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EXERGY ANALYSIS OF THE CHILEAN SOCIETY

MEMORIA PARA OPTAR AL TÍTULO DE
INGENIERO CIVIL EN BIOTECNOLOGÍA

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SUMMARY

RESUMEN DE LA MEMORIA PARA OPTAR AL
TÍTULO DE: Ingeniero Civil en Biotecnología
POR: Sebastián Eduardo Ramírez Ibaceta
FECHA: 12/04/2017
PROFESOR GUÍA: Felipe Díaz Alvarado

EXERGY ANALYSIS OF THE CHILEAN SOCIETY

The present report contains an exergy analysis of the Chilean society in 2013. Wall's approach was taken to assess the exergy efficiency of four main economic sectors: mining, manufacturing, transportation, and households.

Several assumptions were taken to simplify the complex thermodynamic interactions within the society model. For instance, exergy flows among economic sectors were not considered, due to the lack of relevant statistical data on these interactions. On the other hand, only some of the exergy carriers entering and leaving the society were accounted, as the focus of this work is to provide a first outlook of the Chilean exergy efficiency from a chemical exergy standpoint. An extended exergy analysis (EEA) is proposed for future studies, in order to integrate exergy of labor and capital into the analysis. Statistical power plays an important role in this matter, as key data required to perform an EEA is nowadays unavailable.

The efficiency of the society in 2013 was 24%. Comparing with other societies, the Chilean case was found to be in between advanced economies and less developed countries. The current development model is criticized, as the most developed countries previously analyzed have the lowest thermodynamic efficiency. In the long term, a shift of paradigm is expected, fostering local development and educating about resources overconsumption. Regarding Chilean economic sectors, exergy efficiency was found to be higher in extractive activities, such as mining (53%), and manufacturing (53%). In general, exergy efficiency was lower in services and end-use sectors, such as transportation (21%), and households (10%). This is considered to be related with omission of labor in the analysis, as end-use sectors show a higher dependency on human work compared to industrial/extractive activities.

Despite of methodological difficulties, interesting suggestions were obtained from the analysis. Structural changes are proposed in the manufacturing sector, to improve the efficiency of transformations carried out in agriculture, livestock, and aquaculture activities. Food industry as a whole would improve its thermodynamic performance if steps in this direction were taken. Likewise, fostering a technological shift towards electric vehicles would imply a much better use of the available resources. In the same way, improvements in water and space heating are desirable, as these two end-uses are the most exergy intensive applications in household consumption.

RESUMEN EJECUTIVO

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ANÁLISIS EXERGÉTICO DE LA SOCIEDAD CHILENA

El presente trabajo contiene un análisis exergético de la sociedad chilena en 2013. Usando la metodología propuesta por Wall, se estudió la eficiencia exergética de cuatro sectores económicos principales: minería, manufactura, transporte y residencial.

Algunos supuestos fueron tomados para simplificar el modelo termodinámico de la sociedad y sus interacciones. Por ejemplo, los flujos de exergía intersectoriales no fueron considerados, debido a la falta de información en relación a estas interacciones. Por otra parte, sólo se tomaron en cuenta las materias primas y productos más relevantes para la sociedad, ya que el enfoque del trabajo es proveer una primera aproximación a la eficiencia exergética chilena, desde un punto de vista de la exergía química. Se propone usar un análisis exergético extendido (EEA) en modelos futuros, integrando la exergía del trabajo humano y flujos de capital. En este punto, el poder estadístico del país juega un rol importante, pues hoy en día la información necesaria para realizar un análisis de tipo EEA no está disponible.

La eficiencia de la sociedad en 2013 fue del 24%. En comparación con otras sociedades, la chilena se encuentra en medio de economías avanzadas y países menos desarrollados. En el presente estudio se critica el modelo de desarrollo actual, ya que, de acuerdo a estudios previos, los países más desarrollados poseen la eficiencia termodinámica más baja. En el largo plazo, se espera un cambio de paradigma que favorezca el desarrollo local y eduque respecto del consumo excesivo de recursos. En cuanto a los sectores económicos chilenos, se encontró que la eficiencia exergética es mayor en actividades de tipo extractivas, como minería (53%) y manufactura (53%). En general, la eficiencia termodinámica es menor en sectores de uso final y servicios, como transportes (21%), y residencial (10%). Esto dice relación con la omisión del trabajo humano en el análisis, puesto que los sectores de usos finales tienden a ser más dependientes del trabajo y actividades humanas que los sectores extractivos o industriales.

A pesar de dificultades metodológicas, se obtuvo interesantes propuestas del análisis. Se proponen cambios estructurales en el sector de manufactura, a fin de obtener una mayor eficiencia de transformación en los procesos relativos a agricultura, ganadería y acuicultura. Así también, la industria de alimentos se beneficiaría de dichos cambios. Del mismo modo, promover cambios tecnológicos hacia tecnologías eléctricas de transporte beneficiaría en gran medida el uso de los recursos disponibles. Mejoras en calefacción de espacios y agua también aportarían a la situación, ya que estos dos usos finales son los más intensivos en exergía en el sector residencial.

A todos ustedes,
que cambian nuestra forma de ver las cosas

Gracias a todos los que me han acompañado en este *largo* camino, y que de cualquier forma contribuyeron a la persona que soy hoy. En especial, agradezco a

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1. Introduction

In a world with finite natural resources and large demands, designing efficient and cost-effective systems is one of the foremost challenges that engineers face. Meeting environmental constraints and avoiding the undesirable effect of poor utilization of resources requires careful analysis and planning. It becomes crucial to understand the mechanisms that degrade energy and resources, and systematic approaches are needed for improving systems in terms of efficiency, cost, environmental impact, and so forth [1].

On the other hand, it has become widely known that technologies using fossil fuels are major sources of air pollutants and contribute significantly to environmental concerns such as regional acidification and climate change. These concerns, combined with uncertainties about fossil fuel reserves and ever-growing oil prices, have increased interest in alternative fuels and energy conversion technologies. Countries worldwide are shifting to technologies that limit environmental impact, provide energy security, and facilitate economic growth and sustainable development [1]. Chile has been no exception to this paradigm shift; an overview of the country focusing on this transition is provided hereafter.

1.1 Economy overview

Over the past decade, Chile has been one of the fastest growing economies in Latin America. After a considerable expansion between 2010 and 2012, the Gross Domestic Product (GDP) growth fell significantly in 2014, as a result of slowdown in the mining sector due to economic deceleration of major trading partners. However, the Latin American region is expected to recover by 2017, while Chile's GDP growth is expected to increase slowly but steadily, reaching 2.0% by 2017 [2][3].

Despite the current economic slowdown, Chile is regarded as a stable and serious country; in 2014, it ranked first in 4 out of 6 indexes of governance in Latin America [4]. Accordingly, Chile has benefitted from important foreign direct investment (FDI); in fact, as of 2014, it was the second recipient of monetary inflow in the region, and the nineteenth in the world [5]. Between 2009 and 2014, main providers of FDI were the United States, Netherlands and Spain; regarding investment destination, mining, services, electricity, gas, water, and manufacturing industry have been the primary beneficiaries [6].

The country's GDP is composed by several economic activities, from services to mining, as shown in Figure 1. Business, personal, and financial services represent more than one third of the gross product. On the other hand, as a geographically diverse country, Chile has abundant and varied natural resources. Mining and manufacturing activities make almost one fourth of the GDP. Within mining, copper is by far the main economic activity, while manufacture is dominated by food and drinking products [7]. In terms of exportations, mining takes more than half of the shipments (56%), followed by manufacturing and other industries (36%), leaving livestock-forestry and agricultural activities last (8%), as shown in Figure 2 [8].

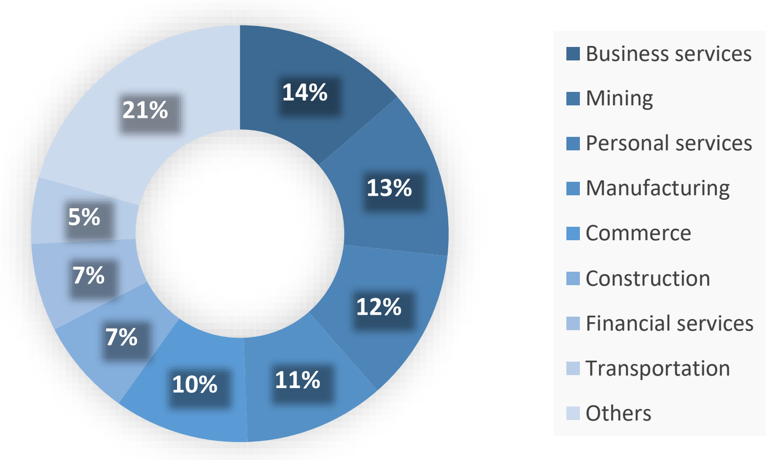


Figure 1: Chilean Gross Domestic Product (GDP) by economic activity [7].

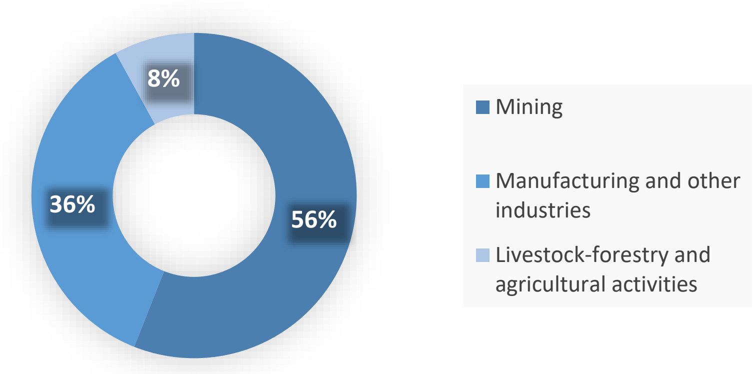


Figure 2: Exports shipments by economic sector, 2014 [8].

1.2 Energy context

In the last couple of decades, energy production and utilization has become one of the main topics of discussion across the world. Increasing population and energy demand has driven governments worldwide to seek new forms of energy, as well as better ways to use the available one. In Chile, the discussion around this topic has been centered in the lack of a clear long-term plan to meet the increasing demand, but also on the need to decrease the fossil fuels contribution to the energy sources. In the last few years, the country has been powered mainly by fossil fuels, electricity and biomass [9], as shown in Figure 3.

However, investment on new facilities such as solar, wind, and small hydro has increased sharply, positioning Chile as the third most attractive country regarding investment in renewable energies. Chile is also the regional leader in solar power [10].

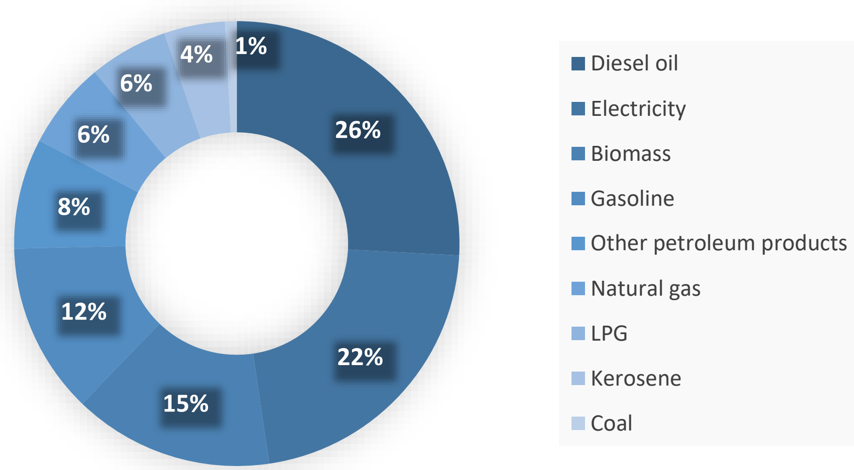


Figure 3: Energy consumption in Chile by energy source, 2014 [9].

1.3 Energy policy overview

In 2008, the National Energy Commission (CNE) laid down for the first time the need for a long term energy policy, carried out as a State policy with a systemic approach, integrating key players of the energy sector. Later on, in 2009, the International Energy Agency (IEA) acknowledged some of the changes in the energy policy during the past years, emphasizing the creation of the Ministry of Energy, but criticizing the lack of a long term energy policy. By 2012, the Ministry of Energy designed and published the *National Energy Strategy* for the 2012-2030 period, establishing that energy should be included as a government policy, in order to support the country's development. The document also stated that the strategy implementation should be defined in collaboration with different national and regional actors, including citizen participation instances [11].

In this way, by 2014, the Ministry of Energy structured the "Energy 2050" (E2050) initiative, conceived as a participative process to construct the Chilean energy policy. This process was completed and published in 2015, establishing several guidelines and goals for both the energy sector and the country. By 2050, the goal of the government is to count with a reliable, inclusive, competitive and sustainable energetic sector. The policy is composed by four main pillars [11]:

1. Reliability and quality of the energy supply

This idea states the need of a reliable system in order to provide a stable access to energy; this will be the base of a competitive market, contributing to better production and energy use, as well as lower environmental impacts.

2. Energy as engine of development

This feature promotes a set of goals of inclusive development in a competitive economy. Energetic development is essential to create national, regional and local infrastructure aiming at lowering social and environmental impacts.

3. Environmentally compatible energy

This pillar advocates for a diversified, flexible and renewable energy matrix, which will contribute to the system's safety. Renewable energies as well as energy efficiency will be developed in an integrated manner, taking advantage of the synergies between them, fostering a more sustainable energy supply. Environmental impacts shall be reduced, both locally and globally.

4. Energetic Efficiency and Education

The last pillar is meant to facilitate global long term goals as a whole. On the one hand, the system's trustworthiness shall be held by means of efficient energy use by the population; on the other, energy efficiency will reduce household expenditure, as well as increase the sector's competitiveness. Energetic education will contribute comprehensively to achieve all the described objectives.

1.4 Exergy Analysis of a Society

In light of the country's current position expressed by the energy policy, in which decisions regarding multiple economic sectors must be discussed and analyzed, an analysis of the society's functioning would be a useful way to fuel the discussion among policy makers. To accomplish such a task, an *Exergy Analysis* is proposed. This concept was initially introduced by Reistad [12] to address the available energy conversion and utilization in the US; however, the concept has been applied ever since in many other societies, such as China [13], Norway [14], Japan[15], Italy[16], and Sweden[17], among others.

Exergy is a thermodynamic concept defined as the maximum work that can be done by a system given a reference baseline. Unlike energy, exergy is only conserved in reversible processes, that is to say, exergy is destroyed during irreversible processes. This occurs because exergy represents the *energy quality* or usefulness in terms of the work a system is capable to do [1]. In this sense, it is exergy – rather than energy – the genuine concept to address scarcity, because energy is never destroyed [18].

In such a way, an exergy analysis allows the identification and quantification of energy wastes or losses in the society, providing information for a more efficient energy use. It also allows computation of meaningful efficiency parameters, in order to assess the country's efficiency compared to other societies. These results would enable students, engineers, policy makers, and the general public, for a better understanding of the country's needs and possible improvements in energy use.

1.5 Objectives of the analysis

General objective

To evaluate the efficiency of the Chilean society by means of exergy accounting, aiding decision and policy makers to better comprehend the country's functioning and needs.

Specific objectives

- To address the energetic consumption of the Chilean society, in order to determine the most relevant economic sectors for the exergy analysis.
- To compute the exergy efficiency of the Chilean society and its relevant economic sectors.
- To compare results with other societies that have already been analyzed in other works.
- To identify exergy inefficiencies, based on the analysis of the economic sectors.
- To propose alternatives for more efficient energy utilization.

1.6 Scopes

The aim of this work is to provide a first glance of the Chilean society's exergy performance. As such, many assumptions will be taken to simplify the complexity of the thermodynamic interactions within the country. The ultimate goal is to propose general guidelines for a more efficient resource utilization. These guidelines may be further detailed in future analyses.

2. Exergy Analysis

2. Exergy Analysis

The exergy of a system is defined as the maximum work that can be done by the composite of the system and a specified reference environment. Such reference environment is assumed to be infinite, in equilibrium, and to enclose all other systems. Typically, the environment is specified by stating its temperature, pressure, and chemical composition. In this way, the exergy of a system increases the more it deviates from the environment, that is to say, exergy is not simply a thermodynamic property, it is a property of both the system and the reference environment.

Unlike energy, exergy is conserved only when all processes occurring in a system and the environment are reversible, and it is destroyed whenever an irreversible process occurs. For instance, when performing an exergy analysis of a power station, a chemical processing plant or an economic sector, thermodynamic imperfections can be quantified as exergy destructions, which represent losses in energy quality or usefulness. On the other hand, exergy – like energy - can be transferred or transported across the borders of a given system; for each type of energy transfer or transport, there is a corresponding exergy transfer or transport.

Exergy analysis of macrosystems such as regions, countries, and economic sectors was first introduced by Reistad in 1975 [12], who assessed the available energy (exergy) of the United States. Since then, several other countries have been studied with a similar approach, namely China[13], Norway[14], Japan[15], Italy[16], and Sweden[17], among others. Exergy analysis arises from the ever-growing need to design efficient and cost-effective systems, which also meet environmental and social constraints. Exergy analysis has proven to be a useful tool to improve the efficiency of energy utilization; for instance, it can help locate and quantify wastes and losses within a system. It also establishes an upper bound to determine how much a process can be improved by reducing its inefficiencies, as well as establishing some criteria for sustainable development, as in the case of providing energy with minimal environmental degradation. Thus, exergy analysis provides a useful link between engineering and the environment, determining the true efficiency of a system or process.

