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Thesis

Development of an energy model to study the impact of long-term energy storage in electricity zones with 100% Renewable energy sources:

comparison between Belgian and Spanish cases.

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DEDICATION

Por supuesto, en primer lugar y siempre, a mi familia. A mi madre, la madre más madre de todas las madres. La mujer con el corazón más grande y mi ejemplo a seguir. A mi papuchi, mi saco de lágrimas y de rabietas, mi mejor amigo y lo mejor que me ha pasado en la vida. A mis dos hermanos. Carlos, gracias por todo lo que me has dado este año, por toda una vida juntos. Asier, tan pequeño y tan indispensable en mi vida. Mi mofletichi, mi razón de ser. Gracias. Sin vosotros no habría podido.

Especial mención a mi abuela Fina, mi heroína. Gracias por darme el amor más incondicional que un humano puede ofrecer y el más grande ejemplo de fuerza.

A la meilleure coloc du monde. Ma patate, ma petite soeur, mon amie pour toujours. Merci pour cette merveilleuse année. Tu as été mon plus grand support. Nos follies, nos journées de lit-friends-chocolat, nos discussions comme un vieux couple... Tu vas beaucoup me manquer. Vivre avec toi a été un plaisir. On se reverra à Lyon.

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1. ABSTRACT

For the present project, six simplified models of an electricity zone with 100% renewables are developed. The approach is applied to three different hypothetical scenarios: (i) a combination of wind energy and methanol storage, (ii) a combination of PV solar energy and methanol storage, (iii) a combination of wind energy with PV solar energy and methanol storage. Those are developed for two European countries with a very different distribution of renewables energies and electrical network: Belgium and Spain.

These three scenarios are not entirely realistic as in reality, wind and solar will be complemented by other sources such as hydro or biomass. However, the idea is to study the impact of having large shares of variable renewable sources with different variability profiles on the electricity grid.

The purpose of this study is to minimize the energy cost (euros/kWh) by determining the optimal combination of energy generators (windmills, solar panels or both) and long-term storage based on methanol production (power-to-fuel). This combination must respect two constraints, a period of LOLH (lost of load hours) lower than 0.25h during the period (5.8 years for Belgium and 4 years for Spain), and preserve the same storage level (amount of methanol stored) at the beginning and the end of the period. This condition ensures the match between installed capacities and system requirements.

Then, this model determines the viability of power-to-fuel storage technology. One significant advantage of power-to-fuel methanol is the fact that the storage

is very very cheap (storing a liquid at ambient T and P) so that the marginal cost of storage itself is neglected.

Another assumption is that curtailed energy occurs when wind and/or solar generation surpasses both the demand and the storage capacity without incurring on detrimental consequences to the grid stability. Furthermore, all the models consider a system optimum rather than an agent-based approach. So, it is assumed that the energy that is stored is free as a result of a zero cost for the storage units. Also, market competitiveness, other applications for methanol or oxygen (electrolysis by-product), and grid limitations and control costs are not contemplated.

The grid of both of the countries considered in this job is different. In Belgium, natural gas and nuclear energies are much more exploited. However, in Spain, the coal is the second energy source more used, but the demand supplied by renewables energies is 15% higher in this region. Consequently, the actual emissions of CO_2 per kWh are much higher in Spain than in Belgium, being 243.23 gCO_2/kWh and 175.91 gCO_2/kWh, respectively. The average capacity factor for wind is similar in both countries (0.277 Belgium, 0.240 Spain) but, for solar it is almost double in Spain (0.111 Belgium, 0.217 Spain). Finally, the average load during the sample period in Belgium is 8.89 GW and in Spain 28.70 GW.

The first system proposed is the 100% wind energy system. In Belgium, the optimum is found for 9119 windmills with 45.6 GW installed and 58250 storage units with 14.56 GW installed. Wind directly energy served is 72.7% of the total energy served between windmills and power-to-fuel units. In Spain, the resulting grid has 28965 windmills with 145 GW installed and 182295 storage units with 45.57 GW installed. In this country, the energy served by windmills is higher than in Belgium, 81.80%. The final electricity price is 88.3 euros/MWh for Belgium and 85.9 euros/MWh for Spain. The CO_2 emissions savings compared to the actual grid are more significant for Spain, with 94.24%; 92.04% in Belgium.

For the 100% PV solar energy system scenario, the installed capacity needed is enormous due to the low capacity factor. Therefore, these are not realistic systems. In Belgium the resulting grid has 2520 millions of PV panels with 760 GW installed, 405159 power-to-fuel units with 101.29 GW and a 48% of the total energy served by PV cells. In Spain, the optimum cost is obtained for 70430 millions of PV cells with 2112 GW installed, 479565 storage units with 120 GW installed, and 81.42% of energy demand supplied by PV cells (almost double than in Belgium). The energy cost is 951.6 euros/MWh in Belgium and 753.9 euros/MWh in Spain. As said before, neither the system or the energy cost is realistic. The CO_2 emissions are reduced by 74.42% in Belgium and 81.50% in Spain.

Finally, the lowest price is found for a 100% wind and PV solar energy system. In this scenario, the Belgian grid is composed by 8007 windmills with 40 GW installed, 29.92 millions of PV panels with 9 GW installed, and 51256 storage units with 12.81 GW installed. With 76.14% of the total energy served by wind and PV solar. On the other hand, the Spanish grid is formed by 15413 windmills with 70.07 GW installed, 237.56 millions of PV panels with 71.23 GW installed, and 139891 power-to-fuel units with 35 GW installed. In this case, the energy served by windmills and PV panels is 82.62% of the total. The final energy cost is 86.2 euros/MWh in Belgium and 71.10 euros/MWh in Spain. This last one experiences a more considerable decrease on the final price with the combination of both energy sources. That and the larger cost of storage units electricity in Spain for a 100% wind energy system shows that the harmony between the peak load periods and energy generation by renewable sources periods reduces the cost of power-to-fuel energy and, consequently, the final electricity cost. However, for this scenario, the percentage of CO_2 emissions savings is slightly larger in Belgium (88.80%) than in Spain (88.11%).

So, for all the scenarios considered, the final energy cost is larger in Belgium than in Spain, and the overcapacity is necessary for the full energy demand supply. Nevertheless, for both cases, due to the lower installed capacity required, energy cost, and energy curtailed, the most efficient system is the 100% wind and PV solar energy system. With this energy grid, the energy cost in Belgium is less than twice the actual one and, in Spain, around 65% larger. Still, the CO_2 emissions savings are larger for the scenario 100% wind energy system.

In conclusion, to achieve the European Commission objectives assuring the energy supply, and a reasonable energy cost, a 100% RES system combined with power-to-fuel storage is a realistic alternative to the actual grid system.

2. INTRODUCTION

2.1. State of the art

Many actual problems that like air and water pollution, energy insecurity, or climate change can be solved with a transition to perpetual 100% global renewable energy system (RES). A large number of studies and researches about this subject have investigated whether national, continental or global power system could be provided by 100% RES. On those, many different plans for large-scale renewable energy systems have been proposed.

About the global energy system, two relevant articles used for the developing of the present project [35][20] analyzes if it is feasible to provide all global energy with wind, water, and solar power. Considering that the energy demand increases every year, they prove that for 2030 is technically feasible to supply the world energy demand with water, wind, solar system (WWS). Their final scenario for a world WWS system in 2030 is made up of 3.8 million wind turbines of 5MW nameplate power, 49000 CSP (concentrated solar power) powerplants of 300MW, 40000 solar PV (photovoltaic) power plants (1.73 billion of rooftop systems of 3KW), 5350 geothermal power plants with 100 MW, 270 hydroelectric power plants of 1300 MW, 720000 wave devices with 0.75 MW and 490000 tidal turbines of 1 MW. Wind, CSP, and PV are the principal energy sources. Wind supplies 50%, CSP the 20%, and PV 14% of the total global power demand by 2030. This way, the footprint of the WWS device is a 0.74% of global land area with a spacing area of 1.16%, allowing its use for other purposes like agriculture.

That can be reduced to 0.41% an 0.5 %, respectively, by placing half of the windmills, wave and tidal devices over water. Among other options, to ensure the power supply with WWS energy systems, it is considered the storage of electric power on-site or in vehicle batteries.

Nonetheless, this would take longer due to politician difficulties despite several prominent political and scientific calls. They claim for the need of improving the energy efficiency, transmission grid, and the expansion of renewables energies. Another problem for renewable energies is the need for space. However, they demonstrate that just with the wind and solar available in the land outside of Antartica, the power generation could exceed the world power demand by more than one order of magnitude.

Other global simulations have demonstrated that a global decentralized 100% renewable electricity supply based on photovoltaics (PV), wind energy (onshore) and concentrated solar power (CSP) makes possible to reach a global climate-neutral supply system [44]. However, for that, it is essential the use of storage energy systems. In this article, the storage systems selected are batteries, high temperature thermal energy storage coupled with a steam turbine. They obtain the optimum energy cost for the global system at 7,300 GWp installed PV power, 6,700 GW onshore wind power, and 3,900 GW CSP. Wind energy provides almost 50% of the generation, PV and CSP around 15%, and storage system the other 35%.

The global average estimated energy cost of electricity supply for this system is around 142 euro/MWh for the year 2020. This value considerably changes between different world regions. It goes between 80 and 200 euro/kWh (

aggregated on the national level). Nevertheless, the article exposes just a small selection of all the global results for the transition towards a 100% renewable global electricity share, so this simulation is more a reference.

At a continental level, other similar studies exist for America and Europe to provide the whole continent with 100% renewable energy system increasing the use of wind and solar energy. However, some of them were too ambitious. For example, the Alliance for Climate Protection made a study in 2009 for the continent of America in which goal was to achieve a 100% RES system for 2019.

Bussar and Moos studied the optimal allocation and capacity of energy storage systems to reach the new European Commission policy about greenhouse gas emissions in Europe with a 100% renewable energy system [13]. According to them, for that, it is necessary a high efficiency interconnected transport grid and to compensate for the fluctuation of the renewable sources with high energy storage capacities. The appropriate dimension of storage units, the location of generators, and good efficiency of the transmission system are essentials to achieve the most reduced energy cost. Their optimization shows the need for energy storage systems to assure the energy supply and a remarkable dominance of PV generation in Denmark.

Their results for a European RES show a 2500 GW RES with about 240000 GWh of storage capacity to supply a 6% of the yearly energy demand and a transmission grid of 375000 GWkm. The total final cost estimated is 68.7 euros/MWh.

In another study for Europe, Zappa and Junginger [48] model seven different scenarios for Europe to study the feasibility of a 100% renewable energy sources by 2050. They conclude that with today's system adequacy and European resources, it is possible (less than 0.0003% of unserved energy), even in the worst weather periods, but it requires some improvements. The generation capacity has to increase by 90% concerning the currently installed and the cross-border transmission capacity needs 140 GW more than the actual one. The electric vehicles and heat pumps are essential to reduce demand peaks and biogas requirements. An increment of energy efficiency is needed to reduce the biomass demand, generation, and transmission capacity. The actual deployment of solar photovoltaic and wind can be maintained, but the mobilization of biomass resources has to increment, increasing solid biomass and biogas capacity. With respect to their total potential, onshore wind deployment varies between 50% and 64%, and PV ranges between 65% and 85%, always representing the largest installed capacity.

In this study, they consider the scenario of a power system with the generation provided by a mix of renewable energies and low-carbon non-renewable (nuclear or carbon capture and storage) energies. For this, the final energy price is 30% lower than for a 100% RES scenario. Furthermore, the Europe goal of zero carbon footprint by 2050 is not reached for a 100% RES without storage because of the need for biomass with carbon capture and storage.

However, it is impossible to develop a European System 100% RES immediately. A transition period is thus needed. Child and Kemfert [16] develop a transition model towards it by 2050 in two different scenarios, independent regions and areas with regions transmission interconnections. Including current capacities and power plants, they make an hourly resolution since 2015 whose results show that the electricity cost could decrease from the current 69 euros/MWh to 56 euros/MWh in the Regions scenario and 51 euros/MWh in the Area scenario. They consider the use of flexible and low-cost renewable energies complemented by energy storage. The reason for the decrease in cost can reside on the increase of the transmission interconnection by a four factor.

These pathways manifest the increase of wind energy, bioenergy, and PV (especially) during the transition. By 2050, higher cost energy sources, like coal or nuclear, come to their lifetimes' expectations. Therefore, they are replaced by lower cost renewable energies as PV, wind, or biomass. This tendency agrees with The Nobel-Peace Prize winner AlGore. He provides that some electricity sources that as PV, geothermal, or biomass will grow slowly while others as nuclear and hydroelectricity won't grow.

Child and Kemfert's model estimates that solar PV generation contributes 45%, wind 30% and hydropower 11% without interconnection. With this they contribute 41%,37%, and 11%, respectively. The results indicate that biomethane or synthetic methane will take much more relevance and will gradually replace fossil natural gas. Additionally, the shares of renewable energy increase the importance of storage. In 2020 PHES (pumped heat electrical storage) is the leading storage technology, in 2025, the batteries. However, seasonal storage has less relevance in the area scenarios (regions interconnection). The estimated energy served by biomethane storage by 2050 is around 536 TWh. Therefore, they consider technologically possible to accomplish the Paris Agreement aims with an economical and competitive 100% RES in Europe if an appropriate development in the function of regional contexts occurs.

Batteries, pumped hydro, and gas storage are also studied to determine the role of storage technologies to this transition [15]. The storage energy requirements are 3320 GWh for batteries, 396 GWh of pumped hydro storage, and 218042 GWh of gas storage (biomethane mainly). The cost of the storage share increases to 14 euros/MWh. PHS (pumped hydroelectric storage) long term storage shows a combination of storage during the day in summer and higher storage outputs during winter.

For a more reduced area of study, many models have been developed to propose 100% renewable energy systems for individual countries obtaining more detailed results and proposals. Considering a 100% renewable energy system for a country implies to have the electricity as the main vector for energy, limiting some fuels to transport applications, electrification of surface transportation, heating systems, energy transportation more efficient and better buildings insulation [22].

