École polytechnique de Louvain

Transitioning from EnergyScope to ExergyScope

Exploring the Effects of Exergy Taxes on Belgian Energy System

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Abstract

This thesis explores the concept of an exergy-based tax, which could incentivize lower-emission and less energy-intensive technologies. Exergy, a thermodynamic variable that integrates both the first and second laws of thermodynamics, provides a comprehensive measure of energy quality and quantity, making it a valuable indicator for energy sustainability studies.

This research contributes to assessing the impact of exergy-based taxation. This study aims to move the Belgian energy system towards one that emits less greenhouse gas emissions and consumes less energy to meet the same demand. Various tax systems, including carbon taxes, are tested and compared. These tax systems are analyzed using ExergyScope, an adaptation of EnergyScope designed to handle exergy flows instead of energy flows.

Preliminary findings suggest that exergy-based taxes are highly efficient in optimizing primary energy use and significantly reducing emissions when strategically combined with other tax systems. This study offers a foundational analysis of the effectiveness of exergy-based taxes, advocating for further research to model the broader implications of such a tax system on the international energy landscape.

Contents

Useful Notations

Thermodynamics Variables

U	Internal energy
Q	Heat
P	Pressure
V	Volume
v	Specific volume
H	Enthalpy
T	Temperature
S	Entropy
h_v	Heat of Vaporization
E	Energy
X	Exergy
W	Useful Work
$\dot{m}$	Mass flow

Other Symbols

η_{f2u}	Final-to-useful exergy efficiency
η_{p2u}	Primary-to-useful exergy efficiency
e_{2x}	Exergy Factor

Accronyms

GDP	Gross Domestic Product

0 | Useful Notations

GHG Greenhouse Gas Emissions

VAT Value-Added Tax

TD Typical Days

HVC High-Value Chemicals

PV Photovoltaic

COP Coefficient Of Performance

GWP Global Warming Potential

CCGT Combined-cycle power plants

HP Heat Pump

ICE Internal Combustion Engine

HHV Higher Heating Value

LHV Lower Heating Value

1 Introduction

The Intergovernmental Panel on Climate Change (IPPC, 2023) has repeatedly called for policymakers to make impactful decisions to mitigate climate change. Human activities, primarily through the emission of greenhouse gases, have unequivocally caused global warming, with global surface temperatures reaching 1.1°C above pre-industrial levels (1850-1900) in the decade from 2011 to 2020 (IPPC, 2023). Global greenhouse gas emissions have continued to rise, driven by unsustainable energy use, land use and land-use changes, lifestyles, and patterns of consumption and production. Despite the implementation of various policies, the projected emissions for 2035 at best remain constant rather than decreasing (IPPC, 2023).

To ensure the survival of humanity on Earth, energy policies need to be more ambitious. As highlighted by J. Ghosh, rethinking tax structures is essential for financing a transformation towards sustainability. Belgium, for instance, currently collects €8.5 billion annually through energy taxes (Eurostat) without specifically promoting the energy transition (Commission, 2020). Changing the tax system, as suggested by Szargut (2002), could alter the distribution of taxes without necessarily increasing the total tax burden. Tax collection can be rethought to encourage the reduction of products with a significant environmental impact.

Currently, international income taxes generally penalize the positive effects of human activity, through a tax on Value-Added (VAT) for example. Szargut (2002) proposes introducing taxes that target the negative effects of human activity, particularly those that harm the natural environment. Following this idea, this thesis proposes different taxes that target the loss of exergy, a measure of energy quality, thereby encouraging more sustainable energy use and reducing environmental degradation.

2

Background

EXERGY analysis presents a systematic approach to identifying inefficiencies within infrastructures and highlighting key areas for improvement. By quantifying exergy losses, this methodology provides a comprehensive metric for objectively assessing efficiency and emissions, encapsulating exergy released to the environment. This unified measure empowers decision-makers to strategically prioritize interventions, ultimately optimizing resource utilization and mitigating environmental impact (Dewulf et al., 2008).

2.1 Useful concepts

2.1.1 Evolution of Energy Utilization: From Antiquity to Modernity

Human society has greatly expanded its horizons owing to the utilization of energy. Dating back to prehistoric times, the mastery of fire stands as one of humanity's earliest forays into energy harnessing. Even before the scientific quantification of energy in units like joules and gigawatt-hours, humans tapped into various sources such as wind and hydropower for sustenance (Cottrell, 2009). In contemporary societies, primary energy sources including fossil fuels, uranium, and renewable energy play pivotal roles.

In antiquity, energy was employed directly; for instance, wood was burned for warmth, and wind was harnessed for labor. However, present-day practices involve the transformation of energy into more concentrated and portable forms, such as diesel, oil, and electricity, through various conversion processes. These transformed energies are termed final energy, representing the ultimate energy carrier utilized to fulfill specific demands (Sousa et al., 2017).

Subsequently, this final energy (definition 2.1.1) is deployed to deliver useful energy used by individuals on a daily basis. This encompasses heat emitted by an electric radiator, mechanical work propelling a vehicle, or electromagnetic radiation emanating from a light source. Useful energy (definition 2.1.2), in turn, operates within systems where it inevitably dissipates as undesired heat, exchanged for indispensable energy services like thermal comfort, illumination, and transportation. Unlike useful energy, energy services are not necessarily quantified in energy units; for instance, freight transport is often measured in ton.km.

Definition 2.1.1. Final energy refers to energy that is consumed by end-users for their various needs, such as lighting, heating, transportation, and industrial processes. It is the energy that is directly used to perform tasks or provide services (Madureira, 2014).

Definition 2.1.2. Useful energy refers to the portion of final energy that is actually utilized to perform useful work or provide a desired service. It excludes any energy that is wasted or lost during conversion processes or due to inefficiencies in energy systems (Madureira, 2014).

Figure 2.1 shows the energy chain with the primary, final, and useful energy to provide different services such as illuminance, cooking, or transportation. Thermodynamics emerged in the late 18th century, laying the foundation for understanding the relationships governing energy and its transformations. Today, the field of thermodynamics is built upon two fundamental principles. The first principle, the conservation of energy, asserts that energy cannot be created or destroyed but can only change forms. The second principle acknowledges the limitations of energy conversion processes, recognizing that not all energy can be converted into useful work.

The concept of energy has become central to modern economies, where energy serves as a valuable commodity exchanged for monetary value.

However, traditional energy analysis often fails to consider the constraints outlined by the second principle. This limitation highlights the importance of incorporating exergy analysis, which offers deeper insights into the efficiency and quality of energy utilization within various processes.

2.1.2 Energy and the First principle

The first law of thermodynamics asserts the conservation of energy within an isolated system, stipulating that the total energy within such a system remains constant; it cannot be created or destroyed, only converted between different forms. Energy exists in

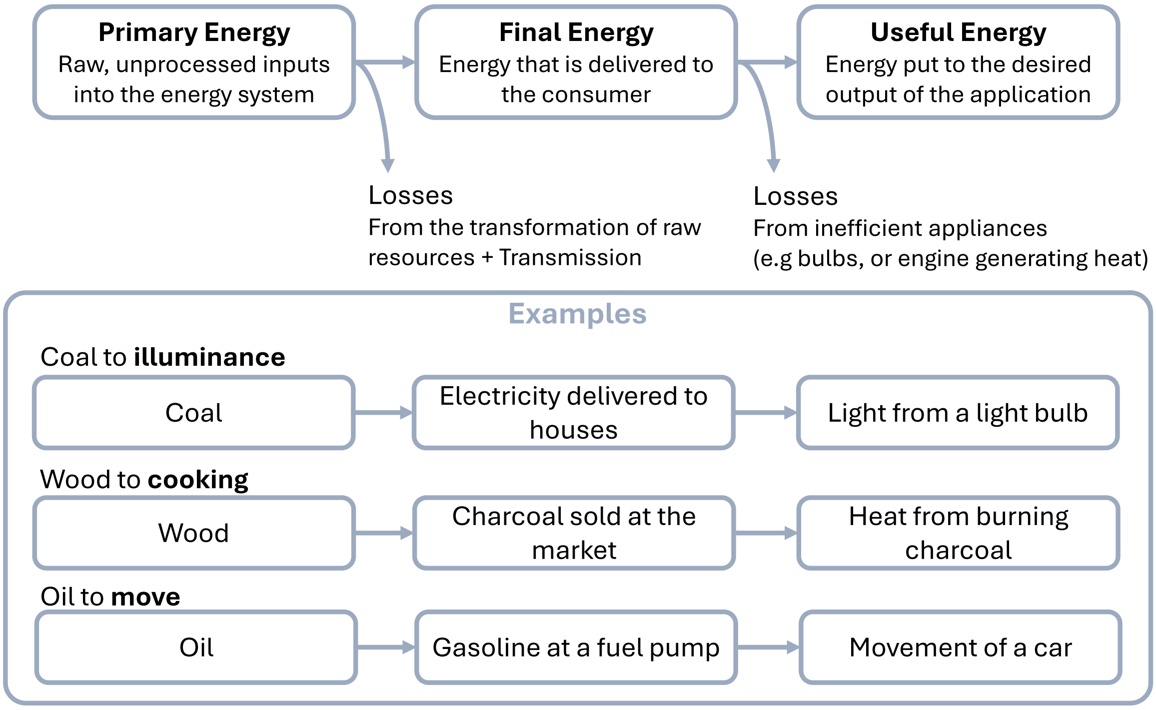


Figure 2.1 Energy chain to provide services (illuminance, cooking, transportation) (source: Our World in Data)

four principal types: potential energy, linked to an object's position in a force field (e.g., gravity); kinetic energy, associated with motion relative to a fixed frame of reference; heat; and mechanical work (Ayres et al., 1996). The last two forms of energy deserve a little more explanation.

Mechanical work involves motion against resistance, such as pressure, gravity, or friction. For example, a system expanding over a distance d against an environmental pressure P exerts work on the environment. This work is defined as $W_{p-v} = PAd = P\Delta V$, where A is the contact surface between the environment and the system, and V is the system's volume.
In addition, heat is closely related to temperature; as heat is added to a system at constant volume (or constant pressure), the temperature generally rises (except during phase changes where the temperature remains constant) (Ayres et al., 1996).

In the 19th century, the concept of heat became better-understood thanks to more microscopic analysis. It was realized that macroscopic bodies are made up of microscopic particles such as atoms and molecules, which interact with each other. Researchers found that heat is actually the result of the kinetic energy of molecular motion (Einstein et al., 1905). Meanwhile, it was discovered that potential energy is also present in molecules in the form of interatomic forces. These interatomic forces are commonly referred to as "chemical energy" (Thomson, 1888). Chemical energy can be transformed into kinetic energy (that can be transferred in the form of heat) and vice versa through chemical reactions involving atomic species.

To describe these microscopic phenomena, internal energy (U) has been defined, encompassing both chemical energy and the kinetic energy of molecular motion. This energy is linked to heat transfer and work (considered at a macroscopic level) by the conservation of energy. The first law of thermodynamics implies that the change in the system's internal energy (i.e. the chemical and kinetic energy of the molecules) is equal to the heat transferred to the system minus the work provided by the system (W) :

$$\Delta U = Q - W \tag{2.1}$$

Definition 2.1.3. The term enthalpy (H) has been introduced by Gibbs including both internal energy and the pressure-volume product, i.e.:

$$H = U + PV$$

where U is the internal energy (Ayres et al., 1996).

The change in enthalpy[1] of a closed system, at constant pressure, is equal to the heat exchanged with the exterior:

$$\Delta H = \Delta U + \Delta(PV) = Q - W + P\Delta V + V\Delta P = Q - P\Delta V + P\Delta V = Q$$

In open systems, there is an additional energy transfer at the boundaries associated with mass transfer. The energy that is associated with mass flows is enthalpy (which includes both internal energy and the flow work). The flow work is the work required to move mass in and out of the system. For open systems in steady-state (no changes in energy):

$$0 = Q - W_{ext} + (H_{in} - H_{out})$$

Implying that:

$$\Delta H = Q - W_{ext} \tag{2.2}$$

Where ΔH is the change in enthalpy between the output and the input. W_{ext} includes all types of work except the one associated with mass flows (that is not extractable). For a chemical reactor, where only flow work is produced ($W_{ext} = 0$), $\Delta H = Q$ i.e., the heat of reaction equals the change in enthalpy between products of reaction and

[1] Only changes in energy are considered. That is because the absolute quantity cannot be measured. It is the same for heat, while one often speaks of the "heat content" or "heat capacity" of a body, what can actually be measured is the flow of heat from one body to another. As far as energy forms are concerned, they are always defined as a difference in relation to a defined reference.

reactants.

Enthalpy serves as a "first law" measure of energy, as it does not reflect the quality (or exergy content) of energy.
Even if the first principle links heat and work as comparable forms of energy, distinguishing them is crucial. Work can be entirely converted into heat with 100% efficiency, but the reverse is not true. While it is feasible to convert some heat into work (via a "heat engine"), this process has limitations. This concept will be further explored by the second law of thermodynamics.

2.1.3 Entropy and the second principle

As already mentioned, the transformation of heat into work is subject to fundamental limits. This is the content of the famous "Second Law" of thermodynamics and was first understood by Carnot (1824).

For a heat engine operating in cycles to perform mechanical work, two bodies at different temperatures are needed. The body at the highest temperature is called the heat source while the one at the coldest temperature is called the cold sink. Carnot derived an expression for the maximum amount of work that could be extracted by an idealized reversible heat engine.

> **Definition 2.1.4.** A reversible cycle is one in which each transformation can be considered reversible. A reversible transformation is defined as one that can be completely reversed at each of its stages, leaving no residual change in the system or the surroundings. In the real world, thermodynamic transformations are not reversible because irreversibilities occur (presence of friction, turbulences, unrestrained expansion, mixing of dissimilar substances, etc.)

The Carnot cycle operates through four reversible transformations: expansion and compression, heat extraction ($Q_h > 0$) from the hot source (at temperature T_h), and heat rejection ($Q_c < 0$) into the cold source (at temperature T_c). Reversible heat transfer means that both the system and the heat source are at the same temperature. Carnot defines the maximum extractable work $W_{m,max}$ as follows :

$$W_{m,max} = Q(1 - \frac{T_c}{T_h}) \tag{2.3}$$

The equation 2.3 shows that the greater the temperature difference between the cold source and the hot source ($T_c >> T_h$), the greater the amount of heat that can be converted into work (Ayres et al., 1996). By showing that even in reversible processes, not all heat can be converted into work, Carnot introduced the content of the second principle.

Clausius continued his work by introducing the first mathematical formulation of the second law. To do so, he defined a new variable called entropy (S) as :

$$dS = dS_i + dS_e = dS_i + \frac{\delta Q}{T} \tag{2.4}$$

where δQ is an incremental heat flow, T is absolute temperature, dS_i is the internal production of entropy due to irreversibilities in the system (when the process is reversible $dS_i = 0$, otherwise $dS_i > 0$), and dS_e the entropy change due to heat transfer with the environment[1].

> The second law formulation provided by Clausius is : $dS \geq 0$ for any process (Ayres et al., 1996). This means that the direction of a spontaneous process never decreases the system's entropy.

Clausius formulation implies that when a system is isolated, the entropy of the system continually increases due to irreversible processes. For example, the spontaneous heat transfer from one body to another at a lower temperature is an irreversible event: heat cannot return from the cold body to the hot body without some action from the outside world.
The increase in entropy stops when the systems attain a state of thermodynamic equilibrium (see definition 2.1.5). The entropy has then reached the maximum possible value (Dincer and Rosen, 2021).

> **Definition 2.1.5.** A thermodynamic system is said to be in thermodynamic equilibrium when it is in thermal equilibrium, mechanical equilibrium, and chemical equilibrium (Knight, 2017).

The entropy can be used to prove Carnot's formulation for the maximum extractable work (Equation 2.3). Indeed, imposing that the cycle is reversible requires that the change in entropy of the cycle and its internal production are both null. The only changes in entropy occur at the cold and hot sources (no heat transfers in other reversible transformations).

The entropy change at the hot source is: $\Delta_h S = \frac{Q_h}{T_h}$

The entropy change at the cold source is: $\Delta_c S = -\frac{Q_c}{T_c}$

Imposing total entropy change equal to zero over the cycle is equivalent to imposing:

$$\Delta_h S + \Delta_c S = 0 \leftrightarrow \frac{Q_h}{T_h} = \frac{Q_c}{T_c}$$

[1]The two symbols for differential changes in a quantity, d and δ distinguish between exact (state variable) and inexact differentials (depends on the transformation path). Thus, equation 2.4 implies that the temperature is used as an integrating denominator to convert the inexact differential element of heat into the exact differential of the state function S.

From the law of conservation of energy, we can deduce that:

$$W_m = Q_h - Q_C = Q_h(1 - \frac{T_h}{T_c})$$

Carnot's contribution concerning the maximum work that can be extracted from a heat engine demonstrated that even in a reversible cycle, part of the heat reversibly extracted from the hot source must be transferred to the cold source. This necessity stems from the need to export the entropy received from the hot source.

Now that entropy and enthalpy have been well explained, the exergy can be introduced since it is the physical quantity of interest in this work.

2.1.4 Exergy : The measure of energy quality

In 1889, Louis-Georges Gouy introduced the concept that a system's capacity to perform work could be expressed by a function combining its fluid's internal energy and the thermodynamic characteristics of its environment. Gouy initially termed this function "useful" energy or "available" energy, a term that was later adopted and further developed by Zoran Rant as exergy (definition 2.1.6).

> **Definition 2.1.6.** Exergy is the maximum amount of work that can be obtained from a system (a resource or a flow) when it is brought to equilibrium with the surrounding environment through a reversible process (Manso et al., 2017).

To define exergy, it is first necessary to determine the maximum work extractable from a system. First of all, maximum work is calculated for closed systems. Then, this definition will be generalized to open systems, which are the systems considered in this work.
For closed systems, the work is given by:

$$W = W_{\text{others}} + W_{p-v}$$

where W_{others} includes all types of work except for the work associated with volume changes.

According to the first law of thermodynamics:

$$\Delta U = Q - W_{\text{others}} - W_{p-v}$$

From the second law of thermodynamics:

$$dS = \frac{\delta Q}{T} + dS_i$$

The definition of the maximum work requires that a reversible process is considered. dS_i is then assumed to be zero. Hence, the heat exchange is:

$$Q = TdS$$

The expression for exergy, which represents the maximum work not including the work associated with volume changes, is then [1]:

$$X = -W_{\text{max, others}} = \Delta U - T\Delta S + P\Delta V \tag{2.5}$$

This expression can be extended to open systems. As mentioned previously, in the context of such systems, mass flow can occur, resulting in flow work. The energy balance accounting for this work has been provided in equation 2.2 (open system in steady state). Given the reversibility of the process, we can assume $Q = TdS$.
The maximum work provided by an open system is then defined as :

$$W_{max} = T\Delta S - \Delta H \tag{2.6}$$

Exergy is the maximum work that can be extracted from a state (H, S) of disequilibrium with the environment (H_0, S_0). Furthermore, it is assumed that all heat is exchanged during that process at the temperature of the environment T_0 (Ayres, 2003).

