Import the data needed

```
#Fullfitting matrixes with the data of generation and CAP. Data that
   we need.
for i in range (0,56732):
   for j in range (0,4):
      z=2+j*6
      matriz_onwindgen[i][j]=matriz_OnShoreWind[i][z] #Real time
         measure

      k=3+j*6
      matriz_onwindcap[i][j]=matriz_OnShoreWind[i][k] #Monitored
         capacity
```

5. Creation of the vectors

```
#Vector generation
row_onwindgen=np.zeros((56732*4),np.float64);
#Vector installed capacity
row_onwindcap=np.zeros((u),np.float64);
```

6. Fullfitting vectors with the data of the matrix

```
#Power generation
rw=0;
for j in range (0,4):
   for i in range (0,56732):
         row_onwindgen[rw]=np.absolute(matriz_onwindgen[i][j]);
         rw=rw+1;
row_onwindgen = row_onwindgen[~np.isnan(row_onwindgen)]

#Installed capacity
row_onwindcap=np.zeros((u),np.float64);
rz=0;
for j in range (0,4):
   for i in range (0,56732):
         row_onwindcap[rz]=np.absolute(matriz_onwindcap[i][j]);
         rz=rz+1;
```

7. Creation generation and installed capacity vectors utilised in the model

```
onwind_gen = np.absolute(row_onwindgen)
onwind_cap = np.absolute(row_onwindcap)
```

8. Calculation of the capacity factor and capacity demand

```
#Capacity factor cf
cfon = np.zeros(length, np.float64);
for i in range (0,length):
    cfon[i] = onwind_gen[i]/onwind_cap[i]
#Capacity demand cd
cdon = np.zeros(length, np.float64);
for i in range (0,length):
    cdon[i] = load[i]/cfon[i]
```

With the purpose of having interesting values regarding the consumption and production of energy from renewable energies, the following parameters have been calculated:

```
cfon_av = np.mean(cfon)
cfoff_av = np.mean(cfoff)
cfpv_av = np.mean (cfpv)
load_av = np.mean(load)
load_min = np.min(load)
load_max = np.max(load)
```

A.2 Import of technical and economical parameters

After importing and defining all the data referred to the different sources, it has been necessary to define all the parameters useful to describe the technologies. In the following example is shown how Pumped Hydro Energy Storage parameters have been defined:

```
########################### Hydro parameters ###########################
p_in_max_h = 1.8e6; #kW, power capacity in pumping operation
p_out_max_h = 1.8e6; #kW, power capacity in generation operation
RTE_h = 0.75; #Round trip efficiency: pumping + generation operation
st_max_hu = 7.7e6; #kWh of storage unit, upper reservoir;
st_max_hb = 7.7e6; #kWh of storage unit, lower reservoir;
capex_st_h = 1600*p_in_max_h; #eur/kW, capital costs
u_var = 5/1000; #eur/kWh, variable costs
fixed_opex_st_h = 0 #eur/kW per year, Fixed O&M costs
life_st_h = 60.0; #years, Lifetime
annuity_cst_st_h = r/(1.0-(1.0+r)**(-life_st_h)); # %, Annuity factor
```

A.3 Optimization function

The model proposed in the present work has the objective to minimize the cost function in presence of constraints and variables. The process in consideration, in which the objective function corresponds to the cost function, is called ”constrained optimization”. The problem has the task to find an optimum combination of four variables in order to satisfy the constraints imposed and minimize the function cost.

Because of the structure of the problem, Cobyla method has been utilized as optimization process. Within the definition of a function called ”*opticost*” the entire problem (variables, iteration, constraints, objective function) has been solved.
The opticost function depends of four variable:

- Number of onshore windmills [*n_onwm*]
- Number of offshore windmills [*n_offwm*]
- Number of solar parks [*n_pv*]
- Number of units of methanol [*n_st_m*]

In the Python code, this implementation has been done in the following way:

```
def opticost(x):
    n_onwm = np.zeros(index_max, np.float64);
    n_offwm = np.zeros(index_max, np.float64);
    n_pv = np.zeros(index_max, np.float64);
    n_st_m = np.zeros(index_max, np.float64);

    n_onwm[index] = x[0]
    n_offwm[index] = x[1]
    n_pv[index] = x[2]
    n_st_m[index] = x[3]
```

In case of not time-dependent variable, the value *index_max* is equal to 1. Several parameters have been defined in the model with the purpose of representing in a complete way the model; the way to define them is different if they are time-dependent or not time-dependent. The example below shows the implementation in the Python code.

```
# Time dependent variable (length = number of period takes into
    consideration)
spread = np.zeros(length, np.float64);
#Not time dependent
cost_st_m = np.zeros(index_max, np.float64);
```

After the definition of the variables inside of the optimcost(x) function, a *for* loop is used to iterate over the period *length* an algorithm explained in the next section of the work. Consequently, the objective function has been defined at the end of this loop. The implementation of the objective function is shown below.

```
# Cost function (eur/kWh)
cost_tot[index] =
(((capex_st_b*annuity_cst_st_b+fixed_om_st_b)+
(capex_onwm*annuity_cst_onwm+fixed_om_onwm)*n_onwm[index] +
(capex_offwm*annuity_cst_offwm+fixed_om_offwm)*n_offwm[index] +
(capex_pv*annuity_cst_pv+fixed_om_pv)*n_pv[index] +
(capex_st_m*annuity_cst_st_m + fixed_om_st_m)*n_st_m[index] +
(capex_bio*annuity_cst_bio + fom_bio) +
(capex_st_h*annuity_cst_st_h + fixed_opex_st_h))*(float(a)/365.0)+
cost_co2*serv_total_st_m[index] +
fuel_bio/eff_bio*serv_total_bio[index] +
u_var*serv_total_st_h[index]) /
(serv_total_ren[index] + serv_total_st_m[index] +
serv_total_st_h[index] + serv_total_st_b[index])
```

With the purpose to export some results at the end of the simulation, several output have been defined in this way:

```
outlet[0] = n_onwm[index];
outlet[18] = cost_tot[index];
outlet[26] = st_level_m[index];
outlet[27] = LOLH[index];
```

A furthermore definition has been written in order to assign the cost function to the optimization problem.

```
def optim_cost(x):
    optim = opticost(x)
    return optim[18] #optim[18] corresponds to result of the cost function
```

Moreover, it was necessary to define some constraints that the optimization problem must satisfy. First of all, for physical reason the number of production units has been imposed to be higher than zero.
A parameter called LOLH (loss of load hours) has been defined to count the sum of the time periods in which the demand is not served. A constraint has been applied to this parameter to obtain at the end of the optimization a value equal to zero.
The other constraint of the system requires the amount of methanol stored at the end of the period to be equal to the amount at the beginning. In this ways it is ensured that the installed capacities match exactly the system requirements with no net consumption or production of methanol.
The implementation of the constraints in the model are shown below.

```
# Constraint functions: must all be >=0
c1 = lambda x: np.asarray([opticost(x)[27]-0.1]) #LOLH = 0
c2 = lambda x: np.asarray([(opticost(x)[26])-level_m0]) #level_m[0] ==
```

```
    level_m[length]
c3 = lambda x: np.asarray([opticost(x)[0]]) #number of onshore windmill
    positive
c4 = lambda x: np.asarray([opticost(x)[1]]) #number of offshore windmill
    positive
c5 = lambda x: np.asarray([opticost(x)[2]]) #number of solar park positive
c6 = lambda x: np.asarray([opticost(x)[3]]) #number of unit of methanol
    positive
constraints = np.asarray([c1, c2, c3, c4, c5, c6])
```

The optimization routines improve iteratively the initial guess in an attempt to converge to an optimal solution. This process needs an assumption of a set of initial guess; afterwards they go to converge to an optimum solution. These values have been implemented inside a vector called *VI* and then used in the call of the optimization function.
The following formulation has been defined with the purpose of joining all the constraints and the functions in only one.

```
VI = [4000, 3500, 2300, 55000] #VI : initial values
x = optimize.fmin_cobyla(optim_cost, VI, cons=constraints, rhobeg=1000,
    rhoend=0.5, maxfun=200)
#optim_cost: objective function
#cons : vector of the constraints
#rhobeg : reasonable initial changes to the variables
#rhoend : final accuracy in the optimization
#maxfun : maximum number of function evaluations
```

A.4 Iteration of the parameters - for loop

The most elaborated part of the code is characterized by a long *for* loop with the presence of several *if/else* statements. It represents the central part of the code and it is used for iterating all the variables inside of this cycle over the time period taken into consideration.
After the definition of the iteration process, a time dependent variable called spread has been defined. This parameters is equal to the difference between the energy production from all the renewable sources in a certain instant and the correspondent energy consumption. This parameter can assume positive values in case that the production from renewable energies is larger than the demand (surplus energy needs to be stored) or negative values if the renewable sources can not satisfy completely the demand (the storage units will supply the lack of energy).

```
for i in range (0,length):
    spread[i] = p_bio + n_onwm[index]*p_onwm*cfon[i] +
        n_offwm[index]*p_offwm*cfoff[i] + n_pv[index]*p_pv*cfpv[i] -
        load[i]
```

```
if (spread[i]>0):
    ...
else:
    ...
```

In order to understand better the meaning of the variable spread, the trend of RES production and demand have been represented in FIG:A.2.
The green area shown in the figure represents the surplus of energy generated from renewable energy sources; in contrast, the red area represents the lack of energy production and therefore the needs of storage supply.