One of the significant challenges of this 100% renewable energy systems is the fluctuation of power and demand. Ernst considers different reasons for it such as the power generated fluctuations due to the daily, weekly, monthly or seasonal irregularities of renewable sources (wind, solar, waves), and the increase of energy demand during periods on which the production is low. To ensure the power supply, he proposes the use of storage units, the control of generated power or the energy demand. Although this last option is helpful for short-term imbalances, for long term imbalances (seasonals), long term thermal storage is proposed. For any of the options, the most important thing is the optimization of the cost by deciding which would be the better technology to invest on.

As said before, the limitations for 100% RES systems are more political or social than technological. Therefore, Ernst proposes governments' investments more oriented to define rules for stakeholders by setting upmarket structures and mechanisms than to generation or storage investment.

In the study done by the University of Lappeenranta about a 100% RES in Eurasia [45], wind energy is the most prominent electricity source which supplies about 47% of the total energy demand by 2050. For storage energy system, they consider the batteries as the key technology with an output of 82% of the total storage. They conclude that it is possible to remove all greenhouses emissions by 2050 and supply the energy demand with a 100% RES comprising the existing RE technologies. At the same time, it is more competitive and efficient than fossil energy systems. Wind and solar energy sources are the most appropriate technologies for this transition.

Another country where 100% RES is being intensely studied is in Germany. Henning and Palzer published in 2013 a powerful tool to develop regional and national 100% energy systems for the transition to a 100% RES in Germany or other industrialized countries [32] [43]. They demonstrate that it is technically possible with a combination of wind, PV, and hydroelectric power plants with long-term storage to cover the periods with low generation. The required installed capacity is about 200 GW with 130 GWh of PV and CSP. This model also considers systems still partly based on fossil fuels with a 70% supply from renewable energies. That needs much less wind and photovoltaic systems and, especially, long-term storage units. That could be used then as a transition vector for industrial countries.

The present work is meant to be the continuity of the simulation done by

Léonard and François on their article *"Electricity storage with liquid fuels in a zone powered by 100% variable renewables"* [30]. In it, they make a simulation for a 100% RES on the country of Belgium over a three years period. The wind is the only energy source considered in combination with storage of electricity for methanol production (power-to-fuel), for which is evaluated its economic viability. The results obtained are an installed wind capacity of 44.6 GW and 13.5 GW for storage. The energy served directly by windmills corresponds to 74.6%, and the final energy cost is 83.4 euros/MWh.

Summing up, all the studies agree that for 2050 a 100% RES is achievable both nationally and globally. However, it is indispensable to define an energy grid which accomplishes three characteristics: reliability, adequacy (supply required energy fulfilling operational and blackout constraints) and security (be able to withstand unexpected irregularities). The Council on Large Electric Systems (CIGRE) and the European Network of Transmission System Operators for Electricity (ENTSO-E) define reliability as "the ability of the power system to deliver electrical energy to all points of utilization within acceptable standards and in the amounts desired" [3] [10]. Therefore, it is indispensable the use of energy storage technologies to deal with the variability of the renewable energies and to assure a continuous energy supply. For all the models, more than half of the demand supply comes from wind and solar energies. The sum of the wind, solar, and storage energy supply varies between 70 and 100% of the total energy demand for all the models. The final energy cost varies between 142 euros/kWh and 51 euros/kWh, which is still a realistic cost. A 100% wind and/or PV solar RES in combination with power-to-fuel storage may comply with all the required characteristics, and it is interesting to study the results and its reliability for different models and regions.

2.2. Motivation of work

This project is born from the need for a radical change in the global energy system. Extreme weather events are becoming more frequent. There are extreme heat waves in Europe almost yearly. In the Arctic Circle during the summer, the average temperature has increased 5°C. Loos of the sea ice sheet, droughts, floods, forest fires, hurricanes, and typhoons are being more extreme and are affecting new zones, such as Ireland, Portugal, or Spain [24]. On the other hand, the atmospheric concentration of greenhouse gases (GHG) as CO_2, CH_4 and NH_2 increases each year 0.4, 0.6 and 0.25%, respectively [14]. That contributes to the change in global climate. So, our environment is changing and, based on scientific evidence; the human-induced global warming is the principal reason [42].

The global temperature has already reached 1°C with respect to preindustrial levels (0.2°C per decade). With an increase of just 1°C, 4% of earth territories would suffer a transformation of their ecosystems. With 2°C, this ratio raises to 13%. The consequences of it would generate problems for global productivity, infrastructure, health, biodiversity, and political stability [24].

So, immediate climate changes are imperative. The European Commission has developed long-term strategics and agreements to achieve a competitive and climate-neutral economy by 2050. Among other things, the European Commission calls for the inversion and research of realistic technological solutions which can lead Europe to zero carbon footprint and to keep the global temperature increase to 1.5°C. In 2011, the European Union (EU) proclaimed as objective to decrease the emissions of greenhouse gases (GHG) by 80%-90% for

2050 to 1990 levels. The Intergovernmental Panel on Climate Change (IPCC) [42] set the temperature rate to 2°C. In 2016, the Paris Agreement reduced it to the actual 1.5°C before pre-industrial levels [9] [2]. For reach these goals, it is necessary that the world global energy system moves towards renewable energy sources to achieve net-zero GHG emissions, or even negative, in 2050. Last year, 28th November 2018, in Brussels the European Commission presented its strategy for a climate-neutral economy by 2050 "A Clean Planet for All" [24]. They consider that a neutral economy requires the improvement of seven areas: energy efficiency, deployment of renewables clean, safe and connected mobility, competitive industry and circular economy, infrastructure and interconnections, bio-economy and natural carbon sinks and carbon capture and storage.

So, it exists a consensus on the needed of a change in the energy system. However, how it should be done is not still clear. One of the most promising solutions is 100% RES. For which is essential large-scale energy storage and carbon capture and storage. The transition towards it depends not only on technological innovation but also on political strategy. That is why around all the world, scientists have to investigate and develop realistic and efficiency strategies to develop affordable 100% RES by 2050. The reduce of the cost of renewable energies has advanced, but financial and market support is necessary. Moreover, to obtain that it is indispensable to continue with the research to find the best climate-neutral energy system.

Being Belgium one of the 195 countries that adopted this legally consolidated climate deal, the Departement of Chemical Engineering of the University of Liège is developing a modelization of a zone powered with 100% renewables energies and long-term storage.

The present work aims to develop an energy model to study the relevance of long-term energy storage within the Belgian and Spanish electricity zones powered with 100% renewables. A first model of an electricity zone powered with 100% wind energy system has been described previously for Belgian electricity zone by Profesor Léonard [30]. This model simulates a system that could be encountered in 2050 if the guidelines suggested by the European Commission are respected and that the electricity sector is almost fully decarbonized (-93 to -99% CO2 as compared to 1990 emissions). An electricity zone with 100% wind energy system is simulated to determine the optimal sizing of generation and storage capacities in such a zone. However, this model is affected by several limitations, and the goal of the present work is to improve this model.

Among other possible improvements, a new version of the model is done in this work to address two main topics. Firstly, solar PV (photovoltaic) energy source is added. Between others, this renewable energy has a completely different variability profile with respect to wind so the specific study of their combination with long-term energy storage capacities may be of interest for the planning of future grid development. Three different hypothetical 100% RES scenarios are developed:

1. A combination of wind energy and methanol storage

2. A combination of PV solar energy and methanol storage

3. A combination of wind energy with PV solar energy and methanol storage

Secondly, another version of these three models is elaborated for an entirely different electricity zone, Spain. This country presents a very different distribution of renewables energies and electrical network. So the study of the different results can be of interest for the developing of a more general model.

Thus, six models are developed. Them evaluate the economic viability of a power-to-fuel storage technology that combines water electrolysis, CO2 capture, and methanol synthesis. The main advantage of using methanol as an energy carrier is that liquid fuels are suitable for (long-term) energy storage thanks to their high energy density. Finally, the goal of the research is to contribute to the evaluation of the economic potential of power-to-fuel storage technology in different electricity zones where power is only generated by wind and/or solar renewables energies and power-to-fuel.

3. RENEWABLE ENERGIES

After reading the articles and researches exposed on the bibliography and the section 2.1, it is remarkable that, between all the renewable energies used for those modelizations, wind and solar energies are the ones with more outstanding influence and repercussion on 100% renewable energy systems. Between both, they supply around 50% and 85% of the total energy demand. Even more, these are inexhaustible sources available all around the world and do not imply a combustion process, which means there is not toxic gases production. Therefore, these are the one used for this modelization.

3.1. Wind energy

Wind energy is kinetic energy transformed into mechanical energy with windmills. Those, finally, convert it into electric energy using magnetic camps and transformers to adequate the voltage.

The energy capacity of one windmill is equivalent to 1000 kg of Petrol and has a higher lifecycle. There are two kinds of windmills, upwind turbines, and downwind turbines. The first type is the most common. They have the rotor in front of the unit and need a yaw drive to orient them facing the wind when the direction changes. Its advantages are the reduced tower shading and power losses because the air starts to bend around the windmill before it gets by. The disadvantage is that the yaw mechanism needs to avoid blade strikes. Thus, the blades must be stiff to avoid bending the tower. Therefore, the part of the union to the rotor shaft suffers high stresses during high wind conditions. In small scale renewable energy generation, upwind turbines are the most common.

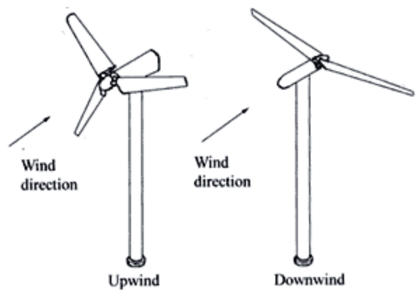


Figure 3.1: Upwind and downwind turbines.

The most common machines used in wind turbines base their operation on electromechanical devices Faraday's law. That means, they function through the interaction of magnetic fluxes and electric current. In large wind turbines AC synchronous (or AC Generator), and AC induction (or Alternator) generators are the usual ones. For residential wind turbines tend to use low voltage DC machines (or Dynamo) due to their smaller size, cost, and easier use.

A magnetic field moving beyond an electrical coil of wire is what make the turbine generator work. Following the Faraday's law of magnetic induction, this generates an induced voltage in the coil (electro-motive force, efm) starting a flow of electrons, an electrical current. That means it is generating electricity, sinusoidal waveform.

The induced voltage is proportional to the rotation speed of the coil and to the power of the magnetic field (ϕ) because it cuts more often the magnetic flux.

$$emf \propto \phi$$

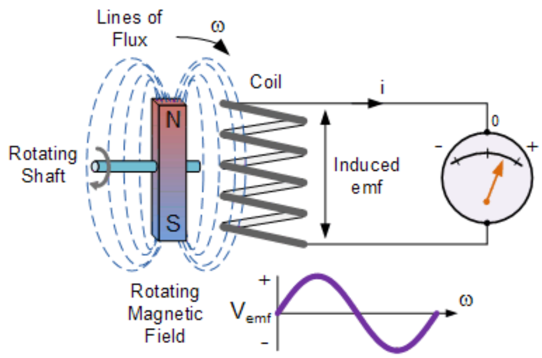


Figure 3.2: Magnetic induction generator.

The cost of the wind energy generation is several affected by the distance between windmills and transmission lines. The annual energy output can be calculated per square meter of area scope by the rotation of the blades; this factor is named specific yield. The increase in blades length means a higher swept area. This increases significantly the power output from a windmill. Therefore, the size of it is expected to increase over the next years, as shown in figure 3.3. That haze the actual dilemma about the space needed for renewables energies.

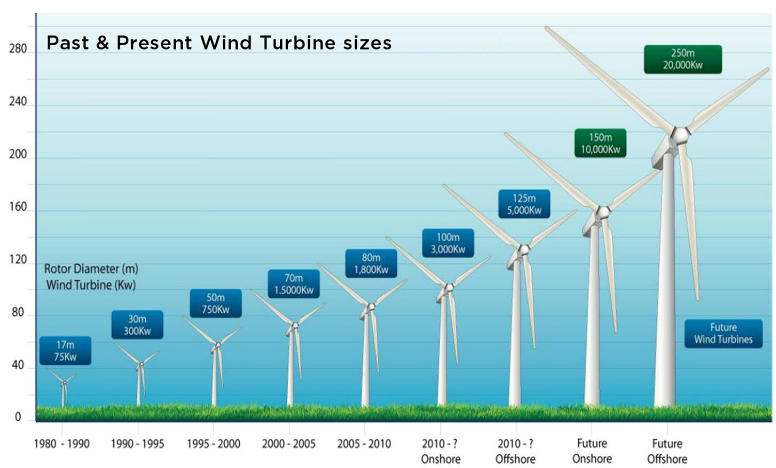


Figure 3.3: Expected windmills size.

However, areas with huge potential for energy production but remote from load centers are not exploited yet. Even so, windmills are compatible with agricultural and livestock activities, enriching the local economy.

So, the most outstanding problem to deal with when working with windmills is the variability of wind. Modern turbines include electronic controls to adjust their output to the electricity demand to balance it. That makes it more flexible and easier to stabilize the grid. However, it is not enough having to resort to storage technology to improve reliability.

3.2. Solar energy

The combination of hydrogen atoms on the Sun to form heavier helio atoms liberates energy in the form of luminous radiation. Part of it arrives at the Earth, around $1000W/m^2$, and can be used both for photovoltaic solar energy or concentrating solar power (CSP).

The most common is the first one. It uses photovoltaic cells where the incident solar rays of some specific spectrums (visible light, ultra-violet or infra-red) move electrons and channelize them to produce electricity without needing any moving parts. The cells are usually made of specially treated silicon semiconductor, a highly purified in *Si* silicon doped with penta or trivalent impurities that give them an abundance of "free electrons" or "holes" within its structure.

