Master Thesis

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Environomical analysis of peak hours' electricity production in targeted European countries

MSc Energy for Smart Cities

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Spending time with ambitious people makes you more driven.

Spending time with positive people makes you more hopeful.

Spending time with kind people makes you more generous.

Spend time with people who you want to be like, and work on being the person who they want to be like too.

(Jen Heemstra)

Abstract

The generation of electricity is one of the most impactful factors related to climate change. In order to mitigate the effects of Global Warming, analyzing electricity production with a time-dependency perspective is essential, to better develop further efficient grid improvement strategies. Environmental impacts and prices are two main outputs related to the power generation. This work presents the methodology to assess the potential environmental impacts and the market prices of hourly generation profiles, by means of the ENTSO-E Transparency Platform, and applying Attributional Life Cycle Assessment. This methodology is then applied to analyze the electricity production of the five pilot-sites in the INVADE H2020 Project. Green House Gases emissions are determined, using the Global Warming potential indicator to assess the environmental impacts of the hourly electricity production on each targeted country. The electricity prices related to peak hours are then analyzed to discover possible links with the emissions. The highlight is on the type of resources used to meet peak hours demand, in order to understand the time variability outcomes of electricity generation. The results show the importance of having a base load covered by nuclear power plants. Furthermore, it reveals the usefulness of hydro resources, especially the flexible reservoir and pumped storage. In addition, evaluating the time-slots in which peak hours occur becomes relevant to implement energy storage strategies and peak-shaving solutions. This study can be seen as optimal support in the development of policies to increase the grid integration of renewable energy resources.

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Abbreviations The following abbreviations are used in this manuscript:

ALCA	Attributional Life Cycle Assessment
BAU	Business As Usual
CES	Centralized Energy Storage
CHP	Combined Heat and Power
CLCA	Consequential Life Cycle Assessment
DER	Distributed Energy Resource
DSM	Demand-Side Management
DSO	Distribution System Operator
ENTSO-E	European Network of Transmission System Operators for Electricity
FU	Functional Unit
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GWP	Global Warming Potential
H2020	Horizon 2020
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost of Energy
KPI	Key Performance Indicator
O&M	Operation and Maintenance
PHS	Pumped Hydro Storage
PP	Power Plant
PUC	Pilot Use Case
PV	Photovoltaic
RES	Renewable Energy Sources
TP	Transparency Platform
TSO	Transmission System Operator
TPES	Total Primary Energy Supply

1 Introduction and objectives

1.1 Context

The energy sector is approaching a global revolution needed to meet the environmental goals of this era. Especially in Europe, the interest in innovative technologies is growing since it can help to decrease the emissions of pollutant agents in the air, in the water and in the ground [1]. Fossil fuels are the main cause of these environmental concerns. The time in which we live is named by the anthropologists "The age of the hydrocarbon man". From the beginning of the industrial revolution during the XIX century, human society initially started to burn biomass, and then coal, crude oil and gas to satisfy its energy needs [2]. All the current products or services of our everyday life have a direct or indirect link with energy: food, households, transportation, goods production are all involved with consumption. Especially, since 1950 and thanks to hydrocarbons, the World energy consumption has multiplied by five and as a consequence the human lifestyle has improved: the global Gross Domestic Product (GDP) has grown by a factor close to seven and the World's population by more than two. Therefore, in the last 70 years, the CO_2 concentration in the atmosphere has multiplied by more than four times [3]. This data is due to the fact resources like oil, natural gas and coal account for around 85,5% of the Total Primary Energy Supply (TPES). The first year the NASA's Goddard Institute for Space Studies (GISS) started to record the temperature anomalies of the planet was in 1880. Since that time, 2017 has been the second warmest year documented [4]: the temperature increased of 1.2 °C and the PPM passed from 300 to 420, compared to the end of XIX century. We are living the boiling frog syndrome: the temperature of our planet is increasing extremely fast compared to the past but we do not realize it because the changes do not affect our usual life.

The study of the ice core is giving us more proofs of how this exponential increase has never happened before. 800,000 years dated ice bubbles revealed that nowadays the concentration of carbon dioxide and methane are incredibly higher than the top value every discovered [5]. Carbon dioxide and methane are two of the most known Green House Gases (GHG), sadly famous because of the namesake effect. Methane is a gas that has a climate warming effect 84 times higher than CO_2. Natural gas extraction and use account for the second highest methane emissions cause across the world, following only enteric fermentation (digestion by ruminant animals) [6]. Nitrous oxide has 300 times the effect of carbon dioxide regarding global warming and it has an atmospheric lifespan of over 100 years [4]. The activity of human beings is leaving its mark and transforming the planet so that geologists and other scientists argue whether that mark is sufficiently distinctive and enduring to differentiate a new epoch, the Anthropocene, which is directly correlated to the definition of "The age of hydrocarbon man" [7]. During the last 70 years, urban population, water use, transportation, telecommunication, international tourism, tropical forest loss, terrestrial biosphere degradation, marine fish capture, ocean acidification and coastal nitrogen have all grown dramatically affecting the climate of the planet. The estimated shares of global anthropogenic GHG are divided as 90% for CO_2, 9% for methane and just 1% for Nitrous oxide. Remember that, even if the last two gases have just a partial percentage of the total emissions, they have a global warming effect much higher than the carbon dioxide. The energy consumption account for 68% of the overall emissions, according to [8]. It includes the electricity generation, but also the use of gas in building applications and the fuels used in the transportation sector. 7% is covered by industrial processes, another 12% by agriculture and the remaining 13% comes from other factors. Electricity itself is the largest single source of global greenhouse gas emissions and the one where the best improvements should be done.

With the organization of the Conference of the Parties (COP 21) held in Paris in 2015, more than 190 countries agreed in collaborating and setting new policies and regulations to limit the effects of Climate Change [9]. The main goal of the 2015 Paris Climate Conference was to develop "a framework for action aimed at establishing atmospheric concentrations of GHGs to avoid dangerous anthropogenic interference with the climate system", with the aim of keeping global warming below 2 °C compared with pre-industrial levels. Apparently, this data was even too optimistic: according to a special report by IPCC (Intergovernmental Panel on Climate Change), to prevent natural disasters, climate migrations and wars for resources, the human activities should confine the emissions of GHG to reach a maximum of 1.5 °C increase in global temperature [10]. The major and probably easier improvements can be done about energy efficiency, reducing the demand for electricity and improving the number of renewables in our grids. Without a technological breakthrough, this transition will not be fast and it will deserve substantial economic resources.

The challenges are multiple: which nations should take the responsibility of reducing their impacts? The 19.5 million inhabitants of New York state consume in a year the same electricity (40 TWh) than 791 million people in sub-Saharan Africa [11]. Developed countries need to control their supply of electricity in order not to increase it, cutting the losses and improving the efficiency and the flexibility of the services. Developing countries need to foster their growth through both conventional and renewable power plants. Behind this transition, there are socio-economic, financial and geopolitical risks. Nowadays, according to [12], renewable energies and nuclear account for one-quarter of the global primary energy mix, but in 2040 renewable sources need to be the main used resource, likely supported by natural gas. The remaining amount of hydrocarbons on our planet is not well defined: unconventional resources and new extraction methods would be possibly enough to fulfil the planet energy demand for the next decades. In this eventuality, governments and policymakers would be less pushed to develop regulations to limit the use of fossil fuels for electricity generation purposes. Despite, more than two-thirds of the known fossil-fuel reserves should not be extracted in the next three decades to avoid the emissions in the atmosphere of 900 Gt of CO_2, as claimed by the IPCC [10]. These two-thirds of reserves are concentrated in four regions: North America, Middle East, China and Russia and 74% of the carbon reserves are publicly-owned. The social-political instability which is created by this distribution of resources could be avoided or at least limited if the energy transition would count on renewable resources that are better distributed on the planet. Countries that rely on fossil fuels production for large portions of their Gross Domestic Product (GDP) will be the ones finding the more difficulties to shift to a low-carbon economy. This is why low-carbon technologies have to be sponsored and financed now that these countries have the economic strength to act.

Regardless of the challenges and the difficulties, the low-carbon investments are rising and they can be fundamental to meet the emission goals worldwide [13]. The "Age of Renewables" is now ready to substitute the fossil fuels era. More than half of the global primary energy demand should be covered from renewable before 2050, and also power plants ran by nuclear and natural gas will help this conversion. Energy storage will be a central technology as well. In this context, Horizon 2020, the programs founded and financed by the European Union have the ambitious goal of transforming the energy sector, accelerating the needed changes to improve the quality of the energy-related services [1]. The INVADE project, which will be described in details in Section 6, is part of H2020 Research and Innovation Programme, and the main driver of this master thesis topic choice. Denominated "Integrated electric vehicles and batteries to empower distributed and centralized storage in distribution grids", this project belongs to the topic "Demonstration of smart grid, storage and system integration technologies with an increasing share of renewables: distribution system" of the call "Low-Carbon Energy" of the Work Programme 2016-2017.

Climate change has pushed the electricity grid to an evolution towards smart grids, by including Distributed Energy Resources (DERs) and digitization [14]. At the same time, the increase of the electricity consumption is directly related to a significant contribution to the carbon footprint of the electricity supply, since CO_2 emissions in the power sector drove up by 2.5% caused by a rise of 4% in the Global Energy Demand (GED) [12]. Renewable Energy Sources (RES) are helping the energy transition by increasing their share in the energy mix. Despite this, the variable nature of these resources leads to a need for flexibility in the energy system. The goal is to allow the consumption of the generated power at a different time than when is effectively produced, by implementing energy storage systems or by activating Demand-Side Management (DSM) activities in flexibility markets [15]. This can lead to lower use of widespread fossil fuels for electricity generation, which are usually required to meet load peaks. This shift in the energy mix does entail environmental burdens, and it requires an analysis of the resources used during those time-slots in which the demand at its highest during the day, and their effects on the environment. Life Cycle Assessment (LCA) is one of the most established methods to assess the potential impacts of a product or system throughout its entire life cycle.

Greenhouse gases (GHG) like carbon dioxide (CO_2), methane (CH_4), hydro and chlorofluorocarbons (HFC and CFC), nitrous oxide (N_2O) are emitted when producing electricity [16]. The combustion of fossil fuels like coal, natural gas and oil produce emissions according to the nature of the fuel. Despite the evident contribution of the combustion of fossil fuels in terms of GHG, this is not the only responsible element: upstream inputs are related to the entire life-cycle of the fuel, meaning from where it is extracted until the final use; in addition to this, the efficiency of the power plant and the related infrastructures are influential aspects too. In fact, even renewable technologies have an associated Global Warming Potential (GWP) factor which is non-zero, due to raw material extraction and manufacturing procedures. For example, the construction of wind turbines requires a huge amount of different materials [17] and the solar panels need energy-intensive processes to be manufactured [18]. Specifically, the GWP measures the warming impact from the emission of one unit of a certain gas when compared to one unit of carbon dioxide. Due to normalization procedures, the results are expressed in CO_{2eq}, because it refers to the equivalent amount or concentration of carbon dioxide that every pollutant emits [19].

Policies in terms of energy planning and grid expansion try to tackle climate change by restricting GHG emissions in the electricity sector since GHG emissions are closely linked to the production and use of energy [20]. However, each national electricity mix has unique characteristics based on the resources located inside the borders and geopolitical conditions, and this has to also be considered when defining energy policies [21]. The five targeted countries are the ones in which the pilot sites of the INVADE project are located, in alphabetical order: Bulgaria, Germany, Netherlands, Norway and Spain. These are five nations with different cultures, histories and mentalities regarding the electricity sector. In Bulgaria, the Transmission System Operator (TSO) is Electroenergien Sistemen Operator - EAD. In Germany, four main different entities operate independently from the other electricity market players, and they are TransnetBW GmbH, TenneT TSO GmbH, Amprion GmbH and 50Hertz Transmission GmbH. In the Netherlands, TenneT TSO B.V., the same company which works with the German grid, serves also the Dutch market. Statnett SF and Red Eléctrica de España S.A. are responsible for the transmission of the electricity in Norway and Spain, respectively. The cited TSOs are the ones which share the hourly data of production and the prices of the electricity on the ENTSO-E TP [22].

The electricity sector is governed by economic purposes. The energy transition will be possible only once the price of renewable energies production will be lower than conventional methods. This is the reason why an overview including the environmental and the economic issues of electricity generation is needed to better understand how and why certain decisions are taken by the energy industry.

1.2 Purpose of the study and expected outcomes

The intended application of this work is to provide a detailed study of the relationship between the price and the environmental impacts of electricity production, focusing on peak hours. The cost of producing 1 kWh from coal or through a wind turbine is substantially different and so are their environmental impacts. The GWP potential depends on the resources used to deliver power to the grid while the price of electricity depends on many variables (the real-time demand, the weather conditions, the availability and price of certain resources, the forecast accuracy, etc.). If it would be possible to find a correlation between the two main aspects of electricity production, certain better strategies could be studied to decrease both in one fell swoop.

Understanding how different countries manage the energy supply in peak hours time periods can be a significant and strategic information for decision makers and policies experts. A technical and comprehensive analysis is furthermore developed to meet the needs of the interested governments and administrations. Reducing the pollution of air, water and land related to the electricity generation is a matter of fundamental importance for the developed countries which want to be part of the energy transition.

The structure of this manuscript is articulated in order to offer a clear view of the correlation between environmental impacts and the price of the electricity generation during peak hours. Section 2 includes an exhaustive review of the previously made studies about electricity generation LCAs and the market strategies to involve more renewable resources into the grid. The LCA general methodology is explained in Section 3, divided into its four fundamental steps. Section 4 gives an overview of the main concepts about the Levelized Cost Of Energy, and it can be seen as the bridge between the environmental and the economic segments of the electricity production. In Section 5, a brief introduction of the general European market structure is given, focusing on the Day-ahead market, from where the data about the prices are extracted. The case studies, so the targeted countries electricity grid mixes, are referred to the H2020 project called INVADE, which is fairly described in Section 6. The methodology, described in Section 7, is fundamental to understand the procedure which is followed to obtain valuable outcomes. The results are shown in Section 8, divided in subsections representing the targeted countries. Section 9 and Section 10 finalize the research, discussing on the obtained results and on the possible implementations of the energy context.

2 Literature Review

2.1 Studies on electricity grid mixes LCAs

In terms of LCA, there are two approaches that are currently being implemented and discussed in the literature: Attributional and Consequential LCA. Attributional LCA (ALCA) is defined as a methodology focused on describing the environmentally relevant physical flows to and from a life cycle and its subsystems [23]. On the contrary, Curran et al. defined Consequential LCA (CLCA) in [24] by the aim to describe how environmentally relevant flows will change in response to possible decisions and scenarios. Therefore, consequential LCA should be applied for decision-making purposes [25–28].

There are some experiences in carrying electricity mix LCA, and some authors based their study in a targeted country. García et al. studied in [29] the possible implementations of capacity and new technologies regarding the electricity generation in the Spanish grid, setting as a goal, two different scenario targets related to European Commission Directives accomplishments and CO_2 cuts. Consequential LCA is used by Lund et al. in [30] to set a Business As Usual (BAU) projection of the Danish energy system, focusing on the marginal production unit with particular attention to day/night and summer/winter variations. Jones et al. in [31] used the same tool but assisted by a net energy analysis to describe the future environmental outcomes of distributed electricity production in the United Kingdom. Thomson et al. analyzed in [32] the GHG emissions displacement provided by wind power in the marginal generation of Great Britain, considering the uncertainty of the production. Moreover, this value can be as effective as demand-side management activities for consumption reduction. However, the unpredictability associated to renewable resources may cause an increase on GHG emissions due to the dispatch of conventional generator to fulfill the uncertainty. Howard et al. developed in [33] an LCA model to calculate the GHG emissions from a baseline year of 2011 and projected until 2025. This model includes the grid operation and considers different scenarios such as wind turbine integration, power plants additions and dismantling. As a result, the marginal GHG emissions are reduced in all scenarios, and this can support the development of new energy policies. Garcia et al. described in [34] the average electricity grid mix in Portugal looking at different impact categories. The same authors improved their study by looking at GHG emissions implications for electric vehicles (EVs), including time constraints regarding electricity peaks of production [35]. The EV integration into the grid is a topic of broad and current interest which has been studied by Moro et al. in [36], to understand the positive outcomes of substituting gasoline vehicles for electric cars.

The common point of previously cited papers is that LCA of electricity grid mixes takes into account the yearly average electricity production of a certain country. To understand which are the environmental impacts related to the resources used during peak hours, a time-varying approach should be implemented. The electricity generation model should differentiate between marginal, and so whichever amount of production that is not considered base load and average models, which consist of the combination of base and peak load, as highlighted by Curran et al. in [24]. According to methodological reviews of LCA electricity mixes ([37], [38]), the difference between average yearly and shorter time periods could be significant, especially when there is a consistent difference in the strategy used to cover peak hours in comparison with the base load. At the same time, the electricity demand change depending on seasons, weather, resources availability and therefore the used mixes during base load and peak hours can differ significantly.

Studies that took into consideration the time-varying dependence of electricity production to assess consistent environmental impacts are taken as examples in this manuscript. It is the case of Nilsson et al. [39] who analyzed the change in residential electricity consumption through the possibility for the final customer to visualize in real-time the electricity prices. A similar path is followed by Cubi et al. [40] in Canada, to assess the building environmental impacts related to the variability of the resources used during day-time. In [41], Khan et al. approached the electricity mix environmental impacts thanks to an analysis in which peak hours and off-peak hours are finely compared, leading to useful results for the policies makers regarding Bangladesh's grid. This method has been followed by Khan et al. in [42] to evaluate GHG emissions in New Zealand.

2.2 Studies on economy of electricity markets

One of the main problems of the electricity markets is that the prices are difficult to predict. Especially, the unpredictability of renewable sources production make difficult to know exactly how much energy will be produced. Therefore there is a need to implement complicated market mechanisms to compensate the unbalances. Many studies are focused on finding forecasting mathematical models based on stochastic analysis. This is the case of Fanelli et al. in [43], who focused their investigation on the seasonality of the electricity prices, correlating them with demand forecasting techniques to find out the reasons behind volatility and peak hour consumption. They observed that the implementation of such a model can be further explored to better schedule the production of electricity. The identification of peak hours and seasonal elements is the target of Janczura et al. in [44], who in their conclusions affirmed that a valuable stochastic modelling can be efficiently developed looking at periodic trends, filtering frequent data and working with different recognized approaches. Huisman et al. [45] do not recommend to use daily average prices as a reference price for marking the market behaviour. The time dependency of prices is confirmed through an analysis that shows how in the three examined markets (Germany, the Netherlands and France), prices increase during 5-8 pm time slots and decrease after 11 pm, estimate supported by the fact that demand is low in weekend and off-peak hours, while it is high during weekdays and peak hours. An interesting search about the Dutch electricity market by M. Lijesen [46] is focused on real-time prices. It shows that the price elasticity of demand, so the change in demand for electricity in response to a percent change in price, may not be effective because of the low awareness of the customers about electricity prices. Hypothesis confirmed by [39], as already mentioned. The obvious question is: what if, together with the real-time electricity prices, the customer receives the real-time carbon intensity of the electricity he/she is consuming? Would it be a more powerful strategy to reduce and/or switch the demand?

As already specified in the introduction, one of the most important constraints regarding the grid is stabilizing the frequency in a moment in which the penetration of renewable energies, and so the intermittence of the generation, is booming. Thus, the implementation of energy storage systems can help to solve the problem, distressing the grid, flattering the production curve. For example, wind farms can generate a high amount of electricity at night, when usually the demand is low and as a consequence, some turbines have to reduce their production or even they have to be turned off. Consequentially, the interest of researchers about this topic is increasing exponentially. Garcia et al. in [47], investigated the potentiality of stochastic optimization of merging wind generation and pumped water storage units. They discovered that through an optimized model, the net power delivered to the network can precisely support the schedule cleared by the wind farm owner in the market, which is exactly the reason why the two technologies should be joint. In any case, this accuracy would depend on the technical specifications of the reservoir, which should be well sized. Also, Dicorato et al. in [48] explored the same opportunity, pushed by the penalties the wind farm owners incurred in whenever they are not able to deliver the power they suggested in the day-ahead and future markets. Their results have confirmed that well-sized storage improves the market performance of the studied wind farm thanks to the accomplished delivery plans. The flexible hydropower plants, both the ones with and without a pumping system to pump up the water to the upper reservoir, are essential in the peak power production field because they can virtually store huge amount of energy. Taking into consideration this extreme important aspect, Kougias et al. in the investigation "Pumped hydroelectric storage utilization assessment: Forerunner of renewable energy integration or Trojan horse?" [49], analyzed four out of five targeted countries of this study (Bulgaria, Germany, Norway and Spain) to look at the utilization strategies of hydropower plants. Collecting, harmonising and analysing datasets in the range period 19912006, they determined the change in the utilization factor of PHS (Pumped Hydroelectric Storage), discovering that some countries have increased their use of this source while others are heavily under-utilizing the installed capacity. The suggestion of the authors is that the factors which can be related to this usage difference are several, starting from the ownership of the power units, the price setting mechanism, the carbon pricing and power plant efficiency. For example, if the same entity owns both PHS and gas turbine power plants, there could be an application of different strategies concerning the marginal price of electricity production, as it will be further explained in Figure 7. Lu et al. in [50], developed an innovative strategy to allow pumped-storage hydropower plants to make them more competitive. Depending on the fact "price peaks and valley do not necessarily coincide with load peaks and valleys", they built up an algorithm to maximize the profit achievable with a pumped-storage unit. Their model takes a basic weekly forecasted market clearing price curve, which does not take into consideration any stochastic deviation.

3 LCA: Life Cycle Assessment

LCA, or Life Cycle Assessment, is a method that enables evaluating the potential environmental impacts of a product during its entire lifetime, starting from a series of inputs and outputs related to the product itself. The International Standardization Organization has specified the standards ISO 14040 and ISO 14044 [51] that provide framework for the LCA in this manufacture.

There could be many intended use applications for a LCA: comparison of specifics goods and services, monitoring environmental impacts of a product and even of an entire industry sector, greening the supply chain. As well, it is very useful as a policy information: it can help public institutions, industries and decision makers in general to let them choose the right pathway to develop a new project, regarding its environmental performances. As companies experience serious challenges regarding their relationship with the overall society and their customers, LCA emerges as a prime instrument and reference in order to achieve societal and customer approval. Medias pay acute attention to possible violations of proper conduct with respect to people's welfare and environmental threats. Most of the project partners promote a social responsibility with respect to sustainability. The principal question that needs an answer is whether such declarations of societal responsibility are truly genuine. This study aims to determine the overall sustainability of the electricity production in the five targeted countries of the INVADE project.