The expression for exergy, which represents the maximum work not including the work associated with mass flow, is then:

$$X = -W_{max} = (H - H_0) - T_0(S - S_0) \tag{2.7}$$

With H_0, S_0, and T_0 respectively the enthalpy, the entropy, and the temperature of the reference environment.

Equation 2.7 gives a new interpretation for the entropy. The entropy generated or created in a process is a measure of the extent to which energy becomes unavailable, i.e. the exergy that is depleted (Ayres et al., 1996).

Exergy of the reference environment

Equation 2.7 requires the definition of the environment ($\cdot_0$). In this work, the reference is defined as the atmosphere. Atmospheric conditions vary in space and time. For the coherence of this work, it is essential to define a reference atmosphere. Conventional thermodynamic parameter values for the environment set the temperature T_0 and the pressure P_0 as follows:

[1] The opposite value is used because the work received by the environment W_{envi} is now considered (extractable). It is no longer the work produced by the system W_{syst}. $W_{envi} = -W_{syst}$.

$$T_0 = 15°C \quad \text{and} \quad P_0 = 10^5 Pa \tag{2.8}$$

Furthermore, given the omnipresence of water on Earth, it is assumed that the atmosphere is water-saturated air. In this work, it will be assumed that the reference environment is air with the following chemical composition.

Component	Concentration		Ref
Nitrogen	$[N_2]$	0.7667	
Oxygen	$[O_2]$	0.2064	
Water	$[H_2O]$	0.0170	Martin and Wauters
Argon	$[A]$	0.0095	
Carbon Dioxide	$[CO_2]$	0.0004	

Exergy of fuels

An inert (that does not react with the environment) fluid exhibits an exergy of zero when it is at the reference pressure P_0 and temperature T_0. However, for a non-inert fluid, its exergy at standard conditions ($T_1 = 15°C$ and $P_1 = 100kPa$) is non-zero (Martin and Wauters, 2009). This is due to three distinct disequilibrium with the reference state:

1. Chemical mobility, which involves the fluid's ability to undergo reactions with certain components present in the air.
2. Phase mobility, describing the tendency of water vapor to condense due to air saturation.
3. Diffusion mobility, which describes the tendency of flue gas components to reach their partial pressures in the reference atmosphere if they deviate from this state.

To estimate the exergy contained in a fluid, we must determine the maximum work that can be extracted when the fluid returns to equilibrium (definition 2.1.5) with the atmosphere. This process involves chemical reactions.

In this work, the chemical reactions considered are combustion reactions to bring the fuels back to equilibrium. The only components involved are oxygen, hydrogen, and carbon. The reaction yields water and carbon dioxide as products. To achieve equilibrium with the environment, all water vapor must be completely condensed (the reference environment is saturated), and carbon dioxide must be fully diluted in the atmosphere.

Coming back to equation 2.7, the exergy of a fuel at standard conditions ($T_1 = T_0 = 15°C$ and $P_1 = P_0 = 100kPa$) comprises two terms. The first one ($H_1 - H_0$) corresponds to the difference of enthalpy between the reactants and the products of combustion both at temperature T_0 and pressure P_0. By definition, this corresponds to the Higher

Heating Value (HHV)[1] of the fuel.

The second term ($T_0(S_1 - S_0)$) accounts for the difference in entropy (which can be found in the thermodynamics tables) between the reactants and products (water and carbon dioxide) of combustion.

This calculation allows us to estimate the exergy contained in the different combustibles (see Table 2.1).

Combustible	Energy content LHV [MJ/kg]	Exergy content [MJ/kg]	$e_{2x,i}$	Ref.s
Methane	50.15	52.16	1.04	Martin and Wauters
Oil	40.6	43.04	1.06	Martin and Wauters
Hydrogen	120.90	118.79	0.98	Martin and Wauters
Biomass	15.4	17.09	1.11	Felício et al.
Methanol	19.9	19.84	0.98	Al-Breiki and Bicer
Ammonia	18.6	22.4	1.2	Al-Breiki and Bicer

Table 2.1 Energy and Exergy Content of the different fuels used in this work

Table 2.1 shows that the energy content is defined using the Lower Heating Value (LHV). This convention is commonly adopted because, during combustion, the resulting temperature typically causes water to remain in a vapor state, unlike the liquid state of the fuel. Consequently, a portion of the heat released by the fuel is used to vaporize the water. However, a heat exchanger can be added after the combustion process to recover some of the heat contained in the flue gases by condensing the water. Using LHV instead of HHV is then a matter of convention for the energy content. This work uses the LHV convention, excluding any additional heat recovery after the combustion phase. The relationship between LHV and HHV is given by:

$$LHV = HHV - h_{v,w}$$

Where $h_{v,w}$ represents the water's heat of vaporization.
From an exergetic point of view, the exergy content includes the heat of vaporization. To reach equilibrium with the environment, the water needs to be fully condensed after the combustion.
The difference between the exergy and energy content is then given by:

$$X_i - E_i = h_{v,w} - T_0 \Delta S$$

As shown in Table 2.1, the exergy content is usually higher than the energy content. However, if the HHV is used for the energy content, the term related to irreversibilities

[1]The Higher Heating Value (HHV) is the quantity of energy released by the complete combustion of a unit of fuel, the water vapor is assumed to be condensed, and the heat is recovered. (Basu, 2010)

($-T_0 \Delta S$) implies that the exergy content is lower than the energy content.

In the following section the exergy factor e_{2x} is defined as the the ratio between the exergy (X) and the energy (E) content.

$$e_{2x,i} = \frac{X_i}{E_i}$$

To find the exergy content of a fluid X_i, the exergy factor can be used :

$$X_i = e_{2x,i} E_i \tag{2.9}$$

Exergy factor of heat energy

The Carnot cycle defines the maximum amount of work that can be extracted from a hot source. Considering a Carnot cycle operating between a hot source at temperature T and a cold source which is the environment at temperature T_0, the work produced W thanks to the calorific action Q is given by :

$$W_{carnot} = Q(1 - \frac{T_0}{T}) \tag{2.10}$$

Since the maximum extractable work is also the exergy content of a fluid, Carnot also defined the exergy content of heat.

To transform the energy content of a heat source into exergy content, the exergy factor $e_{2x,h}$ can be applied and is defined by :

$$e_{2x,h} = (1 - \frac{T_0}{T}) \tag{2.11}$$

with T the temperature of the source considered (in Kelvin).

In the next sections, four different heat sources will be used.

1. High-Temperature heat used in the industrial sector (HT Heat).
2. Medium-temperature heat provided by electrical resistance in the residential sector (MT Heat Res.)
3. Low-temperature heat for hot water (LT Heat HW).
4. Low-temperature heat for heating systems (LT Heat H).

The three first categories are required on a constant basis throughout the year. The environment temperature is then 15°C (cfr section 2.8). For the category of LT Heat H, the environmental temperature is taken as 5°C, i.e. the average temperature of the winter months in Belgium (Weather in Belgium).

Exergy factor of cold energy

Definition 2.1.6 needs to be clarified to enable the definition of cold exergy. By definition, the energy of a system in a given state is the maximum amount of work that can be produced (or the minimum amount of work required) when the system is returned to equilibrium (Thirumaleshwar, 1979). Heat transfer from a cold source to a warmer source (environment) is not the spontaneous direction of transfer. This process requires work. It follows that the exergy of a cold source (at temperature $T_c < T_0$) is defined as the minimum work required to bring the cold source back to equilibrium with the environment.

This definition comes from a reverse Carnot Cycle (see Figure 2.2b). Imposing that the cycle is reversible requires that the change in entropy of the cycle and its internal production are both null.

$$\Delta U = Q_h - Q_c - W = 0$$

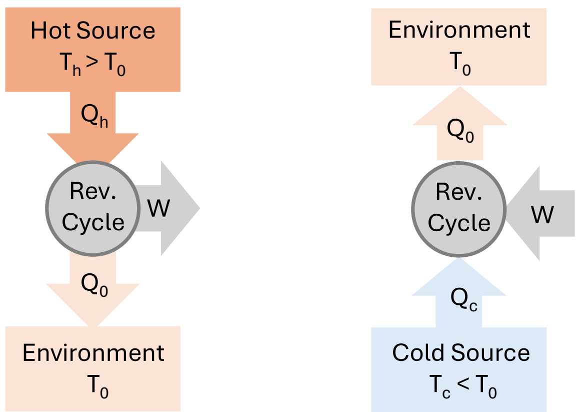
$$\Delta S = 0 \rightarrow \frac{Q_c}{T_c} = \frac{Q_h}{T_h}$$

The exergy of cold is then :

$$X = Q_c(\frac{T_h}{T_c} - 1)$$

The exergy factor is then defined as :

$$e_{2x,c} = (\frac{T_0}{T} - 1) \tag{2.12}$$



(a) Heat Source **(b)** Cold Source

Figure 2.2 The exergy of heat is the maximum extractable work from a heat engine and the exergy of cold is the minimum work required to extract it from the cold source.

In the next sections, three different cold sources will be used.

1. Low-temperature cooling needed in the industrial sector
2. Low-temperature cooling needed for food cooling

3. Cooling needed for air conditioning.

Once again, if the source is needed during the whole year (source 1 et 2) 15°C is taken as the reference temperature. Otherwise, for the air conditioning, 25°C is assumed for the reference temperature (assumed to be the temperature at which air conditioning is required (Felício et al., 2023)).

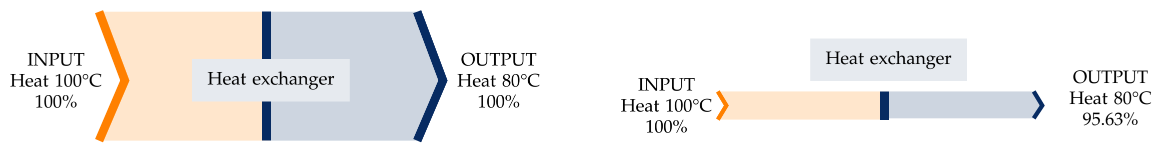
Table 2.2 summarizes the different service and ambient temperatures for each cold and heat source used in this work.

Heat/Cold Source	Service T° [°C]	Ambient T° [°C]	Exergy Factors : $e_{2x,i}$
HT Heat	500	15	0.63
LT Heat H	40	5	0.11
LT Heat HW	50	15	0.11
MT Heat Res.	100	15	0.24
Space Cooling	20	25	0.02
Food Cooling	-10	15	0.10
Industrial Cooling	-10	15	0.10

Table 2.2 Exergy Factors of the heat and cold sources used in this work (with their ambient and service temperatures).

2.1.5 Comparison between energetic and exergetic approaches

The comparison between the energetic and exergetic approaches can be illustrated in a heat exchanger. Figure 2.3 shows the energy and exergy flow between the input and output of a system transferring heat between fluids at differing temperatures. Both diagrams show the transfer of the same physical quantity but seen from an energetic or exergetic point of view. While energy conservation dictates that a well-insulated heat exchanger should incur no energy losses, exergy analysis reveals otherwise. This is attributed to the destruction of exergy that occurs between energy carriers of varying qualities (high-quality energy at elevated temperatures and lower-quality energy at reduced temperatures).



(a) Energy flow **(b)** Exergy flow

Figure 2.3 Comparison between energy and exergy flow in a heat exchanger

Given Q_h the energy (heat) transferred from the hot fluid ($\cdot_h$) to the cold fluid ($\cdot_c$) and Q_c the heat received by the cold fluid, the energetic balance (ΔE) can be written as:

$$\Delta E = E_h - E_c = Q_h - Q_c = 0$$

$$Q_h = Q_c = Q$$

The exergy balance is given by :

$$X_h - X_c = Q\Big((1 - \frac{T_0}{T_h}) - (1 - \frac{T_0}{T_c})\Big) = 0.044Q$$

This example shows how the exergetic approach offers rapid identification of the dissipations caused by irreversibilities. This analysis is helpful when trying to increase the efficiency of a system.

Now that its definition has been clarified, exergy emerges as a powerful concept for assessing irreversibilities in transformations—a crucial initial step before endeavoring to enhance efficiency. However, exergy analysis also demonstrates its potency at the scale of a country, as elaborated in the following section.

2.2 Societal exergy study

Exergy emerges as a potential primary concept for elucidating the chain from the energy source to services. Figure 2.1 shows the energy chain. It is also possible to adapt it into an exergetic chain simply by converting all forms of energy (primary, final, and useful) into their ability to produce work. The concept of useful exergy can then become interesting to quantify user demand.

Definition 2.2.1. Useful exergy is the minimum amount of work required to produce a given end-use. It quantifies the effective amount of exergy that is delivered to a final function, e.g., the mechanical work from electricity used by a metal-bending machine or the exergy of the heat provided to an industrial process by a steam boiler (Santos et al., 2018).

Useful exergy offers intriguing insights into systems and facilitates straightforward comparisons between them, even in cases involving both heat and work. The exergy balance method effectively evaluates various terms by considering their quality, namely their capacity to generate work (Serrenho et al., 2014).

The historical and political factors influencing the predominance of energy over exergy in describing pre-service transformations are significant considerations. Placing exergy at the forefront of the public debate is an ambitious endeavor, as it necessitates a widespread understanding of thermodynamics among the general public. This challenge likely contributes to the continued prevalence of energy as the primary concept in contemporary discourse.

However, this work aims to explore and assess the potential benefits of utilizing exergy for societal studies despite these challenges. By delving into the advantages and implications of adopting an exergetic approach, it seeks to shed light on its potential contributions to our understanding of complex systems and inform future discussions and decisions regarding energy utilization and resource management.

2.2.1 Exergy Analysis: Evolution, Applications, and Future Directions

In 1974, Reistad introduced the concept of societal exergy study. Since then, interest in exergy analysis has grown for two primary reasons. Firstly, it has been used to characterize historical or future energy consumption patterns. Secondly, it has been employed to explore the role of exergy efficiency in economic growth.

Sousa et al. (2017) provided a partial review of research conducted over the past four decades. From these studies, exergy analysis emerged as a relevant tool for various purposes. Exergy allows for the computation of an aggregate exergy efficiency that is meaningful at the scale of a country, as demonstrated by Felício et al. (2023). Unlike energy aggregate efficiency, which may overlook the nuances of diverse heat and work technologies, exergy efficiency comprehensively considers both heat and work. However, exergy analysis appropriately accounts for such instances, enabling meaningful comparisons across different countries, irrespective of variations in their technologies. Moreover, unlike energy efficiencies (e.g. heat pump), exergy efficiencies are always bounded by 100%, simplifying the identification of improvement potential [1].

Moreover, exergy analysis plays a crucial role in comprehending societal evolutions, particularly in terms of the economy.

Exergy and Economy

Ayres (2003) initially explained economic growth through improvements in final-to-useful exergy efficiency since the Industrial Revolution.

> **Definition 2.2.2.** The final-to-useful exergy efficiency η_{f2u} refers to the efficiency of converting final exergy into useful exergy.

Serrenho et al. (2014) furthered this work, showing that there's a significantly greater correlation between useful exergy demand and Gross Domestic Product (GDP) than between final or useful energy and GDP. They noted that the ratio (named intensity) of useful exergy demand to GDP remained relatively constant over time. This constancy suggests that despite fluctuations in economic activity, the useful exergy intensity (see

[1] In some cases, exergy efficiencies surpass energy efficiencies (see Annex 1.1). In general, technologies that use heat as an input have a higher exergy efficiency than energy efficiency.

definition 2.2.3) remains relatively constant.

Definition 2.2.3. Energy/Exergy intensity is utilized as an indicator of economic performance or even as a measure of the productivity of energy uses. It is calculated as units of energy/exergy per unit of GDP (Serrenho et al., 2014).

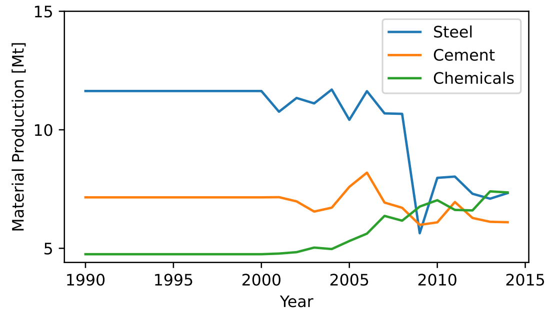
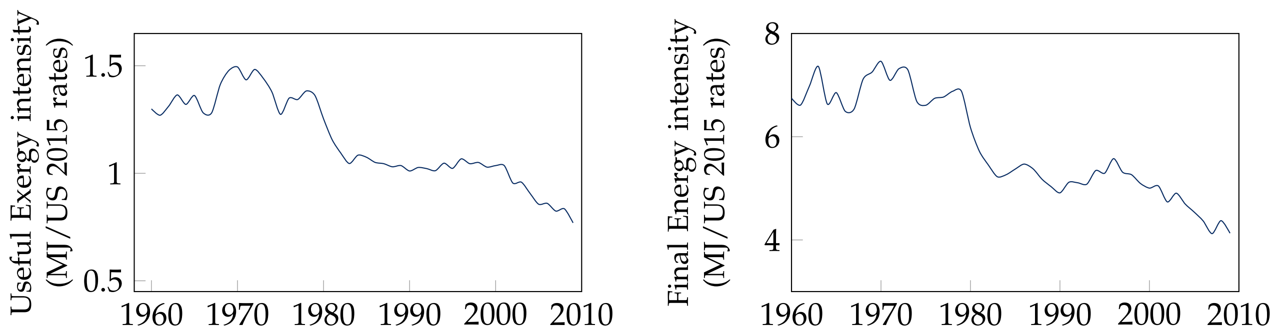


Figure 2.4 Material Production in Belgium. After 2006, steel and cement industries decline in favor of chemicals (EUCalc).

Serrenho et al. also demonstrated that structural changes in the economy or the outsourcing of energy-intensive activities could alter this relationship. For example, in the 1970s, Figure 2.5a shows an abnormal trend in Belgium probably associated with the oil crisis that occurred during those years. This led to structural changes in energy use, stimulated by high oil prices in the seventies and eighties. This rise in prices led to an increase in energy efficiency, particularly in the consumption of petroleum products by households and businesses (Belgium, 2006).

Then, between 1990 and 2000, there was no structural change in the industry in Belgium (EUCalc), leading to a constant ratio between GDP and useful exergy demand. In contrast, the final energy intensity displayed variability, as shown in Figure 2.5b during those years.