Solar power generation creates a DC current flow over the surface of the PV cell. The PV panels have two electrical connections for conventional current flow to connect the semiconductor with the external load. Metallic strips are connected to the P-type and N-type semiconductor to collect the electrons, forming the positive connection. A coat of aluminum and molybdenum metal creates the negative one which is on the opposite side from the sunlight. Therefore, photovoltaic solar cells act as a battery generating both voltage and DC current.

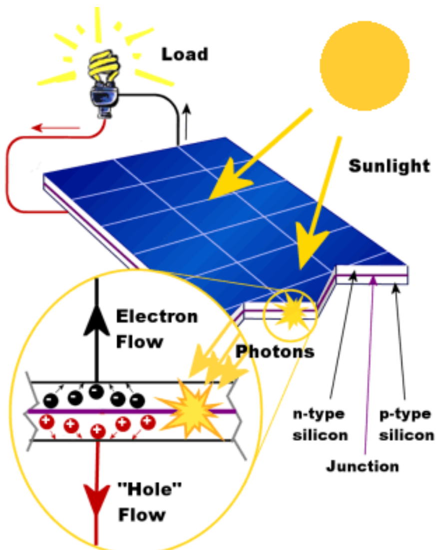


Figure 3.4: Photovltaic solar panel operation.

The maximum current provided by one PV solar cell is named the "maximum deliverable current" (I_{MAX}), and it is independent of the suns radiation. Its value is a function of the whole area of the cell, but mainly, of the junction, the direct sunlight incising on it, its efficiency and on the semiconductor material (silicon, cadmium, sulfide...). The maximum deliverable solar power (P_{MAX}) is

$$P_{MAX} = V_{OUT} \cdot I_{MAX}$$

where V_{OUT} is the cell voltage and I_{MAX}, the cell current.

The available power at any moment is as before (voltage times current). For obtaining the highest possible electrical power, the surface of the photovoltaic cell must be oriented straight toward the sun to increase the photovoltaic effect or increase its efficiency by changing the material type of cell. Nowadays, most commercial one is silicon.

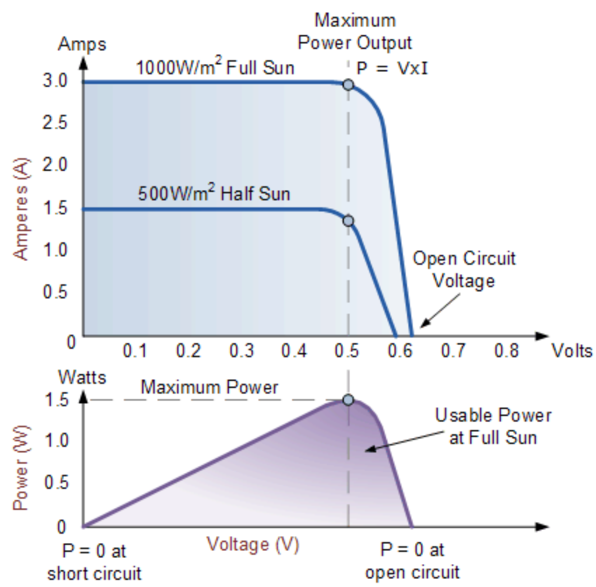


Figure 3.5: Photovltaic solar cell power generation.

These installations are ideal for residential installations as their only cost is the solar panel and its placing. Even, in some countries, if your power generation is higher than your load, it can be directly transmitted to the general grid and embossed.

On the other hand, CSP consists on using thermal energy concentrators (usually mirrors) to capture, concentrate and transform the solar radiation into high-temperature heat, using a heat transfer fluid, to produce electricity through a steam turbine. This system allows the plant to operate even when the sun does not shine. The amount of radiation that the Earth receives is enough to consider this technology as a part of a green energy future.

In brief, solar energy is a clean, easy to harness, and worldwide available energy source. It generates no waste products, air or water pollution and neither noise pollution. That makes solar energy an ideal resource for a 100% RES.

4. ENERGY STORAGE WITH METHANOL PRODUCTION

Renewable energies have significant advantages, but they have a considerable drawback. Due to their intermittency, there are successive periods of shortage and excess of energy. That leads to the waste of energy (if it is not consumed) or to blackouts, in addition to other high costs like switching off windmills due to the strong wind because of the need of demand and supply balance in power [11]. Thus, countries can consider this as a burden on the use of renewable energies. One way to solve it is the utilization of energy storage technologies. When the electricity generation of solar or wind energy is higher than the demand, the difference can be stored and consumed when it is needed. That leads to a decrease in the energy sources capacity and the payback period.

In this project, the considered storage is power-to-fuel storage technology that combines water electrolysis, CO_2 capture, and methanol synthesis. Because, as Noble Prize Georges Olah mentioned in its book *The Methanol Economy* (2005), methanol appears to be the most convenient energy carrier. One big advantage of power-to-methanol is the fact that the storage is very cheap because it is stored as liquid at ambient temperature and presion. Therefore, the marginal cost of storage itself is neglected in this work.

4.1. Methanol production

The main advantage of using methanol as an energy carrier is that liquid fuels are suitable for long-term energy storage thanks to their high energy density (22.7 MJ/kg for methanol, HHV). Even though this hydrocarbon is biodegradable and can be produced without using fossil fuels or biomass and used in the existing infrastructure (fuel distribution and vehicles). Therefore, the infrastructure required and the conversion cost are low. Considering the motivation of this work, power-to-fuel storage is a good option due to the need for the capture of CO_2 of the atmosphere for methanol production, that makes this technology a CO_2-neutral energy carrier.

Methanol is a liquid which makes its storage and transportation easier and safer than for other hydrocarbons, such as hydrogen, as methanol is non-toxic, non-corrosive and non-flammable. Actually, the methanol production comes 90% of the methanol from natural gas [40], but it can be produced as well from natural gas, biomass, coal (converting it into syngas) or from CO2. This last option is the one considered for the energy storage technology of the present project.

The stability of the CO_2 makes necessary an energy input of around 230 kJ and six electrons to reduce the C^{4+} of CO_2 to C^{2-} of methanol [27]. For this reason, it is needed an adequate catalytic conversion by hydrogenation.

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O$$

Where the CO_2 can be captured from the environment and the H_2 is obtained by water electrolysis.

The two most common systems for the methanol synthesis are adiabatic and isothermic processes. Adiabatic reactors reach low conversions and high recycle ratio, reagents dilution, and catalysts volume due to the high temperatures required for the equilibrium. They are usually modeled by fixed bed reactors with heat removal [28]. The most adequate reactor to reduce the process temperature is the indirect cooled (succession of adiabatic reactors with intermediate cooling). But, the most simple one is the quench reactor on which a part of the reactants is inserted preheated, and the other portion is fed in intermediate phases, but cold to reduce the reactor temperature. Despite its simplicity, it presents a non-uniform catalytic activity.

Isothermal reactors are constantly cooled with the exchange of energy for water evaporation. Its limitations are the space needed, due to the exchanger, and the high installation costs, however, it has a good process control.

Therefore, long-term energy storage into methanol is possible, and research is studying its application at small scale.

4.2. Methanol as fuel

Because of its low cetane rating, methanol can be utilized as a substitute of diesel fuel in combustion ignitions engines or vehicles with a mixture of 85% methanol and 15% gasoline (M-85) to prevent the corrosive effect of pure methanol on vehicles. However, it has functional applications as marine fuel being much more cheaper than marine distillate fuels and sulfur-free [41].

In the production of biodiesel, the methanol is applied for the esterification and transesterification to obtain utilizable biodiesel. During the transesterification, methanol reacts with triglyceride oils, from different sources such as animal fats or vegetable oils, to generate biodiesel as fatty acid alkyl ester. The biodiesels produced contain between 48 and 52 cetane number and less than 20 ppm of sulfur, which make them a good option regarding the actual fuels [28].

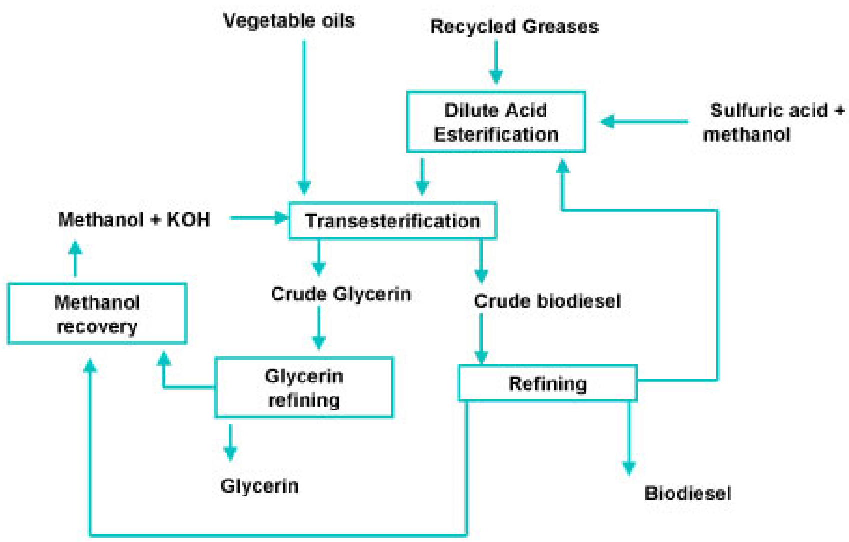


Figure 4.1: Biodiesel production flow-chart.

A way to produce electricity from methanol, to transform chemical energy into electrical energy, are the Fuel Cells. It consists of a catalytic reaction produced with an anode, a cathode and an electrolyte between them. Between all the kinds of Fuel Cells, Direct methanol fuel cells (DMFC) present some advantages over the others, like its simplicity, high fuel energy density, liquid fuel easily stored, lower required temperature or lower pollutants emission [26].

DMFC are composed by an anode current collector (ACC), a cathode current collector and a membrane electrode assembly (MEA) formed by an anode diffusion layer (ADL), an anode catalyst layer (ACL), a polymer electrolyte membrane (PEM), a cathode catalyst layer (CCL) and a cathode diffusion layer (CDL) [36], as shown in figure 4.2. The overall reaction in the cell is

$$\frac{3}{2}O_2 + CH_3OH \longrightarrow CO_2 + 2H_2O + heat$$

Where the elecrochemmical reactions occured are

$$Anode : CH_3OH + H_2O \longrightarrow CO_2 + 6H^+ + 6e^- + heat$$

$$Cathode : \frac{3}{2}O_2 + 6H^+ + 6e^- \longrightarrow 3H_2O + heat$$

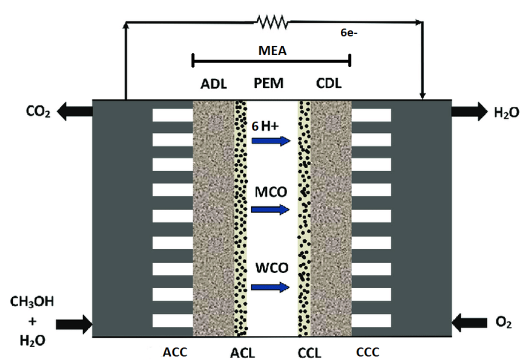


Figure 4.2: Direct methanol fuel cell schema.

For these cells, methanol can be supplied both in liquid or gas forms, and the operating temperature is between 40 and 80 degrees [46]. However, the principal drawback is the methanol crossover because the electrolyte is not an efficient methanol barrier. This problem that can be faced by reducing methanol concentration and temperature [12].

Methanol has then several applications and can be further use in other fields. Therefore, the methanol stored can be harnessed to the fullest and used in different fields in function of the economic interests at each moment. That makes the power-to-fuel storage technology an interesting technology in order to decrease as much as possible the energy price.

5. MODEL DESCRIPTION

For the present project, three different models to 100% RES systems are developed in different scenarios. In this section, the different models, its goals and performance are described. Then, the considered assumptions and economic variables are discussed. After that, the used parameters and variables are explained and the problem formulation is developed.

5.1. Description

Model goals and performance

Three simplified models of an electricity zone with 100% renewables are developed. The approach is applied to three different hypothetical scenarios:

1. A combination of wind energy and methanol storage

2. A combination of PV solar energy and methanol storage

3. A combination of wind energy with PV solar energy and methanol storage

These 3 scenarios are not fully realistic as in reality, wind and solar will be complemented by other sources such as hydro or biomass. However, the idea is to study the impact of having large shares of variable renewable sources on the electricity grid. Also, solar and wind energy present different variability profiles (night/day and interseasonal), so the specific study of their combination with long-term energy storage capacities may be of interest for the planning of future grid development. Those are developed for two European countries with a very different distribution of renewables energies and electrical network: Belgium and Spain.

Therefore, in total there are six scenarios:

- Scenario 1: Belgian system provided 100% by wind energy and methanol storage.
- Scenario 2: Spanish system provided 100% by wind energy and methanol storage.
- Scenario 3: Belgian system provided 100% by PV solar energy and methanol storage.
- Scenario 4: Spanish system provided 100% by PV solar energy and methanol storage.
- Scenario 5: Belgian system provided by a combination of wind and PV solar energy with methanol storage support.
- Scenario 6: Spanish system provided by a combination of wind and PV solar energy with methanol storage support.

The purpose of this study is to minimize the energy cost (euros/kWh) by determining the optimal combination of energy generators (windmills, solar panels or both) and long-term storage based on methanol production (power-to-fuel). Then, this model determines the viability of power-to-fuel storage technology.

This technology combines CO_2 capture, water electrolysis, and methanol synthesis to finally produce a CO_2 neutral liquid fuel. The reason for using this technology is that methanol is a liquid fuel suitable for long-term energy storage to a very cheap cost because of its store at ambient temperature and pressure.

Based on the generation and load data (section 5.2) disponible at [4] [7], the program compares at each resolution time (15 minutes for Belgium and hourly for Spain) the historical demand, on the country that corresponds, with the power that can be generated by the theoretical installed power of wind and/or solar and power-to-fuel capacities. If wind and/or solar power generation capacity is larger than the load, the surplus electricity is stored with power-to-fuel technology. But, if the demand is higher than the generation, the missing electricity is obtained by converting back to electricity some methanol from the storage units. Finally, the program changes the number of windmills and/or PV cells and storage units and repeats the procedure in order to find the optimal combination to minimize the electricity cost.