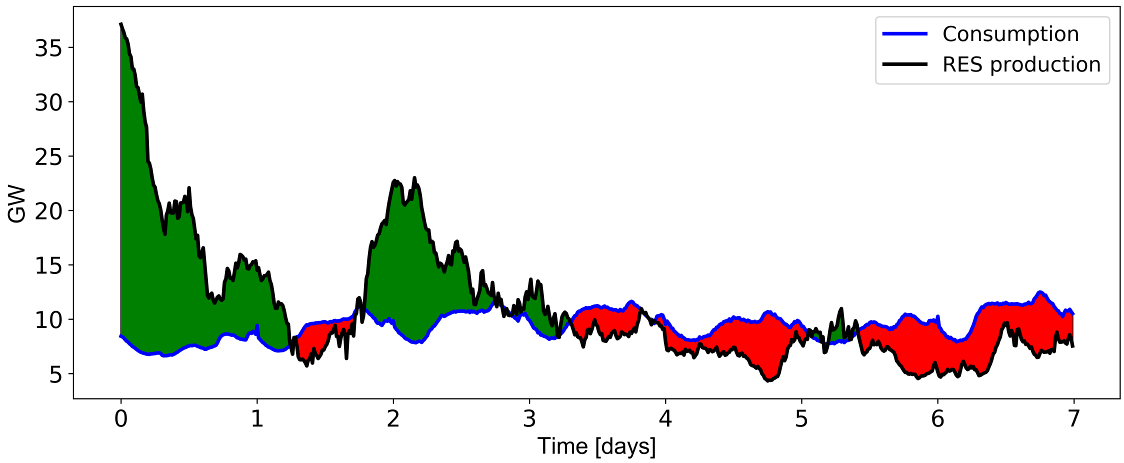

FIG: A.1. Difference between renewable production and demand (1st January - 7th January 2013)

In case of positive spread, the quantity of the renewable energy production in a certain instant i is different from the quantity of served energy directly in the same moment; as a matter of fact, part of the energy generated is not served for the demand but it is stored. With the purpose of defining the energy directly served to the consumption, a weighted coefficient that take into account the ratio between the energy generated from solar energy and the total energy generated has been defined. Biomass energy has been defined as base-load production unit and for this it has not been included in the total energy generated.
The following formulations show how the energy served at a certain instant i has been implemented in the model in case of surplus of energy:

```
#Calculation of the weighted percentages
perc_on=(n_onwm[index]*p_onwm*cfon[i])/((n_onwm[index]*p_onwm*cfon[i])+
(n_offwm[index]*p_offwm*cfoff[i])+(n_pv[index]*p_pv*cfpv[i]))

perc_off=(n_offwm[index]*p_offwm*cfoff[i])/((n_onwm[index]*p_onwm*cfon[i])+
(n_offwm[index]*p_offwm*cfoff[i])+(n_pv[index]*p_pv*cfpv[i]))
```

```
perc_pv=(n_pv[index]*p_pv*cfpv[i])/((n_onwm[index]*p_onwm*cfon[i])+
(n_offwm[index]*p_offwm*cfoff[i])+(n_pv[index]*p_pv*cfpv[i]))

#Calculation of the directly served energy
#The coefficient 0.25 is used to convert kW to kWh(15 minutes step period)
serv_onwm[i] = (perc_on * (load[i]-p_bio))*0.25
serv_offwm[i] = (perc_off * (load[i]-p_bio))*0.25
serv_pv[i] = (perc_pv * (load[i]-p_bio))*0.25
```

In case of negative spread, the quantity of energy produced in a certain instant from a renewable energy technology is equal to the quantity of energy directly served in that instant in order to satisfy the demand. In this case the implementation in the model does not need the computation of the weighted percentages such as the previous case. The following formulations show how the energy served at a certain instant i has been implemented in the model in case of lack of energy:

```
serv_onwm[i] = (n_onwm[index]*p_onwm*cfon[i])*0.25
serv_offwm[i] = (n_offwm[index]*p_offwm*cfoff[i])*0.25
serv_pv[i] = (n_pv[index]*p_pv*cfpv[i])*0.25
```

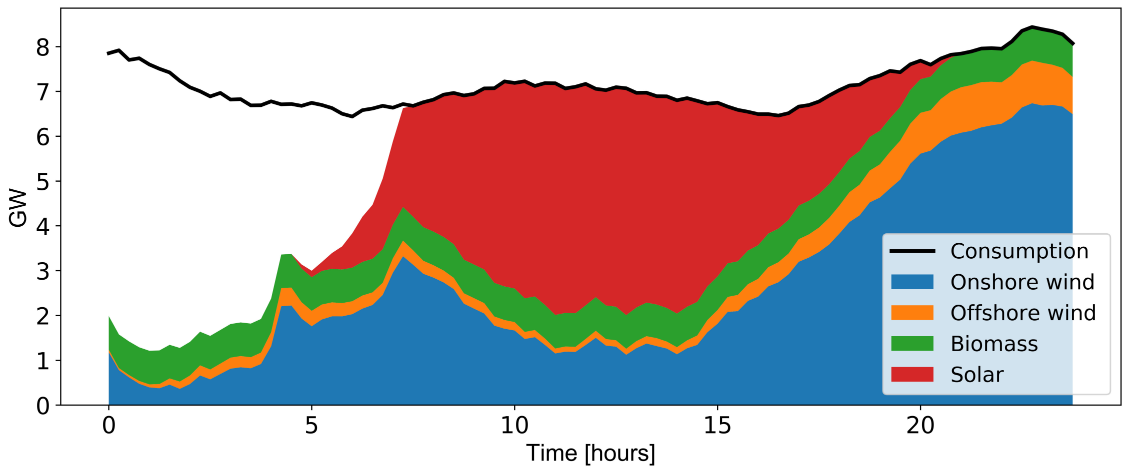

FIG: A.2. Distinction between energy served by different RES - 30th June 2013)

After that all the parameters have been defined, several *if/else* statements lead the way to store and to release energy. The presence of three energy storage technologies in the model makes it necessary to define the order of technologies in which the energy must be stored/released. PHES has been assumed as first technology, battery energy storage as second and Power to Methanol is the last one. Each technology presents constraints due to maximum power input/output and energy stored capacity. For this reason, if/else statements have been utilized in order to take into account also these limits. A summary of the implementation in the code is shown below:

```
for i in range (0,length):
    if (spread[i]>0):
        ...
        if (p_in_max_h < spread[i]):
            res_h = p_in_max_h #part of energy that can be stored in PHES
            res_b = spread[i] - res_h #part of energy that can be stored
                in battery
            if ((st_max_hu - level_hu[i])*4/RTE_h < res_h):
                st_in_h = st_max_hu - level_hu[i]
                res_b = res_b + (res_h - st_in_h)
            ...
        ...
    else:
        ...
        if (p_out_max_h < spread[i]):
            ...
        ...
```

At the end of each iteration, all the cumulative and time-dependent parameters are updated using the values computed in that cycle. An example of this implementation is shown below:

```
# Updating of the storage levels
level_hb[i+1] = level_hb[i] + serv_st_h[i]
level_m[i+1] = level_m[i] - serv_st_m[i]
level_b[i+1] = level_b[i] - serv_st_b[i]
# Updating of the cumulative parameters
serv_total_onwm[index] += serv_onwm[i]
serv_total_st_m[index] += serv_st_m[i]
```

Some results obtained from the simulation have been exported in a .txt file in order to be analyzed and saved. The implementation in the Python code of this procedure is shown below:

```
tablename = str('OOAAA') #format of the output
np.savetxt('output_new.txt'.format(tablename), opticost(x), delimiter='.')
```

As said previously, *opticost(x)* corresponds to the optimization function and it contains all the variables defined inside.