Exergy provides a common unifying measure for all resources; regardless of whether it is an energy resource or a material substance, they can both be expressed in terms of their exergy content. For instance, the exergy of an energy resource can be expressed in terms of its chemical exergy content, which reflects the ability of such a substance to produce thermal work. Likewise, a certain material or chemical substance can be considered by computing how much work was needed to produce such a substance, which reflects the exergy value of that substance, in other words, the maximum work that can theoretically be obtained from it. The thermodynamic origin of these concepts as well as the methodology to obtain exergy values for all resources will be explained further on.

When analyzing a society as a thermodynamic system, exergy inputs and outputs of the society can be estimated in terms of their exergy content. All imported goods, services, and energy sources can be viewed as exergy inputs. On the other hand, goods and services produced by the society can be considered exergy outputs of the system. In such a way, the efficiency with which the society is transforming raw materials and other inputs into complex products and services can be addressed through the exergy concept. Depending on the depth of the analysis, exergy losses could be identified within the system. For example, in the transportation sector, exergy analysis can help clarify if energy is being wasted primarily because of the sector's transportation infrastructure or because of low engine efficiency. On the first case, exergy analysis might suggest to invest on railway over highway transportation, while on the latter, modernization of the lorry fleet could be fostered.

In such a way, exergy analysis provides meaningful insight of a thermodynamic system functioning. In the case of a society, it offers a technically rigorous outlook of the country, fueling the discussion of public policies among students, engineers and policy makers.

2.1 Definitions

2.1.1 Environment and interactions

As previously stated, exergy is a thermodynamic property of both the system and the reference environment. The environment is defined as a very large body or medium in the state of perfect thermodynamic equilibrium. Thus, there are no gradients or differences in pressure, temperature, chemical potential, kinetic or potential energy and, therefore, no possibility of producing work from any form of interaction between parts of the environment. When a system differs from the environment, this system has a work potential. The work potential depends on the magnitude of the aforementioned difference, expressed in terms of a variable, e.g. pressure, temperature, or chemical potential. For practical purposes, the environment includes the atmosphere, seas and oceans, as well as the Earth's crust. Therefore, there are three possible ways by which the environment can interact with a certain system:

Thermal interaction
The environment is defined as a reservoir (source or sink) of thermal energy at temperature T_0. Due to its enormous heat capacity, it is able to exchange heat with any human-made system without suffering a significant change in its temperature.

Mechanical interaction
As a reservoir of unusable work, mechanical interactions occur whenever a system undergoes a change in volume during the studied process. For instance, during an expansion process, and considering that systems are usually immersed in the atmosphere at pressure P_0, an increase in volume ΔV results in the work $P_0 \Delta V$ being done on the atmosphere. Of

course, this work is unavailable for use, although it can be recovered when the volume of the system returns to its original value.

Chemical interaction

Occurs whenever an open system rejects matter to the environment or draws substances from it with low chemical potential. In this case, the environment is assumed to be a reservoir of such substances, which are in perfect chemical equilibrium with one another.

When analyzing a society, besides services, the most relevant outcome is related with chemical interactions. Societies invest exergy in the form of exergy carriers such as fossil fuels and raw materials to obtain substances of higher exergy value, such as highly concentrated minerals or food.

Thermal interactions are relevant in some chemical processes as well as in residential heating and cooling. In this cases, average exergy efficiency of such devices are used to address the possible losses involved. This simplification arises from the difficulty of evaluating a wide variety of devices and technologies used in the society. Despite this, inefficiencies of this kind are indirectly reflected in the global exergy efficiency of each sector through the amount of chemical exergy consumed via fossil fuels, electricity, and other exergy carriers, and the sector's exergy output.

On the other hand, mechanical exergy is neglected. It is considered that the ability of any natural resource or product to perform mechanical work is marginal compared to the chemical exergy embodied in such a substance. Volumetric variations within the system are neglected, as the reference environment is defined to be constant throughout the domain of analysis.

Therefore, this work will focus mainly on chemical interactions. Changes in chemical compounds and their corresponding potential to perform work will be computed and analyzed. As previously stated, mechanical interactions will be neglected, unless stated otherwise.

2.1.2 Equilibrium

Equilibrium definitions between system and environment will be used throughout this study:

Restricted equilibrium

Refers to the case in which there is a physical barrier that prevents the exchange of matter between system and environment. Under this condition, thermal and mechanical equilibrium between the system and the environment are satisfied, as temperature and pressure in both the system and the environment are equal. On the other hand, there is generally no chemical equilibrium between the system and the environment.

Unrestricted equilibrium

In unrestricted equilibrium, the conditions of mechanical, thermal, and chemical equilibrium between the system and the environment are satisfied. Thus, in addition to pressures and temperatures, the chemical potential of substances within the system and the environment must be equal. This means the system cannot undergo any change, no matter how the interaction between the system and the environment is performed. In other words, a system is in unrestricted equilibrium if it is in mechanical, thermal, and chemical equilibrium with the environment.

As previously stated, exergy contained in materials is one of the most important aspects considered in this study. A general framework on chemical exergy is presented in the following section; specific methodology to estimate the exergy content of complex products and materials will be explained further on.

2.1.3 Chemical exergy

As defined by Kotas [19], "chemical exergy is equal to the maximum amount of work obtainable when the substance under consideration is brought from the restricted equilibrium state to the unrestricted equilibrium state by processes involving heat transfer and exchange of substances only with the environment". Equivalently, chemical exergy can be defined from the products point of view, as the "minimum amount of work necessary to synthesize and to deliver in the restricted equilibrium state, the substance under consideration (…)". By taking into account the latter definition and considering an ideal gas isothermal expansion process, Equation (1 represents the work obtained from such a process per mole of substance.

$$\overline{ex}_{ch}^{0} = RT_0 \ln \frac{P_0}{P_i}$$	(1)

$\overline{ex}_{ch}^{0}$ is the molar chemical exergy and R is the molar ideal gas constant. T_0 and P_0 represent the system temperature and pressure, and P_i is the unrestricted equilibrium pressure, which is the partial pressure of the gaseous reference substance under consideration as a component of the atmosphere.

To obtain the chemical exergy of other components not present in the environment, idealized chemical reactions are used to theoretically obtain new components from other components for which the standard chemical exergy has already been computed. From an exergy balance on the ideal chemical reaction, the standard chemical exergy for a certain substance can be determined using Equation (2) [20].

$$\overline{ex}_{ch}^{0} = -\Delta G + \left\{ \sum_{P} n_i \overline{ex}_{ch}^{0} - \sum_{R} n_i \overline{ex}_{ch}^{0} \right\}$$	(2)

Where ΔG is the change in the Gibbs free energy function for the reaction, with T_0 and P_0 as conditions. The term in curly brackets corresponds to the known standard chemical exergies of the species reacting to form the substance whose chemical exergy is being evaluated, weighted by n_i, which represents the stoichiometric coefficients of the reaction.

To illustrate this case, Equation (3 shows a chemical reaction considered to compute the chemical exergy of graphite:

$$C(s) + O_2(g) \rightarrow CO_2(g) \tag{3}$$

Using Equation (2), the standard chemical exergy for graphite can be obtained in the following fashion:

$$\overline{ex}^0_{ch,C(s)} = -(\Delta G^0_{298.15})_f + 1 \times \overline{ex}^0_{ch,CO_2(g)} - 1 \times \overline{ex}^0_{ch,O_2(g)} \tag{4}$$

Using thermodynamic tables to obtain the Gibbs energy of formation [21], as well as standard chemical exergy for oxygen and carbon dioxide from Table 1 [19], exergy of graphite can be computed as shown in Equations (5 and (6

$$\overline{ex}^0_{ch,C(s)} = -\left(-394360\left[\frac{kJ}{kmol}\right]\right) + 20140\left[\frac{kJ}{kmol}\right] - 3970\left[\frac{kJ}{kmol}\right] \tag{5}$$

$$\overline{ex}^0_{ch,C(s)} = 410530 \text{ kJ/kmol} \tag{6}$$

The previous procedure can be used to calculate the exergy content of many other components, as attached on Table 1 [19]. Standard chemical exergy values used in the analysis are included in Appendix A: Standard Chemical Exergy. Note that the obtained value differs in $0{,}1\%$ from the value shown on Table 1. Standard exergy values can slightly vary due to different Gibbs energy of formation value or because different theoretical chemical reactions were considered.

Table 1: Standard chemical exergy of selected substances.
$T_0 = 298.15, P_0 = 1.0132\ bar = 1\ atm$ [19].

Component	Chemical Formula	State	Standard chemical exergy $\overline{\mathbf{ex}}^{\mathbf{0}}$ [kJ/kmol]
Copper	Cu	Solid	134,400
Carbon	C	Solid, graphite	410,820
Carbon dioxide	CO_2	Gaseous	20,140
Lithium	Li	Solid	396,170
Water	H_2O	Liquid	3,120

Water	H_2O	Gaseous	11,710
Oxygen	O_2	Gaseous	3,970
Nitrogen	N_2	Gaseous	720

2.1.4 Energy carriers

Regarding fossil fuels, exergy can be computed from an exergy balance on the corresponding combustion reaction, as shown in Equation (*7*.

$\overline{ex}_{ch}^{0} = -\Delta h_0 + T_0 \Delta s_0 + RT_0 \left(x_{O_2} \ln \frac{P_{0,O_2}}{P_i} - \sum_k x_k \ln \frac{P_{0,k}}{P_i} \right)$	(7)

k refers to the components of the products of combustion [19]. Solid and liquid industrial fuels have a complex composition, usually not properly characterized. The lack of a characterization imposes a problem to determine the entropy of the combustion, Δs_0, with a reasonable degree of accuracy. The ratio of chemical exergy ($\overline{ex}_{ch}^{0}$) to net calorific value (NCV^0) for solid and liquid industrial fuels is assumed to be the same as for pure chemical substances having the same ratios of constituent chemicals [19]. This ratio is denoted by $\boldsymbol{\gamma}$, and defined as shown in Equation (*8*.

$\boldsymbol{\gamma} = \frac{\overline{ex}_{ch}^{0}}{NCV^0}$	(8)

These ratios are direct exergy-energy interconversion values [14]. Exergy is obtained from correlations based on the C, H, O, N, and S content of organic compounds, while energy is accounted through the lower or net heating value obtained from the fuel combustion [19]. By following the correlations presented by Kotas, exergy ratios can be obtained for organic substances, as listed in Table 2 [19].

Table 2: Exergy factors proposed by Kotas [19].

Fuel form	Exergy ratio, $\boldsymbol{\gamma}$	Fuel form	Exergy ratio, $\boldsymbol{\gamma}$
Coal	1.06	Kerosene	1.07
Coke	1.05	Fuel oil	1.06
Crude oil	1.08	LPG	1.06
Gasoline	1.07	Other petroleum products	1.06
Diesel oil	1.06	Natural gas	1.04

2.1.5 Exergy balance and exergy efficiency

To define the exergy efficiency of a certain system, it is necessary to identify both a *product* and a *fuel* for the thermodynamic system being analyzed. The product represents the desired result produced by the system, while the fuel represents the resources expended to generate the product. Both the product and fuel are expressed in terms of exergy.

Let us consider a system at steady state where, in terms of exergy, the rates at which the fuel is supplied and the product is generated are $\dot{E}_F$ and $\dot{E}_P$ respectively. An exergy rate balance for any given system is shown in Equation *(9*.

$$\dot{E}_F = \dot{E}_P + \dot{E}_D + \dot{E}_L \tag{9}$$

$\dot{E}_D$ and $\dot{E}_L$ denote rates of exergy destruction and loss, respectively. The exergy efficiency is the ratio between product and fuel, defined in Equation (*10*.

$$\psi = \frac{\dot{E}_P}{\dot{E}_F} = 1 - \frac{\dot{E}_D + \dot{E}_L}{\dot{E}_F} \tag{10}$$

The exergy efficiency shows the percentage of the fuel exergy provided to a system that is found in the product exergy. Moreover, the difference between 100% and the actual value of the exergy efficiency, is the percentage of the fuel exergy wasted in this system as exergy destruction and exergy loss.

An important use of exergy efficiency is to assess the thermodynamic performance of a component, plant, or industry, relative to the performance of similar components, plants, or industries. The performance of a new design of gas turbine, for instance, can be gauged relative to the present performance level of gas turbines. A comparison of exergy efficiencies for dissimilar devices – gas turbines and heat exchangers, for instance- is generally not meaningful. It is also important to highlight that when analyzing a given system, decisions must be made concerning what is the fuel and the product of the system, and how to count their flows, which might greatly impact the exergy efficiency value for such a system.

3. Preparing the exergy analysis of the Chilean Society

3.1 Problem definition

3.1.1 System boundaries

Exergy accounting has been developed as an assessment model conceived to gain insight of a certain thermodynamic system. In order to do that, a system boundary must be defined, so that inputs and outputs of the system can be clearly identified and considered in the analysis. In the case of the Chilean society, the boundary is defined as presented in Figure 1. The society is considered to be a thermodynamic system in restricted equilibrium with the environment. The study focuses on chemical interactions, as in most cases, the system is considered to be in mechanical and thermal equilibrium with the environment.

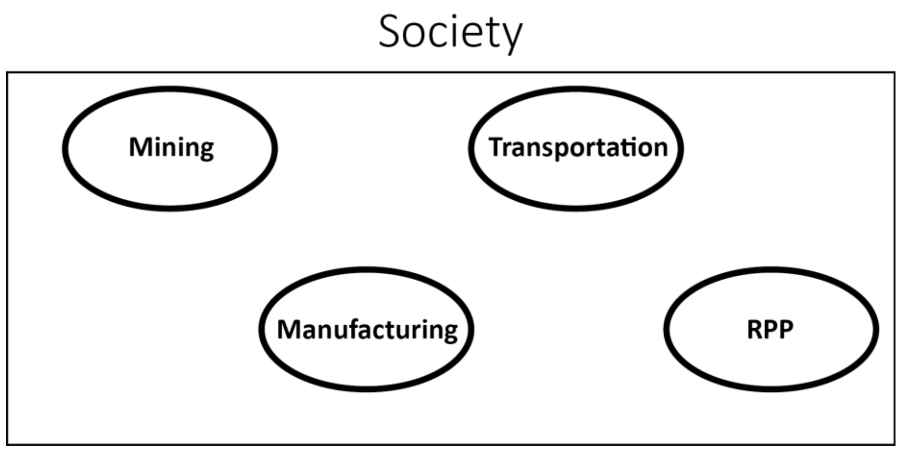


Figure 1: Boundaries of the exergy analysis of the Chilean society.

Exergy flows considered in the analysis are show on Figure 2. Exergy input includes all energy sources entering the country, without regard to whether these were imported or produced in the country (Figure 2A). Other exergy carriers, such as materials produced elsewhere, were accounted only if considered a main raw material for an important activity conducted within the country, as one of the objectives of the analysis is to address the operation of the economic sectors within the country. Likewise, goods and services produced in the society are considered outputs (Figure 2B). Exergy flows between sectors were neglected, with the exception of RPP sector (Residential, Public, and Private), which considers an inflow from the manufacturing sector (Figure 2C). This simplification was taken due to the lack of detailed statistical data of flows between sectors. This consideration might result in an overestimation of the exergy efficiency of a certain sector in detriment of others. Despite this, the overall exergy efficiency remains unchanged.

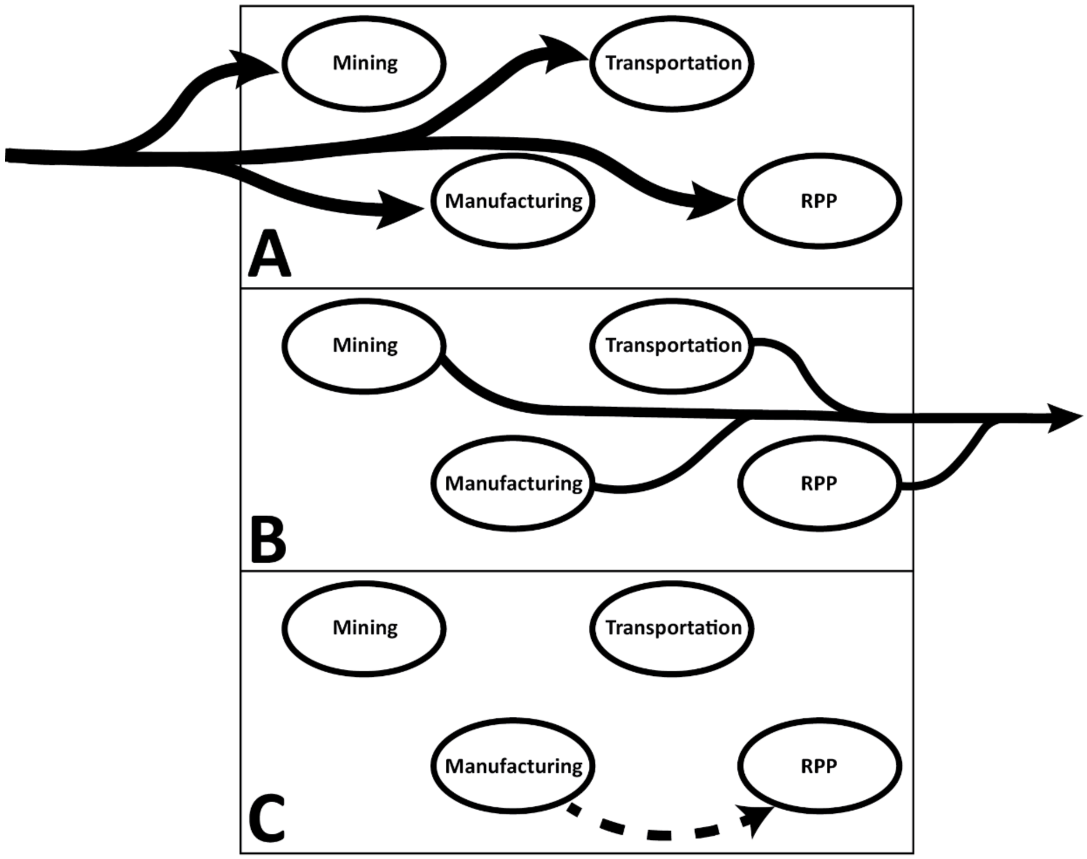


Figure 2: Exergy flows considered in the analysis.