After 2006, steel and cement production declined in favor of chemical production (see



(a) Useful exergy intensity

(b) Final energy intensity

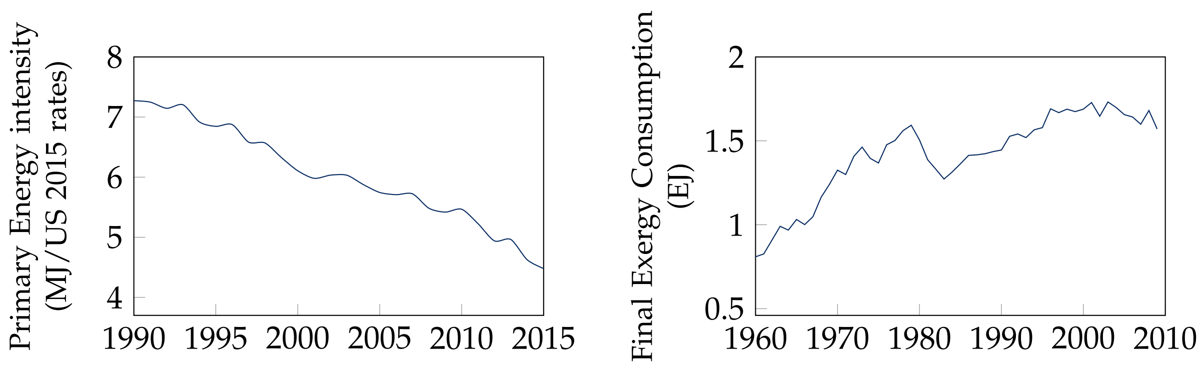
Figure 2.5 Useful Exergy (Serrenho et al.) and Final Energy (EUCalc) Intensity Evolution between 1960 and 2009 in Belgium. Useful exergy intensity indicates a relatively stable trend, especially noticeable between 1990 and 2000. In contrast, the final energy intensity displayed variability.

Figure 2.4). Instead of using coal and natural gas like the other two, that type of industry uses more electricity and gas, resulting in a more efficient sector.

These observations lead to a decrease in useful exergy intensity after the year 2000 (see Figure 2.5a). These observations open up new prospects for future research. Indeed, examining past trends helps to understand which activities might disappear and how they would impact exergy demand, GDP, and primary energy use.

Exergy and sustainability

The societal exergy studies of Serrenho et al. and Ayres et al. have incited further research to highlight sustainability concerns. First, Brockway (2016) showed how despite the increase in aggregate efficiency, the final exergy consumption always increased (see Figure 2.6b). This suggests that human society continues to consume more and more exergy but this can not be unlimited. Secondly, Haberl et al. (2020) showed that decoupling useful exergy from GDP growth is an inevitable step towards respecting the planet's limits. To fully understand those claims, it is essential to examine the underlying phenomena driving them.



(a) Primary energy intensity (EUCalc) shows a decoupling between energy use and GDP.

(b) Final Exergy Consumption (Serrenho et al.) has globally increased since 1960

Figure 2.6 Primary Energy and Final Exergy Evolution in Belgium.

Firstly, Santos et al. (2021) elucidates how increases in final-to-useful exergy efficiency contribute to GDP growth. This is primarily because higher efficiency translates to lower costs per unit of useful exergy. Ayres identified a trend of increasing efficiency in converting final exergy to useful exergy since the 1960s, a pattern that can be generalized to other countries. Consequently, the rise in efficiency has likely contributed to higher GDP levels.

As GDP is tied to useful exergy, it follows that useful exergy consumption has also increased. This interplay between improved efficiency and higher useful exergy consumption suggests that the demand for final exergy might increase or stabilize, depending on the net effect of these factors.

However, as evidenced by Brockway (Figure 2.6b), final exergy use in Belgium has increased. The phenomenon observed, wherein increased efficiency leads to lower costs, subsequently driving GDP growth and encouraging greater utilization of efficient technologies, is precisely described as the rebound effect (Parrique, 2019). The rebound effect is depicted in Figure 2.7 and represents a significant challenge to reducing consumption. Despite initial efficiency gains, the rebound effect often results in increased energy usage, thereby negating the anticipated reductions in overall energy consumption. This phenomenon highlights the complexities and unintended consequences in the pursuit of energy efficiency and sustainability.

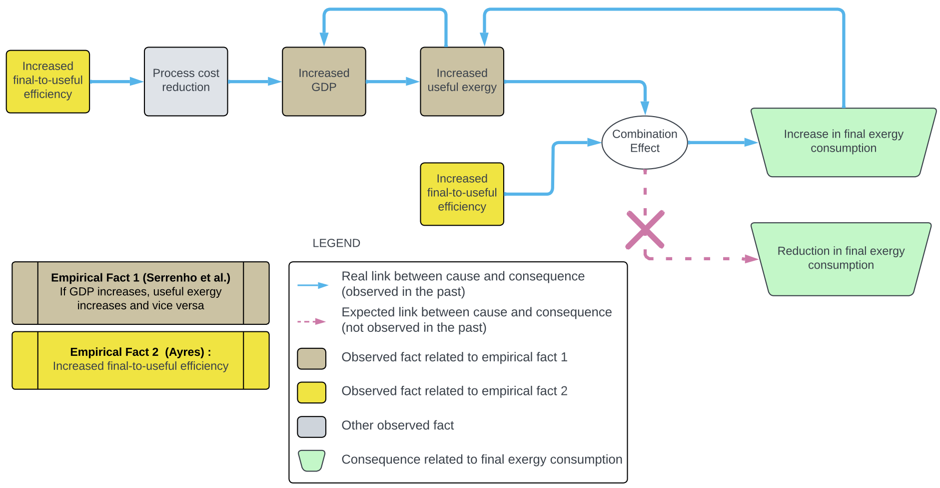


Figure 2.7 Rebound effect. The increase in final-to-useful efficiency does not, as expected, lead to a reduction in useful exergy consumption, but rather to an increase due to greater use of efficient technologies (because they cost less).

Moving on to the imperative of decoupling useful exergy demand from GDP growth, Haberl et al. demonstrates that if this is not the case, the primary energy supply will increase. Indeed, since 1990, an increase in useful exergy demand has not led to a specific increase in primary energy consumption. Indeed, the primary-to-useful efficiency always increased, leading to a decoupling between GDP growth and primary energy supply (see figure 2.6a).

> **Definition 2.2.4.** The primary-to-useful exergy efficiency η_{p2u} refers to the efficiency of converting primary exergy into useful exergy.

However, this decoupling can only occur to the extent that the efficiency of converting primary energy into useful exergy can be increased (Serrenho et al. and Ayres). However, this efficiency is limited by thermodynamics. Thus, if there is no decoupling between GDP and useful exergy, an increase in GDP will lead to an increase in useful exergy, which in turn will lead to an increase in primary energy supply if the primary-to-useful ratio reaches its maximum. Haberl et al. has shown that too great an increase in resources would lead to an ecological catastrophe and that it would therefore be preferable to decouple the demand for useful exergy from GDP. However, as mentioned above, this has never been done. Is this societal change really possible?

Despite these challenges, there are avenues for improving conversion efficiency today. Besides the imperative to decouple GDP from exergy demand for a more sustainable society, technical research must continue to promote efficiency improvements. Policy-makers also play a crucial role in ensuring that such advancements do not inadvertently lead to increased demand (Vivanco et al., 2016).

In this context, researchers have demonstrated that conversion efficiency, particularly final-to-useful exergy efficiency, can be based on two levers of action. First, the improvement of technologies efficiency involved in final-to-useful conversion (Ayres, 2003). Secondly, the composition of the final energy mix used to meet various demands also influences efficiency. For instance, Pinto et al. (2023) focused on electricity consumption at a world level, illustrating how electrification could increase final-to-useful exergy efficiency. Projections indicate a substantial escalation in global electricity consumption, from 19% in 2022 to over 40% of total final exergy consumption by 2050. This underscores the potential for notable efficiency gains in the final-to-useful exergy conversion process. Notably, the efficiency of electricity conversion from final-to-useful forms consistently surpasses the aggregate final-to-useful efficiency. For instance, empirical data from Portugal spanning the years 1900 to 2009 reveals a persistent aggregate final-to-useful efficiency below 25% (Serrenho et al., 2014), while electricity conversion efficiency consistently exceeds 30% (Felício et al., 2023). This trend is spreading to other countries.

Sejkora et al. (2022) conducted a study focusing on Austria to identify key areas where significant overall exergy efficiency improvements can be achieved. The study pinpointed two main areas: heat supply, particularly through complete excess heat utilization and heat pumps, and transportation, specifically through electric and fuel cell vehicles. The investigated exergy optimization resulted in a notable increase in the final electrical energy demand, amounting to a 44% rise compared to the current situation. Consequently, it is imperative for electricity generation to be robust enough to accommodate and support this transition.

Future of societal exergy studies

Recently, Heun et al. (2024) developed new databases that facilitate the exergy analysis of any country worldwide from 1971 to today. This innovative package opens up a plethora of research possibilities across a wide range of fields. Accounting for demand and resource utilization can significantly influence the analysis, and having a common database for every country in the world enhances the potential for meaningful results even further.

Heightened awareness of the urgent need for climate change mitigation has prompted countries to develop policies aimed at reducing greenhouse gas emissions and resource consumption. To date, environmental and climate policies have at best achieved relative decoupling between GDP and resource use, as well as Greenhouse gas (GHG) emissions (Haberl et al., 2020). Meeting the goals outlined in the Paris Agreement necessitates the implementation of new and more effective policies compared to those previously deployed.

The global imperative demands policies that not only mitigate greenhouse gas emissions but also optimize primary exergy utilization. Even in regions abundant with renewable resources, efficient utilization is paramount to ensure widespread access to renewable energy. Recognizing that renewable resources are not uniformly distributed across the globe underscores the necessity of utilizing them judiciously to sustain our systems.
The preceding studies underscore the profound potential of exergy analysis in tackling modern challenges. For example, it can accelerate decarbonization endeavors by advocating for initiatives such as electrification. However, incorporating exergy considerations into the political discourse presents a formidable challenge. Nevertheless, an innovative approach such as an exergy tax could provide an interesting solution. That leads to the next section which overlooks different tax possibilities to push the system towards a sustainable economy.

2.3 Sustainable tax system

According to Eurostat, total energy-related tax revenues amounted to around 8.5 billion euros in Belgium in 2022. Including the cost of carbon, which is gradually being excised in Belgium, total tax revenue for 2030 is expected to be 10 billion euros for the energy sector. This substantial revenue stream offers a promising opportunity to develop and implement tax policies that effectively promote sustainability in various sectors.

Since the 1960s, western countries have implemented a value-added tax (VAT) that is charged at every stage of the supply chain, with businesses being responsible for collecting the tax on behalf of the government. However, this taxation system does not differentiate between sustainable and non-sustainable products, making it difficult to promote the adoption of eco-friendly transformations. To tackle this issue, the European Commission has proposed a VAT exemption for green products to encourage the shift towards sustainability without disrupting the existing tax system (Prasad, 2022).

Different researchers have been exploring sustainable ways to implement taxes. Szargut (2002) argues that taxes should not be a penalty for positive human activity, such as productivity and invention. Instead, taxes should burden negative effects, such as the depletion of natural resources and the negative impacts on the environment (Rosen and Dincer, 1999).

If the goal is to change the mindset of society towards caring for resources and promoting a sustainable economy, high energy consumption should also be penalized. For instance, when choosing between a heat pump with a higher energy efficiency and an electric resistance with a lower efficiency, the sustainable choice is to go for the heat pump. Some may argue that the heat pump is more expensive than the electric resistance. However, a sustainable tax could be designed so that the heat pump becomes more advantageous than the electric resistance without reducing the purchasing power. To achieve this, favoring the heat pump and penalizing the electric resistance could be an effective approach. However, subsidies need to be well thought out. As noted by Li et al. (2021), when the government directly subsidizes the product, companies offering low-carbon products raise the price per unit in order to indirectly obtain part of the subsidy. This is why implementing a price cap on green technologies could be a more effective option for moving society towards a greener market. A good example is Flanders' implementation of a system to encourage the purchase of electric vehicles (Vlaanderen). They subsidize these but they also apply a price cap to prevent the price of EVs from rising as a result of the subsidies.

On the other hand, when the option exists between a highly efficient but high-emitting power plant or a slightly less efficient one with zero emissions, the most sustainable choice would be to opt for the latter. This could be promoted through the implementation of a tax system. However, the challenge lies in finding a way to incorporate efficiency and emissions into a single tax that can be applied to all types of processes.

A solution is the carbon tax, as promoted by the European Commission. That tax could be used as a complement to the VAT, resulting in higher consumer prices. In the future, some scholars argue that carbon taxes should replace the VAT system (Prasad, 2022). However, carbon tax does not penalize inefficient processes directly even if it is related. This presents a challenge, particularly in regions where renewable resources are scarce. In such contexts, the imperative to consume resources efficiently remains paramount, even if they are non-emitting. Therefore, while carbon taxes offer a pathway towards environmental sustainability, a comprehensive approach that addresses both efficiency and emissions considerations is imperative for effective environmental policies. A tax that is based on exergy could be an interesting alternative.

2.3.1 Exergy Taxes

In every process, the amount of exergy output is always lesser than the exergy input. The difference in exergy between the input and output is the result of two sinks, which are illustrated in Figure 2.8: exergy wasted to the environment and exergy destroyed due to inefficient process and unavoidable irreversibilities. The combination of the two will be referred to as exergy loss in the following sections.

> **Definition 2.3.1.** Exergy wasted refers to the exergy released to the environment due to mechanical, thermal, and/or chemical disequilibrium with the reference environment (e.g. flue gases in combustion). (Ao et al., 2008)

> **Definition 2.3.2.** Exergy destruction refers to the loss of the working potential of natural resources and where irreversibility occurs. This part of exergy loss has, by definition, no environmental effects (e.g. exergy destruction by heat transfer between two bodies at different temperatures). (Gong and Wall, 1997)

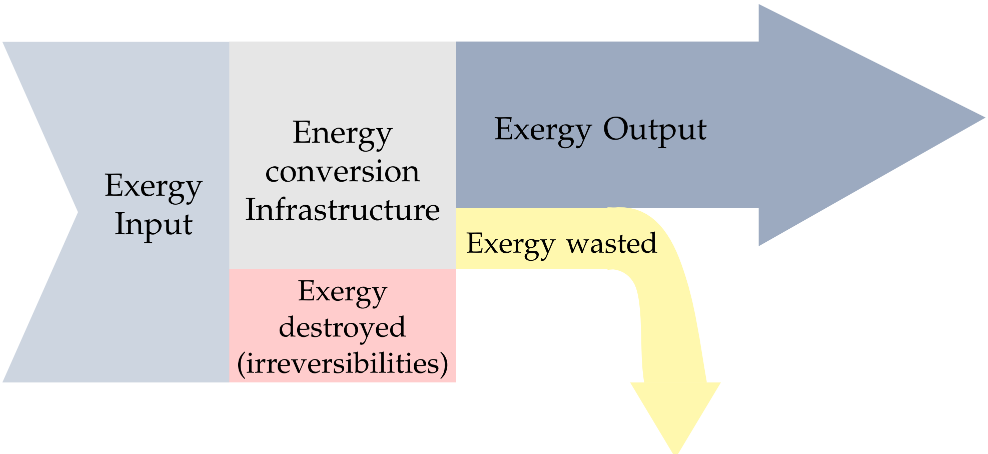


Figure 2.8 Exergy flow through a specific infrastructure. Exergy losses include exergy wasted to the environment and exergy destruction due to inefficiencies.

Exergy losses are a relevant way among others to assess the depletion of natural resources. An exergy tax can help minimize the use of natural resources. This has been discussed in research studies such as Ayres (2003) and Rosen (2004). Taxing exergy losses has then the potential to reduce greenhouse gas emissions and resource use.

Wall (1993) initially proposed in 1993 the introduction of an exergy tax system as an alternative to the VAT, aiming to establish a more sustainable tax framework. Over the past three decades, only a select few researchers have endeavored to implement exergy taxes within localized systems. For instance, Gong and Wall (1997) proposed an exergy tax scheme targeting non-renewable inputs and wasted exergy released into the environment. He concluded that utilizing exergy as the basis for taxation offers several advantages. Firstly, exergy can be calculated using readily available physical data for the flow and environmental conditions, potentially standardized through international agreements. Secondly, exergy is intricately linked to the utility of extracted resources and their physical (environmental) value, representing the "cost" of resource production from the ambient environment. Moreover, exergy serves as a measure of the physical value of environmental stress induced by exergy waste when it is discharged into the environment. Finally, exergy consistently maintains a positive value, as it is referenced against the natural (ambient) environment, offering a robust framework for taxation. However, Gong and Wall did not quantify the benefits of the exergy tax.

Santarelli (2004) expanded upon this by investigating the impact of a carbon exergy tax compared to conventional carbon taxation. This study focused on cogeneration plants and demonstrated that the exergy-based tax shifts the minimum cost design point to the plants' most efficient operating conditions, thereby promoting environmentally friendlier operation. In contrast, conventional carbon taxation failed to incentivize optimal efficiency and pollutant reduction in plant operation. While the carbon tax merely translated operation costs to higher values, the minimum cost design condition remained unchanged. This case study aimed to show that an exergy system could optimize the operation of a technology. He did not study the choice between different technologies.

2.4 Contribution of this work

Implementing an exergy tax at the scale of a country represents a novel and potentially instructive endeavor, yet one that has not been explored. The main objective of this thesis is to investigate the feasibility of introducing an exergy tax in Belgium and evaluate its efficiency in mitigating greenhouse gas emissions and curbing primary exergy consumption. By conducting this study, the aim is to contribute to the understanding of how such a system could evolve and its potential impact on sustainability within the Belgian context.

3

Methodology and Case Study

The previous section showed how an exergy tax could be an interesting way of mitigating current challenges. The model chosen to analyze its effectiveness is EnergyScope. This section aims to present this model and how it is transformed into ExergyScope, a model that optimizes a system based on its exergy flows.

3.1 Research approach

This study evaluates different tax systems to identify the most suitable option for generating revenue, given the taxation target of €10 billion, as outlined in section 2.3. This will be done using ExergyScope, an adaptation of EnergyScope. This model was selected for its ability to optimize system design based on cost, providing a practical tool to assess the effectiveness of various tax schemes in shaping system evolution while minimizing costs under taxation.

This work will analyze taxes targeting exergy loss, non-renewable energy imports, and carbon emissions. It will assess various combinations of these taxes. Subsequently, these combinations will be compared to evaluate their potential advantages over the carbon tax system. Through this comparative analysis, the study seeks to offer valuable insights into the most effective taxation strategy for attaining desired environmental and economic goals.

The various case studies will be examined using different key performance indicators to evaluate their effectiveness. Each scenario will be analyzed based on its emissions, cost, and exergy loss, relative to a baseline without any tax. Minimizing costs is paramount to proposing a viable system without significantly increasing tax burdens. Moreover, maintaining low levels of emissions and exergy loss is critical for establishing a sustainable system that aligns with the goals of the Paris Agreement and optimizes primary exergy utilization.