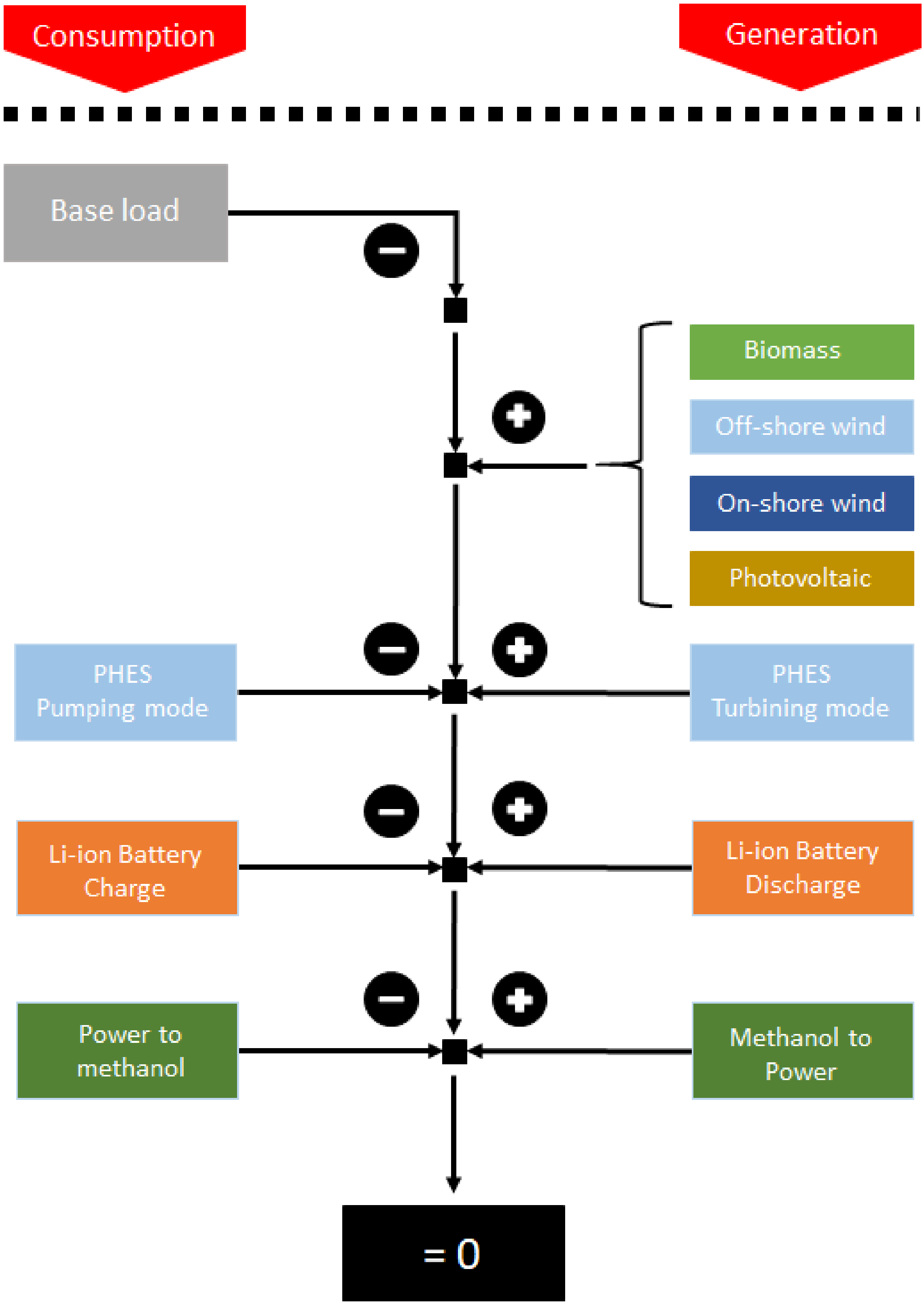

FIG: A.3. Algorithm used in the for-loop

Appendix B

Python code import data

```
import sys
import math
import os
import pandas as pd
import numpy as np
from numpy.random import random
from scipy import optimize
import matplotlib.pyplot as plt
import xlrd
import xlwt
import csv
#Opening file 'Datos' where is all the information until year 2018
datos=pd.ExcelFile('historical_data.xls')
######################### ONSHORE ########################
#All the data information from the first sheet "OnShoreWind"
OnShoreWind=datos.parse('OnShoreWind')
#Making a matrix with all the data
matriz_OnShoreWind=OnShoreWind.values.tolist()
#Generating an empty matriz to fullfit it with the data we want to.
matriz_onwindgen=np.empty((56732,4))
matriz_onwindcap=np.empty((56732,4))
#Fullfitting matrixes with the data of generation and CAP. Data that we need.
for i in range (0,56732):
    for j in range (0,4):
        z=2+j*6
        matriz_onwindgen[i][j]=matriz_OnShoreWind[i][z] #Real time measure
        k=3+j*6
        matriz_onwindcap[i][j]=matriz_OnShoreWind[i][k] #Monitored capacity
######################## OFFSHORE ##############################
#All forecasts information from first sheet "offshore data"
OffShoreWind=datos.parse('OffShoreWind')
#Making a matrix with all the data
matriz_OffShoreWind=OffShoreWind.values.tolist()
#Generating an empty matriz to fullfit it with the data we want to.
matriz_offwindgen=np.empty((56732,4))
matriz_offwindcap=np.empty((56732,4))
#Fullfitting matrixes with the data of generation and CAP. Data that we need.
for i in range (0,56732):
    for j in range (0,4):
        z=2+j*6
        matriz_offwindgen[i][j]=matriz_OffShoreWind[i][z] #Real time measure
        k=3+j*6
```

```
        matriz_offwindcap[i][j]=matriz_OffShoreWind[i][k] #Monitored capacity
######################## SOLAR ##############################
#All forecasts information from first sheet "offshore data"
Solar=datos.parse('Solar')
#Making a matrix with all the data
matriz_Solar=Solar.values.tolist()
#Generating an empty matriz to fullfit it with the data we want to.
matriz_Solargen=np.empty((56732,4))
matriz_Solarcap=np.empty((56732,4))
#Fullfitting matrixes with the data of generation and CAP. Data that we need.
for i in range (0,56732):
    for j in range (0,4):
        z=2+j*6
        matriz_Solargen[i][j]=matriz_Solar[i][z] #Real time measure
        k=4+j*6
        matriz_Solarcap[i][j]=matriz_Solar[i][k] #Monitored capacity
################## ELIA LOAD ###############################
#All EliaLoad information from second sheet
Eliaload18=datos.parse('Eliaload18')
#Making a matrix with all the data
matriz_Eliaload18=Eliaload18.values.tolist()
#Taking just the data (not the day and time)
matriz_Eliaload18data=np.empty((2069,96))
for i in range (0,2069):
    for j in range (0,96):
        matriz_Eliaload18data[i][j]=matriz_Eliaload18[i+1][j+3];
###################### ONSHORE VECTOR ##################
u=56732*4;
row_onwindgen=np.zeros((u),np.float64);
rw=0;
for j in range (0,4):
    for i in range (0,56732):
            row_onwindgen[rw]=np.absolute(matriz_onwindgen[i][j]);
            rw=rw+1;
row_onwindgen = row_onwindgen[~np.isnan(row_onwindgen)]
row_onwindcap=np.zeros((u),np.float64);
rz=0;
for j in range (0,4):
    for i in range (0,56732):
            row_onwindcap[rz]=np.absolute(matriz_onwindcap[i][j]);
            rz=rz+1;
row_onwindcap = row_onwindcap[~np.isnan(row_onwindcap)]
################## OFFSHORE VECTOR ########################
row_offwindgen=np.zeros((u),np.float64);
rw=0;
for j in range (0,4):
    for i in range (0,56732):
            row_offwindgen[rw]=np.absolute(matriz_offwindgen[i][j]);
            rw=rw+1;
row_offwindgen = row_offwindgen[~np.isnan(row_offwindgen)]
row_offwindcap=np.zeros((u),np.float64);
rz=0;
for j in range (0,4):
    for i in range (0,56732):
            row_offwindcap[rz]=np.absolute(matriz_offwindcap[i][j]);
            rz=rz+1;
row_offwindcap = row_offwindcap[~np.isnan(row_offwindcap)]
################ TOTAL WIND VECTOR ######################
row_totwindgen=np.zeros((u),np.float64);
rw=0;
for j in range (0,4):
    for i in range (0,56732):
```

```
            row_totwindgen[rw]=np.absolute(matriz_offwindgen[i][j] + matriz_onwindgen[i][j]);
            rw=rw+1;
row_totwindgen = row_totwindgen[~np.isnan(row_totwindgen)]
row_totwindcap=np.zeros((u),np.float64);
rz=0;
for j in range (0,4):
    for i in range (0,56732):
            row_totwindcap[rz]=np.absolute(matriz_offwindcap[i][j] + matriz_onwindcap[i][j]);
            rz=rz+1;
row_totwindcap = row_totwindcap[~np.isnan(row_totwindcap)]