Two constraints must be respected. Firstly, assure that the demand is always supplied restraining the lost of load hours (LOLH) below to 0.25 hours for the whole sample period (no blackouts). The second is to have the same storage level (amount of methanol stored) at the beginning and the end of the period. This condition ensures the match between installed capacities and system requirements.

Curtailed energy is assumed to occur when wind and/or solar generation surpasses both the demand and the storage capacity (limited by level or power input). It is supposed to not incur on detrimental consequences to the grid stability.

Assumptions

Both zones are assumed to have as the only primary source for electricity generation wind power, solar power or a combination of both, in function of the scenarios described previously. It is combined with long-term storage in the form of methanol to avoid blackouts and energy losses due to the variability profiles of wind and solar energies.

The CO_2 capture for this system is supposed to be the one previously developed by Léonard and al (2015). It consists of an interconnection of energy consumption, solvent degradation, and emission. It uses amine solvents and an absorption regeneration loop to absorb CO2 into it. The capture reaches an achieved is around 90%.

It is considered that the methanol is virtually centralized in a single storage tank, whose capacity is evaluated so that $85.75 \cdot 10^{18}$ kWh, which corresponds to the value in actually deliverable energy after considering the virtually applied RTE for storage technology (RTE = 0.5). The initial storage level is conditioned to be the same at the beginning and the end of the period. The maximal size of the storage tank is the one with which the storage level never gets negative. In this way, the minimum storage level is defined to be zero.. For almost all scenarios, the value done by Léonard et al. has been maintained, $4.42 \cdot 10^9$ kWh. Just for Belgian 100% wind energy system the value has been changed to $1.55 \cdot 10^9$ kWh.

Recall that one significant advantage of power-to-methanol is the fact that the storage is very cheap (storing a liquid at ambient T and P) so that the marginal cost of storage itself is neglected.

One important approach is that all the models consider a system optimum rather than an agent-based approach. That means a communist country where both windmills and storage units belong to the state rather than a capitalist system with different actors. In consequence, it is assumed that the energy that is stored is free as a result of a zero cost for the storage units. Neither market competitiveness or the possible different uses for liquid fuels (fuel substitute, biodiesel production, its potential in the transport sector...) are contemplated. So there is no interaction with neighboring zones, and the results aim to be an orientation on the technology needed to reach the zero carbon footprint in a state-controlled electricity zone. Furthermore, oxygen applications (as water electrolysis by-product), limitations on transmission and distributions, and the cost of grid control units (measure renewable energies generation and transmission to storage units) are not considered.

Concerning the economic and technical parameters, they are assessed from the literature, mostly from *Energy Technology Reference Indicator projections for 2010-2050 (ETRI 2014)*. The economic parameters for both countries are assumed the same as on this document, the indicators are referred to all Europe. All these parameters are exposed in section 5.2.

The discount rate value is assumed to be 0,07 for wind energy and 0,06 for solar energy. That takes into account the different value of the actual annuity cost and the future one. Therefore, a lightly higher descent is considered for the economic value of wind energy. It is assumed that storage technology may further evolve, so a RTE for the storage technology of 0.5 seems achievable by 2050. This assumed value is different from the 0,45 indicated at [31].

The data of energy demand and generation comes from the historical data for the Belgian and Spanish transmission system, available at official webs [5] and [4]. The period covered is of 5.8 years for Belgium and 4 years for Spain. Those are different due to the available data at the moment of starting the model.

Besides, the solar energy generation data for Spain combines photovoltaic solar energy (PV) and concentrated solar power (CSP). The available generation data of [7] includes both installations. Actually 85.53% of generation comes from PV and 14.47% from CSP, it is estimated 90% PV and 10% CSP for 2050. The capacity factor and the installed capacity for both technologies is completely different, CSP works with mirrors an PV with panels. For the model, in order to obtain a 100% PV RES system it is needed the generation due just to PV. If not, the resulting PV panels are not realistic because it is considering CSP installations and it is suposed that the only primary energy source is PV solar. To adapt the data to the currently proposed system (served 100% by PV cells) the generation data is then multiplied by 0.9 to consider just the power generated by PV cells.

The linear combination of off- and on-shore wind in Belgium leads to very high capex (capital expenditures referred to funds used to acquire, improve or maintain physical assets) and FOM (recurring annual cost that occurs regardless of the size or architecture of the power system). Thus, in this work is taken the same hypothesis done for the articles [44][48] and [30]. It is, the values are kept for on-shore only, in order to have more reasonable prices for wind. On the other hand, in Spain, there are no off-shore wind farms. The fundamental reason, according to Ignacio Cruz, director of Wind Energy Center for Energy, Environmental and Technological Research (Ciemat), is the high depth of the seabed about four or five kilometers from the coast, which is where these farms are usually built. This limitation affects off-shore fixed-foundation wind turbines because they need to be fixed on the seabed. Furthermore, there is space to build twice as much wind on land and at much lower costs (Ciemat).

From National Survey Report of PV Power Applications in Belgium (IEA,2015), the PV installations are 60% residential and 40% industrial. This data is taken into account for the capex of solar panels. The capex and the FOM for residential installations are 800 euros/kW and 2% of capex, and for industrial installations 720 euros/kW and 2.5% of capex [17], the total capex and FOM are

$$capex_{pv} = (0.6 \cdot 800 + 0.4 \cdot 720) \cdot p_{pv}$$

$$FOM_{pv} = (0.6 \cdot 0.02 + 0.4 \cdot 0.025) \cdot capex_{pv}$$

5.2. Data

Input data includes power production and installed capacity for solar and wind energy sources and the total load for each country. All of them available at 15 minutes resolution for Belgium [4] and hourly for Spain [5]. This way, the input data is representative of a real electricity zone. From now on, this variable of 15 min or 1 hour is refered by the term "measurement period". The sample period changes for each country due to the available data at the time of beginning each model. In Belgium comes from 14/11/2012 to 31/08/2018. For Spain comprises from 01/01/2015 to 31/12/2018. That is what, from now on, is called "period of time". Over these periods of time the average load of the system is 8.9 GW for Belgium and 28.7 GW for Spain. The average capacity factor for wind in Belgium is 0.277 and 0.240 in Spain. For solar 0.111 and 0.217, respectively.

To calculate the average electricity cost, it is used the levelized Capex and Opex of storage, wind and/or solar energy over the respective periods of time divided by the corresponding served electricity. From [17] has been obtained the technical and economic parameters for onshore wind and solar energy estimated for the year 2050, as shown in the tables 5.1 and 5.2. Thus, market competitiveness and time cost variations are not taken into account. So, it would not be profit of selling energy at that price. The final electricity cost may be seen as upper bound price that just depends on renewable energies and storage installed capacities and the assumptions exposed above.

Table 5.1: Technical and economic parameters for wind energy.

Parameters	Units	Value
Windmill nameplate	kW	5000
Capex	euro/kW	1100
FOM	euro/kW	1.7% capex
Lifetime	years	25

Table 5.2: Technical and economic parameters for solar energy.

Parameters	Units	Value
Solar panel nameplate	kW	0.3
Capex (residential)	euro/kW	800
Capex (industrial)	euro/kW	720
FOM (residential)	euro/kW	2% capex
FOM (industrial)	euro/kW	2.5\capex
Lifetime	years	20

The reference indicators for methanol storage, adding RTE and storage size, are designated in the table 5.3, taking as reference [18] for capex, FOM, opex and lifetime of storage.

Table 5.3: Technical and economic parameters for methanol storage.

Parameters	Units	Value
Power capacity	kW	250
Capex	euro/kW	856
Opex	euro/kWh	0.006
FOM	euro/kW · year	25
Lifetime	years	20
RTE	-	0.5
Size	kWh/storage unit	$85.75 \cdot 10^{18}$

The parameters used for determining the CO_2 emissions reduction are [8]

Table 5.4: Emissions of CO2 for different energy sources.

	Emissions (gCO2/kWh
Wind	14
Coal	870
Natural gas	464
Nuclear	12
Solar	45
Hydro	7
Liquid fuels	280
Biomass	14

The different grid characteristics for each country are reflected in the table 5.5

Table 5.5: Belgian and Spanish electric system.

	Belgium (2017)	Spain (2018)
Installed power (GW)	22	104
Demand (GWh)	81000	269000
Peak load (GW)	13	40
Renewables capacity (%)	26.55	40
Wind capacity (%)	12	19
Solar capacity (%)	4	5.5

The ratio of energy sources for each country varies [4][7]. The respective values are given in the table 5.6 .

Table 5.6: Percentage of installed capacity for different energy sources for each country.

	Belgium	Spain
Wind	12	19
Coal	0	13.5
Natural gas	35.5	24
Nuclear	36.5	20.5
Solar	4	5.5
Hydro	8.4	13.5
Liquid fuels	1.45	2
Other renewables (Biomass)	2.15	2
Total renewables	26.55	40

Then, the CO2 emissions for each country are different. The equation used to calculate it is

$$CO_{2emissions,country} = \sum y_r \cdot e_r(g/kWh)$$

where y_r is the percentage of each energy source for the different countries and e_r its recpective emissions.

5.3. Parameters and variables

Below are shown the parameters used for the models and their definition. *Economical and characteristics indicators for windmills, solar panels, and storage units:*

- Nameplate power (p_x; kW): the amount of electric energy that a generator can output sustained under ideal conditions.
- Storage power (p_{st}; kW): input power capacity of a large-scale solid oxide electrolyser cells (SOEC).
- Capex ($capex_x$; euros/kW): capital expenditures referred to funds used to acquire, improve or maintain physical assets.
- Opex ($opex_x$; euros/kW): costs expended on a daily basis to run the installation.
- FOM (% capex): recurring annual cost that occurs regardless of the size or architecture of the power system.
- Lifetime ($life_x$; years): a period of time while something is still useful.
- Discount rate (r): interest rate used to calculate a value to future cash flows. Therefore, the higher the discount rate, the lower the future value will be.
- Annuity cost ($annuity_{cst}$): the current value of future payments from an annuity, given a specified rate of return or discount rate. The higher the discount rate, the lower the annuity cost.

- Round trip efficiency (RTE): the ratio of the energy put into the device and the retrieved from the storage. The more efficient the system, the higher the round trip efficiency and the less energy lost due to the storage.

$$RTE = \frac{Energy_{recovered}}{Energy_{input}} \cdot 100$$

Parameters related to the energy served and/or produced and the power:

- Expected unserved energy (EUE; kWh): the amount of demanded energy not served by the supply.
- Loss of load hours (LOL; h): the sum of time periods during which the demand is not served. That will be equivalent to a blackout during it.
- Ratio of expected unserved energy (REUE): percentage of the demanded energy that is not served.
- Probability of loss of load (PLOL): the amount of time during which the demand is not served over the total time period that is considered.
- Size losses ($loss_{size}$; kWh):total curtailed energy due to limited storage size.
- Efficiency losses ($loss_{eff}$; kWh): energy lost due to RTE.
- Power input losses ($loss_{pin}$; kWh): energy that cannot be stored due to the limitation of power input into the storage unit.
- Cost of windmills or solar panels ($cost_i$; euros/kWh): cost of the energy served by windmills or solar panels.

- Cost of storage ($cost_{st}$; euros/kWh): cost of the energy served by storage units.
- Total cost ($cost_{tot}$; euros/kWh): cost of energy provided by both wind or solar panels and storage units.
- Power capacity installed (power; GW).
- Service of windmills or solar panels ($serv_i$; kWh): the amount of energy generated by windmills or solar panels and used for the load (not for the storage) every 15 minutes for Belgium and each hour for Spain.
- Service of storage units ($serv_i$; kWh): the amount of energy delivered by the storage every 15 minutes for Belgium and each hour for Spain.
- Service total by windmills or solar panels ($serv_{total_i}$; kWh): the total amount of energy generated by windmills or solar panels and used for the load (not for the storage) during all the period of time.
- Service total by storage units ($serv_{total_st}$; kWh): the amount of energy delivered by the storage during all the period of time.
- Storage units level (st_{level}; kWh): level of deliverable energy at the storage units at the end of the period.
- Spread (kW): the difference between the power demand and the production for every 15 minutes in Belgium and each hour in Spain.

5.4. Problem formulation

The developed models formulate an energy cost optimization, for the year 2050, comprising two renewables energy sources (wind and solar) in combination with power-to-fuel. Economic parameters evolution, operating and investing costs are taken into account for the realization of the most realistic optimization. Generation and load historical data, as well as technical parameters (as installed capacity), are required for running the optimization. It gives the most optimal combination of energy generators and storage units to minimize the energy cost; assuring, at the same time, a continuous energy supply.

For quantifying the losses, are taken into account the limitations of the grid for power input, the limitations of the storage units size and the losses due to the round trip efficiency.

In what follows, the performance of the models will be described denoting the different energy generators (windmills or solar panels) as "x" and the storage units as "st".

5.4.1. Renewable technologies

The power capacity depends on the number of energy generators.

$$Power = n_x \cdot p_x$$

being n_x the number of energy generators and p_x the nameplate power for each generator.

In the combination of both energy sources (wind and solar)

$$Power = n_{wm} \cdot p_{wm} + n_{pv} \cdot p_{pv}$$

where n_{wm} and n_{pv} are the number of windmills and of solar panels, respectively; and p_{wm} and p_{pv} the nameplate power for windmills and solar panels, respectively.

The investment and operating costs for each energy generator expressed as

$$capex_x = capex(euro/kW) \cdot p_x(kW)$$

$$FOM_x = FOM_x(\%) \cdot capex_x(kW)$$

$$annuity_{cst,x} = \frac{r}{1-(1+r)^{-life_x}}$$

5.4.2. Storage technologies

The range for storage units level varies between 0 and the total storage size in actually deliverable energy (after RTE).

$$st_{max} = n_{st} \cdot size_{st}$$

Being n_{st} the number of storage units and sizest the size of one storage unit. This value is $4.42 \cdot 10^9$ kWh for all scenarios except for Belgian 100% wind energy system. On it the value has been changed to 1.55· 10^9 kWh.

