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Assessment of calculation methods for Primary Energy Factors

Case Study of Swedish electricity mix

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Preface

This Master Thesis is the final achievement of the Master Programme in Energy Systems at the University of Gävle. The main source of inspiration for this work has been Professor Abolfazl Hayati, who has been very interested in the subject from the very first meeting we had.

I would also like to give a special thanks to Professor Björn Karlsson, who has always been willing to share his extensive knowledge on the subject in the meetings we had prior to the development of the master thesis, and whose past and present research work is more than inspiring to me.

Javier Ferrero Andrés
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Abstract

The use of the concept of "primary energy" is present in all types of regulations at both European and national level, so that all aspects related to the reduction of energy use and energy efficiency measures speak in terms of primary energy and Primary Energy Factors, necessary for its conversion. The existing consensus on the use of the term is not such in terms of the methodology for calculating the Primary Energy Factors to be adopted, which is the reason for the search for a methodology that acquires the status of global and standard.

Using an analytical methodology, this study will analyze and compare the main methods used by agencies and institutions: the Physical Energy Content Method and the Partial Substitution Method, together with another less widely used method, the Exergy Method. The three calculation methodologies will be applied to the case study of the Swedish electricity production mix. The main objective of this thesis is to analyze the advantages and disadvantages of those methodologies, as well as discuss the difficulties of defining some variables such as efficiencies and system boundaries.

The results obtained in this study demonstrate the complexity of trying to analyze a system as complex as the energy consumption of a country based on the calculation of a single number or Primary Energy Factor. The system boundaries affect the results. At the same time, the use of the Physical Energy Content Method is discarded because it incurs thermodynamic discrepancies. On the other hand, the use of the Partial Substitution Method and Exergy Method is encouraged, since they reflect more accurately the primary energy consumption, as long as the values of efficiencies that they use are clearly defined and referenced. However, there is a more widespread use of the Physical Energy Content Method in the institutions since the other methods present the great difficulty of establishing a consensus on the energy and exergy efficiencies values adopted.

The complexity of choosing a calculation methodology is not only due to the choice of efficiencies but other factors, such as system boundaries, also influence the final results and they have to be reflected in some way. Therefore, it is difficult to decide on a single solution and future studies on other indicators and variables affecting primary energy usage are needed, for instance, CO2 emissions associated with generation technologies.

Keywords: Primary Energy, Primary Energy Factor, Calculation methods, Partial Substitution, Exergy, Physical Energy Content.

Nomenclature

PEF	Primary Energy Factor
EIA	Energy Information Administration
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
EU	European Union
IEA	International Energy Agency
UN	United Nations
CED	Cumulative Energy Demand
IPCC	Intergovernmental Panel on Climate Change
RUF	Resource Utilization Factor
EROI	Energy Returned on Investment
LCA	Life Cycle Assessment
W	Work (kWh)
Q	Heat (kWh)
T	Temperature (K)
η	Energy Efficiency (-)
ε	Exergy Efficiency (-)
CHP	Combined Heat and Power
CCS	Carbon Capture Storage
RES	Renewable Energy Sources
kWh_{elec}	Electric Kilowatthour produced by a specific source
kWh_{PE}	Kilowatthour of Primary Energy
kWh_{fossil}	Kilowatthour of Fossil Equivalent
$\eta_{technology}$	Energy efficiency of a determined generation technology
η_{fossil}	Energy efficiency of fossil power plant
Btu	British Thermal Unit
kWh_{exer}	kWh of exergy
$kWh_{source,rev}$	kWh of Primary Energy of the reversible process
PE	Primary Energy
TWh	Terawatt hour

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1 Introduction

The following sections will introduce the reader the topic of the report, as well as the motivation and aims of the study.

1.1 Background

The Paris Agreement established in 2015 the global basis of the fight against climate change. The main objective of this agreement was to limit the global increase of the temperature to 2º Celsius or preferable 1.5º Celsius above the pre-industrial or 1990s levels (United Nations, 2015). Since then, several revisions and regulations to the European policy framework have been made in order to set more specified targets regarding the reduction of greenhouse emissions, the increase of usage of renewable energies, as well as energy efficiency and interconnection of European electricity systems (Matteo Ciucci, 2021). The most recent policy agenda adopted by the European Council in 2021 is in line with the Paris Agreement but setting more ambitious targets by 2030 such as: reducing the emissions by 55%, increasing the share of renewable energies up to 40% and a reduction of the final and primary energy of 36-39%; among other aspects ("Delivering the European Green Deal," 2021).

The term "primary energy" has been used to evaluate the consumption and use of energy since 2012 in (European Parliament, 2021a). The energy savings are defined in terms of primary energy, as well as the energy efficiency measures. Moreover, the use of the term has been extended to other sectors and European regulations including the Building Sector (European Parliament, 2018a) and the Energy Efficiency (European Parliament, 2018b).

As it can be deduced from the regulations, there is a general consensus in Europe to refer energy to "primary energy", which would help to harmonize the comparisons. In order to accomplish this, the Primary Energy Factors (PEF) establish a relationship between secondary energy and primary energy. However, institutions use diverse methodologies to calculate these PEFs, as well as different definitions of the term.

This problem is the main motivation of this study: although there is extended use of primary energy and PEFs, there is a lack of standardization of its calculation method. The research and assessment of the existing methodologies can influence the energy policies from a national or even European perspective, and this is something that all researchers related to energy issues find inspiring and encouraging.

1.2 Literature Review

The previous and current research has been carried out with two clearly differentiate searches. Firstly, the research has been focused on the definitions of "primary energy" and "secondary energy". For this purpose, it has been consulted publications and regulations of institutions that can be easily found on their websites. Once the meaning and scope of the basic terminology has been widely understood, one can start thinking about searching information regarding the nexus between both terms, that is the "primary energy factors". This second part of the research has been carried out using the databases: ScienceDirect and WorldCat Discovery. The keywords used in the literature review searches were: *primary energy*, *secondary energy*, *methodology*, *calculation*, *primary energy factor*, *PEF*, *exergy* and *energy statistics*; as well as combinations between them.

The U.S Energy Information Administration defines "primary energy" as the first energy that is used in energy balance, prior any kind of transformation (EIA, n.d.). In a similar way, the Institut national de la statistique et des étides économiques states that it is the energy creation that has not been exploited (INSEE, 2016). In line with this two definitions, Kydes (2007) expresses that the term accounts for the energy that has not experimented conversions of any type. All these definitions try to set the boundaries of the energy system in the resource, for instance: wind, sun, coal, crude oil and so on; as all the resources have either a limited existence in the Earth or an intermitted availability.

When trying to find the definition stated by the European Union, it has been found that there is no definition for the term *primary energy*. Instead, two distinct terms can be found: *primary production of energy*, which refers to products obtained from natural sources that can be consumed (Eurostat, 2013); and *primary energy consumption*, which encompasses energy consumption, losses and end-use (Eurostat, 2018). It can be extracted from these definitions that this time the boundaries of the energy system are not set in the resource itself but in the useful part of it. The primary energy production for hydro-power, wind power and photovoltaic is the gross electricity that it is generated in the facilities (European Commission, 2015), instead of being the energy available in the water, wind and sun respectively.

With regard to "secondary energy", the Institut national de la statistique et des étides économiques defines it as energy obtained when transformations are applied to primary energy and mentions electricity obtained by power cycles in thermal power plants (INSEE, 2020). Similarly International Energy Agency (2004) established that "secondary commodities" (understanding "commodities" as electricity, heat and fuels) are those that come from "primary commodities". It is also mentioned in that reference that electricity and heat can be considered either primary or secondary energy: primary heat is considered as the one that is obtained from thermal reservoirs (geothermal) or directly from the sun in thermal solar panels while secondary heat is obtained from nuclear and other combustible fuels; similarly, primary electricity is obtained from solar PV cells and other renewable energies (hydro, tidal, wind), and secondary electricity comes from heat used in thermal power plants (nuclear, combustible and geothermal).

From this first search and from the definitions of primary and secondary energy given by different organizations, it can be seen that the boundaries of energy systems are not clearly established. Moreover, since both heat and electricity can be considered as belonging to both groups, there may be a tendency to consider both forms of energy as equivalent. It is possible to glimpse the problems in the search for common energy policies in the European Union, generally due to the lack of standardization as well as to the existing ambiguity in terminology. These difficulties are aggravated when we move on to analyze the PEFs.

PEFs are mentioned and used in legislative publications as well as in scientific publications and reports (to be discussed later). In general they are defined as the amount of primary energy that must be consumed to deliver one unit of consumable energy, taking into account the losses and energy used in the processes of extraction, transport and storage (Hitchin et al., 2018). At the European level, there are three pieces of legislation that promote the use of PEFs:

- Energy Efficiency Directive (EED) applies the "first of all, energy efficiency" policy and establishes that electrical energy savings must be made in terms of primary energy, applying a PEF of 2.1 (previously 2.5) for electrical energy. The reciprocal of 2.1, i.e. 1/2.1=0.4769, represents the amount of electricity produced per unit of primary energy, that is the electrical efficiency. The directive states in a table the conversion factors for fuels and electrical energy. When applying energy saving measures for electrical energy in terms of primary energy based on final consumption the conversion factor is 1, but when these measures are applied to the electricity itself, the 2.1 factor should be used in order to assure a correct transformation of those savings to PEF savings (European Parliament, 2021a).

- Energy Performance of Buildings Directive (EPBD): focuses on regulating energy consumption in buildings and establishes that member states' regulations must contain an energy use indicator based on primary energy consumption (European Parliament, 2021b).

- EcoDesign Directive and Energy Label Directive: focuses on products or technologies that use different energy inputs but have the same functionality, e.g. space heaters (European Parliament, 2017). The mean objective is to compare technologies and to establish an energy efficiency category for the product.