################### SOLAR VECTOR #########################
row_solargen=np.zeros((u),np.float64);
rw=0;
for j in range (0,4):
    for i in range (0,56732):
            row_solargen[rw]=np.absolute(matriz_Solargen[i][j]);
            rw=rw+1;
row_solargen = row_solargen[~np.isnan(row_solargen)]
row_solarcap=np.zeros((u),np.float64);
rz=0;
for j in range (0,4):
    for i in range (0,56732):
            row_solarcap[rz]=np.absolute(matriz_Solarcap[i][j]);
            rz=rz+1;
row_solarcap = row_solarcap[~np.isnan(row_solarcap)]
################ DATA LOAD VECTOR ########################
u=2069*96;
row_Eliaload18data=np.zeros((u),np.float64);
rx=0;
for j in range (0,2069):
    for i in range (0,96):
            row_Eliaload18data[rx]=matriz_Eliaload18data[j][i];
            rx=rx+1;
row_Eliaload18data = row_Eliaload18data[~np.isnan(row_Eliaload18data)]
b=24*4 #24*4 timeslots within one day
length=198624 #198624
a=length/b
load = row_Eliaload18data
onwind_gen = np.absolute(row_onwindgen)
onwind_cap = np.absolute(row_onwindcap)
offwind_gen = np.absolute(row_offwindgen)
offwind_cap = np.absolute(row_offwindcap)
totwind_gen = np.absolute(row_totwindgen)
totwind_cap = np.absolute(row_totwindcap)
solar_gen = np.absolute(row_solargen)
solar_cap = np.absolute(row_solarcap)
# Creating matrices with capacity factor and capacity demand
################# CF ONSHORE #################
cfon = np.zeros(length, np.float64);
for i in range (0,length):
    cfon[i] = onwind_gen[i]/onwind_cap[i]
cdon = np.zeros(length, np.float64); #cd=capacity demand
for i in range (0,length):
    cdon[i] = load[i]/cfon[i]
################### CF OFFSHORE ###############
cfoff = np.zeros(length, np.float64);
for i in range (0,length):
    cfoff[i] = offwind_gen[i]/offwind_cap[i]
cdoff = np.zeros(length, np.float64); #cd=capacity demand
for i in range (0,length):
    cdoff[i] = load[i]/cfoff[i]
#################### CF TOTAL #################
```

```
cftot = np.zeros(length, np.float64);
for i in range (0,length):
    cftot[i] = totwind_gen[i]/totwind_cap[i]
cdtot = np.zeros(length, np.float64); #cd=capacity demand
for i in range (0,length):
    cdtot[i] = load[i]/cftot[i]
#################### CF SOLAR ################
cfpv = np.zeros(length, np.float64);
for i in range (0,length):
    cfpv[i] = solar_gen[i]/solar_cap[i]
'''
####### SELECTED ONLY ONE YEAR #######
n_year=1 # 1=2014, 2=2015 ecc...
s=35040*n_year
p=0
for i in range (0,35040):
    cfon[p] = cfon[s]
    cfpv[p] = cfpv[s]
    load[p] = load[s]
    cfoff[p] = cfoff[s]
    p=p+1
    s=s+1
'''
# Other special values
cfon_av = np.mean(cfon)
cfoff_av = np.mean(cfoff)
cftot_av = np.mean (cftot)
cfpv_av = np.mean (cfpv)
load_av = np.mean(load)
load_total = np.sum(load)/4.0 #total energy demand over the considered period, kWh
load_min = np.min(load)
load_max = np.max(load) #maximum load of the period, kW
```

Appendix C

Python code - import parameters

```
#Wind mills parameters
############## ONSHORE ###############
p_onwm = 5000.0
capex_onwm =1100*p_onwm
fixed_om_onwm = 0.017*capex_onwm
life_onwm = 25.0
r = 0.07
annuity_cst_onwm = r/(1.0-(1.0+r)**(-life_onwm))
############ OFFSHORE ##################
p_offwm = 5000.0
capex_offwm =2280*p_offwm
fixed_om_offwm = 0.023*capex_offwm
life_offwm = 30.0 #25*(1122.51/1834.71)+ 30*(712.2/1834.71)
r = 0.07
annuity_cst_offwm = r/(1.0-(1.0+r)**(-life_offwm))
############ Storage Methanol ############
p_st_m = 250.0;
capex_st_m = 2500*p_st_m;
fixed_om_st_m = 40*p_st_m;
cost_co2 = 0.00492 ; #eur/kWh ;
life_st_m = 20.0;
RTE_m = 0.35;
size_st_m = 85750.0e15;
r = 0.07
annuity_cst_st_m = r/(1.0-(1.0+r)**(-life_st_m))
############ Batteries ############
n_st_b=100
p_st_b_max= 5e4*n_st_b; #kW (50 MW*100 = 5GW)
st_max_b=p_st_b_max/2; #kWh (25 MWh)
st_min_b = 0;
capex_st_b = 140*p_st_b_max;
fixed_om_st_b = 1.4/100*capex_st_b;
RTE_b = 0.97;
life_b = 20 ;
cycle_life = 20000;
r=0.07
annuity_cst_st_b = r/(1.0-(1.0+r)**(-life_b));
############ PHES ############
p_in_max_h = 1.8e6;
p_out_max_h = 1.8e6;
RTE_h = 0.75;
st_max_hu = 7.7e6;
```

```
st_max_hb = 7.7e6;
capex_st_h = 1600*p_in_max_h;
u_var = 5/1000;
fixed_opex_st_h = 0
life_st_h = 60.0;
r=0.07
annuity_cst_st_h = r/(1.0-(1.0+r)**(-life_st_h))
############ Biomass ############
p_bio = 2e6;
capex_bio = 800.0*p_bio;
fom_bio = 5/100*capex_bio;
fuel_bio = 0.033
eff_bio = 0.35
life_bio = 30.0;
r=0.1
annuity_cst_bio = r/(1.0-(1.0+r)**(-life_bio));
############ Solar ############
r=0.07
p_pv = 3000.0
capex_pv =650*p_pv
fixed_om_pv = 1.85/100*capex_pv
life_pv = 30.0
annuity_cst_pv = r/(1.0-(1.0+r)**(-life_pv))
############# Parametric study ############
index = 0
index_max = 1
level_m0 = 1e10
level_b0 = st_max_b/2;
```