The limitations of the input and output of power will depend on the number of storage units. Evaluating the input before the RTE and the output after, they are expressed as

$$p_{in,max} = n_{st} \cdot p_{st}$$

$$p_{out,max} = n_{st} \cdot p_{st}$$

As well, the investment and operating costs for one storage unit are

$$capex_{st} = capex(euro/kW) \cdot p_{st}(kW)$$

$$FOM_{st} = FOM_{st}(euro/kW) \cdot p_{st}(kW)$$

$$annuity_{cst,st} = \frac{r}{1 - (1 + r)^{-life_{st}}}$$

considering other parameters values, as nameplate power, power capacity, round trip efficiency, opex or storage size, the one exposed on section 5.2.

5.4.3. Energy spread

The energy generated can be used for the load supply or be stored. It depends on the spread, which is the difference between the energy generated by wind and/or solar and the load on the measurement period. The maximum generation capacity of wind and/or solar energies will be the number of windmills and/or PV cells multiplied by its nameplate power. This value is multiplied by its capacity factor in order to obtain the actual energy generated. So, the spread is defined as

$$spread_i = n_x \cdot p_x \cdot cf_i - load_i$$

where i corresponds to the measurement period of load and generation (being 15 minutes for Belgium and 60 minutes for Spain), n_x to the number of generators (windmills or PV cells) and p_x to the nameplate power of each.

In the combination of both energy sources (wind and solar)

$$serv_{wm} = n_{wm} \cdot p_{wm} \cdot cf_{wm,i}$$

$$serv_{pv} = n_{pv} \cdot p_{pv} \cdot cf_{pv,i}$$

$$spread_i = serv_{wm} + serv_{pv} - load_i$$

being $serv_{wm}$ and $serv_{pv}$ the energy generated by windmills and solar panels, respectively. A part of it can be used for storage and not be directly served. That will depends on the value of $spread_i$ (spread at each measurement period).

5.4.3.1 Positive spread

If the spread is positive, meaning the generation is higher than the load, this last one is totally provided by the energy generated at this sampling time by the energy generators (windmills or solar panels).

$$serv_{x,i} = load_i \cdot t$$

being t the measurement period in hours (t = 0.25 for Belgium, t = 1 for Spain).

In this case, the energy input of the storage units is determined by the minimum between the maximal power input ($p_{in,max}$), the spread and the available free storage space in the storage units ($st_{max} - \frac{level_i}{RTE \cdot t}$) at this moment.

$$p_{in} = min(p_{in,max}, spread_i, st_{max} - \frac{level_i}{RTE \cdot t})$$

The energy increment in the storage units and the new storage level, after considering the RTE, are

$$st_{in} = p_{in} \cdot RTE \cdot t$$

$$level_{i+1} = level_i + st_{in}$$

For being rigorous, it should be considered the effectiveness of the conversion of electricity to methanol to know how much energy is on the storage. Moreover, when the power is left from the storage, it would be necessary to apply the effectiveness of the conversion of methanol to electricity. However, this is simplified by considering the RTE. Due to the RTE the amount of energy sent to the storage is not the same that arrives. RTE is applied to the power input; therefore, the energy that is stored has no longer losses. In order to consider the "net" energy, this energy loss is already virtually removed by multiplying the power input by the RTE.

Additionally, energy losses are different in function of the maximal power input, the spread, and the available free storage space in the storage units.

If the maximal power input is the smallest of these parameters, then it causes a curtailed of energy due to insufficient power intake.

$$loss_p = min((spread_i - p_{in,max}) \cdot t, (st_{max} - \frac{level_i}{RTE \cdot t} - p_{in,max}) \cdot t)$$

In the first situation, figure 5.1, the free storage level is enough to store all the available energy (spread). However, it is not possible because not all the energy can be sent to storage due to the power input limitation. Therefore, the energy loss is the difference between the spread and the maximum power input. The energy stored is the maximum power input multiplied by the measurement period.

$$loss_p = (spread_i - p_{in,max}) \cdot t$$

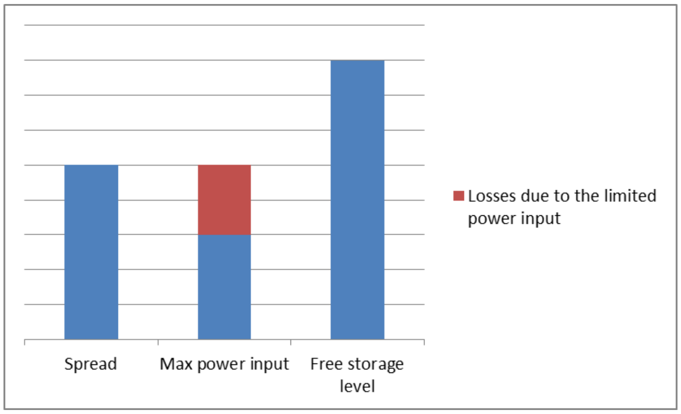


Figure 5.1: Representation of energy losses if maximal power input is the limiting variable followed by spread.

In the second, figure 5.2, the free storage level is the second limiting variable. Which means, there are energy losses due both to the limited power input and to the storage size. The loss due to the maximum power input is the energy that could be stored if having a higher maximum power input. This lost energy is the difference between the available storage level and the maximum power input. The free storage level is the difference between the maximum level (st_{max}) and the actual ($level_i$). This last one is divided by the RTE in order to obtain the "net" energy stored. The loss due to the storage size is the energy that can not be stored because of the lack of space, and that does not depend on the maximum power input. Therefore, the energy stored is once more the energy that can be sent with the maximum power input value.

$$loss_p = (st_{max} - \frac{level_i}{RTE \cdot t} - p_{in,max}) \cdot t$$

$$loss_s = (spread_i - (st_{max} - \frac{level_i}{RTE \cdot t})) \cdot t$$

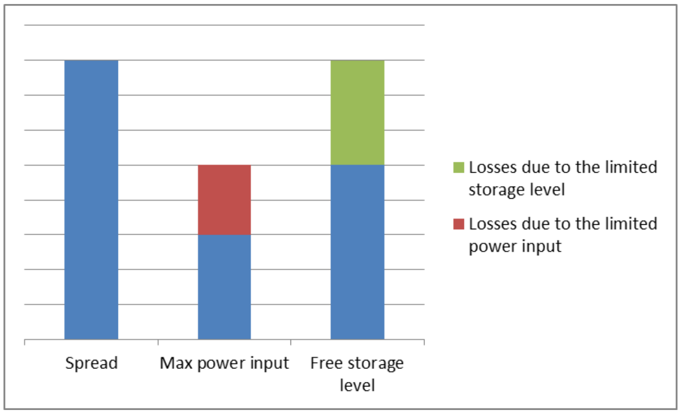


Figure 5.2: Representation of energy losses if maximal power input is the limiting variable followed by free storage level.

On the other hand, if the available free storage space is the smallest one but spread is higher than the maximum power input there are again losses due to the maximum power input and to the storage size, figure 5.3. The loss of energy because of the limited power input is the energy that can not be stored even if the storage size is enough. The loss of energy because of the limited storage level is the energy that would be possible to store with larger storage size and the same power input limitation still stays. The energy loss is the difference between the maximum power input and the available storage level. The energy stored is the available energy storage level.

$$loss_p = (spread_i - p_{in,max}) \cdot t$$

$$loss_s = (p_{in,max} - (st_{max} - \frac{level_i}{RTE \cdot t})) \cdot t$$

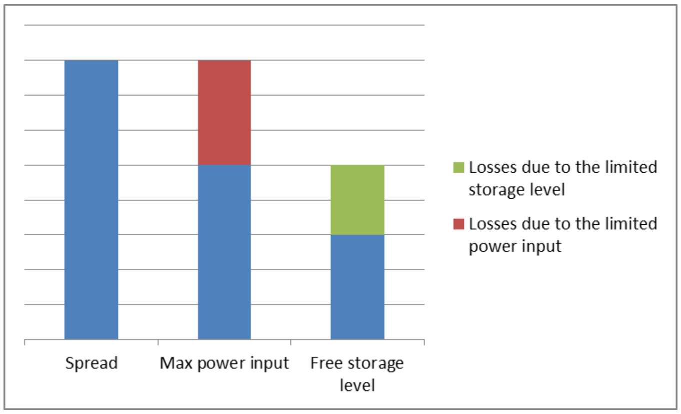


Figure 5.3: Representation of energy losses if free storage level is the limiting variable followed by maximum power input.

The last situation, figure 5.4 is that the available free storage space is the smallest one, but the spread is smaller than the power input. In this case, there are no energy losses due to the maximum power input. More energy could be sent to the storage units if necessary. However, there are energy losses due to the limited storage level. The losses are the difference between the spread and the available storage capacity. The energy stored is the available energy storage level.

$$loss_s = (spread_i - (st_{max} - \frac{level_i}{RTE \cdot t})) \cdot t$$

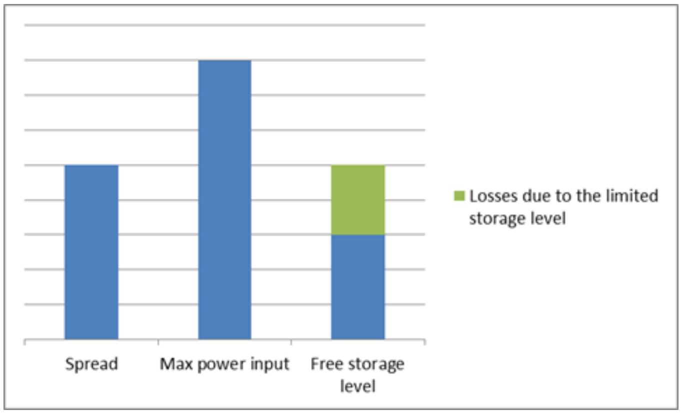


Figure 5.4: Representation of energy losses if free storage level is the limiting variable followed by spread.

For all the cases described there are losses of energy due to the RTE of the energy sent to the storage. It evaluated as

$$loss_e = st_{in} \cdot \frac{1 - RTE}{RTE}$$

5.4.3.2 Negative spread

A negative value for the spread represents that the energy generated at this period is not enough to supply the load. Therefore, the difference between the generation and the load is provided by the storage units. Pointing that the spread is negative, the energy contributed by the generators is

$$serv_{x,i} = (spread_i + load_i) \cdot t$$

In this case, there is no energy input but energy output of the storage units. Which is determined by the minimum between the maximal power output

($p_{out,max}$), the stored energy level in the storage units ($level_i - st_{min}$) and the absolute value of the spread (the energy needed) at this moment. If the maximum power output is lower than the other two variables, the capacity of the installation does not allow to send the energy needed even if the stored energy level is enough to supply it. Then the power output is limited by its maximum value. However, if the stored energy level is the minimum variable, there is not enough energy stored to supply the spread. The power output is then the corresponding to the stored energy. Finally, if the spread is the lowest value, then all the energy can be served, and the power output will be the power needed to supply all the spread.

$$p_{out} = min(p_{out,max}, \frac{level_i - st_{min}}{t}, |spread_i|)$$

Therefore, a blackout situation happens if the stored energy level and/or the maximum power output are lower than the energy needed (absolute value of spread). The total energy supply is not possible and this period of time (t) is included in lost of load hours parameter (LOLH).

5.4.4. CO_2 emissions reduction

The reduction of CO_2 emissions depends on the distribution of energy sources for each country (table 5.6) and its respective emissions (table 5.4). With the actual electrical system, the CO2 emissions in g/kWh are

$$CO_{2_{actual}} = \sum \frac{y_r}{100} \cdot e_r$$

where y_r is the actual percentage for the different energy sources, and e_r the

CO_2 emissions on g/kWh for each.

For the proposed systems, it is supposed that the only primary source for electricity generation is wind power, solar power, or a combination of both. Also, the CO_2 emissions of power-to-fuel units due to lifecycle (manufacture, disposal, ...) are neglected as any data about it was found and that it is presumably low. Therefore, the emissions of the proposed energy systems correspond to the ones of the renewable source. In the combination of wind and solar energies, it is their emissions by their ratio of installed capacity.

Therefore, the percent of emissions savings for the energy served by renewables sources are

$$CO_{2_{saved}} = 100 - (\frac{CO_{2_{model}}}{CO_{2_{actual}}} \cdot 100)$$

With the storage units, the captured CO_2 is reemitted when the methanol is used, so it is not a netto reduction of CO2 emissions, it is just neutral at best. The amount of CO_2 needed for the energy served by power-to-methanol units is calculated in base to the reaction stoichiometry and CO_2 and methanol molar masses

$$1molCO_2 \rightleftharpoons 1molCH_3OH$$

$$44kgCO_2 \rightleftharpoons 32kgCH_3OH$$

Knowing the HHV of methanol (22.7 MJ/kg) the amount of CO_2 that is needed is

$$C0_{2_{needed}} = \frac{Energy\ served\ by\ storage\ units\ (kWh) \cdot 3.6(MJ/kWh)}{22.7(MJ/kg\ CH_3OH)} \cdot \frac{44\ (kg\ CO_2)}{32(kg\ CH_3OH)}$$

5.4.5. Planning model

The price of the energy produced by the generators and supplied by the storage units depends on their economic indicators

$$cost_x = (capex_x + annuity_{cst,x} + FOM_x) \cdot n_x \cdot \frac{years}{srv_{total,x}}$$

$$cost_{st} = \frac{\frac{opex_{st} \cdot serv_{total,st}}{RTE} + (capex_{st} \cdot annuity_{cst,st} + FOM_{st}) \cdot n_{st} \cdot years}{serv_{total,st}}$$

The objective function to be minimized is the total cost of the supplied energy respecting the constraints. Those are two: (i) have the same energy stored level at the beginning and the end of the period and (ii) the maximum value of LOLH has to be 0.25 to make sure that the system is working without significant blackouts. This function is different for 100% wind or 100% PV solar energy systems and 100% wind and PV solar energy system. In the first case, it is calculated as follows,

$$cost_{tot} = \frac{((capex_x \cdot annuity_{cst,x} + FOM_x) \cdot n_x + (capex_{st} \cdot annuity_{cst,st} + FOM_s t) \cdot n_s t) \cdot years + \frac{opex_{st} \cdot serv_{total,st}}{RTE}}{serv_{total,x} + serv_{total,st}})$$

For the second case,

$$cost_{tot} = \frac{(\sum(capex_x \cdot annuity_{cst,x} + FOM_x) \cdot n_x) \cdot years + \frac{opex_{st} \cdot serv_{total,st}}{RTE}}{serv_{total,wm,PV} + SERV_{total,st}}$$

where x is windmills, PV and storage.