It is important to note that the above regulations suggest PEF values but it is up to the individual EU member states to choose their own value. Furthermore, these three regulations have different scopes: the EED focuses on primary energy consumption at the level of a country's electricity generation, while the EPBD and the EcoDesign Directive and Energy Labelling Directive have smaller system boundaries: buildings and products such as heat pumps or electric boilers, respectively. These differences open the door to the debate, which will be discussed later, as to whether different PEFs should be established (or the way they are calculated) depending on the system boundaries, and therefore be different in each legislation.

Hamels et al. (2021) carried out an extensive literature review to try to analyze the different PEF calculation methodologies. The different references consulted were classified in groups according to system boundaries: from appliance level to country level, including buildings and municipalities. In addition, six parameters (geographical scope, temporal scope, import perspective, parameter source, assessment boundary and market perspective) were established to analyze each reference. It was concluded that most approaches consider annual historical data of electricity produced at country level without considering interconnections, since this would imply a much more complex modeling. Special emphasis was placed on the lack of transparency found in the different publications in terms of methodologies, as well as in the few that exist regarding the calculation of PEF of the technologies themselves.

Macknick (2011) compares the data used and calculation methods of four international organizations: International Energy Agency (IEA), United Nations (UN), United States Energy Information Administration (EIA) and BP (previously British Petroleum). It is stated that there are important differences between the results provided by each agency. These differences are mainly due to: differences in categorization of energy sources, different data values for fuels such as calorific value, and the use of different methods for converting electricity from renewable and nuclear energy into primary energy. On the one hand, IEA and UN use the "physical energy content method", while EIA and BP use the "substitution equivalence method", resulting in differences in primary energy consumption between the two methods of up to three times more with respect to the "physical energy content".

The two methods mentioned above are the most commonly used when calculating the PEF of the different technologies. The idea behind the physical energy content method is to consider as primary energy the first type of energy that has a certain utility, that is: heat in fuels, nuclear and geothermal, and electricity in hydro and the rest of renewables (Eurostat, 2022). On the other hand, the substitution equivalence method considers the contributions of non-fossil fuel energy sources (renewable and nuclear energies) as if they had been produced in conventional fossil fuel thermal power plant ("Energy Accounting," 2021). It can be deduced from the definitions of both methods that they are strongly dependent on the efficiencies or conversions applied to the technologies.

Modahl et al. (2013) discusses the latter and points out the importance of transparency in terms of constants used to calculate efficiencies, such as heating values in the case of fuels or downstream losses. In addition, the paper collects data from different references and for different energy sources of the Cumulative Energy Demand (CED), equivalent to the PEF. This indicator takes into account not only the energy inherent to the resource itself, but also the energy used for the extraction, processing and transportation of the resource, as well as the energy required for the construction of buildings and infrastructure associated with these processes. The paper concludes that there is less variation between the different references for hydropower and wind, as opposed to biomass, coal and natural gas. It can be extracted that special attention should be paid to the values used for the calculation of indicators in fuel technologies.

Hitchin (2019) continues to emphasize the idea that different institutions use different assessment methods depending on the technology. It argues that the fact that a physical measurement of energy is necessary leads to a tendency to abandon the deeper meaning of primary energy, i.e., the one related to the resource itself, and hence the use of methods such as physical energy content which, a priori, contradict the purest definition of primary energy. This publication concludes that it is very difficult and unrealistic to establish a generic and universal standardization for the calculation of PEFs, given that they depend not only on the aforementioned conversions and efficiencies, but also on factors that inherently differ from country to country, such as the structure of the electricity grid and the interconnections it has. Instead, the search for the greatest possible transparency in publications and regulations should be pursued in terms of data and assumptions used.

Lightfoot (2007) also examines the problem of primary energy assessment by the IEA, the Intergovernmental Panel on Climate Change (IPCC) and the EIA with another approach along the same lines as the previous references, but different. The paper states that the Joules designating energy have a different meaning for each of the three institutions, especially with regard to the assessment of renewable and nuclear energies, and proposes the adoption of a single system to be able to compare and avoid errors.

The references discussed so far have focused on analyzing the calculation methods of the main institutions, with special emphasis on how difficult it is to establish a universal methodology given the many variables that influence a country's primary energy consumption, and the differences between countries. However, the increasing percentage of renewable energies in the energy mix makes it necessary to compare these scenarios with those in which this percentage was lower. The different ways of calculating PEF try to find the fairest comparison, but there are references that, in addition to analyzing them, propose other approaches.

Walmsley et al. (2018) proposes a new indicator called Resource Utilization Factor (RUF). This indicator aims to introduce the concept of energy quality when assessing the potential to generate electricity from energy resources, or in other words, how well they are utilized. RUF is based on the concept of exergy, which is defined as the maximum theoretical work that a thermodynamic system can do until it reaches equilibrium with the environment (Moran et al., 2010). Thus, Walmsley et al. (2018) analyzes both RUF and PEF for different technologies (coal, natural gas, hydro, wind, solar PV, geothermal and nuclear) and concludes that RUF represents a more equitable comparison of resources and a way to see which are more susceptible to efficiency improvement, since it is being compared at all times with the theoretical maximum through the concept of exergy. In this paper it is also defined the Energy Return on Investment Standard ($EROI_{Std}$) as the energy output of the system divided by the energy used within the system to process and transform the resource. This indicator is a measure of the ease with which a resource is extracted and processed, and it should not be mistaken with the EROI indicator defined below by Weißbach et al. (2013).

Weißbach et al. (2013) develops a methodology for calculating the Energy Returned on Investment (EROI) indicator, based on the exergy concept, as he considers that this thermodynamic property is the one that allows comparing results more independently. The EROI is defined as the ratio between the useful exergy produced by an energy system and the total exergy that had to be invested to produce that useful energy (Weißbach et al., 2013). It can be deduced from this definition that the reciprocal of the EROI is similar to the PEF (as it is defined in the paper). According to Weißbach et al. (2013) there is a substantial difference between PEF and the reciprocal of EROI; the former has a larger macro scope and considers the energy inherent in the resource, while the latter focuses more on the technology itself with a more economic view. However, the methodology proposed by Weißbach et al. (2013) does include the "embodied energy" obtained through LCA of the technology in question. In addition, other publications discussed above also calculate the PEF of different technologies, so it can be said that they "forget" about the macro level of the indicator that is proposed by Weißbach et al. (2013). Regardless of the differences above mentioned, both publications agree that exergy is the property that best allow comparison whatever the indicator considered but information about the process and exergy efficiencies should be defined and used, so this will be a very important aspect throughout the development of this project.

The Table 1 summarizes the different energy indicators that have been collected from the references, as well as the definition. The definition of PEF does not include the lifespan of the facility as it is usually applied to the macroscale previous mentioned, that is, to countries. It can be seen that it is the most general definition so the concept of "energy extracted" must be specified as much as possible.

Table 1: Indicators for electricity generation (WALMSLEY ET AL., 2018)

Name	Nomenclature	Definition
Primary Energy Factor	PEF	Energy extracted from resource per unit of electricity delivered
Cumulative Energy Demand[1]	CED	Energy extracted from resource plus all energy used to transform and to process it per unit of electricity delivered during system lifespan
Energy Return on Investment Standard	$EROI_{Std}$	Electricity delivered per unit of energy used to transform and to process the resource during system lifespan (including the self-use of energy by the system)
Resource Utilisation Factor	RUF	Electricity delivered per unit of exergy extracted from resource plus all exergy used to transform and to process it during system lifespan
Energy Return on Investment[2]	EROI	Exergy delivered during lifetime per unit of exergy used to transform and process the resource during lifespan

These considerations open the door to a debate that will be discussed throughout this project on whether the PEF should be defined in the same way regardless of the system boundaries, or whether it should have different definitions depending on whether a country or a technology is being considered.

To summarize the literature review, it can be seen that the European Union establishes in its main energy directives the use of the term *primary energy* as essential for a correct evaluation of energy savings and efficiency, and therefore proposes the use of the PEF as a link between resource and energy consumption. What in essence seeks to find a standardized, fair and simple comparison of resource use, in reality has several complications. On the one hand, the variables that influence the calculation of PEF, such as system boundaries or reference parameters (conversions), are complex and numerous. On the other hand, energy institutions use different PEF calculation methodologies, generally the physical energy content method and the substitution method, with a great lack of transparency regarding the data they use. In addition, there is a lack of practical application of other methods and concepts such as exergy analysis, which can lead to questioning the very definition of primary energy and the use of PEF as the best indicator of resource exploitation.

[1] This definition was obtained from Modahl et al. (2013)
[2] This definition was extracted from Weißbach et al. (2013)

1.3 Aims

The starting point of this master thesis has been the meetings held with Professors Björn Karlsson and Abolfalz Hayati, supervisors of this work. The methodologies for calculating PEFs currently in use by the European Union and other institutions, as well as their lack of transparency, have been presented. The studies consulted show that there is a generic desire to create a common and standardized methodology that allows the comparison of resource use by the different countries that make up the European Union.

The importance of PEFs lies in the fact that they make it possible to analyze the consumption of a resource in a neutral manner, i.e., allowing comparison between countries. However, for this to be carried out in a fair manner, the calculation methodology underlying the PEFs must be clearly defined, and this is where the main objective of this thesis appears.

The main objective of this master thesis is to investigate the different methods used to calculate PEFs. The strengths and disadvantages they have will be analyzed, and especially if they represent a true picture of the consumption of energy resources. Other objectives will be to describe the evolution of the Swedish electricity mix in terms of PEF and to see how system boundaries can affect the PEFs.

