Primary-to-Final Energy and Exergy Flows in the Portuguese Energy Sector
1960 to 2009

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Thesis to obtain the Master of Science Degree in Mechanical Engineering

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July 2013
Acknowledgements

To Prof.ª Dr.ª Tânia Sousa for providing me the opportunity to elaborate my thesis on a topic I am passionate about. Her support and guidance throughout this thesis, as well as her openness to fruitful discussions, made this journey an enjoyable one.

To Eng. André Serrenho, for his valuable knowledge and support. His expertise was proved fundamental to understand the workings of the IEA database and our discussions constituted a great learning opportunity.

To the team at the EDP Foundation, in particular Eng. Pires Barbosa, Eng. Luis Cruz and Eng. Eduardo Moura for their technical expertise and valuable insight on the history of energy production in Portugal. Also to the team at the Electricity Museum in Lisbon, in particular Raquel Eleutério, for providing the opportunity to undertake a 6-month internship, which helped me develop a better technical, historical and societal understanding of the evolution of energy supply in Portugal from 1920 to the present.

To Eng. Ana Pipio and Prof. Dr. José Santos-Victor, for their mentorship and support while I worked at the International Affairs team at Instituto Superior Técnico.

To Prof. Dr. Robert Schaeffer, for providing me with material on the topic of energy and exergy analysis of the Brazilian economy.

To Pascal Richard and Samvit Dutta for being great mentors inside and outside of Ingersoll Rand, and for giving me the chance to conclude this thesis while working for the company.

To Nuno Pereira for his support and for acting as my representative at IST while I was working abroad.

To my family and friends, in particular my grandfather Carlos Anjo, for the motivation he has given me to pursue engineering studies.

Last but definitely not least, to my parents, Alda and Carlos Silva, to whom I dedicate this thesis, for their undying support and love. Thank you for your patience during yet another chapter of my life, all which would not be possible without you. I hope I can continue to make you proud.
Abstract

Nowadays, it is difficult to imagine a society without electric energy. To face the growing population, scarcity of natural resources and increasing energy demand, countries are revising their energy sectors to ensure that the maximum viable efficiency is achieved when transforming primary energy into final energy. Portugal has not fallen behind, having developed new energy policies for a more efficient production and utilization of energy.

The concept of exergy is useful when applied to a national energy economy as a tool for energy planning, since it provides a better understanding of the quality of energy involved. In this thesis, the transformation of various energy carriers from their primary to final states is computed and analyzed from an energetic and exergetic perspective, namely for Portugal between 1960 and 2009. Data is obtained from the IEA 2011 database. Sankey and Grassman diagrams are drawn for 1960, 1990 and 2009, providing a visual representation of the energy and exergy flows.

Electricity plants and cogenerations plants are analyzed, establishing a link between the results obtained and the technological evolution in Portugal. Within electricity plants, combined cycle plants are found to have the highest average energy and exergy efficiency (55% and 53%, respectively). The cogeneration sector is found to have a lower overall efficiency than conventional power plants and renewable energy systems due to the low quality of heat. Biofuels and waste are identified as the primary resource having the lowest transformation efficiency.

A literature survey is carried out to provide an understanding of the energy and exergy analyses for steam turbine plants, diesel engine cogeneration plants and gas turbine cogeneration plants.

**Keywords:** Portuguese Energy Sector; Energy flow; Exergy flow; Energy efficiency; Exergy efficiency; Primary energy; Final energy.
Resumo

Hoje em dia, é difícil imaginar uma sociedade sem energia eléctrica. Para enfrentar o cresimento da população, escassez de recursos naturais e aumento de procura energética, vários países veem-se forçados a reavaliar o seu sector energético para assegurar que a máxima eficiência viável é alcançada quando se transforma energia primária em energia final. Portugal não fica para trás, tendo desenvolvido novas políticas energéticas para uma produção e utilização mais eficazes de energia.


Centrais eléctricas e centrais de cogeração são analisadas com base na literatura e relacionadas com os dados obtidos tendo em conta a evolução tecnológica no País. Dos vários tipos de centrais, as de ciclo combinado obtiveram maior eficiência energética e exergética (55% e 53%, respectivamente). No sector de cogeração verificou-se uma eficiência de transformação mais baixa comparada às centrais eléctricas devido à baixa qualidade exergética do calor. Biocombustíveis e resíduos foram identificados como o recurso primário com a eficiência de transformação mais baixa.

Através da literatura, análises energéticas e exergéticas são apresentadas para centrais eléctricas com turbinas a vapor, centrais de cogeração com motores de diesel e centrais de cogeração com turbinas a gás.

Palavras-chave: Sector Energético Português Fluxo energético; Fluxo exergético; Eficência energética; Eficiência exergética; Energia primária; Energia final.
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Symbols & Abbreviations

Greek letters

\( \eta \) Energy (first law) efficiency
\( \epsilon \) Exergy (second law) efficiency

Nomenclature

B Exergy
H Enthalpy
HHV Higher heating value
I Irreversibility, exergy consumption
IP Exergetic improvement Potential
ke Kinetic energy
LHV Lower heating value
m Mass
pe Potential energy
Q Heat transfer
q Exergy or quality factor
U Internal energy
S Entropy
T Temperature
W Shaft work

Indices

c cold
e electrical
f fuel
h hot

Units

ktoe Kilo-tonnes of oil equivalent
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CHAPTER I

Introduction

1.1. Thesis Disposition

Studying the efficiency of energy systems is important because it provides an opportunity to maximize useful output by consuming the least primary input possible. In a nutshell, energy efficiency allows us to calculate the ratio between input and output, thus quantifying the energy flows in a system. However, this measure can be rather misleading and confusing (Lior & Zhang, 2007; Herring, 2006).

Exergy, on the other hand, is a quantity which can be used to assess and improve the efficiencies of energy systems by providing more useful and meaningful information than energy provides (Wall, 1977). Exergy is, by definition, the maximum work producible from a system or flow of matter or energy relative to a reference environment. In other words, it is a measure of the potential of the usefulness or value of a system or flow. Additionally, exergy is a measure of the system’s potential to cause change, a consequence of not being in equilibrium relative to the reference environment. This makes exergy a tool to clearly identify efficiency improvements and reductions in thermodynamic losses.

When performing an exergy analysis on a system, we are ultimately evaluating the margin available between the current system performance and its ideal performance, and this allows us to have a better and more correct assessment of the system and its losses, as well as where and how to improve the efficiencies. Therefore, exergy has an important role to play in assessing efficiencies of energy systems and technologies (Vousough et al, 2011; Hammond, 2004; Dincer, 2000).

The benefits of using exergy as a measure when assessing efficiencies have been thoroughly discussed and published (Hepbasli, 2008; Hammond, 2004; Dincer, 2000; Hinderink, 1999). Moreover, the benefits of exergy are not restricted to assessing efficiencies and losses, but can also be applied in areas such as economics and environmental impact assessment. Exergoeconomics, e.g. economic methods based on exergy, have evolved and gathered the conditions to play a relevant role in energy policies, especially when addressing issues related to sustainable development and sustainability of energy use.

Exergy methods have been performed on all kinds of systems, including some national energy sectors. When entering this domain, it becomes all the more necessary to integrate the exergy analysis with economic and environmental factors. The relationship between exergy and
economics, in particular the trade-offs that normally occur between efficiency and costs, has been an important concern for decades and continues to be so. Therefore, decision and policy makers could also benefit from an appreciation of the exergy concept and its applications (Dincer, 2000).

There have been a number of studies undertaken to analyze primary energy utilization of several countries (Hepbasli, 2008). However, up to this date no energy studies have been carried out for Portugal. Therefore, the motivation behind this thesis is to provide an exergy assessment of the Portuguese Energy Sector and compare it to the currently used energy assessment. Furthermore, this work intends to shed some light on the evolution of exergy use in the Energy Sector from 1960 to 2009, as well as the potential future trends and scenarios in the years to come.

1.2. Objectives

The current work has set out to comply with the following objectives:

1. Provide an overview of thermodynamic concepts related to energy, exergy and efficiencies;
2. Present the benefits of using exergy indicators in the analysis of energy systems;
3. Provide a full understanding of the Portuguese Energy System and describe its evolution between 1960 and 2009;
4. Perform an exergy analysis of the Portuguese Energy Sector in 1960, 1990 and 2009 and carry out a comparative study with the energy analysis;
5. Identify the main losses in the Portuguese Energy System and provide solutions to increase the efficiency of the energy conversion sector;
CHAPTER II
Fundamental Concepts

2.1. First Law of Thermodynamics

The First Law of Thermodynamics – also known as the ‘conservation of energy’ – states that energy cannot be created nor destroyed in any normal physical or chemical process, but rather transformed from one form into another (Moran & Shapiro, 2004). This transformation can be translated into a variation of the energy of a closed system \( E \), which is usually formulated as being the amount of heat \( Q \) supplied to the system, minus the amount of work \( W \) performed by the system. For open systems, one must also take into account energy flows associated with mass flows. Other forms of energy are, for example, kinetic energy, chemical energy, potential energy, etc. We can define the energy of the system according to Equation (2.1), being the sum of all these forms of energy (Moran & Shapiro, 2004):

\[
\delta Q - \delta W = \delta E \tag{2.1}
\]

For cases where the kinetic and potential energy are either constant, or their variation is negligible when compared to variations in internal energy, the energy of the system can be simply defined as the internal energy of the system, according to Equation (2.2):

\[
\delta E = \delta U \tag{2.2}
\]

The internal energy of the system arises from the random motion of molecules in the system. This molecular motion is dependent on temperature and pressure. For an ideal gas, internal energy depends only on temperature, and therefore it is common to refer to internal energy as thermal energy (Dincer & Cengel, 2001).

2.2. Second Law of Thermodynamics

Although the First Law is used as a basis for many energy analyses, it has a number of limitations. While such energy analysis allows energy or heat losses to be estimated, it gives no information regarding the optimal conversion of energy (Patterson, 1996; Rosen & Bulucea, 2009).

It can easily be observed that, in a natural process, heat always flows to regions at a lower temperature, never to regions of higher temperature (unless external work is performed on the system). Taking into account that the First Law focuses only on the initial and final states of an evolving system, it doesn’t account for any factors that deal with the ‘spontaneity’ of systems. Therefore, the Second Law introduces a new variable which works as a key concept for the explanation of this phenomenon: entropy \( S \). Defined by Rudolph Clausius in 1865, entropy is a
thermodynamic property used to measure the energy which is not available for work in a process (Clausius, 1856). Devices such as engines or machines, and especially energy conversion devices, can only be driven by convertible energy. Therefore, it is possible to calculate a theoretical maximum efficiency when converting energy to work. Entropy accumulates in the system during a thermodynamic process, having then to be dissipated in the form of waste heat in order for the system to return to its initial conditions (Dincer & Rosen, 2012).

The Second Law states that the entropy of an adiabatic system always increases or remains constant:

\[ \Delta S \geq 0 \] (2.3)

This property allows us to use entropy as a measure of the tendency of a process. Relating to the example given above, entropy is what determines that thermal energy always flows spontaneously from high-temperature regions to low-temperature regions. Furthermore, in a reversible process, we can relate the variation in entropy to heat transfer according to the following expression, where \( T \) is the temperature of the system:

\[ T\delta S = \delta Q \] (2.4)

### 2.3. Exergy: Formulations

The Second Law provides the basis for the definition of parameters that facilitate the assessment of the maximum amount of work achievable in a given system with different energy sources. This introduces us to the concept of exergy.

The term exergy was used for the first time by Rant in 1956, and refers to the Greek words \textit{ex} (external) and \textit{ergos} (work) (Vosough et al, 2011). Exergy can be defined as the maximum amount of work that can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment (Utlu & Hepbasli, 2007). It is consumed and destroyed due to the irreversibilities that exist in any real process, and therefore it is not subject to the same conservation law as energy.

The exergy content of a substance (\( B \)) can conveniently be expressed as the sum of its kinetic (\( B_{KE} \)), and potential energy (\( B_{PE} \)), its physical exergy (i.e. related to temperature and pressure, \( B_{ph} \)) and its chemical exergy (\( B_0 \)):

\[ B = B_{KE} + B_{PE} + B_{ph} + B_0 \] (2.5)

This form is used by Kotas (Kotas, 1985) following the work of Szargut (Szargut, 1965). The physical and chemical exergy can be evaluated by considering a hypothetical reversible device that extracts work as the substance is returned to ambient conditions and reference substances in three stages.
In the first stage, physical exergy is evaluated as pressure \( P \) and temperature \( T \) return to ambient conditions \( (P_0 \text{ and } T_0) \). In the second and third stages, the chemical exergy is evaluated as the substances form reference compounds at standard conditions through isothermal reactions.

In short, exergy can be defined for a closed system according to Equations 2.5 and 2.6, for a steady flow:

\[
B = V^2/2 + gZ + (U - U_0) + p_0(V - V_0) - T_0(S - S_0) \quad (2.5)
\]

\[
B = V^2/2 + gZ + p_0(V - V_0) - T_0(S - S_0) + Q + W \quad (2.6)
\]

The irreversibility of a process, \( I \), is defined as the difference between the desired exergy outputs \((B_{\text{out}})\) and the required exergy inputs to it \((B_{\text{in}})\) (Kotas, 1985). The energy lost through this irreversibility takes the form of heat transferred to the environment (which is at a temperature \( T_0 \)). This can also be referred to as the Guoy-Stodola relationship:

\[
I = \sum B_{\text{in}} - \sum B_{\text{out}} = T_0(\sum S_{\text{out}} - \sum S_{\text{in}}) = T_0S_{\text{generated}} \quad (2.8)
\]

Finally, combining the first and second laws of thermodynamics, we obtain a relation between entropy \( S \) and internal energy \( U \) (Dincer & Cengel, 2001):

\[
dU = TdS - PdV \quad (2.9)
\]

### 2.3.1. Importance of Exergy

The importance of exergy was highlighted by Dincer and can be summarized by the following key points (Dincer, 2000):

- When the energy loses its quality, it results in the exergy being destroyed. The exergy is the part of the energy which is useful in the society and therefore has an economic value, making it a primary tool in best addressing the impact of energy resource utilization on the environment;

- It uses both the conservation of mass and conservation of energy principles together with the Second Law, providing an effective method for the design and analysis of energy systems;

- It enables the locations, types, and true magnitudes of wastes and losses to be determined, and is therefore a more suitable technique for furthering the goal of more efficient energy-resource use. Additionally, it reveals whether or not and by how much it is possible to design more efficient systems just by reducing the inefficiencies in existing systems;

- It is a key component in obtaining sustainable development, and therefore pays a crucial role in energy policy-making activities.
2.3.2. Quality factors of energy forms

Conceptually, exergy can be defined as the fraction of the energy that can be converted into useful work as a system proceeds to its final state in equilibrium with the environment (Schaeffer et al., 1992). Considering that, in general, the work content is a more valuable form of energy, this makes exergy a prime quantity for setting the cost of energy. Therefore, it is also useful to be able to relate energy with exergy. Before doing so, however, the relation between enthalpy \( H \) and internal energy \( U \) is explained.

Enthalpy is a measure of the total energy of a thermodynamic system, including the internal energy (Equation 2.2), i.e., the energy required to create a system, and the amount of energy required to make room for it by displacing its environment and establishing its volume and pressure (Moran et al., 2004):

\[
H = U + pV
\]  

where \( H \) is the enthalpy of the system, \( U \) is the internal energy, \( p \) is the pressure and \( V \) is the volume. Under the conditions of constant pressure and temperature, however, enthalpy becomes equivalent to internal energy by applying a Legendre transformation in the thermodynamics convention. For this reason, energy statistics calculate primary and final energy based on enthalpy rather than internal energy.

Energy cannot be thought of as a singular property consisting of enthalpy (heat), but rather as a dual property, consisting of both an enthalpy property \( H \) and a quality property \( q \), where \( q \) is the measure of the exergy – or work – contained in \( H \) (Schaeffer et al., 1992). Therefore, energy and exergy contents are directly related through a quality factor. In other words, the exergy content of an energy resource can be obtaining by multiplying its energy content by a quality factor that applies to the energy form in question (Equation 2.11).

\[
q = \frac{\text{Amount of exergy}}{\text{Amount of energy}}
\]  

Chemical energy is a much-used basis for primary energy conversion, often through combustion. The temperature levels that can be reached in such combustion processes determine the amount of the chemical exergy that in practice can be converted into thermal exergy. In other words, in combustion processes there is always a certain amount of unavoidable exergy loss due to the limited degree of achievable temperature levels. The exergetic efficiency \( \varepsilon_{\text{combustion}} \) of an ideal combustion process is determined by the second law of thermodynamics, and depends on the absolute temperature levels of combustion \( T_{\text{combustion}} \) and of the environment \( T_0 \) (see Equation. 2.12) (Muller et al., 2011).
\[ \varepsilon_{\text{combustion}} = \frac{B_{\text{heat}}}{B_{\text{fuel}}} = (1 - T_0 \cdot T_{\text{combustion}}^{-1}) \] (2.12)

The exergy content of heat depends on the temperature of the energy carrier and the temperature level of applicable ambient (dead state). Some energy forms and their respective quality factors are found in Table 2.1 (Wall, 1977).

<table>
<thead>
<tr>
<th>Energy form</th>
<th>Quality factor, q</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical energy</td>
<td>1.0</td>
</tr>
<tr>
<td>Electrical energy</td>
<td>1.0</td>
</tr>
<tr>
<td>Chemical energy</td>
<td>~1.0</td>
</tr>
<tr>
<td>Nuclear energy</td>
<td>0.95</td>
</tr>
<tr>
<td>Sunlight</td>
<td>0.93</td>
</tr>
<tr>
<td>Hot steam (600ºC)</td>
<td>0.6</td>
</tr>
<tr>
<td>District heat (90ºC)</td>
<td>0.2 – 0.3</td>
</tr>
<tr>
<td>Heat at room temperature (20ºC)</td>
<td>0 – 0.2</td>
</tr>
</tbody>
</table>

Table 2.1 – The quality factor for some common energy forms (Wall, 1977)

According to Table 2.1, mechanical and electrical have a quality factor equal to 1, meaning that their energy content is equal to the exergy content. That's why these forms are usually referred to as ‘high-quality’ forms of energy (i.e., no entropy change is involved). The chemical energy is approximately 1 and depends on the chemical energy carrier, as we will discuss in Section 2.1.3.3.