In this way, the current analysis offers an overview of the main exergy inputs and outputs of the country as a whole, providing a first approach to the exergy efficiency of the Chilean society.

To gain insight of the system inefficiencies, a second boundary was defined around each of the most relevant economic sectors, as shown in Figure 1. These were chosen by taking into consideration energy use as well as proportion of the country's GDP. Economic sectors considered in the analysis comprise mining, manufacturing, transportation and RPP (Residential, Public, and Private use). This sector-level analysis also allows for specific comparison with similar sectors in other societies. It is important to highlight that comparing different economic activities is meaningless from an exergy point of view. As explained in section 2, exergy efficiency must be compared among similar thermodynamic systems in order to obtain meaningful conclusions.

Due to simplicity and information availability, this analysis focuses mainly on materials accounted through chemical exergy. It is also important to highlight that not all substances were taken into account, but only those representing most of each sector's activity. This will be further explained and discussed, in order to ensure results accuracy and reliability.

Services outputs and other human related activities were not considered; an exergo-economic point of view should be adopted in order to address this matter in further works. Despite this, transportation sector was addressed through the methodology used by Ji and Chen in their analysis of the transportation sector in China [18]. Exergy consumption in households was also integrated in the analysis through Ertesvåg's methodology of study of the Norwegian society [14].

The following section presents the inputs and outputs of the society model. Economic and other criteria are used to support the selection of exergy carriers. The exergy model applied for each of the considered substances and products is also detailed hereafter.

3.2.2 Society

As previously described, the society is considered to be a thermodynamic system in restricted equilibrium with the environment. This system is capable of chemical interactions, as it is not in chemical equilibrium with its surroundings.

The society is a system that produces goods and services from raw materials, fossil fuels, and other sources of energy. In this scenario, products and services are viewed as exergy outputs of the society, whereas raw materials, fossil fuels, and other sources of energy are considered exergy inputs. It is important to mention that all these exergy carriers are taken into account regardless of their origin or destination, as the goal of the analysis is to obtain insight on how the society performs these transformations. With this calculations, the efficiency of these transformations will be discussed. Each sector will be presented in the following section, describing its inputs, outputs, and overall exergy balance.

3.2.3 Mining

It is one of the most relevant economic sectors in the country, representing 13% of the GDP in 2013 [22]. Mining activities are divided into three subsectors: metallic mining, non-metallic mining, and energy resources. Within metallic mining, copper and iron are the most relevant products [8]. On the other hand, sodium chloride, calcium carbonate and sulphur compounds are the most relevant products of non-metallic mining [8]. Energy resources obtained in the country comprise carbon, petroleum, and natural gas, although most of the fossil fuels used in the country are imported [9].

Inputs

Exergy carriers considered as inputs of the mining sector were fossil fuels and other energy sources. Exergy embodied in these carriers was estimated through their chemical exergy content and taking into account the energy-exergy conversion factors proposed by Kotas [19]. Thus, 193 [PJ] exergy entered the mining sector in 2013. 50% of the exergy used by the sector was in the form of electricity, while 41% was diesel oil. 77% of the exergy input was used by copper mining, as shown in Figure 3 [9].

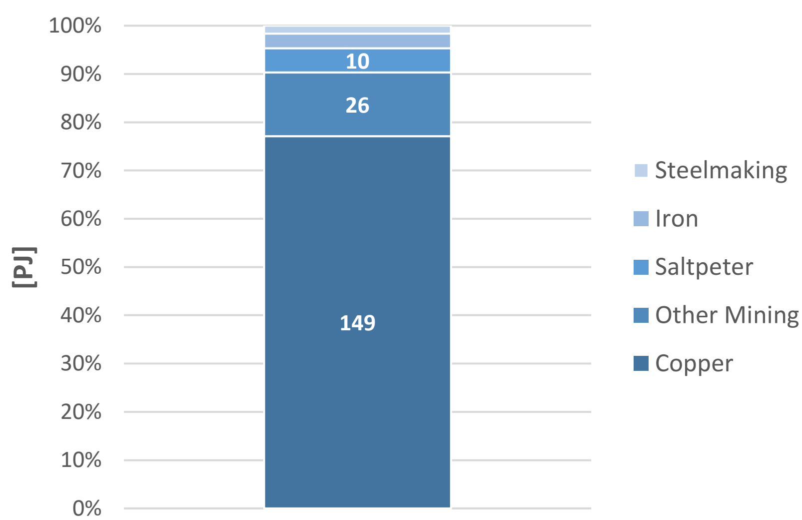


Figure 3: Use of exergy carriers by mining subsectors in 2013 [9].

Outputs

In 2013, metallic mining produced 15 million tons (hereafter [t]) of fine material, of which 9 million [t] were iron, and almost 6 million [t] were copper, as shown in Figure 4 [8].

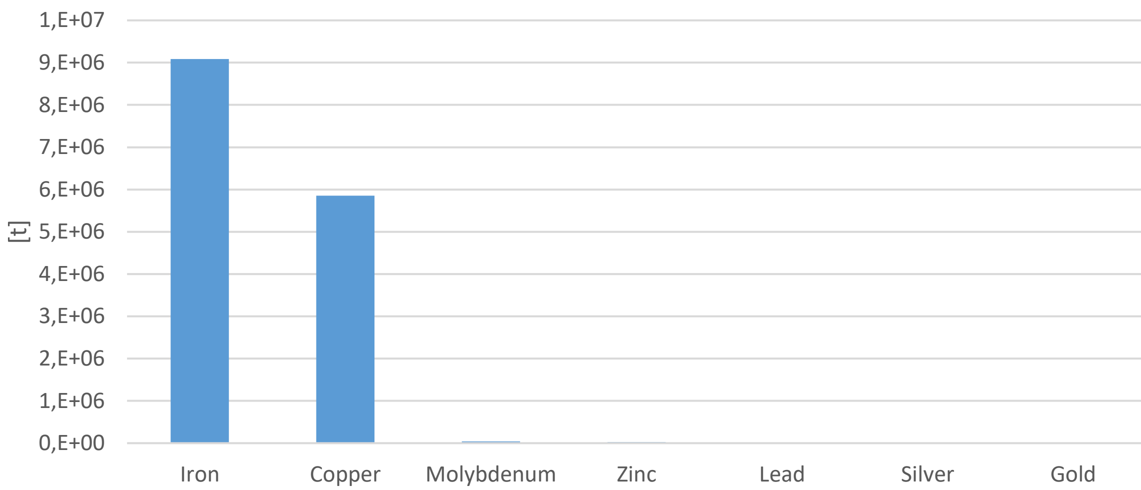


Figure 4: Metallic mining production in 2013 [8].

On the other hand, the industrial minerals and rocks subsector produced 24 million [t] of a wide variety of chemical compounds and rocks. Sodium chloride and calcium carbonate contributed to more than half of the physical production, as shown in Figure 5 [8].

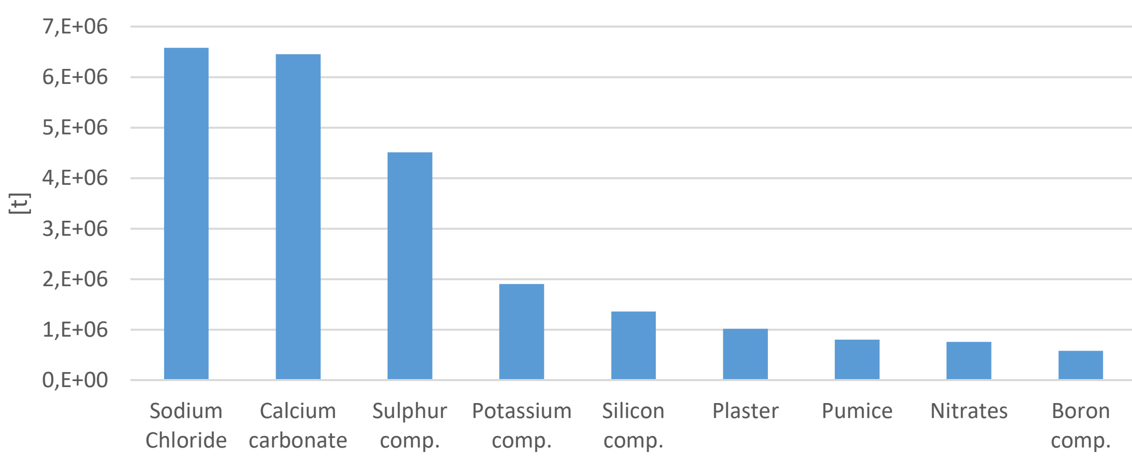


Figure 5: Industrial minerals and rocks production in 2013 [8].

Coal, petroleum, and natural gas refined in the country are also considered outputs of the mining sector. Production of these fuels during 2013 is shown in Table 3 [8].

Table 3: Energy resources produced in 2013 [8].

Substance	Production	Unit
Natural gas	893,433,000	$[m^3]$
Coal	2,902,044	[t]
Petroleum	401,428	$[m^3]$

Exergy of mining products is obtained by taking into account standard chemical exergy computed by Kotas [19]. Standard chemical exergy values used in the analysis are shown in Table 15 under Appendix B: Standard Chemical Exergy of Mining Products. The mathematical procedure followed to obtain these results is detailed in Appendix C: Computing exergy embodied in mining products. The computed exergy value of metallic mining, industrial minerals, and rocks is shown in Table 4.

Table 4: Exergy output of metallic, industrial minerals, and rocks mining in 2013.

Substance	Exergy Output [PJ]
Iron	61
Copper	12
Molybdenum	0.29
Zinc	0.15
Lead	0
Silver	0
Gold	0
Industrial Minerals and Rocks	11
Total	**85**

Furthermore, energy content of coal, petroleum, and natural gas was estimated through the net calorific value (or lower heating value, LHV) of each fossil fuel. Exergy-energy conversion factors estimated by Kotas [19] were applied to obtain the corresponding exergy values. The detailed procedure to obtain this exergy values is further explained in Appendix D: Chemical Exergy of Fossil Fuels. Exergy output of energy resources is attached in Table 5.

Table 5: Exergy output of energy resources in 2013.

Substance	Exergy Output [PJ]
Natural gas	17
Coal	0.09
Petroleum	0.02
Total	**17**

Thus, exergy outputs of the mining sector are shown in Figure 6. In terms of exergy, the main products were iron, natural gas and copper, with 61, 17, and 12 [PJ] exergy respectively.

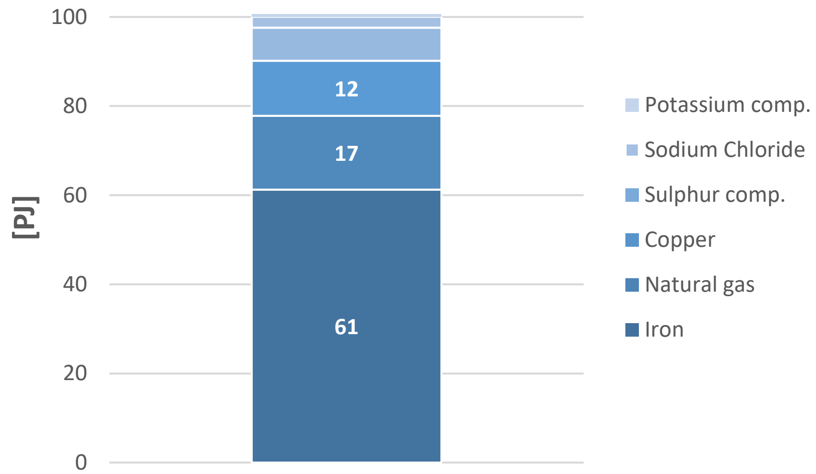


Figure 6: Exergy value of mining sector's main products in 2013.

Balance

In summary, 193 [PJ] entered the mining sector in 2013, while products reached 102 [PJ]. This gives a sector exergy efficiency of 53% in 2013.

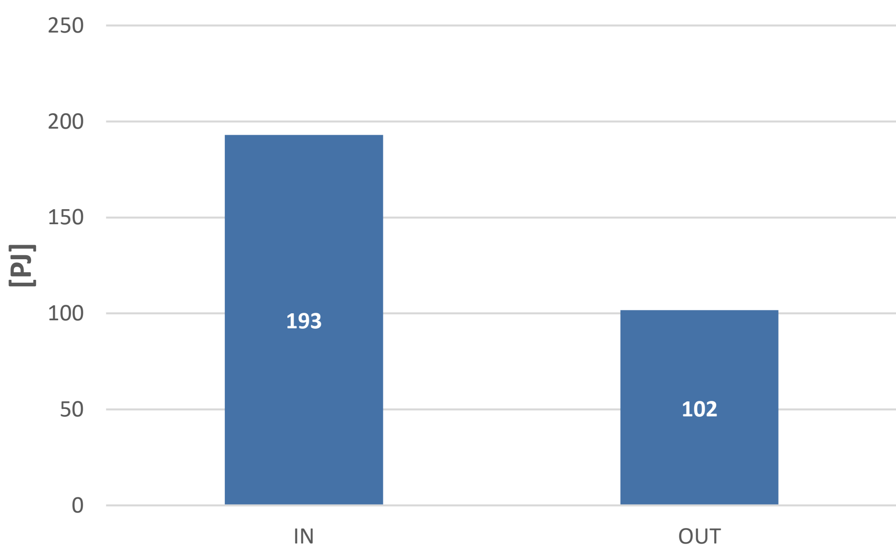


Figure 7: Exergy balance of the mining sector in 2013.

3.2.4 Manufacturing

Industrial economic activity is defined as all actions of physical or chemical transformation of materials or components into new ones [23]. In 2013, this sector represented almost 11% of the Chilean GDP [22]. The most relevant player was food industry, which is responsible for 22% of the sector's product. Drinks and tobacco, pulp and paper, metal products, and chemical industry all hold a similar stake, around 10% of the sector's economic activity. On the other hand, nonmetallic minerals (8%), refined oil (5%), wood and furniture (5%) and textiles (4%) are minor participants, as shown in Figure 8 [24].

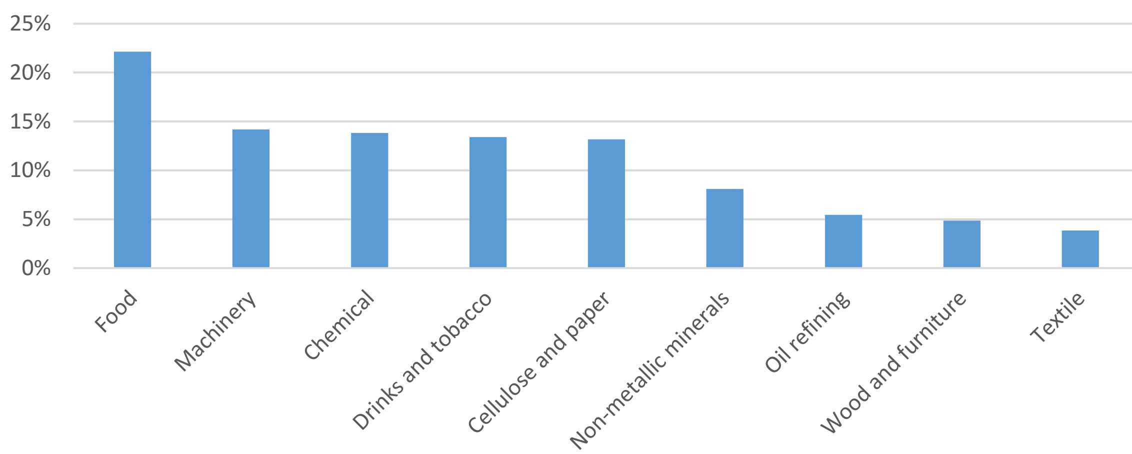


Figure 8: Manufacturing sector GDP by type of activity [24]

Due to methodological difficulties regarding statistical availability, manufacturing and some extractive activities were jointly addressed. Agriculture, forestry, fishing and livestock were considered the main economic activities to study from an exergy point of view. These activities add 6% of the country's GDP [7]. Machinery, chemical, and cellulose and paper industries were not considered, as the exergy models to compute available work of such products are still under development. Exergy on food and wood products, on the other hand, are much more straightforward to obtain. Due to the lack of more appropriate models, the exergy content of food products is estimated through the nutrient energy (or caloric content) of each product [14]. Nutrition facts were taken from the USDA Food Composition Database [25]. On the other hand, exergy of wood and wood derived products can be estimated using Wall's figure of 18 [MJ] exergy per kilogram of dry solid wood [17].