The previous meetings together with the literature research have given rise to a series of reflections that in chronological order can be conceptualized in the following questions:

- Which is the PEF calculation method that best considers the ability of the resource to produce useful energy (i.e work)?
- Does the term *primary energy* as it is defined and use in European regulation actually follow the thermodynamic definition of energy use?
- Is it really feasible and correct to reduce the exploitation and use of energy resources to a PEF, even if the calculation method is standardized?

1.4 Approach

The present study has been carried out firstly by means of an analytical methodology, that is, a large number of sources have been consulted and a series of data and information has been compiled. These data correspond to efficiencies and data from Swedish electricity generation.

In order to see the advantages and disadvantages of each method and which one reflects in a more realistic way the primary energy consumption, the equations to be used in each method have been analyzed, describing the factors and units that appear in them. The description of the equations and of the physical units that compose them will allow to see if and to what extent the methods conform to the most basic thermodynamic assumptions. This information will try to answer the first and second research questions.

For each calculation method, two types of PEF have been calculated with different system boundaries. Firstly, the PEF associated with each generation technology which means that the system boundaries are fixed to the facility itself. Secondly, the PEF associated with Sweden as a country, where the system boundaries are now fixed to the whole energy consumption of the country. This will allow to see the influence that a factor (system boundaries) has on the final results in a complex system, which will encourage the discussion of the last research question.

2 Theory

This section will first present the fundamental theoretical concepts related to the definition of energy, exergy and energy efficiency. Their understanding is essential for a correct comprehension of the PEF calculation methods that will be explained in the following subsection.

2.1 Thermodynamic concepts

The concept of energy is familiar to everyone, since in one way or another they will have used it throughout their lives. However, when it comes to the definition of energy, anyone will have doubts, even if they are very versed in the subject. One simple definition of energy is "the capacity of a physical system to do work, or alternatively, to produce heat"(Coburn and Farhar, 2004).

In the field of thermodynamics, energy is one of the most basic concepts that exist. If one goes to a book on technical thermodynamics to consult its definition, one will see that, as a general rule, a generic definition of the term is avoided and the different forms in which it manifests itself are defined: kinetic, potential, electrical, thermal, magnetic, chemical and nuclear. This is because it is the experimental evidence that governs these energy concepts (Moran et al., 2010). A thermodynamic system can store energy in any of the above forms, but across its boundary it can only exchange energy by means of work, heat transfer and /or mass. Furthermore, the first law of thermodynamics states that energy is transformed and is neither created nor destroyed, so the energy transfers of a system across its boundary (either work or heat transfer) must be equal to the energy stored in the system (Cengel et al., 2011).

The First Law of thermodynamics therefore establishes a relationship that allows us to *quantify* energy, that is, to establish the quantities of energy. The relationship established between the different forms of energy and the transformations from one to another is that they are all equivalent to each other and can therefore be added together. However, from the second law of thermodynamics it is known that energy not only has a *quantity* but also a *quality* and that when transformations from one form of energy to another occur there is always a *degradation* of energy (Cengel et al., 2011). Alternative statements of the Second Law state that heat cannot be entirely transformed into work, since there will always be a transfer of heat to the cold source. However, work can be entirely transformed into heat. This again gives us an idea that heat and work are forms of energy transfer of different quality, and that work has a higher quality than heat.

These concepts are embodied in the thermal efficiency, defined as the desired useful output effect divided by the required input energy. In Figure 1 it can be seen represented: a thermal machine, which works by absorbing heat from a hot reservoir to produce useful work while transferring a certain amount of heat to a cold reservoir; and a heat pump, which takes heat from a cold reservoir to a hot one at the cost of absorbing an amount of work; both machines developing reversible cycles. In addition, taking into account that the definition of Kelvin scale indicates that the ratio between absorbed and transferred heat is equal to the ratio of the temperatures of the sources in Kelvin, the efficiencies can be defined as follows:

$$\eta_{Thermal\ Machine} = \frac{W}{Q_{IN}} = \frac{Q_{IN} - Q_{OUT}}{Q_{IN}} = 1 - \frac{Q_{OUT}}{Q_{IN}} = 1 - \frac{T_{cold}}{T_{hot}} \quad (1)$$

$$\eta_{Heat\ Pump} = \frac{Q_{OUT}}{W} = \frac{Q_{OUT}}{Q_{OUT} - Q_{IN}} = \frac{T_{Hot}}{T_{Hot} - T_{Cold}} \quad (2)$$

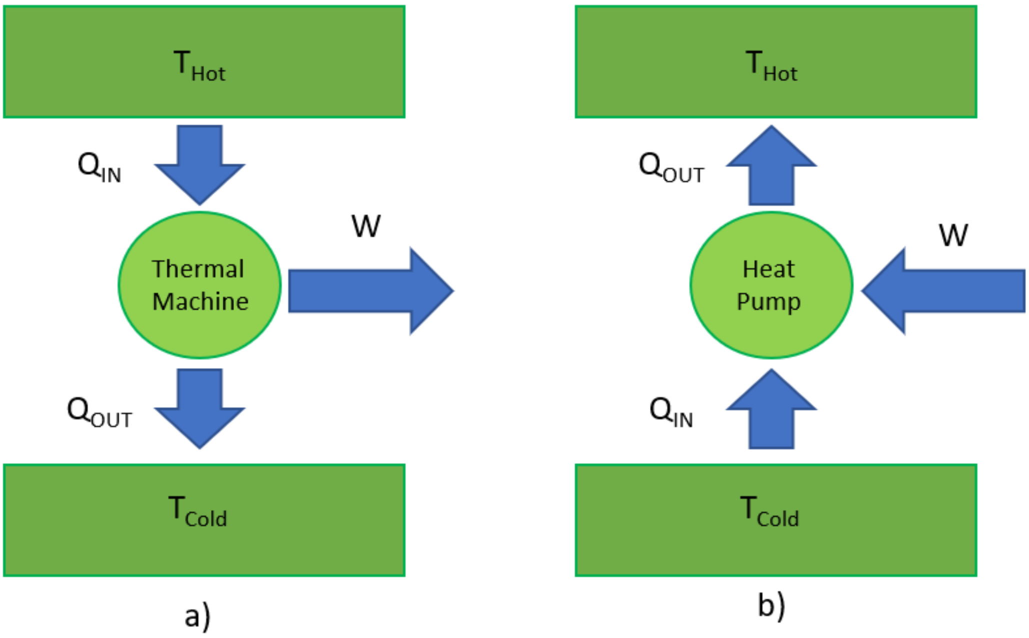

Figure 1: a) Scheme of thermal machine, b) heat pump

The above equations represent mathematically, on the one hand, the restrictions imposed by the second principle: to produce work by exchanging heat with a single focus and to transfer heat from low to high temperature without consuming work. On the other hand, and given that T_{hot} is greater than T_{cold}, they indicate that the conversion of heat into work always has an efficiency less than unity while the conversion of work into heat always has an efficiency greater than unity. This shows that work is a more valuable form of energy transfer than heat, and that the heat has more value when the temperature is as high as possible.

Therefore, it can be concluded that, despite being measured in the same unit (Joules), different forms of energy have different value or quality. These qualitative differences between energy sources are discussed by Giampietro and Sorman (2012). In this paper it is established that the scale or system boundaries that are being considered when making a quantitative energy analysis is very important. Just as within the same science there can be differences when talking about scales, i.e. classical mechanics and quantum mechanics; when analyzing a complex energetic system, one should not only look at the inputs and outputs but also at the nature of the conversion process. Thus, although the kinetic energy and the chemical potential are both measured in Joules, they should not be added together but transformed into the equivalent through a conversion factor. This transformation implies that the direct empirical measurement of one (or more) energy sources is lost so that the details and methodology used for the definition of that conversion factor gain greater importance.

Another very important thermodynamic concept that will be used later is the concept of exergy. Exergy is a thermodynamic property that is defined as the maximum theoretical work that a system can develop until it reaches total equilibrium with the environment without violating any law of thermodynamics (Moran et al., 2010). The idea behind this concept is that any thermodynamic system can continue to develop work while it is in a state different from the environment, since theoretically a device could be connected to it that takes advantage of the imbalance (whether thermal, mechanical or chemical) between the system and the environment to produce work (Cengel et al., 2011). It can therefore be said that exergy is a measure of the actual potential use or availability of a resource and it is destroyed when the system evolves into an equilibrium with the environment.

It is important to note and make clear that exergy has units of energy but, as noted above, the exergy flows into or out of the system represent theoretical opportunities to do work that would take place if the appropriate devices were connected to it. This implies that exergy transfers associated with heat transfer, chemical exergy or exergy associated with work represent all of them *potential work*; therefore, it can be said that exergy Joules or kWh regardless the nature of the process (heat, chemical…) do represent the same concept (work), as opposed to the energy ones as discussed above.

The concept of exergy brings with it the introduction of the concept of exergy efficiency, also sometimes called Second Law Efficiency. This exergy efficiency is defined generically as the ratio between *exergy recovered* and *exergy supplied* to the system (Cengel et al., 2011). *Exergy recovered* is usually defined as the exergy associated with useful work or heat transferred depending on whether it is a power cycle or a heat pump. *Exergy supplied* is the exergy that would be developed if the process were carried out reversibly. In other words, the exergy efficiency compares the real process and the real exergy obtained from it, with the reversible process, which would be the one developed in the best possible way (without irreversibilities, with zero exergy destroyed).

$$\varepsilon = \frac{Exergy\ recovered}{Exergy\ supplied} \tag{3}$$

2.2 PEF Calculation methods

Although the three main methods for calculating PEFs have already been mentioned in the literature review, this subsection will briefly explain their characteristics and how they have been and are applied by different international organizations.