3.2 Case study

The case study will involve validation tests using data from Belgium for the years 2015 and 2020. These tests will ensure the accuracy and reliability of the ExergyScope model in capturing the dynamics of the Belgian energy system during those years.

Following the validation phase, the analysis of the exergy tax will be performed using projected data from 2035. This forward-looking analysis will assess how the implementation of an exergy tax could impact the future trajectory of the Belgian energy system, providing valuable insights into potential policy interventions and their implications for sustainability and economic efficiency.

The different years will be modeled using ExergyScope, which can be constrained with an upper bound value for emissions. However, in this study, emissions will not be constrained to analyze how the system evolves without such limitations. This enables the reduction of emissions to be identified in terms of the different taxation systems, without constraining them. ExergyScope will be tested on three different Belgian energy datasets provided in EnergyScope. These datasets will be modified to express exergy flows. The three datasets are:

Data for the year 2015: This dataset constrains the capacities of technologies to best represent the Belgian energy system in 2015. The optimization is forced to match the system existing in 2015 closely.

Data for the year 2020: This dataset is a projection based on the calibration of the 2015 data. Unlike in 2015, the technologies are less constrained, allowing the optimization to explore the most cost-effective options within physical limits (e.g., geographic constraints on maximum installed PV capacity).

Data for the year 2035: This dataset continues the projection from 2020, extending it to 2035. Similar to 2020, the optimization is free to identify the most effective system configuration within the given physical constraints.

3.3 EnergyScope Model

EnergyScope is an open-source model developed by the UCLouvain and EPFL. The EnergyScope version used for this work is EnergyScope TD (available on Github). All versions of EnergyScope are open-source.

3.3.1 EnergyScope TD Formulation

EnergyScope is a powerful linear optimization tool designed to model energy systems, from primary sources to end-use demand. Its optimization process focuses on minimizing either system cost or emissions through iterative adjustments of two key variables: technology capacities and hourly production levels. The total cost (C_{tot}) encompasses investment (C_{inv}), maintenance (C_{maint}), and resource costs (C_{res}):

$$C_{\text{tot}} = \sum_{i \in \text{technologies}} (C_{\text{inv},i} + C_{\text{maint},i}) + \sum_{j \in \text{resources}} C_{\text{res},j} \tag{3.1}$$

EnergyScope TD optimizes system design and operation to meet hourly demand, based on typical day formulations, reducing computational complexity while allowing for the representation of energy storage across various time scales. The calculation of typical days depends on the time series relating to demand, and on the time series relating to variable renewable generation. For renewable generation, the relative importance of the different time series is weighted by the maximal installed capacity of the associated technologies.

Moreover, the model incorporates constraints to uphold emissions limits and ensure hourly energy carrier balance. EnergyScope TD operates as a snapshot model in the sense that it projects the energy system for a future target year without considering existing infrastructure.

The model's workflow comprises preprocessing, optimization, and post-processing stages. Preprocessing readies input data, optimization employs mathematical algorithms to find optimal solutions, and post-processing facilitates analysis through output files and visualizations.

A representation of the EnergyScope TD is shown in Figure 3.1. It provides a summary of the model's inputs and outputs.

3.3.2 Inputs of EnergyScope

EnergyScope works by taking three different inputs concerning the resources, the technologies, and the demand.

Resources

Resources in EnergyScope are defined based on their availability, cost, and emissions intensity. Additionally, for renewable sources such as wind, solar, and hydropower, an hourly profile is provided. The availability of these resources is represented by their total capacity that can be installed, weighted by the capacity factor.

Technologies

These inputs concern all the conversion technologies involved in transforming one form of energy into another, including storage technologies. EnergyScope takes their investment costs and operational costs as inputs. Additionally, a file summarizes all inputs and outputs, providing information on their efficiency. This file is structured as a table with columns representing all steps in the energy chain and rows listing all technologies. Moreover, the inputs for technologies also include information on their emissions.

Demand

The end-use demand includes heat (both high and low temperature), mobility (both freight and passenger), electricity, and non-energy demands (ammonia, HVC, and methanol). It is noteworthy that the electricity used for mobility and heating has been subtracted from the electricity demand. Moreover, the electricity demand is separated into two different sub-categories, one independent of time (the baseload demand), and the other varying according to a given input time series (the variable demand).

Each demand category is segmented into four sectors: residential, service, industrial, and transport sectors. The values for the first three sectors are provided in GWh for each category, while for the transport sector, freight transportation is given in t.km and passenger transportation in passenger.km.

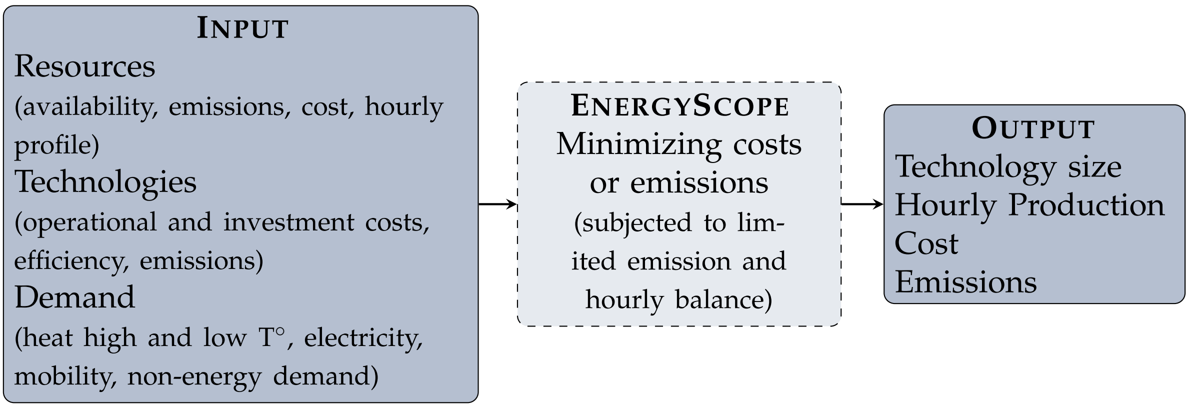


Figure 3.1 EnergyScope TD model representation

3.3.3 Output of EnergyScope

The output of the model comprises the results of the optimization process. This includes the installed capacity of the chosen technologies and their hourly production. Additionally, EnergyScope provides information on the cost and emissions associated with the chosen configuration.

3.3.4 Disadvantages of EnergyScope

EnergyScope is a powerful tool for optimizing entire energy systems to identify the most cost-effective options. However, it has several notable disadvantages.

Firstly, EnergyScope has a spatial resolution of only one cell. This limitation means that the tool cannot model energy exchanges between different countries, which is crucial for comprehensive energy system analyses involving cross-border interactions and trade.

Additionally, EnergyScope offers only a simplified representation of various technologies. As mentioned in the previous section, Santarelli (2004) explored the impact of an exergy tax on the operation of a specific power plant. Such detailed analyses are not possible with EnergyScope, as it assumes a single efficiency for each technology, rather than allowing for variations within individual technologies or specific operational conditions. This simplification can limit the accuracy and applicability of EnergyScope's results in scenarios requiring detailed technological assessments.

But in any case, to offer a first analysis of an exergy-based tax at the scale of a country, EnergyScope is a sufficient tool. The following section explains how EnergyScope is adapted to handle exergy flows.

3.4 EnergyScope Model to ExergyScope model

The adaptation of the EnergyScope model into ExergyScope involves modifying the inputs of the model and making adjustments to the code. This section outlines the methodology used to transform energy flows into exergy flows. Subsequently, the model will undergo validation to ensure that it provides a reliable basis for analyzing the exergy tax.

The new version of ExergyScope is available on Github. The Excel files used to convert EnergyScope input data into ExergyScope are also available on this link. Moreover, Appendix 1.2 explains how those files are used.

3.4.1 Premises of ExergyScope

The work by Codina Gironès et al. (2017) initiates a significant discussion on the potential adaptation of EnergyScope into ExergyScope, aiming to enhance the understanding of energy utilization through the lens of exergy. Their methodology introduces a novel approach to estimating the useful exergy demand projected for 2050. Unlike previous approaches such as Serrenho et al. (2014), where the demand is categorized into distinct useful categories like mechanical work, heat, light, and other electric appliances, Codina Gironès et al. opted to retain the existing division of demand as observed in EnergyScope, albeit modifying it to reflect a useful demand.

This decision to not segregate the demand into specific categories brings certain advantages, notably in simplifying the estimation process by applying a single factor. Indeed, Codina Gironès et al. decided to keep the end-use demand categories as they are. And just applying to each category an average exergy factor. Conversely, Serrenho et al.'s method, with its detailed categorization, offers benefits in facilitating demand projections by providing a more granular understanding of energy utilization across various sectors.

A pivotal aspect in both methodologies lies in estimating the final-to-useful efficiency, which serves as a critical parameter in assessing the effectiveness of energy utilization. By accurately determining this efficiency, researchers can better gauge the actual utility derived from energy consumption and identify areas for improvement in energy conversion processes.

In this work, the Serrenho et al.'s method is used. Indeed, it offers a more detailed insight into energy utilization across different useful services.

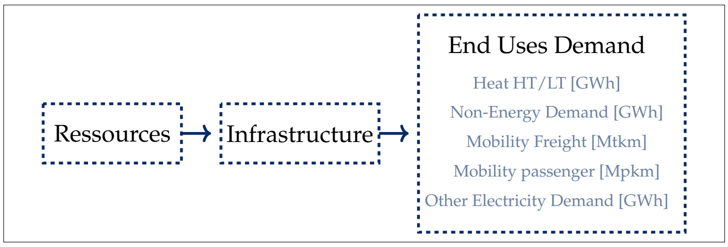
3.4.2 Demand Modification

To modify the demand, two steps must be taken. Firstly, the demand should be extended to the useful layer, as shown in Figure 3.2. Secondly, the useful energy demand needs to be converted to a useful exergy demand. In ExergyScope, the electricity demand is no longer separated into a baseload and a variable demand. Then, a new time series is defined to account for the new variations as done in the multi-cell version of EnergyScope (Thiran et al., 2020).

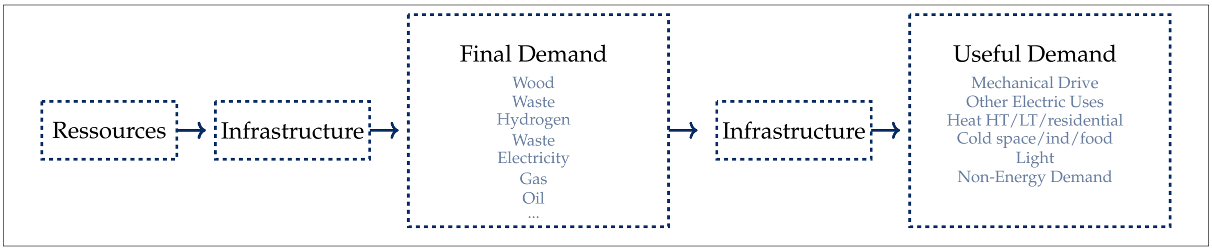
Extension to the useful layer

As stated by definition 2.1.6, exergy quantifies the useful content of energy used for performing a specific task such as lighting or transportation. As a reminder, useful exergy is the minimum amount of work required to perform a service (definition 2.1.2). Before incorporating useful exergy, the demand needs to be separated into different useful categories.

Based on the definitions 2.1.1 and 2.1.2, it is clear that the EnergyScope model depicted in figure 3.2a does not effectively distinguish between final and useful demand. For instance, while heat demand falls under the useful layer, electricity is categorized under the final layer.



(a) Actual EnergyScope with End-Use Demand mixing useful demand categories and final demand categories.



(b) EnergyScope extended to the useful stage by dividing the demand into useful categories

Figure 3.2 EnergyScope and ExergyScope model formulation

The major adaptation, as shown in figure 3.2b, concerns the electricity demand that needs to be divided into useful demands such as light, heat, mechanical drive, cold, and other electric end-use demands. This section concerns the method used to divide properly the electricity demand for each sector.

For the residential sector, numerous electric appliances are utilized and need to be classified into useful demand. To do so, Felício et al.'s method was employed. The method divides the residential electricity demand into five categories, as illustrated in Figure 3.3. The data are taken from a study on residential electricity consumption in France (Enertech, 2021), assuming that the distribution of the various categories is similar in Belgium.

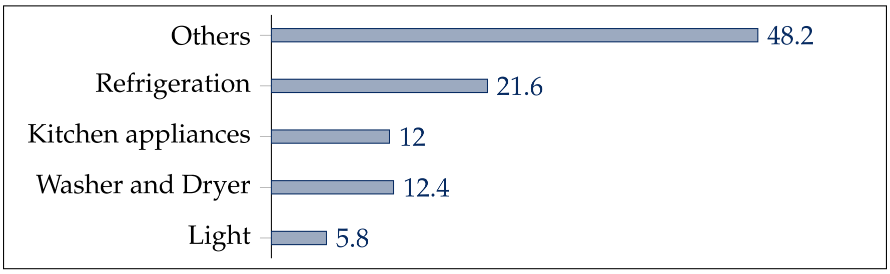


Figure 3.3 Share of electricity consumption in the residential sector by service category (Enertech, 2021).

The five categories of residential electricity demand are :

Washer and dryer appliances which represent 12.4% of the electricity consumption. This includes dishwashers and laundry appliances, which require 80% low-temperature heat and 20% mechanical drive.

Kitchen appliances which represent 12.0% of the electricity consumption. This includes all appliances in the kitchen except for dishwashers and refrigeration appliances. The electricity demand of these appliances is divided into 40% mechanical drive and 60% low-temperature heat.

Refrigeration appliances which represent 21.6% of the electricity consumption. This includes food refrigeration and space cooling.

Lighting which represents 5.8% of the electricity consumption.

Other appliances which represent 48.2% of the electricity consumption. This includes all other appliances such as electronic devices, televisions, vacuum cleaners, etc. This category is divided into 22% mechanical drive, 44% other electric uses, and 34% low-temperature heat.

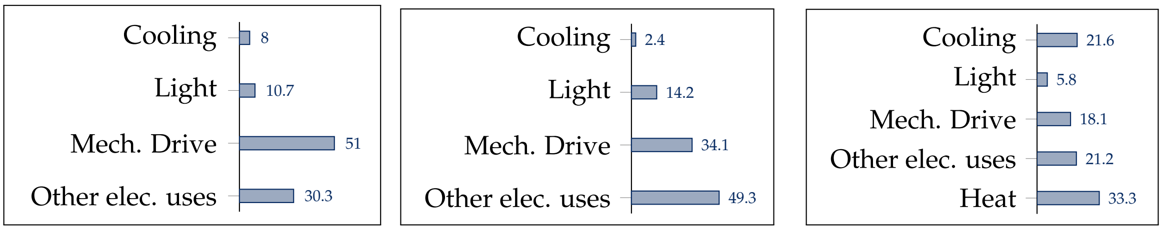
In these subdivisions, it is crucial to note that the heat used for domestic hot water and heating has been excluded. The low-temperature heat considered here specifically pertains to the heat generated by electric appliances, such as a coffee machine, dishwashers, air dryers, etc.

By accounting for both the consumption share and the allocation into useful demand across each of the mentioned categories, we can accurately segment residential demand into its useful components. Figure 3.4c shows the breakdown of EnergyScope electricity demand into useful demand categories.

For the service and industrial sectors, information on electricity distribution was obtained from Serrenho et al. (2014). As heat is already separated from electricity demand in EnergyScope, heat from Serrenho et al. distribution has also been removed. Moreover, Serrenho et al. combines the mechanical drive and the cooling demand, which need to be analyzed separately. Cooling demand data for Belgium was provided by Thiran et al. (2020). By using the average refrigeration Coefficient Of Performance (COP) prevalent in Belgium, which was reported to be 3.34 in Heun et al. (2024), the cooling demand could be subtracted from the Mechanical Drive (MD).

$$\begin{aligned}\text{Useful Energy MD} = {} & \text{Elec. Demand} \times \text{MD share (incl. cooling)} \\ & - \frac{\text{Cooling Demand}}{\text{COP}}\end{aligned}$$

These adjustments were made to calculate the distribution shares, which are visually represented in Figure 3.4.
Finally, the transportation demand is quantified in terms of mobility services within the energy model. This demand remains represented as a service in the exergy model. This decision is based on the fact that the service representation better aligns with the actual user demand. To calculate the exergy demand, a straightforward conversion factor can be applied, as elucidated in Section 3.4.2.



(a) Industrial sector **(b)** Services sector **(c)** Residential sector

Figure 3.4 Electricity repartition into useful demand for each sector

Energy to Exergy demand

Knowing how the electricity is divided into the useful categories, Serrenho et al. (2014) defined final-to-useful exergy efficiencies (η_{f2u}) for electricity demand. To transform final electricity demand $E_{f,i}$ into useful exergy demand $X_{u,i}$ of a useful category ($\cdot_i$), the electricity exergy factor $e_{2x,elec}$ and the final-to-useful exergy efficiencies must be applied as follows:

$$X_{u,i} = e_{2x,elec} \cdot \eta_{f2u} \cdot E_{f,i}$$

Since electricity has an exergy factor equal to one (Felício et al.), the useful exergy of the i-th category ($\cdot_i$), becomes :

$$X_{u,i} = \eta_{f2u} \cdot E_{f,i}$$

Definition 3.4.1. The final-to-useful exergy efficiency η_{f2u} refers to the efficiency of converting final exergy into useful exergy.

Table 3.1 summarizes the final-to-useful exergy efficiency presented by Serrenho et al.. The assumption made for the efficiencies in 2035, as presented in Table 3.1, stipulates that all of them will remain constant between 2020 and 2035, except for lighting, where an efficiency of 0.12 will be applied for 2035 by assuming that only LED light will be used (Sejkora et al., 2022).
The heating and cooling needs are already represented as useful energy demands. The corresponding useful exergy demand (X_i) is calculated from the useful energy demand ($E_{u,i}$) using an exergy factor ($e_{2x,i}$) as follows:

$$X_i = E_{u,i} \cdot e_{2x,i}$$

For heating and cooling, the exergy factors were defined in sections 2.1.4 and 2.1.4. Table 3.2 provides a summary of the exergy factors for heating and cooling.