Inputs

Similar to the mining sector, fossil fuels and other energy sources were considered the main exergy carriers entering the manufacturing sector. Owing to insufficient statistical detail regarding energy usage within the extractive and manufacturing sector, the exergy input to these activities was estimated through GDP figures [7]. First, the total energy input to the country was weighted by the percentage of the GDP each activity represents. Then, since the energy balance does not specify which were the sources of energy used by these activities, the average manufacturing energy mix was considered to be representative of the input to the selected activities. The average energy mix used to convert estimated energy

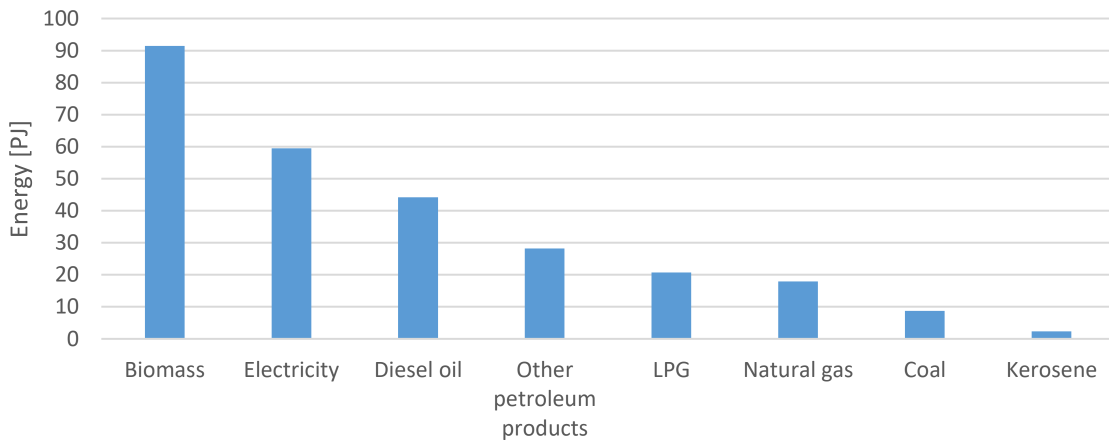


Figure 9: Most commonly used energy sources in the manufacturing sector in 2014 [9].

input values to exergy input is shown in Figure 9 [9].

Given this assumption, exergy input was computed accordingly, as shown in Table 6 [22]. Exergy carriers entering the sector provided 78 [PJ] to selected manufacturing activities (Appendix E: Exergy Carriers consumed by the Manufacturing Sector contains a detailed explanation on how the data was obtained and processed).

Table 6: Exergy input estimation for extractive activities based on GDP figures [22].

Activity	GDP 2014 [th. CLP]	% GDP	Estimated exergy input [PJ]
Agriculture, livestock and forestry	2,799,027	2.7%	34
Fishing	507,950	0.5%	6
Food	2,565,956	2.4%	31
Wood and furniture	563,904	0.5%	9
Total	**6,436,837**	**6%**	**78**

Imported goods within these categories were also taken into consideration in the exergy balance. Data of fruits, vegetables, cereals, wood, meat, and fish products imported to the country were obtained from the International Trade Statistics Database [26]. Exergy value of these items was computed using the U.S. Food Composition Database [25] in the case of food products (see Appendix G: Computing exergy embodied in food products), and from Wall's approach in the case of wood, and wood derived products [17]. Representative products used to account for different categories of products are attached in Table 7 [26][25]. The full list of food products used in the analysis can be found in Appendix F: Standard Chemical Exergy of Food products.

Table 7: Standard chemical exergy of selected fruits, vegetables, cereals, fish, and meat products in 2013 [26][25] .

Product	Representative product	Chemical exergy [kcal/100g]
Grapes, fresh or dried.	Grapes, red or green (European type, such as Thompson seedless), raw	69
Onions	Onions, raw	40
Maize (corn)	Corn grain, yellow	365
Fish, frozen, excluding fish fillets and other fish meat of heading	Fish, fish sticks, frozen, prepared	277
Meat of swine, fresh, chilled or frozen.	Pork, fresh, loin, tenderloin, separable lean only, raw	109

Exergy of forestry products was weighted according to the woodchips and sawdust production, as this products were considered to have negligible exergy from a *structural exergy* point of view, as presented by Wall's approach [17]. On the other hand, exergy obtained from biomass burning (from sawdust and woodchips, for instance) was included in the analysis through the National Energy Balance [9]. Exergy of selected wood products is displayed in Table 8 [17]. Table 19 in Appendix H: Standard Chemical Exergy of Wood products displays exergy values used for all wood and wood related products considered in the analysis [17]. Likewise, Appendix I: Computing exergy embodied in wood products contains further details on exergy of wood and wood related products [17, 27].

Table 8: Standard chemical exergy of wood and wood derived products [17, 26].

Product	Exergy	Unit	Weighting factor
Fuel wood, in logs, in billets, in twigs, in faggots or in similar forms; wood in chips or particles; sawdust and wood waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar forms.	18	[PJ/t]	0.4

It is also worth mentioning that not all of these imported items were used within the manufacturing sector to produce other goods. Fruits and vegetables, for instance, were most likely directly consumed by households. This might overestimate the exergy input to manufacturing in detriment of other sectors (such as RPP). Despite this, the society's exergy efficiency remains unchanged, as these flows are being considered in the analysis regardless of their destination. Exergy input embodied in imported goods is attached in Figure 10 [26][25].

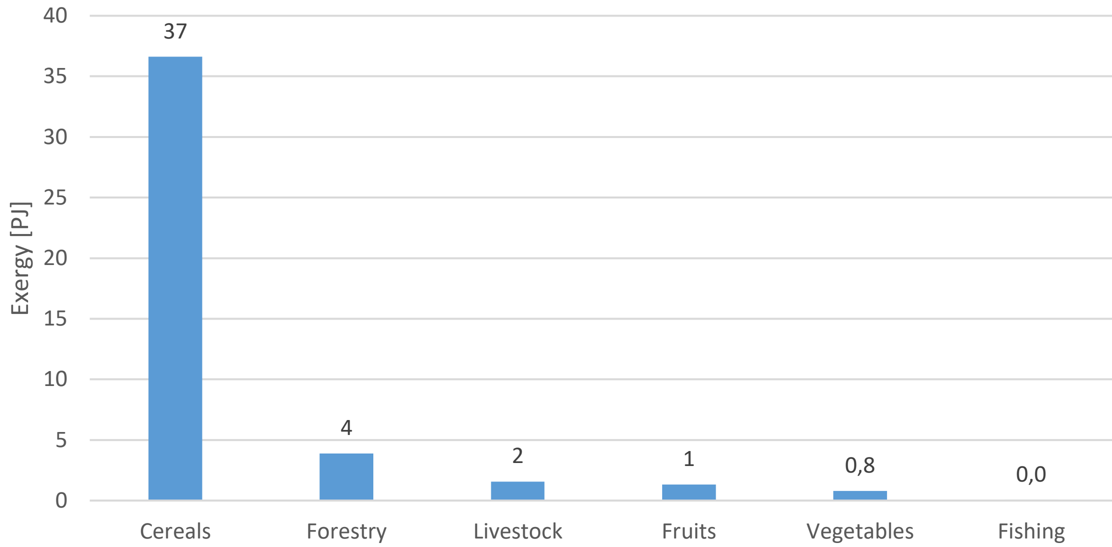


Figure 10: Exergy input to the society in the form of agricultural, livestock, fishing, and forestry products in 2013 [26][25].

Outputs

Following the methodology described in the previous section, exergy was computed for wood, fruit, fish, cereals, meat, and vegetable products produced in the country. Results are shown in Figure 11 [25, 26].

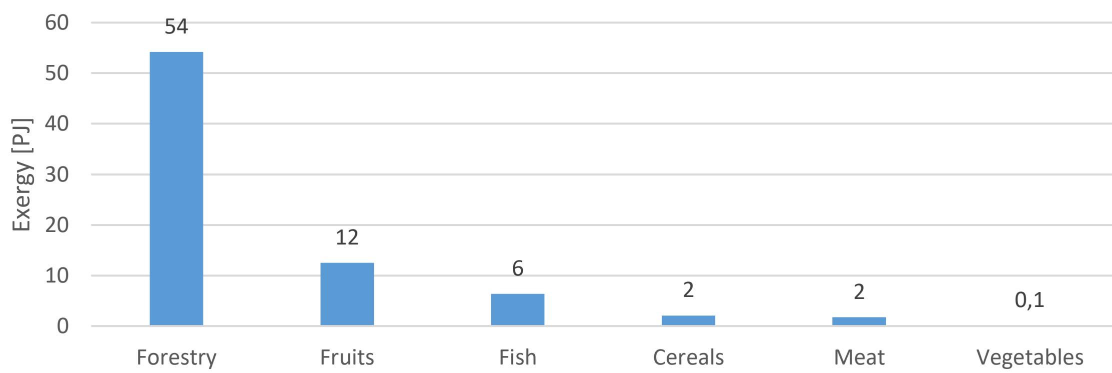


Figure 11: Exergy output of forestry, agriculture, aquaculture, and livestock products in 2013 [26][25].

A comparison of the different inputs and outputs per economic activity is shown in Figure 12 and Figure 13. It is important to mention that exergy input in the form of fossil fuels and other energy sources is jointly displayed in the National Energy Balance for agriculture, livestock, and forestry activities [9]. This input was equally split among fruit, vegetables, cereals, forestry, and meat input for illustrative purposes. Likewise, exergy used in manufacturing of food products was equally divided among agriculture, livestock, and aquaculture activities for illustrative purposes as well. A summarized version of the local efficiencies obtained within manufacturing is displayed in Figure 14.

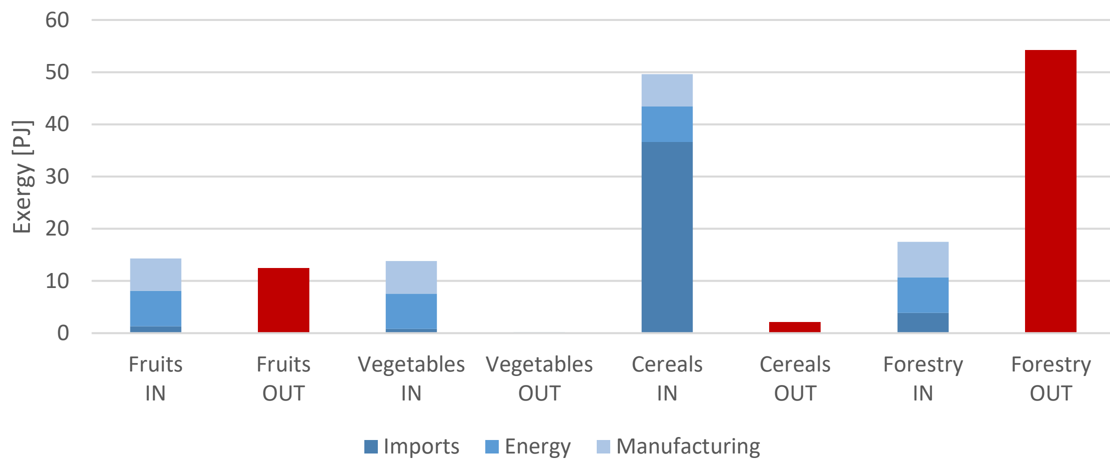


Figure 12: Inputs and outputs of forestry and agricultural activities in 2013. Exergy inputs are detailed according to importations, energy carriers used by each economic activity, and energy carriers used in products manufacturing [9][26][25].

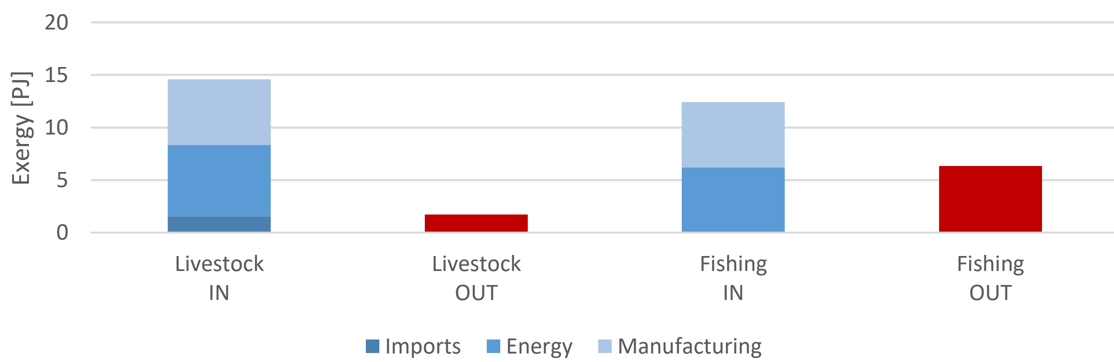


Figure 13: Inputs and outputs of livestock and aquaculture activities in 2013. Exergy inputs are detailed according to importations, energy carriers used by each economic activity, and energy carriers used in products manufacturing [9][26][25].

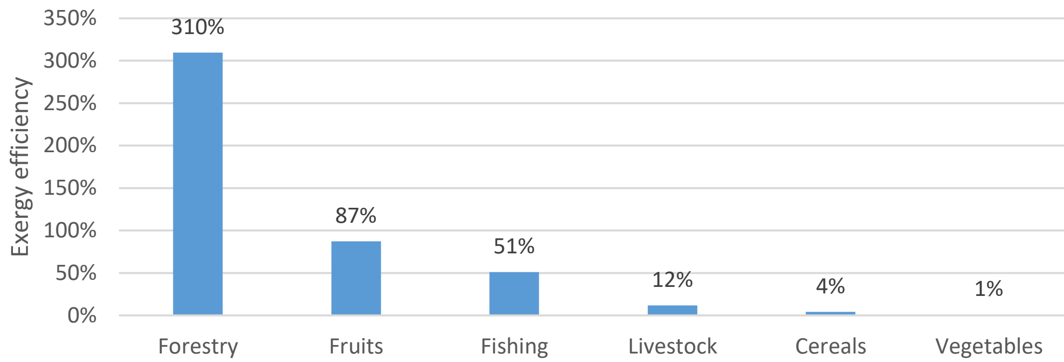


Figure 14: Exergy efficiency obtained for activities within manufacturing/extractive sector.

Balance

In summary, the manufacturing sector received 122 [PJ] exergy in the form of energy carriers such as electricity, fossil fuels, and agricultural, forestry, fishing, and livestock products. On the other hand, the sector produced an estimated output of 77 [PJ]. These numbers imply a sector efficiency of around 63%.

3.2.5 Transportation

In 2013, transportation accounted for around 5% of the country's GDP [24]. Nevertheless, the sector was responsible for more than one third of the country's energy consumption. In fact, ground transportation took more than 27% of the energy consumed, being the most energy intensive subsector, even more than copper mining [9]. On the other side, railway, maritime and air carriers held only 20% of the energy used for transportation. Regarding the nature of the exergy carriers used by the sector, 99% of them were fossil fuels, while electricity usage reached only 1%, as shown in Figure 15 [9].

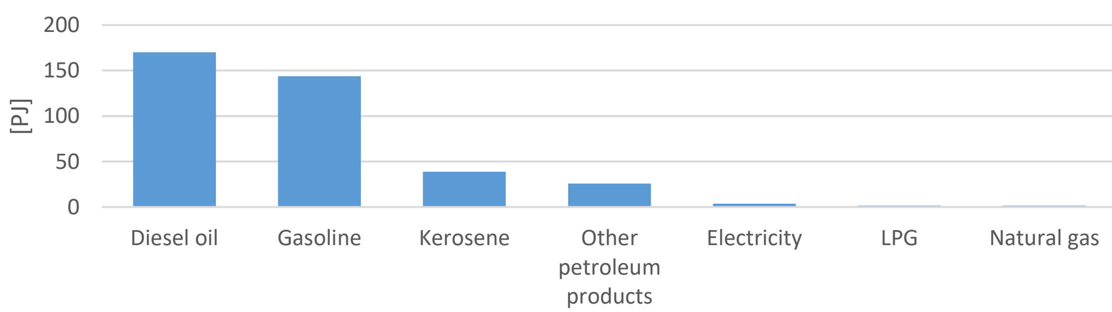


Figure 15: Energy sources used by the transportation sector in 2013 [9].

Inputs

Using energy-exergy conversion factors proposed by Kotas [19], the sector consumed 410 [PJ] exergy. As expected, the main exergy consumer was Ground transportation (82%), followed by Airways (10%), Waterways (7%), and Railways (1%), as shown in Figure 16.

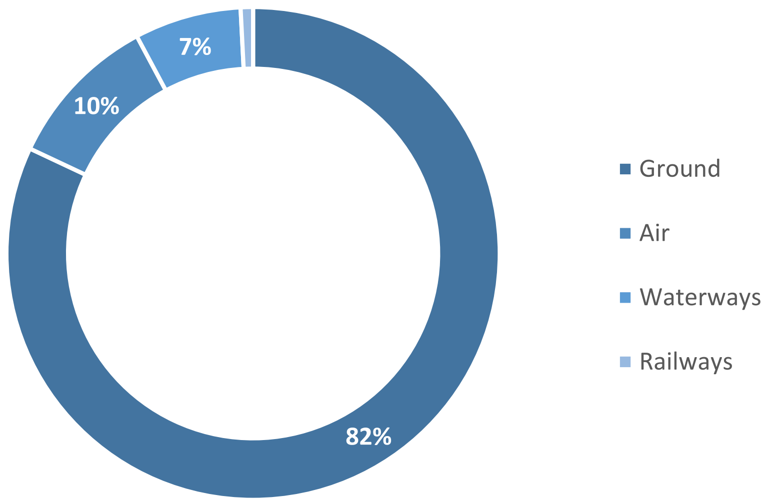


Figure 16: Exergy consumption in the transportation sector in 2013.