As a reminder, the PEF is defined as the ratio between primary and secondary energies, i.e. the amount of primary energy consumed to produce one unit of secondary energy. From the definition it can be deduced that the PEF is somehow the reciprocal of the efficiency of the transformation from primary energy to secondary energy. There are different methods for its calculation that mainly differ from each other in the concept of primary energy and the efficiencies or conversion factor that are applied to the different type of technologies or energy sources:

- **Physical Energy Content:** in this method the primary energy equivalent for the different energy sources is considered to be the first useful energy input flow to the system. In the case of combustibles, the heat generated in combustion is considered to be the first flow with a practical use. For non-combustible products we find two cases: for nuclear, geothermal and solar thermal, the heat generated will be considered as the primary energy flow; while for the rest of energies (photovoltaic, wind, hydro, tide, wave) the generated electricity is considered as the primary energy flow (Esser and Sensfuss, 2016). This method is used by the IEA and Eurostat.

- **Partial Substitution Method:** in this method, the energy content of traditional fossil fuels (oil, coal and gas) is considered as primary energy. For all other energy sources (renewables, nuclear) the primary energy is considered to be the amount of energy that would need to be produced in a conventional thermal power plant of standard efficiency, i.e. as if all non-fossil electricity production were replaced by conventional power plants (Adapt Consulting, 2013). This method is used by EIA and BP.

- **Exergy Method:** there is a general lack of information regarding the application of this method, as it is not known to be used by any agency. The idea behind this method is to consider the maximum work-producing potential of each energy source, i.e., the exergy efficiency of the transformation. Thus, regardless of whether the type of energy to be considered is fuel or non-fuel, renewable or non-renewable, the primary energy flow will be exergetic kWh in all of them.

The choice of PEF calculation method involves a number of considerations, ranging from technical to political, as well as a number of difficulties. (Adapt Consulting, 2013) carried out a comparison of the physical energy content and the partial substitution method calculating the PEF of Norway, Sweden and Denmark; obtaining different results. The difference between the PEF calculated using one or the other method is especially accentuated if the country has a significant percentage of renewable electricity generation, as is the case of Norway. This is why the publication alludes to the difficulties and risks involved in reducing a country's resource consumption to a single number. A country and its energy inputs and outputs form a complex system that has certain nuances that are not covered by the methods described, such as:

- Energy interconnections between countries.
- The electrical efficiencies that are taken for each type of energy. It is being considered that all gas-fired thermal power plants have the same efficiency, when the reality is that depending on whether, for example, they are peak or base plants, the efficiency is different.
- In Combined Heat and Power (CHP) it is not clearly defined how the production and energy losses are distributed between the two products (heat and electricity).
- The introduction of certain systems, such as Carbon Capture Storage (CCS), into the energy mix.

Esser and Sensfuss (2016) aims to establish a general methodology for calculating PEF through a decision tree that seeks to classify all the options and variables that affect the process. It provides three general thematic groups in which it includes different categories and options:

- The political dimension: this group includes all those options that have to do with political decisions such as: the scope of application of the PEF (if different forms of calculation are taken according to different system boundaries), the process of reviews (PEF constant or subject to periodic revisions) or if the PEF value is calculated or prefixed and from this fixed value the primary energy is calculated.
- The description of the electricity system: this group includes the different options that exist when describing the electricity system, such as: borders and interconnections (i.e. EU, country, smaller regions), the temporality of the electricity generation data (hourly, seasonally, annual, several years…), as well as whether base or peak power plants of the electricity mix are considered as reference generation for the calculations.
- The PEF calculation method finally applied: classifies generation technologies into: fossil fuels, nuclear, combustible RES, non-combustible RES, CHP; and for each of them, either the physical energy content or the partial substitution method can be applied. It contemplates the possibility of applying to each technology a Life Cycle Assessment (LCA) perspective or not, but it does not contemplate or mention at any time the exergy method or the use of exergy efficiencies.

It can be seen how the difficulties or challenges that were mentioned in Adapt Consulting (2013), are taken into account in Esser and Sensfuss (2016) and collected in a decision tree within the different thematic groups aforementioned. To evaluate the different options and make decisions, the paper defines a series of criteria (accuracy, data availability, consistency with EU objectives, complexity and transparency) to which it assigns a number from one (best) to five (worst) and a weighting. It should be underlined that the study has been carried out in close contact between EU institutions and stakeholders in order to establish the scores. In this way, each variable or option obtains a final score, and the paths of the decision tree with the best score can be selected. For certain categories there was a clear dominance of a series of options that reduced the paths of the decision tree, such as applying a regular revision to the PEF calculation (instead of considering it constant over time) and using the same calculation methodology for the different regulations, among others. The Figure 2 shows the reduced decision tree, so that the reader can get an idea of its appearance.

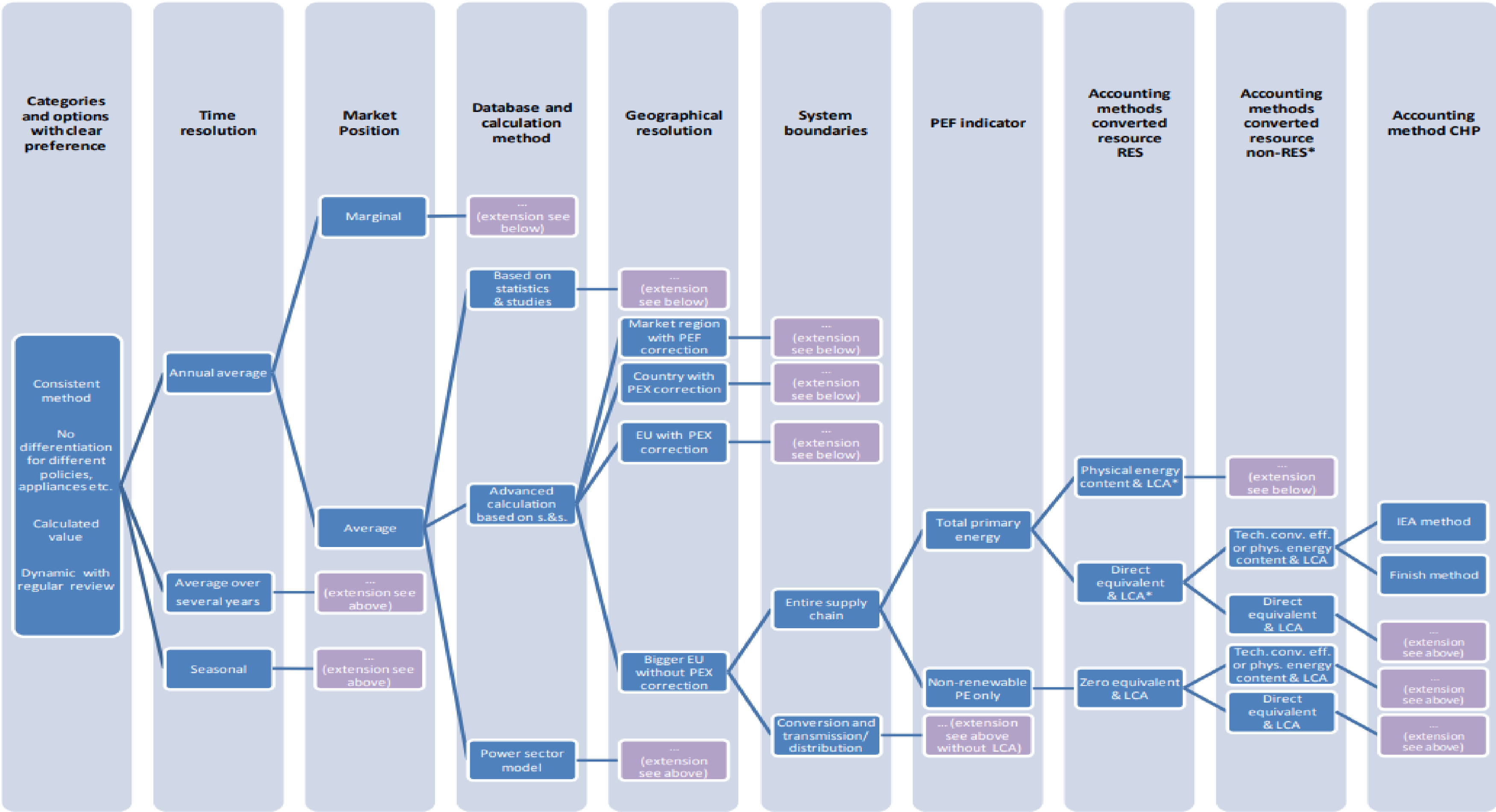

Figure 2: Reduced decision tree (Esser and Sensfuss, 2016)

3 Method

The methodology applied to study the three PEF calculation methods previously mentioned has been an analytical methodology. An extensive bibliographic study has been carried out, which has allowed us to know in depth the different calculation methodologies. Based on the references consulted, we proceeded to collect data on the variables necessary to apply the different methods to the case of the Swedish electricity generation mix. Needless to say, that ethical considerations are irrelevant to the development of methodology.

In the analysis carried out in Esser and Sensfuss (2016) there are a number of characteristics relating to the PEF calculation methods whose score is such that they allow the other options to be ruled out. These are the common characteristics that a PEF Method **should** have, as shown in Table 2. In contrast, there are others in which all or many of the options have a good score, so it cannot be said a priori that there is only one possible option. These other characteristics that a PEF Method **can have** been listed in Table 3.

Table 2: Characteristics a PEF method should have

PEF Method **should**	Comments
Be calculated	Instead of being a prefixed value
No differentiation	Same method for countries, regulations or application
Be reviewed	Subject to a periodic review or adjustment
Be dynamic	Instead of constant over time
No differentiation between hour of the year	Use annual average consumption for countries, seasonal values for appliances
Use average values of electricity generation	Not consider peak or base power plant but an average

Table 3: Characteristics a PEF method can have

PEF Method **can have**	Comments
Geographical resolution	Electric system can be EU or Member States
System boundaries	LCA assessment depending on availability of data and they are up to date
PEF Indicator	Including RES generation is more realistic but adding it to traditional sources is complicated

As can be deduced from both tables, there is agreement on the more general characteristics of the PEF, i.e., those listed in Table 2; it is when it comes to going into details of how the PEF is calculated (characteristics in Table 3 especially system boundaries and how renewable energies are treated in the mix) where the choice is not so clear and an in-depth study is required. In this way, the institutions select the method they consider most appropriate, as well as the conversions or efficiencies of the different technologies.