LCA is an effective method also because it can perform a multi-media analysis (air, water, waste, resources depletion, etc.) and at the same time, the results cover multi-attributes impacts (Global Warming Potential, Abiotic Depletion Potential, Acidification Potential, etc.). An overview of the LCA process is shown in Figure 1.

From Section 3.1 to Section 3.4, the definition of LCA and the guidelines to develop it, according to the ISO standards [52] is presented. In Section 7, the detailed LCA structure of the grid mixes is carried out, following the same steps suggested by the regulatory framework.

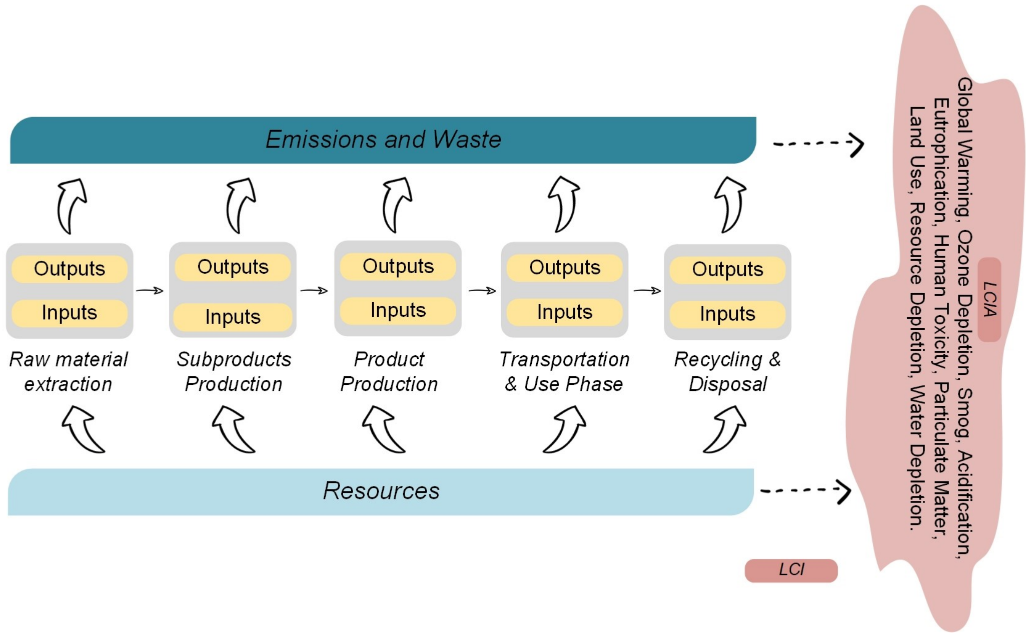

Figure 1: Overview of an LCA process

3.1 Screening LCA

The first calculation of the Life Cycle Assessment is also known as Screening LCA. LCA is considered an iterative process as it can be detected from Figure 2. The first iteration loop refers to the Screening LCA approach. It stands for defining the value chains and devices, calculation model and data collection of the studied system. The data that is considered for this assessment are those that are available readily in literature and databases. For example, if some important data are missing or the obtained results are not valuable, who is performing the LCA can return to the first phase and starting again the study with new hypothesis or system boundaries. Each consecutive step allows to obtain beneficial improvements in the quality of the LCA. Alongside these pages, the standardized references are detailed, as well as the definition of all the steps to perform an LCA, with particular attention to the INVADE project.

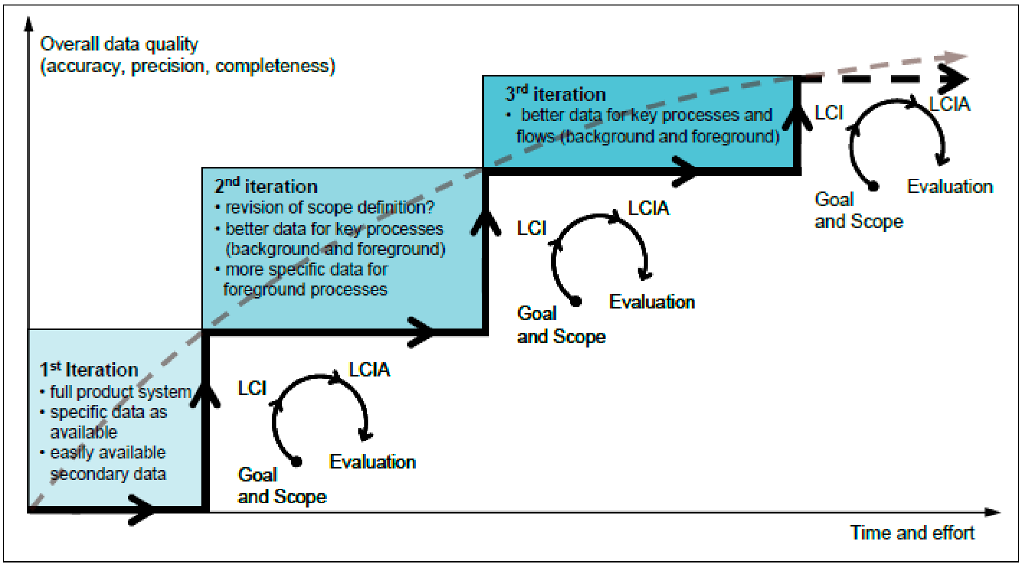

Figure 2: LCA as iterative process

The recommended structure to perform a Life Cycle Analysis is shown in Figure 3. According to ISO 14040 and ISO 14044 [51], the four needed steps are Goal and Scope definition, Life Cycle Inventory, Life Cycle Impact Assessment and Interpretation of the results. The two-way arrows in the figure reflect that the LCA is an iterative process and it means that the steps can be re-performed during the process because of different reasons (recollection of data, goal and scope of the results, etc.).

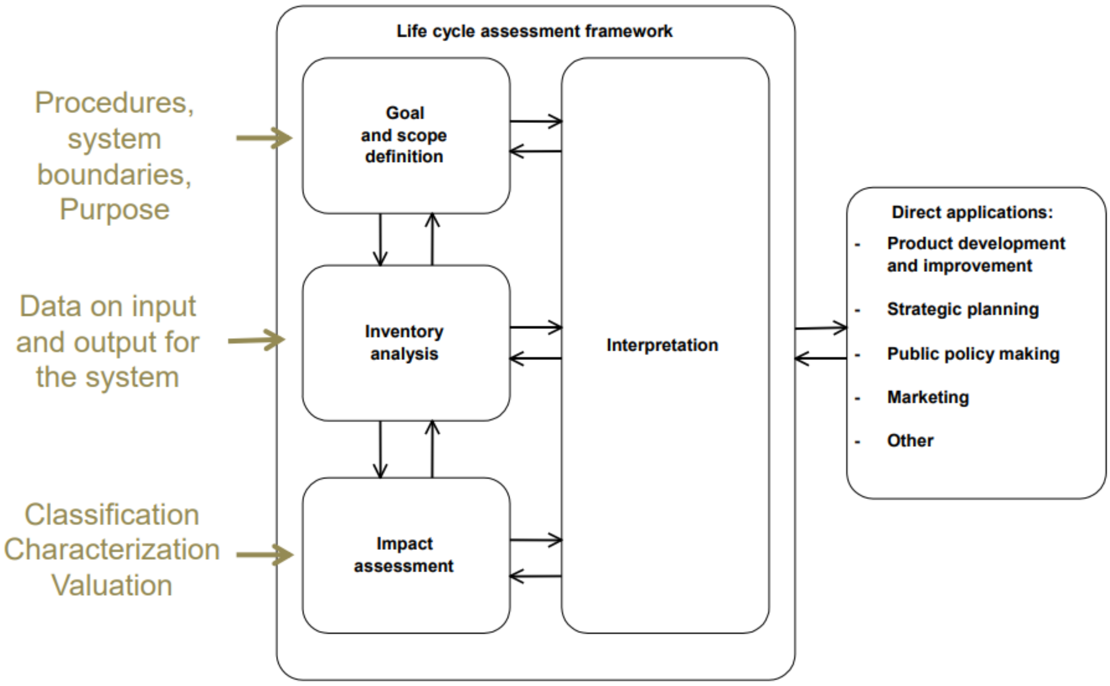

Figure 3: LCA steps according to ISO 14040 and ISO 14044

3.2 Goal & Scope definition

The first step of a Life Cycle Assessment is to define the objectives. Goal and Scope should be consistently related to the product/project and they have to be clearly defined.

Goal definition

To define the goal of the LCA, different points have to be taken into consideration:

- *Intended application*: marketing, product improvement, product development, product evaluation, strategic planning, etc.
- *Purpose of the study* : is the study made for an internal analysis or to be published? Different purposes require different types of writing, more or less technical and comprehensive.
- *Intended audience*: Who will utilize the LCA results? It can be a stakeholder of the project, the public administration, engineers, customers, etc.

- *Comparative analysis*: If the LCA compares two different alternatives, it should be defined at the beginning of the report.

Scope definition

The scope of the study frames the system that will be analysed. In this step, the assumptions and the methodology of the process should be precisely defined. It is a priority in this stage, to let the reader having a clear comprehension on which are the relevant points of the study. Functional Unit and System Boundaries are fundamental notions for the LCA development.

- *Function of the product*: refers to a basic description of how the product or system works.
- ***Functional unit***: It is one of the most important definitions since the results are based on this. The unit is related to the product or system to be analysed and it has to give a good qualitative and quantitative description of the process. It is not always easy to evaluate, because the functions and the performances of the product cannot be easily described or isolated. The comparison between different systems is made on the basis of this equivalent function and a clearly quantitative measure is crucial for comparative LCAs. For example, during the electricity generation process, does it emit more GHGs a power plant fueled by coal or a nuclear reactor, considering that both produce 1 kWh? The functional unit to compare the two power generators should be 1 kWh of electricity produced.
- *Reference flow*: the reference flow is the measurement of product materials and components needed to fulfil the function, as it has been defined in the functional unit. The data used in the Life Cycle Assessment should be calculated referring to the reference flow.
- *Description of the system*: performing the description of the studied system allows the reader to better understand the specifics.
- ***System Boundaries***: the system boundaries limit the LCA scope. To not let the analysis be too broad or too less specific, who performs a Life Cycle Assessment should set some boundaries to simplify the study case. There are several options to set up the system boundaries for a LCA. The most complete Cradle to Grave; the Cradle to Gate which takes into consideration just until the use process of the product; the Gate to Grave that includes the processes between the factory gate and the disposal of the product; the Gate to Gate which starts from the reception of raw material

until the factory gate. In Figure 4 the first two examples are shown in a more representative way.

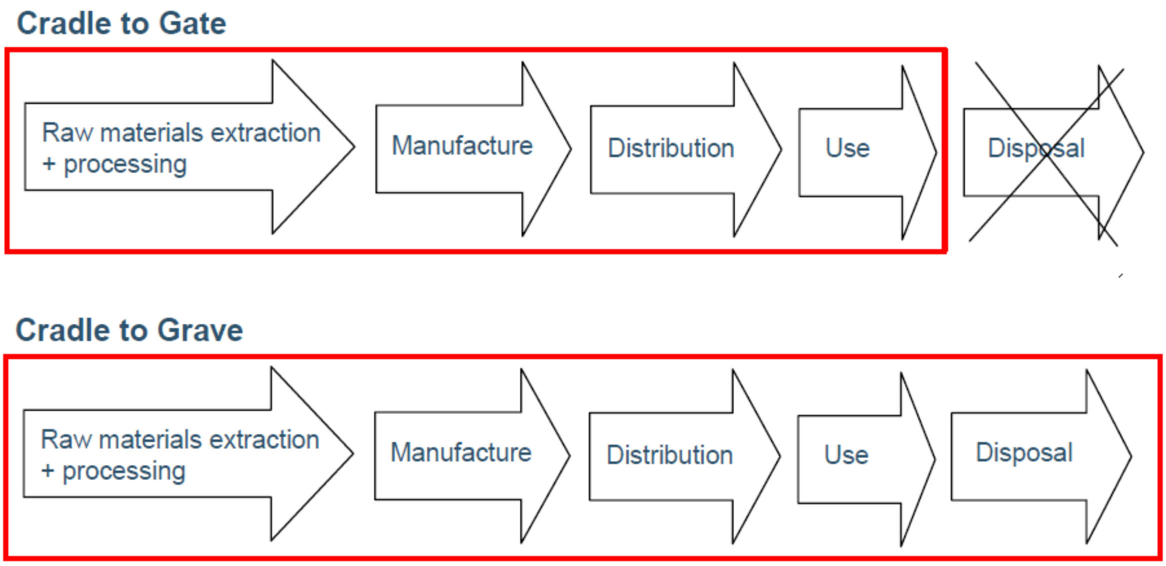

Figure 4: Cradle to Gate and Cradle to Grave system boundaries examples

- *Allocation Procedures*: for example, in multi-output processes different by-products are manufactured, thus, it is needed to portion the inputs and outputs of the system in order to allocate the justified quantities (of material, energy, waste) to the different by-products. Finding the suitable allocation factor may be sometimes problematic, and there might be significant impact of these choices on the LCA results. Hence, according to ISO 14040 and ISO 14044 recommendations [52], allocation should be avoided whenever possible.

- *Impact categories and Impact assessment method*: the results of a Life Cycle Assessment are expressed with the help of the inventory results and the impact assessment method. The method includes typically different environmental impacts such as climate change. The impact categories include emission-specific characterization factors to express the potential environmental impact:

  - *Atmosphere*: climate change, ozone depletion, smog formation.
  - *Hydrosphere*: eutrophication, acidification.
  - *Biosphere*: soil depletion, deforestation.

- *Data requirements*: it is needed to evaluate the quality of the data to further analyse. All the data requirements should be properly documented. The more detailed the data, the more relevant the LCA.

A detailed description of the LCA applied to the specific topic of this research is presented as Table 5 in Section 7.

3.3 Life Cycle Inventory (LCI)

The main objective of this stage is to compile an inventory of energy and material inputs and environmental outputs across the whole lifetime, referred on the goal and scope phase.

Data collection is the basis of the Inventory Analysis. This is one of the most time-consuming parts when performing a LCA. It demands a detailed knowledge of the processes included inside the system boundaries. Again, procedures suggested by the references ISO 14040 and 14044 [51] should be used. Figure 5 include the inputs, the usual steps and the outputs of an ordinary LCA.

- *Data quality*: data should be able to satisfy stated requirements.
- *Data acquisition*: measured, calculated or estimated? Primary data (measured) or secondary data (calculated, taken out from literature and database)?
- *Time-reference*: when was the data obtained and until when it is supposed to be valid?
- *Geographical reference*: from where the data was obtained (Country or Region)?
- *Technology coverage*: define specific single technology or technologies mix.
- *Uncertainty of the information*: define assumptions and limitations of the model.

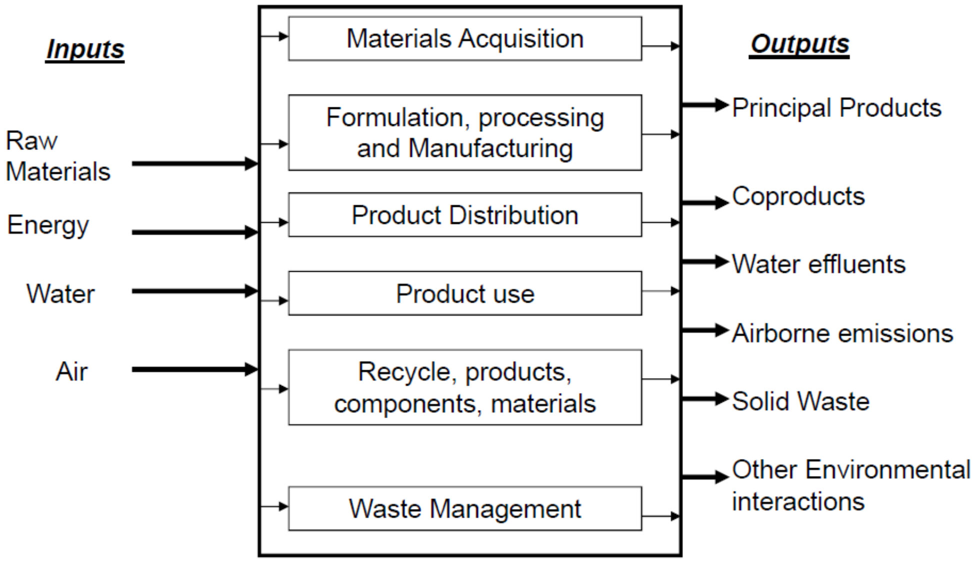

Figure 5: Inputs/outputs analysis for LCI

3.4 Life Cycle Impact Assessment (LCIA) & Interpretation of the results

Emissions, used raw materials, and energy demand quantified in "Inventory Analysis" are translated into the related environmental impacts. LCIA is is carried out within the following mandatory steps: Selection of impact categories, Classification and Characterization.

- *Impact category*: class that represents environmental issues of concern to which Life Cycle Inventory analysis may be assigned (ISO 14044) [51].
- *Characterization model*: This is the model that calculates the environmental impacts by describing the relationship between the LCI results and category indicators [51]. There are several characterization models available to assess the potential environmental impacts of a certain system. The most complete methodology is the CML Impact Method, a problem-oriented LCA method developed by the Institute of Environmental Sciences of the University of Leiden.
- *Characterization model*: it is used to merge environmental impacts that are related between each other.

The interpretation of the results is is the last one and the most interesting step of the whole Life Cycle Assessment. It is needed to assess the real and effective environmental impact of the product or project that has been studied. Then, the results can be compared with the existing literature, to observe if they are aligned with the goal and scope of the project. At this stage it is possible to understand if the right data and assumptions were taken into consideration, realizing which are the weaknesses and the limitations of the assessment.

4 Basic economics of power generation

Which are the power plants that are responsible for the generation of power in a determinate moment and why? Starting from this question, this section aims to explain the basic concepts related to the economics of electricity production.

The Levelized Cost of Energy (LCOE) is a measure of the cost of producing electricity which takes into account fixed and variable costs of power plants plus the site characteristics and/or the resources used in the process. Therefore, LCOE is a tool that allows a valuable comparison of electricity costs between different energy sources. In Figure 6, a schematic visualization of the LCOE is shown.

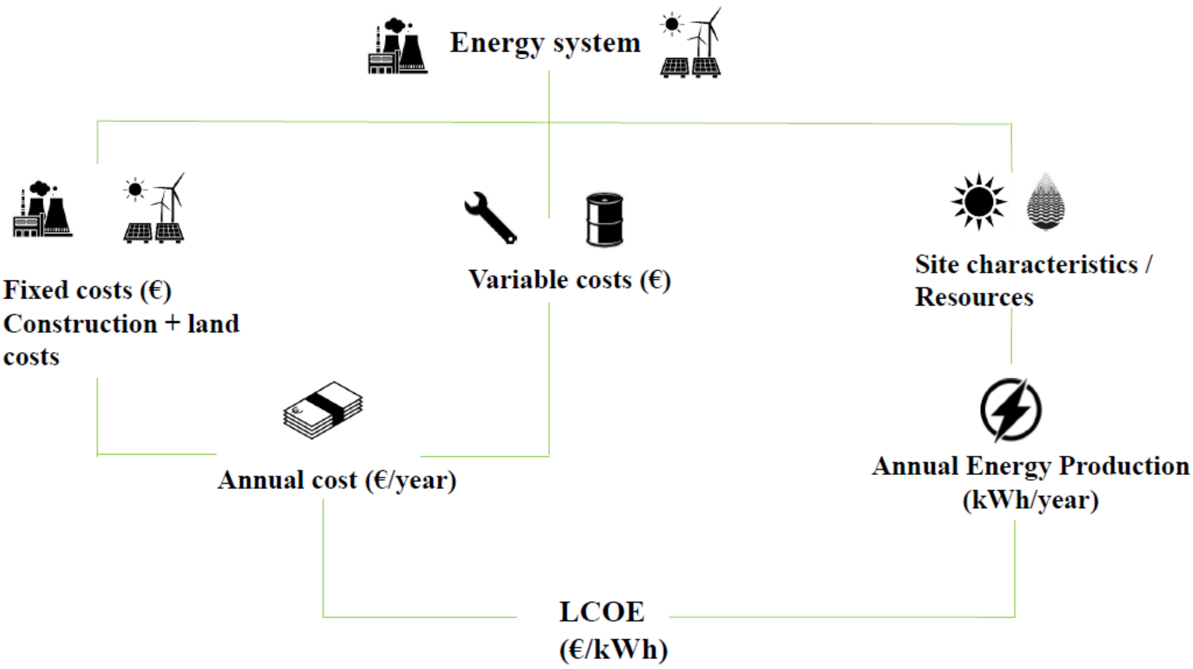

Figure 6: Levelized Cost of Energy scheme

Rearranged from [53]

Besides the fixed costs a power plant has to deal with (mainly land and capital costs), there are other variable costs that are related to the operation of the generator. These last ones consistently influence which power plants have to produce a determinate amount of power at a settled time. The operating costs include the maintenance of the power plant, the labour force and the cost of the fuel. In every case, they are related to the amount of electricity produced. Solar and wind farms, which do not require any fuel to run, do not have to deal with this extra expense, while fossil fuel based power plants are sensitive to the combustible prices. In Table 1, an overview of the most common power plants costs is presented. Being both the initial and operating costs very variable, depending on the country, the size and the technology, this table just aims to give basic knowledge about the overall trend of power plants expenses.

Table 1: Capital cost and O&M costs of power plants generation. Note this list does not include subsidies, incentives and social costs. Rearranged from [54]

Technology	Initial capital costs ($/kW)	Operating/variable cost ($/kWh)
Coal PP	500 - 1,000	0.04 - 0.20
Natural Gas PP	400 - 800	0.04 - 0.10
Nuclear PP	1,200 - 5,000	0.02 - 0.05
Solar PV	4,500 and up	Less than 0.01
Wind	1,200 - 5,000	Less than 0.01
Hydro	1,200 - 5,000	Less than 0.01

Another important element to observe when analyzing peak hours production is the time a power plant has to run before effectively providing energy to the grid. For example, the fission of uranium inside the core of a nuclear power plant is not a short process and it can take up to a day to the generator to release electricity to the TSO. Contrariwise, the water that falls down from a dam reaches rapidly a turbine that in turn generates electricity. So, in this case, power can be delivered in a short time. To operate during unexpected peak hours, a power plant should be fast and flexible enough to deliver power as quick as possible.