The same principle can be applied to materials, which is proven very useful when analyzing the economy of a country and relating it to energy and mass flows (e.g. resource accounting). To obtain the equivalent of a material in exergy units, one can simply multiply its quantity or mass-flow rate by the appropriate exergy factor for the material. The unit of this factor could be J/m³ or J/kg. However, it is important to note that exergy can only represent one extensive physical quality of goods, thus not implying anything about other physical or biological qualities (e.g. conductivity, nutritive value, toxicity, etc.) (Wall et al, 1994). However, when we calculate the exergy equivalent of a material, we are mainly motivated by the quality of interest of the material for a specific application. For example, if two materials are being used as electric conductors (specific application), then a material with poor electric conductivity has a larger exergy loss than a material with good electric conductivity. This implies that when performing an exergy conversion of a given system, it is important to define the scope of the application, as well as the reference state.
2.3.3. Quality factors of energy carriers

According to ISO 13600, an energy carrier is a substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes. It differs from the concept of energy form in the sense that an energy carrier ‘transports’ energy and an energy form is a ‘type’ of energy. For example, gasoline is an energy carrier transporting chemical energy. Even we, as human beings, are energy carriers, transporting energy in all sorts of forms.

Analogously, quality factors can also be used to relate the energy and exergy contents of a given energy carrier. For fuels, the quality factor can be defined according to Equation 2.13 where $B_{fuel}$ is the exergy content of the fuel, defined by Equation 2.14 (Van Gool, 1987). In general, the energy content is equal to the higher heating value of the fuel in question (Schaeffer et al, 1992).

$$q = \frac{\Delta B_{fuel}}{|-\Delta H_{fuel}|}$$

(2.13)

$$\Delta B_{fuel} = -\Delta H_{fuel} + T_0 \Delta S$$

(2.14)

By combining Equations 2.13 and 2.14, we obtain:

$$q = 1 + \frac{T_0 \Delta S}{(-\Delta H_{fuel})}$$

(2.15)

Equation 2.15 shows that the quality factor can sometimes exceed 1. This happens due to the definition of the system boundaries and final states, depending upon whether the entropy change for the chemical reaction is zero, negative or positive in algebraic sign. In fact, in most chemical fuels, $\Delta S$ can be larger than 1 J/(K.mol) (a consequence of the increase of number of gas molecules in the processes).

Table 2.2 compiles the quality factors for energy carriers used in this study.

<table>
<thead>
<tr>
<th>Energy carrier</th>
<th>$q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal and coal products</td>
<td>1,06</td>
</tr>
<tr>
<td>Oil and oil products</td>
<td>1,06</td>
</tr>
<tr>
<td>Natural gas</td>
<td>1,04</td>
</tr>
<tr>
<td>Combustible renewables</td>
<td>1,11</td>
</tr>
<tr>
<td>Electricity</td>
<td>1</td>
</tr>
<tr>
<td>Process Heat (hot steam, 600ºC)</td>
<td>0,6</td>
</tr>
</tbody>
</table>

Table 2.2 – Quality factors for some energy carriers (Sources: Chen et al. 2006; Ertesvåg et al. 2000; Wall et al. 1994.)
2.3.4. Reference environment

The outdoor air temperature can be sufficient as a reference environment for the exergy calculation. (Vosough et al, 2011). The average air temperature in continental Portugal between 1960 and 2009 is 15 ºC (source: IM/MCTES). Serrenho et al distinguished two different reference temperatures for each year to compute second-law efficiencies: (a) the average temperature for the winter months in Lisbon for space heating uses; (b) the yearly average air temperature for Lisbon for the remaining heat uses (Serrenho et al, 2013). Lisbon’s temperatures were considered as reference temperatures due to Lisbon being the biggest city in Portugal (comprising a significant share of Portuguese industries) and the fact that thermal amplitudes within the Portuguese territory are not that significant. For this study, only the average global temperature is considered as a reference due to the fact that we are more focused on obtaining results for the primary to final energy than the final to useful energy as in Serrenho et al.

2.4. Energy and Exergy Efficiencies

Energy efficiency has become a broadly used term at many levels, ranging from industries, political agendas, to even social media. Using energy more efficiently is also considered to be the key to reducing carbon dioxide emissions, thus mitigating the problem of global warming. However, the definition of energy efficiency is as vague as its interpretation. Therefore many times it is not clear what one means when referring to the “energy efficiency” of a system or process. Moreover, authors often use unsuitable definitions that lead to inadequate interpretations. This presses the urge to standardize the definition of energy efficiency and understand which factors are influenced by it (Patterson, 1996).

In order to understand what efficiency implies in an energetic context, many studies have been carried out. In 1996, Patterson wrote that “energy efficiency is a generic term, and there is no one unequivocal quantitative measure of ‘energy efficiency’”. Ten years later, Lior attempted to clarify the definitions and use of energy and exergy-based performance criteria aiming at the advancement of international standardization of these vital concepts (Lior, 2006). These results, as well as others, will be further discussed.

2.4.1. Energy Efficiency - Definition

In general, energy efficiency can be seen as a comparison, where the objective is to use less energy to produce the same amount of services or useful output. In short, it can be translated into the expression:

$$\eta = \frac{\text{Useful output of a process}}{\text{Energy input in a process}}$$  \hspace{1cm} (2.16)
2.4.2. Exergy Efficiency

This subchapter sets out to define exergy efficiencies of steady-state processes in open systems. In this case, the system boundaries include all irreversibilities associated with the process. According to the literature, three different definitions for exergy efficiency can be defined:

- Simple efficiency
- Rational efficiency, Kotas (1995)
- Efficiency with transiting exergy, Sorin and Le Goff (1994)

2.4.2.1. Simple efficiency

The formulation of the simple exergy efficiency is based on the exergy balance (where $\dot{E}_x$ is the exergy flow and $\dot{l}$ is the irreversibility):

$$\dot{B}_{in} = \dot{B}_{out} + \dot{l} \quad (2.17)$$

The ratio of the total outgoing exergy flow to the total incoming exergy flow can be defined as:

$$\varepsilon = \frac{\dot{B}_{out}}{\dot{B}_{in}} \quad (2.18)$$

Although this definition can be applied to all process plants and units, it only gives a good impression of the thermodynamic perfection of the system when all the components of the incoming exergy flow are transformed to other components (e.g., power stations). When this is not the case, the untransformed components give a false impression of the performance of the process plant or unit. The higher the quantity of untransformed components, the lower the sensitivity of the simple efficiency to changes in the process plants or unit (Lior, 2006).

2.4.2.2. Rational efficiency

The rational efficiency is a form of exergy efficiency defined by Kotas in 1995 and allows us to rationalize the outputs of the system (including by-products) and calculate the efficiency as the ratio of the desired exergy output to the exergy used:

$$\varepsilon_r = \frac{\dot{B}_{desired\ output}}{\dot{B}_{used}} \quad (2.19)$$

The factor $E_x\_{desired\ output}$ is the sum of all exergy transfers from the system, which includes the desired output plus any by-product produced by the system. The desired output is determined by
examination of the function of the system. The factor $\dot{B}_{used}$ represents the exergy input required for the process to take place.

It is a necessary condition for $\dot{B}_{desired\, output}$ and $\dot{B}_{used}$ to cover all the exergy transfers terms in the exergy balances, which means that the control surface should also enclose all the irreversibilities related to the process under consideration (thus excluding the possibility of external irreversibilities). This allows us to write the exergy balance as:

$$\dot{B}_{used} = \dot{B}_{desired\, input} + I$$  \hspace{1cm} (2.20)

Using Equations (2.19) and (2.20), an alternative form for the rational efficiency can be expressed as:

$$\varepsilon_r = 1 - \frac{I}{\dot{B}_{used}}$$  \hspace{1cm} (2.21)

The rational efficiency can be applied to virtual systems, the only exception being purely dissipative systems (because no desired product can be defined in this case).

### 2.4.2.3. Efficiency with transiting exergy

In 1994, Sorin and Le Goff developed a new form of exergy efficiency called efficiency with transiting exergy. It is an improvement of the simple efficiency because it subtracts the untransformed components from the incoming and outgoing streams. The efficiency with transiting exergy can be defined as follows, where $\dot{B}_{tr}$ is the transiting exergy:

$$\varepsilon_e = \frac{\dot{B}_{out} - \dot{B}_{tr}}{\dot{B}_{in} - \dot{B}_{tr}}$$  \hspace{1cm} (2.22)

As explained by Sorin et al (1994), “the transiting exergy can be considered as the part of the exergy which traverses a system without taking any part in the mechanical, thermal, or chemical changes which take place in the system. To some extent, the transiting exergy is analogous to an inert species traversing a chemical reactor without being involved in the chemical rearrangements taking place in the reactor (in which the reactor is isothermal and isobaric). The amount of transiting exergy does not affect the thermodynamic efficiency of the process and it should be subtracted from the incoming and outgoing exergy flows before the efficiency is computed”.

Table 2.3 summarizes the three types of exergy efficiencies.
The definition used in this study will be the **simple efficiency** as it is considered the most appropriate by the author given its limitations and the scope of this work, i.e., it is assumed that all the components of the incoming exergy flow are transformed into other components.

### 2.4.3. Exergy efficiency versus energy efficiency

Although the energy analysis method, based on the First Law, is most commonly used when obtaining the efficiency of a given process or system, it has lately become popular to consider a complementary approach: exergy analysis, which combines both the First Law and Second Law (Hammond, 2004).

It’s important to understand the difference between energy and exergy efficiencies in order to provide a good analysis of a given system or process. In broad terms, the energy efficiency refers to the quantity of energy used to achieve a given objective, whereas the exergy efficiency takes also into account the quality of this energy.

Considering a non-steady flow process in a system during a finite time interval, the energy and exergy balances can be written according to Equations 2.23 and 2.24 (Utlu *et al*, 2007):

\[
\text{Energy input} - \text{Energy output} = \text{Energy accumulation} \tag{2.23}
\]

\[
\text{Energy input} - \text{Energy output} - \text{Internal Irreversibilities} = \text{Exergy accumulation} \tag{2.24}
\]

In the Equations above, the product term can refer to shaft work or electricity generated, heat transfer, combined heat and work, etc. Losses include things such as waste heat slack gases vented to the surroundings without use. Consequently, energy (first law) and exergy (second law) efficiencies can be respectively defined as:

\[
\eta = \left(\frac{\text{Energy in products}}{\text{Total energy input}}\right) \times 100 \tag{2.25}
\]

\[
\varepsilon = \left(\frac{\text{Exergy in products}}{\text{Total exergy input}}\right) \times 100 \tag{2.26}
\]
Exergy methods identify accurately the margin available to design more efficient energy systems by reducing inefficiencies. In other words, the exergy efficiency, $\varepsilon$, provides a more accurate understanding performance than energy efficiency, $\eta$. When the latter is computed, the same weight is assigned to energy whether it becomes shaft work or a stream of low-temperature fluid (Ulu et al, 2007). Additionally, energy efficiency focuses on reducing losses to improve efficiency, whereas exergy efficiency weighs energy flows taking each into account in terms of availability.

For example, in a study conducted by Rosen (Rosen et al, 2009) it was shown that heating systems using gas furnaces and electric resistance dashboards are efficient based on energy (85-100%), but inefficient based on exergy (7-8%). In addition, the article explains that exergy efficiencies are low because the energy delivered via warm air has little exergy relative to the exergy input to the process. Almost all exergy losses are associated with internal exergy destructions for actual devices, meaning that little exergy escapes to the environment via thermal or waste emissions.

As we will study further, the exergy analysis is also very useful when analyzing the energy economy of a country, as it provides more clarifying information regarding the quality of energy that is generated and lost throughout the transformation processes. In a study conducted by Schaeffer for Brazil from 1989 to 1990, for example, it was shown that the overall energy efficiency with which the economy used its energy assets in 1987 was 32.4%, whereas the exergy efficiency was lower – 22.8%. The main conclusion drawn by using the exergy analysis was that there was an inadequate match between the quality of energy supplied to end users and the quality required by final consumers to perform energy services, meaning also that there was room for improvement in the nation’s energy conversion and utilization systems (Schaeffer et al, 1992).

### 2.4.4. Efficiencies of selected processes

#### 2.4.4.1. Heating

Product heat, $Q$, can be generated at a constant temperature, $T$, from mainly two types of heating processes: electric (electrical energy, $e$) and fossil fuel (mass fuel, $fuel$). The energy and exergy efficiencies for electric and fuel heating can be described, respectively, as (Acar, 2008):

\[
\eta_e = \frac{Q}{W} \tag{2.27}
\]

\[
\varepsilon_e = \frac{\dot{Q}}{\dot{B}} = \left( 1 - \frac{T_o}{T} \right) \times \frac{Q}{W} = \eta_e \times \left( 1 - \frac{T_o}{T} \right) \tag{2.28}
\]

\[
\eta_{fuel} = \frac{Q}{H_{fuel}} \tag{2.29}
\]

\[
\varepsilon_{fuel} = \frac{\dot{B}}{\dot{B}_{fuel}} \tag{2.30}
\]
When the exergy balance can be reduced to the chemical exergy, Equation (2.30) becomes Equation (2.31):

$$\varepsilon_{fuel} = \left(1 - \frac{T_v}{T_f}\right) * \frac{q}{(q*H_f)} = \frac{\eta}{q} * \left(1 - \frac{T_v}{T_f}\right)$$  \hspace{1cm} (2.31)

It can be noted that when the quality factor, \(q\), equals 1, \(\varepsilon_{fuel} = \varepsilon_e\).

There are some cases when heat is not directly used, e.g. for space and water heating processes. However, because these cases are more relevant for a final-to-useful analysis, they will not be covered in this thesis. Furthermore, it is worth mentioning that in these cases it is rather the convectional heat transfer which is used, and therefore the efficiencies should weigh in this difference (Acar, 2008).

### 2.4.4.2. Electricity generation

The energy and exergy efficiencies for generating electricity from fossil fuels are represented by Equations (2.32) and (2.33), respectively (Acar, 2008):

Energy efficiency:

$$\eta = \frac{W}{m_{fuel} * H_{fuel}}$$ \hspace{1cm} (2.32)

Exergy efficiency:

$$\varepsilon = \frac{B_w}{B_{fuel}} = \frac{W}{q * m_{fuel} * H_{fuel}} = \frac{\eta}{q}$$ \hspace{1cm} (2.33)

As seen in Table 2.2, for most of the fuels used in electricity generation, the quality factor is approximately 1. Therefore, it is expected that the energy and exergy efficiencies for electricity generation through fossil fuels should quantitatively similar. However, for hydroelectricity and wind power plants, it is assumed that exergy and energy values are equivalent to potential and kinetic energies, respectively (Acar 2008). Therefore, the efficiencies can be written according to Equations (2.34) and (2.35):

Energy efficiency for hydro and wind:

$$\eta_{hydro} = \varepsilon_{hydro} = \frac{W}{pe}$$ \hspace{1cm} (2.34)

$$\eta_{wind} = \varepsilon_{wind} = \frac{W}{ke}$$ \hspace{1cm} (2.35)
The efficiencies have been summarized in Table 2.4:

<table>
<thead>
<tr>
<th>Process</th>
<th>$\eta$</th>
<th>$\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>$\eta_e = \frac{W}{H_f}$</td>
<td>$\varepsilon_e = \eta \left( 1 - \frac{T_o}{T} \right)$</td>
</tr>
<tr>
<td></td>
<td>$\eta_f = \frac{Q}{m_f \cdot H_f}$</td>
<td>$\varepsilon_f = \frac{\eta}{q} \left( 1 - \frac{T_o}{T} \right)$</td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>generation</td>
<td>Fuel $\eta_f = \frac{W}{H_f}$</td>
<td>$\varepsilon_f = \frac{\eta}{Q}$</td>
</tr>
<tr>
<td>Wind power</td>
<td>$\eta_{wind} = \frac{W}{ke}$</td>
<td>$\varepsilon_{wind} = \frac{W}{ke}$</td>
</tr>
<tr>
<td>Hydroelectricity</td>
<td>$\eta_{hydro} = \frac{W}{pe}$</td>
<td>$\varepsilon_{hydro} = \frac{W}{pe}$</td>
</tr>
</tbody>
</table>

Table 2.4 – Energy and exergy efficiencies of selected processes (Acar, 2008)
CHAPTER III
Characterizing the Portuguese Energy Sector

3.1. Preliminary notions

3.1.1. Primary versus Final energy

When analyzing the energy balance of a country, is it important to define the three different stages of energy. The definitions undertaken in this study were suggested by Benichou in his thesis on Future Energy Supply (Benichou, 2011):

- **Primary energy**: describes energy resources naturally available (i.e. available in their primary state) such as fossil energies (Coal, Oil, and Gas), wood, uranium, wind or solar energy;
- **Final energy**: describes the energy as it is delivered to the user, then further measured and billed at the delivery point (gasoline for car, household electricity, city gas, etc.);
- **Useful energy**: is a more conceptual approach compared to the previous terms. It embodies the actual service provided by the use of a given final energy. Some examples of useful energy are heat, mobility and work. Given its final utilization, some authors also refer to useful energy as “service” (Praz, 2012).

The transition between energy stages is defined by an efficiency that relates the total energy input to the energy output considered useful taking into account its finality. For example, the transition from primary energy to final energy is related to the transformation efficiency (i.e., how well the sector can transform the physical energy in coal into heat or electricity), whereas the final-to-useful transition is related to the conversion efficiency of the devices used to transform energy in its final form (i.e., electricity, heat...) into a concrete service (mobility, lighting...).

The three energy forms considered in this study and the efficiencies marking the transitions between them are shown schematically in Figure 3.1.