The probability of load hours (PLOL) and the ratio of expected unserved energy (REUE) allow the comparison between the results for different countries and periods of time.

$$PLOL = \frac{LOLH}{\sum t}$$

$$REUE = \frac{EUE}{\sum lad}$$

where $\sum$ t corresponds to the total amount of hours and $\sum$ load to the total load of the sample period.

It is needed to emphasize that for these models are used economic parameters reduced to 2050 equivalents to approximate the results to the planning horizon and make the computation less dense. Improvements of this modelization are underway but have not been considered in the frame of the present study. The models are implemented in Python and solved with Spyder in between 6-10 minutes on a laptop with i7 processor and 16GB of RAM.

6. RESULTS

Throughout the following sections, the results for the six different studied scenarios are displayed and analyzed.

Firstly, a comparison of the grid system in both countries is made and their structure and distribution with respect to the different energy sources is analyzed. That is then reflected on the CO2 emissions on g/kWh for each country. Finally, the differences between capacity factors and average load during the period are mentioned.

Then, the first scenario analyzed is the 100% wind energy system. Following, the 100% PV solar energy system and the 100% wind and PV solar energy system. For each of them, it is analyzed the installed capacity and energy served by each source (wind, PV and storage), the energy cost and the CO_2 emissions savings and needed to generate the energy served by storage units.

After, the results for the different 100% RES are examined for each country individually to determine the best option for each region.

6.1. Grid characteristics

The comparison between the different grid characteristics for each country reflected on the table 5.5, reveals a higher percentage of demand currently covered with renewables energies in Spain. It is explained by the most potent use of nuclear and natural gas energies in Belgium.

However, despite this different percentage of use of renewables energies (table 5.6), the actual emissions of CO_2 per kWh are much higher in Spain than in Belgium, 243.23 gCO_2/kWh and 175.91 gCO_2/kWh, respectively. That implies 25% more of CO2 emissions for the first one, due to the different proportions of non-renewables energies used. The most impressive difference is located in the use of coal. While in Belgium, it is almost non-existent, in Spain, it reflects 22.5% of the non-renewables energies used (table 6.1). Belgium resorts to natural gas, nuclear and liquid fuels non-renewables energy sources, and Spain uses less natural gas and nuclear energies but an important percentage of coal. Nuclear is the less CO_2 emissions producer (12 g/kWh), even less than wind. Liquid fuels generate 23.3% more, natural gas 38.6% and coal 7250% more.

Table 6.1: Distribution of the demand supplied by non-renewables energies in both countries.

Non renewable energy source	% Belgium	% Spain
Coal	0	22.5
Natural Gas	48.33	40
Nuclear	49.7	34.16
Liquid fuels	1.97	3.34

Therefore, despite the greater use of renewable energies in Spain, the ratio of the non renewables energies used to supply 60% of the total demand generates more CO_2 emissions.

The average capacity factor for each country varies. It is the ratio between the actual electrical energy output and the maximum electrical energy output that would have been possible over a period of time. For wind it is similar in both countries but, for solar it is almost double in Spain with respect to Belgium.

Table 6.2: Average capacity factor for each energy source in Belgium and Spain.

	Belgium	Spain
Wind	0.277	0.240
Solar	0.111	0.217

The average load for this period of time in Belgium is 8.89 GW and in Spain 28.70 GW.

6.2. 100% wind energy system

Considering a 100% wind RES, the model finds the minimum electricity cost. For that, it varies the number of installed windmills and storage units. Some constraints are imposed: no blackout (maximum period of blackout 0.25 hours during the sample time) and the same level in the storage tank at the beginning and the end of the optimization period. In order to avoid non-sense results, it has also been imposed the constraints of having positives values for the number of windmills and storage units.

Table 6.3: Results for the case 100% wind energy system.

	Belgium	Spain
Number of windmills	9119	28965
Windmills installed capacity (GW)	45.6	145
Number of storage units	58250	182295
Storage installed capacity (GW)	14.56	45.57
Wind energy cost (euros/kWh)	0.0910	0.0796
Storage energy cost (euros/kWh)	0.0810	0.1140
Total energy cost (euros/kWh)	0.0883	0.0859
Total energy served by windmills (kWh)	$32.84 \cdot 10^{10}$	$82.32 \cdot 10^{10}$
Total energy served by storage units (kWh)	$12.34 \cdot 10^{10}$	$18.30 \cdot 10^{10}$
Losses due to storage size (kWh)	0	0
Losses due to RTE (kWh)	$12.34 \cdot 10^{10}$	$18.30 \cdot 10^{10}$
Losses due to power intake (kWh)	$7.75\ 10 \cdot 10^{10}$	$4.60 \cdot 10^{10}$

Installed capacity

As is shown on the table 6.3 Belgium needs 45.6 GW of windmills installed capacity and Spain, 145 GW. For storage installed capacity it is needed 14.56 and 45.57 GW, respectively. That means that in Belgium, the total installed capacity is 75.85% from wind and 24.15% from storage. In Spain, this relation is quite similar, 76.09% and 23.91%.

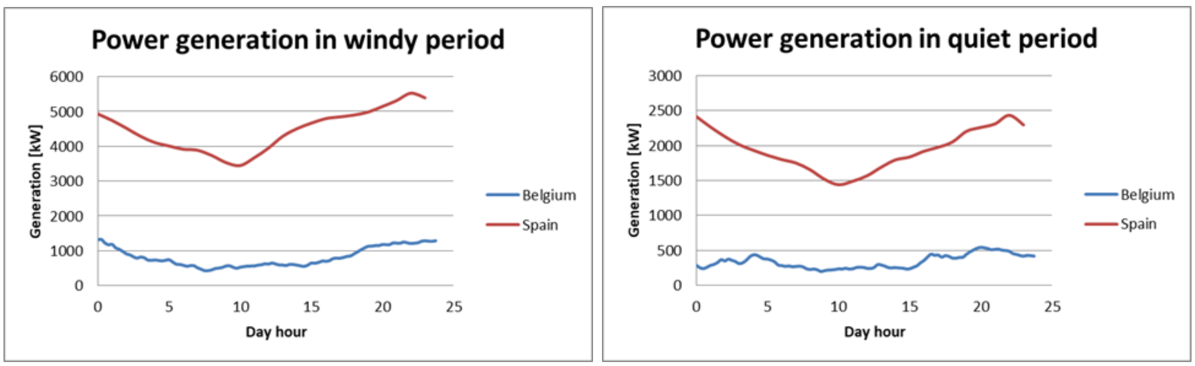
Cost comparison

For this scenario, the prices obtained are displayed on the table 6.3. The price of the energy served by storage units is around 40% smaller in Belgium. That depends on the following factor (section 5.2.6)

$$cost_{st} \propto \frac{n_{st} \cdot period\ of\ time\ (years)}{energy\ served\ by\ storage}$$

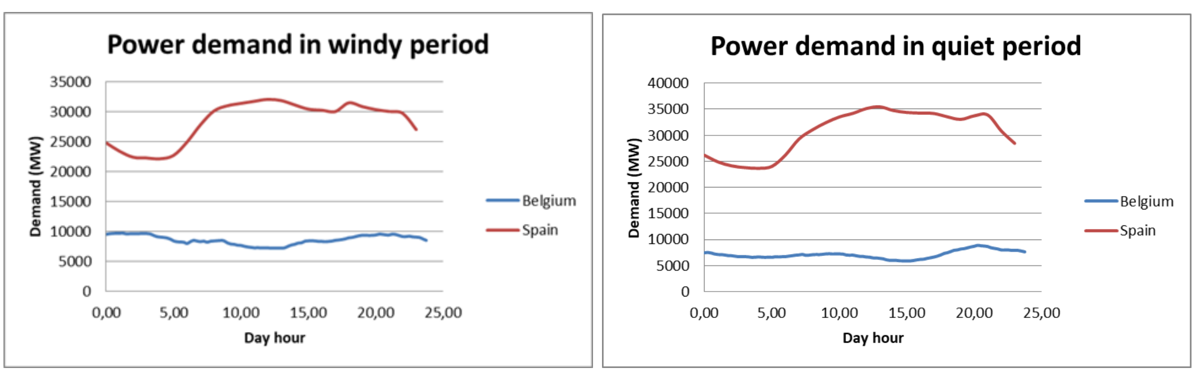
It is necessary to remember that the period of time for each country is different due to the available data at the moment of beginning the modelization. It is 5.8 years for Belgium and 4 years for Spain.

Although the number of storage units is 3 times larger in Spain than in Belgium, the energy served by storage is only 45% larger. The reason for this difference and the larger relative need for storage units in Spain can come from the lack of correspondence between the maximum load and generation periods. This supposition is sustained by the graphs 6.1 and 6.2. On those it is represented the daily average power generation of windmills and demand in Spain and Belgium during a week of both the windy and the quiet period of the year (April and September for both countries [7][4]). It can be observed that the periods of highest generation are, for both countries, during the first and last hours of the day. However, the greatest loads are demanded between 10 and 20 hours in Spain and the first hours in the morning and the afternoon in Belgium. Therefore, this discoordination in Spain creates a greater need for storage capacity in terms of power.



(a) Windy day. (b) Quiet day.

Figure 6.1: Daily average power generation for windy and quiet year periods.



(a) Windy day. (b) Quiet day.

Figure 6.2: Daily average power demand for windy and quiet year periods.

Another observation concerning this factor is that in Spain, even having a higher percentage of installed capacity for storage (table 5.6) the energy served by them is just an 18.20% over the total energy served, while in Belgium it is a 27.30%. The Belgian price of the energy served by storage units is an 11% lower, with respect to the served by windmills, in Spain it is a 43.2% higher (table 6.4). Indeed, there are proportionally more storage units per unit of stored energy. That is due to the LOLH constraint. To accomplish it, Spain needs more storage units due to the different variability profile, as discussed above. The energy supplied by the storage is reduced, as it needs to increase the number of storage units, in order to have enough storing capacity (kW) for the same amount of energy.

On the other hand, it is assumed that the energy that is stored is free (cost for the storage unit = 0). That is related to the approach of a system optimum (communist country, where both windmills and storage units belong to the state) rather than an agent-based approach (capitalist system, with different actors). Therefore, to have a cheaper cost for energy stored than for the directly served by windmills is reasonable for the system proposed.

Table 6.4: Energy served by windmills and storage units

	Belgium		Spain	
	kWh	%	kWh	%
Served energy by windmills	$32.84\cdot10^{10}$	72.67	$82.32\cdot10^{10}$	81.80
Served energy by storage	$12.34\cdot10^{10}$	27.33	$18.30\cdot10^{10}$	18.20

The energy served by windmills is 12.5% more expensive in Belgium than in Spain. This value is proportional to a similar factor to that of storage cost.

$$cost_{wm} \propto \frac{n_{wm} \cdot period\ of\ time\ (years)}{energy\ served\ by\ windmills}$$

This factor is around 14 percent higher for Belgium. Two factors affect to the cost. Firstly, the capacity factor. If it increases, more energy is served for the same number of windmills, so the cost decreases. Second, the curtailment rate. The higher this value, the more energy is wasted for the same number of windmills (less energy is served), so the cost increases.

In this case, the capacity factor is similar in both countries, 0.277 in Belgium and 0.240 in Spain (table 6.2). Therefore, the only difference is the curtailment. In Belgium it is $7.75 \cdot 10^{10}$ kWh. In Spain, $4.60 \cdot 10^{10}$ kWh. That implies around 60% more energy curtailment in Belgium. Which explain the lowest energy cost in Spain.

However, despite the difference in the cost of the energy served by wind and storage, the final energy price just varies on 2.4 euros per MWh. It is lower in Spain than in Belgium.

CO_2 emissions

In the actual Belgian grid, the $C0_2$ emissions are 175.91 gCO_2/kWh. With the modelized system, it would be reduced to 14 gCO_2/kWh. The amount of energy generated by wind in the model (served energy + curtailed energy) is $40.6 \cdot 10^{10}$ kWh. With the 100% wind energy system proposed the emissions are 5.68 MT of CO2. Therefore, with this scenario, 92.04% of CO2 emissions are saved.

On the other hand, in Spain, in the actual energy system, the emissions are 243.23 gCO_2/kWh. The energy generated by wind in the model is $86.92 \cdot 10^{10}$

kWh, which means 12.17 MT of CO_2. That is 94.24% fewer emissions than with the actual grid system.

Table 6.5: CO_2 emissions savings for 100% wind RES.

	Belgium	Spain
Actual CO2 emissions (gCO2/kWh)	175.91	243.23
Model CO2 emissions (gCO2/kWh)	14	14
CO2 savings (%)	92.04	94.24

For the amount of energy served by the storage units, the $CO2$ needed by them is recollected on the table 6.6. As the energy served by storage units in Spain is larger than in Belgium, so will be the amount of CO_2 needed.

Table 6.6: CO_2 needed for storage units in 100% wind RES.

	Belgium	Spain
Energy served by storage units (kWh)	$12.34 \cdot 10^{10}$	$18.30 \cdot 10^{10}$
Methanol used (MT)	19.6	29
CO2 used (MT)	27	40

6.3. 100% PV solar energy system

Now, another model is developed for a 100% PV solar RES. Considering the same constraints imposed for the previous system, the program varies the number of installed PV panels and storage units to find the optimal energy cost for this case.

Table 6.7: Results for the case 100% PV solar energy system.

