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PRIMARY EXERGY COST OF GOODS AND SERVICES: AN INPUT - OUTPUT APPROACH

Doctoral Dissertation of:
Matteo Vincenzo Rocco

Supervisor:
Prof. Emanuela Colombo

Tutor:
Prof. Fabio Inzoli

The Chair of the Doctoral Program:
Prof. Carlo Bottani

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«Il vero output del processo economico non è un efflusso fisico di spreco, ma il godimento della vita.»

Nicholas Georgescu–Roegen
Analytical Economics: Issues and Problems, 1966

Ai miei nonni

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Contents

Nomenclature

Note about the adopted notation

a, A, a, A	scalars;
$\boldsymbol{a}, \boldsymbol{A}$, **a**, **A**	vectors, matrices;
$\mathbf{i}, \mathbf{i}(n \times m)$	vector of 1s, with n rows and m columns;
$\mathbf{I}, \mathbf{I}_{\boldsymbol{n}}$	identity matrix of order *n*;
$\mathbf{0}(n \times m)$	$n \times m$ empty matrix;
$diag(\mathbf{a}), \hat{\mathbf{a}}$	diagonal matrix, with elements of the **a** vector as diagonal elements;
$\mathbf{a}^{\mathrm{T}}, \mathbf{A}^{\mathrm{T}}$	transposed vector and matrix;
$\mathbf{A}^{-1}$	inverse matrix;
$a, \bar{a}$	per mass unit, per mole unit;
$row_i(\mathbf{A})$	identify the *i*th row of matrix **A**
$column_i(\mathbf{A})$	identify the *i*th column of matrix **A**

Symbols

$\mathrm{e_i}$, E	exports (for *i*th sector and total) [€]
$\mathrm{f_i}$, **f**	final demand of the *i*th process, final demand vector
$\mathrm{g_i}$, G, g	government purchases (for *i*th sector and total) [€], gravity acceleration [9,81 m/s^2]
$\mathrm{h_i}$, H	household purchases (for *i*th sector and total) [€]
$\mathrm{i_i}$, I	purchases for private investment purposes (for *i*th sector and total) [€]
$\mathrm{l_i}$, L	payments for labor compensation (for *i*th sector and total) [€]
$\mathrm{m_i}$, M	imported products (for *i*th sector and total) [€]
$\mathrm{n_i}$, N	government expenses and other minor voices (for *i*th sector and total) [€]
$\mathrm{r_i}$, **r**, **R**	exogenous resource of the *i*th sector, exogenous resources vector and matrix
$\mathrm{w_i}$, **w**	waste of the *i*th sector, waste vector
$\mathrm{x_i}$, $\mathrm{x_{ii}}$, **x**	total product of *i*th process, product from *i*th to *j*th, total production vector
$\mathbf{E_{NS}}$, $\mathbf{E_{SN}}$	upstream cutoff matrix, downstream cutoff matrix
C_i, **C**	total resources cost of the *i*th process, total exogenous resources cost matrix
$\dot{Q}$, Q	heat rate [*W*], heat [*J*]
c_i, **c**	specific resources cost of the *i*th process, specific exogenous resources cost matrix
c_p, c_v	isobaric heat capacity [*J/kgK*], isochoric heat capacity [*J/kgK*]
k_i	resources consumption of the *i*th process
$\dot{m}$, $\dot{n}$	mass flow rate [*kg/s*], molar flow rate [*mol/s*]
η_{ex}	exergy functional efficiency
ψ	junction ratio
ρ	residues production coefficient
a, **A**	technical coefficient, technical coefficients matrix
b, **B**	input coefficient, input matrix
g, **G**	waste generation coefficient, waste generation matrix
h, $\mathbf{h_W}$	hours [*h*], working hours requirements vector,
h, $\dot{H}$, H	specific enthalpy [*J/kg*], enthalpy rate [*W*], enthalpy [*J*]
i	summation vector
l, **L**	Leontief coefficient (multiplier), Leontief inverse matrix
M2	monetary circulation [€]

n	number of productive processes [-]
p	pressure [Pa]
R	Universal gas constant [8,314 *J/kmolK*]
t, T	time [s], temperature [K]
V	volume [m^3]
v, **v**	value added [€], value added vector
w, $\dot{W}$, W	velocity [*m/s*], work rate [W], work [J]
X	total outlays of the nation [€]
y	mass fraction [*g/g*]
z	elevation [m]
Z	transaction matrix
HV	Heating Value [*J/kg*]
e, $\dot{E}$, E	specific energy [*J/kg*], power [W], energy [J]
ee, $\dot{EE}$, EE	specific extended exergy [*J/…*], extended exergy rate [W], extended exergy [J]
ex, $\dot{Ex}$, Ex	specific exergy [*J/kg*], exergy rate [W], exergy [J]
g, $\dot{G}$, G	specific Gibbs function [*J/kg*], Gibbs function [W], Gibbs function [J]
s, $\dot{S}$, S	specific entropy [*J/kgK*], entropy rate [*W/K*], entropy [*J/K*]
x	mole fraction [*mol/mol*]
β	Szargut factor [-]
$\lambda(\mathbf{A})$	eigenvalues of matrix **A**
μ	chemical potential [*J/kmolK*]
ν	stoichiometric coefficient [-]
ρ	spectral radius [-]

Subscript

0	environmental state
00	dead state
B	Bioeconomic
C	closed
ch	chemical
D	destruction
D	destruction
D	direct
env	environment
ex	exergy
ext	externalities
f	final demand
gen	generation
H	hybrid, household
I	indirect
K	capitals
kn	kinetic
L	labor
L	losses
LC	life cycle
mix	mixture
N	national

O	environmental remediation
P	products
ph	physical
pt	potential
Q	heat interaction
R	reactants
rev	reversible
S	system
tot	total
W	work interaction
W	World
Wh	working hours
Z	intermediate consumption