Outputs

Exergy efficiency was addressed following the methodology used by Ji and Chen in their analysis of the transportation sector in the Chinese society [18]. Physical exergy was considered negligible compared to chemical exergy, as estimated by Kotas [19]. Specific fuel exergy is given by Equation (*11*).

$$\epsilon = \gamma \times \mathrm{LHV} \tag{11}$$

Where γ stands for the exergy factor or exergy-energy ratio based on LHV or lower heating value. This is the heat obtained of each fuel combustion when water in the products is in vapor form. Exergy factors used in the analysis are shown in Appendix D: Chemical Exergy of Fossil Fuels, Table 16 [19] .

On the other hand, conventional energy efficiency of a certain mean of transportation is given by Equation (*12*).

$$\eta = \frac{\text{work}}{\text{energy input}} \tag{12}$$

As vehicles are generally not operated at rated load, part-load energy efficiencies for each mean of transportation are considered. Transportation devices used in Chile were assumed to be similar to those in China and the US. Part-load efficiencies were taken from Ji's analysis of the Chinese transportation sector [18], which were based on Reistad's study of the available energy in the U.S. [12]. Part-load efficiencies used in the analysis are shown in Table 9 [18].

Table 9: Part-load energy efficiencies considered in the analysis of the transportation sector in Chile in 2013 [18].

Mean of transportation	Part-load efficiency, η
Ground	0.22
Railways	0.28
Waterways	0.15
Airways	0.28

Similarly, exergy efficiency is defined in Equation (*13*) as

$$\psi = \frac{\text{work}}{\text{exergy input}} \tag{13}$$

Therefore, it is clear to see that the energy-exergy ratio relates both efficiencies in the following fashion

$$\psi = \frac{\eta}{\gamma} \tag{14}$$

To assess the exergy efficiency of the entire transportation sector, the weighted mean overall exergy efficiency is computed following Ji's methodology, as shown in Equation (*15*) [18]:

$$\psi_{\text{overall}} = \sum_{i,j} \psi_{ij} \times \text{Fr}_{ij} = \sum_{i,j} \left(\frac{\eta_i}{\gamma_j}\right) \times \text{Fr}_{ij} \tag{15}$$

Where ψ_{ij} denotes the exergy efficiency of the ith transportation mode using the jth fuel form, η_i is the energy efficiency of the ith transportation mode, γ_i is the energy-exergy conversion factor of the jth energy form, and Fr_{ij} stands for the fraction of the jth energy form used by the ith transportation mode.

Balance

Thus, transportation exergy efficiency was computed for 2013. Overall transportation efficiency reached 21%, as shown in Figure 17. The left bar shows the exergy input by mean of transportation, while the left bar shows the apparent exergy output of the sector, which was approximately 85 [PJ].

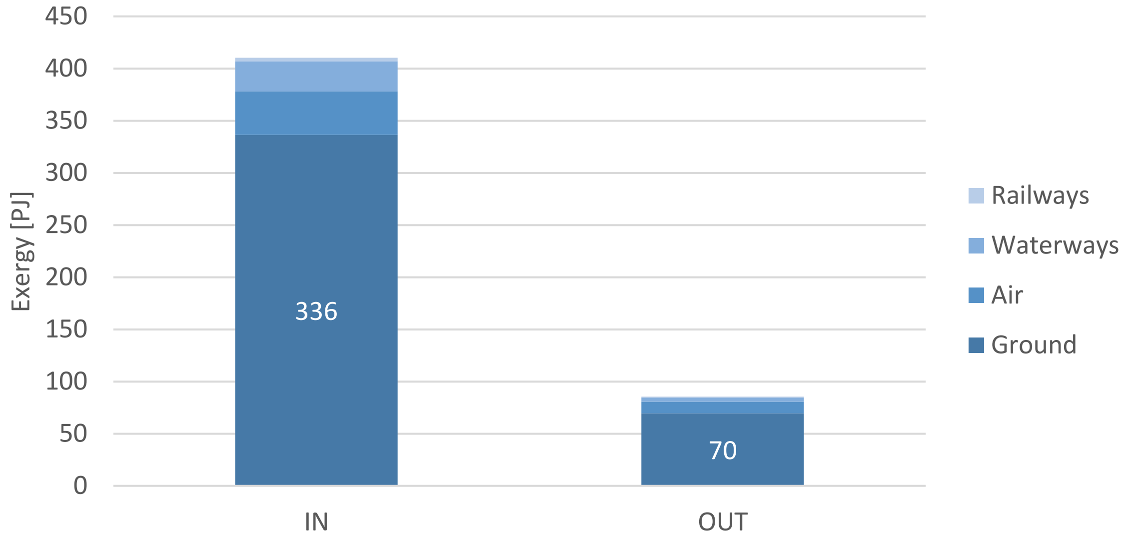


Figure 17: Exergy efficiency in the transportation sector in 2013.

3.2.6 Residential, Public, and Private (RPP)

The residential, public, and private sector is composed primarily of households, public and private offices, and commercial establishments. Most of the energy consumed by the sector is related to households, as shown in Figure 18 [9].

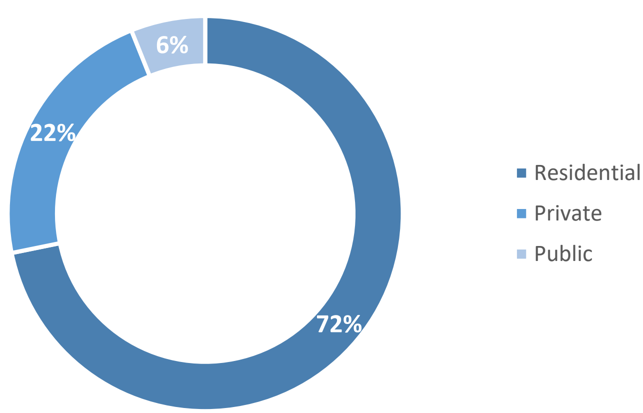


Figure 18: Energy consumption in the RPP sector in 2013 [9].

Inputs

Like in the other economic activities considered in the analysis, exergy carriers entering the RPP sector were primarily fossil fuels and other forms of energy. The main exergy carrier used in the subsector was electricity (34%), followed by fuelwood (31%) and LPG (18%), as shown in Figure 19 [9]. The total exergy input to the sector was computed through exergy factors proposed by Kotas [19], which help gauge exergy content in fossil fuels. Thus, exergy inflow reached 264 [PJ] in 2013.

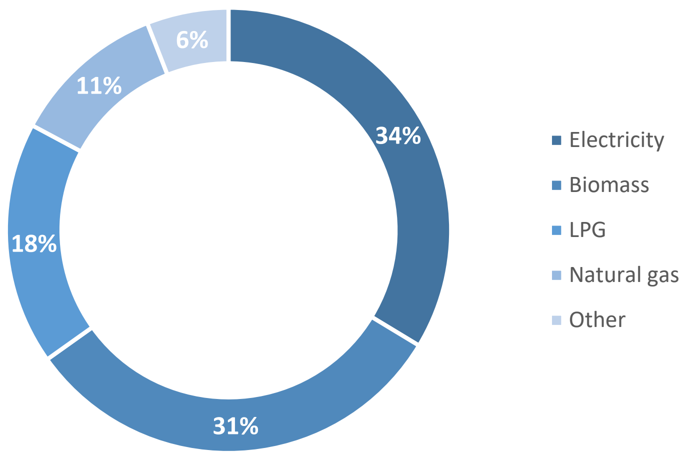


Figure 19: Main exergy carriers used in the RPP sector in 2013 [9].

Outputs

Services and other human activities were not measured, as exergy models were considered inadequate to address this issue. An exergo-economic point of view (or extended exergy models), in which money and other parameters are used to estimate the exergy value of human activities, can be considered in future works to address this issue [13, 28]. Given this, the output of this economic sector in particular shall be computed through the estimated exergy efficiency of the most commonly used household appliances in the country. According to the 2002 census, more than half of the energy consumed by an average house is used in space heating (56%), followed by water heating (18%), and cooking (10%), as shown in Figure 20 [29]. Due to the lack of updated information, it was assumed that the sector's structure of end-uses remained the same in the year of analysis, 2013.

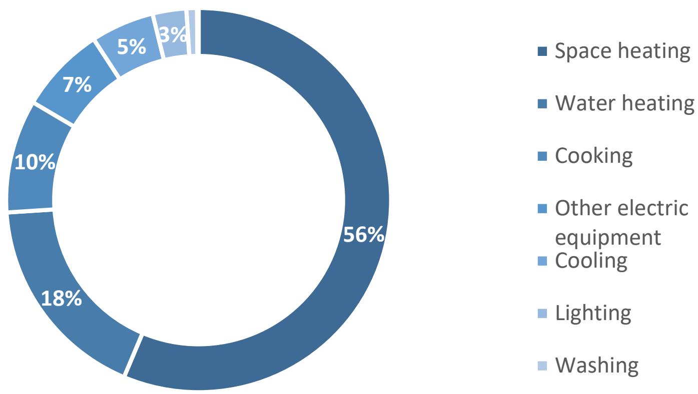


Figure 20: Households exergy consumption by purpose in 2002 [29].

On the other hand, mean exergy efficiencies of commonly used household appliances were taken from Ertesvåg's analysis of the Norwegian society, as shown in Figure 21 [14].

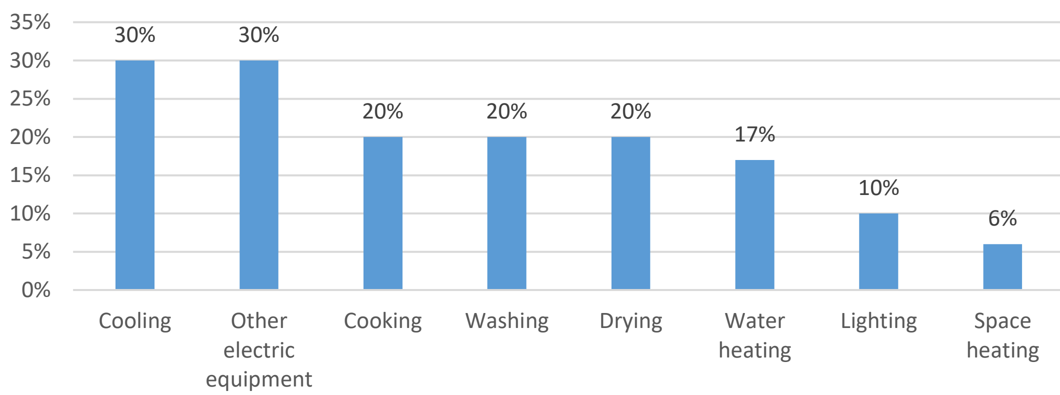


Figure 21: Exergy efficiency of household appliances according to Ertesvåg [30].

Weighting exergy consumption by exergy efficiency on each of the abovementioned applications, an apparent exergy output can be computed. Apparent exergy output of the RPP sector is attached in Figure 22.

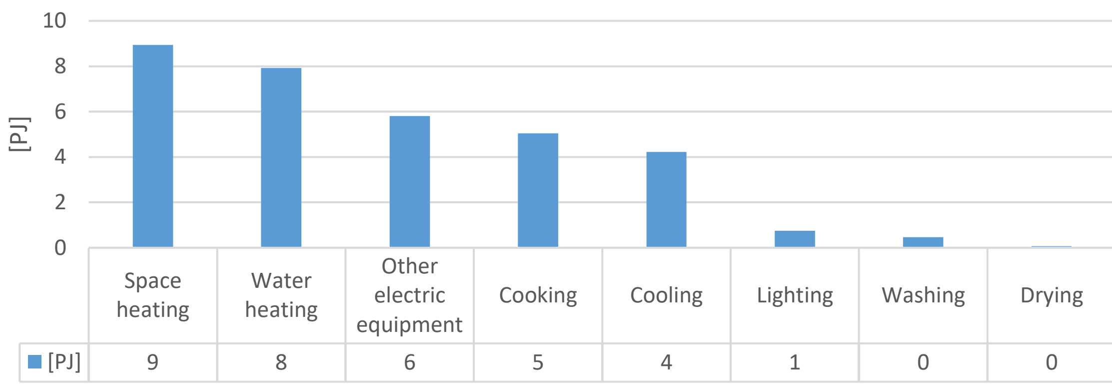


Figure 22: Apparent exergy output of the Residential, Public, and Private sector in 2002.

Balance

In 2013, the exergy consumption of the household sector was 264 [PJ]. The efficiency of this sector was addressed through the efficiency of the most commonly used household appliances. Following Ertesvåg's methodology, exergy efficiency reached 13% in 2013. Thus, the apparent exergy output was 33 [PJ]. A summary of this sector is presented in Figure 23.

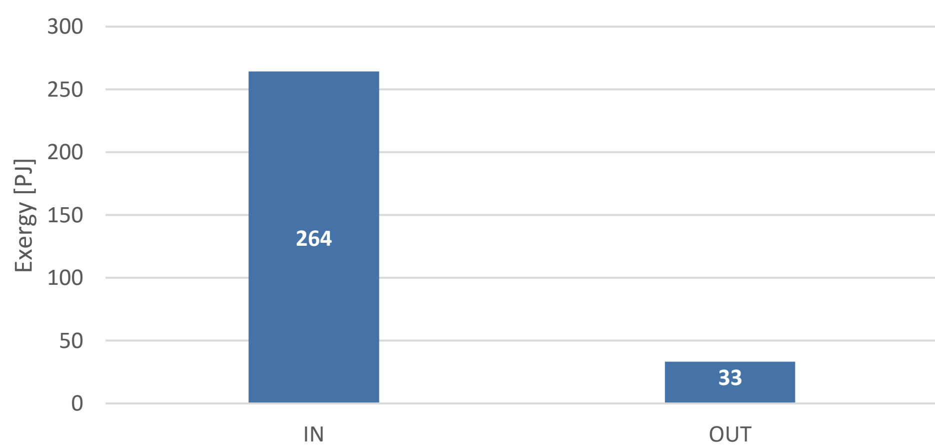


Figure 23: Exergy balance in the Residential, Public, and Private sector in 2014.

4. Discussions

4.1 Summary of results

The Chilean society was addressed from a thermodynamic point of view. Exergy carriers entering and leaving the system were accounted. A total of 1246 [PJ] exergy in the form of fossil fuels and other sources of energy entered the society in 2013. Of this total, only 1057 [PJ] were consumed in end-uses considered in the analysis. In other words, the present analysis takes into account 85% of the energy carriers entering the society. On the other side, 298 [PJ] was estimated to be the output of the society. Products were accounted through different exergy models, as described in section 3. Products considered were those related with extractive activities, such as mining, agriculture, livestock, aquaculture, and forestry. Transportation was also included, as it is one of the most energy intensive sectors in the economy. Likewise, household consumption was integrated in the analysis as well. Overall, exergy efficiency of the Chilean society in 2013 was 28%. A summary of the main exergy inputs and outputs is attached in Table 10.

Table 10: Exergy efficiency of the Chilean society in 2013. Exergy entering and leaving each of the considered economic sectors is detailed. Exergy efficiency of each sector is shown in the rightmost column.

Sector	Inputs [PJ]	Outputs [PJ]	Exergy Efficiency
Manufacturing	122	77	63%
Mining	193	102	53%
Transportation	410	(86)	21%
RPP	331	(33)	10%
Total	**1057**	**298**	**28%**

Figure 24 shows exergy efficiency of the analyzed economic sectors; it can be easily noted that exergy efficiency of extractive activities was much higher than that of sectors related with services. As previously explained, comparison among different thermodynamic systems is not advisable, since the transformations and processes occurring on each of the economic sectors are fundamentally different. As a consequence of not including labor in the analysis, service-related sectors are expected – in general – to have a much lower exergy efficiency than extractive activities, as the main output of the first ones is not being accounted through an exergy standpoint.

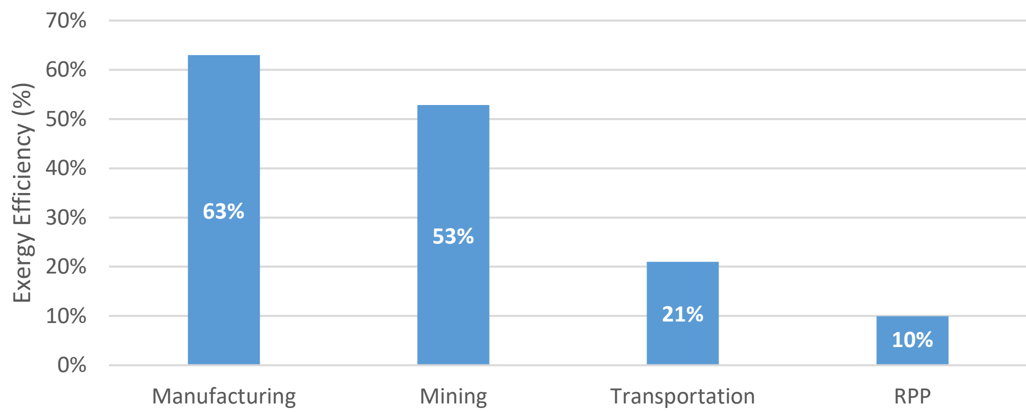


Figure 24: Exergy efficiency of the main economic sectors of the Chilean society in 2013.

To provide a clear overview of the situation in 2013, Figure 25 compares the magnitude of inputs and outputs throughout the society. Most of the exergy input is used by transportation and households. Mining and manufacturing combined used less exergy than households in 2013.