	Belgium	Spain
Number of PV panels (millions)	25320	70430
Solar PV installed capacity (GW)	760	2112
Number of storage units	405159	479565
Storage installed capacity (GW)	101.29	120
PV energy cost (euros/kWh)	1.7017	0.8657
Storage energy cost (euros/kWh)	0.2579	0.2677
Total energy cost (euros/kWh)	0.9516	0.7539
Total energy served by PV panels (kWh)	$21.71 \cdot 10^{10}$	$81.93 \cdot 10^{10}$
Total energy served by storage units (kWh)	$23.48 \cdot 10^{10}$	$18.70 \cdot 10^{10}$
Losses due to storage size (kWh)	0	0
Losses due to RTE (kWh)	$23.48 \cdot 10^{10}$	$18.70 \cdot 10^{10}$
Losses due to power intake (kWh)	$24.03 \cdot 10^{10}$	$11.51 \cdot 10^{10}$

Installed capacity

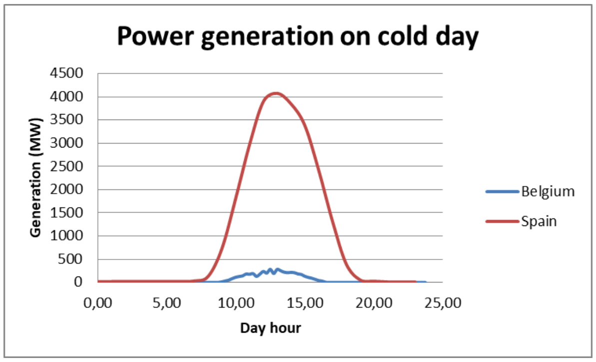
For this scenario, Belgium needs 760 GW of PV installed capacity and Spain, 2112 GW. Those values are huge (due to a very low capacity factor) so, those are not realistic systems. For storage there are 120 GW in Spain and 101.29 GW in Belgium. Expressed in percentage, in Belgium, 88.24% of installed capacity belongs to PV and 11.76% to storage. In Spain, 94.62% and 5.38%.

Cost comparison

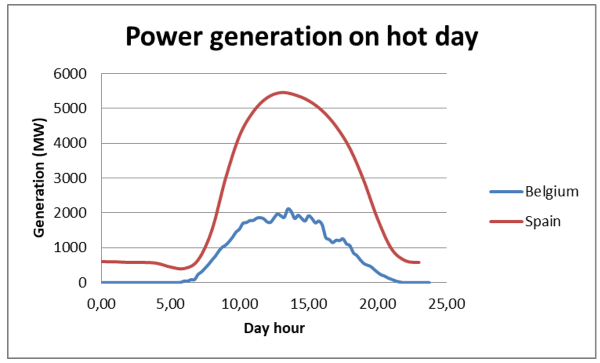
The price of energy supplied by storage is similar for both countries, just 4% higher for Spain. This value is proportional to the ratio between the number of storage units and energy served by them, as expressed in section 5.2.6.

$$cost_{st} \propto \frac{n_{st} \cdot period\ of\ time\ (years)}{energy\ served\ by\ storage\ units}$$

In this case, the factor is around 3 percent higher for Spain. That can be caused because of the moments of higher energy demand in Spain are between 10 and 20 hours; while, in Belgium, it increases slightly during the first hours in the morning and the afternoon (figure 6.4), same for winter and summer. Therefore, in Spain, it exists a better correspondence between the maximum load and generation periods. In the figures 6.4 and 6.3 it is represented, respectively, the average load and power generation for the coldest and hottest week over the last year 2018, having this place in July and January for both countries [4][7]. Therefore, despite the higher load in Spain, the storage capacity needed is similar in both countries. The energy served by storage units will be proportionally lower, and consequently, the price increases.

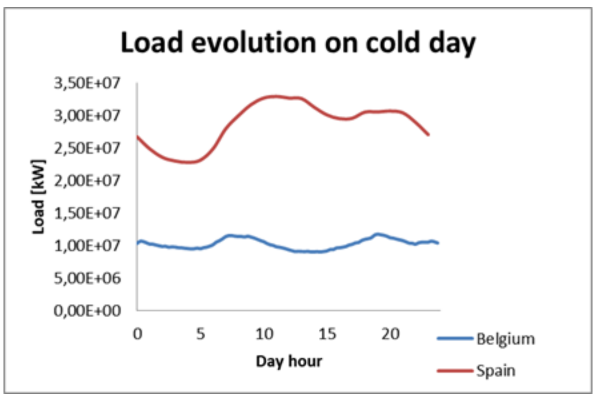


(a) Cold day.

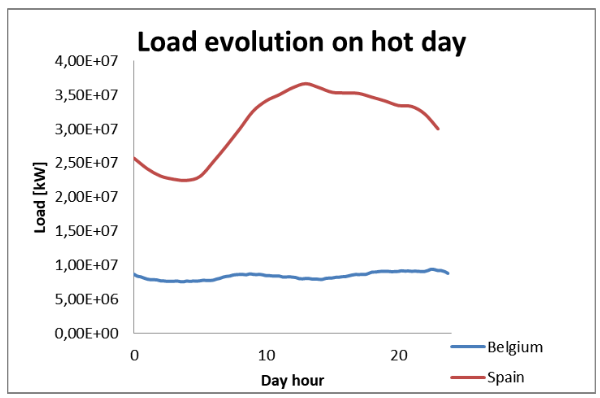


(b) Hot day.

Figure 6.3: Daily average power generation for the hotest and coldest month of 2018.



(a) Cold day.



(b) Hot day.

Figure 6.4: Daily average power demand for the hotest and coldest month of 2018.

Hence, most of the energy in Spain can be directly served by PV cells, taking advantage of the sunlight during the highest load demands, and requiring less output of the storage units. On the contrary, in Belgium, the energy served by storage corresponds to 52% of the total versus the 18.58% in Spain.

Table 6.8: Energy served by PV cells and storage units.

	Belgium		Spain	
	kWh	%	kWh	%
Served energy by PV cells	$21.71{\cdot}10^{10}$	48	$81.93 \cdot 10^{10}$	81.42
Served energy by storage	$23.48 \cdot 10^{10}$	52	$18.70 \cdot 10^{10}$	18.58

The difference in the price between PV and storage energy in Belgium is surprising. The one that comes from solar generation is 660% more expensive. Considering the capacity factor, 0.217 in Spain and 0.111 in Belgium, the energy served by the same amount of PV panels in Belgium is almost half than in Spain. So to accomplish the LOLH constraint, Belgium needs much more PV panels per unit of power generation in order to have enough power generation, increasing the price. Furthermore, one immportant approach is done. All the models consider a system optimum rather than an agent-based approach. That means a communist country where both PV panels and storage units belong to the state rather than a capitalist system with different actors. In consequence, it is assumed that the energy that is stored is free as a result of a zero cost for the storage units. That makes reasonable the higher price of the energy served by PV cells.

On the other hand, the curtailment rate in Belgium is twice than in Spain ($24.0 \cdot 10^{10}$ and $11.51 \cdot 10^{10}$, respectively). The higher this value, the more energy is wasted for the same number of PV's (less energy is served), so the cost increases. That explains the double price for the the energy in Belgium.

$$cost_{pv} \propto \frac{n_{pv} \cdot period\ of\ time\ (years)}{energy\ served\ by\ PV cells\ units}$$

Finally, the total energy cost in Spain is around 25% lower than in Belgium; being, respectively, 0.7585 euros/kWh and 0.9516 euros/kWh. These values are much higher than the actual solar cost (around 0.3 euros/kWh). That is due to the need for a very large overcapacity and a lot of storage units. Which makes this scenarion non realistic.

CO_2 emissions

For this scenario, in Belgium, the CO2 emissions generated by PV energy cells ($45.71 \cdot 10^{10}$ kWh) cells are 20.6 MT CO_2. In the actual energy system, the emissions are 175.91 gCO_2/kWh. For this scenario it is 45 gCO_2/kWh, 74.42% less. Otherwise, in the actual Spanish energy system, the total solar energy generation for this scenario would generate 42 MT CO_2. The percentage of emissions saving is around 81.50%.

Table 6.9: CO_2 emissions savings for 100% PV solar RES.

	Belgium	Spain
Actual CO2 emissions (gCO2/kWh)	175.91	243.23
Model CO2 emissions (gCO2/kWh)	45	45
CO2 savings (%)	74.42	81.50

In this scenario, the amount of energy served by storage units is larger in Belgium than in Spain. Therefore, in Belgium the amount of CO_2 needed is higher as the table 6.14 reflects.

Table 6.10: CO_2 needed for storage units in 100% PV solar RES.

	Belgium	Spain
Energy served by storage units (kWh)	$23.48 \cdot 10^{10}$	$18.70 \cdot 10^{10}$
Methanol used (MT)	37.3	29.7
CO2 used (MT)	51.2	40.8

6.4. 100% wind and PV solar energy system

The last system proposed has as primarly energies both solar and wind energies. The results for this 100% wind and PV solar RES are analyzed in this section and compared to the previous cases in the next one. The imposed constraints are the same as before. The objective is still to find the minimum electricity cost. In this case, by changing the number of installed windmills, PV panels, and storage units.

Table 6.11: Results for the case 100% wind and PV solar energy system.

	Belgium	Spain
Number of windmills	8007	15413
Number of PV panels (millions)	29.92	237.56
Wind installed capacity (GW)	40	77.07
Solar PV installed capacity (GW)	9	71.23
Number of storage units	51256	139891
Storage installed capacity (GW)	12.81	35
Wind and solar energy cost (euros/kWh)	0.0890	0.0657
Storage energy cost (euros/kWh)	0.0772	0.0984
Total energy cost (euros/kWh)	0.0862	0.0711
Total energy served by Windmills an PV panels (kWh)	$34.38 \cdot 10^{10}$	$84.14 \cdot 10^{10}$
Total energy served by storage units (kWh)	$10.78 \cdot 10^{10}$	$16.49 \cdot 10^{10}$
Losses due to storage size (kWh)	0	0
Losses due to RTE (kWh)	$10.78 \cdot 10^{10}$	$16.49 \cdot 10^{10}$
Losses due to power intake (kWh)	$6.60 \cdot 10^{10}$	$6.07 \cdot 10^{10}$

For the following conclusion is taken into account the combination of both energy sources (wind and solar) and the results for the previous scenarios.

Installed capacity

In the case of wind and PV solar combined system, Belgium needs around 40 GW of wind installed capacity, about 9 GW for solar and 12.8 GW for storage. In percentage, it corresponds to 64.8%, 14.5%, and 20.70%, respectively.

By the other hand, Spain requires around 77 GW for wind (42%), 71.27 GW for solar (28.9%) and 35 GW for storage (19.90%).

Cost comparison

For this scenario, it has been obtained the prices for the energy directly supplied by wind and solar, for the storage energy served and for the total energy cost (table 6.11).

The energy supplied by storage is around 21.5% more expensive in Spain than in Belgium. Conversely, the price of the energy supplied by wind and PV is almost 35.5% higher in Belgium.

As in the previous scenarios, the cost of the energy served by the storage units is proportional to the factor.

$$cost_{st} \propto \frac{n_{st} \cdot period\ of\ time\ (years)}{energy\ served\ by\ storage\ units}$$

This factor is around 26% higher for Spain. The storage installed capacity is similar in both countries. However, the percentage of energy served by them is much lower in Spain. While in Belgium the price of the energy served by storage units is a 13% lower, for the served by windmills, in Spain it is almost

50% higher. That is due, once more, to the LOLH constraint.

As discussed before, the correspondence between solar energy generation and maximum load periods (figures 6.4 and 6.3) decreases the proportional storage capacity needed and the energy served by storage units. However, with wind energy does not exist this correspondence (figures 6.1 and 6.2). That creates a greater need for storage capacity in terms of power.

The combination of both energies decreases, even more, the percentage of energy served by storage units. Therefore this trend is maintained. Spain needs more storage units but the energy supplied by them is reduced, as it needs to increase the number of storage units, in order to have enough storing capacity (kW) for the same amount of energy.

Table 6.12: Energy served by Windmills + PV cells and storage units.

	Belgium		Spain	
	kWh	%	kWh	%
Served energy by windmills and PV cells	$34.38 \cdot 10^{10}$	76.14	$84.14 \cdot 10^{10}$	83.62
Served energy by storage	$10.78 \cdot 10^{10}$	23.86	$16.49 \cdot 10^{10}$	16.38

The final energy cost is 21% higher for Belgium than for Spain. Furthermore, the price of the energy served by wind and solar energy is 35.5% higher in Belgium. The reasons can be the capacity factors or the energy curtailment. The capacity factors have a real difference in the case of solar energy (0.111 for Belgium and 0.217 for Spain). Even more, the installed capacity for PV in Spain is higher and has a better correspondence with the load. On the other hand, the curtailment is much higher in Belgium, almost 9% ($6.60 \cdot 10^{10}$ GW in Belgium and $6.07 \cdot 10^{10}$ in Spain). Both, capacity factors and energy curtailment, increases the Belgian energy cost.

CO_2 emissions

Concerning the CO_2 emissions, in order to estimate the saving emissions, the proportion of energy served by wind and solar energies is supposed to be the same as their installed capacities ratio. That means 81.7% for wind and 18.3% for solar in Belgium; and 52% versus 48% in Spain.

As said before, in the actual Belgian grid, the $C0_2$ emissions are 175.91 gCO_2/kWh. With the modelized system, it would be reduced to 19.7 gCO_2/kWh. The amount of energy generated by wind and solar energy in the model (served energy + curtailed energy) is 41 $\cdot 10^{10}$ kWh. With the 100% wind and PV solar energy sytem proposed the emissions are 8 MT CO_2. Therefore, with this scenario, a 88.80% of CO_2 emissions are saved.

In Spain, in the actual energy system, the emissions are 243.23 gCO_2/kWh. The energy generated by windmills and PV cells in the model is 90.21 $\cdot 10^{10}$ kWh, which means 17.7 MT CO_2. With the ratio of renewables energies (52% wind and 48% solar), the emissions for the model are 28.9 gCO_2/kWh. That is 88.11% fewer emissions than with the actual grid system.