Acronyms, abbreviations

B-ExIO	Bioeconomic Exergy based Input – Output Analysis
CEENE	Cumulative Exergy Extraction from Natural Environment
CEnC	Cumulative Energy Consumption
CExC	Cumulative Exergy Consumption
DCs	Developing countries
EEA	Extended Exergy Accounting
EGM	Entropy Generation Minimization
ELCA	Exergetic Life Cycle Assessment
EROI	Energy Return on Investment
ExIO	Exergy bases Input – Output Analysis
ExROI	Exergy Return on Investment
GDP	Gross Domestic Product
HDI	Human Development Index
H-ExIO	Hybrid Exergy bases Input – Output Analysis
HIOT	Hybrid Input – Output table
ICEC/ECEC	Industrial/Ecological Cumulative Exergy Consumption
IFIAS	International Federation of Institutes for Advanced Study
ILCD	International Reference Life Cycle Data System
IOA	Input – Output analysis
ISIC	International Standard industrial classification of economic activities
ISO	International Organization for Standardization
LC	Life Cycle
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCM	Leontief Cost Model
LExCOE	Levelized Exergy Cost of Electricity
lhs, rhs	left/right hand side
LPM	Leontief Production Model
MFA	Material Flows Analysis
MIOT	Monetary Input – Output table
MUt	Make and Use Table
NACE	Statistical Classification of Economic Activities in the European Community
NBER	National Bureau of Economic Research

PA	Process analysis
PIOT	Physical Input – Output table
SAM	Social Accounting Matrix
SETAC	Society of Environmental Toxicology and Chemistry
SNA	System of National Accounts
TA	Thermoeconomic Analysis
TEC	Thermo-Ecological Cost
TPES	Total Primary Energy Supply
WtE	Waste to Energy

Summary

The thesis is the result of three years of research in the fields of *advanced exergy analyses* and *Thermodynamic Life Cycle based methods* carried out at *Department of Energy*, *Politecnico di Milano*.

Context and motivation

Among the large multiplicity of natural resources, the class of *non-renewable primary energy-resources*, mainly fossil fuels, plays a crucial role in sustaining the human economies and their productive activities. Indeed, the prosperity and the stability of modern society is inextricably linked to the extraction and consumption of fossil fuels, and the projections clearly shows that this trend will be kept as it is for decades.
Political initiatives as well as research efforts are thus facing the issue of the increasingly scarcity of fossil fuels acting in two main directions: (1) claiming a *transition* towards alternative power sources and (2) promoting a rational use of primary fuels through the so-called *energy saving* practice. This thesis focuses on the latter, since it aims to provide a comprehensive and novel methodology to assess and to reduce the total fossil fuels requirements due to production of goods and service.

Emerging needs in Environmental Impact Analysis

In general, the purpose of the economy is the production of goods and services to satisfy the demand of human activities. Modern economies can be represented as intricate networks of productive processes connected to each other by flows of material goods, energy and nonmaterial services. Such networks are connected to natural environment, drawing natural resources and rejecting wastes. The acknowledged interdependency of the productive sectors with both the environment and the society at large makes quantitative environmental impact evaluation of goods and services a very challenging task.
Indeed, production of all the goods and services are sustained, in a both direct and indirect way, by flows of energy-resources extracted from natural environment. Therefore, environmentally conscious political and technological decisions require to know the *overall* (primary) fossil fuels requirements of individual products. From the analyst perspective, two major gaps emerge from the literature:

- *Identification of a standardized accounting method.* Consensus about the most appropriate resources cost accounting scheme is still nonexistent. Indeed, Life Cycle based methods suffer of many flaws: they are not defined in a unique and unambiguous way and they rely on extensive data collection procedures, causing large uncertainties in results and making their application expensive in terms of time and data requirements;
- *Energy-resources characterization*. Identification of one comprehensive thermodynamic-based metric for energy-resources characterization is claimed;
- *Evaluation of efficiency of energy systems in a Life Cycle perspective*. Performances evaluation of energy conversion systems by means of traditional First and Second Law indicators neglect the indirect effects linked to the consumption of non-energy related products and externalities. Novel thermodynamic based indicators are claimed to obtain useful insight for the optimization procedure;

- *Role of externalities.* Finally, the role that externalities of productive systems (and working hours requirements among others) plays in primary resources consumption need to be deepened and clarified.

Objectives of the research

The general objective of the research is the *development of a resource accounting method for the evaluation of non-renewable primary energy-resources (i.e. fossil fuels) requirements of any product of a given economy*. Specific objectives of the research stem from the emerging issues highlighted by the literature review:

1. The method should be formalized in order to allow *reproducible, reliable* and *accurate* resource accountings in a *fast* and *simple* way;
2. The proposed approach should account for primary fossil fuels requirements through one *suited thermodynamic based indicator*;
3. The method should be able to analyze *energy conversion systems* in detail, proposing a set of indicators useful for optimization purposes;
4. The method should clarify and quantify the role that *working hours* requirements due to goods and services production has on primary fossil fuels consumption.

Achievements of the research

The general objective of the research has been reached through the definition and the formalization of the *Exergy based Input – Output framework* (ExIO). The proposed method aims at integrating traditional *Input-Output analysis* and *Exergy analysis* into one comprehensive method for the thermodynamic system analysis and optimization in a Life Cycle perspective.
The main features of the developed framework are aimed at dealing with the specific objectives previously introduced:

1. The mathematical formulation of ExIO is based on *Input – Output analysis*, which allows to define standardized time and space boundaries for any analyzed system or product, encompassing its whole Life Cycle. The approach relies on standard and freely available data sources, avoiding extensive data mining processes and making the application of the analysis simpler and faster than traditional *process based* LCA. Moreover, accuracy of results can be selectively increased through the *Hybrid-ExIO approach*, which allows to evaluate the primary fossil fuels requirements of detailed products;
2. *Exergy* is assumed by ExIO as the best suited thermodynamic based metric for fossil fuels characterization and for energy conversion systems analysis;
3. The application of a modified version of the Hybrid-ExIO approach allows to analyze energy conversion systems, leading to the definition of quantitative criteria and suited indicators in order to *identify* and to *optimize* the primary fossil fuels requirements of system's products in a LC perspective;
4. The *Bioeconomic ExIO model* has been proposed as a *partially closed* Input – Output model to account for the effect that *working hours* requirements due to goods and services production have on primary fossil fuels consumption.