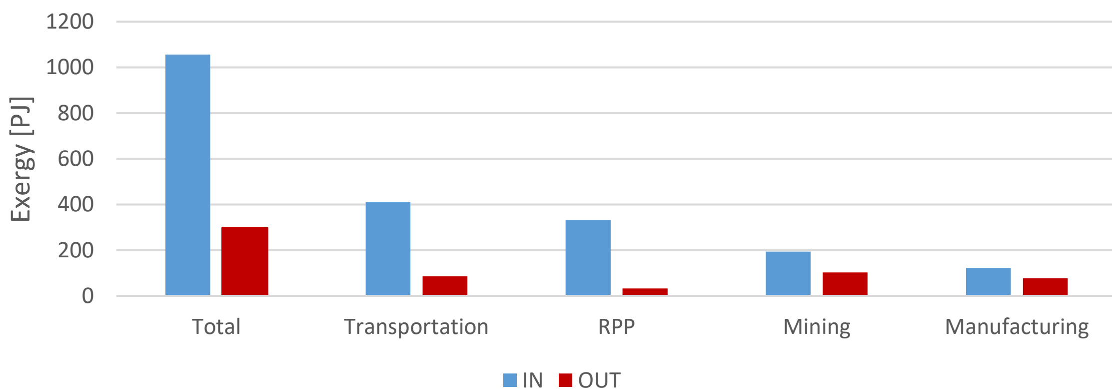


Figure 25: Exergy input and output of the society compared to flows in transportation, RPP, mining, and manufacturing.

4.2 Discussions

The exergy analysis presented in this work follows Wall's approach [17]. Energy, metals, minerals, biomass, food, and other exergy carriers are taken into consideration to compute the exergy efficiency of each economic sector. In the last couple of years, however, exergy analysis has been extended to consider capital and labor flows, as proposed by Sciubba's analysis of the Italian society and Ertesvåg's work on the Norwegian society [31][14]. This methodology, which integrates capital and labor, has become the standard regarding exergy analysis in the las couple of years.

Extended Exergy Analysis (EEA) provides a concept capable of incorporating monetary fluxes and human activities (services) in the study of a thermodynamic system. This kind of approach is proposed for future works on the Chilean society. The purpose of the present work is to provide a first approximation to the exergy conversion of the society from a chemical exergy point of view. Besides, major improvements are needed in the country's statistical power in order to achieve such a task. Detailed fluxes of materials, energy sources, and monetary flows among sectors are needed to build a more dynamic and comprehensive analysis of the Chilean society.

In light of this matter, the efficiencies obtained in the present analysis are based in the resources accounting methodology. These results can only be compared with previous analysis following the same approach. Comparison of different analyses following the abovementioned methodology are shown in Figure 26.

Exergy efficiency of the Chilean society in 2013 was lower than that of Sweden (1920), Norway (1995), and Ghana (1975), and higher than that of Sweden (1975, 1980, 1994), Japan (1985), and Italy (1990) [32]. This result might be counterintuitive at first, but it is important to recall that exergy analysis is based on a thermodynamic standpoint, regardless of the level of development or wealth of the society under study. Note that Sweden, in the last available year of analysis (1994) has an exergy efficiency almost ten points lower than that of 1920 (16% versus 25%). Thus, thermodynamic efficiency is not a trivial matter, and is certainly not proportionally related with the society's GDP, but rather with the way the system is performing the transformation processes inherent to any society. Indeed, Figure 26 shows a general trend of lower exergy performance in countries classified as *developed*, and a higher exergy efficiency in less developed economies and in former times.

This general result indicates that the actual model of development is not efficient from a thermodynamic point of view. The exergy model might imply that the current trend of development leads societies towards poorer resource utilization, as seen in Figure 26. In this sense, it is worth wondering how development is defined nowadays, and how development should be addressed in years to come, so as to lead society into a future of wiser resources utilization. Today, the general trend of development appears to imply an increasing rate of exchange with other societies, despite the fact that transportation was estimated to be one of the most thermodynamically expensive activities within a society. A measure to address this issue might be to foster local development, in which exchange among nearby actors reduces the need for long transportation costs. Likewise, finding alternative products to solve local problems will certainly improve the thermodynamic efficiency. Overconsumption should also be reduced, educating the population to achieve a sustainable level of resource utilization.

In the following subsections, results for each economic sector will be analyzed and discussed. Data obtained will be compared with that of other societies, in order to address how efficiently the processes are occurring in the Chilean society.

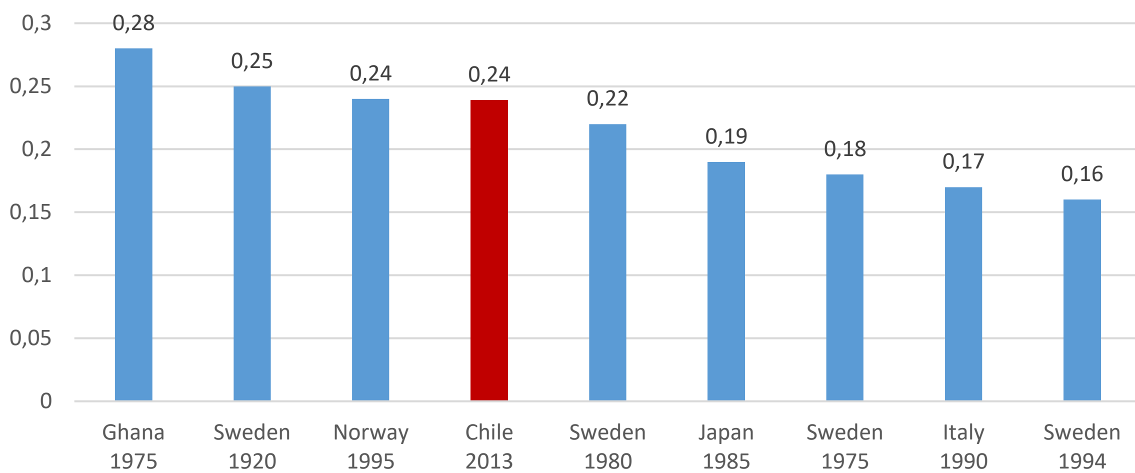


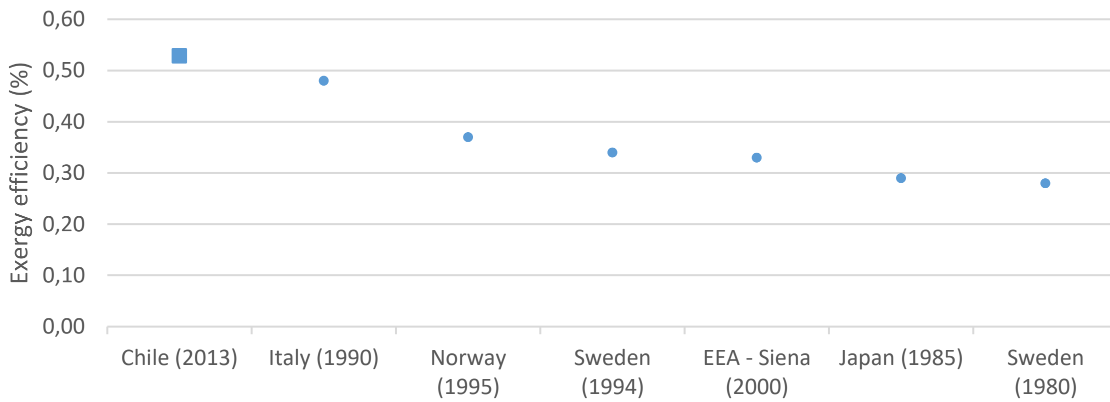
Figure 26: Exergy efficiency of the Chilean society compared to other societies [32].

4.2.1 Mining

Exergy efficiency of the mining sector was 53% in 2013. Metallic mining represented 73% of the output, while energy resources followed (16%), leaving industrial minerals and rocks third (11%). As described in section 3, most of the sector's output is involved with iron production rather than copper mining. Chemical exergy of iron is almost three times the available work of copper (Table 15), and also iron production in mass units was much higher than that of copper in 2013 (Figure 4). Thus, thermodynamically, iron production has a higher importance for the country than copper mining. However, it seems counterintuitive for the country to spend 77% of its mining resources in copper mining, and only 3% in iron production. Exergy efficiency of these activities was 8% and 679% respectively. These figures suggest that the exergy methodology might be overestimating the thermodynamic value of iron, or alternatively, underestimating the exergy required for its production. Some important exergy carriers in the form of raw materials or labor might have been neglected in the analysis, resulting in a much higher efficiency for iron production.

Another constraint of the analysis is the low statistical power regarding energy flows in to the sector. Neither the National Energy Balance [9] nor the Mining Annual Report [8], show disaggregated data of the exergy carriers consumed by each of the most relevant mining activities. Due to this difficulty, exergy efficiency of each sub activity could not be addressed.

Notwithstanding the above, the average efficiency of the sector was within the expected range, as shown in Figure 27. Exergy of mining activities in Chile was much higher than that



of the countries previously assessed following Wall's approach. These societies are not particularly characterized by mining production, which might explain why the Chilean economy has a higher efficiency in this sector, and also why the Chilean society has a higher overall exergy efficiency. As previously stated, the year of analysis might also influence the results, as the level of technology has certainly increased from the previous analyses.

4.2.2 Manufacturing

Owing to the lack of detailed statistical exergy inflows to the manufacturing and extractive sector, raw approximations and assumptions were taken to address this economic sector. As specified in section 3, many activities were not considered in the analysis due to the lack of statistics of production and energy consumption. Most complex products, such as chemicals and machinery were left out of the analysis, as the focus of the work is to provide a first glance in terms of chemical exergy. In this sense, agriculture, aquaculture, livestock, and forestry activities were included, since exergy models to obtain chemical exergy of these products has already been developed, as exposed in previous sections. Roughly 6% of the

Figure 27: Exergy efficiency comparison of the mining sector among different societies [33][34][34].

GDP was studied in this section through selected activities. In total, agriculture, livestock, forestry, aquaculture, and manufacturing industries (including complex products not considered in the analysis), represent 14% of the GDP. This means 43% GDP of extractive/manufacturing activities were included in the study.

Raw approximations were made to estimate the exergy efficiency of the manufacturing and extractive sector. Exergy input was computed using GDP figures, as explained in section 3. This approximation might underestimate the exergy input to the considered activities, as extractive processes are generally more energy intensive than other economic activities. Therefore, exergy efficiency of the manufacturing sector might be overestimated. Like it was stated in the previous section, statistical power is required to build a better estimation of the exergy efficiency. In particular, disaggregation of energy carriers used by agriculture, livestock, aquaculture, and forestry should be constructed in order to clarify and better estimate these results.

Nonetheless, to evaluate the extent in which the GDP input estimation impacts the global efficiency, a sensibility analysis was performed. A range of $\pm$10% was considered reasonable to evaluate the society's global efficiency change. If the energy input were 10% higher than the one estimated through GDP figures, the society's exergy efficiency would shift from 28.2% to 27.9%. In the opposite case, in which the exergy input is 10% lower than the baseline, the exergy efficiency would reach 28.5%. In other words, a 10% variation in the exergy input to manufacturing produces a 1% variation in the global exergy for the society.

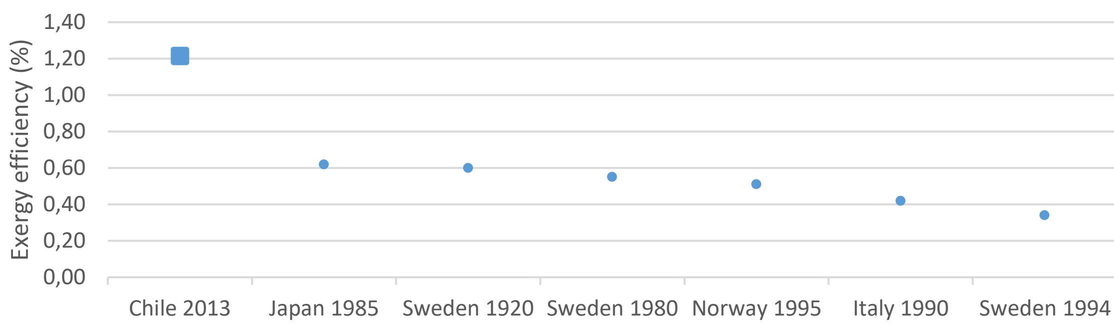


Figure 28: Exergy efficiency comparison of the forestry sector among different societies [33].

Unexpectedly, exergy efficiency of the forestry sector reached 121% in 2013, as shown in Figure 28. In the National Energy Balance [9], energy carriers used by forestry are not disaggregated, being part of the *Other Industries* category. Likewise, in the official GDP figures [22], forestry is jointly displayed with agriculture and livestock. Given this, the exergy consumption estimate using GDP figures was equally distributed among agriculture, livestock, and forestry. This assumption might have caused a higher efficiency in some activities in detriment of others. However, the global landscape shall remain unchanged, despite the differences in local sub activities.

On the other hand, exergy of food production was within expected results, as seen in Figure 29. Exergy efficiency of the Chilean society was second only to Japan (1985). Thermodynamically, this result means there is a broad improvement potential in the way food is being produced in the Chilean society, since Japan in 1985 was still much more efficient from an exergy standpoint. As the boundaries of the system are stablished outside of the whole sector, it is not possible to provide specific guidelines to improve exergy efficiency. This might be addressed in future studies when flows within economic sectors are fully integrated in the analysis. However, it seems reasonable to suggest that a technological update might be useful for more efficient agriculture, livestock, and aquaculture processes.

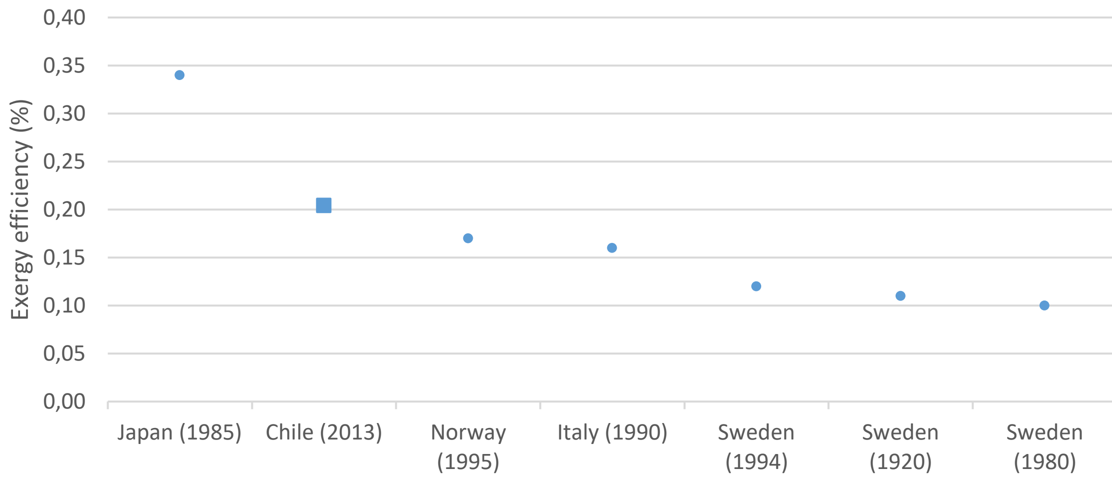
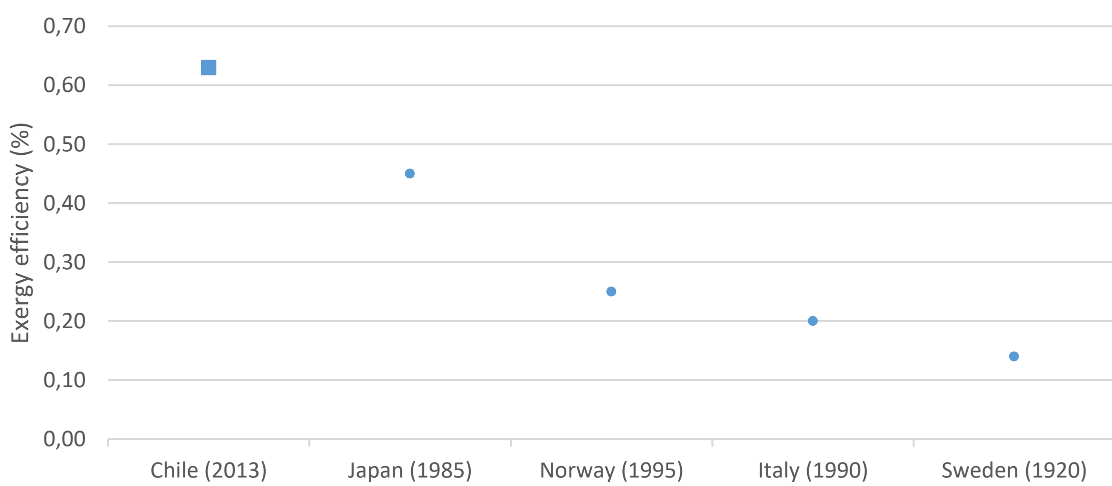


Figure 29: Exergy efficiency comparison of the food sector among different societies [33].

Additionally, exergy efficiency of the whole industry sector in Chile was 63%. This result was higher than those obtained in previous analyses, which might be a consequence of technological shifts observed in the last couple of decades. This result might also be a consequence of the activities that were considered in the analysis. It might be possible that including industries such as petrochemical, textile, cellulose, among others, will contribute to lower the efficiency of the processes within manufacturing. Indeed, the tendency of this study is to observe lower thermodynamic efficiency towards end-use sector, and higher efficiencies among extractive activities. Further analysis is required in order to clarify this matter, as discussed in previous sections.