![Figure 3.1: The evolution model from primary energy to useful energy.](image-url)
3.1.2. IEA Energy Database

In order to be able to calculate sectorial efficiencies, national energy statistics must be provided. This work uses the IEA database *World Energy Balances 2011*, as it is referred to by many authors as the database with a secure and transparent methodology, as well as detailed statistics (Praz, 2012). This database comprises a great amount of statistics regarding energy production, transformation and consumption worldwide from 1960 to 2009. In order to use the data provided by the IEA statistics, it is important to understand how the database is organized and what is the methodology and conventions used by the organization.

The construction of an energy balance implies the adoption of conventions for primary energy from several sources, such as nuclear, geothermal, solar, hydro, wind, etc. The IEA makes two assumptions that are described below:

- The **primary energy form** is the first energy form downstream in the production process for which multiple energy uses are practical. The IEA assumes as primary energy forms:
  - Heat for nuclear, geothermal and solar thermal;
  - Electricity for hydro, wind, tide/wave/ocean and solar photovoltaic.

- When calculating the primary energy equivalent of the energy sources described above, the IEA adopts the **physical energy content method**\(^1\). This method uses the physical energy content of the primary energy. For example, in the case of nuclear electricity production, the primary energy equivalent is the heat generated in the reactors. Nevertheless, because the amount of heat in these situations is not always known, the IEA estimates the primary energy equivalent from the electricity generation by assuming an efficiency of 33%, which is the average of nuclear power plants in Europe (IEA, 2011). In the case of hydro and solar PV, being electricity the primary energy form assumed, the primary energy equivalent is the physical energy content of the electricity generated in the plant, which amounts to assuming an efficiency of 100%. Regarding geothermal, the primary energy equivalent is calculated by assuming 10% efficiency for geothermal electricity and 50% for geothermal heat.

---

\(^1\) Initially, the IEA used the ‘partial substitution method’, which assumes that the primary energy equivalent of the energy sources of electricity generation represent the amount of energy that would be necessary to generate an identical amount of electricity in conventional thermal power plants, using their average generating efficiency. This method fell out of use due to its many shortcomings, including the difficulty of choosing an appropriate generating efficiency and the fact that the method is not relevant for countries with a high share of hydro electricity (IEA, 2011).
3.1.2.2. Conventions and nomenclature

The IEA uses specific terms and conventions for characterizing the energy balance. For the sake of creating a common base, the main definitions used in the IEA and which will also be used in this study go as follows:

- **Product**: any type of energy under a given form. Example: coal, oil, natural gas or electricity;
- **Flow**: units through which the energy can pass. Some examples of what can be characterized as a flow include power plants, refineries, extraction units and residential buildings. Types of flows will be further described in Section 3.2.1.

The Professional Browser © by Beyond 20/20 Inc. was the software used to navigate the IEA database. A partial screenshot of the database is shown in Figure 3.2 and provides its main features. The software allows the alternation of the study variables such as the country, unit (TJ or ktoe) and year. In addition it is possible to change the display of the table according to our convenience.

As shown in Figure 3.2, each column of the database corresponds to a product whereas the lines correspond to flows. Each white cell therefore represents the interaction between a given flow and product for a given year and country or region. It should be noted that some values appear as negative. According to the IEA’s convention, a negative value in the transformation sector means that the product is consumed by the flow, whereas a positive value means that the product is actually produced by the flow. For example, for Portugal in 2009, the oil refineries consumed approximately 465 TJ in crude, NGL and feedstocks, whereas they produced approximately 459 TJ in oil products (IEA Energy Balances, 2011).

The IEA database comprises a very detailed and robust tree of flows and products. The flows are structured in a way that matches most of the energy balances of countries, including the Portuguese energy balance (*Balanço Energético Nacional*, BEN). An exhaustive study has been performed on the BEN by A. Ramos (Ramos, 2011). Similarly to the BEN, the IEA structure can be presented according to the scheme in Table 3.1.
As mentioned in the Thesis Disposition, the study will cover three distinct stages: the primary energy products as a starting point and ending with their distribution as energy products across the different end-use sectors. This study aims to cover the energy sector that is the sector which comprises the flows that transform primary energy into final energy available to society. This sector can also be referred to as utility sector.

As seen in the previous subsection, the IEA database covers the whole energy balance, defining the energy sector per se. To perform an energy or exergy analysis, however, it is necessary to describe the system, i.e., the energy system per se.

### Figure 3.2: Screenshot of the IEA World Energy Balances 2011 database using Professional Edition

Browse © by Beyond 2020 Inc.
Table 3.1: Flows considered in the IEA database (IEA, 2011)

Although the Energy Industry Own Use and Distribution Losses flows appear integrated in the Transformation Processes category, the IEA treats these flows separately in the extended energy balance. Here, for simplification purposes, they are included in the transformation processes and treated as negative flows (i.e., they are subtracted from the energy available for final consumption).

Vide footnote 2.
Following the IEA nomenclature as described in Table 3.1, our study will focus on the Supply and Transformation Processes categories. Distribution losses and energy industry-use data are included in the analysis of the transformation sector.

The categories considered for primary energy are: coal and coal products, oil and oil products, natural gas, combustible renewables (also referred to as biofuel and waste) and electricity (including renewable resources, such as solar energy and wind energy). The categories considered for final energy include electricity, CHP heat and fuels used for final consumption. The transition from primary to final base is related to energy and exergy transformation efficiencies, $\eta$ and $\varepsilon$ respectively.

In Section 3.2, the energy sector will be further described.

### 3.1.5. Sankey and Grassmann diagrams

Sankey diagrams are a specific type of flow diagram often used to visualize in an intuitive manner the energy accounts at a regional or national level. They are named after Irish Captain Mathew Sankey, who used this type of diagram in 1889 in a publication on the energy efficiency of a steam engine. However, the use of Sankey-type diagrams mount all the way back to 1869, when Charles Minard created a map of Napoleon's Russian Campaign of 1812 (Schmidt, 2008).

In a Sankey diagram, the widths of the arrows are shown proportionally to the flow quantity. The most common flow quantities are energy, material or cost transfers. They are helpful in locating dominant contributions to an overall flow. In the case of non-conserved quantities, such as exergy, Sankey diagrams can also be useful to locate where the highest losses occur in a system.

An early example of a Sankey diagram mapping the scale of energy use is in the *Pathways to end uses* mapping of U.S. energy flow (Summers, 1971). Since then the use of Sankey Diagrams has been employed by many applications, including a global greenhouse gas emissions flow diagram (Baumert et al, 2005), global exergy flow diagrams (Cullen et al, 2010) and energy flow diagrams for China (Ma et al, 2012).

A Grassmann diagram is a specific application of the Sankey diagram to an exergy flow, and therefore and also be called an exergy-flow diagram. Little is known about the origin of the Grassmann diagram, and therefore it is common to classify exergy-flow diagrams as Sankey diagrams. In this work, in order to differentiate between energy and exergy flows, the energy flow diagrams are called Sankey diagrams, and the exergy flow diagrams are classified as Grassmann diagrams. Figure 3.3 shows a generic Grassman diagram.
3.2. Description of the energy sector

In this section we will address the energy sector using a system approach. According to Charles West Churchman, a system can be defined as a whole of subsystems interacting with each other to achieve a set of goals (Churchman, 1984). Later, Kotas described a system by focusing on thermodynamic laws and technical aspects related to energy flows, transformation and efficiencies (Kotas, 1995).

In order to describe our ongoing system, the following elements will be considered:

- **Boundary**: trace the frontiers of the system in order to further describe incoming and outgoing flows;
- **Actors or sub-systems**: systems acting within the overall system, in this case the Portuguese energy sector;
- **Resources**: means that the system has its disposal to achieve its goal. The resources exist within the system;
- **Environment**: surroundings of the system which the latter can have an impact or influence on;
- **Goal**: what the system components all work towards achieving.

The goal of the energy sector can be defined as the task to transform and allocate energy from natural resources to our society, matching the needs (Praz, 2012). In other words, the primary energy resources are transformed into more convenient forms of energy in an efficient and sustainable manner.
The boundary of the system is in this case the energy sector of a country, namely Portugal.

The environment can be defined by two main elements, society and nature (Praz, 2012). In case of the first, the goal of the energy sector is to provide energy in its final form to society, which in turn has become highly dependent on it. As for nature, awareness has been raised regarding the negative impact that activities related to the energy sector have on it. Climate change, pollution and greenhouse gas emissions are some examples that the system can have on its environment.

It should be furthermore noted that the definition of ‘environment’ in this subsection is in no way related to the concept of ‘reference environment’ which has been mentioned previously in Chapter I and will be further mentioned when we perform our exergetic analysis on the energy sector. In the case of the energy analysis, the environment is a concept defined in order to provide a comprehensive analysis of the system we are studying. In the case of the exergy analysis, the reference environment is needed to be able to calculate the deviation of the system from its system of equilibrium.

### 3.2.1. Actors and resources of the energy sector

Now that the goal of the energy sector is known from the previous section, we move forth to identify the main actors and resources in the system.

When examining the flows displayed in the IEA database (Table 3.1), it is possible to identify three main types:

- **Extraction flows**: the first units in the overall energy sector chain that consist in all the primary energy extraction units;
- **Transformation flows**: consisting in the transformation units for the energy (for example, petroleum refineries, power plants…)
- **Energy transportation flows**: i.e. pipelines and electricity grid.

Apart from these operating flows, the energy sector system also includes an influential actor described in Praz’s work as politicians, economic world and other stakeholders (Praz, 2012). This actor comprises oil and gas companies, energy companies, research centers, banks, investment funds and governmental bodies. Apart from allocating resources to the energy sector (investments, technologies, primary resources), all these stakeholders can have a significant impact on the system. Local legislation and economic factors can drive financial investment towards a certain type of primary energy source (for example, Portugal witnessed a relevant expansion of its Renewable Energy sector over the past few years due to European and governmental incentive). Likewise, stakeholders can also influence the demand of final energy (the high price of energy can drive the decrease of energy consumption and, consequentially, demand).
Each actor can be associated to different fallouts, such as:

- **Energy losses**: can be either conversion losses (associated to the process and the technology) or distribution losses (associated to the technology which involves transporting the energy from one point to another);
- **Own use**: amount of energy produced that is going to be consumed by the actual energy industry in order to be able to function;

The main resources that can be associated to the energy sector are (Praz, 2012):

- **Primary energy resources**: representing practically all the natural sources that can be exploited. Furthermore, natural resources can be classified as ‘stocks’ (coal, oil, combustible renewables…) and ‘flows’ (solar beam, wind…) (Wall, 1986);
- **Technologies available**: enabling extraction, transformation and transportation of energy. This is a very important resource given that it can lead to significant gain in terms of efficiency and pollutant emissions;
- **Funds and investments**: representing the absolute mean to shape the energy sector. Political and corporate decisions influence resource availability, climate and final energy price.

### 3.2.2. Summary of the energy sector

The topics discussed in Section 3.2 have been summarized in this subsection. Figure 3.4 shows a qualitative Sankey Diagram of the energy flow from primary to final stages, showing the losses and industry own uses as discussed in Section 3.2.1. The aim of this work is to evaluate the energy and exergy efficiencies related to this sector by quantifying the losses and own use and to compare the exergetic with the energetic perspective.

![Illustrative example of the primary to final energy flow](image)

**Figure 3.4**: Illustrative example of the primary to final energy flow
The elements of the system considered in this study have been summarized in Table 3.2.

<table>
<thead>
<tr>
<th>Element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal of the system</td>
<td>Transform and allocate energy from natural sources to society</td>
</tr>
<tr>
<td>System boundary</td>
<td>All that contains the energy industry in Portugal, as well as cogeneration in other industries</td>
</tr>
<tr>
<td>Sub-systems</td>
<td>Extraction units, transformation units, transportation and politicians, economic world &amp; other stakeholders</td>
</tr>
<tr>
<td>Resources</td>
<td>Primary energy resources (stocks and natural flows), technologies available and investments &amp; funds</td>
</tr>
<tr>
<td>Environment</td>
<td>Nature and society</td>
</tr>
</tbody>
</table>

Table 3.2. Elements of the energy sector system
CHAPTER IV
Energy Sector: Energy and Exergy Analysis

4.1. Methodology

The methodology used in this chapter comprises of three main stages:

- **Stage one**: Compilation of data regarding primary energy/exergy consumption in the Portuguese energy sector and the final energy/exergy made available by it (input-output configuration);
- **Stage two**: Estimation of energy and exergy efficiencies in the transformation sector;
- **Stage three**: Qualitative and quantitative comparison between the exergy and energy balances in order to identify the main losses in the energy sector in Portugal.

To carry out the compilation, we first begin by introducing the model that represents the energy/exergy flows through the economy in order to perform an energy/exergy balance. The first step requires identifying the main energy carriers. These have been grouped according to the IEA categories: (a) Coal and coal products, (b) Oil and oil products, (c) Natural gas, (d) Combustible renewables and (e) Electricity and CHP heat.

The energy values and statistics have been compiled using the IEA database 2011. To convert the energy data into exergy data, quality factors have been used according to Table 2.2. More information regarding these quality factors can be found in Section 2.3.3. The Sankey Diagrams in Section 4.7 were built using the software e-sankey©.

**Figure 4.1** – Energy carriers, final energy forms, end-use sectors and useful work categories identified for this study. The dotted line marks the main scope of this work.
4.2. Primary to Final Energy: Results

4.2.1. Primary Energy/Exergy Supply

The first step towards calculating the overall efficiency of the energy sector is to determine the input to the system. For this the total primary energy/exergy supply was calculated for each year. Table 4.1 summarizes the different terms that were considered when calculating the supply. The resources supplied to the system are composed of products that are both produced internally and imported from another country. However, it is necessary to subtract the amount of product which is exported, as well as the amount of product that is used by international marine and aviation bunkers. This is why the latter values appear as negative in the IEA database (to symbolize that they are being extracted from the system). Moreover, the last term to be considered is the stock changes\(^4\). A stock build is shown as a negative number, and a stock draw as a positive number.

Figure 4.2 plots the values for the total primary energy and exergy supply for Portugal between the years 1960 and 2009. As expected, the two plots show a similar trend. Exergy values are slightly higher for coal and coal products, natural gas, combustible renewables, and oil and oil products. This is a consequence of the fact that the energy content values are multiplied by their respective quality factors, which in turn are larger than 1 (see Section 2.1.3.3. for further discussion). Consequentially, the total primary exergy supply is 2%-6% higher than the total primary energy supply.

Regarding the trend of total energy/exergy supply to the utility sector, it is noted that there has been an increase in the total figures since 1960, with a more accentuated increase taking place from 1968 to 1997, motivated by the industrial drive that emerged in the country – especially the textile and energy industry (Rocha, 1977). From 2004 onwards, the total primary energy/exergy supply started experiencing an overall decrease, mostly driven by the decrease in oil consumption. The supply of natural gas only becomes evident from 1997 onward, following the construction of a gas pipeline that enabled natural gas to be transported from Algeria to Portugal (Serrenho et al, 2013).

Figure 4.2 also plots the trend of electricity output by product from 1960 to 2009. Here, the label “Primary Electricity” refers to renewable sources (hydro, wind, solar, geothermal) and electricity imports. All products show a general tendency to increase except for oil and oil products. This relation reflects the change in energy policy that has taken place in Portugal over the last decades, which in a nutshell looks to reduce the dependency on fossils fuels and shift to higher percentage in

\(^4\) Stock changes reflects the difference between opening stock levels on the first day of the year and closing levels on the last day of the year of stocks on national territory held by producers, importers, energy transformation industries and large consumers.
use of renewable sources. Furthermore, this tendency is expected to attenuate due to the closing of down the fuel-oil driven cogeneration plant in Barreiro in 2010, and the construction and conversion of new plants burning alternative fuels, such as natural gas and biomass. At first glance, the relatively lower percentage of electricity output from oil & oil products seems to contrast with the high quota of primary energy/exergy supply. However, it should be noted that not all of the primary energy/exergy supply is transformed into electricity and heat. Part of the supply is delivered directly to end-use sectors for final consumption without undergoing any transformation process. However, those flows do not fall within the scope of this part of the study.

<table>
<thead>
<tr>
<th>INFLOW (+)</th>
<th></th>
</tr>
</thead>
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<tr>
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<td>Imports</td>
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<table>
<thead>
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<th>OUTFLOW (-)</th>
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<td>Exports</td>
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<tr>
<td>International Marine Bunkers</td>
<td></td>
</tr>
<tr>
<td>International Aviation Bunkers</td>
<td></td>
</tr>
</tbody>
</table>

| STOCK CHANGES (+ OR -) | TOTAL PRIMARY ENERGY SUPPLY |

Table 4.1 – Total Primary Energy Supply Configuration

Figure 4.3 provides a clearer understanding of the primary supply trends by product. Note that, for combustible renewables, data was made available by the IEA from 1994 for biogas, 1999 for municipal waste and from 2003 for industrial waste. Between 1989 and 1990, a significant gap is seen in terms of primary energy supply of combustible renewables, in particular primary solid biofuels. This relates to a period when combustible renewables data was revised the Portuguese Administration, and therefore validity concerns are raised regarding data prior to 1990. It is possible that, after the revision, solid biomass consumption (such as wood and vegetal residues) consumed in the residential sector as fuel was accounted for as well, since this is accounted for in the National Energy Balance (Ramos, 2011).

To provide information on transformation efficiencies as accurate as possible, data relative to combustible renewables prior to 1990 is not accounted for in Chapter V and Chapter VI. Additionally, when analyzing input data for the production of electricity and heat in CHP plants, we will include in the balance biofuels consumed as final energy in the main CHP industries, since this will bring us closer to the real input required for the production of electricity and CHP heat, and therefore provide a better understanding of the transformation efficiencies.
4.2.2. Final Energy/Exergy Availability

The previous section focused on determining the input of the overall energy/exergy balance to determine the respective efficiency. This section will seek to define the output which we will further use to compute the efficiencies in Section 4.4.

The output of the utility sector is defined as the final energy which is made available to end-use sectors. The system boundaries, as well as the different flows through the energy sector, have been previously discussed in Chapter III. Recalling the IEA database structure shown in Table 3.1, the
final energy/exergy availability corresponds to the flow which results from the transformation processes excluding distribution losses and energy industry own use.