Advantages and drawbacks of ExIO framework have been highlighted and discussed. Finally, the method has been applied to different case studies: (1) analysis of goods and services produced by national economies, (2) Thermoeconomic analysis of a Waste to Energy power plant and a (3) comparative evaluation of cleaning dishes by hand washing and dishwasher.

1.
Introduction

This chapter aims at clarifying the concept of *Natural Resources*, providing a first classifications and highlighting the relevance that non-renewable energy-resources have in the Economic process. The emerging needs of resource accounting methods are finally identified.

1.1. Role of Natural Resources in the Economic Process

Natural resources can be defined as all the goods and services provided by nature that are useful in order to sustain human economic systems. Economic production consists the transformation of such natural resources into something of values for humans, that is, something that creates welfare, quality of life, utility of whatever else provide us satisfaction. All the productive processes, even the production of immaterial services, require raw resources to sustain their production, and inevitably generate wastes.

In last decades, many scientists argued that the nature of economic and biological processes are similar: the human economy can be productive and satisfy human needs *only* by transforming available raw materials and energy into unavailable flows of waste [30, 71, 72, 125]. However, Traditional economic paradigms have not paid much attention to the physical roots of economic production, according to the assumption that the biophysical world do not constrain the development of the economic system [43].

The issues of natural resource scarcity and the environmental effects of resources exploitation lead both public opinion and policymakers in recognize that the growth of modern economies is physically constrained [30, 38, 40]. Therefore, attention to thermodynamic limits on the economy, indeed to the *entropic* nature of the economy, is now critical, as first emphasized by *Nicolas Georgescu-Roegen* is his *The Entropy law and the Economic Process* (1971) [8, 125]. Nowadays, efficiency in resources use become one of the main goal of political initiatives such as the *European 2020 strategy* [1].

1.1.1. Primary and secondary factors of production

Since natural resources are directly harvested from nature, literature usually refers to them as the *primary factors of production* or *natural capital*. The following general classification can be found in literature [30, 43]:

- *Fossil fuels.* Raw coal, crude oil, natural gas and nuclear fuels are part of this category. All of these fuels are classified as non-renewables, since the rate of its extraction by the world economies results faster than the rate at which they are reproduced by natural processes. Our modern societies are strongly dependent on this fixed stock of energy, and the quantification of its total amount is extremely difficult;
- *Mineral resources.* Are represented by the highly concentrated stocks of metals and minerals ores in the Earth crust. They are classified as non-renewable resources, because even if they can be recycled, it has been demonstrated that 100% recycling is theoretically impossible;

- *Water*. In contrast to fossils, minerals and metals stocks, many water resources are renewable as a result of the hydrologic cycle.
- *Land*. It is defined as the soil that supports physical human infrastructures and soil that can be used for agriculture;
- *Solar energy*. This category encompasses solar radiation as well as its derivatives, such as kinetic energy of the wind, potential energy of water and biomass. Obviously, solar energy is defined as renewable.

Based on their physical and chemical qualities, material resources *consumption* can be classified in two sub-categories: resource *use* or *depletion*. A resource is said to be *used* if it is possible to reuse it again after the consumption process: mineral resources, water and land are often part of this category. On the other hand, if the consumption of a resource imply a radical change of its chemical and physical properties, as for the combustion process of fossil fuels, resources are said to be *depleted* [8].

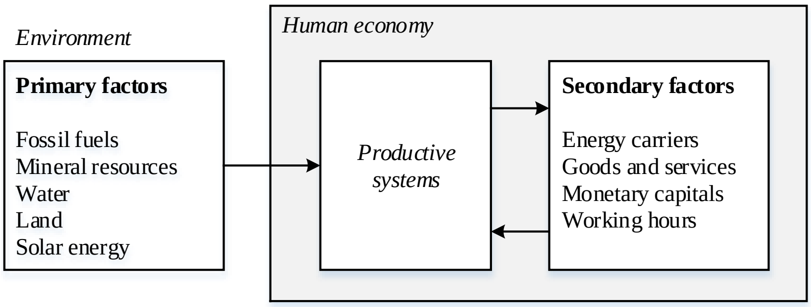

Figure 1. *Distinction among Primary and Secondary factors of production*.

Natural resources sustain economic production, allowing to produce *energy carriers*, *goods*, *services*, *monetary capitals* and *labor* (*working hours*): since also these products are essential for economic production, they can be simultaneously considered as input and output of the human economy, as depicted in Figure 1. For such reason, these contributions are here defined as the *secondary factors of production*. The distinction among primary and secondary factors of production is crucial for the development of primary resource accounting methods and will be very useful in further chapters.

1.1.2. A focus on non-renewable energy-resources

The crucial role of energy in modern economic activities is undeniable [216]. Indeed, the production of economies and the requirements of energy are strictly related, as showed in Figure 2, where the trends of the World's *Gross Domestic Product* (GDP) and *Total Primary Energy Supply* (TPES) per capita in the period 1971-2011 are compared. Already in 1933, *Soddy* wrote:

> *«If we have available energy, we may maintain life and produce every material requisite necessary. That is why the flow of energy should be the primary concern of economics.»* [36, 216].

Based on IEA data, fossil fuels provide more than 75% of the total world energy consumption: as stated by *Odum*, the prosperity and stability of modern societies are then inextricably linked to the production and consumption of fossils, mainly *raw coal*, *crude oil* and *natural gas* [82, 139].