If turning on a power plant can require peculiar ramp times, the same happens for turning them off. If it takes a large amount of time to turn on a fission reactor, it would be a counter-sense to turn it off after just a short time of operation. Especially this type of power plants needs a complicate turning off process in which the fuel bars should be slowly and carefully removed from the core, to avoid an overheating of the reactor. At the same time, it should be waited some days before turn it on again. Besides, for renewable energies like wind and hydro, the power plants just have to turn the switch off and the infrastructure stops to work [55]. This is why when there is an over-production and the frequency goes up more than 50 Hz, the wind farms are the first ones to interrupt the generation. The minimum run time is the reasonable shortest amount of time a plant can operate once it has been turned on. In Table 2 the different ramp and minimum run times are listed.

Table 2: Typical ramp and minimum run times of most common power plants.
Rearranged from [54]

Technology	Ramp time	Minimum Run Time
Simple-cycle combustion turbine	minutes to hours	minutes
Combined-cycle combustion turbine	hours	hours to days
Nuclear PP	days	weeks to months
Wind Turbine	minutes	none
Hydro	minutes	none

Knowing these power plants properties, it is possible to draft a scheme to understand which are usually the power plants required to deliver power during unexpected peak demand times. The flexibility of the technology, so ramp time and minimum run time, is an essential quality for a power plant that works for peak hours production. If also the operating costs are low, this makes a power station suitable for the scope, letting the owner get high revenues on the electricity market. Historically, power plants which have the duty to offer power just during peak hours are used less than 20% of their operating lifetime, but they are the most polluting ones due to their ramp up and shut down times [56]. Let them run just for this short amount of time, it surely is a waste of space, resources and human labour. Gas, coal and oil fueled power plants are the ones that contaminate the most, but also the most adaptable to the electricity variability, as shown in Figure 7. Luckily, Pumped Hydro Storage (PHS) is even more flexible, because the amount of water that leaves the upper reservoir is easy to control. Consequently, when available, it is the best resource to use for peak hours, without any doubt.

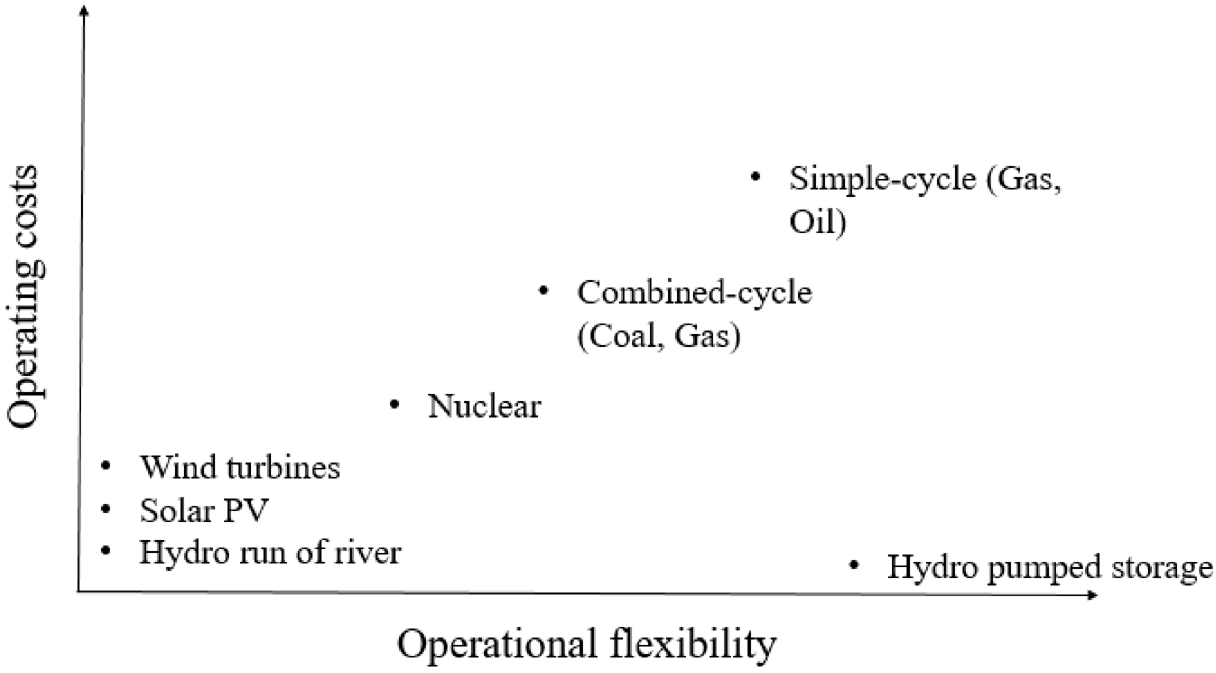

Figure 7: Scheme of flexibility and operating costs of different power plants

Initially, PHS systems were in charge of use and store the extra produced power of coal-fired units and nuclear reactors, to allow base load power plants to function with high efficiency and not as partial-loaded. This is why usually, the power plants that are the less flexible (nuclear, hydro run of river and renewable energies when present) are used to serve the required base load energy, while coal, gas and hydro storage are better structured to cover the peaks. In addition, the power plants ran thanks to fossil fuels are the ones that can make the highest profits if the demand is really high, as proved in Figure 8. Renewable energies serve the base load with lower prices but a major input of these resources can help to reduce the electricity prices.

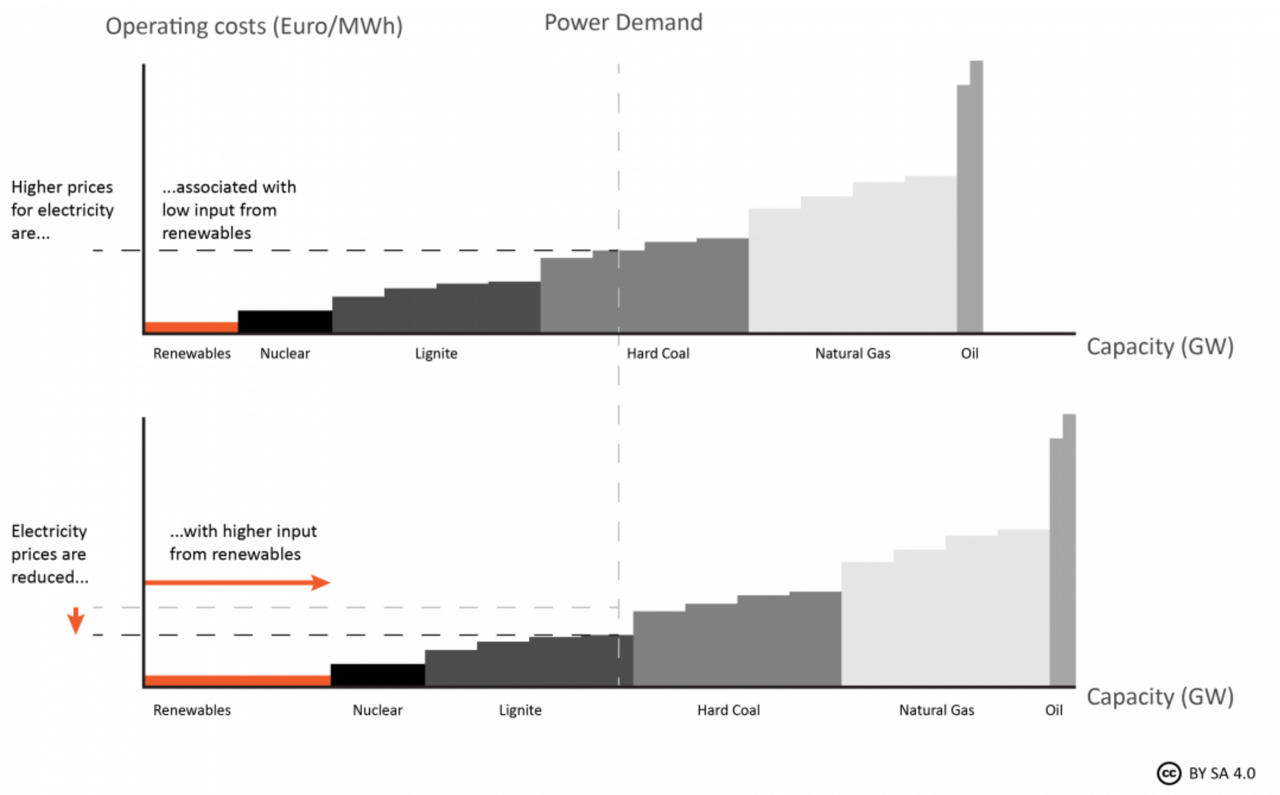

Figure 8: Electricity price fluctuations due to merit-order effect.
Source: Clean Energy Wire [57]

Especially regarding the PHS, the financial return is obtained when the ratio of the price of pumping up the water to then release it exceeds the round-trip efficiency of the power plant, which is generally quite high (65-80%). Furthermore, the price of electricity to pump up the water should at least be 25% - 30% lower than the selling price [49]. Countries which can take advantage of this source have different strategies to improve its use, as further discussed in Section 8.

5 Typical European market organization

The role of the electricity market is to ensure the matching of demand and supply during every instant of time. In Europe, to avoid a system collapse, the frequency in the grid should always be equal to 50 Hz. On one side, the electricity generators produce electricity at a certain price that is related to different factors (the cost of the fuel used, O&M costs, policies and regulations). On the other hand, the final consumer needs a certain amount of electricity, willing to pay it a certain price. When the supply curve meets the demand one, the so-called "clearing price" is set. A system of bids and offers, which consists of a pair of values (e.g. Volume of electricity in MWh and Price of electricity in €/MWh), is indeed the base of the trading. Every actor offers/requires a certain amount of electricity in MWh and the price he is going to sell/buy it in €/MWh. The electricity trade carried out prior to the hour of operation is normally based on one-hour contracts auctions. During the time of operation, the real-time market is in charge of allowing a settlement of deviations between bids/offers, usually based on time-frames of 15 minutes. More details regarding the specifications for each country are given in Table 9. The Intra-day and the balancing markets assure the stability of the grid and the satisfaction of all the players involved. In Figure 9, a time consecutive visualization approach of the electricity market is shown. In the next subsections, a brief description of the different kind of markets is presented.

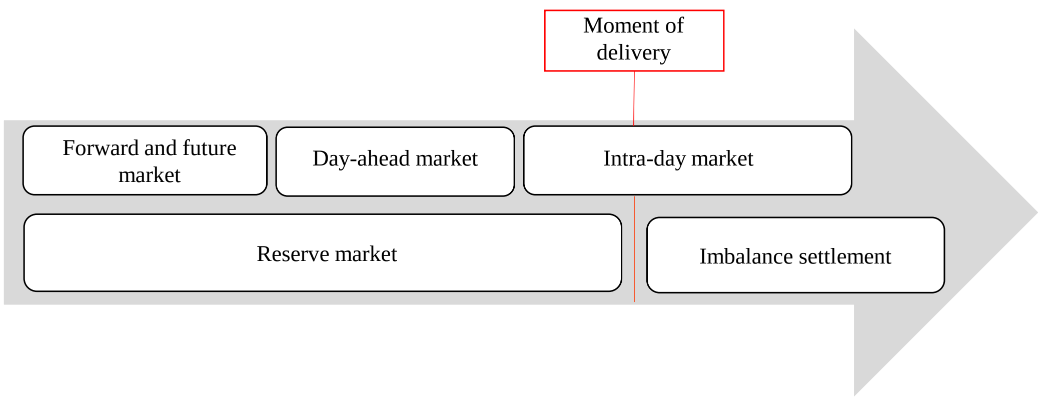

Figure 9: Temporal ordering of electricity markets

- **Forward and future market**

  The contracts in the forward and future markets are generated from years in advance until the day before the electricity delivery. These bilateral contracts are signed in order to ensure to power producers and affiliated users a certainty of delivering/consumption of a set amount of electricity. This strategy enables both parts to have a correspondent "insurance": electricity generators secure their future revenues, minimizing the risks of possible electricity prices decreases; at the same time, large and so usually industrial consumers, establish an agreement which provides them with an amount of electricity they know they will surely consume. The difference between forward and future markets lies in the fact that the first one is a standardized market and the contracts are possibly further traded while the future one is more flexible, based on private agreements and usually the arrangement between two parties remains unchanged until the final delivery of electricity.

- **Day-Ahead Market**

  The day-ahead market is the base of the electricity trading, because as will be further explained in Section 7.5, the highest amount of electricity in a country is traded during this market. At the end of the correspondent time-slot (24 hours before the physical dispatching), the market zone has to be in equilibrium (supply=demand). As the name suggests, in the day ahead market the electricity is traded one day before the actual delivery. A country can have one or more bidding or market zones and everyone has to manage itself (it has to be in balance), even if it depends on other zones for imports/exports. Different countries can be coupled in the day-ahead market to improve the flexibility and differentiation of the suppliers. A more detailed description of the day-ahead markets in the targeted countries is given in Section 7.5.

- **Intra-day market**

  The intra-day market has the goal of adjusting the previous set contracts, correcting the shifts in the forecasted production/use of electricity due to unpredictable weather conditions, unexpected extra need for electricity or sudden power plants issues. Usually, the electricity traded during the intra-day market is just a minor part of the total, as explained in Section 7.5.

- **Balancing market**

In the European markets, the Transmission System Operators (TSOs) are the entities responsible for keeping the grid in a frequency balance. Whenever the frequency on the grid is higher than 50 Hz, it means there is an extra production while the opposite happens when the consumption is higher than the generation. In normal conditions, the frequency can vary of $\pm 2\%$ of its nominal value [58]. TSOs have agreements with power stations that intervene in case of unbalances caused by a lack of electricity availability. This instability is caused by erroneous forecasting in terms of production or demand of the energy retailers. The Balance Responsible Parties (BRP) are those private entities that have to pay the penalties given by the TSO to maintain the grid stability. Usually, BRPs and retailers are the same entity, but depending on the country the regulations can change. In fact, during the real-time delivery, primary reserves are activated immediately after an unbalance and they are assigned through bilateral contracts between TSOs and power plants (for example in Spain) or through a market pool (for example in Norway). Secondary and tertiary reserves are applied after a longer time interval to fully mitigate the imbalance market mechanism.

6 Case study: the INVADE project

The penetration of renewable energies in the grid is regularly increasing but with a undesired pace, because of technological and economic issues. The transition from fossil fuels to clean energy sources has to prioritise those already available tools that can speed up the decarbonisation of the electricity sector. Trusted and tested technologies like batteries, electric vehicles and flexible loads can play a relevant role in the future grid. Energy storage will be a fundamental player in tomorrow's smart grids because it assures the best possible utilisation of renewable technologies. First, the connection of batteries to renewable power plants implies the storage of the not directly used electricity. Secondly, groups of connected buildings with installed solar panels and household batteries will be able to trade electricity with the grid in real time. These two elements will directly improve the sustainability of the field, and they will affect the electricity production curve as well. Furthermore, the integration of Electrical Vehicles (EVs) and batteries can increase the hosting capacities of renewable energies. Nowadays, the production has to meet regularly the demand in real time, but from the next decades, it will be possible to shift the highest production time slots to hours in which the renewable power plants do not produce any electricity.

The INVADE project aims to integrate electric vehicles and batteries to empower the centralised and distributed energy storage. It is an EU funded Horizon 2020 project, developed in five different pilot sites based in as many countries (Bulgaria, Germany, Norway, Spain and the Netherlands) that can count on 12 partners divided into pilot implementors, research institutes and technology providers. CITCEA-UPC is the research centre belonging to the Universitat Politècnica de Catalunya that is responsible for, among other tasks, the WP 3. This WP deals with different involved technologies and the related Life Cycle Assessments.

The methodology described in Section 7 has been applied to analyze and assess the potential environmental impacts of the integration of DERs and of flexibility services supply in smart grids, which are the tasks of the INVADE H2020 Project. The main focus is to design a flexible management system using batteries that supports the distribution grid and electricity market while coping with grid limitations, uncertainty and variability with high penetration of renewable energy, electric vehicles and an increased number of diverse smart grid actors. as displayed in Table 3. To provide these services, the INVADE Platform is based on a flexibility cloud that enables flexibility operations to be provided by means of algorithms, functions and control dashboards using the Internet of Energy Things and Big

Table 3: INVADE main overall goal and project goals

Main overall goal
Combining existing infrastructure with inexpensive technologies into a new framework to solve the main problems of the energy grid.
Project goals
Design a flexibility management system using batteries that supports the distribution grid and electricity market.
Develop a model for batteries including EVs focusing on the prediction of batteries lifetime and optimization.
Deliver the Integrated INVADE Platform based on Flexibility Cloud enabling flexible management algorithms and integrate it with existing infrastructures.
Design innovative business models to enter the market.

Data analytics. The integration of DERs, as well as electric vehicle and storage, may change the total electricity production and consumption patterns on each country pilot-site. Therefore, it can lead to a change in the potential environmental impacts of the energy system, being this the main objective of the LCA task in the INVADE Project.

To better frame the different pilot sites and their objectives, PUCs (Pilot Use Cases) and KPIs (Key Performance Indicators) are defined, to assess the correct performance of the project and the achievement of the expected outcomes at the end of the project. The PUCs link the pilot sites to the technologies involved. The main ones are centralized and distributed energy storage, with connection to EV chargers, solar panels or directly to the grid. Every pilot site represents one or more PUCs, as highlighted in Table 4. The KPIs represent the set goals for each pilot in terms of technology, economic or environmental aspects. The different KPIs are thought in order to recognize the improvements obtained in the electricity grid through the appliance of the project. The specific KPIs related to the environmental analysis are listed below, divided by country. To achieve the scopes proposed by the KPIs, the electricity grid mixes have to be studied because all the environmental goals are somehow related to the electricity delivered by the grid.

Table 4: INVADE Pilot Use Cases

	PUC
Bulgaria	PUC.1 and PUC.2
Germany	PUC.4
Netherlands	PUC.1
Norway	PUC.1 and PUC.3
Spain	PUC.2

Pilot Use Cases (PUCs):

- PUC 1: Mobile energy storage from EVs to buildings, houses and grid (V2B, V2H, V2G)
- PUC 2: Centralized energy storage
- PUC 3: Distributed energy storage (individual batteries in households)
- PUC 4: PUC 2 + PUC 3

Key Performance Indicators (KPIs):

- Bulgaria: Benefits from a battery at Substation level for % increase in renewable for self-consumption.
- Germany: Percentage of decrease in emissions from the diesel generator previously used to offer back up solution to the local grid.
- Netherlands: Show the improvement in share of renewable energy during the EV charging service.
- Norway: Optimise utilization of selfproduced - To test different set-ups of battery / flexible loads, for self-consumption vs feed-in to the grid.
- Spain: Percentage of decrease in emissions from the diesel generator previously used to offer controlled islanding to the DSO control centre.

7 Methodology

Regarding the investigation presented in this research, the aim of the LCA is to understand the potential environmental impacts of electricity production in terms of GWP. More specifically, the focus in on peak hours and the comparison is made with a yearly average GWP value. In this respect, inputs and outputs are attributed to the functional unit, which is 1 kWh of electricity generation, and not the assessment of the consequences of a change in demand of the functional unit. For this reason, an Attributional LCA is presented (see the definition of ALCA in Section 3.1). The same steps explained for a general LCA in Section 3, are now interpreted regarding the electricity grid analysis.

7.1 Goal & Scope for the Electricity Grid Mix LCA

To better assess the model and its characteristics, a screening LCA is performed and the analysis structure is shown in Table 5.
It contains the basic information to understand the goal of the system and the applied procedures to reach it, referring to the ISO recommendations presented in Section 3.

Table 5: Electricity grid mix LCA Goal and Scope Structure

Goal	**Intended application**	Explorative study
	LCA Typology	Attributional LCA
	Purpose of the study	Provide the reader knowledge to understand the proper environmental impacts of peak hours' electricity production
	Comparative Analysis	This is not a comparative analysis. Every single country has its own installed capacity and therefore any comparison would be incorrect
Scope	**Function of the system**	The targeted country's electricity grid mixes are in charge of producing the electricity needed to meet the national load in any instant
	Functional unit	1 kWh ([39], [41], [42])
	Reference flow	Energy flow (kWh) of electricity
	Description of the system	The targeted countries' electricity grid mixes are described accurately in Section 8
	System Boundaries	From Cradle to Gate. A detailed definition is explained in Section 7.2.2
	Allocation procedures	Allocation procedures are explained in Section 7.2.2 [37]
	Impact Assessment Method	CML 2015. Impact category to be assessed: GWP [kg CO_{2eq} /kWh]
	Data requirements	Secondary data provided by ENTSO-E Transparency Platform

7.2 LCI for the Electricity Grid Mix

The time variability of electricity production is a fundamental issue to consider in order to correctly assess the GWP during different moments of the year. This report bases its results on the data extracted from the Transparency Platform (TP) of the European Network of Transmission System Operators for Electricity (ENTSO-E). This online data platform includes various electricity data, mainly reported by country or bidding zone. The data used for this study come from the sections "Installed Capacity per Production Type" and "Actual Generation per Production Type". These data are directly from the primary data owners, as the TSO or the generator companies. Thanks to the hourly data provided by the TP, it is possible to find out when peak hours occur and which resources are used during those times. A critical review of the TP from 2017 in [59], points out a number of imperfections, but at the same time it reveals that it is the single most important data source for European researchers. More than 9000 users from different sectors (Academia, Data service providers, Industry, NGOs, Policies) currently take advantage of the TP for their own studies and this fact gives the platform an additional reliability. For the purpose of this study the compatibility of the data is guaranteed, supported by the fact they were compared, when possible, with the statistics from the national Transmission System Operators (TSOs).

7.2.1 Functional Unit

The functional unit (FU) is related to the product or system to be analyzed and, it is a value that has to give a good qualitative and quantitative description of the process [52]. As previously done in similar studies ([39], [41], [42]), the functional unit was set to 1 kWh of electricity produced. Thanks to this approach, different amounts of generation are compared observing the relative environmental impacts. The more electricity is produced, the more GHG are emitted. The scope of this analysis is to compare different quantities on the same base, as 1 kWh. Hence, the GHG emissions can be calculated corresponding to every kWh generated by the grid as kilogram of $CO_{2eq.}$/kWh.