As explained above, transport demand will be retained as a service. However, for a more detailed exergy analysis, it is necessary to take into account exergy losses during transport in the post-preprocessing phase. For the various transport vehicles, the final-useful exergy efficiency was used to find the useful exergy demand $X_{u,v}$ associated

Useful demand	Final to Useful Technology	Technology efficiency : $\eta_{f2u,i}$	Ref.s
Mechanical drive	Electric Motor	0.83 (2015) 0.87 (2020) 0.87 (2035)	Felício et al.
Other electric Uses	Electronics	0.019 (2015) 0.019 (2020) 0.019 (2035)	Ayres
Light	Light Bulb	0.06 (2015) 0.09 (2020) 0.12 (2035)	Serrenho et al.
Heat residential heat	Electric Resistance	0.11 (2015) 0.11 (2020) 0.11 (2035)	Eq. 2.11 with T= 50°C (Felício et al.)

Table 3.1 Final-to-Useful Electricity technology and efficiency

Useful demand	Exergy Factors : $e_{2x,i}$
Heat high-temperature	0.63
Heat low-temperature	0.11
Space Cooling	0.02
Food Cooling	0.10
Industrial Cooling	0.10

Table 3.2 Exergy Factor for useful heating and cooling demand.

with a final exergy demand $X_{f,v}$. The final exergy demand associated with each vehicle is an output of ExergyScope and will be explained in more detail in section 3.4.5. The useful exergy demand $X_{u,v}$ is then derived as :

$$X_{u,v} = \eta_{f2u,v} \cdot X_{f,v}$$

It was not possible to find references for each vehicle considered in EnergyScope. The methodology used assumes that the same amount of mechanical work is required to move a person by bus, for example, whatever the type of bus. This method was used for all vehicle types. In this way, the final-to-useful exergy efficiency $\eta_{f2u,v}$ of a vehicle v, was calculated using the mechanical drive W_i required for a given vehicle category i and the final exergy required to move one person (or one tonne) over one km ($X_{p.km/t.km,v}$) of that specific vehicle:

$$\eta_{f2u,v} = \frac{W_i}{X_{p.km/t.km,v}}$$

Transport Technology	Final Exergy [kWh/(pass-t.km)]	Mechanical Drive [kWh/(pass-t.km)]	$\eta_{f2u,i}$
Tram or metro	0.063	0.051	0.81
Bus diesel	0.281	0.062	0.23
Bus diesel hybrid	0.210	0.062	0.31
Bus gas	0.279	0.062	0.23
Bus fuel cell (H2)	0.222	0.062	0.29
Train (passenger)	0.065	0.052	0.81
Car gasoline	0.527	0.101	0.20
Car diesel	0.461	0.101	0.23
Car gas	0.358	0.101	0.30
Car methanol	0.450	0.101	0.24
Car hybrid (gasoline)	0.356	0.101	0.30
Car plug-in hybrid	0.253	0.101	0.42
Car electric	0.161	0.101	0.66
Car fuel cell (H2)	0.215	0.101	0.49
Train (freight)	0.068	0.055	0.81
Boat diesel	0.113	0.023	0.26
Boat gas	0.128	0.023	0.23
Boat methanol	0.121	0.023	0.24
Trucks diesel	0.543	0.125	0.23
Truck methanol	0.577	0.125	0.22
Truck fuel cell	0.432	0.125	0.29
Truck electric	0.249	0.125	0.50
Truck gas	0.614	0.125	0.20

Table 3.3 Final-to-useful exergy efficiency in the transport sector (Tostes et al.)

3.4.3 Technologies adaptation

The technologies must be depicted as exergy converters rather than energy converters. In Section 2.1.4, we discussed the transformation of an energy carrier into an exergy carrier using an exergy factor e_{2x}.

In EnergyScope, each technology is characterized by its inputs and outputs, with a reference output set to a value of one. Additional outputs and inputs are adjusted to yield one unit of the specified reference output. To transition this framework to exergy, each value must be appropriately adjusted. Denoted by $e_{2x,\text{ref}}$, representing the exergy factor of the reference output, and $e_{2x,i}$, denoting the exergy factor of the energy carrier i (refer to Table 2.1), the exergy quantity X_i of the fluid i engaged in the transformation is calculated from its energetic equivalent E_i as follows:

$$X_i = E_i \cdot \frac{e_{2x,i}}{e_{2x,\text{ref}}} \tag{3.2}$$

$e_{2x,\text{ref}}$ is used in order to keep a unitary value for the reference output in exergy terms.

The energy efficiency (η_E) and exergy efficiency (η_X) are determined based on the outputs ($\cdot_o$) and inputs ($\cdot_i$) using equation 3.3 and 3.4:

$$\eta_E = \frac{\sum_{\forall i \in \text{inputs}} E_i}{\sum_{\forall o \in \text{output}} E_o} \tag{3.3}$$

$$\eta_X = \frac{\sum_{\forall i \in \text{inputs}} X_i}{\sum_{\forall o \in \text{output}} X_o} \tag{3.4}$$

Illustrating this with an example, an electrolyzer configured in the energy system is designed in EnergyScope to produce one unit of hydrogen (exergy factor is 0.98). In this process, 0.02 units of low-temperature heat are generated, along with a requirement of 1.07 units of electricity and 0.19 units of high-temperature heat. In the exergy system, it becomes (where $\cdot_o$ denotes outputs and $\cdot_i$ denotes inputs):

$$\begin{aligned}
X_{o,H_2} &= 1 \\
X_{o,\text{heat LT}} &= 0.02 \cdot \frac{0.11}{0.98} = 0.0022 \\
X_{i,\text{heat HT}} &= 0.19 \cdot \frac{0.63}{0.98} = 0.12 \\
X_{i,\text{elec}} &= 1.07 \cdot \frac{1}{0.98} = 1.09
\end{aligned}$$

This results in an exergy efficiency of 82.83% and an energy efficiency of 80.95% (see Figure 3.5). It is noteworthy that technologies not reliant on heat inputs exhibit lower exergy efficiencies compared to energy efficiencies. This discrepancy arises from the neglect of irreversibilities in energy efficiency. All the energy and exergy efficiencies of the technologies used in ExergyScope are presented in Annex 1.1.

(a) Energy flows **(b)** Exergy flows

Figure 3.5 Electrolyzer : Comparison of energy and exergy flows shows that the electrolyzer has a higher exergy efficiency than the energy efficiency.

In EnergyScope, technology costs (investment and operation) are provided per installed energy capacity of the reference output. However, to characterize the installed exergy capacity, these costs need to be converted. This conversion involves simply dividing all costs by the exergy factor of the reference output. The same method is applied to the emissions produced.

3.4.4 Resources Adaptation

In terms of resources, the methodology consisted of considering the loss of exergy in each technology transforming primary energy into another, with the exception of electricity produced directly from renewable sources (hydroelectricity, wind power, geothermal energy, solar energy, etc.). Indeed, these sources were considered to be costless and abundant, on the assumption that the loss of exergy linked to these transformations is not decisive in assessing the sustainability of the energy system.

For other sources, such as uranium and gas, the loss of exergy to transform the primary exergy into another form is already taken into account in the conversion technology, as explained above. However, to take account of exergy resources instead of energy resources, their exergy factor is used to estimate their exergy availability. The energy availability is multiplied by the exergy factor of the resource in question to obtain the exergy equivalent. Conversely, the costs and emissions produced must be divided by the exergy factor (see Table 2.1 [1]).

3.4.5 Code adaptation

The demand in ExergyScope is presented as useful exergy demand, differing from the end-use demand as defined in EnergyScope. The code requires adaptation to accommodate this change in demand subdivision. However, only the electricity category has been subdivided. For each electricity subcategory, only one technology is considered, except for the cooling demand. The technologies considered for each subcategory are presented in Table 3.1.

Given that only one technology is defined for each useful electricity subcategory except for cooling, this adaptation does not need to be implemented in the optimization phase because there is no technology choice to optimize. The electricity demand $X_{\text{elec,tot}}$ can then be reconstructed during the preprocessing phase, accounting for each specific useful exergy demand ($X_{\text{demand},i}$) and the final-to-useful efficiency ($\eta_{f2u,i}$) of the associated technologies (defined in Table 3.1).

$$X_{\text{elec,tot}} = \sum_{i \in \text{Useful Cat.}} \frac{X_{\text{demand},i}}{\eta_{f2u,i} \cdot e_{2x,elec}} = \sum_{i \in \text{Useful Cat.}} \frac{X_{\text{demand},i}}{\eta_{f2u,i}}$$

[1] The exergy content of uranium has been estimated by dividing the exergy efficiency of a nuclear power plant by its energy yield. These data are given in appendix 1.1 and give an exergy content of 1.12 for uranium.

This electricity demand is then given as an input as it was previously done in EnergyScope.
For cooling, it has been integrated into the optimization model of EnergyScope letting the model choose the technology used. The cooling demand is not constant throughout the year. Separating the cooling demand from the electricity demand requires a yearly time series, as specified by Thiran et al. in the multi-cell version of EnergyScope (Available on Github).
As presented by Thiran et al., different cooling technologies can be envisaged to provide this specific demand. Those are presented in Table 3.4. The different COP of the cooling technologies have been adapted based on Heun et al.'s data.

Technology Unit	c_{inv} [€ 2015/kWe]	c_{maint} [€ 2015/kWe/y]	gwp_{constr} [kgCO2$_{eq}$/kWe]	**Lifetime** [years]	c_p [%]	**COP** [%]
Elec refrig. cycle	474	20.3	165	20	100	333
Th refrig. cycle	304	9.1	382	20	100	146
Ind. electric cooling	617	5.0	175	20	95	107

Table 3.4 Refrigeration technologies used in ExergyScope

Output Modification of the Model

To comprehensively analyze exergetic flows within a country, ExergyScope has been updated to provide additional outputs for improved analysis. The model now offers aggregate final-to-useful (definition 3.4.1) and primary-to-useful (definition 3.4.2) exergy efficiency metrics, allowing for a more nuanced understanding of exergy utilization.

Definition 3.4.2. The primary-to-useful exergy efficiency η_{p2u} refers to the efficiency of converting primary exergy into useful exergy.

To facilitate these, each technology is now categorized as either a final-to-useful conversion technology or not. The new outputs require the definition of new variables such as total exergy input ($X_{in.,tot}$) and useful exergy demand ($X_{out.,tot}$), as well as the total exergy loss ($X_{destr.,tot}$) and the final-to-useful exergy loss ($X_{destr.,f2u}$).

The exergy loss $X_{destr.,i}$ within a technology is given by the difference between all the inputs and outputs of a technology [1]. Let F_t be the total production of this output per year, $X_{in,i}$ and $X_{out,i}$ respectively input and output involved in this production. The exergy loss associated with a transformation is given by equation 3.5.

[1] As a reminder, a file (provided as input to the model) summarizes all the inputs and outputs associated with the production of one unit of each technology's main output.

$$X_{destr.,i} = \left(\sum_{i \in \text{input}} X_{in,i} - \sum_{o \in \text{output}} X_{out,o} \right) \cdot F_t \tag{3.5}$$

The exergy destroyed during the final-to-useful transformation processes is then :

$$X_{destr.,f2u} = \sum_{k \in \text{final-to-useful techno}} X_{destr.,k}$$

The total exergy loss in the system is :

$$X_{destr.,tot} = X_{in.,tot} - X_{out.,tot} = \sum_{k \in \text{techno.}} X_{destr.,k}$$

$X_{in.,tot}$ is defined as the sum of each exergy input associated with resource i :

$$X_{in.,tot} = \sum_{i \in \text{resource}} X_i$$

And $X_{out.,tot}$ is determined by summing the useful exergy demand $X_{dem.}$ for each sector except the transportation sector (expressed as a service), the total exported exergy $X_{\text{exp, tot}}$, and the useful mechanical work required for transportation. The mechanical work for transportation is dependent on the transport technology selected and can be computed using the final-to-useful efficiency η_{f2u} (see Table 3.3) and the final exergy X_f used for that transport. Therefore, the total output exergy is calculated as:

$$X_{out.,tot} = \sum_{i \in \text{sector} \notin \text{transport}} X_{dem.,i} + \sum_{j \in \text{Transport Techno.}} X_{f,j} \cdot \eta_{f2u,j} + X_{\text{exp, tot}}$$

With those variables, during the postprocessing phase, it is possible to define the aggregate primary-to-useful and the final-to-useful exergy efficiency as :

$$\eta_{p2u} = \frac{X_{out.,tot}}{X_{in.,tot}} \quad \text{and} \quad \eta_{f2u} = \frac{X_{out.,tot}}{X_{out.,tot} + X_{destr.,f2u}} \tag{3.6}$$

Moreover, ExergyScope gives a breakdown of total exergy loss within each technology, facilitating the identification of key areas for potential enhancement.

Tax implementation

Adding a tax in ExergyScope simply involves incorporating a term into the cost function defined by equation 3.7. As previously mentioned, three different taxes will be studied: one concerning exergy loss, one concerning the import of non-renewable resources, and one concerning emissions.

In the cost function, these three terms will be added, each associated with a coefficient representing the price of the tax in €/kWh or in €/kgCO_2. Subsequently, three different parameters are added to the model: an exergy loss fee (exergy price), a non-renewable resource fee (NR price), and a carbon fee (CO_2 price).

The cost function then becomes:

$$\begin{aligned} C_{\text{tot}} = & \sum_{i \in \text{technologies}} (C_{\text{inv},i} + C_{\text{maint},i}) + \sum_{j \in \text{resources}} C_{\text{res},j} \\ & + \text{NR price} \cdot \sum_{j \in \text{NR resources}} X_j \\ & + \text{Exergy price} \cdot X_{destr.,tot} \\ & + \text{CO}_2 \text{ price} \cdot \text{GWP}_{\text{tot}} \end{aligned} \tag{3.7}$$

With X_j the exergy input associated to the resource j and GWP_{tot} the total emissions of the system.

4

Model Validation and Exergy Analysis

BEFORE analyzing the taxes themselves, it is important to ensure that ExergyScope is a good model. This section aims to verify that ExergyScope represents an exergy system consistent with EnergyScope and previous exergy studies. In addition, this section will carry out an exergy analysis of the Belgian system in 2015 to understand the main possible improvements in terms of exergy losses.

4.1 Model Validation

4.1.1 Consistency Between ExergyScope and EnergyScope Models

To validate the ExergyScope model, it is first necessary to compare the EnergyScope and ExergyScope models globally. Table 4.1 shows the results deviation (in %) of ExergyScope from EnergyScope. Both models have been applied to the years 2015 and 2035, with cost optimization under no emissions constraints, excluding any form of taxation (see section 3.2). The choice of model (energy or exergy) should not impact costs and emissions, indicating that the two models should converge on solutions with similar values in terms of those variables. As shown in table 4.1, the comparison reveals a high degree of consistency between the two models concerning these two results.

Year	Cost [B€/year]	Emissions [MtCO_2-eq/year]
2015	-0.03%	+0.01%
2035	+0.1%	+0.3%

Table 4.1 ExergyScope Model Deviation from EnergyScope [%]. The models comparison shows that they present similar values for cost and emissions [1].

[1]The cost and emissions related to cooling technologies in ExergyScope have been deduced to make the models comparable.

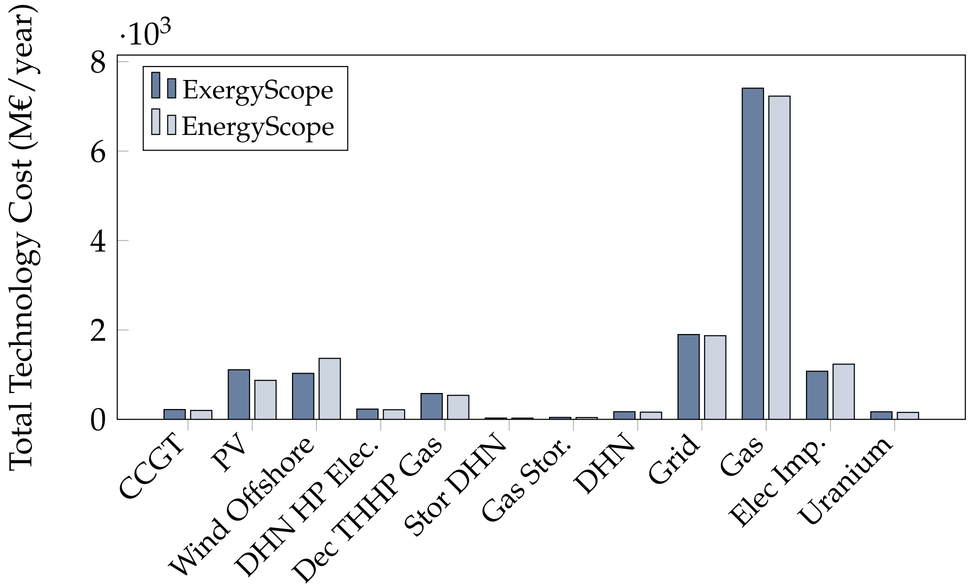


Figure 4.1 Models divergence in technology costs greater than 0.5 % for 2035. EnergyScope and ExergyScope approach a similar solution, except for a few disparities due to different typical days.

Given the overall similarity in values, a more precise analysis is necessary. Ensuring congruence between the two models in terms of technology selection and installed capacity is essential. This is verified by examining the cost breakdown for each technology. For the model run in 2015, there are no significant differences, which can be explained by the model's constraints designed to best represent the Belgian energy system at that time.

To ensure the model selects the same technologies, it is crucial to verify the choice of technologies with a model where optimization has a more pronounced impact. This is done for the year 2035. The cost breakdown for that year is illustrated in Figure 4.1. The figure highlights where cost disparities between the models exceed 0.5%, indicating potential areas of divergence.

For instance, ExergyScope tends to favor greater photovoltaic (PV) installation and reduced wind energy deployment compared to EnergyScope. These variances likely stem from slight differences in the typical days utilized by each model, impacting irradiance and wind power predictions. Indeed, an examination of the profile of typical days verifies this hypothesis. As explained above, the time series have been slightly modified between the two models to account for a single electricity demand (no longer separating baseload and variable demand) and to incorporate a cooling time series. Since typical days are calculated partly based on demand time series, these changes affect the outcome.

The most notable contrast emerges in gas importation, attributed to EnergyScope's higher reliance on imported electricity relative to ExergyScope's preference for gas-based energy production. The two models are different optimization problems that lead to slightly different but very similar solutions. When considering emissions, the overall impact remains comparable.

4.1.2 Consistency Between ExergyScope and Previous Studies

To ensure the reliability of ExergyScope, its outcomes must be cross-referenced with findings from prior studies. In Section 2.2.1, the study by Serrenho et al. was introduced, examining the correlation between exergy demand and GDP. Incorporating the exergy demand results obtained from ExergyScope for 2015 and 2020 into this trend enables an assessment of whether a consistent pattern persists. As depicted in Figure 4.2, the trends observed with ExergyScope closely mirror the relatively constant curve identified by Serrenho et al., suggesting that ExergyScope effectively models the Belgian energy system. This validation underscores the utility of ExergyScope for analyzing the potential implementation of an exergy tax in Belgium [1].