Figure 4.4 provides valuable information regarding the energy mix contributing to the production of electricity. This overview comprises both cogeneration plants, conventional power plants and renewable energy plants. Over the past decade, coal and coal products, natural gas and primary electricity (hydro, wind) have been the predominant sources for final energy in the form of electricity. This is a very different scenario from the one which Portugal faced during the 1960’s and 1970’s, when hydro power and oil products were the main sources for electricity.

Heat output, in particular CHP heat, is further analyzed in Chapter VI.

![Figure 4.4](image-url) – Share of total electricity output by product in relation to the total electricity output

4.3. Efficiencies of the energy sector

4.3.1. Estimation of the efficiencies by product

The efficiencies were computed based on the definition of simple efficiency (see Section 2.3.3.1). Following Equation 2.12, the efficiencies can be estimated by using the following formulas:

\[
\eta_f = \frac{(electricity \ output + q_{heat } + heat \ output + fuel \ exergy)_f}{(primary \ exergy)_f}
\]  

(4.1)

\[
\eta_f = \frac{(electricity \ output + heat \ output + fuel \ energy)_f}{(primary \ energy)_f}
\]  

(4.2)
where \( q_{\text{heat}} \) is the quality factor for heat defined in Table 2.2.

Figure 4.5 plots the ratio between final and primary exergy (\( \varepsilon_f \)) for Portugal between 1960 and 2009 for the four main fuels: coal, oil, natural gas (since 1997) and combustible renewables (biofuel and waste). The latter shows the highest exergy efficiency, whereas coal represents the lowest exergy efficiency and, coincidentally, the only fuel with a significant decrease in efficiency since 1986. This resulted was expected simply by observing Figures 4.3, 4.5 and 4.6. The primary supply of coal and coal products has increased substantially since 1986, though the use of coal has changed from being used directly by end-use sectors (e.g. industry, transport and residential) to being used in thermal power plants to generate heat and electricity (i.e. electricity output). For example, in 1960 the total primary exergy supply of coal and coal products was approximately 25 PJ, of which 94% was used directly by end-use sectors, and only 6% was used to generate electricity. In 2009, the total supply had reached 127 PJ, of which less than 1% was used directly by end-use sectors (i.e. the industry sector) and only approximately 37% is transformed by the energy sector into electricity output. Energy industry own-use and distribution losses were null in 2009, meaning that the remaining 62% of primary supply were “lost” in irreversibilities within the transformation processes. Natural gas, which was introduced in 1997, motivated the shift to newer technologies such as gas turbines and gas engines, especially in CHP plants since they present a more cost-effective solution in comparison to diesel engine technologies. Between 48% and 61% of total natural gas primary energy supply was used within transformation processes for the production of electricity. The second largest consumer is the industry (mainly for CHP applications), standing at 23% of the total primary natural gas supply in 2009. Finally, a smaller quota (16% in 2009) was consumed by the transport, residential and commercial sectors.

A similar analysis can be made regarding combustible renewables. Between 83% and 96% of the primary supply is used directly by the end-use sectors (namely industry and residential), the remaining constituting as input for the production of electricity in CHP auto-producer plants.

**Figure 4.5** – Ratio between total final exergy availability and primary exergy supply for selected fuels from 1960 to 2009
4.3.2. Overall energy sector efficiencies

The overall electrical efficiency is given by the ratio between the energy/exergy supplied directly to the transformation units and the electricity output. Therefore, in this section, CHP heat output will not be considered.

Figure 4.6 plots three curves: the electrical efficiency of the overall cogeneration transformation units (CHP), and the efficiency of the main activity electricity producers (MAEP). It is clearly seen that the overall electrical efficiency of the energy sector is mostly driven by the transformation efficiency of MAEP plants, which was expected considering these transformation units hold the highest share of the input/output in the energy sector (electricity plants produced 80% to 100% of the total output of the energy sector between 1960 and 2009).

The relatively high efficiencies of the MAEP plants up until 1975 are due to the fact that the predominant energy source during the 1960’s and 1970’s was hydroelectricity. From that point forward, conventional thermal power plants, burning coal and fuel-oil, substantially increase their installed capacity due to the increase in electricity demand. This leads to a decrease in the overall efficiency, since thermal power plants have lower transformation efficiency compared to hydro plants (approximately 40%).

Figure 4.6 – Energy and exergy efficiencies of cogeneration plants, main activity electricity producers and overall Portuguese Energy Sector from 1960 to 2009
4.4. Losses and energy industry own use

As seen previously in Chapter III, losses occur during the transport of energy from the transformation units to the end-use consumer. In Section 4.3.2, these losses were not taken into account when calculating the transformation efficiency.

Energy industry own use covers the amount of fuels used by the energy producing industries (e.g. for heating, lighting and operation of all equipment used in the extraction process, for traction and for distribution). It includes primary and secondary energy consumed by energy industries for heating, pumping, traction and lighting purposes. Included here are, for example, own consumption in power plants (which includes net electricity consumed for pumped storage) and energy used for oil and gas extraction. Losses comprise energy distribution, transmission and transport.

Figure 4.7 shows the losses for each product between 1960 and 2009, as well as the energy industry own use. Note that the results presented below refer not only to energy production in power and CHP plants, but also to the oil refinery section. The data as presented by the IEA does not allow to fully understand the breakdown of energy own use within the energy sector, since the results are presented by product, and not by transformation unit. Therefore, it is unknown to the author how this energy was used within the sector, as well as the differentiation of usage of primary resources between power plants and refineries. In addition to this limitation, it is unclear how the losses are divided between energy distribution, transmission and report.

Between 1960 and 2009, there has naturally been an overall increase in energy industry own use and losses due to the increase in installed capacity in the country. Figure 4.8 shows the weight of both the losses and own use when compared to the total primary energy supply to the Portuguese energy sector. It is seen there that from 1976 onwards, these ratios have been somewhat constant with a slight tendency to decrease, which is reflected in the continuous efforts to reduce energy consumption within the plant and to improve the distribution network in order to minimize energy losses.

4.5. Exergetic Improvement Potential in the Energy Sector

The maximum improvement of the exergy efficiency for a process or system is achieved when the exergy loss or irreversibility is minimized (Van Gool, 1987). Therefore, when analyzing different processes or sectors of the economy, as is the case, it becomes useful to employ the concept of an exergetic ‘improvement potential’ (IP). This potential is given by Equation 4.3:

\[
IP = (1 - \varepsilon) \times (B_{in} - B_{out})
\]

(4.3)
Equation 4.3 has been applied to the overall electrical efficiencies of CHP plants and main activity electricity plants. As expected, the lower the exergy efficiency, the higher the IP. In 2009, both CHP and MAEP plants had approximately 60 PJ improvement potential, despite having different efficiencies. Naturally, these figures must be interpreted with caution... The efficiencies calculated refer to electricity production only and do not account for heat production in CHP (due to insufficient data, as we will discuss in Chapter VI). Therefore, it should be noted that the “real” efficiency of CHP plants is expected to be higher when heat output is considered. However, since heat has a low quality compared to electricity, the IP will not vary in the same proportion.
4.6. Sankey & Grassmann diagrams

As discussed in Chapter 3.5, Sankey and Grassman Diagrams provide a visual representation of the energy and exergy flows in the Portuguese Energy Sector, respectively. Furthermore, Sankey diagrams allow a quick analysis of an energy/exergy flow through a system and identify main losses. In this study, we are focused on understanding the flow of primary to final energy/exergy revolving around the energy sector. Furthermore, input and output flows for the refineries have also been included in the diagrams.

In this study, Sankey and Grassmann diagrams have been drawn for 1960, 1990 and 2009 and can be consulted in Appendix I.

For example in 1990, predominance is seen in the use of crude oil which in turn is fed directly to the oil refineries for the production of oil and oil products. Approximately 23% of these products are fed to the power stations for production of electricity and heat and 6% is either returned to the energy industry for own use and/or lost during distribution to the end-use sector. The Sankey Diagram also shows that 70% of the total primary supply of combustible renewable (i.e. biofuels and waste) was supplied directly to the end-use sectors as a fuel, whereas the remaining 6% were fed to CHP plants for the production of electricity\(^5\).

\(^5\) Note that in the case of biofuels and waste, the final energy consumed by the paper and pulp industry has been accounted for as primary input for the CHP sector. Further discussion in Chapter VI.
Power stations (or, according to the IEA nomenclature, main activity electricity plants and auto-producer electricity plants) received, in 1990, 197.1 PJ of primary energy, namely through coal and coal products (43%), oil and oil products (40%) and electricity and CHP heat mainly from renewable sources (17%). From an exergy perspective, the primary supply was of 206.7 PJ.

The total electricity output from power stations in 1990 was 96.3 PJ, resulting in an energy and exergy efficiency of 48.9% and 46.5%, respectively.

Other transformations include combined heat and power plants (both main activity plants and auto-producers). The primary energy supply to CHP plants in 1990 was 45.5 PJ, approximately 8.6% lower compared to primary exergy supply (49.8 PJ). Oil and oil products are the main products supplied, followed by biofuels and coal products.

In terms of output, in 1990 CHP plants produced 1.2 PJ of heat and 6.4 PJ of electricity. Heat is assumed to be hot steam at 600ºC with a quality factor of 0.6. Considering electricity has the same energy and exergy content, this amounts to a total final exergy supply of 7.1 PJ, resulting in an energy and exergy efficiency of 16.7% and 14.3%, respectively.

A similar analysis is carried out for 1960 and 2009. The overall results are presented in Table 4.2.

<table>
<thead>
<tr>
<th></th>
<th>1960</th>
<th>1990</th>
<th>2009</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>ENERGY</td>
<td>EXERGY</td>
<td>ENERGY</td>
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<td><strong>POWER STATIONS</strong></td>
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<tr>
<td>Input (PJ)</td>
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<td>15.5</td>
<td>197.1</td>
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<td>11.8</td>
<td>96.3</td>
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<tr>
<td>Transformation Efficiency</td>
<td>77.6%</td>
<td>76.1%</td>
<td>48.9%</td>
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<td><strong>OTHER TRANSFORMATIONS (INCLUDES CHP)</strong></td>
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<td></td>
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<tr>
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<td>N/A</td>
<td>45.5</td>
</tr>
<tr>
<td>Electricity Output (PJ)</td>
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<td>N/A</td>
<td>6.4</td>
</tr>
<tr>
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<td>N/A</td>
<td>1.2</td>
</tr>
<tr>
<td>Transformation Efficiency</td>
<td>N/A</td>
<td>N/A</td>
<td>16.7%</td>
</tr>
</tbody>
</table>

Table 4.2 – Overall results obtained from Sankey and Grassman diagrams
CHAPTER V
Power Plants in Portugal

5.1. Introduction to Power Plants

5.1.1. Current landscape in Portugal
Portugal’s power system is primarily based on thermal power units, which mostly use fossil fuels as primary energy sources (Table 5.1). In 2009, the total installed capacity amounted to 11.3 GW, comprising 6.7 GW from thermal power plants with an additional capacity of 1.6 GW from thermal power plants classified as producers with special status (Produção em Regime Especial - PRE), such as CHP and in smaller amounts waste, biomass, and biogas facilities. In total, 49% of the installed capacity derives from thermal units. The installed power in hydro power was also high, i.e. 4.6 GW with an additional 413 MW from hydro power plants acting as special producers (smaller plants) totaling 29% of the installed power capacity. The third largest installed power capacity relates to wind power plants, amounting to 21% or 3.5 GW.

<table>
<thead>
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<th>Installed Power Capacity in Portugal</th>
<th>2009</th>
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<tr>
<td>Installed Power Capacity PRO (MW)</td>
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<tr>
<td>Hydro plants</td>
<td>4578</td>
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<tr>
<td>Thermal plants</td>
<td>6690</td>
</tr>
<tr>
<td>Coal</td>
<td>1776</td>
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<tr>
<td>Oil</td>
<td>1476</td>
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<tr>
<td>Oil / Natural Gas</td>
<td>2636</td>
</tr>
<tr>
<td>Diesel</td>
<td>165</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>3036</td>
</tr>
<tr>
<td>Installed Power Capacity PRE (MW)</td>
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<tr>
<td>Hydraulic</td>
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<tr>
<td>Thermal</td>
<td>1631</td>
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<td>Wind energy</td>
<td>3524</td>
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<tr>
<td>Solar Photovoltaic</td>
<td>82</td>
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<tr>
<td>Wave energy</td>
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</tbody>
</table>

Table 5.1 – Installed power capacity (MW) in Portugal in 2009 (Source: REN 2009)

This chapter will seek to relate the energy/exergy efficiencies of the overall power plants in Portugal with the technologies used within the period 1960 – 2009. Firstly, the basic principle of a power plant is described.
5.1.2. Types of Power Plants

A power plant – or power station – is a general term used to describe a system where a certain input, let it be fuel or a renewable source, is transformed to produce electricity. Some power plants produce electricity and heat simultaneously and are known as cogeneration plants. These will be discussed in Chapter 6.

Thermal power plants use thermodynamic processes to transform chemical energy of a fossil fuel into different forms of energy until electricity – the final energy – is generated. These plants can be classified according to their prime mover. There are mainly three types of power plants:

- **Steam turbine** plants, which use the pressure generated by expanding steam to turn the blades of a turbine;
- **Gas turbine plants**, using the heat from the gases to directly operate the turbine. Fuelled by natural gas, these plants can start more rapidly and are therefore used to supply “peak” energy during periods of high demand;
- **Combined cycle** plants have both a gas turbine fired by natural gas, and a steam boiler and steam turbine which use the exhaust gas from the gas turbine to produce electricity. Most base-load power plants use this technology, since it improves the overall efficiency.

--- | --- | --- | ---
Type | Steam turbine | Steam turbine | Combined Cycle
Fuel | Fuel-oil | Coal | Natural gas
Capacity | 946 MW | 1192 MW | 1176 MW

**Figure 5.1** – Examples of different power plant types in Portugal

Although in smaller number and low percentage of installed capacity when compared to conventional fossil fuel power plants (roughly 1% in 2011 according to DGEG), forest residue power
plants are also in activity in Portugal. Mortágua Power Station is one of the largest power plants burning biomass, with an installed capacity of 9 MW.

5.2. Description of a power plant

5.2.1. Steam turbine cycle
A fuel-based power plant ideal cycle can be characterized by a Rankine cycle (Figure 5.2), a mathematical model used to predict the performance of steam engines. This ideal cycle does not involve any internal irreversibility and consists of the following four processes:

- 1-2: Isentropic compression in a pump;
- 2-3: Constant pressure heat addition in a boiler;
- 3-4: Isentropic expansion in a turbine;
- 4-1: Constant pressure heat rejection in a condenser.

![Figure 5.2 – Schematic of a simple steam turbine plant and Rankine cycle](image)

There are many ways as to how to improve the energy efficiency of the Rankine Cycle, such as lowering the condenser pressure, superheating the steam to high temperatures, increasing the boiler pressure, and/or use a reheater cycle by introducing two stages in the turbine and avoid undesirable levels of moisture in the steam (Reddy et al, 2010).

We now look at how the Rankine cycle can be applied to a power plant. Figure 5.3 shows the schematic of a steam turbine plant.

The heat produced by combustion of the fossil fuel (generally diesel or coal, as seen in the previous chapter) is used to boil water under high pressure in a large boiler (generally speaking, the steam
production unit). The steam is then supplied to the turbine, where the energy due to the enthalpy variation (which, in turn, is driven by the pressure drop) is transformed into useful work output (i.e. rotation of the turbine shaft). At the other end of the shaft, an electric generator is located, producing electric power. As the steam passes through the turbine, it transmits exergy (or useful work) to the electric generator. Below the turbine there is the condenser through which the lower quality steam passes and condenses into water. The water is then pumped and brought back to the boiler, thus closing the cycle.

![Figure 5.3 - The energy and exergy flow through a condensing power plant [Wall, 1977]](image)

In order to improve the efficiency of the plant, pre-heaters are also installed, therefore pre-heating the water before it enters the boiler to be converted into high pressure steam again. The electric power, in the form of final energy or exergy, is then transported to the end-consumer through a vast and complex transport and distribution grid.

The process, which begins with the chemical energy/exergy in the fuel and ends with the useful output produced by the electric generator, endures significant losses along the way. Counting the total system, from the preparation of the energy raw material to the finishing treatment of the waste products, there are even greater losses. Generally, the energy efficiency of a power plant is below 60% (Wall, 1977; Rosen et al., 2001).

5.2.2. Gas turbine cycle

The gas turbine cycle (or Brayton cycle) represents the operation of a gas turbine engine. The ideal cycle consists of four processes, as shown in Figure 5.4:

- 1-2: Adiabatic, quasi-static (or reversible) compression in the inlet and compressor;
- 2-3: Constant pressure fuel combustion (idealized as constant pressure heat addition);
• 3-4: Adiabatic, quasi-static (or reversible) expansion in the turbine and exhaust nozzle, with which we
  o retrieve some work out of the air and use it to drive the compressor, and
  o take the remaining work out and use it to accelerate fluid for jet propulsion, or to
    turn a generator for electrical power generation;
• 4-1: Cool the air at constant pressure back to its initial condition.

The fuel utilized is generally natural gas, making the gas turbine cycle generally more attractive economically. In some cases, diesel can also be used. Although Figure 5.4 depicts a closed cycle, in a gas turbine plant the cycle is generally open, and the air intake is atmospheric air.

![Diagram of an open cycle gas turbine engine and a closed cycle gas turbine engine](image)

**Figure 5.4** - Thermodynamic model of an ideal gas turbine engine cycle for power generation and a simple gas turbine cycle

### 5.2.3. Combined cycle

The combined cycle power plant, or combined cycle gas turbine, consists of a gas turbine generator which generates electric power. The waste heat that results from this process is used to produce steam which then generates additional electric power via a steam turbine. The use of distillate liquid fuels, such as diesel, is also common as alternate fuels.

This type of cycle became very popular in particular countries where natural gas is sufficiently available for electricity generation. Combined cycle plants can achieve thermal efficiencies up to 60%, based on the LHV of the fuel, and with present day gas turbine technology (Woudstra *et al.*, 2010). Recently, a German combined cycle power plant claimed it had achieved the world’s highest
energy efficiency (over 60%) by using a pioneer gas turbine technology developed by Siemens (Siemens press release, 30 May 2011).