7.2.2 System Boundaries

The system boundaries limit the LCA framework by establishing resources inputs and emissions outputs of the system, excluding those that are out of the LCA scope. Setting the system boundaries is a fundamental step to obtain valuable outcomes. In this research, the included limitations derive from the available hourly data from the ENTSO-E TP. Soimakallio et al. in [37], described the challenges of performing a LCA about electricity mixes, suggesting the main factors and variables to consider and to deal with. Elements such grid losses, import/export, power plant own consumption and allocation procedures are widely described in the following subsections.

Grid losses

Specifically in this LCA, the background system regards all the previous steps of the final electricity production process (e.g. the extraction of the fuel, the refinement, its transportation to the power plant) while the foreground system is related to the effective production of 1 kWh inside the power plant. For the background system, the used dataset includes imported electricity from neighbouring countries and transmission/distribution losses (e.g. the electricity mix of the country which exports the fuel, the losses in the transportation, etc). However, the foreground system does not include the same values, meaning that it not contains the exports of the produced electricity in other countries, the imports of electricity from bordering nations and the grid losses to distribute the produced electricity [60] . This is why grid losses (distribution, transmission) of the targeted countries are not considered in the model. Even if grid losses do not represent a large portion of the total electricity produced in Europe (6,63%) [61], they could be taken into consideration. According to [37], the difficulties in how grid losses should be allocated between high, medium, and low voltage consumers make the process excessively complicated for the losses contribution in the final results, especially in terms of GHG emissions. In addition, Garcia et al. found out in [34] that the transmission and distribution losses correspond to the 0.13% and 0.12% of the total life cycle impact of Portuguese electricity generation mix. Contrariwise, transformation losses are part of the model because the used software estimates them through the efficiency of the power plants.

Import/Export

Another subject of discussion is the importation and exportation amounts of electricity from neighbouring countries. In the ENTSO-E TP, the classification named "Actual Generation per Production Type" includes the natural resources used for the electricity production. It means that the amount of fuels utilized includes the import of these substances from other countries. On the contrary, it does not include the already produced electricity imports between bordering countries. This last specific data is integrated in a different class, "Cross-border physical flows", not taken into account in the study. In fact, incorporating electricity imports and exports of electricity in a national grid mix could lead to inaccuracy and imprecision, when dealing with GWP calculations, due to the fact it is not possible to know from which power plants the electricity comes from. As a result, the analysis of Nillson et al. in [39], which included Swedish electricity imports, can include minor defects compared to a baseline where exchanges are not considered. Taking into account just the geographical borders avoids any possible misconception, as done by Khan in [41] as well. Cubi et al. in [40], do not specify if imports and exports are counted and Khan et al. in [42] do not include them, being the study performed in New Zealand, a country that imports resources but not already made electricity. Furthermore, in a recent paper by Moro et al. [36], four out of five targeted countries of this study (Bulgaria, Germany, Spain and the Netherlands) have a very low carbon intensity variation of the electricity production after trading with other countries (-2%, +2%, -6%, and -1% respectively). Regarding Norway, the country imported in 2017 just 4,5% of its electricity gross consumption [62], data which can assume as negligible the carbon intensity variance.

Power plants own consumption

Regarding power plants own electricity consumption values, they are taken from official statistics of IEA (International Energy Agency) through the used software tool and so they are included in the model [60]. Specifically own consumption to pump up the water in hydro pumped storage power plants is considered when data from TP are available.

Allocation procedures

Finding the suitable allocation factor may be sometimes problematic and it can lead to significant impacts on the LCA results. Whenever it is possible, allocation should be avoided, according to [52]. Combined heat and power plants (CHP) produce two outputs and so it is needed to allocate the environmental impacts of just the electricity production. GaBi software presents a database for every resource used in CHP power plants as natural gas, biogas, heavy fuel oil, hard coal, lignite, and biomass. In the database there are data regarding the share of electricity, the overall efficiency and the share of electricity to thermal energy within a CHP plant. According to the description of the used dataset, for the combined heat and power production, allocation by exergetic content is considered. Whenever there seems to be a lack of data regarding the amount of produced heat or the efficiency of CHP plants in a country database, the research found out that this is due to the low percentage of produced heat on the total energy originated, which is rounded down to 0.0 since it is usually only about 0.01 [60]. Therefore, the allocation of CHP plants is considered as a part of the analysis just when data are available (Bulgaria, Germany and the Netherlands).

7.3 LCIA of Electricity Grid mix

The selected impact category for this project is the Global Warming to which it is related the indicator called Global Warming Potential (GWP). Every indicator has to be linked to the elementary flows of the system (Classification). The Characterization involves the quantification of the impact of interest relative to a reference substance: GWP is a measure for Global Warming in terms of radiative forcing of a mass - unit [kg $CO2_{eq}$]. It is one of the most important and surely the most known environmental index. It was chosen as single studied indicator because of its link with climate change: temperature increase and ppm are directly related to GWP. The extensive definition of ppm is Parts per Million of $C0_2$ in the air, and the Global Warming Potential represents the same information, cited in every significant report about future energy scenarios ([3], [5], [9], [10], [12]).

As mentioned in Section 7.2, the impact factors of each technology are dependent on the country they are based in. However, to frame the studied context, Table 6 shows the life cycle emission factors for electricity generation from the most used technologies in Europe, according to Turconi et al. [38].

Table 6: Emission factors of power production technologies. Extracted from [38]

Energy source	**GWP** [kg $CO_{2eq.}$/kWh]
Hard Coal	0.66-1.05
Lignite	0.8-1.3
Natural Gas	0.38-1.0
Oil	0.53-0.9
Nuclear	0.003-0.035
Biomass	0.008-0.13
Hydropower	0.002-0.02
Solar	0.013-0.19
Wind	0.003-0.041

The values of Table 6 include upstream and downstream processes, and so all the steps involved in the electricity generation, like the construction of the power plants and the O&M procedures are part of the analysis. The ranges of values are wide because in the 167 case studies analyzed, different system boundaries and methodologies were chosen [38]. Even so, the software used in this study has a specific country based database for each technology, conferring the results a significant precision.

The time dependency of GHG emissions due to electricity production is the additional value of this research, compared with the previous literature [29–36]. Every peak hour of each day of 2018 is analyzed to define the resources used to meet the highest electricity demand of the day. Through an LCA software tool, the resultant GHG emissions are calculated. The same methodology is applied to determine an average value, considering the 8760 hours per year. The peak hours values are then compared with the average. The results are presented on a monthly basis to show the seasonal variations. A similar approach is followed in [40–42], but the results are presented in order to show the link between demand and carbon intensity and not the time variability of CO_2 emissions. In [39], the aim is to figure out the hourly time-slot when the highest CO_2 intensity takes place throughout the year. Besides, this approach may hide the seasonality between summer and winter, since the peak hour time-slot differs from season to season. In this work, the hourly analysis enhances the differentiation of GHG emissions from peak hours and off-peak hours.

The databases available for the development of electricity grid mixes analysis have limitations that hinders the accurate development of the model. For this reason, certain assumptions and hypothesis are considered. Even if from the ENTSO-E TP the data for hydro production are divided into categories such as Hydro Pumped Storage, Hydro Run-of-river and poundage and Hydro Water Reservoir, they are merged all together in the label "Hydro". The same procedure is used to calculate the environmental impacts of wind power production, combining together wind onshore and wind offshore, being this case just for Germany and the Netherlands, the two countries which rely on both technologies. ENTSO-E shows data including solar thermal and solar photovoltaic electricity in the same box "Solar", without any distinction. Thus, the model is developed incorporating the data in the "Electricity from photovoltaics" if the used software model, without any environmental differentiation between the two technologies.

To develop the GHG emission assessment model, based on LCA framework and considering both peak and off-peak hours from the ENTSO-E TP, the methodology presented in Figure 10 is applied.

First, the hourly production data by resource were extracted from the ENTSO-E TP. If alternative sources of data were available, a comparison was executed to avoid any possible lack of information. Then, on one side, the calculation of daily peak hours generation was implemented, collecting the results on a monthly base to facilitate the final correlation with a yearly average value. Both the 12 monthly and one-year statistics were scaled down from the actual number, in thousands of MWh to 1 kWh, the functional unit of the study. Thus, the environmental impacts related to the production of 1 kWh during a certain time period and in a certain country was realized through a specific LCA software, Gabi, which contains a country-based database. The 12 monthly and one yearly electricity generation values had now their correspondent environmental impacts, ready for the final comparison.

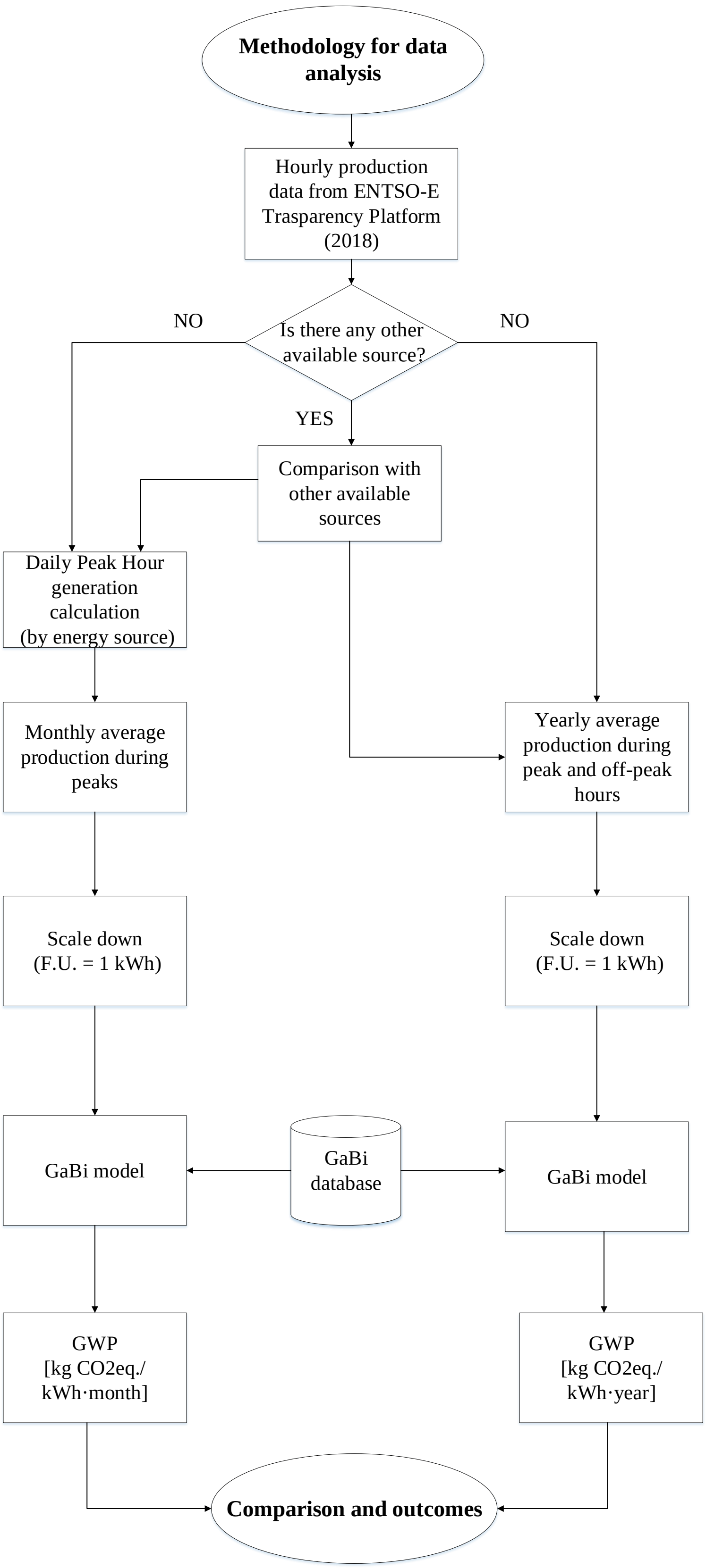

Figure 10: Data analysis methodology for hourly based electricity grid mix LCA

7.4 Tools

The typical representation of hourly generation data from the ENTSO-E TP, extracted from the section "Actual Generation per Production Type", is presented in Figure 11. MTU is the acronym of Market Time Unit and it is specified as a one-hour interval. *Actual Aggregated* is the power delivered by each source during the MTU. Due to space limitations, the example shows just the four first hours of electricity generation in Spain during the 1st of January 2018, listed by the six first sources in alphabetical order.

MTU	Biomass	Fossil Brown coal/Lignite	Fossil Coal-derived gas	Fossil Gas	Fossil Hard coal	Fossil Oil
	Actual Aggregated	Actual Aggregated	Actual Aggregated	Actual Aggregated	Actual Aggregated	Actual Aggregated
	[MW]	[MW]	[MW]	[MW]	[MW]	[MW]
	D	D	D	D	D	D
00:00 - 01:00	282	0	0	3471	996	194
01:00 - 02:00	275	0	0	3269	959	191
02:00 - 03:00	278	0	0	3541	1014	191
03:00 - 04:00	278	0	0	3450	1043	191
04:00 - 05:00	279	0	0	3318	1063	191

Figure 11: Actual Generation per Production Type example from ENTSO-E TP [22]

MATLAB was used to individuate the peak hour for every day of 2018. A series of sets and variables are needed to better understand the followed methodology and they are displayed in Tables 7 and 8:

Table 7: Sets

t	hours of a day, [1 , 2 , 3 , ... , 24], t ϵ T
n	resources, [n, ... , N], n ϵ N
d	days of a month, [1 , 2 , 3 , ... , D], d ϵ D
m	months of a year, [1 , 2 , 3 , ... , 12], m ϵ M

Table 8: Variables

$P^{res}_{n,t}$	Power produced by a certain resource n during 1-hour time slot t [MW]
P^{tot}_{t}	Total power produced by all the resources during 1-hour time slot t [MW]
t_{ph}	Hour of the day d when the peak hour occurs [h]
$P^{tot}_{d,t=t_{ph}}$	Peak hour production during one single day d [MW]
$P^{res}_{n,d,t=t_{ph}}$	Power produced by a certain resource n during peak hour t_{ph} at day d [MW]
$P^{share}_{n,d,t=t_{ph}}$	Power produced by a certain resource n during peak hour for a single day d out of the total production including all sources [%]
$P^{share}_{n,m,t=t_{ph}}$	Average of power produced by a certain resource n during peak hour for a single month m [%]
$P^{tot}_{m,t=t_{ph}}$	Average peak hour production including all resources during a certain month m [MW]
$C_{d,t=t_{ph}}$	Cost of the electricity during peak hour t_{ph} for one single day d [€/MWh]
C_{m}	Average peak hour cost of electricity during a certain month m [€/MWh]

P^{tot}_{t} is the sum of the electricity generation coming from all the different sources used in the country, both renewable and conventional, during one-hour period t. Equation (1) is applied to every hour of 2018. Furthermore, the maximum value of P^{tot}_{t} every 24 hours is equal to the peak hour for a specific day (Equation (2)).

$$P^{tot}_{t} = \sum_{n=1}^{N} P^{res}_{n,t} \qquad \forall n \epsilon N, \forall t \epsilon T \qquad [MW] \tag{1}$$

$$P^{tot}_{d,t=t_{ph}} = max(P^{tot}_{t})_{d} \qquad \forall t \epsilon T, \forall d \epsilon D \quad [MW] \tag{2}$$

Then, the percentage of resources use during those peak times has been calculated, simply dividing the MW of power delivered by a certain resource for the total power delivered, as shown in Equation (3). Note that this calculation is done for every resource used in the selected country.

$$P^{share}_{n,d,t=t_{ph}} = \frac{P^{res}_{n,d,t=t_{ph}}}{P^{tot}_{d,t=t_{ph}}} \qquad \forall n \epsilon N, \forall d \epsilon D \quad [\%] \tag{3}$$

The monthly average use of a certain resource during peak hours is calculated thanks to Equation (4).

Summing all the daily percentage uses and dividing them per the amount of days of the month, the average utilization of a resource during one specific month is obtained.

$$P^{share}_{n,m,t=t_{ph}} = \frac{\sum_{i=1}^{D}(P^{share}_{n,d,t=t_{ph}})}{\sum_{i=1}^{D} d_m} \qquad \forall n\epsilon N, \forall d\epsilon D, \forall m\epsilon M \quad [\%] \tag{4}$$

The same approach is followed to estimate a yearly average, but in this case all the 8760 hours are considered, split by energy source, as expressed in Equation (5), where y rpresents the year 2018. This important data is represented by the dotted line in Figures 13, 17, 21, 25, 29 and by the label *AVG* in Tables 11, 12, 13, 14, 15. These values represent the term of comparison between peak hours and general conduct of electricity production in the targeted countries.

$$P^{share}_{n,y,t=t_{ph}} = \frac{\sum_{i=1}^{365}(P^{share}_{n,d,t=t_{ph}})_y}{\sum_{i=1}^{365} d_y} \qquad \forall n\epsilon N, \forall d\epsilon D, \forall m\epsilon M \quad [\%] \tag{5}$$

The peak hour of every day of the year is found looking at the amount of power delivered each hour and choosing the maximum value ($P^{tot}_{d,t=t_{ph}}$). Then, to look at the possible links between GWP and power production, the monthly average power production is calculated ($P^{tot}_{m,t=t_{ph}}$), through Equation (6). The results of the calculations are expressed in Figures 12, 16, 20, 24, 28.

$$P^{tot}_{m,t=t_{ph}} = \frac{\sum_{i=1}^{D} P^{tot}_{d,t=t_{ph}}}{\sum_{i=1}^{D} d_m} \qquad \forall d\epsilon D, \forall m\epsilon M \quad [MW] \tag{6}$$

Having the percentages of use of every source for every peak hour of the year, the environmental impacts of all the resources can be calculated thanks to a specific LCA software. The total power delivered during a peak hour ($P^{tot}_{d,t=t_{ph}}$) is scaled down to 1 kWh, the functional unit.

In order to carry out Life Cycle Assessment efficiently, software tools need to be used. GaBi Software is developed by the German company PE International, thinkstep. This software contains a modular and parameterized architecture. The user just has to collect all the inputs (related to energy, mass, etc.) and outputs (energy, mass, emissions, waste). Then, the software evaluates the potential environmental impacts, according to several life cycle impact methodologies available on its database. The database includes countries' specific data about electricity production which allow to perform a country based analysis underlining the environmental impact differences, e.g. the production of 1 kWh from a hard coal power plant based in Germany has a different output compared with the same typology in Bulgaria; 1.01 kg $CO_{2eq.}$/kWh in Germany and 1.28 kg $CO_{2eq.}$/kWh in Bulgaria.

7.5 Day-ahead market analysis

To find a relationship between the electricity produced and its cost, a certain market price should be detected. Different prices are allocated to different time-slots, so one single market should be chosen. For this study, the day ahead market was selected. According to EPEX SPOT, the electricity market operator in Germany and the Netherlands, 85.5% of the traded volume of electricity in 2018 was sold during the day-ahead market [63]. Nord Pool, Europe's leading power market, which works in Germany, the Netherlands, Norway and for servicing power markets in Bulgaria as well, reveals that 98.5% of the traded electricity in the operated countries in 2018, was purchased during the day-ahead market [64]. The Iberian market operator OMIE published the annual report of 2017 affirming that 87.2% of the amount of electricity generated in Spain and Portugal was traded in the day-ahead market too [65]. In short, the day-ahead market is the non-physical place in which the highest amount of electricity is traded and this is why it was chosen for the comparative analysis. In fact, the intraday and balancing markets which serve as balancing mechanisms to adjust the unexpected fluctuations of the demand/supply structure have just a minor share in the whole electricity market sector. Despite this, unplanned peaks in the electricity generation/consumption could be better-analyzed thanks to the intraday variations, but this aspect is out of the scope of the study. Table 9 illustrates the main characteristics of the studied markets.

As it is noticeable from Table 9, all the countries have the same auction time for the day-ahead market. Just the prices range is different just in Spain. The development of the European project called Price Coupling of Regions (PCR) was needed to create a more unite and harmonised European market. On a day-ahead basis, the electricity prices are calculated regarding the capacity of the relevant network elements. The single price coupling solution takes into account the users and members of the project and their electricity generation and consumption for the next day, delivering specific prices for every country. This solution is possible thanks to EUPHEMIA, an algorithm that maximises the overall welfare, improving the transparency of how the prices are set and the electricity flows between countries. Germany, the Netherlands, Norway and Spain are PCR members and Multi-Regional Coupling users. Bulgaria is an independent user of PCR because its market is not still fully liberalized [66].

A typical question that can arise to whom is approaching the electricity market field is: are the power plants that sell electricity to the grid just chosen because of the price they propose? This is exactly true and it's called merit-order effect. As already explained in Section 4, wind and solar power have a marginal cost almost equal to 0. The smallest running cost, the smallest the price of the offered electricity. The increase of renewable power in the electricity grid mixes leads to a lowering of electricity prices. The penetration of renewable energies will spread in the near future and it will certainly led to even lower clearing price in the market. The day-ahead market is the first one that benefits from the merit-order effect because it is the market in which the highest amount of electricity is purchased.

MATLAB was fundamental to relate the peak hour of electricity production to its cost on the day-ahead market. The peak hour of production is not always the same as the one with the highest cost of electricity during the day. From the own analysis, it was discovered that spikes in production and price are not always related. There can be times slots in which the demand is high but simultaneously a renewable source is highly available, cutting down the price due to its low marginal cost (See Figure 7). The opposite situation can happen as well: demand higher than the base load but lower than spikes during the evening, with a lack of solar and wind power availability, which forces traditional power plants to start running, increasing the cost of the production.