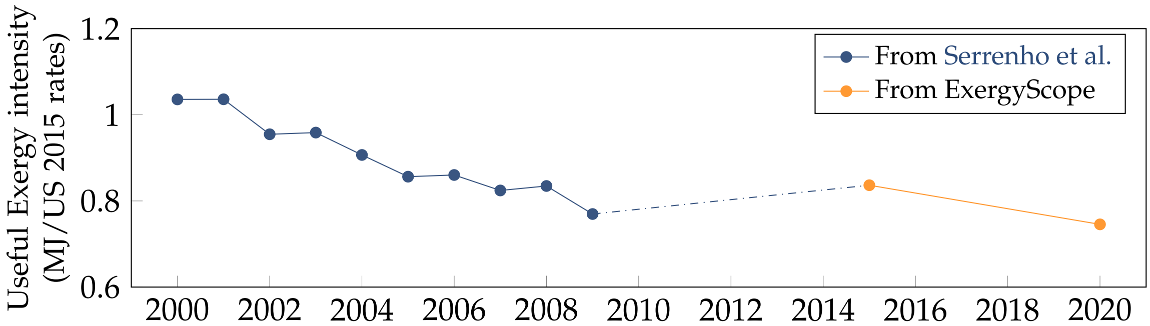


Figure 4.2 Useful exergy intensity in Belgium. The results obtained with the trend derived by Serrenho et al..

4.2 Country Exergy Analysis

Now that ExergyScope has been validated, it is possible to use it to proceed with an exergy analysis to understand the areas of improvement.
For 2015, the model calculates an aggregate exergy efficiency from primary-to-useful of 24.74% and from final-to-useful of 28.03%. Those are achieved when minimizing the total cost of the infrastructure (and operation) and without limiting the total emissions.

[1] To make the results comparable, non-energy demand was neglected and muscle work estimated by Serrenho et al. was added.

Sector	η_{f2u} in 2015
Residential	15.61%
Service	24.27%
Industrial	49.97%
Transport	23.16%
Aggregate	28.03%

Table 4.2 Exergy efficiency (final-to-useful) by sector in 2015

The final-to-useful exergy efficiency can be broken down by sector, as shown in Table 4.2.

Those results reflect how demand is distributed differently across useful categories. For example, as shown in the table 4.3, the industrial sector requires more mechanical drive, which translates into higher final-to-useful efficiency given the high efficiency of this category when the work is supplied with electricity. On the other hand, the transport sector requires only mechanical drive, and so might be expected to achieve a higher efficiency. But as Table 3.3 shows, the Internal Combustion Engine (ICE) typically used in 2015 has a lower efficiency than an electric vehicle. Electrification of the transport sector could be a lever for action to increase final-to-useful efficiency in the transport sector and attempt to move towards the use of less primary energy.

	Industry	Residential	Services	Transport
Mechanical Drive Demand	19.5	2.9	6.8	21.5
Light Demand	0.3	0.07	0.2	0.0
Heat HT Demand	39.2	0.0	0.0	0.0
Heat LT Demand	2.2	9.1	4.2	0.0
Other Uses Demand	0.7	2.5	1.0	0.0
Cooling	0.0	0.3	0.0	0.0
Non Energy Demand	53.0	0.0	0.0	0.0

Table 4.3 Belgian exergy demand for each useful category in 2015 in GWh

In addition, Figure 4.3 shows the breakdown of exergy loss into the energy sector in 2015 [1]. This figure shows where efforts to move the country towards sustainability are most important. The three main sources of exergy loss are boilers, internal combustion engines (used for mobility), and nuclear power plants. It is important to bear in mind that a technology that is used more will naturally destroy more exergy. For example, nuclear power plants produce 46% of all electricity, so it is not surprising that a lot of exergy is lost in this production. However, the appendix 1.1 shows that other power plants are more efficient, such as combined-cycle power plants (CCGT). Renewable energies can also be considered as an alternative from an exergy point of view. However, it is important to remember that nuclear power is treated with an exergy loss, whereas for electricity generated from renewable sources, the exergy loss associated has been

[1] The electricity to useful refers to the exergy loss that occurs in the former end-use demand category defined in EnergyScope.

neglected (cfr section 3.4.4).

Cross-referencing the appendix 1.1 with this exergy breakdown, it also becomes clear that boilers should be avoided from an exergy point of view, as their efficiency never exceeds 10%. They provide 89% of total heat production but account for 97% of the total exergy loss of this demand. The purpose of the following sections is to analyze how the tax system influences these technologies.

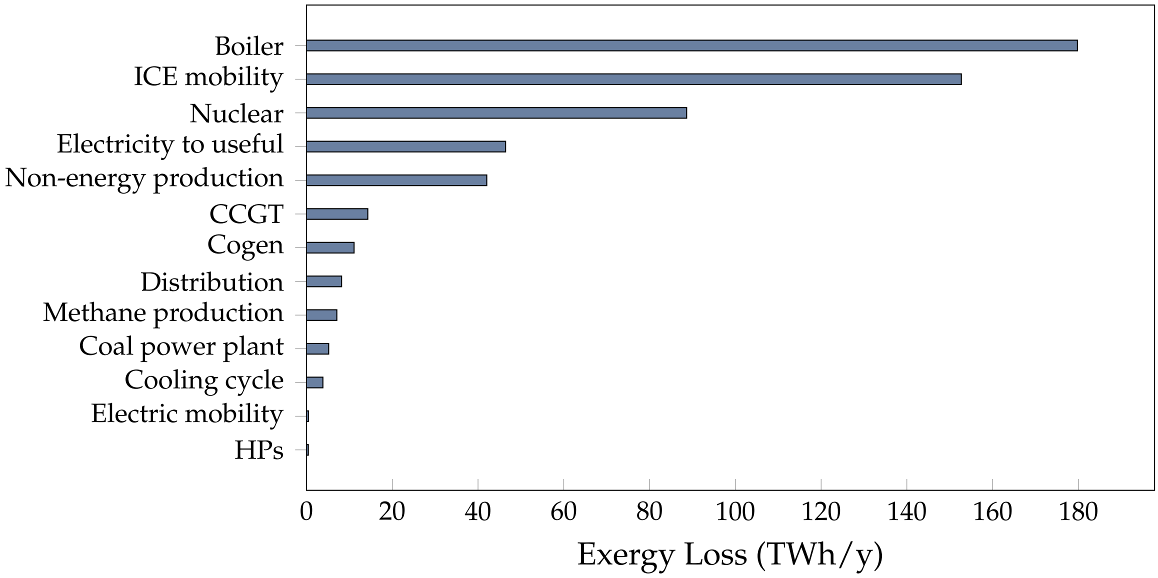


Figure 4.3 Breakdown of exergy losses for the year 2015. The three main technologies requiring special attention in terms of losses are boilers, internal combustion engine vehicles, and nuclear power plants.

5 Tax Systems Evaluation and Discussions

ExergyScope has proven to be a good model for studying the implementation of different tax systems. This chapter aims to analyze different tax systems to build efficient policies in Belgium to reduce emissions while increasing exergy efficiency.

5.1 Baseline Scenario Overview

The reference scenario is the starting point for comparing all other scenarios. It represents conditions in the year 2035, optimized to minimize costs without any emissions constraints.

In addition, instead of giving cost as the objective function to be minimized in the ExergyScope optimization model, the minimization of exergy losses has been tested. This approach aims to find out the theoretical maximum exergy efficiency possible through the implementation of an exergy tax. A summary of the costs, emissions, and exergy efficiency associated with these two case studies is presented in table 5.1.

Output	Baseline : Cost Min.	Exergy Loss Min.
Cost [B€/year]	42.2	76.5
Emissions [MtCO_2-eq/year]	81.3	18.4
Difference with Baseline [%]	0	-77.4
Exergy Efficiency [%]	33.56	49.06

Table 5.1 Results for the year 2035: Cost minimization and Exergy Loss Minimization

5.2 Building a sustainable exergy-based tax system

5.2.1 Exergy Loss Tax

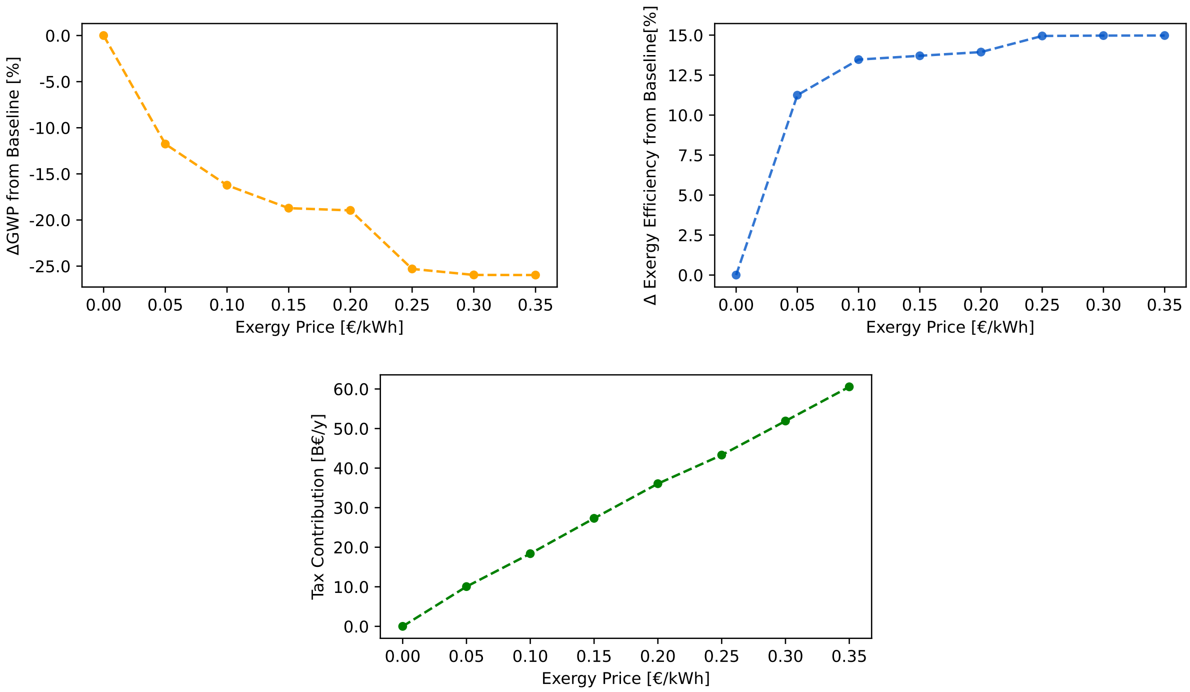


Figure 5.1 The variation in exergy loss shows an increase in the amount of tax levied to reduce emissions of up to 25% and a maximum increase in exergy efficiency of 15%.

From Table 5.1, minimization of exergy loss demonstrates a significant reduction in emissions while maximizing exergy efficiency. To assess the impact of a tax on exergy losses, the associated exergy loss charge (exergy price) was varied between 0 and 0.35 €/kWh to understand the performance such a tax can achieve. However, the tax contribution shows that beyond an exergy price of 0.05 €/kWh, the amount of tax collected is above the current amount of tax collected (€10 billion). For a tax collection of €10 billion, exergy efficiency increases by 11%, and emissions fall by 12% compared to the baseline situation (without tax).

Figure 5.1 illustrates the evolution of emissions as a function of the exergy loss price. Surprisingly, emissions with an exergy tax can be reduced by a maximum of 26%, whereas the maximum reduction, obtained when minimizing the GWP, is as large as 77% see Table 5.1. However, Figure 5.1 reveals that beyond an exergy price of 0.25, it is possible to achieve an exergy efficiency comparable to the maximum obtained with the minimization of exergy loss. This suggests that an increase in exergy efficiency close to 15% can be attained through two different means, one potentially more emitting than the other. To ensure that the tax leads to a more favorable outcome in this case, it is possible to combine it with other taxes.

As illustrated in 5.1, the amount of money collected by the tax system increases proportionally with the price of exergy loss. As mentioned above, exergy loss is inherent in the transformation of one form of energy into another. The tax does not aim to eliminate this loss, only to reduce it. The fact that this tax can be collected even if the system tends towards greater efficiency is an advantage because it is an alternative to the VAT system. The state can recover money from any energy transformation activity with an exergy loss tax system.

5.2.2 Combined Taxation: Exergy loss and Non-Renewable Imports

As mentioned above, a tax on exergy losses alone cannot steer the energy system to a sufficiently ambitious decarbonization. It should therefore be combined with other tax systems. The first idea is to complement the tax on exergy losses with a tax that negatively affects the import of non-renewable resources. Indeed, the previous taxation strategy proposed does not differentiate between renewable and non-renewable resources. However, a sustainable tax should penalize non-renewable resources more. Figure 5.2 illustrates the tax revenues generated by the combined tax system. This figure shows an interpolation of 100 simulations using different combinations of a non-renewable import price and an exergy loss price. With a target tax collection of around €10 billion, the orange dashed line can be seen as the approximate position of the combinations that give the correct tax amount.

Based on this analysis, it becomes feasible to identify a combination that simultaneously enhances exergy efficiency and reduces emissions. By visually examining the graphs depicted in Figure 5.3, a trade-off can be proposed: it would consist of a non-renewable import price (NR price) of 0.0404€/kWh combined with an exergy loss price (Exergy price) of 0.0176€/kWh. This configuration maintains tax revenue at 10 billion euros, concurrently fostering a 10% increase in exergy efficiency from the baseline while reducing emissions by at least 60%.

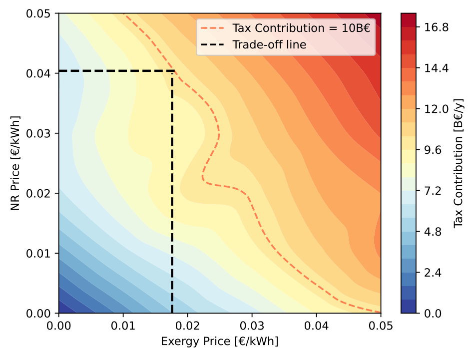


Figure 5.2 Non-renewables and exergy loss tax contribution

The tax on non-renewable imports is calculated with imports accounted in terms of exergy. To find the energy-based price of non-renewable imports, this price must be transformed with the exergy factor of each energy carrier.

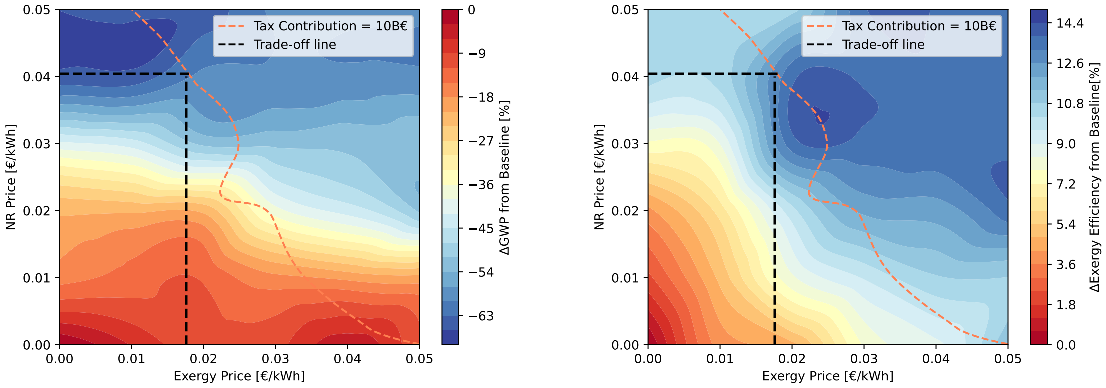


Figure 5.3 Exergy loss and Non-Renewable price variations show that different optimums can be chosen to levy the right amount of taxes. In this work, the optimum chosen is with an exergy price of 0.018€/kWh and a non-renewable import price of 0.040 €/kWh.

5.2.3 Combined Taxation: Exergy loss and Carbon Tax

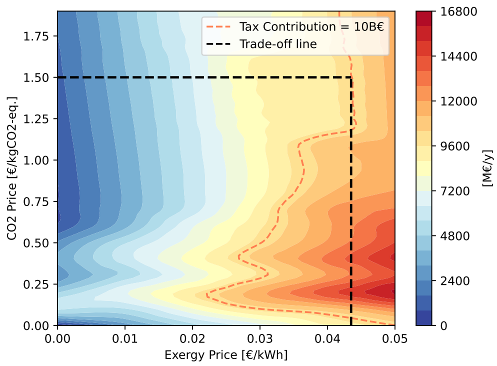


Figure 5.4 Emissions and exergy loss tax contribution

The previous tax proposition was interesting but in the end, it is not much the non-renewables that it is preferred to avoid but more the emissions they produced. As depicted in Figure 5.3, the tax system targeting non-renewable imports is not able to reduce the emissions by more than 65% given the tax collection limits. This level is already really interesting but another tax system could enable the emissions reduction even more.

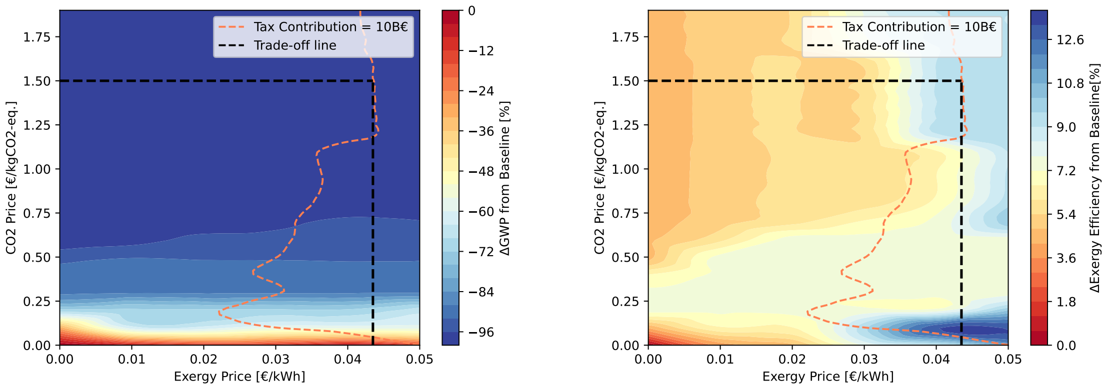


Figure 5.5 Exergy loss and CO_2 price variations. In this work the optimum chosen to levy the right tax amount is with an exergy price of 0.045€/kWh and a non-renewable import price of 1.5 €/kgCO_2.

The most evident alternative is to directly combine the exergy loss tax with a tax on emissions. Figure 5.4 shows the approximated combinations of carbon and exergy loss prices that result in a sufficient tax levy (orange dashed curve). Plotted in Figure 5.5, this curve shows all the valid combinations and their impact on emissions and exergy efficiency. To increase exergy efficiency and radically reduce emissions, an arbitrary compromise is to take a CO_2 price of 1.5 €/kgCO_2-eq. and an exergy loss price of 0.0435 €/kWh.
This choice results in an exergy efficiency increase of 9 % and an emissions reduction of almost 100%.