4.2.3 Transportation

Exergy efficiency of transportation reached 21% in 2013. This result is greatly influenced by ground transportation, the most important mean of transportation in the country in the year of analysis. This activity was responsible for 82% of the exergy input to the sector.

Moreover, part-load energy efficiencies were used to compute the exergy efficiency of the sector. These efficiencies were taken from the analysis of Ji and Chen of the transportation sector in China [18]. Thus, these values might not accurately represent the vehicles used in Chile in 2013. To address in which extent this assumption affects the social and transportation exergy efficiency, a sensibility analysis was performed, as shown in Table 11.

Table 11: Sensitivity analysis of the part-load energy efficiencies used in the analysis of the transportation sector.

	Efficiency, η		
	Ji and Chen [18]	+20%	-20%
Sector efficiency	21%	25%	17%
Society efficiency	**28%**	**30%**	**27%**

As shown in Table 11, a 20% change in this parameter produces a 4% change in the sector's efficiency, and an approximated 2% variation in the society's exergy efficiency. To fully address this issue, the energy efficiency of the machines most commonly used in the country, as well as the frequency of part-load transportation must be integrated in the analysis. Notwithstanding these shortcomings, exergy efficiency of the transportation sector fell within the expected range, as shown in Figure 31 [33]. Transportation efficiency was significantly higher than that of the previously analyzed economies. This might be, as previously stated, a result of the different time periods of analysis, as efficiency of transportation devices has increased in the las decades considerably. In fact, Figure 31 shows an increase of the exergy efficiency of transportation in the years after the analysis of the Italian society.

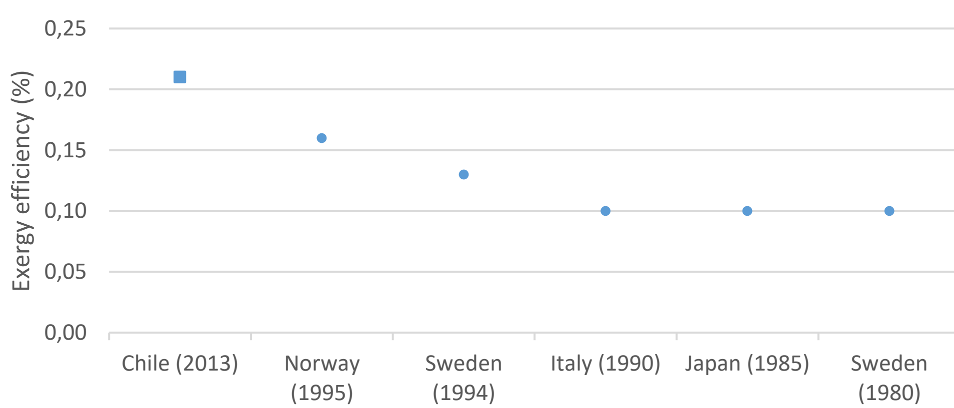


Figure 31: Exergy efficiency comparison of the transportation sector among different societies [33].

Furthermore, a technological shift in ground transportation devices was simulated. Since the aim of this work is to propose new public policies to improve resources utilization, a new policy to promote and facilitate the entrance of electric vehicles to the market was simulated. Given that electric vehicles have a much higher energy efficiency, a part load efficiency of 80% was considered in the simulation. Also, as exergy in electricity is completely available to produce work, the fuel coefficient was set to $\gamma = 1$. Using these parameters, a scenario was simulated in which 25% of the ground transportation is made on electric vehicles. An increase in the sector efficiency was observed, reaching 36%. At the same time, the society's exergy efficiency increased around 20%, reaching 34%, as shown in Table 12.

Table 12: Technological shift simulation in the ground transportation system.

	Ji and Chen [18]	25% ground transportation in electric vehicles
Sector efficiency	21%	36%
Society efficiency	**28%**	**34%**

This simple exercise proves that a policy in this direction would greatly impact the efficiency with which resources are being used in the society. This sector in particular would be greatly benefited from such a policy, as it is one of the most exergy intensive activities. Unlike RPP, which has a strong services and human activities component that were not considered in the analysis, transportation is a sector restricted primarily by the efficiency of the devices used in the society. It seems only natural, then, to foster upgrades to transition to electric vehicles, which are much more energy and exergy efficient.

4.2.4 Residential, Public, and Private

Like in the previous section, it is important to recall that labor was not considered in the exergy efficiency computation for this sector. This simplification leads to a much lower exergy efficiency compared to extractive activities. Human work is expected to contribute greatly to the sector efficiency in future works, as the present model only accounts for exergy losses in end-use applications.

Very much like in the analysis of the transportation sector, in RPP, the energetic efficiencies of the most commonly used appliances were taken from Ertesvåg's analysis of the Norwegian society [28]. This sector structure might not accurately represent the efficiency of the appliances used in Chilean households, which is why a sensibility analysis on these parameters was made, to ensure results reliability.

As shown in Table 13, a 10% shift in devices efficiency produces a 1% variation in the society's exergy efficiency. In this sense, a technological update of this devices would produce little impact on the thermodynamic efficiency of the country. In this sense, it is rather clear to note that exergy efficiency in this sector is highly restricted by the technology roadblocks of the appliances most commonly used in the society.

Table 13: Sensitivity analysis of the energetic efficiency of the most commonly used household appliances in the society.

	Efficiency, η		
	Ertesvåg [28]	+10%	-10%
Sector efficiency	10%	11%	9%
Society efficiency	**28.2%**	**28.5%**	**27.9%**

From Figure 32 it can be noted that despite of using a sector structure similar to that of Norway in 1995 [28], exergy efficiency of the households sector in Chile was relatively lower (12% versus 10%). This result might only reflect methodological differences, because an exergy flow in the form of food was considered as input to the household sector in Chile. According to the National Statistics Institute, in 2013, the population was nearly 17,6 million. Considering a 2500 kcal daily intake, the flow of exergy from food sector to RPP was estimated in 67 [PJ] in 2013. In fact, Figure 33 displays the exergy consumption per capita in the Norwegian (1995), and Chilean (2013) society. In most end-used, exergy consumption in Chile is lower than in Norway. This result was expected, as developed economies tend to have a higher per capita residential energy consumption. Improvement in end-uses must be focused in space heating and water heating, which are the most exergy intensive categories in household exergy consumption.

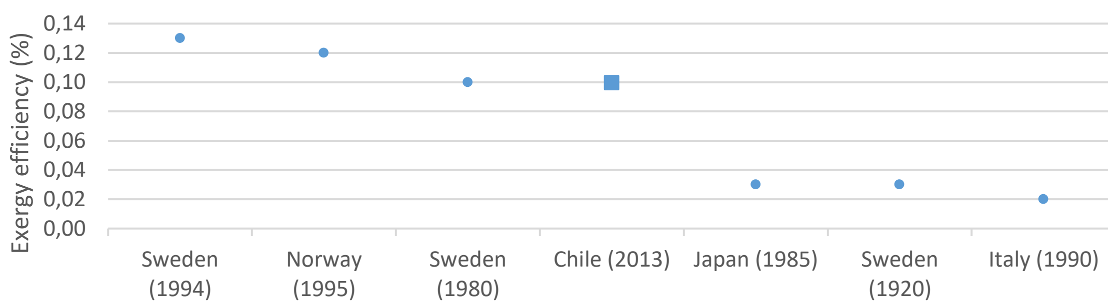


Figure 32: Exergy efficiency comparison of the RPP sector among different societies [33].

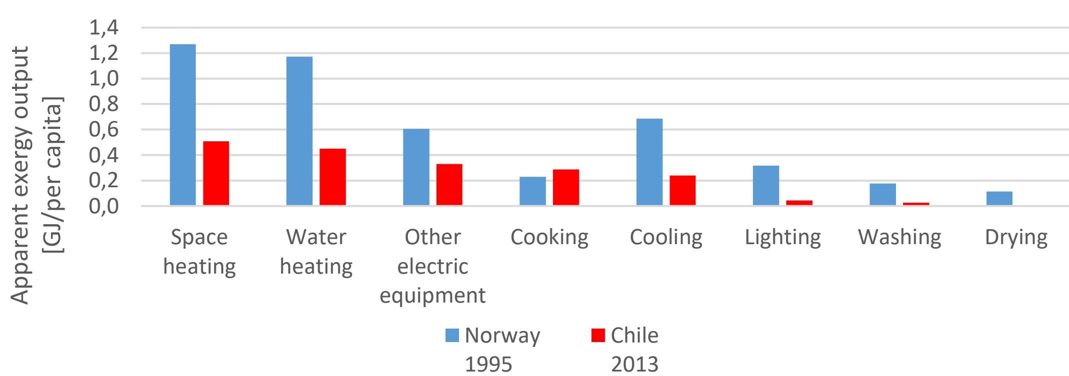


Figure 33: Per capita exergy use of household sector in Chile (2013) and Norway (1995) [30].

5. Future guidelines and Conclusions

5. Future guidelines

As seen in Figure 26, exergy efficiency obtained for the Chilean society in 2013 is relatively high compared to those of developed countries in the eighties and nineties. At the same time, exergy efficiency resulted significantly lower than those of less developed economies and also those of former times.

Indeed, the development model in recent times has proven to be unsustainable. Educating about overconsumption, finding local solutions to local issues as well as discouraging long transportation would contribute to lower thermodynamic inefficiencies. Likewise, shifting towards more exergy efficient machines would make the most of the available resources. In this sense, exergy efficiency of the Chilean society can be significantly improved by following the proposals described hereafter. These measures and policies were obtained from the exergy analysis discussed in section 4.

- Copper mining industry was very inefficient if compared to other industries. Much of the country's energy resources are being invested in this activity, although copper's exergy value is not as high as other products. In the long-term, the country should weight the high amount of work it is using to produce this metal, and discuss weather this is the right path, knowing that other products have a higher exergy value.

- There is a clear improvement potential in the food sector, as shown in Figure 29. Exergy efficiency of the Chilean food sector in 2013 was lower to that of Japan in 1985. A technological update might be useful in agriculture, livestock, and aquaculture processes, in order to obtain higher thermodynamic efficiencies.

- Transportation efficiency can be greatly improved if new transportation devices are fostered to enter the market. If 25% of the ground transportation system shifted to electric technology, exergy efficiency of the sector would increase 15%, and the overall exergy efficiency of the country would grow 6%. Unlike other sectors, this technology is readily available to be implemented in the country, and new energy sources entering the system should also guarantee a renewable transportation system in upcoming years.

- Device upgrade in the household sector produces very little impact in the overall exergy efficiency. Space and water heating applications are the most exergy intensive end-uses. New technologies improving energy efficiency of this devices should be studied, in order to improve available work utilization as much as possible.

All these policies should be further studied and discussed, evaluating not only from a thermodynamic point of view, but also from a social, economic, and environmental perspective.

6. Conclusions

Exergy efficiency of the Chilean society and its main economic sectors was computed. The most relevant economic sectors to analyze were defined using energy consumption criteria, as well as importance regarding economic activity (GDP). Results were compared to those obtained for other societies following Wall's approach, and some opportunities for improvement were found in this analysis.

Exergy methodology allowed to obtain exergy efficiency of the Chilean society. This efficiency was 28% in 2013 considering input to end-uses only. When considering the total input to the system, exergy efficiency reached 24%. These values were observed to be relatively in the middle of advanced and less developed economies. Developed economies according to Ertesvåg's work [32], show a considerably lower efficiency. This might be a consequence of the unfeasibility of the present-day model of development. A shift in this behavior is expected in the years to come, as new technologies with higher energy and exergy efficiency enter the market. In the long term, a shift in paradigm is expected, fostering local development and educating about resources overconsumption.

In this direction, several proposals were introduced in order to improve exergy efficiency of the Chilean society. In mining, copper industry was found to be quite inefficient if compared to other mining activities. The country should study weather this form of income is the most suitable one for the future. Likewise, structural changes were proposed in manufacturing industry to improve the efficiency of transformations within the food subsector. Investment in new agricultural, livestock, and aquaculture technologies might contribute to improve thermodynamic benefit in the society. Regarding transportation, a major opportunity of development was found in the technological shift of ground transportation. A 25% electric vehicles would increase the country's efficiency by 6%. A source of improvement in the household sector is space and water heating, as these end-uses are the most exergy consuming in this sector.

It is also worth mentioning that a future analysis is proposed to integrate the exergy embodied in labor and capital investment. A higher statistical power is required to perform an Extended Exergy Analysis of the Chilean society. Using this methodology would allow to compare the country with a broader number of other analyses, finding new ways to improve the exergy efficiency, and therefore, progressing in the way resources are used in the society.

7. References and Appendixes

7. Bibliography

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8. Appendixes

Appendix A: Standard Chemical Exergy

Standard chemical exergy values are taken from Kotas [19].

Table 14: Standard chemical exergy of substances used in the analysis. $T_0 = 298.15, P_0 = 1.0132\ bar = 1\ atm$ [19].

Component	Chemical Formula	State	Standard chemical exergy $\overline{\mathbf{ex}}^{\mathbf{0}}$ $[\mathbf{kJ/kmol}]$
Copper	Cu	Solid	134,400
Carbon	C	Solid, graphite	410,820
Carbon dioxide	CO_2	Gaseous	20,140
Lithium	Li	Solid	396,170
Water	H_2O	Liquid	3,120
Water	H_2O	Gaseous	11,710
Oxygen	O_2	Gaseous	3,970
Nitrogen	N_2	Gaseous	720

Appendix B: Standard Chemical Exergy of Mining Products

Table 15: Standard chemical exergy of selected substances [19].

Substance	Reference compound	Chemical formula	$\overline{ex}^0$ $[kJ/mol]$
Metallic Mining			
Iron	Iron	Fe	376.4
Copper	Copper	Cu	134.2
Molybdenum	Molybdenum	Mo	730.3
Zinc	Zinc	Zn	339.2
Lead	Lead	Pb	232.8
Silver	Silver	Ag	70.2
Gold	Gold	Au	15.4

Substance	Reference compound	Chemical formula	$\overline{ex}^0$ $[kJ/mol]$
Industrial Minerals and Rocks			
Sodium Chloride	Sodium Chloride	$NaCl$	22.2
Calcium carbonate	Calcium carbonate	$CaCO_3$	5.1
Sulphur comp.	Sulphuric acid	H_2SO_4	161.0
Potassium comp.	Potassium chloride	KCl	21.4

Silicon comp.	Silicon dioxide	SiO_2	2.6
Plaster	Calcium sulfate	$CaSO_4$	4.3
Nitrates	Sodium nitrate Potassium nitrate	$NaNO_3$ KNO_3	-15.5
Lithium comp.	Lithium carbonate	Li_2CO_3	77.2
Phosphoric rocks	Phosphorus pentoxide	P_2O_5	319.5
Copper sulphate	Copper sulphate	$CuSO_4$	80.9

Appendix C: Computing exergy embodied in mining products

In this section, computation of exergy of mining products will be illustrated. Iron will be used as example of calculation. In 2013, 9,088,345 [t] of iron were produced [8]. In grams, whis production is expressed as 9.1E+12 [g]. On the other hand, standard chemical exergy of iron is 376.4 [kJ/mol], while molecular weight is approximately 56 [g/mol]. Therefore, exergy of iron production in Chile in 2013 is computed as shown in Equation (*16*)

$$\mathrm{E_{iron}} = \frac{\mathrm{M_{iron}}}{\mathrm{n_{iron}}} \times \overline{\mathrm{ex}}^{0}_{\mathrm{iron}} \quad (16)$$

Where $\mathrm{E_{iron}}$ is the exergy of iron produced in Chile in 2013, $\mathrm{M_{iron}}$ is the mass of iron produced in the time period, $\mathrm{n_{iron}}$ is the molecular weight, and $\overline{\mathrm{ex}}^{0}_{\mathrm{iron}}$ is the standard chemical exergy of the metal. Replacing the abovementioned constants, exergy is

$$\mathrm{E_{iron}} = \frac{9.1\mathrm{E} + 12\ [\mathrm{g}]}{56\ \left[\frac{\mathrm{g}}{\mathrm{mol}}\right]} \times 376.4\ \left[\frac{\mathrm{kJ}}{\mathrm{mol}}\right] \quad (17)$$

$$\mathrm{E_{iron}} = 6{,}12\mathrm{E} + 13\ [\mathrm{kJ}] \quad (18)$$

$$\mathrm{E_{iron}} = 61\ [\mathrm{PJ}] \quad (19)$$

This result is shown in Table 4.

It is important to highlight that exergy embodied in energy resources obtained through mining, such as natural gas, carbon, and petroleum, is obtained in the same way described in the previous chapter, using energy-exergy conversion factors proposed by Kotas [19].

Appendix D: Chemical Exergy of Fossil Fuels

As an example, exergy of coal is computed hereafter. Lower heating value of solid carbon is 32,800 kJ/kg [21]. Given that the production of coal in the country reached 2,902,044 [t] or equivalently, 2.9E+09 [kg], the energy related to this fuel form can be estimated through Equation (*20*)

$$E_i = LHV_i \times P_i \quad (20)$$

Where E is the amount of energy estimated for the ith fuel form, LHV_i is the lower heating value or net calorific value, and P_i is the production of the ith energy resource. In the case, for coal

$$E_{coal} = 32{,}800 \left[\frac{kJ}{kg}\right] \times 2.9E+09\ [kg] = 9.5E+13\ [kJ] \quad (21)$$

$$E_{coal} = 95\ [PJ] \quad (22)$$

Now, using energy-exergy conversion factors proposed by Kotas [19], exergy can be obtained, by using Equation (*23*)

$$\epsilon_i = E_i \times \gamma_i \quad (23)$$

In the case of coal, exergy is given by

$$\epsilon_{carbon} = 95\ [PJ] \times 1.08 \quad (24)$$

$$\epsilon_{carbon} = 103\ [PJ] \quad (25)$$

Following a similar approach, exergy of various fossil fuels can be computed. Net calorific values and energy-exergy conversion factors used in the analysis are presented in Table 16.