Appendix D

Python code - Optimization problem

```
import sys
import math
import os
import pandas as pd
import numpy as np
from numpy.random import random
from scipy import optimize
import matplotlib.pyplot as plt
import xlrd
import xlwt
import csv
b=24*4 #24*4 timeslots within one day
length= 198624
a=length/b
#variable to save
methanol_level=np.zeros(length, np.float64)
upperhydro_level=np.zeros(length, np.float64)
bottomhydro_level=np.zeros(length, np.float64)
battery_level = np.zeros(length, np.float64)
serv_bio = np.zeros(length, np.float64)
served_energy_res = np.zeros(length, np.float64)
served_energy_st = np.zeros(length, np.float64)
tot_energy_onwm = np.zeros(length, np.float64)
tot_energy_offwm = np.zeros(length, np.float64)
tot_energy_pv = np.zeros(length, np.float64)
tot_energy_bio = np.zeros(length, np.float64)
pow_onwm = np.zeros(length, np.float64)
pow_offwm = np.zeros(length, np.float64)
pow_pv = np.zeros(length, np.float64)
pow_st_m = np.zeros(length, np.float64)
coston = np.zeros(length, np.float64)
costoff = np.zeros(length, np.float64)
costpv = np.zeros(length, np.float64)
costm = np.zeros(length, np.float64)
costh = np.zeros(length, np.float64)
costb = np.zeros(length, np.float64)
costbio = np.zeros(length, np.float64)
costtot = np.zeros(length, np.float64)
counterm = np.zeros(length, np.float64)
counterb = np.zeros(length, np.float64)
spread = np.zeros(length, np.float64);
serv_onwm = np.zeros(length, np.float64);
```

```
serv_offwm = np.zeros(length, np.float64);
serv_pv = np.zeros(length, np.float64);
serv_st_m = np.zeros(length, np.float64);
serv_st_b = np.zeros(length, np.float64);
serv_st_h = np.zeros(length, np.float64);
serv_total = np.zeros(length, np.float64);
onoff = np.zeros(length, np.float64);
onoff_b = np.zeros(length, np.float64);
####################################
for i in range(0,length):
   serv_bio[i]=p_bio*0.25; #baseload power
####################################
#General case: Parametric study
def opticost(x):
    n_onwm = np.zeros(index_max, np.float64);
    n_offwm = np.zeros(index_max, np.float64);
    n_pv = np.zeros(index_max, np.float64);
    n_st_m = np.zeros(index_max, np.float64);
    outlet = np.zeros(30, np.float64);
    LOLH = np.zeros(index_max, np.float64);
    cost_onwm = np.zeros(index_max, np.float64);
    cost_offwm = np.zeros(index_max, np.float64);
    cost_pv = np.zeros(index_max, np.float64);
    cost_bio = np.zeros(index_max, np.float64);
    cost_st_m = np.zeros(index_max, np.float64);
    cost_st_h = np.zeros(index_max, np.float64);
    cost_st_b = np.zeros(index_max, np.float64);
    cost_tot = np.zeros(index_max, np.float64);
    power_onwm = np.zeros(index_max, np.float64);
    power_offwm = np.zeros(index_max, np.float64);
    power_st_m = np.zeros(index_max, np.float64);
    power_st_b = np.zeros(index_max, np.float64);
    power_st_h= np.zeros(index_max, np.float64);
    power_pv = np.zeros(index_max, np.float64);
    power_bio = np.zeros(index_max, np.float64);
    serv_total_onwm = np.zeros(index_max, np.float64);
    serv_total_offwm = np.zeros(index_max, np.float64);
    serv_total_pv = np.zeros(index_max, np.float64);
    serv_total_bio = np.zeros(index_max, np.float64);
    serv_total_st_m = np.zeros(index_max, np.float64);
    serv_total_st_h = np.zeros(index_max, np.float64);
    serv_total_st_b = np.zeros(index_max, np.float64);
    serv_total_ren = np.zeros(index_max, np.float64);
    st_level_m = np.zeros(index_max, np.float64);
    st_level_hu = np.zeros(index_max, np.float64);
    st_level_hb = np.zeros(index_max, np.float64);
    st_level_b = np.zeros(index_max, np.float64);
    counter_m = np.zeros(index_max, np.float64);
    counter_b = np.zeros(index_max, np.float64);
    n_onwm[index] = x[0]
    n_offwm[index] = x[1]
    n_pv[index] = x[2]
    n_st_m[index] = x[3]
    power_onwm[index] = (n_onwm[index]*0.005)
    power_offwm[index] = (n_offwm[index]*0.005)
    power_st_b[index] = p_st_b_max/1e6;
    power_pv[index] = (n_pv[index]*0.003)
    power_st_h[index] = p_in_max_h/1e6;
    power_bio[index] = p_bio/1e6;
    p_in_max_m = n_st_m[index]*p_st_m;
    p_out_max_m = n_st_m[index]*p_st_m;
    st_max_m = n_st_m[index]*size_st_m
```

```
st_min_m = n_st_m[index]*0.0;
p_in_max_b = p_st_b_max;
p_out_max_b = p_st_b_max;
level_m = np.zeros(length+1, np.float64);
level_b = np.zeros(length+1, np.float64);
level_hu = np.zeros(length+1, np.float64);
level_hb = np.zeros(length+1, np.float64);
p_in_m = 0.0;
p_out_m = 0.0;
st_in_m = 0.0;
st_out_m = 0.0;
p_in_h = 0.0;
p_out_h = 0.0;
st_in_h = 0.0;
st_out_h = 0.0;
p_in_b = 0.0;
p_out_b = 0.0;
st_in_b = 0.0;
st_out_b = 0.0;
level_b[0] = level_b0
level_m[0] = level_m0
level_hu[0] = st_max_hu/2; #initial condition of the hydro storage
level_hb[0] = st_max_hb/2;
###########################################################
for i in range (0,length):
    res_h = 0.0;
    res_m = 0.0;
    res_b = 0.0;
    st_in_h=0.0;
    st_in_b=0.0;
    st_in_m=0.0;
    st_out_h=0.0;
    st_out_b=0.0;
    st_out_m=0.0;
    serv_st_m[i]=0.0;
    serv_st_b[i]=0.0;
    serv_st_h[i]=0.0;
    spread[i] = p_bio + n_onwm[index]*p_onwm*cfon[i] + n_offwm[index]*p_offwm*cfoff[i] +
         n_pv[index]*p_pv*cfpv[i] - load[i]
    tot_energy_onwm[i] = n_onwm[index]*p_onwm*cfon[i]
    tot_energy_offwm[i] = n_offwm[index]*p_offwm*cfoff[i]
    tot_energy_pv[i] = n_pv[index]*p_pv*cfpv[i]
    tot_energy_bio[i] = p_bio
    if (spread[i]>0):
        perc_on =(n_onwm[index]*p_onwm*cfon[i])/((n_onwm[index]*p_onwm*cfon[i])+
        (n_offwm[index]*p_offwm*cfoff[i])+(n_pv[index]*p_pv*cfpv[i]));
        perc_off =(n_offwm[index]*p_offwm*cfoff[i])/((n_onwm[index]*p_onwm*cfon[i])+
        (n_offwm[index]*p_offwm*cfoff[i])+(n_pv[index]*p_pv*cfpv[i]));
        perc_pv =(n_pv[index]*p_pv*cfpv[i])/((n_onwm[index]*p_onwm*cfon[i])+
        (n_offwm[index]*p_offwm*cfoff[i])+(n_pv[index]*p_pv*cfpv[i]));
        serv_onwm[i] = (perc_on * (load[i]-p_bio))*0.25
        serv_offwm[i] = (perc_off * (load[i]-p_bio))*0.25
        serv_pv[i] = (perc_pv * (load[i]-p_bio))*0.25
        serv_total[i] = load[i]*0.25
        if (p_in_max_h < spread[i]):
            res_h = p_in_max_h
            res_b = spread[i] - res_h
            onoff_b[i] = 1;
            if ((st_max_hu - level_hu[i])*4/RTE_h < res_h):
                st_in_h = st_max_hu - level_hu[i]
                res_b = res_b + (res_h - st_in_h)
                if (p_in_max_b < res_b):
```

```
        if (p_in_max_b < ((st_max_b - level_b[i])*4/RTE_b)):
            st_in_b = p_in_max_b*RTE_b*0.25
            res_m = res_m + (res_b - st_in_b)
            onoff[i] = 1;
            if (p_in_max_m < res_m):
                #loss_p = (res_m - p_in_max_m)*0.25; #losses due to the lower input power
                if (p_in_max_m < ((st_max_m - level_m[i])*4/RTE_m)):
                    st_in_m = p_in_max_m*RTE_m*0.25
                else:
                    #loss_s = (p_in_max_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                    st_in_m = st_max_m - level_m[i]
            else:
                if (((st_max_m-level_m[i])*4/RTE_m) < res_m):
                    #loss_s = (res_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                    st_in_m = (st_max_m - level_m[i])
                else:
                    st_in_m = res_m*RTE_m*0.25
        else:
            st_in_b = (st_max_b - level_b[i])
            res_m = res_m + (res_b - st_in_b)
            onoff[i] = 1;
            if (p_in_max_m < res_m):
                #loss_p = (res_m - p_in_max_m)*0.25; #losses due to the lower input power
                if (p_in_max_m < ((st_max_m - level_m[i])*4/RTE_m)):
                    st_in_m = p_in_max_m*RTE_m*0.25
                else:
                    loss_s = (p_in_max_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                    st_in_m = (st_max_m - level_m[i])
            else:
                if (((st_max_m-level_m[i])*4/RTE_m) < res_m):
                    #loss_s = (res_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                    st_in_m = (st_max_m - level_m[i])
                else:
                    p_in_m = res_m