As the name suggests, a combined cycle power plant (CCGT) combines existing gas and steam technologies into one unit, yielding significant improvements in thermal efficiency over a conventional steam plant. The first unit is similar to a simple cycle gas turbine plant. An open circuit gas turbine has a compressor, a combustor and a turbine. Intake air is compressed and mixed with natural gas and ignite, which causes it to expand. Consequently, the increase in pressure due to the expansion causes the turbine blades to spin, which in turn are connected to a shaft and a generator, generating electricity. The input temperature to the turbine is generally very high (generally above 1000ºC), as is the output temperature of flue gases. The exhaust heat generated during this process is used to generate steam by passing it through a heat recovery steam generator (HRSG) with a steam temperature between 420ºC and 580ºC (Ramireddy, 2012).

In the HRSG, highly purified water flows through the tubes and the hot gases flow around it, thus increasing the temperature of the water through convection and producing steam. The steam then rotates the steam turbine, which is coupled to a second generator to produce electricity. The hot gases leave the HRSG at around 140ºC and are discharged into the atmosphere. The steam condensing sub-system is identical to the one in a steam power plant.

Figure 5.5 shows a schematic of the combined cycle as described above.

![Combined Cycle Schematic](image)

**Figure 5.5** – Schematic of an example of a combined cycle plant, using a cooling tower as a cooling mechanism (Ramireddy, 2012).
The exhaust heat generated in the gas turbine can also be used for heating purposes instead of generating additional electricity. In this case, however, a combined cycle becomes a combined heat and power (CHP) or cogeneration plant, which we will discuss further in Chapter 6.

5.3. Energy and Exergy analysis of power plants

5.3.1. Primary Energy Input and Final Energy Output

Figure 5.6 plots the primary energy input by source and electricity output. Up until 1971, hydro energy was the most predominant primary source. Geothermal energy has only been accounted for since 1984, and generally held a small share in the total primary energy input landscape (between 0.1% and 2.8%). Therefore, it was been grouped together with solar photovoltaic and wind energy.

Before 1960, the Tejo Power Station – formerly known as Central Junqueira – was one of the most important power plants in the country. Its high-pressure boilers were equipped to burn both coal and naphtha, though during World War II it was known to burn biomass as well due to the low availability of fossil fuels. Excluding this period, coal was the main fossil fuel used as primary energy input. It remained the largest functioning steam turbine power plant in Portugal (excluding hydro plants) until 1951, when the hydro plant Castelo do Bode officially became the main supplier of electricity to the city of Lisbon. The Tejo Power Station continued to work as a back-up plant, until it ceased activity permanently in 1972 (Barbosa et al., 2007).

From the 1960s to the 1990s, steam turbine plants remained the most popular technology, burning fossil fuels such as diesel, fuel-oil and coal. Today, the largest electricity power plants in Portugal burn coal (Table 5.2).

In 1997, the introduction of natural gas also provided an opportunity to shift to technologically more advanced power plants: the combined cycle plant. In 1998 and again 2003, two combined cycle power plants were inaugurated in Portugal, which combined added 2.2 GW of installed power capacity to the national energy system. This also increased the consumption of natural gas as a primary energy resource, as shown in Figure 5.6. Moreover, the Carregado Power Station, burnt fuel-oil up until 1997, when two of its six turbo-Alternator groups were converted to use natural gas instead.
From 1990 onwards, Portugal sees a significant increase in the use of renewable energy resources (RER). The awareness regarding climate change and environmental sustainability drove governments, policy makers and other stakeholders to push for incentives and grants in the field of RER technologies. In fact, during the period between 1986 and 1990, the following decree-laws were approved:

- Regulations for the concession of financial subsidies in the incentive scheme for rational use of energy and development of new energy forms (Portaria nº 464/1986)
- New scheme for the production of electric energy by auto-producers using renewable sources (Decreto-Lei nº189/1988)
- Regulations for the thermal behavior of buildings (RCCTE) (Decreto-Lei nº 40/1990)

<table>
<thead>
<tr>
<th>Plant</th>
<th>Beginning of service</th>
<th>Installed power capacity (MW)</th>
<th>Technology type</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
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<td>Carregado</td>
<td>1968</td>
<td>710</td>
<td>Steam turbine</td>
<td>Fuel-oil/Natural gas</td>
</tr>
<tr>
<td>Tunes</td>
<td>1973</td>
<td>165</td>
<td>Gas turbine</td>
<td>Diesel</td>
</tr>
<tr>
<td>Setúbal</td>
<td>1979</td>
<td>946</td>
<td>Steam turbine</td>
<td>Fuel-Oil</td>
</tr>
<tr>
<td>Sines</td>
<td>1985</td>
<td>1192</td>
<td>Steam turbine</td>
<td>Coal</td>
</tr>
<tr>
<td>Pego</td>
<td>1993</td>
<td>584</td>
<td>Steam turbine</td>
<td>Coal</td>
</tr>
<tr>
<td>Tapada do Outeiro</td>
<td>1998</td>
<td>990</td>
<td>Combined cycle</td>
<td>Natural gas</td>
</tr>
<tr>
<td>Ribatejo</td>
<td>2003</td>
<td>1176</td>
<td>Combined Cycle</td>
<td>Natural gas</td>
</tr>
</tbody>
</table>

Table 5.2 – Main electricity power plants active in Portugal (Source: EDP WikiEnergia)

Figure 5.6 – Primary energy input, primary exergy input and final energy output of main activity electricity plants in Portugal by product from 1960 to 2009.
The growth of renewable energy share is mostly driven by wind energy plants. The sector experienced a considerable expansion, especially during the period 2001-2007, when the installed power capacity increased by 65% per year. By 2007, almost 25% of the electric energy produced in Portugal derived from wind energy farms. Solar energy also began taking its first big steps in the market, especially with the inauguration of the Serpa Photovoltaic Plant (10 MW) in 2006, at the time the largest in the world. In 2008, the Moura Photovoltaic Plant, became the largest one with 46 MW of installed power capacity. Today, the largest photovoltaic plants are in the US, India and China.

Figure 5.7 – Electricity output by product (PJ) for electricity plants in Portugal from 1960 to 2009

5.3.2. Energy and exergy efficiencies of main activity electricity plants

The efficiencies have been calculated according to Equations 5.1-5.2, using data from the IEA database and the quality factors present in Table 2.1:

\[
\eta_{\text{product}} = \frac{(\text{Electricity output})_{\text{product}}}{(\text{Primary Energy Input})_{\text{product}}} \\
\xi_{\text{product}} = \frac{(\text{Electricity output})_{\text{product}}}{(\text{Primary Exergy Input})_{\text{product}}} = \left(\frac{\eta}{\xi}\right)_{\text{product}}
\]

Figure 5.8 plots the results of the energy and exergy efficiency calculations. The relatively high efficiency in the beginning of the 1960s is explained by the predominant use of hydro plants for the production of electricity. Hydro plants have an average energy/exergy efficiency of 90% (Acar, 2008), whereas the average efficiency of thermal power plants is approximately 40%.
In Figure 5.6, the energy and exergy efficiencies are depicted as 100%, due to the nature of the IEA convention, as seen in Section 5.3.1. In 1960 the Carregado power plant goes into service, which causes an increase in oil consumption. Between 1976 and 1980, the electricity produced from hydro power was significantly higher than electricity produced from oil and coal (Figure 5.6), which naturally led to a significant decrease in the energy/exergy efficiency. The year 1992 sees the lowest peak of energy/exergy efficiency (44% and 42%, respectively), driven by the decrease of hydro energy production and increase in the installed capacity of thermal plants. It was also the year for the highest consumption of oil by the energy sector. From 1992 onwards, oil consumptions sees a significant drop and is compensated by the increasing consumption of coal. In 1997, the introduction of natural gas in Portugal favors the construction of large combined cycle plants with a higher efficiency compared to steam turbine plants. Together with the increase in RER technologies, the overall exergy and energy efficiencies has slightly improved since 1992, achieving 53% and 58% in 2009, respectively.

**Figure 5.8** – Primary exergy input by product (PJ) and energy/exergy efficiencies for electricity plants in Portugal from 1960 to 2009

An analysis of Figure 5.8 allows us to estimate average energy/exergy efficiencies based on IEA data. In order to increase the accuracy of these estimations, the interval prior to 1970 was disregarded. Natural gas can also be used as a start-up fuel in forest residue power plants and used as an alternate fuel in steam turbine plants. However, it is assumed that natural gas is utilized mostly by combined cycles.
The average of the solar/wind/geothermal energy/exergy efficiency is discussed in Section 5.4.

<table>
<thead>
<tr>
<th></th>
<th>$\eta$</th>
<th>$\varepsilon$</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam turbine (fuel-oil)</td>
<td>39%</td>
<td>36%</td>
<td>1970 - 2009</td>
</tr>
<tr>
<td>Steam turbine (coal)</td>
<td>39%</td>
<td>37%</td>
<td>1985 - 2009</td>
</tr>
<tr>
<td>Steam turbine (biomass)</td>
<td>25%</td>
<td>22%</td>
<td>1999 - 2009</td>
</tr>
<tr>
<td>Combined cycle (natural gas)</td>
<td>55%</td>
<td>53%</td>
<td>1999 - 2009</td>
</tr>
</tbody>
</table>

Table 5.3 – Average energy and exergy efficiencies based on IEA data

5.3.3. Exergy analysis for a Steam Turbine Plant

Figure 5.9 depicts the qualitative Sankey and Grassmann Diagrams for a condensing power plant. In the Sankey diagram, the width of the flow is proportional to the energy content for the respective energy form. In the Grassmann diagram, the width is proportional to the exergy content.

The inflows (fuel) and outflows (electricity) of a power plant are of high quality, which explains why in both diagrams the width is similar.

The first energy losses take place in the furnace, where the chemical energy is converted into thermal energy. In an oil or coal-fired power plant, the temperature of the flame is close to 2000°C (Wall, 1977). This heat is transferred to the boiling water through heat exchangers. Since the operating pressure is high, the boiling point of the water also increases. Part of the heat in the boiler is transmitted to the walls of the furnace and, through pipes, another part of it is transmitted to the environment, where it is ‘lost’. Heat is also discharged with the exhaust gases from the chimney. However, the furnace losses represent only a small portion of the total energy conversion. Analyzing the exergy diagram shows that during this stage more than one third of the exergy is lost. More importantly, it is shown that the exergy is lost within the process itself, due to the large
quantities of entropy which are created. The steam that leaves the boiler is at a lower temperature and pressure that could be physically possible, due to limitations in the fatigue strength of the components used in the process, mainly the boiler and the turbine blades.

In the Sankey diagram, the losses are heaviest in the condenser, due to the waste heat that is transferred to the cooling water. However, waste heat is at a very low temperature, and therefore it is energy of very low quality… This is why the loss in the condenser is depicted as smaller in the exergy flow diagram.

When transforming from mechanical energy to electrical energy, both with a quality factor of 1, small losses arise through friction. Part of the friction losses consists of mechanical fatigue, i.e. wearing out of shafts and bearings. These losses hold a small percentage of the total loss, both in terms of energy and exergy.

The conclusion we draw from analyzing the diagrams in Figure 5.9 is that an energy analysis depicts that the heaviest losses occur in the condenser, whereas an exergy analysis identifies the main loss in the combustion in the boiler. It is an inevitable “internal loss” and is dependent on the technical solutions available.

5.4. Renewable Energy Systems

5.4.1. Overall transformation efficiencies

There are two predominant RER plant types in Portugal: hydro plants and wind energy plants (Table 5.1). In this section, a brief exergy analysis is provided for each renewable energy conversion system.

As seen in Chapter 5.3.1, the real efficiency of solar and wind power plants cannot be estimated by solely using IEA data, since the form considered for both primary and final energy is electricity, leading to an efficiency of 100%. This way, efficiencies of the technologies are not accounted for and a deeper analysis would need to be carried out in order to understand the energy/exergy efficiencies of these renewable energy systems in Portugal. Similar studies have already been carried out for other countries (Acar, 2008; Koroneos et al, 2003; Ozgener and Ozgener, 2007; Redha et al, 2011; Pope et al, 2010).

However, Figure 5.7 shows that the solar/wind/geothermal efficiency increases exponentially, especially from 2005 onwards. This trend is driven by the exponential increase in electricity input and output of solar and wind plants between 2005 and 2009, and the fact that, according to IEA
definition, the transformation efficiency of these plants being equal to 1. Since the geothermal primary energy form is heat according to IEA convention, it is expected that the transformation efficiency will be substantially lower than 1. In fact, between 2004 and 2009, the average transformation efficiency for geothermal plants was 10%.

Table 5.4 shows the data compiled for these three system types, as well as the cumulative figures. The respective transformation efficiencies are also computed and shown.

<table>
<thead>
<tr>
<th>Year</th>
<th>Wind (input/output (TJ))</th>
<th>Wind (η, %)</th>
<th>Solar Photovoltaic (input/output (TJ))</th>
<th>Solar Photovoltaic (η, %)</th>
<th>Geothermal (input/output (TJ))</th>
<th>Geothermal (η, %)</th>
<th>Total Input (TJ)</th>
<th>Total Output (TJ)</th>
<th>Total (η, %)</th>
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<tr>
<td>1985</td>
<td>134 14</td>
<td>11%</td>
<td>134 14</td>
<td>11%</td>
<td>141 22</td>
<td>15%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1986</td>
<td>67 7</td>
<td>11%</td>
<td>67 7</td>
<td>11%</td>
<td>121 25</td>
<td>13%</td>
<td></td>
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<tr>
<td>1987</td>
<td>34 4</td>
<td>11%</td>
<td>34 4</td>
<td>11%</td>
<td>100 16</td>
<td>12%</td>
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<td>1988</td>
<td>67 7</td>
<td>11%</td>
<td>67 7</td>
<td>11%</td>
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<td></td>
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<tr>
<td>1989</td>
<td>4 100%</td>
<td>100%</td>
<td>4 100%</td>
<td>100%</td>
<td>92 100</td>
<td>10%</td>
<td></td>
<td></td>
<td></td>
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<td>1990</td>
<td>134 14</td>
<td>11%</td>
<td>134 14</td>
<td>11%</td>
<td>226 22</td>
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<tr>
<td>1991</td>
<td>185 18</td>
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<td>185 18</td>
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<td>2087 209</td>
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<td>2001</td>
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<td>10%</td>
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<td>3020 302</td>
<td>10%</td>
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<td>10%</td>
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<td>9%</td>
<td>3240 306</td>
<td>9%</td>
<td>6481 558</td>
<td>21%</td>
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<td>2006</td>
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<td>9%</td>
<td>7663 724</td>
<td>9%</td>
<td>14326 1352</td>
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<td>9%</td>
<td>7320 691</td>
<td>9%</td>
<td>14641 1422</td>
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<td></td>
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</tr>
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<td>9%</td>
<td>7015 662</td>
<td>9%</td>
<td>13830 1324</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>34873 3251</td>
<td>82%</td>
<td>34873 3251</td>
<td>82%</td>
<td>69344 6502</td>
<td>82%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4 – Energy input (TJ), electricity output (TJ) and transformation efficiency of wind, solar photovoltaic and geothermal sources in Portuguese electricity plants (IEA 2011)

5.4.2. Wind turbine plants

In a wind turbine system, the kinetic energy of wind produces a rotational movement of the blades. As the blades turn, the rotor turns a shaft, which in turn transfers the motion into the nacelle (casing
that holds the gearbox, generator, yaw controller and brakes). The gearbox increases the rotational shaft speed. In turn, the shaft output is connected to a generator that converts the rotational movement into electricity at medium voltage. A transformer, located at ground level, increases the voltage of the electric power to the distribution voltage. The yaw controller and brakes enable the movement of the rotor to align with the direction of the wind and the ceasing of the rotation of the shaft in case of power load or system failure, respectively.

In Section 5.4.1. we have seen that the transformation efficiency for wind energy is 100% due to the IEA convention that the primary energy form is the first practical energy form downstream in the production process (i.e., electricity). However, in reality, the efficiency of a wind turbine depends on its type (i.e., if it is of horizontal or vertical axis), on the rotor diameter and on the wind speed. The most common wind turbine type is the horizontal axis, which has been described above. The exergetic efficiency of a wind turbine is defined as a measure of how well the stream exergy of the fluid is converted into useful inverter work output. As potential energy and kinetic exergy are identical, the overall energy and exergy efficiencies are the same.

Wind turbines cannot take advantage of the total power of the wind. According to Betz’s law, a wind turbine can utilize up to 60% of the power of the wind. In practice, efficiencies are generally closer to 40% for relatively high wind speeds (Koroneos et al, 2003). The energy losses exit mainly with the air leaving the device, while the main exergy losses are associated with internal consumptions (Rosen et al, 2009).

This exergy loss can be attributed to the following phenomena (Koroneos et al, 2003):

- Friction between the rotor shaft and the bearings;
- Heat loss between the cooling fluid and the gearbox;
- Heat loss between the cooling fluid and the generator (namely the energy dissipation in the thyristors, which assist in assuring a smooth start of the turbine, of 1-2% of total energy flow through them).

A Grassman diagram representing the losses above is presented in Figure 5.10.