Equation (7) represents the performed calculation to obtain an average monthly value for peak hour electricity prices. Every day, the price of the electricity during the daily peak hour of production is $C_{d,t=t_{ph}}$. Then the values are summed for every day of each month and then divided by the number of days of the month, obtaining the monthly average cost of the electricity during peak hours C_m. The highest price of electricity during the day does not necessarily coincide with the hour in which there is the highest production. Figures 15, 19, 23, 27 and 31 show the average monthly prices for electricity during peak hours, compared with the monthly GWP.

$$C_m = \frac{\sum_{i=1}^{D} C_{d,t=t_{ph}}}{\sum_{i=1}^{D} d_m} \qquad \forall d \epsilon D, \forall m \epsilon M \qquad [€/MWh] \tag{7}$$

Table 9: Day-ahead market structure in the targeted countries

	Power market responsible	Auction time (CET)	Price limitations	Bid time interval
Bulgaria	IBEX	until 12 pm, valid for 24 hours interval	-1000 to 6000 BGN/MWh	1 hour
Germany	EPEX SPOT	until 12 pm, valid for 24 hours interval	-500 to 3000 €/MWh	1 hour
Netherlands	APX	until 12 pm, valid for 24 hours interval	-500 to 3000 €/MWh	1 hour
Norway	NORD POOL SPOT	until 12 pm, valid for 24 hours interval	-500 to 3000 €/MWh	1 hour
Spain	OMIE	until 12 pm, valid for 24 hours interval	0 to 113.92 €/MWh	1 hour

8 Results

8.1 Overview of the installed capacities in the targeted countries

This subsection aims to give the reader an outline of the electricity grid mix composition of the five analyzed countries. The installed capacity represents the total amount of power in MW that is producible in every moment of time in the country. It determines the own power stations the nation have available to meet the demand. As it is possible to notice from Table 10, the targeted countries of the H2020 INVADE Project have different values for the installed capacity. These data represent the percentage of power plants that can produce electricity in the country divided by source used, whereas it is not directly related to the power generation. Generally, the installed capacity of a nation overcomes the peak power requirement of its electricity usage. For example, in Spain, the maximum hourly power request in 2018 was of 42 GW, but the country has nearly 105 GW of installed capacity. It means that even if the power plants which are run by natural gas have the major share for the installed capacity (29.3%), it does not necessarily mean that the highest share of electricity production in 2018 was from natural gas, as determined in Section 8.6. In fact, the highest contribution for electricity generation in Spain came from nuclear power (22.46%).

Table 10: Electricity installed capacity in the targeted countries for the year 2018

	Main	Flexible hydro power	Others
Bulgaria - (12,708 MW)	Lignite (33.3%) Hydro (25.2%) Nuclear (15%)	Pumped storage (6.8%), Reservoir (14.2%)	Solar (8.2%) Natural Gas (6.1%), Wind onshore (5.5%) Others (5.8%)
Germany - (221,020 MW)	Wind (26.6%) Solar (19.6%), Natural Gas (14.3%)	Pumped storage (4.2%), Reservoir (0.5%)	Hard coal (11.4%) Lignite (9.6%) Hydro (6.5%) Others (12%)
Netherlands - (30,531 MW)	Natural Gas (57.6%) Hard coal (14.5%), Wind Onshore (11.5%)	Pumped storage (0%), Reservoir (0%)	Solar (8.1%) Wind Offshore (3%) Waste (2.1%) Others (3.2%)
Norway - (33,755 MW)	Hydro (93.2%), Wind Onshore (3.5%)	Pumped storage (10.8%), Reservoir (78.5%)	Thermal power* (3.3%)
Spain - (104,975 MW)	Natural Gas (29.3%) Hydro (24.7%), Wind Onshore (21.7%)	Pumped storage (5.4%), Reservoir (18.22%)	Hard coal (9.1%) Nuclear (6.8%), Solar (6.4%) Others (2%)

Source: ENTSO-E TP [22]

*The installed capacity data from Norway in ENTSO-E TP are not sufficient. More detailed data come from [62]

To facilitate the comprehension of the results, four types of graphs are presented in this section:

- The green rectangles of Figures 12, 16, 20, 24, 28, represent the average monthly power generation of electricity during peak hours. The calculations are related to Equation (6).
- The area figures (Figures 13, 17, 21, 25, 29) show the impacts of each resource used only during peak hours on the GWP. The outcomes are tabled month by month and compared with the average GWP value, represented by the dotted line, which takes into account all the 8760 hours of the year. This is the reason why the dotted line does not coincide with the average of the 12 months values, as depicted in Equation (8).

$$\frac{\sum_{i=1}^{8760} P_t^{tot}}{8760} \neq \frac{\sum_{i=1}^{12} P_{m,t=t_{ph}}^{tot}}{12} \quad (8)$$

Despite, resources as hydro and nuclear, even if they have a high share in the electricity production, they could not appear in the graph because of their low carbon impact factors (Table 6).

- Figures 14, 18, 22, 26, and 30 correspond to the variation in the percentage of use of the most representative sources during the year, compared with the monthly peak hours GWP variations.
- Figures 15, 19, 23, 27 and 31 show the average monthly prices for electricity during peak hours, compared with the monthly GWP.

8.2 Bulgaria

The power market in Bulgaria is ruled by state-owned companies. Bulgarian Energy Holding (BEH) is the main actor which control the most relevant power plants, like the Kozloduy nuclear power plant that has two 1000 MW reactors needed to cover almost one-third of the electricity generation in the country (see Table 11). Recently, Rosatom, a Russian state nuclear energy company signed an agreement to extend the useful lifetime of the power plant until 2051 [67]. Thanks to this accord, Bulgaria will continue to fulfil a good part of its electricity needs thanks to nuclear power. The TPP Maritsa Iztok 2 is a complex that consists of three lignite-fired thermal power plants, for an overall nominal capacity of 670 MW. In 2015, there was an upgrade of the power plant to extend the units' lifespan by 20 years, showing the interest of the country in maintaining a base production built on nuclear and coal [68]. Mined coal is a vital resource for the energy sector in Bulgaria and the most important mining activity in the country is located in Maritsa region. BEH owns the National Electric Company (NEK) as well. The main functions of the company are generation and supply of electrical energy, import/export and construction and maintenance of power generation facilities. The state-owned company has business with the TSO, Electric System Operator and two natural gas distribution companies (Bulgargaz and Bulgartransgaz). So large producers are principally owned by BEH or, on a minor scale, by private entities. Cold reserves, the reserve capacity usually not ready for immediate service, correspond to 1000 MW, an oversized value composed by old and pollutant power plants [69]. In case of excess of energy production, it can be sold through bilateral contracts, including co-generation plants.

Regarding the south-eastern Europe country, the electricity demand during the year is mainly covered by lignite and nuclear power, as explained in Table 11. The high percentage of hydropower capacity, Table 10, is reflected in the consistent use of hydropower plants. Solar and wind power represent together just 5.35% of the total electricity production in Bulgaria during 2018.

Table 11: Use of resources during peak hours compared with the average during the year (AVG)

	Biomass	Lignite	Natural gas	Hard coal	Hydro	Nuclear	Solar	Waste	Wind Onshore
JAN	0.53%	40.53%	4.75%	1.30%	17.58%	33.11%	0.00%	0.07%	2.14%
FEB	0.56%	38.81%	4.81%	1.10%	20.23%	31.37%	0.00%	0.06%	3.05%
MAR	0.50%	33.35%	4.24%	1.05%	25.60%	32.41%	0.00%	0.06%	2.78%
APR	0.56%	26.31%	3.88%	1.30%	33.83%	31.28%	0.00%	0.07%	2.77%
MAY	0.62%	38.19%	3.77%	1.37%	30.84%	22.37%	0.30%	0.08%	2.47%
JUN	0.50%	35.93%	2.76%	1.20%	19.99%	37.26%	1.04%	0.08%	1.24%
JUL	0.51%	33.43%	2.65%	1.13%	24.22%	36.33%	0.62%	0.07%	1.03%
AUG	0.48%	37.19%	2.45%	1.08%	23.23%	34.33%	0.00%	0.07%	1.17%
SEP	0.50%	45.90%	2.74%	1.07%	21.99%	25.36%	0.23%	0.07%	2.15%
OCT	0.47%	50.28%	3.38%	1.01%	19.82%	22.22%	0.00%	0.09%	2.73%
NOV	0.30%	44.36%	4.06%	1.05%	17.65%	30.20%	0.00%	0.01%	2.37%
DEC	0.40%	43.47%	4.89%	1.03%	18.49%	29.65%	0.00%	0.04%	2.03%
AVG	0.55%	42.29%	4.26%	1.28%	11.42%	34.78%	2.60%	0.07%	2.75%

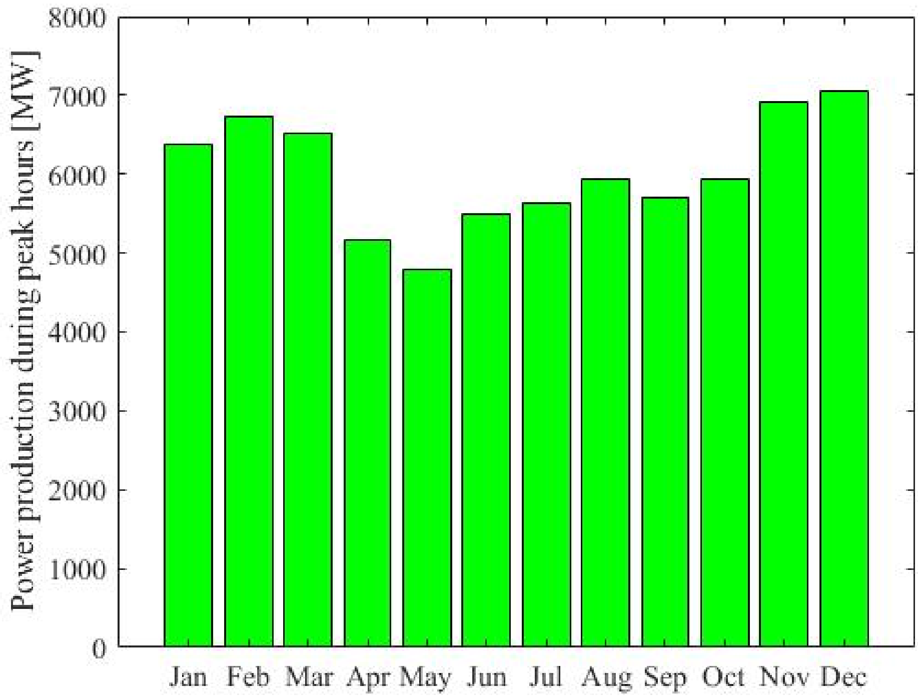

Figure 12: Average monthly power production in Bulgaria during peak hours

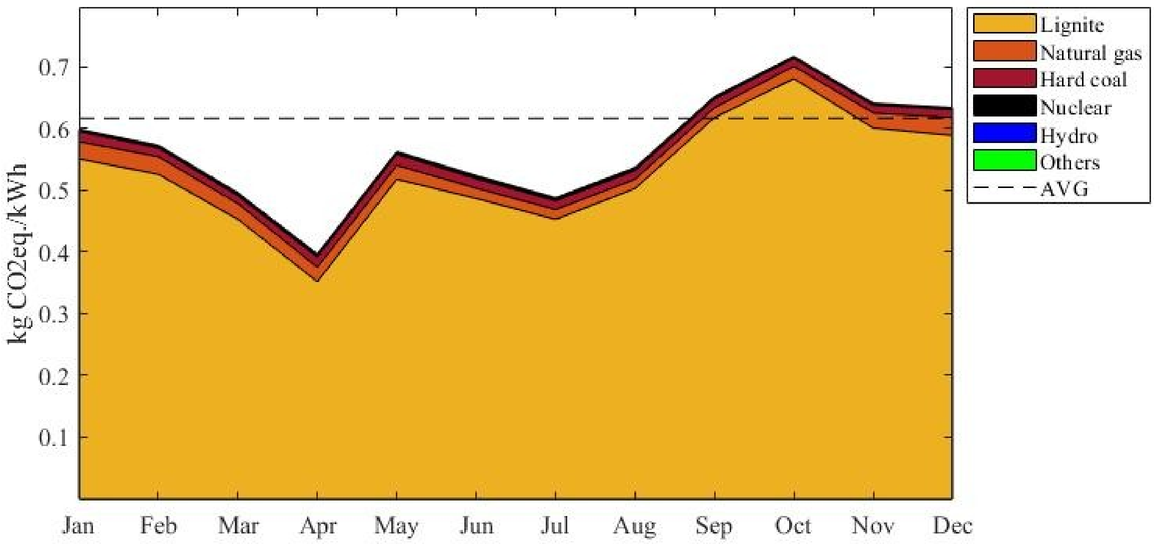

Figure 13: Monthly peak hours GWP compared with average through the year (dotted line) in Bulgaria

When the demand during peak hours is high, more production from conventional sources is required and consequently, the GWP is higher (November and December). The situation is reversed when the power requested is low (April and May). Despite, also during the months of January, February and March the power request is higher than the mean, even though the GWP is lower than the base one. This fact is due to the good use of hydropower reservoirs to cover the daily crests in these months. At the same time, the months of September and October, which present a higher GWP value compared with the base one, display a lower need for power during peak hours. This result comes from the evidence that these two months have the highest values in terms of lignite use during the year (Table 11).

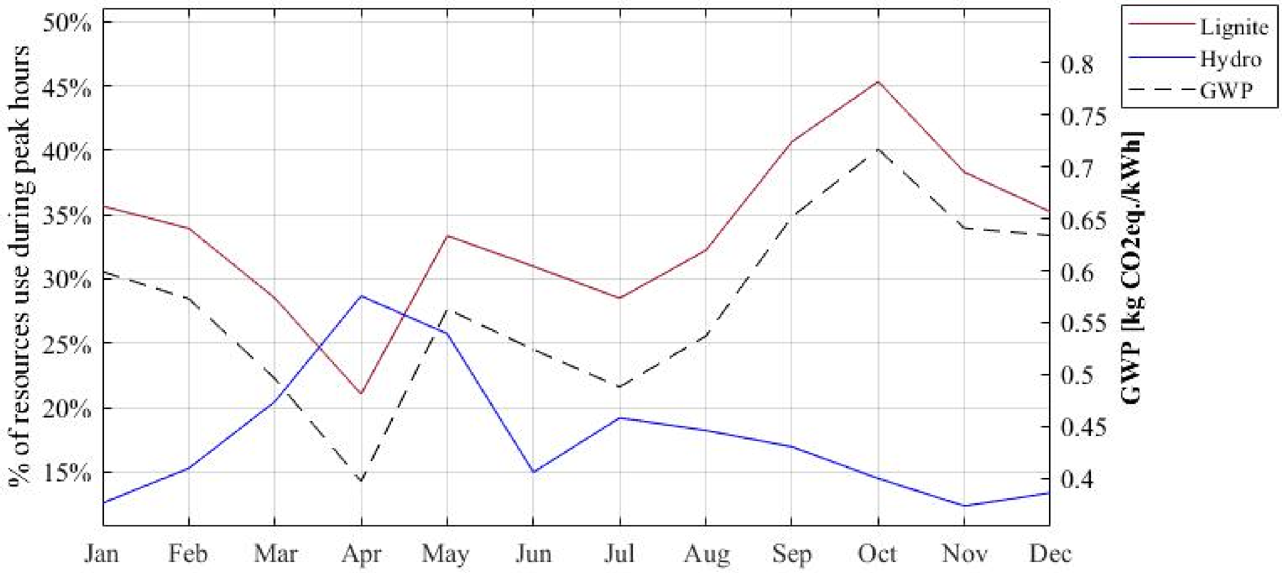

Figure 14: Percentage use of resources throughout the year compared with monthly GWP in Bulgaria, both related to peak hours

Furthermore, the GWP during peak hours is mainly based on lignite (Fig. 13). The GWP during peak hours is higher than the average from September to December because of higher use of lignite and lower use of flexible hydro to cover the peak demand. From Figure 14, it is possible to see the direct correlation between the use of lignite and hydropower during peak hours and the GWP. Hydropower and lignite are the only two represented resources because they are the only ones that have a significant variation in their usage throughout the year. When there is the possibility to use the hydro reservoirs and the hydro pumped storage, the GWP decreases in comparison with the average. The two presented curves of lignite and hydropower have exactly the opposite conduct. Symbolic is the month of April, with the highest share of use of hydro and the lowest of lignite that leads to the lowest GWP of the year. The reasons behind this event are related to the low power production in April [22] and possibly to the abundance of water resources.

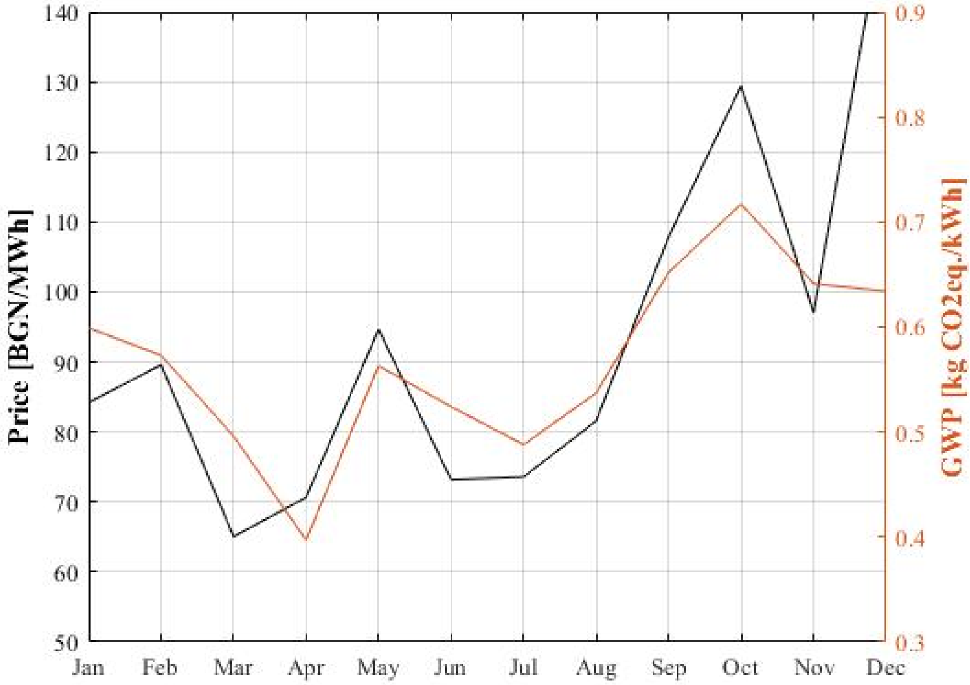

Figure 15: Comparison between electricity price and GWP in Bulgaria

The highest prices of electricity during peak hours follow exactly the highest values of the GWP during the last four months of the year 2018. Figure 15 shows the similarities between the two variables. The price is higher when higher amounts of fossil fuels like lignite and natural gas are used. When run-of-river hydro is at its maximum usage or reservoir are well exploited, the prices decrease. The operation of PHS in Bulgaria is mainly due to store the electricity and allow a continuous mode working on nuclear power plants. After the phasing out of some nuclear reactors, now the focus of flexible hydropower is to increase the penetration of RES and the operation of non-flexible lignite stations. [49].

According to a governmental analysis, Bulgaria suffers for huge non-technical losses due to the large distances the transmission lines have to operate. Investments in traditional transmission systems are not enough to support the development of renewable energy sources. Smart grid projects have to be applied in order to improve the efficiency and the reliability of the grid [69]. Further implementation of large battery storage can be a valuable opportunity to avoid congestion problems and increasing the penetration of renewables into the grid. Nevertheless, the Bulgarian electricity sector is going in the direction of substantial changes: in April 2019, the Parliament supported the Energy Act, to allow every producer with a capacity from 1 to 4 MW to sell electricity on the free market [70]. Nowadays, there are around 372 plants in this capacity range, half of which is solar. This new regulation will accelerate the entering in the market of many more renewable actors which will be able to sell their electricity for the market price, instead of selling it to the National Electricity Company. A framework to reduce the bureaucracy for renewable energy sources below 30 kW was recently improved: now companies that want to install PV panels on industry roofs to auto-consume the produced energy will be able to do so, with fewer regulations. Despite, the first main step the decision makers have to take it's the liberalization of the market, to allow more competition between providers and let the possibility to final users to chose their own supplier.

8.3 Germany

The Energiewende, the energy transformation measures taken by the German government in early 2000, began to get the attention on Germany as a leader for the energy transition in Europe [71]. For example, decentralized solutions including PVs and batteries, enjoy economic support to feed the grid with the energy not used for auto-consumption. In fact, every electricity customer pays an extra amount to support this feed-in market strategy. As a result, more renewable technologies were installed, creating new business and jobs and when the costs went down the government reduced the feed-in tariffs. This forward-looking plan of action allows Germany to be the country with the highest percentages in terms of renewable installed capacity, as displayed in Table 10. Even though the solution is appreciated by environmental-friendly parties, consequentially Germany has now the second highest electricity price for household consumers in Europe [58]. Other than the support to decentralize energy production, the aids are focused on individual users, like the measure that allows any person to install a renewable energy technology (heat pumps included) without paying any initial investment [71]. Coal and lignite are still widespread essentially because of the lack of CO_2 taxation. If Germany would be able to radically change the electricity tax system, it would be a great advantage that will push commodities and enterprises to invest in energy efficiency because polluting would become economically disadvantageous.

Germany has a national production mix which relies on different sources. Regarding the base load, lignite and hard coal are the most used fossil fuels. The use of lignite throughout 2018 is almost constant, as shown in Figure 17. Wind farms have the highest share of capacity in the country and a total share of consumption of 20.63%, as presented in Table 10 and Table 12. Nuclear has still a regular contribution, while solar and biomass power plants have overcome the use of natural gas in 2018. Hydropower accounts for just 2.81% of the total electricity production. In Germany, the use of hydropower has significantly increased in the last 15 years [49]. Five different companies have almost the same share of PHS in the capacity portfolio. New capacity is needed from 2020 on, because of the German government decision who voted to cut out the generation from nuclear power plants.

Table 12: Use of resources during peak hours compared with the average during the year (AVG)

	Biomass	Lignite	Natural Gas	Hard coal	Hydro	Nuclear	Solar	Wind	CDG, FO, GT, O,OR, W
JAN	6.83%	21.82%	6.73%	11.06%	5.31%	12.72%	3.63%	28.98%	2.92%
FEB	6.41%	21.87%	8.32%	17.36%	3.06%	12.10%	13.73%	14.67%	2.47%
MAR	6.36%	20.51%	6.06%	14.91%	2.60%	11.44%	17.05%	18.59%	2.48%
APR	6.79%	20.14%	3.66%	7.97%	2.12%	10.73%	29.42%	16.60%	2.56%
MAY	7.03%	20.31%	3.15%	7.61%	2.53%	9.95%	34.58%	12.40%	2.43%
JUN	6.58%	22.38%	4.02%	9.97%	3.74%	11.59%	29.07%	10.85%	1.80%
JUL	6.15%	21.49%	5.33%	12.51%	2.52%	11.69%	30.96%	7.45%	1.90%
AUG	6.32%	20.26%	5.22%	10.47%	2.22%	12.45%	27.64%	12.32%	3.09%
SEP	6.29%	19.93%	4.90%	11.22%	1.12%	11.12%	26.30%	16.99%	2.14%
OCT	6.41%	20.58%	6.55%	14.22%	2.89%	10.88%	16.85%	19.43%	2.18%
NOV	6.79%	21.28%	9.22%	17.39%	4.17%	12.42%	6.84%	19.18%	2.72%
DEC	7.12%	18.55%	7.96%	11.68%	5.32%	13.59%	2.14%	31.12%	2.53%
AVG	7.63%	24.42%	6.41%	13.72%	2.81%	13.64%	7.83%	20.63%	2.91%

Source: ENTSO-E TP.