5.3 Comparing Exergy-Based Taxes to Carbon Tax

Although three exergy-based tax systems have been analyzed to propose their potential implementation in Belgium, the effectiveness of these measures compared to a carbon tax merits further study. The simplicity of implementing a carbon tax, already envisaged in Belgium (FPS Health and Environment, 2023), raises questions about the effectiveness of more complex systems.

Figure 5.6 illustrates the impact of a carbon tax alone, showcasing variations in CO_2 prices and their influence on emissions and exergy efficiency. As anticipated, the tax significantly reduces emissions; however, it falls short of achieving a similar level of exergy efficiency as those obtained with exergy-based tax systems. In this study, a CO_2 price of 0.7€/kgCO_2 is selected as it corresponds to the minimum price that optimizes the tax's performance, resulting in a remarkable 99.46% reduction in emissions compared to a tax-free scenario.

Table 5.2 presents a comparative analysis of various tax systems, evaluating the effectiveness of an exergy-based tax against a carbon tax. Concerning the defined parameters of a sustainable tax system in this study - one that generates sufficient revenue (€10 billion), enhances exergy efficiency, and maintains low emissions - it becomes evident that a standalone carbon tax does not fully meet these criteria. Prasad (2022) showed that if carbon taxes are substituted for other taxes, then the tax base of the state becomes dependent on the revenue from carbon taxes. If that revenue declines—as it surely must, given the rapid development of alternative energy and energy efficiency technologies, which will make it easier for firms and individuals to reduce carbon emissions and therefore no longer need to pay the tax—then the tax base of the state declines. Consequently, it necessitates integration with another tax scheme to achieve desired taxation levels. Presently, Belgium's approach involves combining the carbon tax with Value Added Tax (VAT), a strategy aimed at both revenue generation and emission reduction (FPS Health and Environment, 2023).

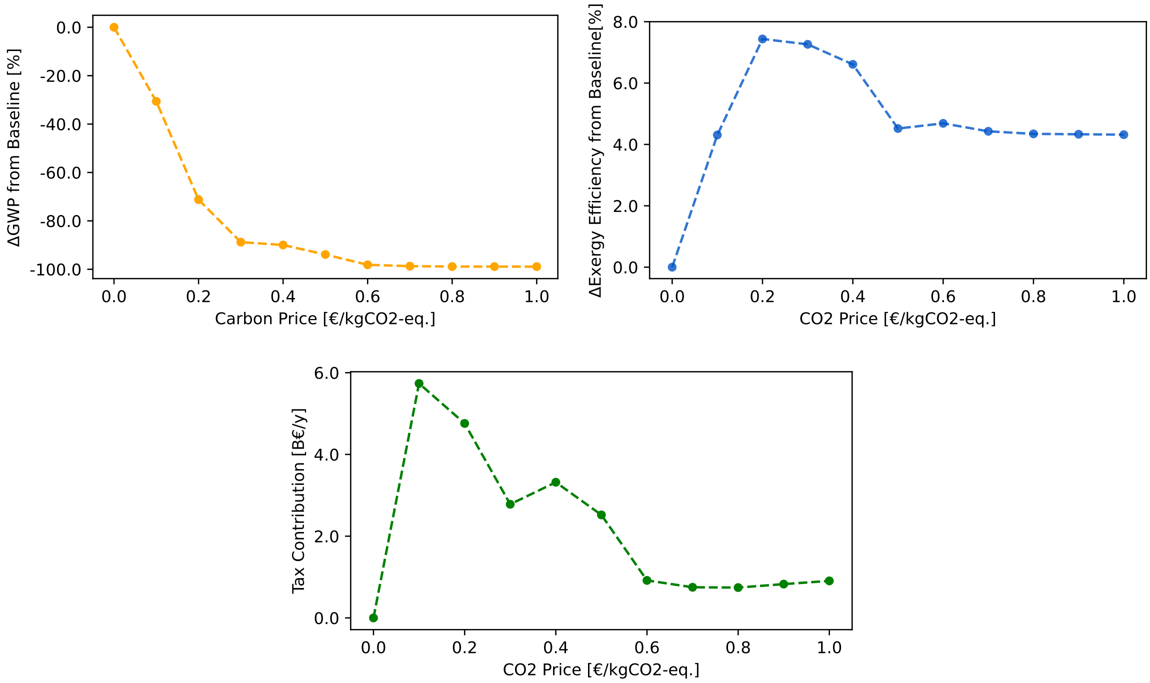


Figure 5.6 Variations on the carbon tax show that it is a tax system capable of reducing emissions by almost 100%, but only with a 4% increase in exergy efficiency and without the right amount of tax levied.

However, it is possible to attain the dual objectives of robust tax revenue and minimal emissions by augmenting considerably exergy efficiency (see Table 5.2) through a combination of a carbon tax with an exergy loss tax. However, it should be noted that the latter option leads to an energy system requiring higher investment and operating costs (+35% compared to the baseline).

	Carbon Tax	**Exergy loss Tax**	**Combined NR and Exergy loss Tax**	**Combined Carbon and Exergy loss Tax**
CO_2 price [€/kgCO_2]	1	0	0	1.5
Exergy price [€/kWh]	0.0	5e-2	1.8e-2	4.4e-2
NR price [€/kWh]	0.0	0.0	4.0e-2	0.0
Tax revenues [B€/y]	0.91	9.96	10.06	10.20
Difference from Baseline [%]				
ΔTotal cost (investment and operation)	30.47	5.74	12.60	35.14
ΔEmissions	-98.90	-11.76	-64.91	-99.46
ΔExergy Efficiency	4.32	11.36	10.50	9.02
ΔPrimary Energy	-4.01	-25.54	-24.09	-21.50

Table 5.2 Comparative Analysis of the different tax systems

Table 5.2 further illustrates that pairing a non-renewable import tax with an exergy tax presents an intriguing alternative, markedly reducing emissions while maintaining relatively lower operational and installation expenses compared to the combined carbon and exergy loss tax scheme.

Exergy loss tax alone is a good start to reduce emissions but it necessitates improvements to reach a more ambitious reduction of emissions in the coming decades. The main advantage of an exergy loss tax is the reduction in primary energy use. As shown in Table 5.2, while the carbon tax only reduces by 4% energy supplied to the system, all the exergy-based taxes reduce by at least 21% the energy resource.

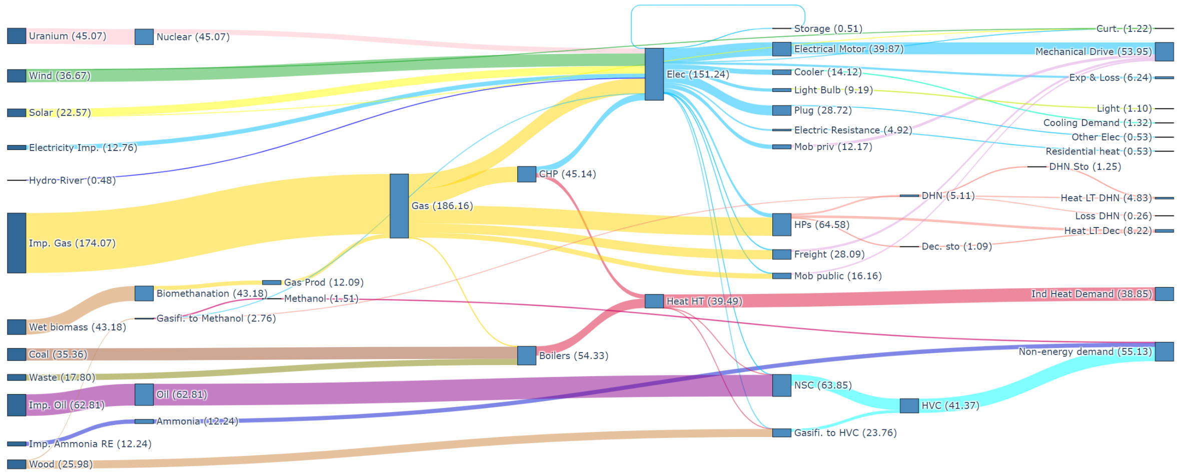
5.4 Exergy-Based tax proposed

The choice of which tax to implement depends on the level of ambition of Belgium. Belgium aims to reduce its greenhouse gas (GHG) emissions by 47% by 2030 compared with 2005. The target aligns with current EU commitments but falls short of international climate agreements. Such agreements would require Belgium to reduce emissions by 60% (CCPP).
In both cases, the tax on non-renewable import and exergy losses is supposed to push the system towards the required emissions level with a cost on investment and operations 12.6% higher than the cheapest system.

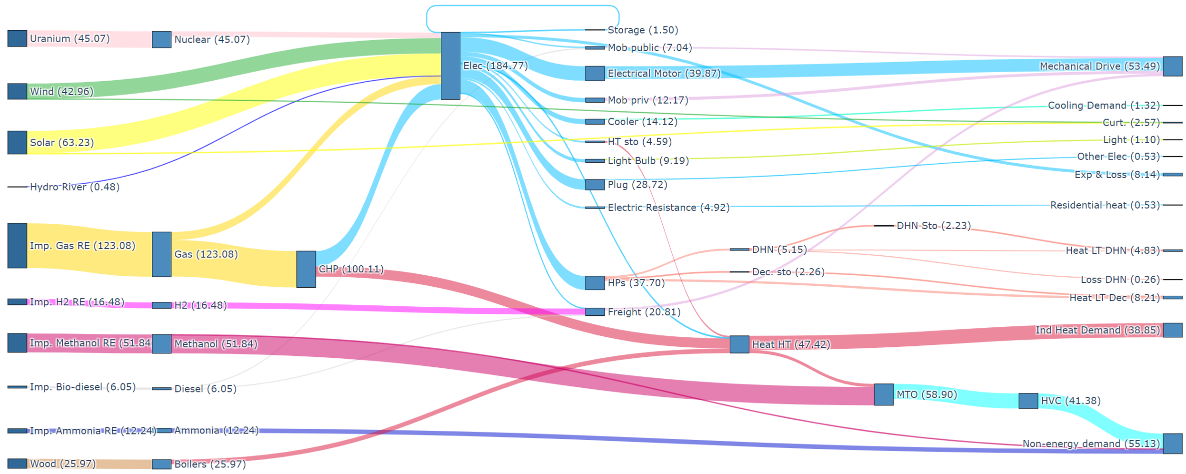
For the year 2050, Belgium and, more generally, the European Union, have set themselves a goal of carbon neutrality (Boussemaere et al.). To achieve this, a more ambitious taxation system can be proposed, targeting emissions and exergy losses. This tax system is then considered the ultimate tax to be implemented in Belgium to achieve the neutrality objective.

5.5 Exergy Analysis of the proposed tax

This section aims to understand the difference between a system projected in 2035 with no environmental tax and the ambitious system under tax targeting emissions (CO_2 price: 1.5€/kgCO_2) and exergy losses (Exergy price: 0.04€/kgCO_2). That tax can move the system towards near-neutrality. In the next sections, the system subject to the proposed tax is called the ideal system.
For a deeper comprehension of the technologies favored by the ideal system, a comparative analysis can be conducted with the exergy system chosen for the baseline system (2035 without any tax). Figure 5.7 shows the exergy flows in the two different systems obtained with ExergyScope for the year 2035. As the figure shows, the ideal system has



(a) Exergy flows in 2035 without tax: baseline



(b) Exergy flows in 2035 with tax on emissions and exergy loss

Figure 5.7 The exergy flow diagrams reveal that the system subject to the proposed tax has opted for the electrification of heating and mobility systems. In addition, the ideal system relies exclusively on renewable energies, with the exception of uranium used in nuclear power plants.

opted for only renewable resources, except for uranium. Whereas the baseline model relies on imported electricity, the ideal system does not. Electricity consumption has increased in the ideal system to supply heat via heat pumps (HP) and mobility (public Mob). This change contributes to an increase in final-to-useful exergy efficiency in all sectors, as shown in Table 5.3. As presented in that table, the tax is able to improve mainly the efficiency in the transport sector and heating systems, as other end-use conversions are determined by the efficiency of a single technology per useful category (see Table 3.1).

In the production of high-value-added chemicals, production has shifted from oil processing to methanol processing, as renewable methanol can be imported. Boiler production has completely disappeared from the ideal system, replaced by higher-efficiency

Sector	2035 without tax	Carbon and Exergy loss Taxed
Industry	53.9%	56.9%
Residential	35.7%	39.2%
Services	53.5%	57.2%
Transport	38.8%	47.0%
Aggregate	43.1%	50.3%

Table 5.3 Evolution of the final-to-useful efficiency per sector in 2035 with and without tax system. Efficiency is increased in all sectors thanks to the chosen tax system.

technology (such as heat pumps). As far as freight is concerned, the ideal system has also opted for a transition from gas-powered to hydrogen-powered (fuel cell) trucks. As shown in the table 3.3, the final-to-useful efficiency of the first truck is lower than that of the second. In addition, electricity is generated by more cogeneration in the ideal system, which increases exergy efficiency. This result aligns with the results presented by Sejkora et al. (2022) for Austria (cfr Section 2.2.1). In that study, exergy analysis favored the electrification of heating systems and the use of electric and fuel-cell vehicles.

The analyses of this tax system proposed lead to the conclusion that the carbon tax mainly limited the choice of resource used, while the exergy loss tax opted for more efficient technologies. However, the combination of the two did more to reduce carbon emissions than a carbon tax alone because exergy losses also include exergy released to the environment (including emissions).

In section 4.2, the exergy loss in the system was studied in 2015. Now, it is possible to compare the system in 2015 with a projected system in 2035 that taxes exergy loss and emissions as presented before. Figure 5.8 shows that the exergy loss is massively reduced. Two phenomena are beneficial. First, the technologies' exergy efficiency was improved due to the technical progress of individual technologies, taken as an assumption by EnergyScope. Secondly, the tax system forced the model to choose conversions that limit exergy loss. As expected, the ideal model decided to install and use fewer boilers, less nuclear, and fewer internal combustion vehicles.

5.5.1 Reflection on the proposed system

This section shows that it is possible to achieve a very low level of emissions with a tax on emissions and exergy losses. However, Figure 5.7b shows that the system relies on a lot of imported renewable fuels such as renewable gas, ammonia, methanol, etc. However, those fuels involve a lot of exergy losses during their production. ExergyScope does not account for their exergy loss abroad. The tax system only aims at improving the exergy efficiency within the country and reducing the resource import to supply the Belgian energy system.

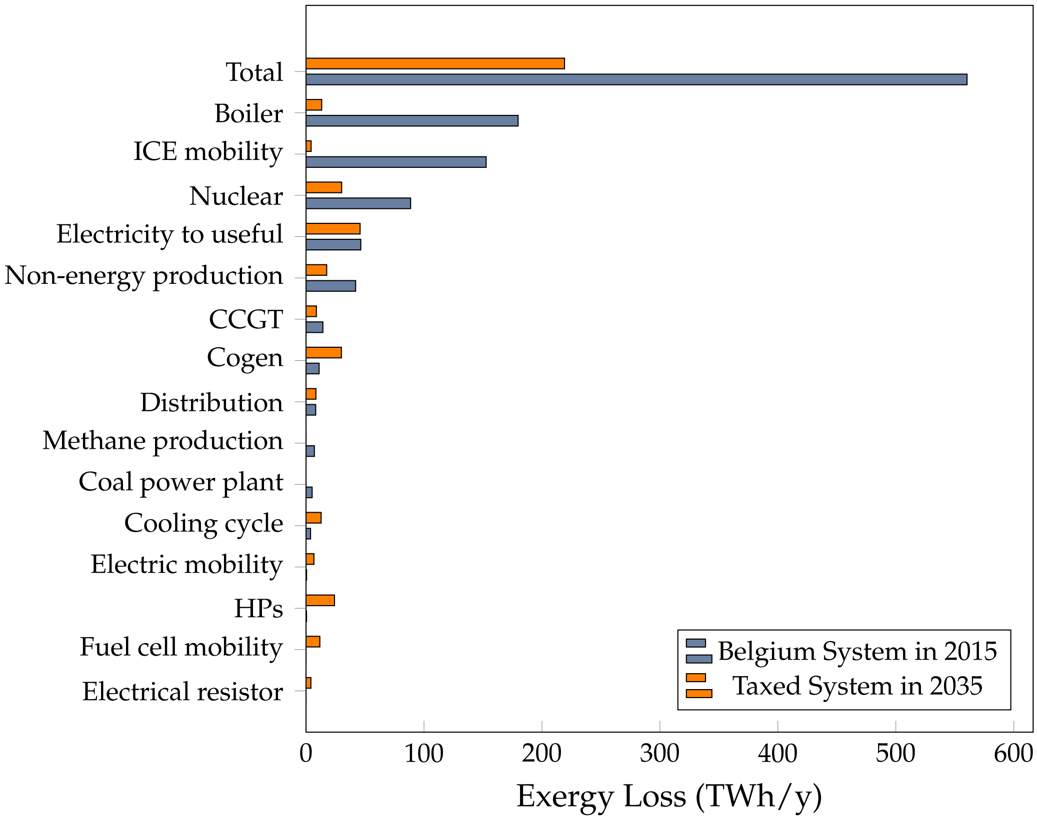


Figure 5.8 Comparison of the breakdown of exergy destruction between the taxed system in 2035 and the system in place in 2015. Boilers, internal combustion engine vehicles, and nuclear power plants, the three main hotspots in 2015, have been reduced.

However, a sustainable country alone will not change the global impact on the planet. The different tax systems need to be thought of on a larger scale to understand better what would be the impact of such a tax and if it changes energy consumption.

5.6 Discussion on Tax Collection

The tax systems were designed to retribute €10 billion. However, this amount is reached only when optimality occurs. That means that the state will collect a higher amount of taxes before the system reaches its optimal cost (incl. investment, operations, and taxes). For example, the exergy tax alone has been tested in the year 2015 which is constrained to represent the Belgian system at that time. A tax collection of 20B€ is estimated with an exergy loss price of 0.05€/kWh. That means that the state collects at the beginning double the amount as is the case today.

Caetano and Marques (2023) has shown how, in a society where profit remains the driving force behind business decisions, industries could move to countries with lower levels of taxation. However, emissions need to be reduced on a global scale. As Jäger (2023) explains, it is important to keep energy-intensive industries in Europe and help them decarbonize, rather than taxing them to the point of driving them away. This could be achieved through the tax revenues collected, as proposed by Prasad (2022).

Gradual implementation of a tax system could prevent investment and operating costs from rising drastically all at once. This is the subject of the next section.

5.7 Gradual Implementation of the Proposed Tax System

The proposed tax system, targeting emissions and exergy losses, can be implemented gradually to minimize systemic stress during its initial phase.