Table 6.13: CO_2 emissions savings for 100% wind and PV solar RES.

	Belgium	Spain
Actual CO2 emissions (gCO2/kWh)	175.91	243.23
Model CO2 emissions (gCO2/kWh)	19.7	28.9
CO2 savings (%)	88.80	88.11

In this scenario, the amount of energy served by storage units is larger in Spain than in Belgium, because of the reasons previously discussed. Therefore, in Spain it is needed a higher amount of CO_2 as the table 6.14 reflects.

Table 6.14: CO_2 needed for storage units in 100% wind and PV solar RES.

	Belgium	Spain
Energy served by storage units (kWh)	$10.78 \cdot 10^{10}$	$16.49 \cdot 10^{10}$
Methanol used (MT)	17.1	26.2
CO2 used (MT)	23.5	36

6.5. Analysis of the different energy systems for each country

Throughout the following section, the previous results are analyzed but, this time, making a comparison between the different 100% RES proposed for each country individually.

6.5.1. Belgium

Comparing the different scenarios in Belgium, wind energy is more efficient than solar energy. Therefore, the installed capacity required for the first system is lower than for the second one. In order to compare all the results on the tables 6.15 and 6.16 are shown the results for all models.

Table 6.15: Installed capacity (GW) for different scenarios in Belgium.

	Capacity (GW)		
Scenario	100% Wind RES	100% PV solar RES	100% Wind and PV RES
Windmills	45.6	0	40
PV cells	0	760	9
Storage	14.56	101.29	12.81

Table 6.16: Installed capacity (%) and energy served (%) for different scenarios in Belgium.

		Installed capacity (%)	Energy served (%)
100% Wind RES	Windmills	75.85	72.67
	Storage	24.15	27.33
100% PV solar RES	PV cells	88.24	48
	Storage	11.76	52
100% Wind and PV solar RES	Windmills	67.48	76.14
	PV cells	14.52	
	Storage	23.86	26.87

Despite the higher percentage of installed capacity for PV in the 100% PV solar energy system than for wind in the 100% wind energy system (table 6.10), the energy served on the first scenario is lower than 50%. This result stands to reason considering that in Belgium the capacity factor for solar energy is more than 40% lower than wind. Hence, the storage installed capacity is half in 100% PV solar energy system than in the other case but serves more than fifty percent of energy. While, in the other scenario, both percentages (installed capacity and energy served) are about 25%.

With the combination of both technologies, the energy served by renewable energies increase slightly with respect to the 100% wind system. Over the total renewable energies installed capacity, the wind has an 81.7% and solar 18.31%. Therefore, with this system, the installed capacity, and energy served by storage do not decrease significantly. The difference between installed capacity and energy served between each scenario, previously discussed, affects the final energy price.

Table 6.17: Energy cost for different scenarios in Belgium.

		Energy cost (euros/kWh)
100% Wind RES	Windmills	0.0910
	Storage	0.0810
	Total	0.0883
100% PV solar RES	PV cells	1.7017
	Storage	0.2579
	Total	0.9516
100% Wind and PV RES	Wind + PV	0.0890
	Storage	0.0772
	Totall	0.0862

The price of solar energy is quite higher than wind energy. Then, the 100% PV solar energy system is the worst economical option, being its final energy price around 1070% bigger than for the wind scenario. However, it is interesting how the combination of wind with just 14.5% of solar installed capacity can decrease the price of around 2.4%. This lower cost is because of the higher efficiency of the system. For the three scenarios, the 100% wind and PV solar energy system has the fewer energy curtailed (table 6.18).

Table 6.18: Energy curtailed for the different scenarios in Belgium.

	Energy curtailment (kWh)
100% Wind RES	$7.75 \cdot 10^{10}$
100% PV solar RES	$24.03 \cdot 10^{10}$
100% Wind and PV RES	$6.60 \cdot 10^{10}$

Accordingly, a 100% RES with the wind as the principal energy source and a small contribution of solar energy is the best economic scenario for Belgium.

CO_2 emissions

Considering the CO2 saving emissions, in the case of 100% wind energy system this corresponds to 92.04% and for 100% PV solar energy system, to 74.42%. In the combined energy system, it is 88.80%.

Table 6.19: Belgium CO2 emissions savings.

	CO2 emissions saved (%)
100% Wind RES	92.04
100% PV solar RES	74.42
100% Wind and PV RES	88.80

Therefore, it can be deduced that the CO_2 emissions savings are higher for 100% wind energy system followed by 100% wind and PV solar energy system. On account of that, the most recommended scenario from the point of view of CO_2 emissions is probably the 100% wind energy system. Emphasize the fact of the CO_2 emissions of power-to-fuel units (due to lifecycle) are neglected.

Concerning the amount of CO_2 needed for the energy served by the storage units, in Belgium is significantly higher for the case 100% PV solar RES. That is logical seeing the percentages of energy served on the table 6.15.

Table 6.20: Amounts of CO_2 needed in Belgium for the different scenarios.

	CO2 needed (MT)
100% Wind RES	27
100% PV solar RES	51.2
100% Wind and PV RES	23.5

6.5.2. Spain

The results for the different 100% RES modelized on this project are reflected on the tables 6.21 and 6.22. It is remarkable how the relevance of wind energy decreases with respect to Belgium's results.

Table 6.21: Installed capacity (GW) for different scenarios in Spain.

	Capacity (GW)		
Scenario	100% Wind RES	100% PV solar RES	100% Wind and PV solar RES
Windmills	145	0	77
PV cells	0	2112	71.3
Storage	45.57	120	35

Table 6.22: Installed capacity (%) and energy served (%) for different scenarios in Spain.

		Installed capacity (%)	Energy served (%)
100% Wind RES	Windmills	76.09	81.80
	Storage	36.63	18.20
100% PV solar RES	PV cells	94.62	81.42
	Storage	5.38	18.58
100% Wind and PV RES	Windmills	42	83.62
	PV cells	38.91	
	Storage	19.09	16.38

For both scenarios, 100% wind and 100% PV solar energy systems, the percentages of energy served are quite similar. Conversely, the installed capacity of PV is about 24% higher than for wind. Even with a reduced percentage of storage installed capacity for the second scenario, it still serves a little bit more of energy than in the first one. That can be explained by the 10% higher wind capacity factor in Spain.

As in Belgium's case, the energy served by renewables energies for 100% wind and PV solar energy system increases a little concerning the 100% wind energy system. Wind contribution to the renewable energies installed capacity is about 52% and 48% of solar. With this configuration, the installed capacity of the storage is reduced by 45.6% with respect to 100% wind energy system. However, the energy served does not vary that much. That means that a 100% wind and PV solar RES is much more efficient.

With respect to the final energy cost, there are several differences in each scenario.

Table 6.23: Energy cost for different scenarios in Spain.

		Energy cost (euros/kWh)
100% Wind RES	Windmills	0.0796
	Storage	0.1140
	Total	0.0859
100% PV solar RES	PV cells	0.8657
	Storage	0.2677
	Total	0.7539
100% Wind and PV RES	Wind + PV	0.0657
	Storage	0.0984
	Totall	0.0711

The economically less recommended option is a 100% PV solar energy system which total energy price is 877% higher than for 100% wind energy system and 1060% larger, than for the combined energy system. As in the case of Belgium, a combination of solar and wind energies gives the best results and the lower energy curtailment (table6.24). However, in Spain, the combination has to be quite different, with almost 29% of solar installed capacity and 42% of wind. Therefore, in Spain, the combination uses more equal proportions of wind and solar energies. The cause is its lower difference in their capacity factors (table 6.2).

Table 6.24: Energy curtailed for the different scenarios in Belgium.

	Energy curtailment (kWh)
100% Wind RES	$4.60 \cdot 10^{10}$
100% PV solar RES	$11.51 \cdot 10^{10}$
100% Wind and PV RES	$6.07 \cdot 10^{10}$

From all the scenarios studied for Spain, a 100% RES with wind and solar power installed capacities combined on proportion 4/3 is the best economical option.

CO_2 emissions

The savings CO2 emissions for Spain in the different scenarios are reflected on the table 6.25.

Table 6.25: Spain CO_2 emissions saved.

	CO2 emissions saved (%)
100% Wind RES	94.24
100% PV solar RES	81.50
100% Wind and PV RES	88.11

That leads to the conclusion that a 100% wind energy system is the best option for CO_2 saving emissions. This result is logical because of the neglected CO_2 emissions of power-to-fuel units.

The amount of CO_2 needed for the energy served by the storage units in Spain is not especially different between the considered scenarios. That is logical seeing the percentages of energy served on the table 6.22.

Table 6.26: Amounts of CO_2 needed in Spain for the different scenarios.

	CO2 needed (MT)
100% Wind RES	40
100% PV solar RES	40.8
100% Wind and PV RES	36

7. CONCLUSIONS

In the present work has been developed a model to describe energy systems including 100% RES and storage. The final objective is to minimize the cost of the electricity system varying the installed capacity of windmills and/or PV and storage. One significant advantage of power-to-methanol is the fact that the storage is really cheap because it is possible to store it at ambient temperature and presion. So the marginal cost of storage itself is neglected.

For it some constraints are imposed: no blackout (maximum period of blackout 0.25 hours during the sample time) and the same level in the storage tank at the beginning and at the end of the optimization period. In order to avoid non-sense results, it has also been imposed the constraints of having positives values for the number of windmills and or PV and storage units.

The optimization of the different models gives the final energy cost collected in the table 7.1.

Table 7.1: Average electricity cost for all scenarios.

	Belgian cost (euros/MWh)	Spanish cost (euros/MWh)
Actual average	43.35	42.98
100% Wind RES	88.30	85.90
100% PV solar RES	951.60	753.90
100% Wind and PV RES	86.20	71.10

Then, it can be concluded that for all the considered scenarios the overcapacity is necessary for the full energy demand supply. Consequently, the electricity cost increases with respect to the current average price. This value is 43.35 euros/MWh in Belgian market [1] and 42.98 euros/MWh for Spanish market [6].

For both countries, the best option is the 100% wind and PV solar energy system. With it, in Belgium, the final price increases less than twice with respect to the current average electricity price in the Belgian market. In Spain, the final cost is around 65% larger than the actual one.

Note that the price for the scenario Belgian 100% wind energy system is around 3 euro/kWh larger than the results of the reference work [30]. The demand yearly increases what changes the ratio of energy directly served by renewables energies and generators/storage units. Thus, the larger the considered time interval for these optimizations, the most realistic results are obtained.

Moreover, the cost of storage units electricity is notably higher for Spain in the case of 100% wind energy system. The lack of correspondence electricity generation and demand increases the losses significantly. That shows that the harmony between the peak load periods and energy generation by renewable sources periods has a considerable effect on the final electricity cost. That is the reason why, for the combination of wind and solar energies, the decrease in the cost is more significant in Spain than in Belgium, with respect to the second best price of the 100% wind energy system.

Even in 100% RES, it would be possible to avoid power-to-fuel technology with biomass or other storage options. But the goal of the work is to evaluate the cost of the system where this storage technology is used. Finally, the resulting energy cost is still reasonable. However, for all the scenarios it is higher than the estimated on the articles of [13] (68.7 euros/MWh) and [20] [35] (51 euros/kWh). That is because the resulting price can be reduced if the assumptions made for this work change (market competitiveness or other applications fields for methanol). With respect to the electricity cost estimated on [44] (between 80-200 euros/MWh) the scenarios of 100% wind RES and 100% wind and PV solar RES have an energy cost into this range. The extremely higher cost for 100% PV solar RES comes from the need for an extremely overcapacity. As said above, it is not a realistic system due to the huge overcapacity needed.

It is needed to remark that, clearly, the combination of different renewable energies involves a decrease of the final electricity cost. However, not necessarily it is going to be the best option from the point of view of CO_2 emissions, which for the two studied countries seems to be the 100% wind energy system. This result is due to the CO2 emissions assumed for each energy source (14 gCO_2/kWh for wind and 45 gCO_2/kWh for solar), and the fact of the CO_2 emissions of power-to-fuel units (due to lifecycle) are neglected. The models proposed on this work obtain between 74% and 95% of CO_2 emissions savings.

Table 7.2: CO2 emissions savings for all scenarios.

	Belgium CO2 savings (%)	Spanish CO2 savings (%)
100% Wind RES	92.04	94.24
100% PV solar RES	74.42	81.50
100% Wind and PV RES	88.80	88.11

That reflects that to achieve the European Commission objectives assuring the energy supply, and a reasonable energy cost, a 100% RES combined with power-to-fuel storage is an excellent alternative to the actual grid system.

8. FUTURE LINES OF WORK

In future work, these models can be completed with transmission models. The interconnection between different countries allows sharing the excess of energy. That entails the reduction of the final electricity cost and a variable electricity price in function of the period.

Also, in large countries, like Spain, the weather is extremely different for each zone. Regionalization of the model is useful in order to exploit as much as possible the renewable resources of each region.

The models of this works are for a country from the south of Europe, rich in solar energy, and one from the middle. Adding a northern European country like Denmark can be interesting in order to compare three situations that would be more representative of the European situation.

Furthermore, the methanol can be used as a fuel substitute, for biodiesel production or a chemical intermediate. So to consider all the possible uses of methanol, the next work would be to consider the possibility of using some methanol in other sectors such as transportation and to build a model that includes both the electricity sector, as well as transportation.

The economic and technical assumptions (Capex, Opex, RTE, etc) can be discussed. Also, the limitations of the renewables energies, as space, are dismissing in this optimization. Considering it can result in obtaining the most realistic distribution of the energy generators.

The results indicate that combining different sources of renewable energies (that have different generation profiles with time) lead to the optimal electricity cost. Including others, like hydro or off-shore wind, can lead to a better modelization.

Hence, the results of the present work must be considered as upper bounds for the real scenario in 2050 because considering other renewable energies, the different possible uses for methanol, transmission models and other variables commented here this price must decrease.

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