*CDG = Coal Gas derived, FO= Fossil Oil, GT = Geothermal, O = Others, OR = Other renewables, W = Waste

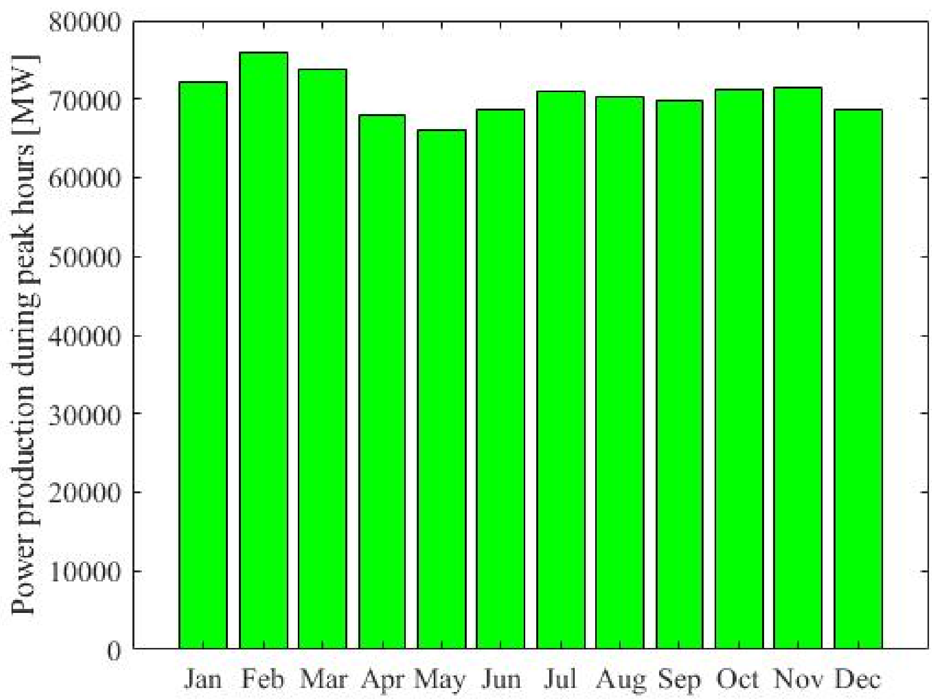

Figure 16: Average monthly power production in Germany during peak hours

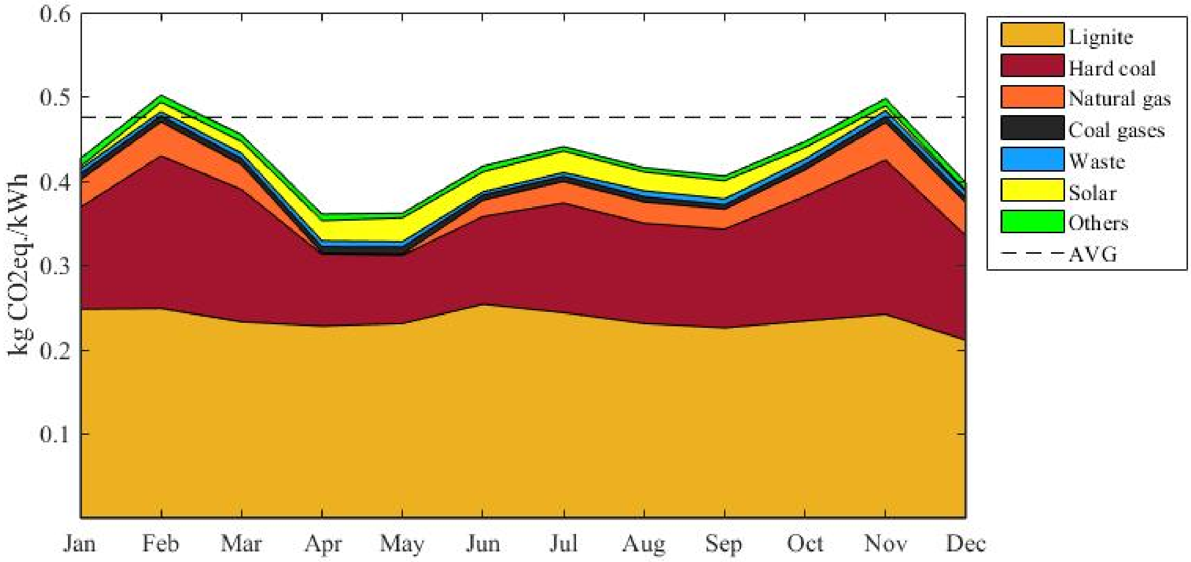

Figure 17: Monthly peak hours GWP compared with average through the year (dotted line) in Germany

In Germany, as in Bulgaria, a large request of power during peak hours, normally leads to higher values of the GWP. The only two months which have a GWP higher than the average value during the year reveal a larger demand for power production than the base value (February and November, Figure 16). Anyway, also in March there is the same peculiarity, being the second ranked month for power requirement, but the GWP in lower than the average value. The favorable weather conditions allowed the solar power to be exploited much than the previous months, making the resource being the third most used one during March (Table 12).

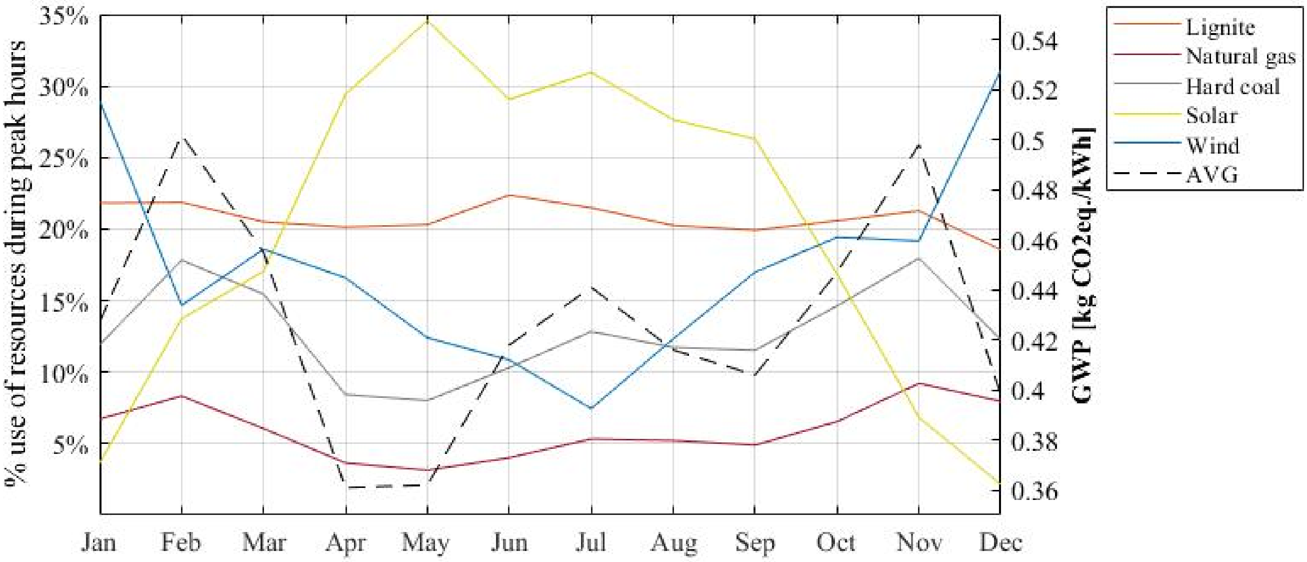

Figure 18: Percentage use of resources throughout the year compared with monthly GWP in Germany, both related to peak hours

According to the LCIA, the GWP during peak hours is higher than the average just in the months of February and November (Fig. 17). This is due to the high percentages of used hard coal and natural gas during the entire year for the base load. Higher use of lignite during February and November in comparison with the average value is a concause. From Figure 17, April and May are the months with the lowest GWP, because of the lower use of fossil fuels compared to the average. This strategy was applicable considering that the two months have peaks of demand way lower than the average. It means that the base power from nuclear power plants had a more important role than during the months in which the production is higher and so fewer fossil fuels have to be used. Solar and wind power have distinct trends: electricity production from solar power is clearly higher during the summer months, while wind production has its maximum in the winter ones (Figure 17). These two facts lead the peak hour GWP to be lower than the average one for 10 out of 12 months. February and November, the two exceptions, see a larger use of fossil fuels compared to the close in time months.

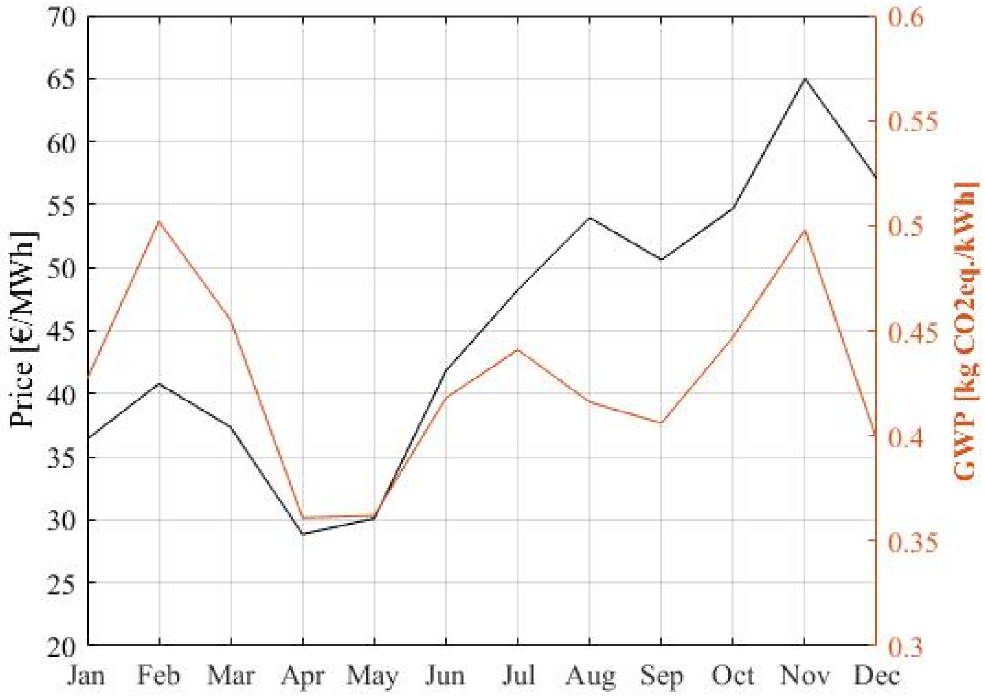

Figure 19: Comparison between electricity price and GWP in Germany

November displayed the highest price of electricity during the year, while February has a value closed to the average even if its power demand is higher than the average. April and May show the lowest amount of power used during peak hours and at the same time the lowest prices for electricity and the lowest values of GWP. The high penetration of renewable energies, especially solar power, was fundamental for this result.

The recent decision to phase out nuclear power [72] could have bad repercussions on the environmental impacts of electricity production. As shown in Table 12, Germany accounts on nuclear power for 13.64% of its power production. Almost one-sixth of the German load is based on fission reactors and if to slowly get rid of it, the German government decides to keep the coal-fired power plants, there won't be any improvement from the GHG point of view. Furthermore, economic growth leads to an increase in the emissions, with raising overall consumption and intensified transportation and if there won't be a powerful energy efficiency promotion, a higher base load will require more electricity to supply. Another issue for the authorities is the relocation of employees of regions in which the coal industry is the main economic driver. Natural gas can be seen as an intermediate solution to decrease the emissions related to energy production and at the current time, Germany has already

31,605 MW installed on its territory. The infrastructures already exist but the country should then rely on imports of the fuel. If the government wants to build new pipelines and power plants to make a profit of natural gas potential, it should be known that these are infrastructures that last at least 30 years, reducing the effectiveness of the solution in terms of future climate impacts [73].

8.4 The Netherlands

As presented in Table 10, the electricity mix is not really various and the Netherlands can count on just few different sources. The Dutch energy sector is nowadays based on natural gas. 30% of the European natural gas reserves are in the Netherlands and so around 20% of the gas consumed in the continent comes from Dutch reservoirs [74]. Being a natural lead country in this sector allows the research and development of "greener" ways of supplying the resource: the European Strategic Gas Hub has patented a process for the gasification of biomass which is now quite used in the transportation sector and in smaller quantities for electricity production (see Table 13). Seen as the windmills territory, the Netherland can count on a good share of wind power, both on and off-shore. The only nuclear power plant, Borssele, helps the base load to not be covered just by natural gas.

In the Netherlands, the use of natural gas for electricity production represents 67.85% of the total and clearly, it is the most important resource that impacts the GWP. Renewable energies like solar and wind are well exploited considering the actual capacity installed (see Table 10). Nuclear power helps to cover a small percentage of the base load, while the lack of hydropower capacity influences the electricity generation strategy. The overall production percentages are presented in Table 13.

Table 13: Use of resources during peak hours compared with the average during the year (AVG)

	Biomass	Natural gas	Nuclear	Solar	Wind
JAN	0.48%	64.99%	6.18%	1.77%	26.57%
FEB	0.43%	67.42%	5.86%	9.84%	16.44%
MAR	0.44%	62.37%	6.55%	6.99%	23.65%
APR	0.32%	58.90%	7.73%	13.17%	19.89%
MAY	0.63%	57.99%	2.52%	21.35%	17.51%
JUN	0.57%	60.72%	5.34%	17.52%	15.84%
JUL	0.42%	64.78%	6.37%	19.32%	9.11%
AUG	0.45%	70.38%	0.61%	14.43%	14.13%
SEP	0.46%	69.26%	3.03%	10.74%	16.52%
OCT	0.45%	68.93%	6.12%	9.21%	15.28%
NOV	0.38%	69.97%	5.69%	5.30%	18.65%
DEC	0.39%	66.71%	5.87%	2.55%	24.48%
AVG	0.58%	67.83%	6.57%	5.53%	19.48%

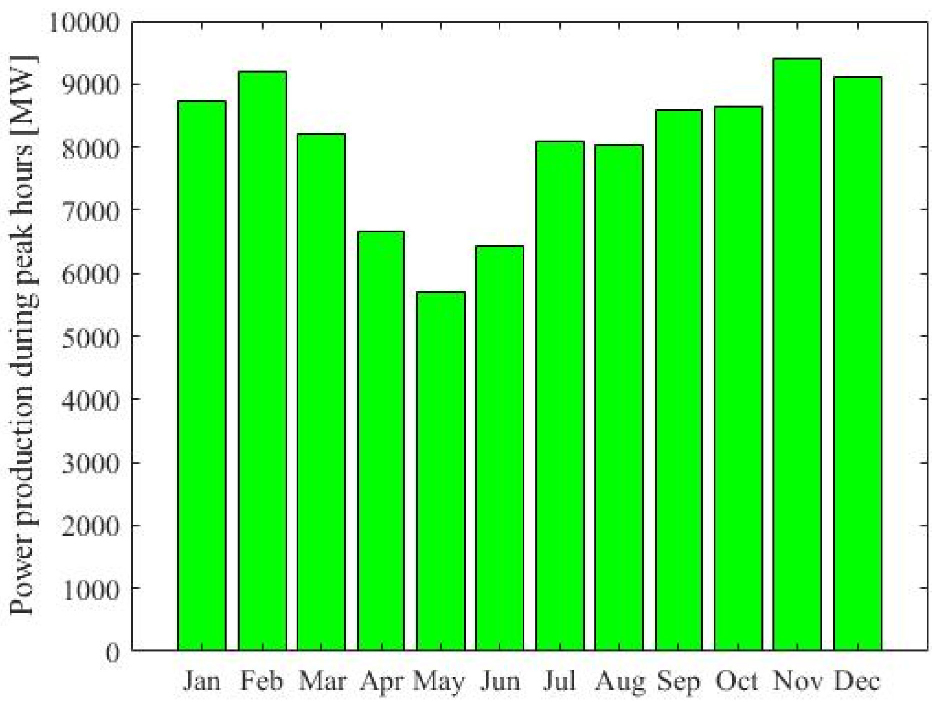

Figure 20: Average monthly power production in the Netherlands during peak hours

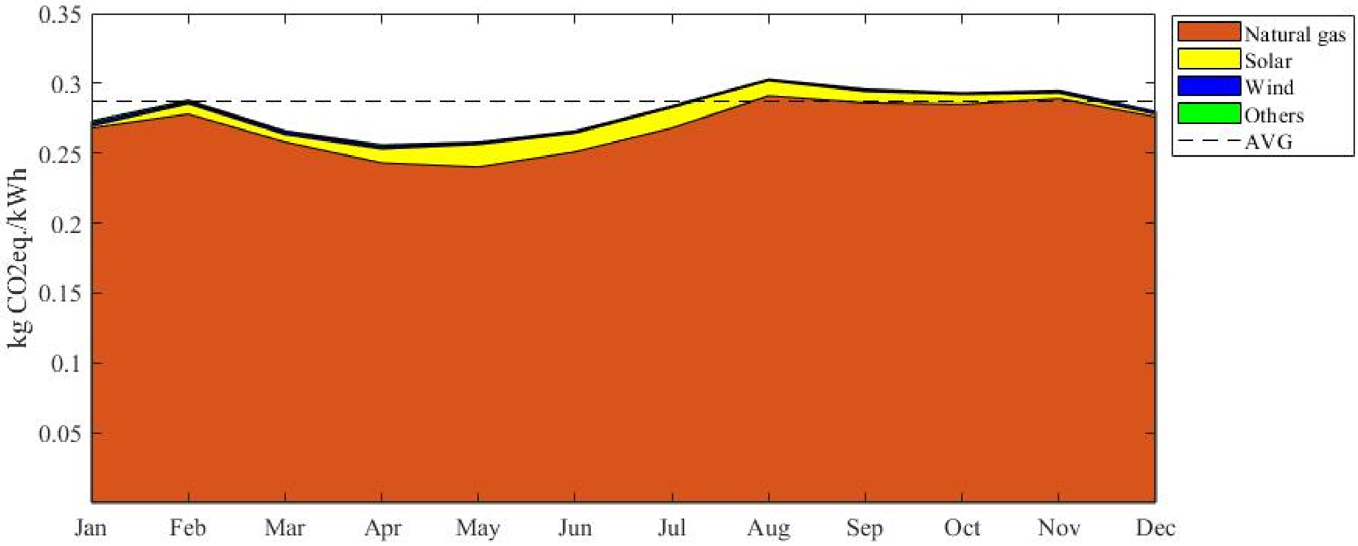

Figure 21: Monthly peak hours GWP compared with average through the year (dotted line) in the Netherlands

Compared with the existing literature, the calculated average GWP is way lower. In the study performed by Moro et al. [36], the average outcome for the GWP is 0.558 kg $CO_{2eq.}$/kWh, while through the analysis related to the ENTSO-E data [22], the yearly value is 0.287 kg $CO_{2eq.}$/kWh. The reason behind this difference lies in the fact hard coal electricity production in the Netherlands was not mentioned by the ENTSO-E TP for 2018. Despite, this source has still a considerable percentage in the energy mix, as notable in Table 10 and from more recent data from the TP. This lack of data reduces the accuracy of the GWP results, but not the effect of the other resources on peak hours generation.

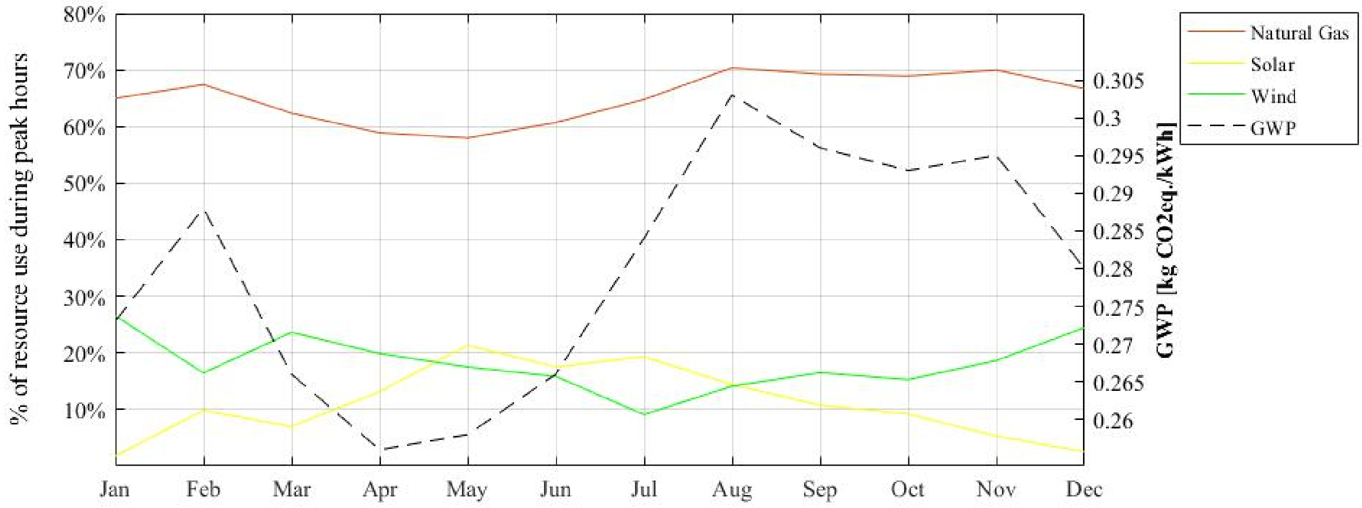

Figure 22: Percentage use of resources throughout the year compared with monthly GWP in the Netherlands, both related to peak hours

As it is possible to notice from Figure 22, the GWP line follows the natural gas use curve. The little valley formed by the dotted line from March to June is linked to a similar one drawed by the natural gas curve. The lowest values for wind production correspond to the highest values of the GWP (Fig. 21). As already observed in the case of Germany, solar and wind power have opposite concavities. It has been proved that in the Netherlands, peak hours occur when solar and wind power are more available than usual. When the availability of solar and wind power during peak hours is higher than the average, lower values of GWP are obtained. The changes in the use of resources through the year are limited and this is why there are no major changes in the monthly GWPs.