                    st_in_m = p_in_m*RTE_m*0.25
    else:
        if (p_in_max_b < ((st_max_b - level_b[i])*4/RTE_b)):
            st_in_b = res_b*RTE_b*0.25
        else:
            if (res_b < ((st_max_b - level_b[i])*4/RTE_b)):
                st_in_b = res_b*RTE_b*0.25
            else:
                st_in_b = (st_max_b - level_b[i])
                res_m = res_m + (res_b - st_in_b)
                onoff[i] = 1;
                if (p_in_max_m < res_m):
                    #loss_p = (res_m - p_in_max_m)*0.25; #losses due to the lower input power
                    if (p_in_max_m < ((st_max_m - level_m[i])*4/RTE_m)):
                        st_in_m = p_in_max_m*RTE_m*0.25
                    else:
                        #loss_s = (p_in_max_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                        st_in_m = (st_max_m - level_m[i])
                else:
                    if (((st_max_m-level_m[i])*4/RTE_m) < res_m):
                        #loss_s = (res_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                        st_in_m = (st_max_m - level_m[i])
                    else:
                        st_in_m = res_m*RTE_m*0.25
else:
    st_in_h = res_h*RTE_h*0.25
    if (p_in_max_b < res_b):
        if (p_in_max_b < ((st_max_b - level_b[i])*4/RTE_b)):
```

```
                st_in_b = p_in_max_b*RTE_b*0.25
                res_m = res_m + (res_b - st_in_b)
                onoff[i] = 1;
                if (p_in_max_m < res_m):
                    #loss_p = (res_m - p_in_max_m)*0.25; #losses due to the lower input power
                    if (p_in_max_m < ((st_max_m - level_m[i])*4/RTE_m)):
                        st_in_m = p_in_max_m*RTE_m*0.25
                    else:
                        #loss_s = (p_in_max_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                        st_in_m = (st_max_m - level_m[i])
                else:
                    if (((st_max_m-level_m[i])*4/RTE_m) < res_m):
                        #loss_s = (res_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                        st_in_m = (st_max_m - level_m[i])
                    else:
                        st_in_m = res_m*RTE_m*0.25
            else:
                st_in_b = (st_max_b - level_b[i])
                res_m = res_m + (res_b - st_in_b)
                onoff[i] = 1;
                if (p_in_max_m < res_m):
                    #loss_p = (res_m - p_in_max_m)*0.25; #losses due to the lower input power
                    if (p_in_max_m < ((st_max_m - level_m[i])*4/RTE_m)):
                        st_in_m = p_in_max_m*RTE_m*0.25
                    else:
                        #loss_s = (p_in_max_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                        st_in_m = (st_max_m - level_m[i])
                else:
                    if (((st_max_m-level_m[i])*4/RTE_m) < res_m):
                        #loss_s = (res_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                        st_in_m = (st_max_m - level_m[i])
                    else:
                        st_in_m = res_m*RTE_m*0.25
        else:
            if (p_in_max_b < ((st_max_b - level_b[i])*4/RTE_b)):
                st_in_b = res_b*RTE_b*0.25
            else:
                if (res_b < ((st_max_b - level_b[i])*4/RTE_b)):
                    st_in_b = res_b*RTE_b*0.25
                else:
                    st_in_b = (st_max_b - level_b[i])
                    res_m = res_m + (res_b - st_in_b)
                    onoff[i] = 1;
                    if (p_in_max_m < res_m):
                        #loss_p = (res_m - p_in_max_m)*0.25; #losses due to the lower input power
                        if (p_in_max_m < ((st_max_m - level_m[i])*4/RTE_m)):
                            st_in_m = p_in_max_m*RTE_m*0.25
                        else:
                            #loss_s = (p_in_max_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                            st_in_m = (st_max_m - level_m[i])
                    else:
                        if (((st_max_m-level_m[i])*4/RTE_m) < res_m):
                            #loss_s = (res_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                            st_in_m = (st_max_m - level_m[i])
                        else:
                            st_in_m = res_m*RTE_m*0.25
else:
    if (((st_max_hu-level_hu[i])*4/RTE_h)<spread[i]):
        st_in_h = (st_max_hu - level_hu[i])
        res_b = spread[i] - st_in_h
        onoff_b[i] = 1;
        if (p_in_max_b < res_b):
```

```
            if (p_in_max_b < ((st_max_b - level_b[i])*4/RTE_b)):
                st_in_b = p_in_max_b*RTE_b*0.25
                res_m = res_b - st_in_b
                onoff[i] = 1;
                if (p_in_max_m < res_m):
                    #loss_p = (res_m - p_in_max_m)*0.25; #losses due to the lower input power
                    if (p_in_max_m < ((st_max_m - level_m[i])*4/RTE_m)):
                        st_in_m = p_in_max_m*RTE_m*0.25
                    else:
                        #loss_s = (p_in_max_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                        st_in_m = (st_max_m - level_m[i])
                else:
                    if (((st_max_m-level_m[i])*4/RTE_m) < res_m):
                        #loss_s = (res_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                        st_in_m = (st_max_m - level_m[i])
                    else:
                        st_in_m = res_m*RTE_m*0.25
            else:
                st_in_b = (st_max_b - level_b[i])
                res_m = res_m + (res_b - st_in_b)
                onoff[i] = 1;
                if (p_in_max_m < res_m):
                    loss_p = (res_m - p_in_max_m)*0.25; #losses due to the lower input power
                    if (p_in_max_m < ((st_max_m - level_m[i])*4/RTE_m)):
                        st_in_m = p_in_max_m*RTE_m*0.25
                    else:
                        #loss_s = (p_in_max_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                        st_in_m = (st_max_m - level_m[i])
                else:
                    if (((st_max_m-level_m[i])*4/RTE_m) < res_m):
                        #loss_s = (res_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                        st_in_m = (st_max_m - level_m[i])
                    else:
                        st_in_m = res_m*RTE_m*0.25
        else:
            if (p_in_max_b < ((st_max_b - level_b[i])*4/RTE_b)):
                st_in_b = res_b*RTE_b*0.25
            else:
                if (res_b < ((st_max_b - level_b[i])*4/RTE_b)):
                    st_in_b = res_b*RTE_b*0.25
                else:
                    st_in_b = (st_max_b - level_b[i])
                    res_m = res_m + (res_b - st_in_b)
                    onoff[i] = 1;
                    if (p_in_max_m < res_m):
                        #loss_p = (res_m - p_in_max_m)*0.25; #losses due to the lower input power
                        if (p_in_max_m < ((st_max_m - level_m[i])*4/RTE_m)):
                            st_in_m = p_in_max_m*RTE_m*0.25
                        else:
                            #loss_s = (p_in_max_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                            st_in_m = (st_max_m - level_m[i])
                    else:
                        if (((st_max_m-level_m[i])*4/RTE_m) < res_m):
                            #loss_s = (res_m - ((st_max_m - level_m[i])*4/RTE_m))*0.25
                            st_in_m = (st_max_m - level_m[i])
                        else:
                            st_in_m = res_m*RTE_m*0.25
    else:
        st_in_h = spread[i]*RTE_h*0.25

level_hu[i+1] = level_hu[i] + st_in_h
level_hb[i+1] = level_hb[i] - st_in_h
```

```
            level_m[i+1] = level_m[i] + st_in_m
            level_b[i+1] = level_b[i] + st_in_b
####### ####### ####### ####### #######
####### ####### ####### ####### #######
        else:
            serv_onwm[i] = (n_onwm[index]*p_onwm*cfon[i])*0.25 #factor 0.25 to convert in kWh
            serv_offwm[i] = (n_offwm[index]*p_offwm*cfoff[i])*0.25 #factor 0.25 to convert in kWh