Table 16: Energy-exergy conversion factors used in the analysis of the Chilean society [19].

Energy source	Lower Heating Value ($\mathbf{LHV_i}$)	Unit	Energy-exergy conversion factor, $\boldsymbol{\gamma_i}$
Coal	7000	kCal/kg	1.08
Coke	7000	kCal/kg	1.05
Oil	10665	kCal/kg	1.06
Diesel oil	10900	kCal/kg	1.06
Gasoline	11300	kCal/kg	1.06
Other petroleum products*	10665	kCal/kg	1.06
LPG	12100	kCal/kg	1.04
LNG	9341	kCal/m3	1.04
Natural gas	4260	kCal/m3	1.04
Biomass	3500	kCal/kg	1.23

Electricity	860	KCal/KWh	1
* an average heating value and conversion factor was udes for other petroleum products			

Appendix E: Exergy Carriers consumed by the Manufacturing Sector

In the case of the Manufacturing sector, different sources of information were used to estimate the use of exergy carriers. On the one hand, the Ministry of Energy through the National Energy Commission (CNE) publishes annually the national energy balance [9], which details the amount of fossil fuels and other energy sources used in the country. On the other hand, the Central Bank of Chile produces annually statistics regarding the Gross Domestic Product and main economic activities in the country [22].

Since the level of detail of the GDP statistics are much higher than those of the energy balance, GDP figures were used to estimate the energy input by economic activity as shown in Table 17. The total energy input to the country was weighted by the product of each economic activity, in order to obtain an estimate of the energetic input to each economic activity. Then, the energy input was transformed into exergy values using the average energy mix used by the manufacturing sector in the country, according to the national energy balance [9].

Table 17: Exergy input estimation using GDP figures [22][9].

Activity	**GDP 2014 [th. CLP]** [22]	**% GDP**	**Proportional Energy input [PJ]**	**Estimated Exergy input [PJ]**
Agriculture, livestock and forestry	2,799,027	2.7%	31	34
Food	2,565,956	2.4%	28	31
Wood and furniture	563,904	0.5%	6	7
Fishing	507,950	0.5%	6	6
Manufacturing	**6,436,837**	**6%**	**71**	**78**
Total	**105,794,047**	**100%**	**1,166**	**1,246**

Appendix F: Standard Chemical Exergy of Food products

Table 18: Standard chemical exergy of fruits, vegetables, cereals, meat, and fish products [25, 26].

Product	**Representative product**	**Chemical exergy [kcal/100g]**
Fruits [25, 26]		

Grapes, fresh or dried.	Grapes, red or green (European type, such as Thompson seedless), raw	69
Apples, pears and quinces, fresh.	Apples, raw, with skin	52
Other fruit, fresh.	Pears, raw	57
Apricots, cherries, peaches (including nectarines), plums and sloes, fresh.	Apricots, raw	48
Other nuts, fresh or dried, whether or not shelled or peeled.	Peanuts, all types, raw	567
Fruit and nuts, uncooked or cooked by steaming or boiling in water, frozen, whether or not containing added sugar or other sweetening matter.	Peanuts, all types, raw	567
Fruit, dried, other than that of headings 08.01 to 08.06; mixtures of nuts or dried fruits of this Chapter.	Peanuts, all types, raw	567
Citrus fruit, fresh or dried.	Lemons, raw, without peel	29
Dates, figs, pineapples, avocados, guavas, mangoes and mangosteens, fresh or dried.	Avocados, raw, all commercial varieties	160
Fruit and nuts, provisionally preserved (for example, by sulphur dioxide gas, in brine, in sulphur water or in other preservative solutions), but unsuitable in that state for immediate consumption.	Apples, raw, with skin	52
Bananas, including plantains, fresh or dried.	Bananas, raw	89
Peel of citrus fruit or melons (including watermelons), fresh, frozen, dried or provisionally preserved in brine, in sulphur water or in other preservative solutions.	Lemon peel, raw	47
Coconuts, Brazil nuts and cashew nuts, fresh or dried, whether or not shelled or peeled.	Nuts, coconut meat, raw	354
Melons (including watermelons) and papaws (papayas), fresh.	Melons, cantaloupe, raw	34

Product	Representative product	Chemical exergy [kcal/100g]
Vegetables [25, 26]		
Onions	Onions, raw	40
Vegetables (uncooked or cooked by steaming or boiling in water)	Onions, raw	40
Vegetables provisionally preserved (for example	Onions, raw	40

Dried vegetables	Onions, raw	40
Dried leguminous vegetables	Broadbeans (fava beans), mature seeds, raw	341
Other vegetables	Onions, raw	40
Potatoes	Potatoes, flesh and skin, raw	77
Carrots	Carrots, raw	41
Tomatoes	Tomatoes, red, ripe, raw, year round average	18
Lettuce (Lactuca sativa) and chicory (Cichorium spp.)	Lettuce, cos or romaine, raw	17
Cabbages	Cabbage, raw	25
Leguminous vegetables	Broadbeans (fava beans), mature seeds, raw	341
Cucumbers and gherkins	Cucumber, with peel, raw	15
Manioc	Potatoes, flesh and skin, raw	77

Product	Representative product	Chemical exergy [kcal/100g]
Cereals [25, 26]		
Maize (corn)	Corn grain, yellow	365
Oats	Oat bran, raw	246
Barley	Barley, pearled, raw	352
Buckwheat, millet and canary seeds; other cereals	Buckwheat	343
Rye	Rye grain	338
Wheat and meslin	Wheat, durum	339
Rice	Wild rice, raw	357
Grain sorghum	Sorghum grain	329

Product	Representative product	Chemical exergy [kcal/100g]
Livestock [25, 26]		
Meat of swine, fresh, chilled or frozen.	Pork, fresh, loin, tenderloin, separable lean only, raw	109
Meat and edible offal, of the poultry of heading 01.05, fresh, chilled or frozen.	Beef, chuck eye roast, boneless, America's Beef Roast, separable lean only, trimmed to 0" fat, all grades, cooked, roasted	183
Edible offal of bovine animals, swine, sheep, goats, horses, asses, mules or hinnies, fresh, chilled or frozen.	Goat, raw	109
Meat of sheep or goats, fresh, chilled or frozen.	Goat, raw	109
Pig fat, free of lean meat, and poultry fat, not rendered or otherwise extracted,	Pork, fresh, loin, tenderloin, separable lean only, raw	109

fresh, chilled, frozen, salted, in brine, dried or smoked.		
Meat of bovine animals, fresh or chilled.	Goat, raw	109
Meat and edible meat offal, salted, in brine, dried or smoked; edible flours and meals of meat or meat offal.	Beef, chuck eye roast, boneless, America's Beef Roast, separable lean only, trimmed to 0" fat, all grades, cooked, roasted	183
Meat of bovine animals, frozen.	Goat, raw	109
Other meat and edible meat offal, fresh, chilled or frozen.	Goat, raw	109

Product	Representative product	Chemical exergy [kcal/100g]
Fishing [25, 26]		
Fish, frozen, excluding fish fillets and other fish meat of heading03.04	Fish, fish sticks, frozen, prepared	277
Fish fillets and other fish meat (whether or not minced), fresh, chilled or frozen	Fish, salmon, sockeye, raw	131
Fish, fresh or chilled, excluding fish fillets and other fish meat of heading 03.04	Fish, salmon, sockeye, raw	131
Molluscs, whether in shell or not, live, fresh, chilled, frozen, dried, salted or in brine; smoked molluscs, whether in shell or not, whether or not cooked before or during the smoking process; flours, meals and pellets of molluscs, fit for human consumption	Mollusks, clam, mixed species, raw	86
Fish, dried, salted or in brine; smoked fish, whether or not cooked before or during the smoking process; flours, meals and pellets of fish, fit for human consumption	Fish, whitefish, dried (Alaska Native)	371
Crustaceans, whether in shell or not, live, fresh, chilled, frozen, dried, salted or in brine; smoked crustaceans, whether in shell or not, whether or not cooked before or during the smoking process; crustaceans, in shell, cooked by steaming or by boiling in water, whether or not chilled, frozen, dried, salted or in brine; flours, meals and pellets of crustaceans, fit for human consumption	Crustaceans, shrimp, raw (not previously frozen)	85
Aquatic invertebrates other than crustaceans and molluscs, live, fresh, chilled, frozen, dried, salted or in brine; smoked aquatic invertebrates other than crustaceans and molluscs, whether or not	Crustaceans, shrimp, raw (not previously frozen)	85

cooked before or during the smoking process; flours, meals and pellets of aquatic invertebrates other than crustaceans and molluscs, fit for human consumption		
Live fish	Fish, salmon, sockeye, raw	131

Appendix G: Computing exergy embodied in food products

Due to the lack of more appropriate exergy models, exergy embodied in food products is accounted through the nutrient energy (or caloric content) of each product [14]. For instance, in 2013, 0.1 [Mt] of maize (corn) was exported. According to the USDA Food Composition Database [25], corn contains 365 [kcal/100g]. Thus in a ton of corn, there is

$$\overline{\mathrm{ex}}^{0}_{\mathrm{wheat}} = 365\left[\frac{\mathrm{kcal}}{100\mathrm{g}}\right] = 3.65\mathrm{E}+6\left[\frac{\mathrm{kcal}}{\mathrm{t}}\right] \tag{26}$$

Therefore, in 0.1 [Mt],

$$\mathrm{Ex}_{\mathrm{wheat}} = 3.65\mathrm{E}+6\left[\frac{\mathrm{kcal}}{\mathrm{t}}\right] \times 0.1\,[\mathrm{Mt}] = 3.66\mathrm{E}+11\,[\mathrm{kcal}] \tag{27}$$

Expressing this value in [PJ],

$$\mathrm{Ex}_{\mathrm{wheat}} = 1.53\,[\mathrm{PJ}] \tag{28}$$

Which is the exergy contribution of wheat to the exergy output of the agriculture subsector.

Appendix H: Standard Chemical Exergy of Wood products

Table 19: Standard chemical exergy of wood and wood derived products [17, 26].

Forestry			
Product	Exergy	Unit	Weighting factor
Fuel wood, in logs, in billets, in twigs, in faggots or in similar forms; wood in chips or particles; sawdust and wood waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar forms.	18	[PJ/t]	0.4
Hoopwood; split poles; piles, pickets and stakes of wood, pointed but not sawn lengthwise; wooden sticks, roughly trimmed but not turned, bent or otherwise worked, suitable	18	[PJ/t]	0.4

for the manufacture of walking-sticks, umbrellas, tool handles or the like; chipwood and the like.			
Wood wool; wood flour.	18	[PJ/t]	0.4
Sheets for veneering (including those obtained by slicing laminated wood), for plywood or for similar laminated wood and other wood, sawn lengthwise, sliced or peeled, whether or not planed, sanded, spliced or end-jointed, of a thickness not exceeding 6 mm.	18	[PJ/t]	0.4
Wood (including strips and friezes for parquet flooring, not assembled) continuously shaped (tongued, grooved, rebated, chamfered, V-jointed, beaded, moulded, rounded or the like) along any of its edges, ends or faces, whether or not planed, sanded or end-jointed.	18	[PJ/t]	0.4
Particle board, oriented strand board (OSB) and similar board (for example, waferboard) of wood or other ligneous materials, whether or not agglomerated with resins or other organic binding substances.	18	[PJ/t]	0.4
Fibreboard of wood or other ligneous materials, whether or not bonded with resins or other organic substances.	18	[PJ/t]	0.4
Densified wood, in blocks, plates, strips or profile shapes.	18	[PJ/t]	0.4
Wooden frames for paintings, photographs, mirrors or similar objects.	18	[PJ/t]	0.4
Casks, barrels, vats, tubs and other coopers' products and parts thereof, of wood, including staves.	18	[PJ/t]	0.4
Tools, tool bodies, tool handles, broom or brush bodies and handles, of wood; boot or shoe lasts and trees, of wood.	18	[PJ/t]	0.4
Builders' joinery and carpentry of wood, including cellular wood panels, assembled flooring panels, shingles and shakes.	18	[PJ/t]	0.4
Tableware and kitchenware, of wood.	18	[PJ/t]	0.4
Wood marquetry and inlaid wood; caskets and cases for jewellery or cutlery, and similar articles, of wood; statuettes and other ornaments, of wood; wooden articles of furniture not falling in Chapter 94.	18	[PJ/t]	0.4
Other articles of wood.	18	[PJ/t]	0.4
Wood in the rough, whether or not stripped of bark or sapwood, or roughly squared.	8E-06	[PJ/m^3]	0.5
Railway or tramway sleepers (cross-ties) of wood.	8E-06	[PJ/m^3]	0.5
Wood sawn or chipped lengthwise, sliced or peeled, whether or not planed, sanded or end-jointed, of a thickness exceeding 6 mm.	8E-06	[PJ/m^3]	0.5
Packing cases, boxes, crates, drums and similar packings, of wood; cable-drums of wood; pallets, box pallets and other load boards, of wood; pallet collars of wood.	-	-	-
Plywood, veneered panels and similar laminated wood.	-	-	-

Appendix I: Computing exergy embodied in wood products

To compute exergy of wood and wood derived products, Wall's approach was taken [17]. According to Wall, wood contains 18 [MJ] exergy per kilogram of dry solid wood. This figure was taken to obtain exergy embodied in wood and wood derived products, due to the lack of more appropriate models.

As an example, exergy of fuel wood will be computed. In 2013, 3.9 [Mt] of this product was exported according to the International Trade Statistics Database [26]. However, this product is comprised in a category of products described as follows:

Fuel wood, in logs, in billets, in twigs, in faggots or in similar forms; wood in chips or particles; sawdust and wood waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar forms.

As this is a diverse category of products, and not just solid dry wood, exergy value was lowered by introducing a weighing factor, as shown in Table 19. This factor represents the average woodchips and sawdust production relative to sawn timber, wood panels and veneer produced in the country [27]. It was considered that these three last categories of products contain exergy as described by Wall's approach, related to chemical and *structural* exergy [17]. Sawdust, on the other hand, was neglected as exergy carrier, despite its calorific value. For data expressed in terms of mass, the factor was 0.4, as by mass almost 60% of the production in 2013 corresponded to woodchips and sawdust. By volume, the factor was around 0.5, since 50% of the volume produced was woodchips and sawdust. It is important to highlight that exergy obtained from biomass burning (from sawdust and woodchips, for instance) was still included in the analysis through the National Energy Balance [9]. It is also noticeable that some of the products in the wood derived category were not considered in the analysis, as their mass content was not expressed in the statistics available, and due to the lack of other exergy models capable of accounting for such products (Table 19).

Appendix J: Computing exergy efficiency of the RPP sector

As an example, apparent exergy efficiency related to space heating will be computed. According to the 2002 census, the most energy intensive consumption regarding households is space heating, with 56% of the energy used in this sector [29]. The national energy balance, on the other hand, states that the total energy use of the sector is 243 [PJ], which converted into exergy values using energy-exergy factors [19], gives 264 [PJ] exergy. In this fashion, exergy input specifically used in space heating is

$\mathrm{E_{in}} = 0.56 \times \mathrm{E_{RPP}}$	(29)
$\mathrm{E_{in}} = 0.56 \times 264\ [\mathrm{PJ}] = 148\ [\mathrm{PJ}]$	(30)

On the other hand, it was assumed that sector's structure (i.e., the appliances and other equipment used in households), is similar to that of Norway in 2000 [30]. Thus, an average exergy efficiency for each end-use can be estimated based on the type of machinery that is most often used. For instance, for space heating, Ertesvåg estimated an average exergy efficiency of 6% [30]. Therefore, the apparent output of exergy using this average efficiency is given by Equation (*31*)

$\mathrm{Ex_{out}} = \mathrm{Ex_{in}} \times \psi_{\mathrm{i}}$	(31)

Where ψ_{i} is the exergy efficiency of the i-th end use, $\mathrm{Ex_{out}}$ is the apparent exergy output of the i-th end use, and $\mathrm{Ex_{in}}$ is the exergy input to the i-th end use. Thus, replacing the abovementioned figures, the apparent exergy output is given by

$\mathrm{Ex_{out}} = 148\ [\mathrm{PJ}] \times 6\%$	(32)
$\mathrm{Ex_{out}} = 9\ [\mathrm{PJ}]$	(33)

This result is shown on Figure 22. To obtain the sector's efficiency, the previously described methodology must be repeated for all end uses as to obtain the total apparent exergy output, and therefore, the sector's efficiency. Alternatively, as this methodology is independent of the exergy input, a weighted average of the end use efficiencies can be computed, where the coefficient for each efficiency is the percentage of energy that the end use represents. Mathematically, this is expressed in Equation (*34*)

$\psi_{\mathrm{RPP}} = \sum_{\mathrm{i} \in \text{ end-uses}} \mathrm{x_i}\, \psi_{\mathrm{i}}$	(34)

Where $\mathrm{x_i}$ is the fraction of energy used by the i-th end use relative to the total energy input, and ψ_{i} is the exergy efficiency of the i-th end used according to Ertesvåg [30].