Figure 23: Comparison between electricity price and GWP in the Netherlands

In the Netherlands, a contradictory situation shows up: for a total of nine months during the year in which the power demand during peak hours is higher than the average, five of these have higher GWP values and higher electricity prices and the other four months have lower GWP values. The first ones are February, August, September, October and December, while during January, March, July and December the GWP is smaller. January and July have also lower electricity prices while March and December higher ones (the last month of 2018 had the top value for the energy price). In the intermediate months, April, May and June, the situation is reversed: lower power request and lower electricity prices. If for the months that need more power during peak hours and have high GWP values, it is possible to assume that more fossil fuels have to be used, which is the reason why the other cited months have lower GWPs? January, March and December relied on high wind production while in July the solar power plants were exploited thanks to favourable weather conditions (Table 13).

One of the largest natural gas reserves in the World, the Groningen field, will see its production halved in the next five years. This decision has been made because the continuous earthquakes the extraction of natural gas was causing. Large industrial users have now to switch to new energy sources, increasing the overall demand for new capacity installations, driven by renewable energies [74]. This situation will move to major investments regarding the grid infrastructure. Currently, according to the Ministry of Economic Affairs of the Netherlands [75], old and overused existing electricity networks are at the end of their technical life and an extra installation of renewable sources will surely bring overvoltage and congestion problems if a solution will not be well addressed. At the contrary, the Dutch government has powerfully invested in 94 pilot projects about smart grid solutions and energy efficiency protocols. Being the second larger market for Electrical Vehicles in the World, the related infrastructure should be able to withstand the impact of a new technology which will need soon huge quantity of power and it will change the energy consumption curve of the country [75]. So, even if the energy efficiency strategies are already in place, the forecasts predict an increase in the energy demand of the country for the reasons listed above [74]. To avoid the risk of a low pace energy transition towards renewable power, the Netherlands is committed to reinforcing its pledge for the Emission Trading System, lowering the extra emission allowances and constricting the environmental requirements.

8.5 Norway

As mentioned in Table 10, Norway bases its electricity needs on hydropower. The high percentage of water reservoirs and pumped hydro storage allows the Nordic country to manage the generation in a flexible manner. Over 1000 reservoirs depend on the precipitation on the country. The resources related to electricity production rely on a natural factor like rainfalls, while in the studied targeted countries, the supply is secured through fossil fuels based power plants and nuclear reactors. The inflow changes according to seasons and as a result, the use of hydropower is strictly correlated.

The deregulation of the electricity market in 1991 was the first step for the integration of the Norwegian grid into the Nordic system. Nowadays, there is a win-win situation because the extra power produced in the country is easily exported to the bordering countries that can rely on a very flexible power supply [62]. Around 90% of the electricity production capacity is owned by the public sector. The state owns the company Statkraft SF, which control 35% of the capacity. From 2008, new licences for waterfalls can also be awarded by partially privately owned companies. There is no need for licences under the Industrial Licensing Act for wind, solar and small scale hydro installations.

Table 14: Use of resources during peak hours compared with the average during the year (AVG)

	Natural gas	Hydro Run-of-river	Hydro Reservoir	Other	Wind Onshore
JAN	1.42%	4.82%	91.64%	0.28%	1.84%
FEB	1.42%	4.22%	92.38%	0.35%	1.64%
MAR	1.63%	3.85%	92.25%	0.33%	1.94%
APR	1.99%	6.91%	88.67%	0.86%	1.58%
MAY	2.10%	10.60%	83.62%	1.90%	1.79%
JUN	2.17%	7.98%	86.49%	1.42%	1.94%
JUL	2.33%	4.42%	90.59%	1.40%	1.26%
AUG	2.19%	6.50%	89.42%	0.42%	1.46%
SEP	2.05%	7.41%	87.69%	0.18%	2.67%
OCT	1.63%	6.62%	88.66%	0.62%	2.47%
NOV	1.58%	5.73%	89.84%	0.52%	2.34%
DEC	1.65%	4.39%	90.71%	0.76%	2.49%
AVG	2.28%	7.45%	86.95%	0.88%	2.44%

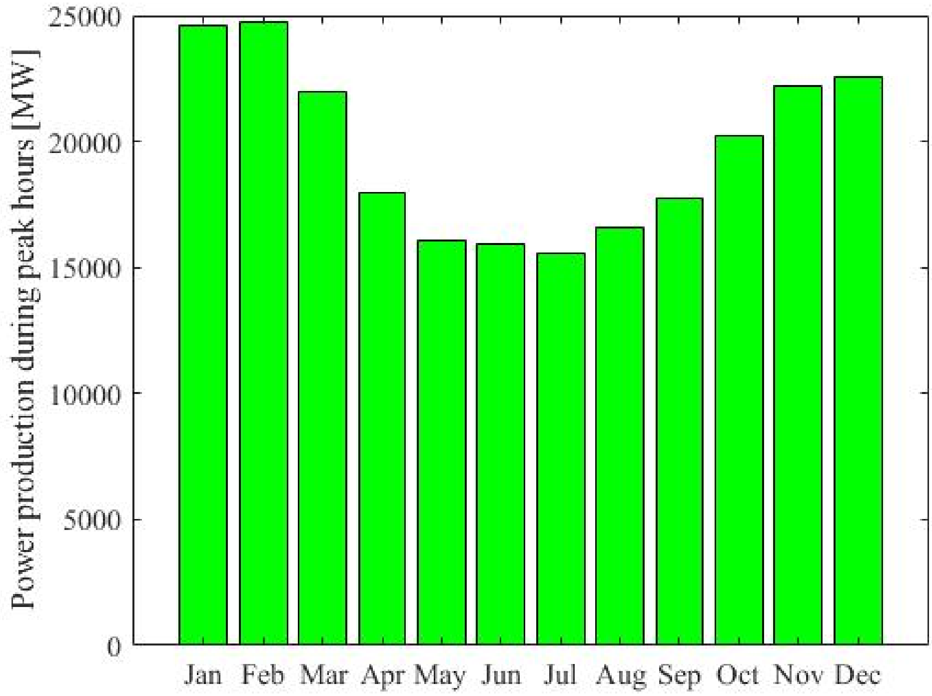

Figure 24: Average monthly power production in Norway

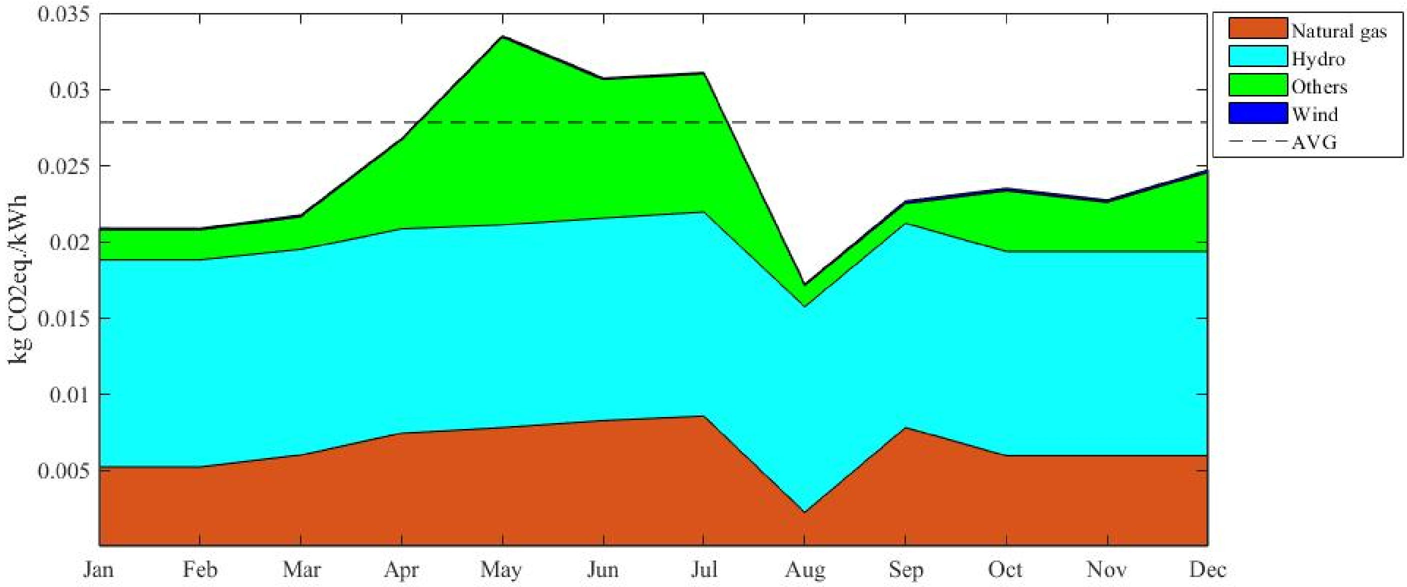

Figure 25: Monthly peak hours GWP compared with average through the year (dotted line) Norway

Thanks to the favourable morphology of the territory, the GWP related to the produced electricity is way lower compared with the other studied countries. Although it is beneficial for the flexibility of the generation, Norway is a good example of a country in which the use of large scale batteries is not really valuable because of the high presence of naturally charged reservoirs. The pumped storage technology (PHS) is just a small percentage compared with the conventional hydropower, (see Table 10). Its use is historically based in the months of June and July [49], and in 2018, through the performed analysis, it is notable a higher use in May as well. The reason to use PHS is to store the electricity that comes from conventional thermal power plants, leading to higher GWP values during those months, as presented in Figure 25.

According to Figure 26, what it is not produced with reservoirs and pumped storage, it is made by natural gas, wind and waste power plants mainly. This is why the GWP line follows the 'Others' resources use curve for the majority of the year 2018. Whenever there is more production from waste and natural gas, the GWP is higher than the average. During the month of August, the amount of power required for the nation needs was close to the yearly average, but less thermal power plants were used while hydropower plants were even more exploited than usual, leading to the lowest value of GWP. During the months when the demand is lower than the average value, more traditional thermal power plants are used to satisfy the demand, being in this case from May to July. This fact is unusual compared to the other studied countries. Anyway, the monthly changes in the use of the resources is always lower than 2% and this is why also the GWP does not differ substantially.

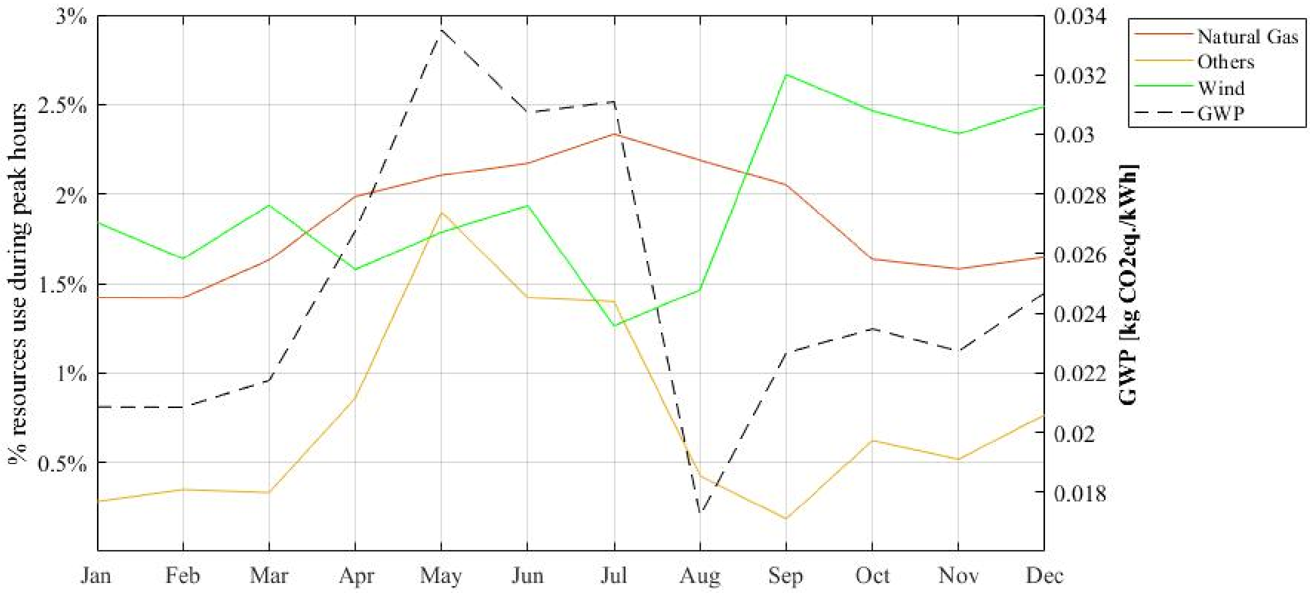

Figure 26: Percentage use of resources throughout the year compared with monthly GWP in Norway, both related to peak hours

As it can be seen from Figure 26, the highest GWP values are during the months PHS are more exploited because they virtually store the power produced by thermal plants fueled by natural gas so that these power plants can run continuously without interrupting their service.

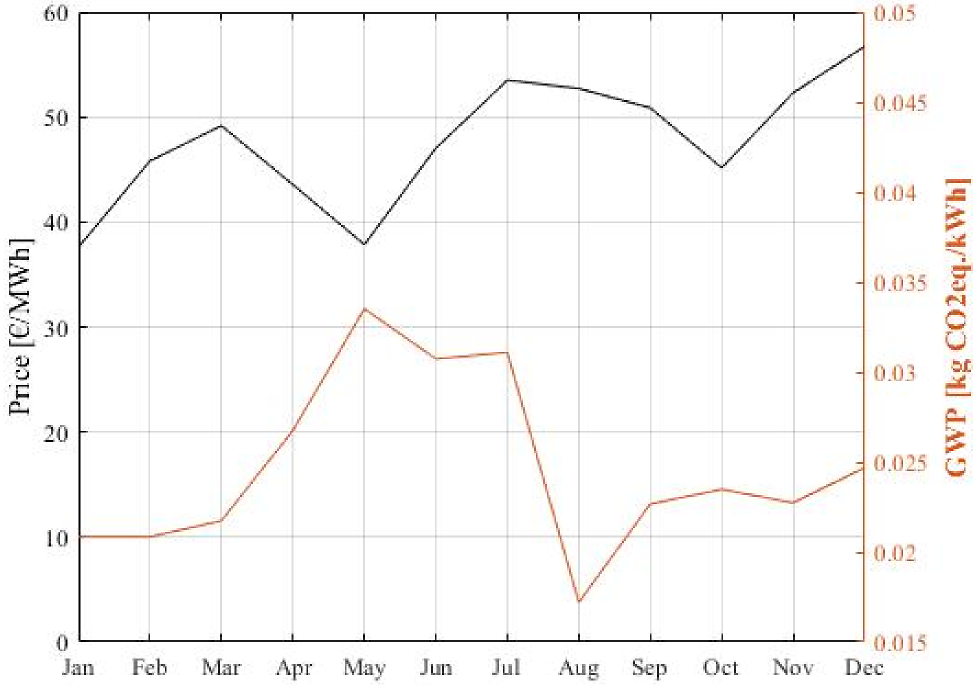

Figure 27: Comparison between electricity price and GWP in Norway

In Norway, there are no direct correlations between GWP, power production and price of electricity during peak hours. This is due to the particular national capacity, based essentially on hydropower reservoirs, which can be managed substantially at will. The months with the highest GWP values (May, June and July) required less electricity than the average during the year and the prices for the consumption were lower in two cases out of three. January, February and October showed more need for power but lower electricity prices. March got more electricity during peak hours and the cost of the produced electricity was higher. In April, both power and prices were lower than average. August and September demanded more power and they got higher prices. November and December had higher GHG values for the electricity sold but also higher prices.

The management of reservoirs in Norway can be difficult. A power plant owner, especially if not pump-hydro, should decide if produce electricity immediately or waiting for better prices and worse weather conditions. Everything is based on forecasting the right electricity prices. This is why the electricity generation is based on short-time price developments [62], in order to avoid any misuse of the hydropower plants. The water resources are not homogeneously located on the country and due to the huge dimensions of the territory, transportation and distribution of electricity to remote areas are vital for the consumers. If the penetration of renewables into the grid will increase in the next years, major investments should be financed in order to keep the grid secure.

Due to the high flexibility of reservoirs and pumped hydro stations, the development of additional energy storage technologies would not be the best strategy for an energy transition pathway. Large scale or household batteries can be useful as grid support just in cases of water shortage and simultaneous low production of the bordering countries. If Norway wants to increase the number of renewable power plants on its territory, it would probably already do so without any major interference or problem.

8.6 Spain

The liberalization of the market in Spain is dated 1997. Retail and generation of electricity are in the hands of production companies, while transmission and distribution are still regulated. The new Spanish government is encouraging self-consumption of produced power by individual citizens, opening the horizon to the energy transition, pushing for investments on photovoltaic [76]. The co-operative GoiEner was created to foster further a new model for the energy generation. "The overall objective is to attract more and more citizens, companies, and entities in the field of the social and environmental economics and public entities" [77]. The bilateral contracts allow private entities to buy and sell electricity on their own, without interfering with the wholesale market.

Phasing out nuclear power is not a current option for Spain. The fission reactors deliver more than 20% of the annual production of electricity. The plan of the actual Spanish government to avoid the use of nuclear from 2035 should be well planned to find out valid alternatives to replace it [78]. The fossil fuels are subsidised, so their role in the next future would still be consistent. New auctions for renewable power capacity are more frequent nowadays, leading to the objective of reducing carbon emission before 2030.

Spain can count different resources that have a high share of electricity production, like Germany. Natural gas and hard coal are the fossil fuels more used, with percentages of 20.91% and 13.29% respectively. Nuclear power plants account for 22.46% of the total yearly electricity production and also wind onshore power represents a consistent share (20.21%). Solar production is present also during night hours because of some Concentrated Solar Power plants with molten salts. Table 15 shows the resources used during the year.

Table 15: Use of resources during peak hours compared with the average during the year (AVG)

	Biomass	Lignite	Natural gas	Hard coal	Hydro	Nuclear	Solar	Wind Onshore	FO, O, OR, W
JAN	1.00%	1.34%	20.86%	12.56%	15.48%	20.94%	2.33%	23.11%	2.37%
FEB	1.10%	1.69%	19.89%	14.57%	16.90%	19.57%	3.13%	20.91%	2.24%
MAR	0.90%	0.15%	14.85%	5.90%	22.79%	17.53%	4.42%	31.28%	2.20%
APR	0.88%	0.00%	15.73%	7.58%	28.13%	17.71%	7.17%	20.47%	2.32%
MAY	1.13%	0.57%	19.41%	10.80%	20.17%	17.94%	13.74%	13.82%	2.42%
JUN	1.19%	1.25%	21.46%	10.64%	21.38%	17.27%	14.17%	10.19%	2.45%
JUL	1.18%	1.92%	20.40%	14.03%	17.70%	19.26%	13.53%	9.62%	2.37%
AUG	1.11%	1.20%	23.61%	14.54%	12.89%	21.45%	10.69%	12.19%	2.32%
SEP	1.19%	2.24%	23.59%	16.92%	12.88%	22.37%	7.30%	11.07%	2.44%
OCT	1.04%	1.58%	24.93%	14.36%	12.45%	21.78%	2.78%	18.61%	2.47%
NOV	1.03%	1.26%	26.95%	16.74%	16.11%	15.91%	1.05%	18.76%	2.19%
DEC	1.08%	1.05%	25.70%	12.52%	17.20%	18.71%	3.44%	18.04%	2.28%
AVG	1.25%	1.28%	20.91%	13.29%	13.22%	22.46%	4.69%	20.21%	2.70%

Source: ENTSO-E TP.

*FO= Fossil Oil, O = Others, OR = Other renewables, W = Waste

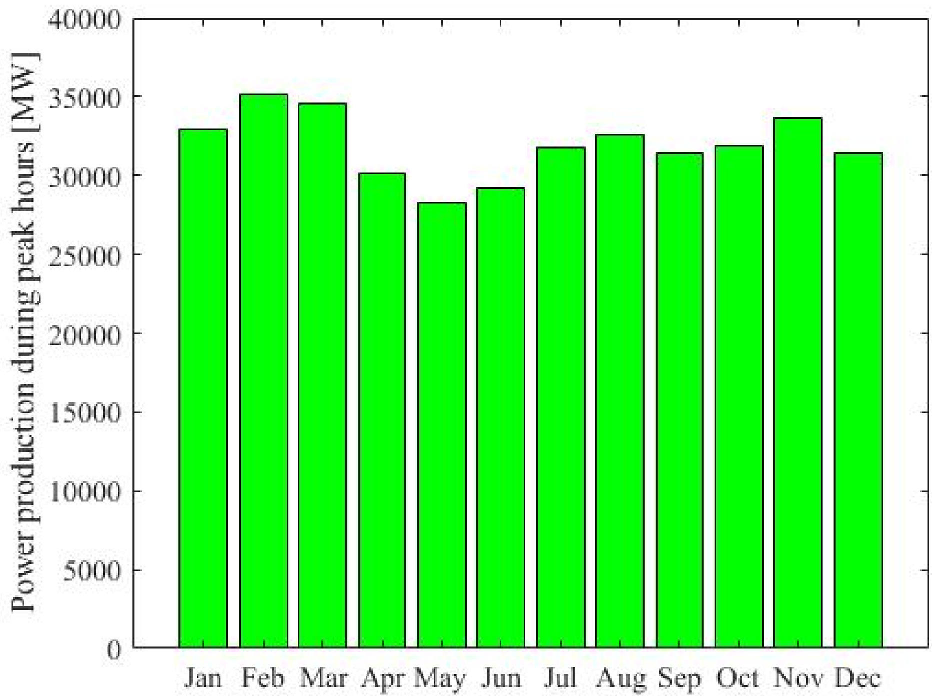

Figure 28: Average monthly power production in Spain during peak hours

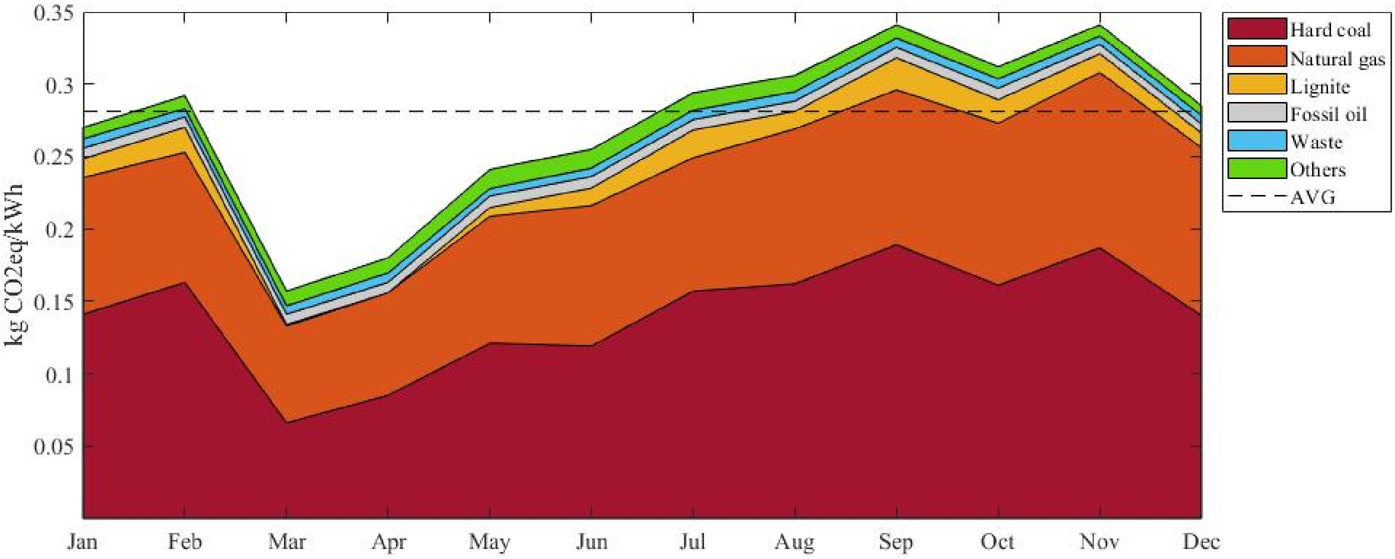

Figure 29: Monthly peak hours GWP compared with average through the year (dotted line) in Spain

The dependence from fossil fuels is the cause of a high GWP in Spain. Figure 29 demonstrates that natural gas and hard coal are the main drivers of a high GWP, and the less they are used, the lower the indicator is. In fact, the GWP curve follows quite precisely the two fossil fuel curves. Figure 30 displays that during the month of March there is a minimum of the GWP due to high penetration of wind power that reached 30% of the share of production and at the same time an increase in the use of hydro storage and solar power plants. In Spain, the utilization of PHS has seen a sustained increased between 1991 and 2013. Then, in the last five years, the usage of flexible hydropower has seen a management approach focused on peak hours [49]. The two maximum GWP points recorded in September and November are due to a decrease in solar electricity production and a consequential increase in fossil fuels to meet the demand needs (Figure 30).