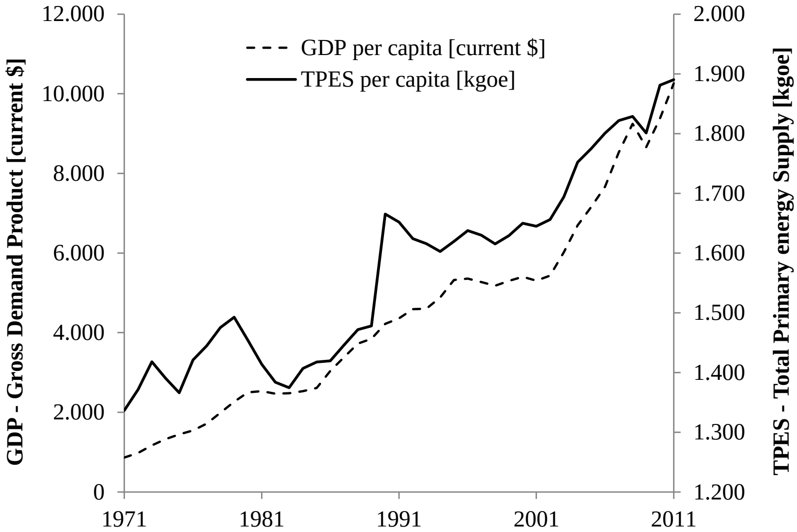

Figure 2. *Trend of Gross Domestic Production per capita (GDP) and Total Primary Energy Supply per capita (TPES) for the World in the period 1971-2011 (IEA data).*

Two main issues are connected with depletion of fossil fuels: *scarcity* and *emissions*.

- *Scarcity*. Since stocks of fossil fuels are finite, the depletion of the presently known global resources which are economically available will probably become reality sometime in the current century [9, 37, 43, 125];
- *Emissions*. Extraction, refinements and combustion of fossil fuels cause emissions of greenhouse gases (mainly CO_2) and pollutants. Emissions due to hydrocarbons are dangerous for the health of humans and ecosystems, and they represent a contribution in raising up the concentration of greenhouse gases in the atmosphere [161].

Political initiatives as well as research efforts are thus facing these issues acting in two main directions: (1) claiming a *transition* towards alternative power sources and (2) promoting a rational use of fossil fuels through the so-called *energy saving* practice. This study focuses on the *second* objective by considering economic and human activities from a *physical* perspective: it aims to provide a comprehensive and novel methodology to assess and to reduce the total fossil fuels requirements due to production of goods and service.

1.2. Emerging needs in Environmental Impact Analysis

Traditionally, increase of the energy efficiency of productive systems was driven by the search for the attainment of the maximum useful product with the minimum consumption of energy-resources. Until recently, the evaluation of the energy-resources consumption of productive systems encompasses the energy flows that are *directly* absorbed by the system under consideration during its operating life.

Today, the concept of energy-resources consumption is undergoing a radical re-evaluation, in response to the acknowledged interdependency of the productive sectors with both the environment

and the society at large. Indeed, all the production processes of modern economies are sustained, in a both direct and indirect way, by flows of fossil fuels extracted from natural environment. Therefore, it can be said that all the goods and services produced within a given economy are characterized by a *primary energy-resources cost* (also called *cumulative*, *primary* or *embodied* cost), which is defined in this thesis as the *direct* and *indirect* amount of primary fossil fuels required to deliver the considered products.
Environmentally conscious political and technological decisions require to know their total effects in terms of primary fossil fuels requirements: literature clearly states that without a proper evaluation of the *overall* resource consumption of one specific productive system, capable to include also the indirect supply chains requirements, misleading results may be obtained. For this reason, many efforts are focused on the definition of methods to account for the overall fossil fuels contribution to individual products. From the analyst perspective, two major issues emerge from the literature:

- *Identification of a standardized accounting method.* Although several methods have been proposed, consensus about the most appropriate resources cost accounting scheme is still nonexistent. Indeed, Life Cycle (LC) methods are often based on arbitrary assumptions and are not defined in a unique and unambiguous way, making results of different analysis of a same system hardly comparable. Moreover, such methods relies on extensive data collection procedures, making their application very expensive in terms of time and data requirements;
- *Energy-resources characterization*. Identification of one comprehensive thermodynamic-based metric for energy-resources characterization is claimed;
- *Evaluation of efficiency of energy systems in a Life Cycle perspective*. Performances evaluation of energy conversion systems by means of traditional First and Second Law indicators neglect the indirect effects linked to the consumption of non-energy related products and externalities. Novel thermodynamic based indicators are claimed to obtain useful insight for the optimization procedure;
- *Role of externalities.* Finally, the role that externalities of productive systems (and working hours requirements among others) plays in primary resources consumption need to be deepened and clarified.

In order to overcome these limitations, literature claims to *deepen system analysis and resources cost accounting methodologies* and to *define methods and criteria for primary energy-resources cost assessment suited for analysis and optimization of energy conversion systems.*

1.3. Objectives of the research

The general objective of the research is the *development of a resource accounting method for the evaluation of primary energy-resources (i.e. fossil fuels) requirements of any product of a given economy*.
With reference to the issues emerging from the literature above introduced, specific objectives of the research are defined as follows:

1. The method should be formalized in order to allow *reproducible, reliable* and *accurate* resource accountings in a *fast* and *simple* way;
2. The proposed approach should account for primary fossil fuels requirements through one *suited thermodynamic based indicator*;

3. The method should be able to analyze *energy conversion systems* in detail, proposing a set of indicators useful for optimization purposes;
4. The method should clarify and quantify the role that *working hours* requirements due to goods and services production has on primary fossil fuels consumption.