The following subsections will explain the three main PEF calculation methods, as well as the values and equations that have been used when applying them to the different Swedish power generation technologies.

3.1 Physical Energy Content Method

Table 4 shows the data used by Eurostat and the IEA, both relating to the Physical Energy Content method. Applying the inverse of these efficiencies to the electrical production of each technology gives the primary energy consumption of each source, so we can define the PEF of this method as in Equation (4). When applying the physical energy content method to the Swedish electricity production mix, the values of electrical efficiency showed in Table 4 have been used together with the Equation (4). This equation will give the value of PEF for each technology.

Table 4: Physical energy content method conversion factors (Esser and Sensfuss, 2016)

	Physical Energy Content ($\eta_{technology}$)
Institution	IEA, Eurostat
Nuclear	33%
Geothermal electricity	10%
Solar thermal electricity	33%
Hydro, wind, marine and solar PV	100%
Biomass[3]	30%
Fossil[4]	40%
CHP	70%

$$PEF_{Physical\ Energy\ Content}^{Technology} = \frac{1}{\eta_{technology}} \quad \left[\frac{kWh_{PE}}{kWh_{elec}}\right] \qquad (4)$$

3.2 Partial Substitution Method

Table 5 shows the data used by BP and the EIA, this time relating to the Partial Substitution Method.

Table 5: Partial substitution method conversion factors (BP, 2022) and (Macknick, 2011)

	Partial Substitution (η_{fossil})	
Institution	BP	EIA
Nuclear	Linear increase 38.6% (2000) - 45% (2050)	28 % - 35.1 %
Geothermal electricity	Linear increase 38.6% (2000) - 45% (2050)	16.20%
Solar thermal electricity	Linear increase 38.6% (2000) - 45% (2050)	34.40%
Hydro, wind, marine and solar PV	Linear increase 38.6% (2000) - 45% (2050)	34.5 % (Hydro), 34.5 % (rest)
Biomass	32%	-
CHP	-	-

It can be seen in Table 5 that BP and EIA use very different values. For the analysis of Swedish electricity production, we have chosen to use BP's performance values and discard the use of the values of the EIA. The reason for this choice is simple: although the EIA values are referenced in Macknick (2011), it was not possible to access this reference because the website is not available.

[3] This value is taken from Adapt Consulting (2013) but it is similar to the ones that appear in Esser and Sensfuss (2016)

[4] Same as for Biomass

As explained before, this method calculates the fossil energy equivalent (kWh_{fossil}) that would be necessary to produce the same amount of energy using fossil free technologies. This fossil equivalent will therefore be the result of applying the performance of the fossil technologies to the rest of the technologies, so the PEF of the partial substitution method for each technology will be calculated using Equation (5), where η_{fossil} is obtained from column of BP in Table 5 and $\eta_{technology}$ is obtained from the Table 4. Further explanation of this equation can be found in Appendix A.

$$PEF^{Technology}_{Partial\ Substitution\ Method} = \frac{\frac{\eta_{technology}}{\eta_{fossil}}}{\eta_{technology}} = \frac{1}{\eta_{fossil}} \quad \left[\frac{kWh_{fossil}}{kWh_{elec}}\right] \tag{5}$$

In trying to clarify the values currently used by the EIA, it has been concluded, after analyzing U.S Energy Information Administration (2010), that the EIA converts the electrical output of all energy sources to thermal primary energy units (Btu) using the heat rates listed in Table 6. In any case, these values will not be used, remaining only for the reader's interest. The PEF by the partial substitution method will be calculated with the BP values and Equation 5 since one of the premises is the comparison between results, and using the EIA data would mean working with Btu instead of kWh. Further explanation on how the EIA calculates primary energy can be found in Appendix B.

Table 6: Heat rates for electricity used by EIA (EIA, 2022A)

Year	Total fossil fuels (Btu/kWh)	Nuclear (Btu/kWh)	Non combustible renewable energy (Btu/kWh)
2015	9.319	10.458	9.319
2016	9.232	10.459	9.232
2017	9.213	10.459	9.213
2018	9.104	10.455	9.104
2019	8.905	10.442	8.905
2020	8.773	10.446	8.773
2021	8.773	10.446	8.773
2022	8.773	10.446	8.773

3.3 Exergy Method

The most exhaustive and complete documentation concerning the exergy method has been found in Walmsley et al. (2018). This publication contains energy and exergy efficiency values for the main power generation technologies. In addition, it is explained with an example of a natural gas combined cycle that in order to relate the net production of electrical energy to the exergy used to produce it, the quotient between energy efficiency and exergy efficiency must be used. In other words, and as can be seen in Equation (6), the quotient between energy efficiency and exergy efficiency gives us two members that are also quotients.

The first member of the equation is the net electrical energy produced for each unit of exergy, that is kWh_{elec}/kWh_{exer}. The second member, that is $kWh_{PE,rev}/kWh_{PE}$, represents the primary energy that would have been used if the process had been carried out in a reversible way, per unit of primary energy actually used. This factor represents how far or close is the development of the technology of the reversible process, which is the theoretical maximum process free of irreversibilities. This will be the factor used to calculate the exergy equivalent of electricity production in Sweden.

$$\frac{\eta_{technology}}{\varepsilon} = \frac{\frac{kWh_{elec}}{kWh_{PE}}}{\frac{kWh_{exer}}{kWh_{PE,rev}}} = \left(\frac{kWh_{elec}}{kWh_{exer}}\right) \cdot \left(\frac{kWh_{PE,rev}}{kWh_{PE}}\right) \qquad (6)$$

The reciprocal of this quotient, as can be intuited and seen in Equation 7, is nothing but an exergy power of the PEF of the Physical Energy Content method. It will be defined as PEF of the Exergy Method for each technology. In this equation, the exergy efficiency multiplies the PEF of the Physical Energy Content Method. This means that we are weighting the energy-based PEF with the exergy efficiency, that is we are adjusting the energy efficiency to the exergy efficiency

$$PEF_{Exergy}^{Technology} = \frac{1}{\eta_{technology}} \cdot \varepsilon = PEF_{Physical}^{Technology} \cdot \varepsilon \quad \left[\frac{kWh_{PE}}{kWh_{elec}} \cdot \frac{kWh_{exer}}{kWh_{PE,rev}}\right] \qquad (7)$$

The ratio presented in Equation (6) and the PEF of the Exergy Method presented in Equation (7) represent both the same idea: how close or far a technology is from the reversible process. This has to do with the margin of technical improvement that a technology presents.

The Table 7 collects for each technology the energy efficiency and exergy efficiency values as well as the quotient between the two and the PEF of the Exergy method. If one only looks at the energy efficiency column, one might think that, for example, natural gas has a 46% chance of improvement but this is not correct: only act on around 32% of improvement (second column). This can be illustrate with a similar example as the one used in Walmsley et al. (2018): a coal power plant that produces 100 MW of electricity would need a coal input of 300 MW (energy efficiency); but if this plant would be perfect (reversible process, no irreversibilities in the facility) to produce the same amount of electricity it would need 193.6 MW[5] of coal input. If we want to produce that amount of electricity, we will need to use 193.6 MW of coal at best. This means that the margin of technical improvement in the power plant is 106.3 MW of coal.

In conclusion, it can be said that the closer to unity the last two columns of Table 7 are, the less room for technological improvement a technology has, or in other words, the better use of the resource it is making.

It is also important to mention where the values of exergy efficiencies come from. As it has been stated, all the values come from the paper Walmsley et al. (2018). Some of them are easily deduced, as in the case of wind power, whose exergy efficiency is the Betz Limit, which symbolizes the maximum energy that can be extracted from the wind regardless of the type of wind turbine or any other technical aspect. However, regarding the exergy efficiencies of the fuels are generally calculated with the equation 8, which compares the change in the Gibbs free energy with the change in enthalpy of the fuel. Gibbs free energy is related to the electricity produced by the fuel in a fuel cell, while the enthalpy is related to the heat produced in the combustion. Then, the quotient represents the percentage of heat that can be ideally converted to electricity.

Another way to calculate the exergy efficiency of fuels is to consider only the combustion process and not the direct generation of electricity in a fuel cell. In this case, which is more related to the Carnot efficiency, the actual heat generated in the combustion process would be compared with the ideal combustion (named as adiabatic combustion), which takes place with no released of energy to the ambient in a complete combustion at adiabatic flame temperature.

$$\varepsilon = \frac{\Delta G_{fuel}}{\Delta H_{fuel}} \tag{8}$$

[5] The coal energy input (300 MW) multiplied by the exergy efficiency of the coal power plant (0.581)

Table 7: Exergy Method conversion factors (Walmsley et al., 2018)

	Energy efficiency $\eta_{technology}$ (kWh_{elec}/kWh_{PE})	Exergy efficiency ε ($kWh_{exer}/kWh_{PE,rev}$)	$\eta_{technology}/\varepsilon$	$PEF_{Exergy}^{Technology}$
Natural Gas	0.540	0.675	0.800	1.250
Coal	0.300	0.581	0.516	1.937
Hydro	0.920	1.000	0.920	1.087
Wind	0.400	0.593	0.675	1.483
Solar PV	0.098	0.687	0.142	7.034
Geothermal	0.065	0.163	0.401	2.495
Nuclear	0.256	0.510	0.502	1.992
Average RE[6]	0.371	0.611	0.607	1.65
Average Fossil[7]	0.420	0.628	0.669	1.50

3.4 Total Primary Energy Factor for Sweden

In order to calculate the total PEF for Sweden, equation 9 will be used. It can be seen that it will be the sum of the primary energies of each source calculated by a specific method, divided by the total net electricity produced.