            serv_pv[i] = (n_pv[index]*p_pv*cfpv[i])*0.25 #factor 0.25 to convert in kWh
            serv_total[i] = (spread[i] + load[i])*0.25
            spread[i]=np.absolute(spread[i])
            if (p_out_max_h < spread[i]):
                res_h = p_out_max_h
                res_b = spread[i] - res_h #remaining part that can be stored with P2F
                if ((st_max_hb - level_hb[i])*4 < res_h):
                    serv_st_h[i] = (st_max_hb - level_hb[i])
                    res_b = spread[i] - serv_st_h[i]*4
                    if (p_out_max_b < res_b):
                        if (p_out_max_b < ((level_b[i] - st_min_b)*4)):
                            serv_st_b[i]=p_out_max_b*0.25
                            res_m = spread[i] - serv_st_h[i]*4 - serv_st_b[i]*4
                            if (p_out_max_m < res_m):
                                #lim_p = (res_m - p_out_max_m)*0.25; #losses due to the lower input power
                                LOLH[index] += 0.25
                                if (p_out_max_m < ((level_m[i] - st_min_m)*4)):
                                    serv_st_m[i]= p_out_max_m*0.25
                                else:
                                    #lim_s = (p_out_max_m - ((level_m[i] - st_min_m)*4))*0.25
                                    serv_st_m[i]=(level_m[i] - st_min_m)
                            else:
                                if (((level_m[i] - st_min_m)*4) < res_m):
                                    #lim_s = (res_m - ((level_m[i] - st_min_m)*4))*0.25
                                    serv_st_m[i]=(level_m[i] - st_min_m)
                                    LOLH[index] += 0.25
                                else:
                                    serv_st_m[i]=res_m*0.25
                        else:
                            serv_st_b[i]= (level_b[i] - st_min_b)
                            res_m = spread[i] - serv_st_h[i]*4 - serv_st_b[i]*4
                            if (p_out_max_m < res_m):
                                #lim_p = (res_m - p_out_max_m)*0.25; #losses due to the lower input power
                                LOLH[index] += 0.25
                                if (p_out_max_m < ((level_m[i] - st_min_m)*4)):
                                    serv_st_m[i]= p_out_max_m*0.25
                                else:
                                    #lim_s = (p_out_max_m - ((level_m[i] - st_min_m)*4))*0.25
                                    serv_st_m[i]=(level_m[i] - st_min_m)
                            else:
                                if (((level_m[i] - st_min_m)*4) < res_m):
                                    #lim_s = (res_m - ((level_m[i] - st_min_m)*4))*0.25
                                    serv_st_m[i]=(level_m[i] - st_min_m)
                                    LOLH[index] += 0.25
                                else:
                                    serv_st_m[i]=res_m*0.25
                    else:
                        if (p_out_max_b < ((level_b[i] - st_min_b)*4)):
                            serv_st_b[i]=res_b*0.25
                        else:
                            if (res_b < ((level_b[i] - st_min_b)*4)):
                                serv_st_b[i]=res_b*0.25
                            else:
                                serv_st_b[i]= (level_b[i] - st_min_b)
                                res_m = spread[i] - serv_st_h[i]*4 - serv_st_b[i]*4
```

```
                if (p_out_max_m < res_m):
                    #lim_p = (res_m - p_out_max_m)*0.25; #losses due to the lower input power
                    LOLH[index] += 0.25
                    if (p_out_max_m < ((level_m[i] - st_min_m)*4)):
                        serv_st_m[i]= p_out_max_m*0.25
                    else:
                        #lim_s = (p_out_max_m - ((level_m[i] - st_min_m)*4))*0.25
                        serv_st_m[i]= (level_m[i] - st_min_m)
                else:
                    if (((level_m[i] - st_min_m)*4) < res_m):
                        #lim_s = (res_m - ((level_m[i] - st_min_m)*4))*0.25
                        serv_st_m[i]=(level_m[i] - st_min_m)
                        LOLH[index] += 0.25
                    else:
                        serv_st_m[i]=res_m*0.25
else:
    serv_st_h[i] = res_h*0.25
    if (p_out_max_b < res_b):
        if (p_out_max_b < ((level_b[i] - st_min_b)*4)):
            serv_st_b[i]= p_out_max_b*0.25
            res_m = spread[i] - serv_st_h[i]*4 - serv_st_b[i]*4
            if (p_out_max_m < res_m):
                #lim_p = (res_m - p_out_max_m)*0.25; #losses due to the lower input power
                LOLH[index] += 0.25
                if (p_out_max_m < ((level_m[i] - st_min_m)*4)):
                    serv_st_m[i]= p_out_max_m*0.25
                else:
                    #lim_s = (p_out_max_m - ((level_m[i] - st_min_m)*4))*0.25
                    serv_st_m[i]=(level_m[i] - st_min_m)
            else:
                if (((level_m[i] - st_min_m)*4) < res_m):
                    #lim_s = (res_m - ((level_m[i] - st_min_m)*4))*0.25
                    serv_st_m[i]= (level_m[i] - st_min_m)
                    LOLH[index] += 0.25
                else:
                    serv_st_m[i]= res_m*0.25
        else:
            serv_st_b[i]= (level_b[i] - st_min_b)
            res_m = spread[i] - serv_st_h[i]*4 - serv_st_b[i]*4
            if (p_out_max_m < res_m):
                #lim_p = (res_m - p_out_max_m)*0.25; #losses due to the lower input power
                LOLH[index] += 0.25
                if (p_out_max_m < ((level_m[i] - st_min_m)*4)):
                    serv_st_m[i]=p_out_max_m*0.25;
                else:
                    #lim_s = (p_out_max_m - ((level_m[i] - st_min_m)*4))*0.25
                    serv_st_m[i]= (level_m[i] - st_min_m)
            else:
                if (((level_m[i] - st_min_m)*4) < res_m):
                    #lim_s = (res_m - ((level_m[i] - st_min_m)*4))*0.25
                    serv_st_m[i]=(level_m[i] - st_min_m)
                    LOLH[index] += 0.25
                else:
                    serv_st_m[i]=res_m*0.25
    else:
        if (p_out_max_b < ((level_b[i] - st_min_b)*4)):
            serv_st_b[i]= res_b*0.25
        else:
            if (res_b < ((level_b[i] - st_min_b)*4)):
                serv_st_b[i]= res_b*0.25
            else:
                serv_st_b[i]= (level_b[i] - st_min_b)
```

```
                    res_m = spread[i] - serv_st_h[i]*4 - serv_st_b[i]*4
                    if (p_out_max_m < res_m):
                        #lim_p = (res_m - p_out_max_m)*0.25; #losses due to the lower input power
                        LOLH[index] += 0.25
                        if (p_out_max_m < ((level_m[i] - st_min_m)*4)):
                            serv_st_m[i]= p_out_max_m*0.25
                        else:
                            #lim_s = (p_out_max_m - ((level_m[i] - st_min_m)*4))*0.25
                            serv_st_m[i]=(level_m[i] - st_min_m)
                    else:
                        if (((level_m[i] - st_min_m)*4) < res_m):
                            #lim_s = (res_m - ((level_m[i] - st_min_m)*4))*0.25
                            serv_st_m[i]= (level_m[i] - st_min_m)
                            LOLH[index] += 0.25
                        else:
                            serv_st_m[i]= res_m*0.25
else:
    if (((st_max_hb-level_hb[i])*4) < spread[i]):
        serv_st_h[i] = (st_max_hb - level_hb[i])
        res_b = spread[i] - serv_st_h[i]*4
        if (p_out_max_b < res_b):
            if (p_out_max_b < ((level_b[i] - st_min_b)*4)):
                serv_st_b[i]= p_out_max_b*0.25
                res_m = spread[i] - serv_st_h[i]*4 - serv_st_b[i]*4
                if (p_out_max_m < res_m):
                    #lim_p = (res_m - p_out_max_m)*0.25; #losses due to the lower input power
                    LOLH[index] += 0.25
                    if (p_out_max_m < ((level_m[i] - st_min_m)*4)):
                        serv_st_m[i]= p_out_max_m*0.25
                    else:
                        #lim_s = p_out_max_m - ((level_m[i] - st_min_m)*4)*0.25
                        serv_st_m[i]=(level_m[i] - st_min_m)