Considering the needs emerging from the literature, the first, second and fourth objectives are aimed at identifying one unique resources accounting method, whereas the third objective is related to the performance evaluation of energy conversion systems.
The research lies in the broad disciplines of *Industrial Ecology*, *Thermodynamics*, *Environmental* and *Economics sciences*. Specifically, it deepen the topics of *Thermoeconomic Analyses*, *Life Cycle Assessment* (LCA) and *Input-Output Analysis* (IOA).

1.4. Structure of the thesis

After the brief overview about the concept of natural resources and their role in the economic process provided in this chapter, the above introduced objectives are faced by the thesis according to the following structure:

- **Chapter 2**. This chapter presents the state of the art of cost accounting techniques: mathematical structure of *Input – Output analysis* (IOA) and *Process Analysis* (PA) are formalized for a generic productive system, compared and finally discussed. What emerges from this chapter is that any cost accounting problem may be described in a more efficient, simple and standardized way through IOA rather than using PA.
- **Chapter 3**. A critical literature review about the *Thermodynamic based methods for system analysis* is provided. *Energy*, *Entropy* and *Exergy* based Life Cycle methods are comparatively analyzed and a taxonomy is proposed. Finally, the use of such metrics for energy-resources characterization is discussed. What emerges from this chapter is that: (1) exergy is widely considered as the most suited numeraire to account for energy-resources consumption; (2) exergy based LC methods require further methodological improvements.
- **Chapter 4**. This chapter is the core of the research activity: it merges the cost accounting technique of IOA with the concept of exergy, formalizing the *Exergy based Input Output analysis* (ExIO). This method allows to evaluate the primary exergy cost of goods and services produced by a specific national economy. The method relies on *Monetary Input – Output Tables* (MIOTs) of national economies as standardized and constantly updated data source. The main methodological achievements of this chapter can be summarized as follows:

  - Complete formalization of ExIO method is proposed. Specifically, three different techniques are proposed to account for imported products in national MIOTs;
  - The *Hybrid ExIO* approach is proposed and formalized in order to increase the accuracy of results obtained through the use of standard ExIO analysis and to perform Life Cycle Assessment of detailed products;
  - Hybrid ExIO approach is adapted in order to perform Thermoeconomic analysis and Design Evaluation of energy conversion systems.

- **Chapter 5.** Among all the secondary factors of production, listed in Figure 1, the role of human labor is the most controversial issues in Environmental Impact Analysis. For such reason, it is here investigated. The *Bioeconomic ExIO model* is proposed and formalized to account for the effects that working hours consumption has on the primary exergy cost of goods and services.

- **Chapter 6.** The ExIO framework is applied to the following case studies: (1) evaluation of primary exergy cost of goods and services produced by different *national economies*; (2) application of Hybrid ExIO model for Thermoeconomic analysis and Design Evaluation of an Italian *Waste to Energy power plant* in a Life Cycle perspective; (3) application of standard and Bioeconomic ExIO analyses to compare the primary exergy costs of *manual dishwashing* and *dishwasher*.

Finally, conclusions of the thesis remark its main achievements and also gives a perspective about the future possible research paths.

2.
Energy-resources cost accounting techniques: a critical review

Development of practical approaches for the evaluation of environmental impact due to goods and services production is one of the most relevant and debated topic of Industrial Ecology. As highlighted in the previous chapter, this thesis focuses on the evaluation of the natural energy-resources consumption, assumed as a partial indicator for environmental impact.
According to literature, one of the major issues in the field of resources accounting methods is related to the definition of a comprehensive and unified cost accounting mathematical scheme. This chapter introduces two cost accounting schemes, widely adopted in literature: *Input – Output analysis* and *Process analysis.* The analytical structure of each approach is formalized and a comparative assessment is performed.

2.1. Introduction to resources accounting

All economic and human activities require natural resources: the production of one generic good or service (e.g. 1 kWh of electric energy, 1 kg of bread, 100 € of insurance policy and so on) may absorb primary resources *directly* from the environment but also *indirectly*, by consuming other goods and services that need to be produced, transported and traded, causing additional direct resources consumption.
Practical evaluation of total resources consumption requires to know and to characterize all the production processes that are part of the supply chain of the considered product. In order to perform such task, three fundamental steps are needed:

1. **Resources.** The kind of resources need to be accounted for must be defined. As stated in chapter 1, this thesis work focuses on non-renewable energy-resources in the form of crude oil, raw coal and natural gas. However, the resources accounting schemes may be adopted to evaluate any kind of resources consumption: water, soil, materials, and so on;
2. **Spatial domain.** Definition of the physical boundaries of the analyzed system is required;
3. **Temporal domain.** Definition of the considered time extension (production, use, disposal of the analyzed product);

Since definition of spatial and temporal domains depends on the choices of the analyst, a unified resource accounting method need to be defined to avoid arbitrariness in the evaluation of resources consumption and to make results of different analysis of a same product comparable to each other.

2.1.1. Main definitions: resources consumption, cost and primary cost

Description of resources accounting techniques requires the introduction of some basic definitions, according to Figure 3. Given a reference time window, say a year, the object of the analysis (either a good or a service) is defined as *final demand* f_i (also called *target product* or *functional unit*), produced by a *productive system* (shaded area in Figure 3), composed by one or more *productive processes* (also called *unit processes*). The amount of products exchanged between *j*th and *i*th process within the considered productive system is defined as *intermediate product* x_{ji}. Productive systems absorb *exogenous resources* r from other productive processes, defined outside system boundaries, or directly taken from environment.