The difference between this PEF and the ones calculated with equations (4), (5) and (7) is that in this case the system boundaries are the whole country from primary energy used to electricity consumed. The PEFs calculated with the other equations give the primary energy usage per electricity generated at the terminals of the transformer of the facility, so the system boundaries were the facility itself. Since the data obtained from Our World in Data (2022) corresponds to the electricity generated by the power plants, when calculating the Swedish PEF with equation (9) a 10% loss in the power transmission line has been considered in order to account for this difference in system boundaries.

$$PEF_{Method\ X}^{Sweden} = \frac{\sum_{source} PE_{Method\ X}}{Net\ Electricity\ Production} \quad \left[\frac{kWh_{PE}}{kWh_{elec}}\right] \qquad (9)$$

The data collected in the above tables will be used to analyze the different methods in the case of the Swedish electricity mix. An Excel spreadsheet has been used to perform the calculations, and when applying the methodology and equations mentioned above, it has been followed the same line taken by Prek (2019), who performed a similar study for the Slovenian electricity production mix.

[6] This value has been calculated as the average of the values for renewable energies and it will be used when the data of electricity production by source does not enter in none of the categories listed in Table 6.
[7] The same applies as in note 3 but for fossil fuels.

4 Results

This section will show the results obtained from applying the three PEF calculation methodologies previously developed to the Swedish electricity generation mix during the period 2010 to 2020. Figure 3 shows the average electricity production of each energy source in that period. Table 8 with the specific values for each year is also shown below:

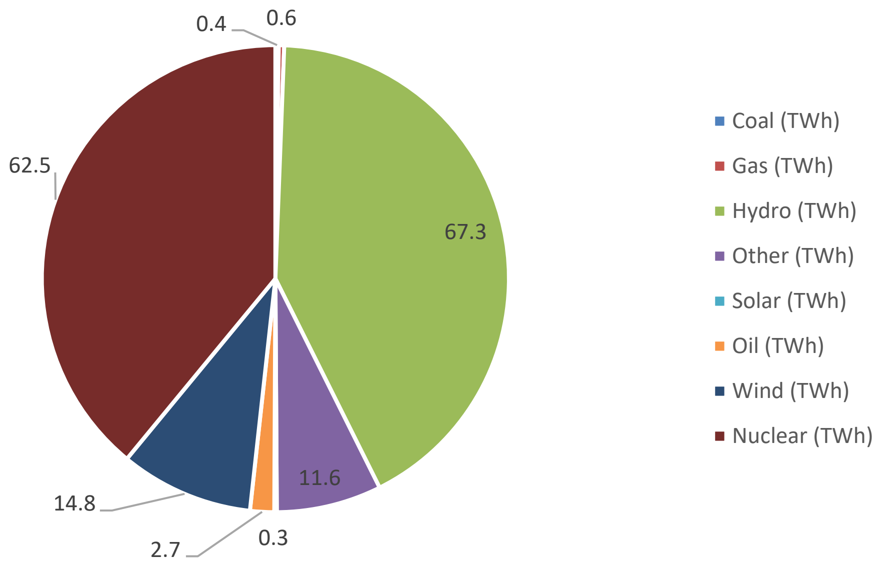

Figure 3: Average electricity production by source in sweden from 2010 to 2020

Table 8: Electricity generation by source in Sweden from 2010 to 2020

Year	Coal (TWh)	Gas (TWh)	Hydro (TWh)	Other[8] (TWh)	Solar (TWh)	Oil (TWh)	Wind (TWh)	Nuclear (TWh)	Total (TWh)
2011	0.7	1.6	66.4	11.5	0.0	3.5	6.1	60.5	150.3
2012	0.5	0.9	78.9	12.2	0.0	2.7	7.2	64.0	166.4
2013	0.7	0.9	61.4	11.5	0.0	2.4	9.8	66.5	153.0
2014	0.4	0.4	63.8	10.7	0.1	2.1	11.2	64.9	153.6
2015	0.4	0.5	75.3	10.8	0.1	2.3	16.3	56.4	162.0
2016	0.3	0.7	62.0	11.5	0.1	2.7	15.5	63.1	155.9
2017	0.3	0.3	65.1	12.1	0.2	2.8	17.6	65.7	164.2
2018	0.3	0.4	62.2	11.9	0.4	2.9	16.6	68.6	163.4
2019	0.2	0.3	65.4	13.0	0.7	2.9	19.9	66.1	168.4
2020	0.0	0.1	72.4	11.2	1.1	2.3	27.5	49.2	163.8
Average	0.4	0.6	67.3	11.6	0.3	2.7	14.8	62.5	160.1
Percentage	0.23 %	0.37 %	42.03 %	7.27 %	0.17 %	1.67 %	9.23 %	39.03 %	100 %

[8] Other includes the rest of renewable energies as well as biofuels.

With regard to the Physical Energy Content method, the following Table 9 shows the primary energy values for the different generation technologies and for each year:

Table 9: Primary Energy use according Physical Energy Content Method

Year	Coal (TWh)	Gas (TWh)	Hydro (TWh)	Other (TWh)	Solar (TWh)	Oil (TWh)	Wind (TWh)	Nuclear (TWh)	TOTAL PE (TWh)
2011	1.7	4.0	66.4	38.5	0.0	8.7	6.1	183.2	308.6
2012	1.2	2.3	78.9	40.6	0.0	6.7	7.2	194.1	331.0
2013	1.6	2.1	61.4	38.2	0.0	6.0	9.8	201.4	320.5
2014	0.9	1.1	63.8	35.7	0.1	5.4	11.2	196.6	314.6
2015	1.0	1.1	75.3	35.9	0.1	5.8	16.3	170.8	306.3
2016	0.7	1.7	62.0	38.3	0.1	6.8	15.5	191.2	316.3
2017	0.8	0.8	65.1	40.3	0.2	7.1	17.6	199.1	331.0
2018	0.9	1.0	62.2	39.7	0.4	7.4	16.6	207.7	335.8
2019	0.5	0.7	65.4	43.5	0.7	7.1	19.9	200.4	338.1
2020	0.0	0.3	72.4	37.3	1.1	5.9	27.5	149.1	293.4

The PEF for Sweden calculated with the Physical Energy Content method for each year is shown in Table 10 below:

Table 10: PEF Sweden according Physical Energy Content Method

Year	Total Electricity Gen (TWh)	Losses 10% (TWh)	Total Net Electricity (TWh)	TOTAL PE (TWh)	PEF SWEDEN
2011	150.3	15.0	135.3	308.6	2.28
2012	166.4	16.6	149.8	331.0	2.21
2013	153.0	15.3	137.7	320.5	2.33
2014	153.6	15.4	138.2	314.6	2.28
2015	162.0	16.2	145.8	306.3	2.10
2016	155.9	15.6	140.3	316.3	2.25
2017	164.2	16.4	147.8	331.0	2.24
2018	163.4	16.3	147.0	335.8	2.28
2019	168.4	16.8	151.6	338.1	2.23
2020	163.8	16.4	147.4	293.4	1.99

Likewise, the following Table 11 shows the primary energy values relative to the Partial Substitution Method, which, let us remember, are nothing more than the fossil energy equivalent for each technology.

Table 11: Primary Energy use according Partial Substitution Method

Year	Coal (TWh)	Gas (TWh)	Hydro (TWh)	Other (TWh)	Solar (TWh)	Oil (TWh)	Wind (TWh)	Nuclear (TWh)	TOTAL PE (TWh)
2011	1.6	3.9	166.0	28.8	0.0	8.7	15.3	151.1	375.6
2012	1.2	2.3	196.7	30.4	0.0	6.7	17.8	160.1	415.2
2013	1.6	2.1	152.4	28.4	0.1	5.9	24.4	165.6	380.6
2014	0.9	1.0	157.9	26.5	0.1	5.3	27.8	161.1	380.7
2015	1.0	1.1	185.9	26.6	0.2	5.7	40.3	139.5	400.2
2016	0.6	1.7	152.6	28.3	0.3	6.7	38.1	155.7	384.0
2017	0.8	0.8	159.8	29.6	0.6	6.9	43.2	161.6	403.3
2018	0.8	0.9	152.1	29.1	1.0	7.2	40.6	168.1	399.9
2019	0.5	0.7	159.3	31.8	1.7	6.9	48.4	161.7	411.0
2020	0.0	0.2	175.9	27.2	2.6	5.7	66.9	119.9	398.3

The Swedish PEF using the Partial Substitution Method yields the results shown in the Table 12:

Table 12: PEF Sweden according Partial Substitution Method

Year	Total Electricity Gen (TWh)	Losses 10% (TWh)	Total Net Electricity (TWh)	TOTAL PE (TWh)	PEF SWEDEN
2011	150.3	15.0	135.3	375.6	2.78
2012	166.4	16.6	149.8	415.2	2.77
2013	153.0	15.3	137.7	380.6	2.76
2014	153.6	15.4	138.2	380.7	2.75
2015	162.0	16.2	145.8	400.2	2.75
2016	155.9	15.6	140.3	384.0	2.74
2017	164.2	16.4	147.8	403.3	2.73
2018	163.4	16.3	147.0	399.9	2.72
2019	168.4	16.8	151.6	411.0	2.71
2020	163.8	16.4	147.4	398.3	2.70

The results obtained using the Exergy Method are presented below. Table 13 shows the primary energy results and Table 14 the Swedish PEF:

Table 13: Primary Energy use according Exergy Method

Year	Coal (TWh)	Gas (TWh)	Hydro (TWh)	Other (TWh)	Solar (TWh)	Oil (TWh)	Wind (TWh)	Nuclear (TWh)	TOTAL PE (TWh)
2011	1.3	2.0	72.2	19.0	0.1	5.2	9.1	120.5	229.3
2012	0.9	1.2	85.8	20.1	0.1	4.0	10.6	127.6	250.3
2013	1.3	1.1	66.7	18.9	0.3	3.6	14.6	132.4	238.7
2014	0.7	0.5	69.3	17.6	0.4	3.2	16.6	129.3	237.6
2015	0.8	0.6	81.9	17.7	0.7	3.5	24.2	112.3	241.5
2016	0.5	0.9	67.4	18.9	1.0	4.1	22.9	125.7	241.4
2017	0.6	0.4	70.8	19.9	1.6	4.2	26.1	130.9	254.6
2018	0.7	0.5	67.6	19.6	2.9	4.4	24.6	136.6	256.9
2019	0.4	0.4	71.1	21.5	4.8	4.3	29.4	131.7	263.5
2020	0.0	0.1	78.7	18.4	7.4	3.5	40.8	98.0	246.9

Table 14: PEF Sweden according Exergy Method

Year	Total Electricity Gen (TWh)	Losses 10% (TWh)	Total Net Electricity (TWh)	TOTAL PE (TWh)	PEF SWEDEN
2011	150.3	15.0	135.3	229.3	1.70
2012	166.4	16.6	149.8	250.3	1.67
2013	153.0	15.3	137.7	238.7	1.73
2014	153.6	15.4	138.2	237.6	1.72
2015	162.0	16.2	145.8	241.5	1.66
2016	155.9	15.6	140.3	241.4	1.72
2017	164.2	16.4	147.8	254.6	1.72
2018	163.4	16.3	147.0	256.9	1.75
2019	168.4	16.8	151.6	263.5	1.74
2020	163.8	16.4	147.4	246.9	1.68

Finally, Table 15 shows the PEF values for the different generation technologies and using each of the three methods. As the values for each technology and applying a specific method remained constant over the years, it has been decided not to show the whole set of values in order not to overload the reader.

Table 15: PEF of different sources and for the three methods

	Primary Energy Factor		
Source	Physical Energy Content Method	Partial Substitution Method	Exergy Method
Coal	2.50	2.46	1.94
Gas	2.50	2.46	1.25
Hydro	1.00	2.46	1.09
Other	3.33	2.46	1.65
Solar	1.00	2.46	7.03
Oil	2.50	2.46	1.50
Wind	1.00	2.46	1.48
Nuclear	3.03	2.46	1.99

5 Discussion

The Swedish electricity production mix is mainly driven by nuclear and hydroelectric power, covering around 80% of generation. The rest of the mix is based on renewable energies, mostly wind power. The use of fossil fuels (coal, oil and natural gas) is very low, around 3%. Furthermore, if we analyze the data from 2011 to 2020, it can be seen how the production of energy using fossil fuels has decreased in favor of a higher percentage of renewables. It can be seen that the trend in electricity generation is towards an increasing share of renewables and an abandonment of fossil fuels, something that is fully aligned with the standards and guidelines of the European Union. It is very important to bear in mind the energy mix of the country being analyzed, since if the results are to be compared with those of another country whose energy mix is very different, errors may be introduced in the assessment, as it will be discussed later.

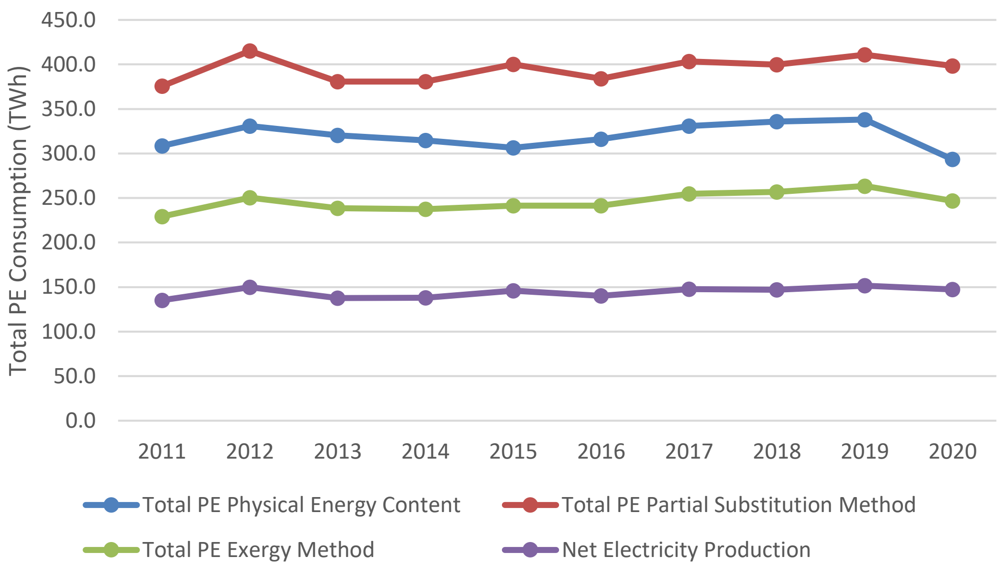

Figure 4: Total PE consumption for the three methods

Figure 4 shows the total primary energy consumption for each of the methods over the period under study, as well as the net electricity produced. It goes without saying that electricity production is lower than primary energy consumption regardless of the calculation methodology applied, since any transformation, by virtue of the second law of thermodynamics, involves losses. It is observed that the three methods follow similar trends, for example in the year 2020, due to the economic standstill caused by the pandemic, there has been a decrease in primary energy consumption, as well as in electricity production. In general terms, if we compare consumption in 2011 and 2019 (avoiding a singular year such as 2020), we observe an increase in both electricity production and primary energy consumption.

Focusing on the three methods, it can be seen that the Partial Substitution Method is the one that obtains the highest primary energy consumption with values of around 400 TWh, while the Exergy Method is the one that obtains the lowest values, around 250 TWh. This is due to the fact that the conversion factors or efficiencies are lower in the Partial Substitution Method (around 40%) and higher in the Exergy Method (around 55%), with those of the Physical Energy Content being between the two. Here we can clearly see the great influence of the conversions or efficiencies and the need to record the values being used, together with the bibliographic reference to these values.

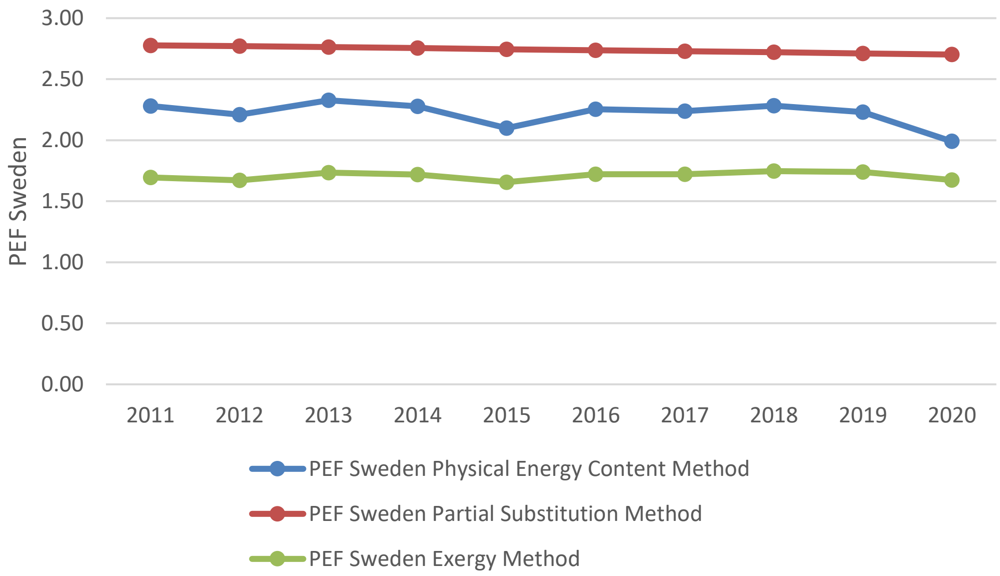

Figure 5: PEF of Sweden for the three methods

Figure 5 shows the evolution of the PEF of Sweden throughout the period studied and calculated according to the three aforementioned methods. It can be seen that once again the PEF calculated using the Partial Substitution Method is higher than that calculated using the Exergy Method, with the Physical Energy Content between the two. This is logical since the net electricity production is the same for the three methods, so the value only depends on the total primary energy consumed, which is what was discussed in Figure 4. It is also important to mention that the difference between the values of PEFs for Sweden showed in Figure 5 and the PEFs calculated for each technology showed in Table 15 corresponds with the transmission losses. This is the reason why the PEF for Sweden is higher than the PEF calculated for the different technologies, the reflection of these losses is that a larger usage of resources is needed to compensate them. As a reminder, this transmission losses were fixed to a 10% of the total electricity production and they reflect the difference in system boundaries that exist when considering the whole country and the generation facility.

Regarding the PEF calculated by the Partial Substitution Method, it is observed that it decreases linearly with time, because it was considered that the energy yield also grew linearly with time. The reason why it is the method with the least annual variations is due to the fact that it uses the same factor or yield for all generation technologies, unlike the other two methods that use very different conversion values depending on the technology. This makes the other two methods more sensitive to changes in the electricity production of a particular technology, especially if the conversion factor of that technology is very small: dividing the electricity generated by that factor will give a very large primary energy consumption.