In 2011, Redha et al carried out a thermodynamic assessment of a wind energy system (Vestas V52, 850 kW rating power) in Sarjah, United Arab Emirates. The results showed that there are noticeable differences between energy and exergy efficiencies and that exergetic efficiency reflects the right/actual performance. Figure 5.11 plots one of the most important results of this study, where energy and exergy efficiencies were evaluated against wind speed. The deviation factor $D_i$ represents the ratio between the efficiency difference ($\eta - \varepsilon$) to energetic efficiency ($\eta$) and can easily be recognized as the percentage of exergy destruction with respect to the available energy. As
seen in the figure below, $D_f$ approached its minimum value at a wind speed of approximately 11.25 m/s, which marks the point where performance approaches the ideal case and irreversibility drops to the minimum level. However, as wind speed increased beyond this point, irreversibility also increased. Therefore, to increase the efficiency of the wind turbine and consequently increase power generation (for a moderate level of wind speed), it is recommended to use a turbine with low cut-in speed\(^6\) to make as much use as possible of the available wind power (Redha et al., 2011).

\[\text{Figure 5.10 – Representative Grassman diagram of exergy losses in the different components of a wind turbine (Koroneos et al, 2003)}\]

\[\text{Figure 5.11 - Energy and exergy efficiency and the deviation factor verses wind speed (Redha et al, 2011)}\]

### 5.4.3. Solar photovoltaic plants

\(^6\) Cut-in speed is the minimum wind speed at which the wind turbine will generate usable power. This wind speed is typically between 3 and 4.5 m/s for most turbines.
Although solar energy currently represents a very small share of the electric energy produced in Portugal (1% of total renewable energy production in 2009), in the beginning of the 21st century Portugal attracted good investments due to the solar energy potential of its southern region. For a solar photovoltaic generating station, the energy of sunlight is converted directly to electricity. As the energy and exergy of sunlight are very close (Wall, 1977; Rosen et al, 2009), they are assumed identical here. Thus, the overall energy and exergy efficiencies are the same.

5.4.4. Hydroelectric power plants

For a hydroelectric generating station, the potential energy of elevated water is converted into electricity. As potential energy and potential exergy are identical, the overall energy and exergy efficiencies are the same. However, the energy losses exit mainly with the water leaving the system, while the main exergy losses are associated with internal consumptions.
CHAPTER VI
Cogeneration Plants

6.1. Introduction to Cogeneration

Cogeneration is the production of more than one useful form of energy (such as process heat and electric power) from the same energy source. In a cogeneration or combined heat and power (CHP) system, wasted thermal energy is captured from an electricity producing device (e.g., steam-turbine, gas-turbine, diesel-engine), and used for space and water heating, industrial process heating, or as a thermal energy source for another system component to produce more electric power.

Cogeneration systems are similar to thermal electricity-generation systems, except that a percentage of the generated heat is delivered as a by-product (normally as steam or hot water). This reduces the quantities of electricity and waste heat that are produced. The "cascading" of energy use from high-temperature to low-temperature uses, often distinguishes cogeneration systems from conventional separate electrical and thermal energy systems (e.g., a power plant and an industrial boiler), and from simple heat recovery strategies (Kanoglu et al., 2009).

Cosijns et al. defined cogeneration as an efficient way to generate heat. Instead of degrading valuable fuel to low temperature heat, which often don't have useful applications, it is beneficial to insert some kind of power conversion equipment (e.g. a turbine or an engine) during the degradation process to produce additional work (Cosijns et al., 2006).

Overall cogeneration energy efficiencies can achieve more than 80%, based on both the electrical and thermal energy products (Rosen, 1998).

In this chapter we take a closer look at the transformation efficiency and energy mix of cogeneration plants in Portugal. The following analysis has been performed for both main activity cogeneration plants and auto-producer plants. From 1974 to 1979, however, the only cogeneration plants in use were auto-producer plants. Up until 1994, the IEA balance accounted only for electric power output for these plants.

6.1.1. Classification of cogeneration systems

A cogeneration plant essentially consists of two subsystems: 1) an electricity-generating system and 2) a heat recovery system that can make use of the waste heat from the electricity-generating system. Alternatively, the heat recovery system can also be used to return outlet heat to the electricity-generating system, create process steam, drive heating or cooling units, or provide hot
water. It can also be used to generate additional electricity, although this introduces extra inefficiencies, reducing the overall efficiency of the system (Flin, 2010).

**Classification according to cycle type**

There are two main types of cogeneration configurations: ‘topping cycle’ plants and ‘bottoming cycle’ plants. In a topping cycle, the fuel supplied is used to first produce power and then thermal energy, which is the by-product of the cycle and is used to satisfy process heat or other thermal requirements. The process heat can also be used to produce more power (e.g. combined cycle). In a bottoming cycle, the primary fuel produces high temperature thermal energy and the heat rejected from the process is used to generate power through a recovery boiler and a turbine generator.

![Diagram of Topping and Bottoming Cycles](image)

**Figure 6.1.** Schematic representation of two main cogeneration systems where C1 indicates primary cycle, C2 indicates secondary cycle, and P refers to industrial process.

There are four types of topping cycle cogeneration systems:

1) **Combined cycle**: Fuel burns in a gas turbine or diesel engine to produce power. The exhaust provides process heat or goes to a heat recovery boiler to create steam to drive the secondary steam turbine;

2) **Steam-turbine topping system**: Fuel burns to produce high-pressure steam that then passes through a steam turbine to produce power. The exhaust provides low-pressure process steam;

3) **Gas-turbine topping system**: A natural gas turbine drives a generator, and the exhaust goes to a heat recovery boiler that makes process steam and process heat.

4) **Heat recovery topping system**: Fuel, such as natural gas, diesel, wood, gasified coal or landfill gas, burns in an engine and drives a generator. The hot water from the engine jacket cooling system flows to a heat recovery boiler, where it is converted to process steam and hot water for space heating;
Bottoming cycle plants are mostly used by heavy industries such as glass or metal-manufacturing units, where very high furnace temperatures are required. A waste heat recovery boiler recaptures the waste heat from the manufacturing heat process, which is then used to produce steam that drives a steam turbine to generate electricity (Flin, 2010).

Selecting an operating scheme for a cogeneration system requires the analysis of various factors, including the availability of fuels, load patterns and energy demand. Since electricity can be bought or sold when it is in excess of site demand (provided they are connected to the public grid), most cogeneration plants are sized to meet minimum heat requirements. Topping cycle cogeneration is widely used and is the most popular method of cogeneration (EDUCOGEN, 2001).

**Classification according to prime mover**

Cogeneration applications can also be classified according to their prime movers (Flin, 2010):

i) **Steam turbine cogeneration system** is the traditional type among CHP systems, with its popularity decreasing due to more recent technologies such as combined cycle, gas turbines and reciprocating engines (due to the availability of natural gas and higher efficiency of combined cycles). It operates mainly on the Rankine Cycle. There are mainly two types of steam turbine cogeneration systems:

a. **Back-pressure turbine**: Steam exits the turbine at a pressure higher or equal to the atmospheric pressure, depending on the thermal load requirement. The steam is then fed directly to the load, where it releases heat and is condensed. The condensate then returns to the system. This configuration offers a higher overall efficiency compared to the extraction-condensing system, since there is no heat rejection to the environment through the condenser. However, the fact that the steam mass flow rate through the turbine depends on the thermal loads makes the system less flexible when matching electricity output to electrical load. Also, the steam turbine operates under a lower enthalpy difference in the steam, which means the unit will be larger for the same power output.

b. **Extraction-condensing turbine**: Steam is extracted from one or more intermediate stages at the appropriate pressure and temperature. The remaining steam is exhausted to the relative low pressure of the condenser and corresponding low temperature of approximately 33°C (Flin, 2010). Unless useful applications are found for this low temperature heat, it is rejected to the environment. In comparison to the back-pressure
turbine, the extraction-condensing turbine has, in general, a lower efficiency. However, to a certain extent, it can control the electrical power independent of the thermal load by proper regulation of the steam flow rate through the turbine.

ii) **Gas turbine cogeneration system**: operates on the Brayton cycle. Air is compressed, heated and then expanded by a gas turbine, generating electric energy. The high temperature exhaust gas is recovered for various heating and cooling applications. Although natural gas is the most commonly used fuel, other fuels such as light fuel oil or diesel can also be employed. Despite having a lower heat to power ratio (HPR) when compared to steam turbine cogeneration systems, more heat can be recovered at higher temperatures. There are mainly two types of gas turbine cogeneration systems:

   a. **Open-cycle gas turbine**: the compressor takes in air from the atmosphere and delivers it at a higher pressure and temperature to the combustion chamber. After combustion, the exhaust gases leave the turbine at a considerably high temperature (450-600ºC), and are then recovered by a heat recovery boiler. The steam produced can have high pressure and temperature, making it useful to drive a steam turbine and generate additional electric power.

   b. **Closed-cycle gas turbine**: Air (or, alternatively, helium), circulates in a closed circuit and is heated in a heat exchanger before entering the turbine. After exiting the turbine, the air is cooled down, releasing useful heat.

   iii) **Reciprocating engine cogeneration system**: Air and fuel are supplied to the gas or diesel engine, where combustion occurs. The heat is generally recovered in the form of hot water or low-pressure steam. Some industrial CHP applications use the engine exhaust directly for process drying.

The different cogeneration system types are summarized in Table 6.1.

In the present work, we will focus mostly on diesel engine and gas turbine-based cogeneration plants, since these were the predominant technologies in Portugal between 1974 and 2009, as we will discuss further.
<table>
<thead>
<tr>
<th>Cogeneration system type</th>
<th>Power requirement</th>
<th>Heat requirement</th>
<th>Preferred fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam turbine (extraction-condensing or back-pressure)</td>
<td>Electrical base load is over 250 kWe</td>
<td>High process steam is required</td>
<td>Cheap, low-premium</td>
</tr>
<tr>
<td>Gas turbine (open cycle or closed cycle)</td>
<td>Power demand is continuous and over 1 MWe.</td>
<td>High demand for medium/high pressure steam or hot water (T&gt;140°C), or hot gases (T&gt;450°C)</td>
<td>Natural gas</td>
</tr>
<tr>
<td>Reciprocating engines (gas or diesel engines)</td>
<td>Power or processes are cyclical or non-continuous</td>
<td>Low pressure steam or medium or low temperature hot water are required</td>
<td>Natural gas or fuel-oil</td>
</tr>
</tbody>
</table>

Table 6.1 – Different types of cogeneration systems according to their prime movers.

### 6.1.2. Performance indicators of cogeneration systems

#### 6.1.2.1. Electrical and thermal efficiencies

The electrical efficiency of a cogeneration system is defined as the net electric power output of the system (i.e., excluding electric power consumed by auxiliary equipment), $W_e$, divided by the total flux of fuel energy, $E_{fuel}$:

$$\eta_e = \frac{W_e}{E_{fuel}} = \frac{W_e}{m_f \cdot q_{LHV}}$$

(6.1)

where $q_{LHV}$ is the lower heating value of the fuel. Note that for systems where the water in the exhaust is not expected to condense, such as in internal combustion engines, it is more customary to use the lower heating value (Kanoglu et al., 2009). Therefore, when there is a possibility of recovering some of the energy of the condensing stream in the exhaust gases, then it is more proper and thermodynamically more accurate to calculate the efficiency based on the higher heating value of the fuel.

The thermal efficiency is defined as:

$$\eta_{th} = \frac{\dot{Q}}{E_{fuel}} = \frac{\dot{Q}}{m_f \cdot q_{LHV}}$$

(6.2)

where $\dot{Q}$ is the useful thermal power output of the cogeneration system, usually in the form of steam at a saturated state.
6.1.2.2. Energy and exergy efficiencies

The thermodynamic performance based on the first law or energy efficiency of a cogeneration system can be obtained by summing Equations (6.1) and (6.2):

$$\eta_{cogen} = \eta_e + \eta_t = \frac{W_e + Q_p}{E_{fuel}}$$  \hspace{1cm} (6.3)

In Eq. 6.3, it is seen that electrical and thermal energies are treated as equal despite having different qualities. Hence, the concept of exergy is introduced and the exergy efficiency can be defined as:

$$\varepsilon_{cogen} = \frac{W_e + B_p}{B_{fuel}}$$  \hspace{1cm} (6.4)

where $B_p$ is the exergy content of the process heat and $B_{fuel}$ is the exergy content of the fuel. Since in this study there is no in-depth information regarding the type of process heat produced by cogeneration plants and the aim is to obtain overall efficiencies for the sector, the process heat temperature is considered constant and equal to 600°C since this is the most common application for this type of heat. According to Table 2.1, the exergy content of process heat equals the energy content multiplied by the respective quality factor, $q = 0.6$.

The primary exergy input, $B_{fuel}$, can also be expressed according Eq. 6.5, where $e_{xfuel}$ is the specific exergy of the fuel:

$$B_{in} = m_{fuel} e_{xfuel}$$  \hspace{1cm} (6.5)

In the previous definitions, electric, thermal and fuel power units are used (energy per unit time), which result in values of the equations valid in a certain instant of time or at a certain load. By integrating Equations (6.3) and (6.4) over a certain period of time (e.g., one year), one obtains the following relations which will be used in this study:

$$\eta_{cogen} = \frac{W_e + Q_p}{E_{fuel}}$$  \hspace{1cm} (6.6)

$$\varepsilon_{cogen} = \frac{W_e + B_p}{B_{fuel}}$$  \hspace{1cm} (6.7)

6.1.2.3. Power-to-Heat Ratio (PHR)

The power-to-heat ratio is one of the most commonly used measures to evaluate cogeneration plant performance, relating the useful thermal energy with the net electrical output:
Using Equations 6.1 – 6.3, Eq. 6.8 becomes:

\[ PHR = \frac{\eta_e}{\eta_{th}} = \frac{\eta_e}{\eta_{cogen} - \eta_e} \] (6.9)

The PHR is useful when evaluating various plant operating regimes. A drawback to the PHR is that it provides no information regarding gas turbine efficiency, nor does it take into account the fuel utilized.

### Table 6.2 – Typical heat-to-power ratio and overall energy efficiency values for different cogeneration systems (EDUCOGEN, 2001)

<table>
<thead>
<tr>
<th>System type</th>
<th>Typical Power to Heat Ratio (PHR)</th>
<th>Typical overall energy efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam turbine</td>
<td>0.1-0.5</td>
<td>60-85%</td>
</tr>
<tr>
<td>Gas turbine (closed cycle)</td>
<td>0.5-0.8</td>
<td>60-80%</td>
</tr>
<tr>
<td>Diesel engine</td>
<td>0.8-2.4</td>
<td>60-85%</td>
</tr>
</tbody>
</table>

6.1.2.4. Fuel Utilization Effectiveness (FUE)

Fuel Utilization Effectiveness (FUE) is defined as the net electrical output divided by the net fuel consumption of the plant. It provides a fairly accurate comparison of different cogeneration designs because it factors in the amount of thermal energy recovered as well as the efficiency of the gas turbine. In the particular case of a simple gas turbine cycle plant, FUE can also be expressed as:

\[ FUE = \frac{w_{e,net}}{E_{fuel} \frac{E_p}{\eta_b}} \] (6.10)

where \( \eta_b \) is the boiler efficiency and \( E_p \) is the thermal energy in the fuel which would have been consumed by the prime mover to produce the process steam separately. According to literature, \( \eta_b \) is assumed to be 0.9 (Prandin, 2010).

6.2. Cogeneration in Portugal

Cogeneration plays a vital role in the Portuguese energy economy, especially for the industry. In 2012, production of electric power from cogeneration accounted for 14% of Portugal’s total production (COGEN Portugal statistics).
Cogeneration systems using internal combustion engines and gas-turbines in open cycle are currently the most utilized technologies worldwide (Kanoglu et al., 2009). Portugal is no exception. In 2011, over 57% of the cogeneration plants used the gas turbine technology (COGEN, 2012). However, this wasn’t always the case, as we will further explore in this chapter.

6.2.1. Legal Framework for cogeneration

Shortly after the first Peak Oil in 1973 and the consequent increase of the price of oil in the international markets, Portugal found itself in a vulnerable position and politicians began to worry about the future of energy production and consumption in the country. In order to reduce energy consumption, in 1976 an incentive program was created to promote the use of more efficient technologies by the Portuguese industry, including cogeneration. The program was extended over a period of eight years, up until 1984. During this period, a total of 279 projects were supported, of which 48% were related to the field of Energy Economy and 42% to the production of energy using biomass.

However, only in 1988 was cogeneration rewarded an adequate legislative framework as a result of the indisputable recognition of its energetic and environmental advantages. Consequentially, a transparent structure came into place which allowed for more funding opportunities. In 1996, 1999, 2000/2001 and 2010, the legislation was revised and more demanding criteria were established regarding the efficiency of cogeneration plants. In 2004, the European Parliament put forward the Directive 2004/8/CE, promoting the use of cogeneration in Europe. It became mandatory for every member of the European Union to carry out a study of the potential for high efficiency cogeneration in the country.

With a favorable framework now in place, aligned with the high cost of electric power and lack of alternative sourcing, industries – especially those competing in an international environment where energetic costs were usually lower – saw an incentive to invest in cogeneration, as shown by the increase of installed capacity in Figure 6.2. A summary description for each of the relevant decree-laws to cogeneration is provided in Table 6.3.
Figure 6.2 – Total Installed capacity (MWₜ) of cogeneration plants in relation to the legislative framework (Source: COGEN).

<table>
<thead>
<tr>
<th>Decree-Law nº</th>
<th>Date</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-L nº 189/88</td>
<td>27/05/1988</td>
<td>Rules applying to the production of energy in special regime are established.</td>
</tr>
<tr>
<td>D-L nº 186/95</td>
<td>27/07/1995</td>
<td>Combined production of heat and power is from here forth regulated according to an autonomous regime. Introduces cogeneration with diesel engines.</td>
</tr>
<tr>
<td>D-L nº 538/99</td>
<td>13/12/1999</td>
<td>Revision of previous norms applying to the generation of power using cogeneration plants. The minimum Electric Efficiency Equivalent (REE) increases from 45% to 55% due to introduction of the combined cycle plant in Tapada do Outeiro.</td>
</tr>
<tr>
<td>D-L nº 313/2001</td>
<td>10/12/2001</td>
<td>Revision of norms regarding exploratory conditions and tariffs for cogeneration activity</td>
</tr>
<tr>
<td>D-L nº 23/2010</td>
<td>25/03/2010</td>
<td>Introduction of a legal framework for cogeneration activity and a new compensation package based on three criteria: 1) Decrease in primary energy consumption and carbon dioxide emissions, 2) Promotion of cogeneration and incorporation of renewable energy, and 3) Promotion of cogeneration in the electricity market.</td>
</tr>
</tbody>
</table>

Table 6.3 – Portuguese Decree-laws relevant to cogeneration activity, established between 1988 and 2010.
6.2.2. Cogeneration technologies used in Portugal

Up until 2004, diesel engine-based cogeneration plants were the most utilized cogeneration systems, burning mostly fuel-oil. During the late 1990’s, there were a total of 65 cogeneration plants using diesel engine technologies, representing an installed capacity of 352 MWe and an average of 4.9 MWe per engine.