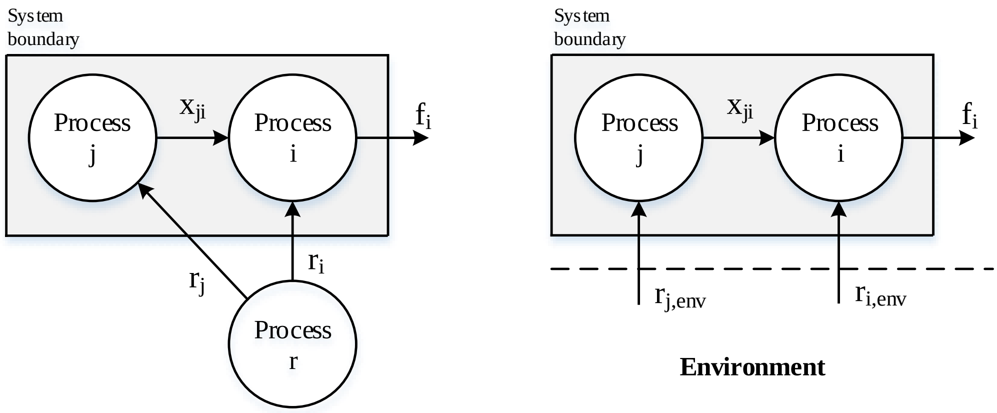

Figure 3. *Productive system fed by resources produced by other processes (left) and fed by primary resources (right).*

In this perspective, the objective of the cost accounting method consists in the evaluation of the amount of exogenous resources allocated on the production of the final demand.
Resources consumption of the *i*th process is defined as the ratio between the exogenous resources r_i and the final demand f_i respectively absorbed and produced by *i*th process, that is,

$$k_i = r_i / f_i \tag{2.1}$$

Resources cost of *i*th process is defined as the ratio between the *total* exogenous resources absorbed *directly* (r_i) and *indirectly* (r_j) by *i*th process and the final demand, as is relation (2.2). If direct and indirect resources contributions are taken from the environment (i.e. they are not products of any previous production process), the *primary resources cost* of *i*th process (also called *embodied*, *cumulative* or *grey* requirements) is defined as follows.

$$c_i = \left(r_i + r_j\right) / f_i \tag{2.2}$$

$$c_{env,i} = \left(r_{env,i} + r_{env,j}\right) / f_i \tag{2.3}$$

It is worth notice that both the input and the output of every production process have to be defined as *one* single kind of product measured with *one* specific *metric*, and that both physical and monetary units can be adopted (*kWh, kg, units, €* and so on). Moreover, literature refers to the metric of exogenous resources as the *numeraire* [137, 151, 208, 220, 221].
Evaluation of resources consumption, cost and primary cost of the final demand produced by the simple systems given in Figure 3 is straightforward. However, real productive systems are usually composed by a very large number of production processes linked to each other, making the identification of indirect contributions a very complex task.
In this perspective, unified rules for the definition of system boundaries and defined cost accounting mathematical schemes are required.

2.1.2. Life Cycle Assessment framework

Consumption of natural resources is closely connected with economic and environmental problems by the intricate nets of processes by which the modern economy transforms, uses and disposes the inputs and outputs of the production system. Therefore, understanding the structure of the economy that governs flows of primary and secondary factors of production between producing industries and consuming households is indispensable for solving the problems of both limited resources availability and pollution [171]. To face these issues, *Life Cycle Assessment* (LCA) emerges as a branch of the broad discipline of *Environmental Impact Analysis*.
The concept of LCA originated in early 1970s, when the issues related to energy efficiency of systems and the consumption of scarce raw materials become relevant, in order to provide a unified framework for the evaluation of the total environmental burdens linked to human activities. In 90s, *Society of Environmental Toxicology and Chemistry* (SETAC) started to define formal guidelines for environmental assessment of products, in order to:

- Provide complete and clear picture about the interaction between system and environment;
- Contribute to the understanding of th overall and interdependent nature of the environmental consequences of human activities;
- Provide information to decision-makers which defines the environmental effects of these activities and identifies opportunities for environmental improvements.

After SETAC attempts to define the LCA framework, the *International Organization for Standardization* (ISO) started to handle the standardization of the methodology, publishing the standards in the 14040 series [197]. Actually, software and databases are specifically developed to perform LCA analysis, and the framework is continuously developing from both theoretical and computational viewpoint [89, 143, 173].
Given a system or a product, the LCA framework aims at evaluating all the direct and indirect environmental burdens connected with its life phases: production, use, disposal [77, 99, 108]. The main classification of environmental burdens associated to a certain final demand distinguish among *loadings* and *impacts*. Loadings are material and energy flows that cross the boundaries of the considered system and that are quantitatively measureable, whereas impacts concerns the consequences of loadings on environment or human health and are sometimes considered qualitatively [77, 81]. The assessment includes the entire life cycle of the product or activity, encompassing extracting and processing raw materials, manufacturing, distribution, use, re-use, maintenance, recycling, final disposal and all the other involved services and treatments.
Standard regulation ISO 14040 defines four step for the application of LCA [197]:

1. **Goal and Scope definition.** In the first step, objective of the analysis, functional unit, temporal and spatial extension of the system (system boundaries) are defined. Moreover, assumptions, strategies and procedures for data collection are established;
2. **Inventory analysis.** It aims at quantifying inputs and outputs that cross the previously defined boundaries: energy, raw materials, products, co-products and wastes that participate to the life cycle of the functional unit are considered and collected in this phase;
3. **Impact assessment.** In this phase, results of the inventory analysis are translated into potential environmental burdens, mainly related to resources use, human health impacts and ecological impacts [128];

4. **Results interpretation.** In this last phase, analysts are called to examine results in order to identify different options that can be undertaken in order to reduce environmental burdens. Therefore, this phase could requires to iteratively repeat one or more previous phases.