This is one of the problems presented by the Partial Substitution Method; although it corrects the error of the Physical Energy Content Method of considering conventional thermal energy and electricity from renewables as equivalent energies, it presents the problem that the choice of the yield used for conversion into fossil equivalent is very important. This conversion or yield must not be constant over time, otherwise the same PEF would be obtained for each year, making it impossible to see annual changes. The Physical Energy Method does allow annual changes to be seen; the higher the percentage of renewables in the mix, the lower the PEF. However, the fact that it does not take energy quality into account conflicts with the most basic thermodynamic definitions.

As far as the Exergy Method is concerned, it can be seen that it reflects the annual changes of PEF and, moreover, as explained above, it is treating all energies as equivalent exergy, which from the thermodynamic point of view is correct. The main problem involved in using this method is that not only an energy efficiency for technology has to be defined, but also an exergy efficiency. It has already been discussed throughout this paper that it is difficult to reach consensus even within EU regulations, so adopting such a number of parameters in a common way is a huge challenge. While it is true that there may be technologies where consensus is greater, for example, taking the Betz Limit as the exergy efficiency of wind power, in other cases the decision is more complex. In the results it can be seen that Solar PV systems are the most suitable to get a technological improvement, as they have the highest PEF. When defining the exergy of fuels, two approaches can be taken; on the one hand, using the exergy associated with the heat of combustion, as has been done in this work, and on the other hand, using the chemical exergy of the fuel. Using the chemical exergy of the fuel would mean comparing the real process with the process of direct conversion of the fuel into electricity through a fuel cell (something currently only possible for hydrogen), which would overestimate the use of fossil fuels. The problem with calculating the exergy of fuels based on the quality of the heat transferred is that it must be calculated for each power plant or an average value must be extracted by statistical processes.

Finally, with regard to the PEF values for the different technologies shown in Table 15, it should be mentioned that the values remain constant because the performances and efficiencies of the Physical Energy Content and Exergy Method do not vary over time. Although it is true that in the Partial Substitution Method a linear variation was considered, given that it did not represent significant changes, it was decided to take it as constant for simplicity. It is necessary to comment on the high value of the PEF Exergy Method of the solar PV, given the low energy yield that has been considered. Again, it is also noted that the PEF of each technology calculated by the Partial Substitution Method is the same, since only one conversion is considered. The use of a single conversion efficiency, that of the equivalent fossil fuel power plant, leads to an overestimation in the case of geothermal energy. Applying an energy efficiency of around 40% to this technology implies saying that geothermal reservoirs are high or very high temperature (around 400ºC), when the reality is that these reservoirs are not very common and in the case of Sweden, low temperature geothermal energy is predominant.

6 Conclusions

This master thesis has sought from the outset to delve into the methodologies for calculating PEFs to try to find an answer to the complex question of whether there is one that more faithfully represents the exploitation of energy resources, and even more if the current way in which the different organizations and institutions apply them is correct.

Since one cannot and should not give a simple answer to something that is complex, it cannot be said that there is one calculation methodology that clearly stands out above the others. Similarly, it would be very bold to claim that the methodologies applied by the various agencies are completely wrong or flawed. Nevertheless, there are several general conclusions that can be drawn from this work. In the same line, it has been proved the difficulties of trying to assess the energy use with a single number due to the assumptions to be made such as efficiencies and system boundaries, among others that have not been discussed in this report.

First, while it is true that the Physical Energy Content Method reflects changes in the energy mix of a country, the way it treats heat and work as equivalent without considering that they are transfers of energy of different quality, goes against the most basic premises of thermodynamics.

With regard to the Partial Substitution Method, it has been shown that it does not contradict any basic premise when assessing the capacity of resources to be converted into electricity, but it has the problem that it is strongly dependent on the choice of an energy conversion efficiency that must be in line with the technological development under consideration.

The Exergy Method, although theoretically by definition it is the closest to a standardization or consensus process, since it compares the real process with the reversible process, and this a priori leaves no room for doubt; in practice it is necessary to define, in addition to the energy efficiencies of each technology, the exergy efficiencies. This can lead to overestimates or to consider as reference processes technologies not yet developed, such as fuel cells.

Not only the choice of conversion efficiencies affects the results, but also the systems boundaries. It is not the same to consider and analyze the generation facility that the whole country. When the system boundaries are extended and a complete country is considered, the losses in the transmission line must be reflected, otherwise it would be considered that the electricity generated at the terminals of the transformer of a generating station is the same that reaches the point of consumption.

Finally, one of the shortcomings found in regulations and even methodologies applied by companies and institutions is the lack of references to the values used, as well as the considerations and assumptions made when applying one methodology or another. The completion of this work allows it to be used as a guide for similar future works since the methodology followed has been explained in great detail, referencing and explaining all the values and equations used. These future works can be directed towards other country case studies, in order to further deepen in the strengths and weaknesses of the PEFs calculation methods.

6.1 Future work

Several aspects should be taken into account in future work. First, in the literature review of this master thesis, several energy indicators have been cited, including the EROI, which have not been analyzed in the case study. This indicator adds a very important perspective when taking energy efficiency or energy saving measures: the economic perspective. The initial costs of an energy system, together with the costs of operation, maintenance and decommissioning of an installation or, in general, of a generation technology, play a very important role. While it is true that an LCA perspective is usually included when obtaining energy yields for different generation technologies, it must be up-to-date and accurately reflect the state of the technology.

This project has pointed out the importance of the energy and exergy efficiencies data of the different generation technologies, but the study has been limited to taking these values from several references. Future work may focus on the calculation of these efficiencies and/or a deeper analysis of the situation of each technology in the current market.

Last but not least, a very relevant aspect when analyzing energy consumption and assessing the use of some generation technologies versus others is the issue of associated CO2 emissions. Future work can study whether there are different methodologies for calculating CO2 emissions as well as the influence they may have on primary energy consumption and the calculation of PEFs.

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Appendix A

The Equation (5) of this work represents the PEF calculated using the Partial Substitution Method and that is associated with a particular generation technology.

The conversion of a determined technology is the electricity that is produced by the technology divided by the primary energy that is used. This PE can be renewable energy or fossil.

$$\eta_{technology} = \frac{kWh_{elec}}{kWh_{PE}} \quad (1)$$

Similarly, the conversion of a standard fossil fuel plant is the electricity produced by that fossil fuel plant divided by the PE used. Now this PE is always fossil fuel so it can be named as kWh_{fossil}:

$$\eta_{fossil} = \frac{kWh_{elec}}{kWh_{fossil}} \quad (2)$$

The Partial Substitution Method calculates first, for a given generation technology, the amount of PE of fossil fuel that would be necessary to produce in a standard thermal power plant the same amount of electricity. If we produce 100 kWh of electricity with wind power, we would need to burn 250 kWh of fossil fuel in a thermal power plant of 40% of efficiency. Substituting the terms in the Equation (5) of the report we obtain the fossil fuel energy that is used to produce the unit of electricity.

$$PEF_{Partial\ Substitution\ Method}^{Technology} = \frac{\frac{\eta_{technology}}{\eta_{fossil}}}{\eta_{technology}} = \frac{\frac{\frac{kWh_{elec}}{kWh_{PE}}}{\frac{kWh_{elec}}{kWh_{fossil}}}}{\frac{kWh_{elec}}{kWh_{PE}}} = \frac{kWh_{fossil}}{kWh_{elec}} \quad (3)$$

Appendix B

For a better comprehension of how the EIA calculates fossil fuel equivalent, it is necessary to consult the Appendix E and Appendix A6 that can be found in EIA (2022).

In this study, Table 6 is directly extracted from the Appendix A6 considering the years 2015 to 2022.

In the Table E1a of the Appendix E in (EIA, 2022b) there is the noncombustible renewable primary energy consumption. Let's take a look to the values of 2010 for the Conventional Hydroelectric Power, where it can be seen that the Total Primary Energy is the sum of the Transformed into Electricity and the Adjustment for Fossil Fuel Equivalence:

Table 1B: Conventional hydroelectric power year of USA in 2010

Conventional Hydroelectric Power year 2010		
Transformed into Electricity (Btu)	Adjustment for Fossil Fuel Equivalence (Btu)	Total Primary Energy (Btu)
888	1651	2539

The term "Transformed into Electricity" (888 Btu) is obtained when multiplying the Electricity Net Generation in kWh (this value does not appear) by the constant 3,412 Btu/kWh. This constant appears in the Table A6 of the Appendix A in (EIA, 2022b) and it represents the heat content of electricity.

The term "Adjustment for Fossil Fuel Equivalence" (1651 Btu) is obtained as it is stated in "Note f" difference between the "Fossil-fuel equivalent value of electricity" and the "Captured energy consumed as electricity.

Moreover, in the same "Note f" the "Fossil fuel equivalent value of electricity" is equal to "Electricity Net Generation" in kWh multiplied by the "Total Fossil Fuel Heat Rate factors", this factor can be obtained from Table A6. For 2010 it has the value of 9.756 Btu/kWh. The "Captured energy consumed as electricity" is equal to "Electricity net generation" in kWh multiplied by the Heat Content of electricity which is 3.412 Btu/kWh. Substituting all these factors, it can be obtained the Total Primary Energy as a function of the Net Electricity Generation in kWh (E_{net}):

$$PE = Transformed\ into\ electricity + Adjustment\ for\ fossil\ fuel$$

$$PE = E_{net} \cdot 3.412 + (E_{net} \cdot 9.756 - E_{net} \cdot 3.412) \quad [Btu] \tag{4}$$

The value of the "Heat Content of Electricity" (3.412 Btu/kWh) is a fixed value by the EIA while the "Total Fossil Fuel Heat Rate factor" (9.756 Btu/kWh) depends on the year and it is the average between the total heat rates of Coal, Petroleum and Natural Gas, as it can be easily seen in Table A6 of the Appendix A in (EIA, 2022b)