According to COGEN Portugal – The Portuguese Association for Energy Efficiency and Cogeneration Promotion – in 2000, the textile industry owned 38% of the existing diesel engine cogeneration plants, followed by the food industry (14%), wood industry (13%) and paper industry (10%).

Natural gas was introduced into the country in 1997, consequentially creating new opportunities for cogeneration. New projects chose Otto Cycles and Gas Turbine Cycles over diesel engines. This allowed the improvement of the energy efficiency and increase of the power capacity of the units installed by using combined cycles.

<table>
<thead>
<tr>
<th>Industry</th>
<th>Gas engines</th>
<th>Diesel engines</th>
<th>Gas turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Textile</td>
<td>64%</td>
<td>38%</td>
<td>2%</td>
</tr>
<tr>
<td>Food and tobacco</td>
<td>12%</td>
<td>14%</td>
<td>3%</td>
</tr>
<tr>
<td>Paper and Pulp</td>
<td>6%</td>
<td>10%</td>
<td>29%</td>
</tr>
<tr>
<td>Ceramics</td>
<td>6%</td>
<td>5%</td>
<td>3%</td>
</tr>
<tr>
<td>Chemical and petrochemical</td>
<td>N/A</td>
<td>8%</td>
<td>53%</td>
</tr>
<tr>
<td>Wood</td>
<td>N/A</td>
<td>13%</td>
<td>N/A</td>
</tr>
<tr>
<td>Others</td>
<td>12%</td>
<td>12%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Table 6.4 – Distribution of cogeneration systems across different industrial sectors in Portugal in 2000 (Source: COGEN)

Over the last ten years, 15 installations (74 MWe) were deactivated, whether due to companies closing down or a no longer existing need for heat production. Furthermore, 7 (42 MWe) installations are currently on stand-by for various reasons, ranging from financial difficulties to lack of a legislative and regulatory framework. In the meantime, five installations (27MWe) were also converted to use gas-turbine technology. All these economical and technological changes will help to explain the shift seen in the primary energy input from 1999 onwards (Figure 5.4), with the increase of consumption of natural gas, and decrease of the oil consumption (COGEN).
Figure 6.4 shows the distribution of new cogeneration plants installed in Portugal, classified according to their prime mover.

![Graph showing the distribution of new cogeneration plants installed in Portugal, classified according to their prime mover.](image)

**Figure 6.3** – Trend of technologies used in cogeneration plants in Portugal (Source: COGEN).

A brief analysis of Figure 6.4 shows that back-pressure turbines were the most utilized technology up until 1990. In the 1990s, the increase of installed capacity for cogeneration was related to the installment of systems using diesel/fuel-oil engines. However, once natural gas was introduced into the country, a new technological shift took place, namely with the use of gas turbines and natural gas engines. By 2012, cogeneration in Portugal amounted to a total of 1300 MW of installed capacity. Gas turbines are the predominant technology (57.25% of total capacity in 2011), followed by gas engines (21.31%) and diesel engines (13.66%).

6.3. Cogeneration: Energy and Exergy Results & Discussion

6.3.1. Methodology and definitions

In order to present the energy/exergy analysis results in the sub-chapters below, a thorough understanding of the IEA database configuration was required. A small number of assumptions were made in order to overcome limitations provided by the database.

We recall the IEA definitions for main activity CHP plants and auto-producer CHP plants:

- **Main activity producers** generate electricity and/or heat for sale to third parties as their primary activity, even though the sale might not necessarily take place through the national public grid.

- **Auto-producer** undertakings generate electricity and/or heat, wholly or partly for their own use as an activity which supports their primary activity. They may be privately or publicly owned, and often appear linked to top energy-consuming industries. Note that fuel inputs for the production of heat consumed within the auto-producer's establishment are not included in the IEA balance, but are included with figures for the final consumption of fuels in the appropriate consuming sector.

![Figure 6.4 – Trend of cogeneration technology types in Portugal (Source. COGEN).](image-url)
Between 1960 and 2009, auto-producer CHP plants accounted for more than 70% of primary energy consumption for all CHP plants. In 2009, for example, cogeneration produced a total of 22 PJ of electricity, of which 20.1 PJ (86%) were generated by auto-producers.

CHP auto-producers refer mainly to industries which use processes that require a lot of energy, mainly process heat. These industries are listed in Table 6.5. The fuels used by auto-producers CHP plants consist mainly of: fuel-oil, natural gas, primary solid biofuels and coal products (coke oven gas and blast furnace gas). When statistics of production of electricity from biofuels are available, they are included in total electricity production. However, the IEA admits that this data is not comprehensive, and that in some industries not all quantities are reported (IEA, 2011).

<table>
<thead>
<tr>
<th>Industry</th>
<th>% of total heat consumption (2009)</th>
<th>Predominant technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper, pulp and print</td>
<td>18%</td>
<td>Gas turbine</td>
</tr>
<tr>
<td>Chemical and petrochemical</td>
<td>39%</td>
<td>Gas turbine</td>
</tr>
<tr>
<td>Non-metallic materials (or ceramics)</td>
<td>3%</td>
<td>Gas engines</td>
</tr>
<tr>
<td>Food and tobacco</td>
<td>12%</td>
<td>Diesel engine</td>
</tr>
<tr>
<td>Textile and leather</td>
<td>13%</td>
<td>Gas engines</td>
</tr>
</tbody>
</table>

**Table 6.5 – Main CHP auto-producers in Portugal**

In this study, the following assumptions are made:

1. Reference state is environment state ($T_0 = 278$ K and $P_0 = 1$ bar)
2. All primary input accounted for by CHP plants are for the production of electricity,
3. Final energy consumed by the main industries listed in Table 6.5 is accounted for as input for the production of electricity and process heat. However, process heat will not be accounted for in the calculation of the energy/exergy efficiencies
4. All process heat is considered to be hot steam at 600ºC;
5. For combustible renewables, in particular primary solid bio-fuels, figures prior to 1990 are disregarded;
6. Since no breakdown is available on how much heat is produced per primary product, only overall efficiencies including process heat for auto-producer CHP plants will be computed.

The quality factors have already been presented in Table 2.1. In this particular case, it is assumed that the process heat generated from cogeneration is equivalent to hot steam, with a quality factor of 0.6. This factor depends on the temperature of the steam (Table 2.1). However, since information
regarding the temperature of the heat output is not given in the data, it is assumed to be constant and equal to 600ºC, since this is the most common application in the heavy industries considered.

Taking into account the assumptions above, Equations 6.1-6.3 can be written as follows:

\[ \eta_e = \frac{c \cdot W_e}{\Sigma E_p} \]  \hspace{1cm} (6.11)

\[ \eta_{cogen} = \frac{c \cdot W_e + Q_p}{\Sigma (E_p + E_{final})} \]  \hspace{1cm} (6.12)

where \( \Sigma E_p \) is the sum of primary energy input per product, \( W_e \) is electricity output, \( Q_p \) is the heat output and \( c \) is the conversion factor to convert electric power (GWh) into an energy quantity (in TJ).

For the exergy analysis, Equations 6.11 and 6.12 are re-written as the following equations, were \( q_f \) is the respective quality factor of the fuel given by Table 2.1:

\[ \varepsilon_e = \frac{c \cdot W_e}{\Sigma q_f E_p} \]  \hspace{1cm} (6.13)

\[ \varepsilon_{cogen} = \frac{c \cdot W_e + 0.6 \cdot Q_p}{\Sigma q_f E_p + \Sigma q_f E_{final}} \]  \hspace{1cm} (6.14)

Additionally, the following deviation factor, DF, will also be used in this study to understand the relation between energy and exergy efficiencies:

\[ DF = \left\{ \left( \frac{\eta - \varepsilon}{\eta} \right) \right\}_{cogen} \]  \hspace{1cm} (6.15)

6.3.2. Production and consumption of heat

Figure 6.5 plots the trend of production and consumption in Portugal between 1980 and 2009. The chemical and petrochemical industry is by far the largest consumer of heat due to its energy intensive chemical processes. The paper, pulp and print industry is the second largest consumer of heat, namely in the form of hot steam, in order to feed its digesters for the production of pulp.

According to IEA statistics, heat in Portugal was entirely produced by CHP plants, with auto-producers being the largest producers, namely after 2001. In turn, heat is majorly consumed by industrials sectors, such as the ones described in Figure 6.4, with a small percentage of the consumption (between 3% and 6%) belonging to residential and public service sectors. The discrepancy seen in 2009 is due to the fact that, for the first time, IEA statistics accounted for 2,9 PJ
energy industry own use of heat in oil refineries, and as a result the total heat output resulting from transformation processes was higher. However, there is some doubt regarding the validity of this data. It is unclear, for example, why this wasn’t accounted for prior to 2009, or whether or not this heating consumption is truly due to non-manufacturing purposes.

Figure 6.5 – Production and consumption of CHP heat in Portugal from 1980 to 2009 (Source: IEA Statistics, 2011)

6.3.3. Primary input mix and final output

Main activity CHP producer plants consume fuel-oil and natural gas as primary energy, due to the predominance of gas turbines, natural gas engines and diesel engine technologies. In addition to these sources, auto-producers also utilize combustible renewables (mainly primary solid biofuels) and coal products such as coke oven gas and blast furnace gas. The final energy generated by both plants consists of electricity and process heat, which in the case of auto-producer plants is used internally within the manufacturing process.

Figure 6.6 plots the trend of primary energy input versus final energy output. The usage of diesel engine technology appears linked with the higher electricity output compared to heat output. This situation is typical of actual diesel cogeneration systems where the power constitutes the majority of the total useful output (Kanoglu, 2009). In fact, this period also corresponds to a time when heavy industries such as glass or metallurgic industries played a predominant role in the energy economy,
therefore transforming the cogeneration plants into bottoming cycle plants, where the “waste heat” is generated in the actual manufacturing process, and then used to produce steam that drives a steam turbine that generates electric power.

Note that in Figure 6.6, the exergy equivalent for heat output is significantly smaller than its energy quantity. This is due to the exergy degradation which takes place when we transform a high-quality energy form (such as gas, oil or biofuel) into a low-quality energy form such as hot steam. The quality degradation is given by the corresponding quality factor for hot steam.

Figure 6.6 – Primary energy/exergy input mix and final energy/exergy output (electricity and heat)
for Portuguese auto-producer cogeneration plants between 1974 and 2009

6.3.4. Energy and exergy efficiencies

Figure 6.7 plots the result of Equations 6.11 and 6.13, i.e. the overall electric efficiencies for the cogeneration sector. In addition, the factor given by Eq. 6.15 is computed in order to gain a better understanding of the deviation between energy and exergy efficiencies. Figure 6.8 plots the electric efficiencies by product. In both cases, a distinction is made between auto-producer plants and main activity plants.
In Figure 6.7, it is clearly seen that auto-producer plants, i.e. the industrial plants using cogeneration, drive the overall performance of the cogeneration sector. The efficiency drop for main activity CHP plants between 1987 and 1988 is driven by a decrease in electricity produced from oil products during the same period. The most likely explanation is that the information provided by the Portuguese administration to the IEA during those two years did not reflect the true output figures, since there was no internal or external event that would have caused such a decrease. As for auto-producer CHP plants, the slight efficiency decrease is due to the beginning of accountability for biofuels. Between 1990 and 2009, the trend clearly shows an increase in energy and exergy efficiencies, which can be explained by two factors: 1) the increase of installed capacity using diesel engines with improved efficiency, and 2) the introduction of gas turbines and combined cycles from 1997 onwards. However, the introduction of gas turbines in the cogeneration energy industry appears to have had a stronger positive impact on the energy efficiency than the exergy efficiency. This phenomenon can be explained by analyzing the quality factors of the respective fuels. Since oil has a higher quality factor, it has more ability to perform useful work. The decrease in oil consumption from 2005 to 2009 – motivated by the conversion of diesel-engine cogeneration plants to gas-turbine technology – was offset both by a 74% increase in natural gas consumption, and 10% increase in combustible renewable consumption within the same period, the latter having a higher quality factor than fuel-oil.

Figure 6.8 plots the results of Equations 6.12 and 6.13, i.e. the overall efficiencies including process heat, which has already been discussed for the cogeneration sector in Section 6.3.2. The first observation is the fact that the efficiencies are substantially higher due to the revalorization of process heat, although still below 80%. However, DF is also higher, reaching almost 25% in 2005 versus 7% in the same year for electricity production. One should bear in mind that the nature of process heat will vary within the auto-producer plants, and therefore it is expected that they will represent different qualities based on their temperature and pressure, and in turn affect the overall exergy efficiency of the plant. Since this study assumes all process heat to be hot steam, the efficiencies presented should be seen as merely indicative.

Analyzing the electric efficiency by product provides us with a better understanding of the transformation efficiency of each fuel. These results are presented in Figure 6.9.

Biofuels, which are mostly for steam turbine technologies, are identified as having the lowest transformation efficiency. The increase of the transformation efficiency for oil products can be related to the technological shifts: up until 1990, back-pressure turbines were predominant, being then surpassed by diesel engine technologies with a higher power-to-heat ratio and generally higher efficiency.
Figure 6.7 – Energy and exergy electric efficiencies of the cogeneration sector in Portugal between 1974 and 2009

Figure 6.8 – Energy and exergy overall efficiencies (including process heat) of the cogeneration sector in Portugal between 1974 and 2009
An interesting phenomena identified in Figure 6.9 is the tendency for the transformation efficiency of natural gas to decrease, even though the consumption of natural gas for cogeneration purposes shows a constant increase. As we will discuss further, this is related to the fact that gas turbine cogeneration technologies generally have a lower efficiency when compared to diesel engines. This is due to the higher temperature difference in the heat exchanger in diesel systems, and consequently the higher exergy destruction in the component. To understand this relation better, a new study would have to be carried out to analyze the variation in the calorific content of the natural gas supplied to Portugal throughout the years, and compare it with the data provided by the IEA, whom in the lack of specific information generally applies an average gross calorific value of 38 TJ/million m$^3$. Additionally, an analysis between the energy and exergy efficiencies of gas turbine and gas engine technologies could provide a better understanding on where the losses are located.

In the following section, a brief discussion is presented on the energy and exergy analysis of cogeneration plants using different technologies, namely diesel engines and gas turbines. Main sources of exergy losses are identified and efficiencies are compared.

### 6.4. Energy and Exergy Analysis in Cogeneration

In 2009, Kanoglu et al conducted a performance assessment of various building cogeneration systems, comparing energy and exergy efficiencies. The CHP plants considered included steam-turbine system, gas-turbine system, diesel-engine system and geothermal system. It was found that diesel-engine and geothermal systems appeared to be more thermodynamically attractive due to higher exergy efficiencies when compared to the steam-turbine and gas-turbine systems (Kanoglu et al, 2009). Furthermore, large diesel engine-cogeneration systems were particularly deemed as
well suited to applications that require a relatively high proportion of electrical power compared to thermal products.

6.4.1. Exergy analysis of diesel engine and gas turbine cogeneration plants

In order to understand the impact of the process heat on the exergy efficiency, we can analyze the relation between the latter and the transfer of process heat. Equation 6.3 can also be defined according to Equation 6.16:

\[
\varepsilon_{cogen} = \frac{E_{x_{out}}}{E_{x_{in}}} = \frac{W_{net, out} + \dot{E}_{x_{process}}}{E_{x_{in}}} = 1 - \frac{\dot{E}_{x_{dest}}}{E_{x_{in}}} \tag{6.16}
\]

where \(\dot{E}_{x_{dest}}\) is the exergy rate destroyed and \(\dot{E}_{x_{process}}\) is the exergy transfer rate associated with the transfer of process heat, \(\dot{Q}_{process}\), which can also be expressed as (Kanoglu et al, 2009):

\[
\dot{E}_{x_{process}} = \int \delta \dot{Q}_{process} \left(1 - \frac{T_a}{T_i}\right) \tag{6.17}
\]

where \(T\) is the instantaneous source temperature from which the process heat is transferred. It is assumed that the functional relationship between \(T\) and \(\dot{Q}_{process}\) is known. For a diesel engine cogeneration plant, the process heat is utilized by the transfer of heat from the working fluid exiting the internal combustion engine, to a secondary fluid in a heat exchanger (Figure 6.10). In a gas turbine cogeneration plant, the steam generated in the combustion chamber is used by the turbine to produce work. The exhaust from the turbine then runs through a heater where the heat transfer occurs.

Figure 6.10 – Topping cogeneration system with a) diesel engine and a heat exchanger for steam production, and b) gas-turbine engine.

Taking into account the state figures shown in Figure 6.10, the energy and exergy efficiencies of the cogeneration plants can be written as follows, where \(m_{water}\) is the mass flow of water:
The main difference between both systems is the temperature variation in the heat exchanger. In studies carried out by Kangolu et al (2005) and Ozkan et al (2010), it was found that, empirically speaking, the water inlet temperature in the diesel engine system (c) is generally higher than the water inlet temperature for a gas-turbine cogeneration plant (6). Simultaneously, the outlet temperature for the diesel engine-based cogeneration plant (d) is lower than outlet temperature (7) (Table 6.6). Consequentially, since temperatures are proportional to the enthalpies in each point and \( T_d - T_c < (T_f - T_a) \), it was found that diesel engine-based cogeneration plants have a higher energy efficiency compared to gas turbine-based cogeneration plants, i.e.:

\[
\eta_{cogen,diesel} > \eta_{cogen,gas}
\]  

(6.22)

Diesel engine systems are more efficient than gas turbine systems, since they have a higher electrical performance. A serious problem of the diesel fuel and heavy fuel which are used in diesel cogeneration are their high percentage of sulphur and it becomes worse when the high cost of the sulphur elimination in the diesel engine cogeneration is considered (Abusoglu et al, 2008).