Fundamental literature about LCA reveals that all the above listed application steps require to be further developed and improved: an exhaustive survey about development and unsolved problems in LCA can be found in [56, 146].
Within the theoretical framework of LCA, the issue of primary resources accounting started to be addressed from a methodological standpoint in response to the energy price rising, growing awareness of materials scarcity and negative impact of economic production on the environment [126]. The new awareness of the negative aftermath caused by the intensive use of fossil fuels moved the focus of the system analysts from the evaluation and reduction of direct direct energy requirements to a wider perspective.
Several studies about the calculation of direct and indirect energy requirements of products were implemented during these years, and different methods were proposed. For instance, *Chapman* estimated the primary energy cost of copper, aluminum and refined oil fuels [25-27]. Over the same period, the first studies about the primary energy cost of national production were introduced by *Bullard* in [22], referring to *Hereenden* and *Tanaka* studies on the energy cost of households purchases in the U.S. economy [93]. *Bullard* and *Hereenden* quantifying the energy cost of goods and services for energy saving purpose, identifying products that required higher total energy use and proposing their substitution [23]. Almost simultaneously, *Wright* estimated the primary energy cost of British national production with a similar approach [218]. A few years later, *Costanza* and *Hereenden* tried to find interrelationships between energy cost and economic cost of goods and services trying to find evidences of the so-called *Energy Theory of Value* [36, 39, 144].
In last decades, methods for primary resources cost accounting were subjected to a refinement by *Treloar*, *Suh*, *Lenzen*, *Duchin*, *Hendrickson*, *Szargut* and other scientists [50, 52-54, 92, 168, 170, 173, 174, 177, 179, 182, 190, 191], and such accounting methods are nowadays applied in various field of economic production: buildings [63, 83, 153, 189], industrial products [116], energy systems [117], automotive systems [114], services [164], and so on.
The accounting methods described in the following represent a unified and comprehensive reformulation of the practical approaches for the application of LCA methodology. Different formalization of the same methods can be found in literature [89, 92, 103, 137, 170].

2.2. Input – Output Analysis

Input – Output Analysis (IOA) is the analytical framework originally developed in late 1930s by *Wassily Leontief* in order to analyze and to understand the interdependence of industries within a given economy [46, 118]. Because of the scientific relevance and the analytical potential of IOA, Leontief was awarded by the Nobel Prize in economics in 1973.
Since Leontief's first publications, hundreds of books and articles on input-output analysis have been published. During last decades, original IOA framework have been modified and developed in order to extend its evaluation to other fields, such as: employment and social accounting metrics associated with production activities, regional and interregional flows of products and services, environmental burdens associated to industrial activities and so on. Today, IOA is one of the most widely applied methods in both classical economics and in the field Environmental Impact Analysis [129, 168].

Although IOA is typically applied for the analysis of national economies, its theoretical formulation makes it suitable to describe and to analyze every kind of productive systems. After a brief historical overview, the Input – Output analysis (IOA) is described and formalized as a comprehensive resources cost accounting method.

2.2.1. Basic model: single production process

Recalling definitions introduced in paragraph 2.1.1, Input – Output model is here defined for a productive system formed by the generic *i*th productive process, represented in Figure 3.

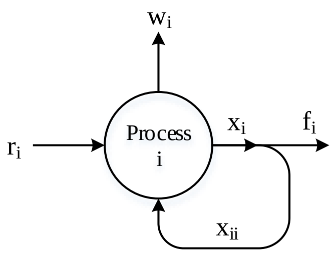

Figure 4. *Representation of a single production process.*

Given a defined time frame, the process produces a net amount of product f_i (the final demand, that is the purpose of system production) by absorbing a portion of its own product x_{ii} (intermediate consumption) and a flow of exogenous resource r_i, and releasing a flow of waste w_i.

Leontief Production Model (LPM)

The total production of *i*th process equals the sum of its intermediate consumption and its final demand, as showed by the *production balance* (2.4). The balance have to be written in one homogenous metric, say, *kg, J, units* or *monetary value*.

$$x_i = x_{ii} + f_i \tag{2.4}$$

For the purpose of IOA, *technical coefficient* (2.5) is introduced as the ratio between the input to *i*th process and its total production: it represent the *direct* input requirements to produce one unit of product. Therefore, production balance (2.4) can be rewritten as follows.

$$a_i = \frac{x_{ii}}{x_i} \tag{2.5}$$

$$x_i = a_i x_i + f_i \tag{2.6}$$

By simple algebraic handlings of (2.6), total production of *i*th process can be expressed as a function of its final demand and its technical coefficient: the *Leontief Production Model* (LPM) is derived as (2.7).

$$x_i = (1 - a_i)^{-1} f_i \tag{2.7}$$

$$l_i = (1 - a_i)^{-1} \tag{2.8}$$

The *Leontief Inverse Coefficient* (2.8), also called *Leontief Multiplier*, is the core of IO model: it represents the amount of *i*th product *directly* and *indirectly* produced to fulfill one unit of final demand.

Leontief Cost Model (LCM)

With reference to Figure 4, total production of the *i*th process invoked by the final demand and evaluated by (2.7), requires a certain amount of exogenous resources and causes waste emissions. Focusing on the exogenous resources, the *exogenous resources cost* of the final demand produced by *i*th process can be evaluated through the *Leontief Cost Model* (LCM). Usually, every system absorbs different kind of exogenous resources; therefore, different numeraires may be defined, depending on which kind of cost need to be quantified: tons of input materials, Joules of energy carriers, hectares of soil, hours of labor, and so on. Here, only *one* single exogenous resource is considered, and one specific numeraire is used.
Every unit of product out of the *i*th process has the same exogenous resources cost, so that expression (2.9) can be written: unit cost of product for final demand or intermediate consumption is obviously the same.

$$c_i = \text{constant} \tag{2.9}$$

The application of LCM to the *i*th process consists in writing the cost balance (2.10), in which the cost of total production equals the cost of intermediate consumption plus the exogenous resources directly absorbed by the process.

$$c_i \mathrm{x_i} = c_i \mathrm{x_{ii}} + \mathrm{r_i} \tag{2.10}$$

In a similar fashion of technical coefficient (2.5), the *input coefficient* (or *intervention coefficient*) (2.11) is defined as the amount of exogenous resources *directly* required to produce a unit of product.