                else:
                    if (((level_m[i] - st_min_m)*4) < res_m):
                        #lim_s = (res_m - ((level_m[i] - st_min_m)*4))*0.25
                        serv_st_m[i]=(level_m[i] - st_min_m)
                        LOLH[index] += 0.25
                    else:
                        serv_st_m[i]=res_m*0.25
            else:
                serv_st_b[i]=(level_b[i] - st_min_b)
                res_m = spread[i] - serv_st_h[i]*4 - serv_st_b[i]*4
                if (p_out_max_m < res_m):
                    #lim_p = (res_m - p_out_max_m)*0.25; #losses due to the lower input power
                    LOLH[index] += 0.25
                    if (p_out_max_m < ((level_m[i] - st_min_m)*4)):
                        serv_st_m[i]=p_out_max_m*0.25
                    else:
                        #lim_s = (p_out_max_m - ((level_m[i] - st_min_m)*4))*0.25
                        serv_st_m[i]=(level_m[i] - st_min_m)
                else:
                    if (((level_m[i] - st_min_m)*4) < res_m):
                        #lim_s = (res_m - ((level_m[i] - st_min_m)*4))*0.25
                        serv_st_m[i]= (level_m[i] - st_min_m)
                        LOLH[index] += 0.25
                    else:
                        serv_st_m[i]= res_m*0.25
        else:
            if (p_out_max_b < ((level_b[i] - st_min_b)*4)):
                serv_st_b[i]= res_b*0.25
            else:
                if (res_b < ((level_b[i] - st_min_b)*4)):
```

```
                        serv_st_b[i]= res_b*0.25
                    else:
                        serv_st_b[i] = (level_b[i] - st_min_b)
                        res_m = spread[i] - serv_st_h[i]*4 - serv_st_b[i]*4
                        if (p_out_max_m < res_m):
                            #lim_p = (res_m - p_out_max_m)*0.25; #losses due to the lower input power
                            LOLH[index] += 0.25
                            if (p_out_max_m < ((level_m[i] - st_min_m)*4)):
                                serv_st_m[i]=p_out_max_m*0.25
                            else:
                                #lim_s = (p_out_max_m - ((level_m[i] - st_min_m)*4))*0.25
                                serv_st_m[i]= (level_m[i] - st_min_m)
                        else:
                            if (((level_m[i] - st_min_m)*4) < res_m):
                                #lim_s = (res_m - ((level_m[i] - st_min_m)*4))*0.25
                                serv_st_m[i]= (level_m[i] - st_min_m)
                                LOLH[index] += 0.25
                            else:
                                serv_st_m[i]= res_m*0.25
            else:
                serv_st_h[i] = spread[i]*0.25

        level_hu[i+1] = level_hu[i] - serv_st_h[i]
        level_hb[i+1] = level_hb[i] + serv_st_h[i]
        level_m[i+1] = level_m[i] - serv_st_m[i]
        level_b[i+1] = level_b[i] - serv_st_b[i]

    if (onoff[i] != onoff[i-1]):
        counter_m[index] += 1 #Parameter to count the number of on/off of the methanol storage. If 'i+1'
            different of 'i' --> on to off or off to on
    if (onoff_b[i] != onoff_b[i-1]):
##################################################################################
##################################################################################
    serv_total_onwm[index] += serv_onwm[i]
    serv_total_offwm[index] += serv_offwm[i]
    serv_total_ren[index] += serv_total[i]
    serv_total_pv[index] += serv_pv[i]
    serv_total_bio[index] += serv_bio[i]
    serv_total_st_m[index] += serv_st_m[i]
    serv_total_st_h[index] += serv_st_h[i]
    serv_total_st_b[index] += serv_st_b[i]
    st_level_m[index] = level_m[i]
    st_level_b[index] = level_b[i]
    st_level_hu[index] = level_hu[i]
    st_level_hb[index] = level_hb[i]
    methanol_level[i]=level_m[i]
    battery_level[i]=level_b[i]
    upperhydro_level[i]=level_hu[i]
    bottomhydro_level[i]=level_hb[i]
    cost_onwm[index] = (capex_onwm*annuity_cst_onwm +
        fixed_om_onwm)*n_onwm[index]*(float(a)/365.0)/serv_total_onwm[index]
    cost_offwm[index] = (capex_offwm*annuity_cst_offwm +
        fixed_om_offwm)*n_offwm[index]*(float(a)/365.0)/serv_total_offwm[index]
    cost_pv[index] = (capex_pv*annuity_cst_pv+fixed_om_pv)*n_pv[index]*
    (float(a)/365.0)/serv_total_pv[index]
    cost_bio[index] = ((capex_bio*annuity_cst_bio+fom_bio)*(float(a)/365.0)/
    serv_total_bio[index])+fuel_bio/eff_bio
    cost_st_m[index] = ((capex_st_m*annuity_cst_st_m +
        fixed_om_st_m)*n_st_m[index]*(float(a)/365.0))/serv_total_st_m[index] + cost_co2;
    cost_st_h[index] = ((capex_st_h*annuity_cst_st_h +
        fixed_opex_st_h)*(float(a)/365.0))/serv_total_st_h[index] + u_var #eur/kWh
    cost_st_b[index] = ((capex_st_b*annuity_cst_st_b+fixed_om_st_b)*(float(a)/365.0))/
```

```
        serv_total_st_b[index] #eur/kWh
        cost_tot[index] = (((capex_st_b*annuity_cst_st_b+fixed_om_st_b) +
             (capex_onwm*annuity_cst_onwm+fixed_om_onwm)*n_onwm[index] +
             (capex_offwm*annuity_cst_offwm+fixed_om_offwm)*n_offwm[index] +
             (capex_pv*annuity_cst_pv+fixed_om_pv)*n_pv[index] + (capex_st_m*annuity_cst_st_m +
             fixed_om_st_m)*n_st_m[index] + (capex_bio*annuity_cst_bio + fom_bio) + (capex_st_h*annuity_cst_st_h
             + fixed_opex_st_h))*(float(a)/365.0) + cost_co2*serv_total_st_m[index] +
             fuel_bio/eff_bio*serv_total_bio[index] + u_var*serv_total_st_h[index])/(serv_total_ren[index] +
             serv_total_st_m[index] + serv_total_st_h[index] + serv_total_st_b[index]) #eur/kWh
######################## OBTAINING DATA ###########################
        served_energy_res[i] = serv_onwm[i] + serv_offwm[i] + serv_pv[i] + serv_bio[i]
        served_energy_st[i] = serv_st_m[i] + serv_st_h[i] + serv_st_b[i]
        pow_onwm[i] = power_onwm
        pow_offwm[i] = power_offwm
        pow_pv[i] = power_pv
        pow_st_m[i] = n_st_m*p_st_m/1e6
        coston[i]=cost_onwm
        costoff[i]=cost_offwm
        costpv[i]=cost_pv
        costm[i]=cost_st_m
        costh[i]=cost_st_h
        costb[i]=cost_st_b
        costbio[i]=cost_bio
        costtot[i]=cost_tot
        counterm[i]=counter_m
        counterb[i]=counter_b
############################ OUTPUT ################################
    outlet[0] = n_onwm[index]; outlet[1] = n_offwm[index]; outlet[2] = n_pv[index]; outlet[3] = n_st_m[index];
    outlet[4] = power_onwm[index]; outlet[5] = power_offwm[index]; outlet[6] = power_pv; outlet[7] = power_bio;
    outlet[8] = n_st_m[index]*p_st_m/1e6; outlet[9] = power_st_b[index]; outlet[10] = power_st_h[index];
    outlet[11] = cost_onwm[index]; outlet[12] = cost_offwm[index]; outlet[13]=cost_pv[index];
    outlet[14] = cost_st_m[index]; outlet[15] = cost_st_b[index]; outlet[16] = cost_st_h[index];
    outlet[17] = cost_bio[index]; outlet[18] = cost_tot[index];
    outlet[19] = serv_total_onwm[index]; outlet[20] = serv_total_offwm[index]; outlet[21] =serv_total_pv[index];
    outlet[22] = serv_total_st_m[index]; outlet[23] = serv_total_st_b[index];
    outlet[24] = serv_total_st_h[index]; outlet[25] = serv_total_bio[index];
    outlet[26] = st_level_m[index]; outlet[27] = LOLH[index]; outlet[28] = counter_m[index]; outlet[29] =
         counter_b[index];
    print (outlet[18])
    return outlet
def optim_cost(x):
    optim = opticost(x)
    return optim[18]
############ Optimization ############
VI = [4000, 3500, 2300, 55000]
############ Constraint functions ############
c1 = lambda x: np.asarray([opticost(x)[27]-0.1])
c2 = lambda x: np.asarray([(opticost(x)[26])-level_m0])
c3 = lambda x: np.asarray([opticost(x)[0]])
c4 = lambda x: np.asarray([opticost(x)[1]])
c5 = lambda x: np.asarray([opticost(x)[2]])
c6 = lambda x: np.asarray([opticost(x)[3]])
constraints = np.asarray([c1, c2, c3, c4, c5, c6])
################################################
x = optimize.fmin_cobyla(optim_cost, VI, cons=constraints, rhobeg=1000, rhoend=0.5, maxfun=200)
################################################
tablename = str('OOAAA')
np.savetxt('output_new.txt'.format(tablename), opticost(x), delimiter='.')
```