ExergyScope is not designed to propose a pathway between two systems. However, it is interesting to understand how the system evolves under different taxation levels. Here is a theoretical study to show how a tax system can be implemented gradually trying to maintain a constant level of tax collected (in this work, €10 billion). As mentioned above, the proposed tax system would produce too high total tax revenues for 2015. It is possible to imagine a different tax combination that limits the tax collection. For the year 2015, the ExergyScope model provides an exergy loss of 486 TWh and emissions of 138 $MTCO_{2,eq}$.

Since emissions reduction is the main goal for 2050, a larger portion of the tax collection will be allocated to the CO_2 tax than to the exergy loss tax. An arbitrary distribution is €7 billion for the CO_2 tax and €3 billion for the exergy loss tax. Based on 2015 data, the exergy price is set at 0.006 €/kWh and the CO_2 price at 0.05 €/kgCO_2, which together allow the collection of the target amount of €10 billion in 2015.

The next step is to define a tax combination that satisfies the emissions target defined by Belgium for 2030. Belgium set a target of 65 $MTCO_{2,eq}$ for 2030. By trying different combinations, it appears that combining a CO_2 price of 0.06 €/kgCO_2 and an exergy price of 0.008 €/kWh achieves the desired emissions level.

Assuming that the amount of tax designed based on 2015 data (emissions and exergy destruction) is applied in Belgium starting from 2025, trends for the gradual tax can be defined. Figure 5.9 shows how the exergy and CO_2 prices evolve between 2025 and 2050. As a reminder, the combination of taxes chosen for 2050 is the one largely explored before. This study does not prove that these combinations allow the collection of €10 billion every year with the system evolving.

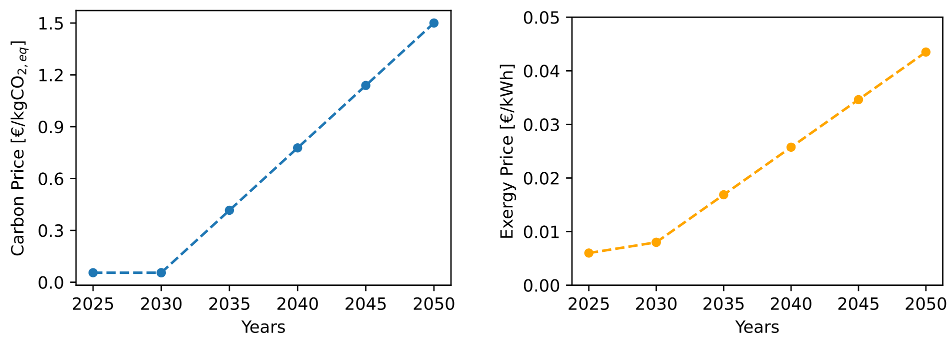


Figure 5.9 Evolution of the CO_2 (on the left) and exergy (on the right) prices for the implementation of the proposed tax in Belgium from 2025 until 2050

However, checking that the different levels of taxation are pushing the system in the same direction is interesting for understanding the feasibility of this method. For the results presented hereafter, let:

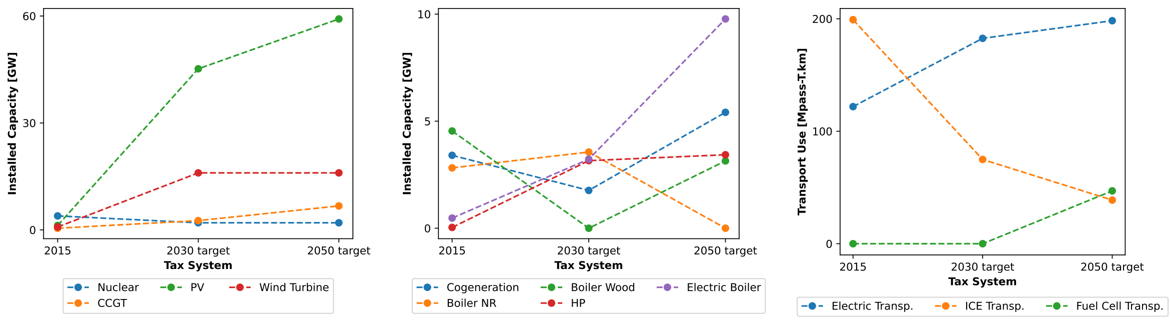
2015: ExergyScope model run for the year 2015 without any taxation and with constraints to best represent the 2015 energy system in Belgium.

2030 target: ExergyScope run for the year 2035 with the taxation level designed to respect the 2030 Belgium emissions target.

2050 target : ExergyScope run for the year 2035 with the taxation designed for the decarbonized system (2050 target).

Figure 5.10 depicts the evolution of the energy system for these three scenarios. The trends in technology adoption are generally coherent, with some discrepancies in heat production. This consistency suggests that a progressive implementation of the tax system leads to a gradual evolution of the technologies used. In other words, lower-emitting technologies gradually replace higher-emitting technologies, without any real abnormal backtracking.
Gradually implementing the proposed tax system ensures that operational and investment costs do not increase too rapidly, allowing for progressive investments towards a decarbonized energy system by 2050. Table 5.4 summarizes the results of the gradual implementation of the emissions targets in 2030 and 2050.

This analysis reaches the limit of ExergyScope TD as highlighted in the heat production evolution (Figure 5.10b). That model does not show high practicality to assess the evolution of a model year after year. It is not possible to account for the existing technologies. Moreover, the 2030 and 2050 scenarios are both tested based on 2035 data, which is a rough approximation. A more precise methodology would be to increase the demand gradually over the years. Another version of EnergyScope allows for the creation of pathways between two systems (Limpens et al., 2024). That model can also be modified to account for exergy flows in the same way as this version of ExergyScope.



(a) Electricity Production **(b)** Heat Production **(c)** Transoportation freight and passengers

Figure 5.10 Technological evolution between 2015 and 2050 in the electricity, heat production, and transport sectors. Trends are generally coherent, except for some disparities in heat production.

	2030 target	**2050 target**
CO_2 price [€/kgCO_2]	0.06	1.50
Exergy price [€/kWh]	0.008	0.044
Emissions [MTCO_2]	63.7	0.45
ΔTotal cost from Baseline[1] (investment and operation) [%]	1.8	36.2
ΔExergy Efficiency from Baseline[1] [%]	3.2	9.2

Table 5.4 Summary of results from the gradual implementation of the proposed tax system. This shows that the two different tax combinations can meet the Belgian target of 2030 and the net-zero target of 2050 while improving exergy efficiency.

Using that tool would offer a more precise technique to assess the effectiveness of this tax year after year. However, the results show that implementing a tax targeting exergy loss and emissions can be done gradually. This offers interesting insights to ensure the transition uptake from an economic point of view.

[1] As a reminder the Baseline scenario is the ExergyScope model run in 2035 without any taxation.

6

Reflection and Conclusion

6.1 Reflection on exergy

This thesis proposed a tax based on exergy, a thermodynamic variable demonstrated to be efficient in societal exergy studies, as extensively discussed in Section 2.2. Exergy provides a comprehensive framework for comparing energy use across different services and evaluating loss of energy quality.

A tax targeting exergy loss and emissions highlights the benefits of electrification in transportation and heating systems, promoting a shift away from fossil fuels. This naturally raises the question: would an energy tax achieve similar outcomes? Based on energy analysis, the advantages of electrification become evident (Aalto et al., 2021). As detailed in Annex 1.1, electric technologies, such as heat pumps and electric vehicles, exhibit superior efficiency. Therefore, implementing a tax based on emissions and energy losses is worth considering, particularly since policymakers are more familiar with energy-related concepts.

However, this approach presents challenges. For instance, the efficiency of heat pumps can exceed one, making it impractical to tax energy loss directly. Exergy, on the other hand, offers a robust framework for taxing various technologies based on their exergy losses, which are always positive.

Moreover, an exergy tax can extend to mineral resources, accounting for resource quality. Exergy can assess the difficulty of using diluted versus concentrated resources by measuring their chemical potential (or chemical exergy) (Brockway, 2016). The conservative property of energy complicates discussions about losses during natural resource transformation, whereas exergy provides a clearer metric (Huysman et al., 2015).
In conclusion, while an energy-based tax could be appropriate for the energy sector, it requires further study to develop a framework applicable to technologies with effi-

ciencies greater than one. If the goal is to create a comprehensive tax framework for all products, an exergy-based tax appears more promising but also demands additional research.

6.2 Limitations of This Work and Further Studies

This work provides an interesting tax framework but some aspects are not well covered and require further studies.

First of all, this work needs to be extended to a larger scale to understand the interactions between countries. Thiran et al.'s development of EnergyScope Multicell could be adapted to handle exergy flows. This could be done in the same way as for ExergyScope TD (available on Github). This would make it possible to implement different tax systems and analyze their expected effects beyond Belgium.

Moreover, this study did not consider different demand scenarios. The implementation of exergy-based tax systems could exert pressure on the economy and potentially lead to the closure of high-emitting industries. It is crucial to account for these factors to propose a viable tax system. Furthermore, for the proposed system to be viable, various strategies need to support it. For example, to prevent industries from moving to less-taxed countries, a strategy to counter this effect must be put in place. This can be achieved by introducing a tax at the borders of a region, as is the case with the Border Carbon Adjustment Mechanism (BCAM). This mechanism was introduced by the EU to set a fair price on the carbon emitted during the production of carbon-intensive goods entering the EU, in order to encourage cleaner industrial production in third countries while avoiding the relocation of industries (CBAM).

Achieving a net-zero energy system is one of the key milestones towards a more sustainable society. However, it must be strategically planned to ensure the economic viability of Belgian society. The United Nations has adopted seventeen Sustainable Development Goals (SDGs) that encompass all facets of a more sustainable society. A more precise method for assessing the benefits and drawbacks of an exergy-based tax concerning different SDGs and scenarios is necessary.

Additionally, these scenarios need to analyze the impact of social acceptance on different policies. A pertinent example is the debate on nuclear energy. As stated in the previous section, the tax system proposed relies on nuclear power plants. According to Latré (2022) (see Figure 6.1), only 37% of the Belgian population is either somewhat or strongly in favor of nuclear power plants, while the rest are either undecided or against them. This was the case in 2017, today a survey done by IPSOS indicates that 6 people out of 10 are in favor of installing new reactors. This indicates a divided and changing public opinion, which would undoubtedly impact policy decisions. Therefore, social acceptance must be considered in such scenarios to avoid failure in transition policies.

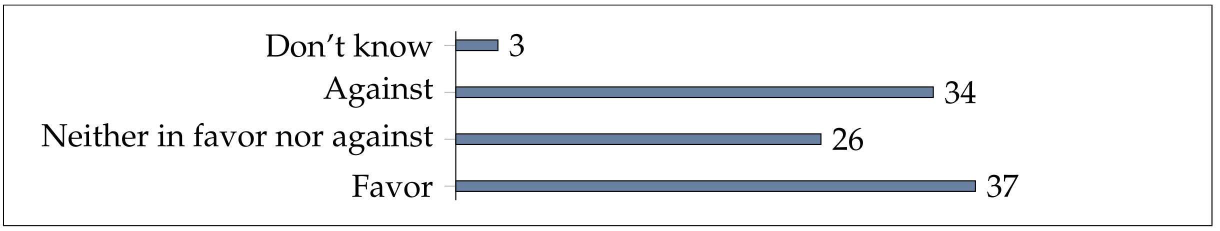


Figure 6.1 Public opinion on nuclear power in Belgium (Latré) in 2017. This shows that the Belgian population is rather divided about nuclear power. It is not possible to guarantee that nuclear power will still be allowed in 2035.

6.3 Conclusion

This thesis began by defining exergy and highlighting its benefits in societal studies, presenting different exergy-based tax systems for potential implementation in Belgium. Without increasing the total tax burden, these taxes can encourage the reduction of products that have a significant environmental impact (Szargut et al., 1988). In this context, a strong environmental impact was defined by the combined high use of primary energy and emissions.
It has been demonstrated that exergy-based taxes can effectively reduce emissions and primary energy use. The most efficient tax targets both emissions and exergy losses, proving to be more effective than a tax targeting solely emissions.

This initial analysis is a crucial first step in assessing their benefits. However, implementing this taxation system would significantly increase system costs (both installation and operations), potentially leading to undesirable economic consequences such as the closure of industries. These potential outcomes must be thoroughly examined and weighed against the benefits. Further research is needed to analyze in depth the impact of exergy-based taxes, particularly their phased implementation.

A significant drawback of exergy-based taxes is their reliance on the concept of exergy, which is not widely understood by the general population and requires knowledge of thermodynamics. Despite this challenge, the analysis presented here has been limited to the energy sector. It would be valuable to extend this analysis to the entire economy. Exergy-based taxes have the potential to reduce resource depletion comprehensively (Szargut, 2002). If proven effective, policymakers would have a new tool to ensure the uptake of the transition to sustainability.

It is important not to overlook the substantial impact that policymakers can have on the transition to sustainability. A great example is the Montreal Protocol, adopted in 1987 (Montreal, 1987). This meeting brought nations together to reach agreements on phasing out ozone-depleting substances.. This has led to significant reductions in problematic species and technological innovations. This success demonstrates that effective policy frameworks can lead to substantial environmental improvements and sustainable practices.

While taxes can initiate the transition, policymakers need to encourage broader changes. Indeed, the tax proposed in this work is designed to maintain or increase current demand levels, but it is also essential to consider the concept of sobriety. As Balzani (2019) pointed out, the least polluting energy is the energy we do not consume.

In conclusion, exergy-based taxes present a promising avenue for promoting sustainability and reducing environmental impact. However, their implementation requires careful consideration of economic and societal impacts, as well as broader public education on exergy and its importance.

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Apendices

1.1 Efficiencies of the technologies of Energy/ExergyScope

Technology	Energy Efficiency	Exergy Efficiency
Nuclear	37.00%	33.00%
Combined cycle gas turbine	63.00%	60.58%
Amonia combined cycle gas turbine	50.00%	41.67%
Ultra-supercritical coal power plant	49.00%	46.23%
Integrated gasification combined cycle with coal	54.00%	50.94%
Photovoltaic	100.00%	100.00%
Wind onshore	100.00%	100.00%
Wind offshore	100.00%	100.00%
Hydro river	100.00%	100.00%
Geothermal power plant	100.00%	100.00%
Cogeneration gas (industry)	90.00%	70.05%
Cogeneration wood (industry)	71.00%	46.17%
Cogeneration waste (industry)	65.00%	48.23%
Boiler gas (industry)	92.72%	55.93%
Boiler wood (industry)	86.45%	48.85%
Boiler oil (industry)	87.25%	51.64%
Boiler coal (industry)	82.00%	48.53%
Boiler waste (industry)	82.00%	51.44%
Electrical resistors (industry)	100.00%	62.73%
Heat pump (DHN)	400.00%	43.57%
Cogeneration gas (DHN)	90.00%	52.27%
Cogeneration wood (DHN)	71.00%	21.42%
Cogeneration waste (DHN)	65.00%	24.90%
Cogeneration wet biomass (DHN)	28.63%	13.21%
Cogeneration hydrolysis (DHN)	58.90%	26.17%
Boiler gas (DHN)	92.72%	9.71%
Boiler wood (DHN)	86.45%	8.48%
Boiler oil (DHN)	87.25%	8.97%
Geothermal (DHN)	100.00%	10.89%
Solar thermal (DHN)	100.00%	10.89%
Electrical heat pump (decentralized)	300.03%	32.50%
Thermal heat pump gas (decentralized)	149.99%	15.62%
Cogeneration gas (decentralised)	90.00%	47.10%

Technology	Energy Efficiency	Exergy Efficiency
Cogeneration oil (decentralised)	82.00%	41.19%
Advanced cogeneration (Fuel cell) gas (decentralized)	80.00%	58.06%
Advanced cogeneration (Fuel cell) H2 (decentralized)	80.00%	61.46%
Boiler gas (decentralised)	90.00%	9.37%
Boiler wood (decentralised)	85.00%	8.29%
Boiler oil (decentralised)	85.00%	8.68%
Solar thermal (decentralised)	100.00%	10.83%
Direct electrical heaters (decentralized)	100.00%	10.83%
Tram or metro	81.00%	81.00%
Bus diesel	24.38%	23.00%
Bus diesel hybrid	32.74%	30.89%
Bus gas	24.17%	23.24%
Bus fuel cell (H2)	28.70%	29.21%
Train (passenger)	81.00%	81.00%
Car gasoline	21.33%	20.13%
Car diesel	24.38%	23.00%
Car gas	30.75%	29.57%
Car methanol	23.06%	23.53%
Car hybrid (gasoline)	31.51%	29.73%
Car plug-in hybrid	43.03%	41.92%
Car electric	65.83%	65.83%
Car fuel cell (H2)	48.36%	49.22%
Train (freight)	81.00%	81.00%
Boat diesel	27.56%	26.00%
Boat gas	23.97%	23.05%
Boat methanol	23.97%	24.46%
Trucks diesel	24.38%	23.00%
Truck methanol	21.21%	21.64%
Truck fuel cell (hydrogen)	28.40%	28.91%
Truck electric	50.19%	50.19%
Truck gas	21.18%	20.37%
Efficiency measures in energy system	100.00%	100.00%
District heating network	100.00%	100.00%
Electrical grid cost	100.00%	100.00%
Electrolysers	80.50%	82.39%
Steam methane reforming	73.28%	69.23%
Biomass to hydrogen	43.25%	38.28%
Wood gasification	86.97%	63.06%
Hydrogen methanation	107.92%	90.93%
Biomass methanation	29.88%	28.00%
Biomass hydrolysis	46.30%	43.24%
Wood pyrolysis to gasoline and diesel	68.18%	65.02%
Wood pyrolysis to LFO	58.38%	55.69%
Carbon capture atmospheric	100.00%	100.00%
Carbon capture from industry	100.00%	100.00%
Hydrogen methanolation	84.62%	78.60%
Methane to methanol	65.40%	61.63%
Biomass methanolation	86.00%	58.70%
Haber bosch (H2 to amonia)	90.54%	98.52%
Amonia to H2	66.00%	51.90%
Oil to HVC	53.86%	51.04%
Gas to HVC	30.64%	29.62%
Biomass to HVC	40.62%	36.98%
Methanol to HVC	63.65%	70.26%

1.2 Files used in this thesis

ExergyScope python code is available on this link on GitHub.This repository also includes the necessary files to adapt EnergyScope into ExergyScope.

Two main files are used:

`LayersInOutAndDemand_adapt` This file allows the input of `Layers_In_Out` and `Demand` files. The Excel file is configured to transform these inputs into compatible files for ExergyScope.

`ResourceAndTechno_price_adapt` This file allows the input of `Technologies` and `Resource` files. These files provide the cost and emissions data related to the respective technology or resource. The Excel file is configured to transform these inputs into compatible files for ExergyScope.

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