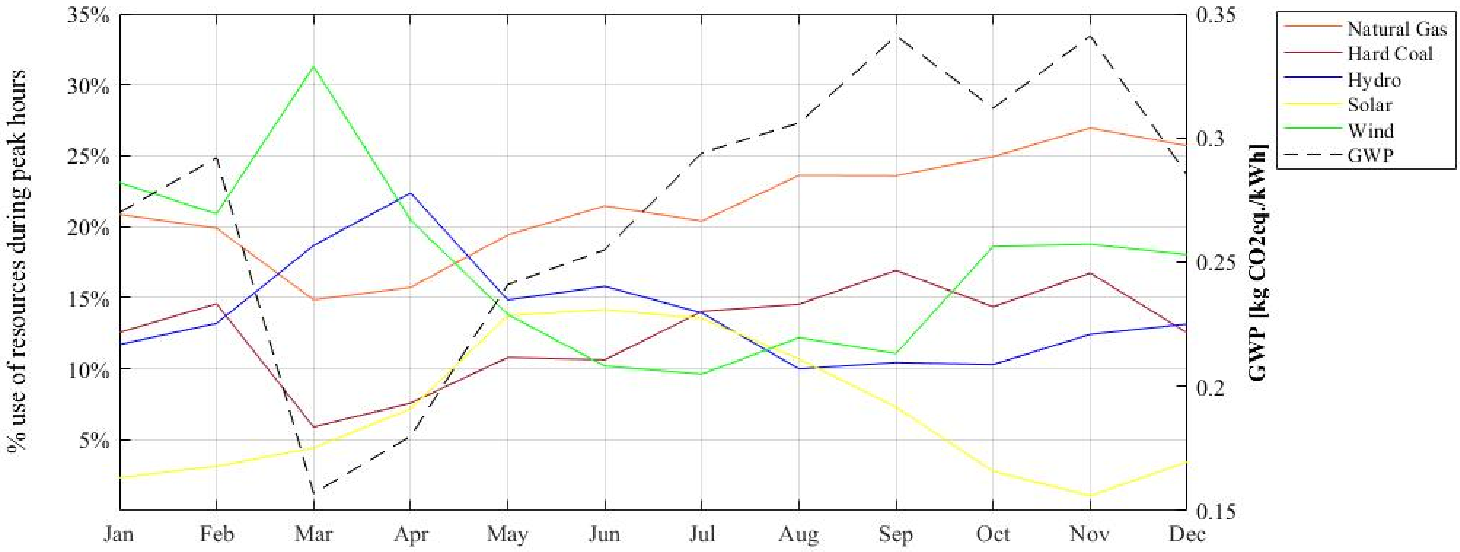

Figure 30: Percentage use of resources throughout the year compared with monthly GWP in Spain (both related to peak hours)

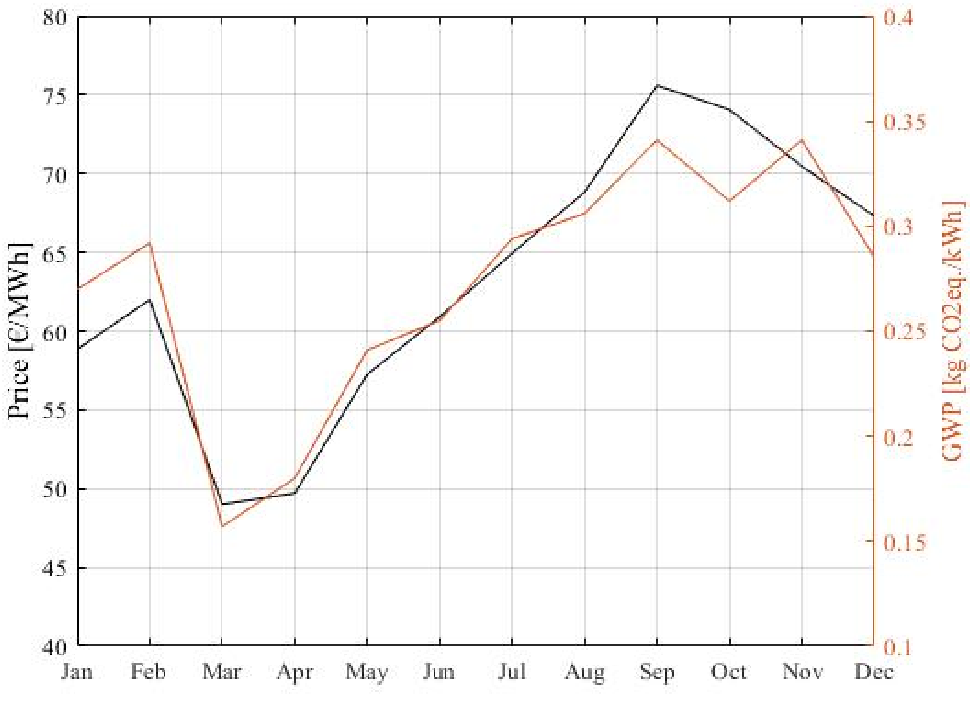

Figure 31: Comparison between electricity price and GWP in Spain

In Spain, the conduct of the GHG emission during peak hours is well related to electricity production and consequent prices. Every month that gets a higher GWP than the base value has also higher values of the annual power generation and energy prices. The months of April, May and June have low values of GWP and at the same time lower request for electricity and lower costs.

2018 has ended as the second most expensive year for electricity in Spain since when the data are recorded [79]. The slow growth of the demand is correlated to the economic recovery of the country. At the same time, the more extreme weather conditions (both in summer and winter) are a concause of the high need and prices. Even if the abundance of rainfalls allowed a more consistent use of hydropower, it did not manage to keep the price low. This fact is due to the increasing cost of fossil fuels throughout the year and the relatively high carbon emission prices, which were 5 times higher than the previous year.

9 Discussion

Section 8 includes the results based on analysis of both environmental impacts and prices during peak hours of electricity production, split by country. The time-variability of GWP and prices assessment has confirmed its importance through this study. Impact indicators can substantially differ depending on the amount of power produced, the different seasons and the used resources throughout the year. In Bulgaria, just four months show a GWP during peak hours that is higher than the yearly average. In Germany, just two out of twelve. In the Netherlands, five. In Norway three and in Spain seven. These outcomes lead to a different reality, compared to what it was expected to obtain as a final result. The hypothesis that higher percentages of fossil fuels are used during peak hours is not completely true. Certainly, more fossil fuels are used, as absolute values, but it is not what the study was aiming to certify. The power plants which run during peak hours are mainly driven because of the price they offer on different time-slots. Thus, the factor that influences the most the demand/offer bids on the electricity market is certainly the marginal cost of producing electricity.

The reader could question himself about the fact that during low demand time, e.g. night hours, the power request is lower than during peak hours and consequently is logic the GWP should be lower than the average, because less resources are used to produce the electricity. On the contrary, it should be noted that the comparison is always done taking into account the functional unit equals to 1 kWh, so the time slots are not compared with their production absolute values but with the relative ones, referring to 1 kWh. An hour with a power generation of 2000 MW can have a higher GWP value compared with a 5000 MW, it depends on the resources used to perform the generation. In outline, the GWP is usually higher not because more electricity is produced since it is based on 1 kWh, but because more fossil fuels should be used to reach the maximum production.

Bulgaria relies on high power capacities of lignite, hydro and nuclear power plants. Nuclear energy covers permanently the base load. Lignite use is less present during peak hours, favourite by the flexible hydro application. Wind power production is stable throughout the year, while solar generation does not coincide with peak time slots. The power requested from the grid varies consistently from April, May to November and December. The Global Warming Potential has dependable variations as well. It doubles in October compared to April. The prices of electricity during peak times are well related to the use of lignite, and the hydro resources affect positively this factor.

In Germany, the capacity is well distributed between many resources. The diversity in the type of power plants present on the territory is one strong point of the national grid mix. Wind and solar lead the amount of power theoretically available, followed by natural gas infrastructures. Wind produces more during winter months, while solar does it during the summer. These two renewable resources are accessible mainly during the peak hours of demand, driving to low national GWP values. Hydro is part of the mix, but even if the capacity in MW related to this source is higher than in other countries, it has a minor role in the extensive German power availability. There are huge differences in power production during peak hours through the different months. Prices and GWP values are associated: when the generation is high the prices increase, and they can change enormously during periods of low demand.

The Netherlands base their electricity production on natural gas, wind power and hard coal. The lack of data regarding this last mentioned resource surely takes to considerable inaccuracies of the model. Nevertheless, it has been proved that during peak hours, the role of wind and solar power is essential to obtain low values of GHG emissions compared to the yearly average. Nuclear has a noticeable portion of the base production. In August, when the power delivered by the only reactor on the territory was close to 0, the GWP had its maximum value. The months in the middle of the year have almost half of the power production compared to the winter ones. The prices of electricity follow an opposite behaviour compared to the GWP curve just in the months of March and December, when the high energy demand led to a significant increase of the cost of energy, without overly affect the GWP. The values of GWP do not change significantly during the whole year, because of the low change in percentages in the use of resources.

Norway is a special case between the targeted countries. The huge presence of flexible hydropower plants allows the country to effectively manage the generation of electricity during peak hours in an environmentally friendly way. Wind production, even if in a small percentage, helps the grid to fulfil the needed requirements. It does it especially during the winter months, when the demand is higher, even 10 MW more in comparison with June and July. During the month of May, June and July, hydro pumped reservoirs are used to support the continuous operation of natural gas-fueled power plants. The deregulated market allows energy actors to participate in bargaining. Despite, the development of short-time prices regulations deny the range of prices to be excessively large. This is the reason why there is no relation between the GWP curve and the prices trend. Actually, the minimum price during the year corresponds to the higher value of GWP, in the month of May. As for the Netherland, the minimal changes in the use of the resources is the cause of little variations in the GWP, which has the lowest average value between the studied country.

Spain, like Germany, has a wide portfolio of different resources to draw on to produce electricity. The most present types of power plants are of natural gas, hydro (in many cases flexible) and wind farms. Nevertheless, nuclear power has the highest share of production for the base load. Hydropower plants were well exploited during the spring months of 2018, wind farms produced a great amount of electricity in the winter and the use of natural gas during peak hours was limited. GWP values greatly differ from periods of high production to months in which less power is needed. The electricity prices curve and the GWP development during the year have the same structure, as the cost of the energy mainly depends on the price of fossil fuels that are imported from other countries.

The recent downward trend in the electricity prices around Europe is confirming the improved stability of the EU energy sector, according to the latest report of the EU Agency for the Cooperation of Energy Regulators (ACER), [80]. This tendency reduces the peaks and the valleys in the market structure as well. The occurrence of high price periods has declined or even disappeared [49]. A great goal that, at the same time, could reduce the profitability of large scale batteries and other storage systems, as Pumped Hydro. Especially Pumped Hydro Storage generates a profitable income for the owner of the plant, but it is also seen as a consumer of electricity in many European countries, dealing with an additional network tariff cost. Furthermore, the current EU Emission Trading System does not still result in higher prices for fossil power plants owners [81] and also gas turbines become a competitive possible choice to cover the peak demand of some countries. Especially power plants owners who hold large shares of PHS in an oligopolistic situation, controlling also different kind of power plants, usually under-utilize their storage capacities [49]. For example, this is the case of Italy, where the single ownership of both PHS and gas turbines affect the use of pumped hydro solutions.

The scope of this study was to look at the environmental concerns related to electricity consumption during peak hours. If during the speaks more fossil fuels are needed, a good strategy would be to store the excess of electricity produced by wind and solar farms and use it when the demand is at its highest. If the outcomes presented in this study would be confirmed, are large scale batteries really needed to store the extra production of electricity from renewable sources? Which will be the policies and regulations set by governments? Will the batteries be seen as prosumers or just as power deliveries? Once this kind of technology will be recognized as economically viable and the environmental and social aspects of the manufacturing processes will be improved, it can surely be vital for a high renewable penetration electricity mix. By any means, the phasing out of carbon and nuclear power plants in certain countries would need suitable action plans to substitute these sources. Nowadays, nuclear and fossil fuels run to ensure the base load needs in many nations. Inevitably, there would be an increase of different sources installations. In this case, energy storage can be essential to allow an improvement in renewable diffusion in the grid.

10 Conclusions and Further Research

This study has proposed a methodology to environmentally and economically assess electricity grid mixes by calculating the carbon footprint or GWP and values and prices throughout one year of study, based on the ENTSO-E TP, currently the database with most reliable data in electricity generation. As LCA can be applied to different purposes, attributional LCA, 1 kWh functional unit and produced electricity as a reference flow have been chosen as specifications to develop the research. Peak hour prices and not daily maximum prices are part of the analysis as well. This methodology has been applied under the INVADE H2020 Project in all the pilot sites that are integrating DERs and flexible loads to provide flexibility services. The study is based in an hourly analysis to ensure that the differentiation between peak hours and off-peak hours can be assessed in terms of GWP. This work presents the results of the Global Warming Potential impact category according to ILCD 2015 of five different pilot-site countries belonging to the project. The differentiation between resources used in peak hours and off-peak hours is highlighted and discussed, which helps to understand the overall GWP value and determines that seasonality is an important factor in terms of resources utilization and so in GWP.

Generally, countries that have a constant base production (e.g. from nuclear), during periods in which the demand is lower than the average, they need less power and consequently less fossil fuel to cover the demand, leading to lower GWP values. Nevertheless, during night times, suitable to off-peak hours, an important low-impact resource like the sun power is not present. As a result, there are some months, especially during the summer time, in which the GWP of peak hours is lower than the average yearly value.

Countries that have a consistent share of flexible hydropower in their capacity portfolio such as Bulgaria, Norway and Spain, mainly use this resource to meet the peak hours demand because of its rapidity in producing electricity and its low marginal cost, leading to lower GWP figures compared to the yearly average. In the months in which the GWP is higher than the comparable value, it was demonstrated that the more conventional power plants are powered to reach the demand during the spikes of production, most probably because of lack of nationwide rainfalls and water shortages. In Bulgaria and Spain this resource affects positively the electricity prices during peak hours, while in Norway, due to special regulations, the link is more complicated.

Germany and the Netherlands mainly have their peak hours production during times in which wind and/or solar power are efficiently running, leading to also lower values of GWP. Especially in Germany, the good alternation of sunny and windy days, the first ones during the summer months and the second ones during winter, are a precious advantage for the national electricity grid. Regarding the Netherlands, the almost constant usage of natural gas to match the national electricity request throughout the year, does not lead to substantial changes in the monthly GWP values. In addition, countries which do not have the geographical morphology to host pumped hydroelectric storage plants, could investigate the potentiality of centralized and distributed energy storage to shave the generation electricity curve and provide flexibility to the electricity grid. In Germany and the Netherlands, prices and high GWP values during peak hours follow the same trend.

The increase of renewable power helps to phase out traditional power plants. The ones that were operating on a constant base are now forced to run just during shorter periods, in which peak hours occur. This fact shortens the useful time in which fossil fuel power plants can sell electricity to cover O&M expenses. Having less time, the owners have to increase the price of the electricity to sell, becoming less competitive and enticing alternatives like energy storage. At the same time, if the declining price trend will continue to affect the market, other alternatives have to be found. If the current situation would be reversed, with rising electricity prices, the development of a carbon trade market that properly works can likely lead to a wider difference between the renewable and the fossil fuel generation costs.

Still, whenever renewable electricity is produced, it is immediately used because it has the lowest marginal cost. The only case in which wind power plants have to be curtailed is when the demand is extremely low and power plants with a long ramp time, like nuclear, are running, as explained in Section 6. Thus, reducing fossil fuels use can be done through a decrease in the demand. An effective technique to reduce peak hours events is a consumers duty. Nowadays, many different power suppliers offer different tariffs based on the time the electricity consumed. Major subsidies should be developed to encourage people to utilize energy during off-peak times. Usually, the price is lower than during the spikes. So, with the massive installation of intelligent smart meters, the final user should be aware of when the electricity price is at its minimum and take advantage of the situation. Different studies were originally trying to understand the effect of real-time electricity price visualization on the users' behaviour [39]. The first results were not encouraging in terms of utilization shifting/reduction. The addition of carbon footprint visualization of the electricity that is consumed in real time could be an adequate method to shift the energy demand, especially in countries where environmental awareness is already significant. Gamification and increasing user interaction can be opportune practices as well. As seen in the performed study, nowadays, from the environmental point of view, this change in users behaviour would not necessarily lead to better GWP values of the consumed electricity. Despite, with the improvement and the further installations of energy storage technologies and smart grid projects, the peak hours environmental issue could be finally solved.

The under-utilization of pumped-hydro storage systems can be solved, boosting the efficiency of PHS through variable speed turbines, flexible operation and increasing the role of these power plants in the balancing market. Nations with a redundant PHS capacity could sell their electricity to cross-border markets. Norway, as deeply analyzed in this study, is the first example of this possible strategy and it shows how well the pumped hydro-storage facilities operation can be implemented. Furthermore, changing the ownership rules in the countries which have an oligopolistic environment would certainly facilitate the best utilization of PHS. EU regulations on de-coupling can be effective to avoid any contradictory action of power plants owners and improving more practical market equilibrium prices.

Nevertheless, the rising integration of centralized and distributed energy storage in the distribution network, as well as combined with DERs, might change the electricity generation and consumption profiles [15]. This approach is out of the scope of the current study presented in this thesis since prospective scenarios have not been defined and the aim is to assess the current situation of the electricity grid mix. Though, it is of the interest of the author to further research developing a consequential LCA, assessing the evolution of the potential environmental and economic impacts by changing the marginal resources of the electricity grid mix due to energy storage systems integration.

As explained, the successive step related to the analysis presented in this study would be a Consequential Life Cycle Assessment. Taking for granted that large scale batteries would be part of the next future electricity grid mix, which would be the resources used to meet the demand spikes? Once the penetration of renewable energies has reached a consistent share of use and the development of energy storage technologies is mature, the market strategies for the electricity supply change. In the eventuality every renewable power plant would have its own large scale battery to store a portion of the producible electricity, the mechanism of bids in the market could involve major issues. For example, a wind farm owner could decide to store the electricity produced and wait for the market price to increase, according to the forecasts. This aspect could create instability and uncertainties in the electricity market. To avoid it, policies and regulations should protect both the producer and the consumer, to ensure the purchase of electricity to be done in a regulated but free market in which every actor can benefit from a more direct way to exchange electricity. The development of Virtual Power Plants, aggregating different prosumers and so merging solar panels and household batteries to offer flexibility services to the grid, it is a first and needed step towards an effective energy transition. Change in European policies, regulations and national generation strategies can be further investigated through a Consequential Life Cycle Assessment too. What if the Bulgaria government breaks down its diplomatic relations with Russia and consequently the country will not have any more access to natural gas? If Germany retreats the idea of phasing out nuclear power plants, is there the possibility to see a free emission coutrny before 2030? These and other similar questions are very interesting for the development of an electricity grid mix CLCA.

To conclude, there are some remaining questions to still be answered, such future strategies to include environmental impacts in the regulatory framework in electricity generation and markets. This analysis can be useful to look at future strategies and policies to enhance the use of renewable sources during certain peak demand periods. The main outcome of this study is the correlation between prices and GWP values of electricity generation during peak hours. Having a clear comparison of these two aspects makes easy to understand the trend in the electricity sector: high prices are mainly set during peak hours in which fossil fuels are used. Definitely, high prices are due to elevating power needs as well. The increasing penetration of renewable power into the grid accelerates the reduction of the GHG emissions, the average prices (as explained through the merit order effect) and indirectly also the power production, thanks to efficient storage solutions and aggregated energy communities. The order to be followed for the power generation should not be based just on economic aspects. If an additional indicator, like the price of CO_2 emissions, would be added to the LCOE, producing electricity through fossil-fueled power plants would become even more costly, accelerating the energy transition towards renewable energies. The development of profitable carbon taxation regulations is an essential step to improve the share of renewable power in the grid.

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