However, when performing an exergy analysis, it was found that the exergy efficiencies for the fossil-fuel systems are lower than their energy efficiencies. These relations are better described in Figure 6.9. Although the lower heating value and chemical exergy of fuels are approximately equal, the exergy outputs are smaller than the energy outputs.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Steam co-generation</th>
<th>Gas-turbine cogeneration</th>
<th>Diesel-engine cogeneration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet temperature of hot fluid to heater (°C)</td>
<td>249</td>
<td>303</td>
<td>400</td>
</tr>
<tr>
<td>Exit temperature of hot fluid from heater (°C)</td>
<td>212</td>
<td>211</td>
<td>111</td>
</tr>
<tr>
<td>Inlet temperature of water to heater (°C)</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Exit temperature of water from heater (°C)</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Net power output, ( W_{net} (KW) )</td>
<td>10,000</td>
<td>10,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Heating supplied, ( Q_{out} (KW) )</td>
<td>13,500</td>
<td>13,500</td>
<td>13,500</td>
</tr>
<tr>
<td>Exergy input to the plant ( \dot{W}_{ex} (KW) )</td>
<td>50,960</td>
<td>52,000</td>
<td>45,020</td>
</tr>
<tr>
<td>Total exergy destruction in the plant, ( \dot{E}_{a} (KW) )</td>
<td>39,200</td>
<td>40,240</td>
<td>23,860</td>
</tr>
<tr>
<td>Exergy efficiency, ( \eta_{ex} )</td>
<td>47.8</td>
<td>46.8</td>
<td>78.2</td>
</tr>
<tr>
<td>Exergy efficiency, ( \eta_{ex} )</td>
<td>23.1</td>
<td>22.6</td>
<td>47.7</td>
</tr>
</tbody>
</table>

Table 6.6 – Energy and exergy analysis for three different cogeneration systems (Kaushik et al, 2011)
Furthermore, in 2009, Kanoglu et al set out to investigate effects of some parameters on the energy and exergy efficiencies of cogeneration plants, such as pressure from the steam withdrawn from the turbine for the heater. It was found that the higher the temperature steam (and, consequentially, the pressure), the lower the energy and exergy efficiencies. Using a high temperature steam for the heater represents the use of higher quality energy for a low-quality job (Kanoglu, 2009). Additionally, this also means that heat transfer between the steam and the water in the heat exchanger occurs at a higher temperature difference, resulting in higher exergy destruction in the heater. By extracting steam at a lower pressure there is a higher enthalpy drop across the turbine, which results in higher work output from the turbine.

For gas-turbine and diesel-engine cogeneration plants, it was found that as the water temperature at the exit of the heater increases, both the energy and exergy efficiencies increase as well (Kanoglu, 2009). This can be explained mainly by the increase in the heating rate. Additionally, the increase in energy efficiency is higher than in exergy efficiency, as also seen in Figure 6.7 for the Portuguese cogeneration sector. This phenomenon can be explained by analyzing Eqs. 6.7 to 6.10. In all the equations, the denominator remains almost constant, since the quality factor is close to one. The main difference is seen in the numerator: the energy efficiency involves heating rate while exergy efficiency involves exergy rate of heating in addition to power output. Because the exergy rate of heating is a fraction of the “normal” heating rate, the energy efficiency increases at a greater rate than the exergy efficiency when the heating rate is increased. Figure 6.9 shows the results obtained in Kanoglu et al’s study.

The exergy analysis above explains why diesel cogeneration systems should only be selected when the thermal demand is small compared to electrical demand, since the high quality (fuel) to low quality (process heat) degradation causes a substantial decrease in exergy efficiency. Nevertheless, economic factors should also be taken into account.

In conclusion, the energy and exergy efficiencies are closer when the temperature of the product heat is higher, and deviate more as the temperature of the product heat decreases toward the reference environment temperature (Rosen et al, 2005). The energy and exergy losses for such systems are identified to be in different locations and due to different causes, which we will discuss now.
Figure 6.11 – Effect of water temperature in the a) gas-turbine cogeneration plant, and b) diesel-engine cogeneration plant on the energy and exergy efficiencies and the rate of heating (adapted from Kanoglu et al, 2009).

Diesel engine cogeneration plant

The Grassmann diagram for a diesel engine plant, based on an existing plant in Turkey in 2008, is presented in Figure 6.12. In this study, carried out by Abusoglu and Kanoglu, the exergetic efficiency of the plant was found to be 40.6%. The diesel engine was identified as the component with the highest exergy destruction rate (almost 46% of the total exergy input and 81% of the total exergy destruction in the plant). This is mostly due to the highly irreversible combustion process, heat losses from the engine and friction. However, the least efficient components of the plant were the waste heat boiler and condenser, with exergetic efficiencies of 11.4% and 16.6%, respectively. The intercooler had an exergetic efficiency of 26.3%. Exergy destructions in these heat exchange units in the plant are mainly due to the high average temperature difference between the two unmixed fluid streams. On the other hand, Figure 6.10 shows that the exergy destruction rate in the lubrication oil cooler is very low. This is due to the cooling of lubrication oil using low-temperature water.

The exergetic performance of the turbocharger was found to be sufficient, since the exergetic efficiencies of the compressor and turbine were calculated as 82.6% and 88.1%, respectively.
Figure 6.12 The rate of exergy destructions of the components of diesel engine powered cogeneration system in Turkey, compared with fuel exergy input to the system, net electricity output and net steam output (adapted from Abusoglu et al., 2008).

Gas turbine cogeneration plants

Ozkan et al. performed an exergy analysis on a gas turbine cogeneration plant in Turkey in order to determine which component of the system should be revised first in order to improve the efficiency of the plant and decrease exergy loss. By applying a second law analysis to each component, it was found that the highest exergy loss – or unused potential to generate useful work - took place in the heat exchanger (44.44%), and the component with the lowest exergy loss was the compressor (2.03%). Besides the heat exchanger, the combustion chamber (29.59%) and the steam boiler (18.68%) were also appointed as components needing improvement in order to increase the overall efficiency (Ozkan et al., 2012).

In 2009, Rosen et al. conducted a similar study and found that the main losses were associated with the boiler, the turbines, the heat exchangers, the electrical generator and transformer, the stack gas and the pumps (Rosen et al., 2009).

Huang et al. performed an exergy analysis on a cogeneration system with steam-injected gas turbine. By specifying the balance equations of mass, energy, and exergy of the components, they determined the exergy loss. By taking the compressor pressure ratio, ratio of the vapor injected,
temperature of the vapor, and amount of the feed water as parameters, they wrote down the outputs of the first and second law and calculated the heat–power ratios. They also stated that while the highest exergy loss occurred in the combustion chamber, the highest exergy leakage occurred through the waste gases (Huang et al., 1990).

![Figure 6.13](image-url) – Exergy and percentage over total exergy loss per component in a gas turbine cogeneration plant (Adapted from Ozkan et al., 2012).

### 6.4.2. Exergy in Cogeneration Systems: Advantages and Limitations

In the subchapters above we have carried out the energy and exergy analysis of cogeneration plants and reflected the result on the Portuguese cogeneration industry. In Subchapter 6.4, the differences between both analyses were discussed, and it was shown why the exergy analysis is a good indicator of the “quality degradation” in the cogeneration process. The energy and exergy efficiencies equations of diesel-engine and gas turbine cogeneration plants were presented and discussed.

In this section, the advantages in assessing cogeneration systems using the exergy analysis are briefly exposed. These advantages can be summarized as follows:

- Energy efficiencies utilize energy quantities which are in different forms, while the exergy efficiencies provide more meaningful and useful results by evaluating the performance and behavior of the systems using electrical equivalents for all energy forms (Rosen et al, 2005).
- Without recognizing the quality differences in electricity and heat, as done with exergy, possible improvements in the efficiency of cogeneration plants, or in their configuration within larger energy systems, can be missed.
- Environmental benefits may not all be identified based on an energy analysis.
• The attribution of costs and environmental emissions to the products of cogeneration is normally inappropriate when based on energy, as is commonly done, but can be done much more meaningfully and rationally based on exergy (Rosen et al, 2009).

• Decisions on power plant operations are normally based primarily on economic criteria. Therefore, it is more appropriate to use also an exergy efficiency based on the exergy of the fuel in a fossil-fuel power or cogeneration system since an important part of exergy costing involves fuel cost (Kanoglu, 2007).

However, the use of exergy analysis also presents barriers. In 2011, Swedish authors Grip et al. carried out a study to evaluate the possibility of using the exergy concept in the analysis of industrial energy systems. Since cogeneration systems are mostly owned by industrial plants, the results obtained through this study could very well relate to the difficulties that owners of Portuguese cogeneration systems would encounter.

In this study, it was found that the major obstacles to the introduction of exergy are actually non-technical factors. According to the respondents of the in-depth interviews and surveys which were carried out by the authors, most missions in the industry are small to medium-sized non-energy intensive businesses, and therefore do not require this type of tool. Another reason is that exergy is felt as too difficult to use. The development of software for exergy analysis could promote its use. A third major obstacle to exergy analysis identified by the authors was the heterogeneity at a technical system level, i.e. different companies have differing conditions for the use of exergy. Lastly, the highest ranked obstacle to the use of exergy analysis was a lack of strategy. One conclusion is that the tool should be competitive in the analysis of large technical systems where it can be used as decision support for industries or society (Grip et al, 2011).
CHAPTER VII
Conclusions

In this work, energy and exergy analyses have been carried out on the Portuguese energy sector, comprising of electricity plants (i.e. conventional power plants and renewable energy technologies) and combined heat and power plants, over the period of 1960 to 2009. The main objectives were to understand the deviation between energy and exergy efficiencies, identify main losses and understand the trend in primary-to-final energy and exergy flows.

The Portuguese energy sector has been characterized in Chapter III and overall results have been presented in Chapter IV. It was found that the sectoral exergy efficiency is lower than the energy efficiency and that during the last four decades there has been a general trend for this efficiency to decrease. This is mostly due to the increase in fuel usage in the Portuguese Energy Sector, contrasting with the predominance of hydro power which was seen in the 1960’s. The exergy efficiency is expected to increase in the upcoming years with the shift to RER technologies, which generally have a higher efficiency due to the high quality of energy which is involved in the transformation.

Chapters V and VI provide a deeper analysis of the power stations (including RER technologies) and cogeneration plants in Portugal, respectively. A literature survey was carried out in order to understand where the main exergy losses associated to each plant type are located.

For conventional power plants, which in this work include renewable energy systems, hydro energy was the predominant source up until 1971, which is reflected in the high energy/exergy efficiency. Steam turbine plants were the most utilized conventional technology up until the 1990s, burning diesel, fuel-oil and coal. The lowest peak of energy/exergy efficiency was seen in 1992 (44% and 42%, respectively), driven by the decrease of hydro energy production and increase in the installed capacity of conventional steam turbine plants. In 1998 and 2003, the installment of combined cycle power plants (with a higher efficiency compared to steam turbine plants) drove the consumption of natural gas and increased the overall transformation efficiency. Together with the increase in RER technologies, the overall exergy and energy efficiencies has slightly improved since 1992, achieving 53% and 58% in 2009, respectively.

The average efficiency per plant type based on input/output data is presented in Table 5.3. Combined cycle plants achieve the highest energy and exergy efficiency (55% and 53%, respectively) whereas the lowest efficiency is attributed to the steam turbine plant burning biomass (25% and 22%, respectively). According to the literature (Wall, 1977), the main exergy losses in a
steam turbine plant occur in the combustion in the boiler, whereas an energy analysis to the same plant would identify the condenser as the component where the heaviest losses occur. Regarding renewable energy systems, the literature was surveyed to understand the difference between energy and exergy efficiencies for wind turbine power plants. The main exergy losses occur in the generator (heat loss through the thyristors) and the rotor (through heat).

**Cogeneration plants** are widely used by the industrial sector in Portugal, having accounted for more than 70% of the primary energy consumption by cogeneration plants between 1960 and 2009. Up to 1990, back-pressure turbines were the predominant cogeneration technology used in Portugal, having been replaced diesel engines in the 1990s. With the introduction of natural gas in 1997, gas turbines and natural gas engines became the new predominant technology in Portugal. According to the literature, it was found that diesel engine plants generally have a higher efficiency when compared to gas turbine plants. However, for both plant types the exergy efficiency was found to be lower than the energy efficiency, due to the low quality of process heat. Energy and exergy efficiencies are closer when the temperature of the product heat is higher, and deviate more as the temperature of the product heat decreases toward the reference environment temperature. For a diesel engine plant, the main exergy losses occur in the diesel engine due to the highly irreversible combustion process (Figure 6.12), whereas for gas turbine plants the main losses occur in the heat exchanger, followed by the combustion chamber (Figure 6.13).

Regarding primary energy usage in cogeneration plants, biofuels and waste were identified as the source with the lowest transformation efficiency, whereas oil products and natural gas have the highest efficiency (Figure 6.9).

Throughout this work, we have highlighted the relevance of applying the exergy concept to the energetic assessment of Portuguese energy production plants, since exergy gives us a much better understanding of the quality of energy involved, and in the case of specific applications enables us to localize the source of real energy losses and identify opportunities for improvement based on design, fuel type usage, temperature and pressure conditions, etc.

Sankey and Grassman diagrams for the Portuguese utility sector are presented in Appendix I for 1960, 1990 and 2009.

Since similar studies have been carried out for the utility sector in other countries (see Table 7.2), the efficiencies obtained were compared to the overall sectoral efficiency obtained in this work (see Figure 7.1). It was found that Portugal is aligned with most countries covered in the study. Countries which showed a higher exergy efficiency were Brazil (due to the increased use of hydro power and biomass [Schaeffer et al, 1987]) and Norway (due to higher usage of RER technologies [REF]). In general, countries with a higher dependency on fossil fuels show a lower exergy efficiency, whereas countries with a higher emphasis on renewable sources tend to have a higher efficiency.
<table>
<thead>
<tr>
<th>Country</th>
<th>Year</th>
<th>Average energy efficiency (%)</th>
<th>Average exergy efficiency (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norway</td>
<td>2000</td>
<td>77</td>
<td>76</td>
<td>Ertesvag (2005)</td>
</tr>
<tr>
<td>Sweden</td>
<td>1994</td>
<td>42</td>
<td>43</td>
<td>Wall (1997)</td>
</tr>
<tr>
<td>Italy</td>
<td>1990</td>
<td>43</td>
<td>37</td>
<td>Wall <em>et al</em> (1994)</td>
</tr>
<tr>
<td>Japan</td>
<td>1985</td>
<td>1</td>
<td>32</td>
<td>Wall (1990)</td>
</tr>
<tr>
<td>Brazil</td>
<td>1987</td>
<td>45</td>
<td>73</td>
<td>Schaeffer and Wirtshafter (1992)</td>
</tr>
<tr>
<td>Canada</td>
<td>1986</td>
<td>53</td>
<td>40</td>
<td>Rosen (1992)</td>
</tr>
<tr>
<td>Finland</td>
<td>1985</td>
<td>40</td>
<td>36</td>
<td>Wall (1991)</td>
</tr>
<tr>
<td>USA</td>
<td>1970</td>
<td></td>
<td>36</td>
<td>Reistad (1975)</td>
</tr>
</tbody>
</table>

Table 7.1 – Literature survey for exergy efficiencies in the utility sector for different countries

Figure 7.1 – Comparison of Portuguese energy sector exergy efficiencies with other countries according to literature

This study has been carried out using the IEA database for reference. Although the Portuguese Administration provides the IEA with the information to build this database, it is possible that some differences might exist compared to the local authority statistics, namely the National Energy Balance provided by the DGEG. These differences – which more often are simply related to the structure of the matrix and how energy inputs/outputs are accounted for – have not been considered in this study.

The energy and exergy analyses for certain plant types that were presented in this work have not been carried out specifically for Portuguese plants (at least to the author’s knowledge at the present...
time that this work is being published). A further recommendation would be to carry out this study at representative electricity and CHP plants, in order to understand the true magnitude of the exergetic losses that have been described in Chapters V and VI, and to perform a benchmarking with similar studies that have been carried out by different authors for different countries and technologies.

Renewable energy is currently the predominant type of energy production in Portugal, however little to no work has been published regarding the energy/exergy efficiency of these system types in Portugal. In this work, renewable energy has a transformation efficiency of 100% given that, according to the IEA, both primary and final energy forms of renewable sources are considered to be equivalent and of high quality (electricity). Another recommendation would be to carry out a further study covering these renewable systems in Portugal, alike what has been done for other countries (Acar, 2008; Koroneos et al, 2003; Ozgener and Ozgener, 2007; Redha et al, 2011; Pope et al, 2010).

Last but not least, cogeneration plants represent heavy industrial energy production in Portugal, where both high quality (electricity) and low quality (process heat) energy forms are required. The information in the IEA database for Portugal, as well as the information publicly available, does not provide us with a very clear and thorough understanding of how primary energy is consumed within the sector. A potentially interesting study for the future would be to gain a better understanding of the transformation efficiencies of the main industrial sectors that utilize cogeneration in Portugal, and their impact on the whole Portuguese energy economy. The data related to heat production and consumption in Portugal is worth reviewing.
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APPENDIX II - B

PORTUGAL 1960
Primary-to-final Exergy Grassman Diagram (PJ)

TOTAL PRIMARY EXERGY SUPPLY, 188,22 PJ

COMBUSTIBLE
RENEWABLES

OIL & OIL
PRODUCTS

HYDRO

COAL & COAL
PRODUCTS

CRUDE OIL

EXPORTS
(INCLUDES INTERNATIONAL BUNKERS)
(29,3 PJ)

OIL REFINERIES

POWER STATIONS

FINAL EXERGY AVAILABLE FOR CONSUMPTION

OTHER FUELS
54,5 PJ

ELECTRICITY
5,9 PJ

OIL & OIL
PRODUCTS
53,9 PJ

Losses
(1,7 PJ)

Energy Industry
Own Use
(4,3 PJ)

Combustible
Renewables

Crude Oil

Hydro/Electricity

Coal & Coal products

Oil & Oil products

Stock changes

TOTAL FINAL EXERGY: 118,34 PJ

Energy Data source: IEA 2011
SCALE: 2 PJ = 1 PJ
PORTUGAL 1990
Primary-to-final Energy Sankey Diagram (PJ)