$$b_i = \frac{\mathrm{r_i}}{\mathrm{x_i}} \tag{2.11}$$

Introducing the definition of technical coefficient (2.5) in the cost balance (2.10), and dividing both sides by total production $\mathrm{x_i}$, the following expression is obtained.

$$c_i = c_i\, a_i + b_i \tag{2.12}$$

Exogenous resources cost of the final demand is then obtained by relation (2.13), which allows to express the exogenous resources cost of the final demand as a function of both technical coefficient and input coefficient.

$$c_i = b_i \left(1 - a_i\right)^{-1} \tag{2.13}$$

Relation (2.13) is known as the *Leontief Cost Model* (LCM): it returns both *direct* and *indirect* exogenous resources requirements invoked to fulfill a unit of final demand by the *i*th process. It is worth to remark that although the specific cost is constant for every unit of process production (intermediate production or final demand), it is defined as the amount of exogenous resources needed to produce a unit of *final demand*: indeed, recalling relation (2.13), (2.5) and (2.11), the following expression can be obtained.

$$c_i = \frac{r_i}{\cancel{x_i}} \cdot \frac{\cancel{x_i}}{f_i} = \frac{r_i}{f_i} \tag{2.14}$$

Therefore, total cost of the final demand equals the total amount of exogenous resources consumed by the process, and results as the product between the specific cost and the final demand, as showed by (2.15).

$$C_i = r_i = c_i f_i \quad \rightarrow \quad C_i = r_i = b_i \left(1 - a_i\right)^{-1} f_i \tag{2.15}$$

For the sake of completeness, the cost balance (2.10) could be written if the objective is the evaluation of the cost in terms of waste emissions: introducing the *waste generation coefficient* (2.16), LCM can be then rewritten as (2.17) and (2.18).

$$g_i = \frac{w_i}{x_i} \tag{2.16}$$

$$c_i = g_i \left(1 - a_i\right)^{-1} \tag{2.17}$$

$$C_i = w_i = c_i f_i \quad \rightarrow \quad C_i = w_i = g_i \left(1 - a_i\right)^{-1} f_i \tag{2.18}$$

2.2.2. Generic system composed by *n* processes

A generic productive system can be formed by *n* productive processes, connected each other by exchanges of inputs and outputs of goods and services. Because of the presence of such endogenous interrelations, production and cost of each single productive process is dependent by the other processes and the system should be analyzed as a whole.
In this paragraph, Leontief Production and Cost Models are formalized for the application to a system formed by *n* productive processes.

Leontief Production Model (LPM)

With reference to Figure 5, it is possible to write one production balance (2.19) for each of the *n* productive processes: total production of *i*th process results as the sum of its self-consumption, the flows of its products that are required by all the other processes and the final demand. All the *i*th balances can be collected in the linear system of equations (2.20).

$$x_i = x_{i1} + \cdots + x_{ij} + \cdots + x_{in} + f_i \quad \rightarrow \quad x_i = \sum_{j=1}^{n} x_{ij} + f_i \tag{2.19}$$

$$\begin{cases} x_1 = x_{11} + \cdots + x_{1j} + \cdots + x_{1n} + f_1 \\ \vdots \\ x_i = x_{i1} + \cdots + x_{ij} + \cdots + x_{in} + f_i \\ \vdots \\ x_n = x_{n1} + \cdots + x_{nj} + \cdots + x_{nn} + f_n \end{cases} \tag{2.20}$$

System (2.20) can be represented in matrix form (2.21), defining the *total production vector* $\mathbf{x}(\mathrm{n} \times 1)$, the *transaction matrix* $\mathbf{Z}(\mathrm{n} \times \mathrm{n})$ (also known as *process-by-process matrix*) and the *final demand vector* $\mathbf{f}(\mathrm{n} \times 1)$.

$$\mathbf{x} = \mathbf{Zi} + \mathbf{f}$$
$$\begin{bmatrix} \mathrm{x}_1 \\ \vdots \\ \mathrm{x}_\mathrm{n} \end{bmatrix} = \begin{bmatrix} \mathrm{x}_{11} & \cdots & \mathrm{x}_{1\mathrm{n}} \\ \vdots & \ddots & \vdots \\ \mathrm{x}_{\mathrm{n}1} & \cdots & \mathrm{x}_{\mathrm{nn}} \end{bmatrix} \cdot \mathbf{i}(n \times 1) + \begin{bmatrix} \mathrm{f}_1 \\ \vdots \\ \mathrm{f}_\mathrm{n} \end{bmatrix} \tag{2.21}$$

In (2.21), vector $\mathbf{i}(n \times 1)$ is a column vector of n rows of 1's defined as *summation vector* [129]. Generally, to create a column vector whose elements are the row sums of one $(a \times b)$ matrix, it is necessary to post-multiply the considered matrix by the *summation column vector* $\mathbf{i}(b \times 1)$ composed by b rows of 1's. Conversely, pre-multiplication of the same matrix by the *summation row vector* $\mathbf{i}(1 \times a)$ creates a row vector whose elements are the column sums of the $(a \times b)$ matrix. Summation vector $\mathbf{i}$ is useful to express matrix operations in compact form and will be often recalled in the following.

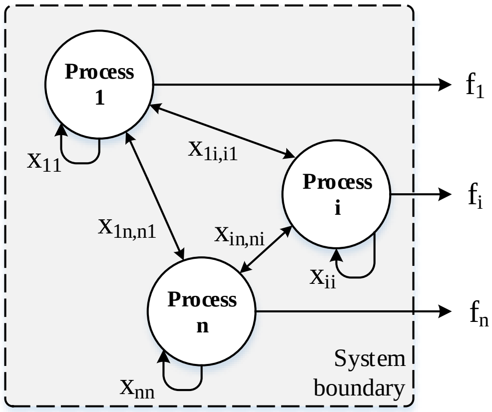

Figure 5. *Flow of inputs and outputs of a system composed by n production processes.*

For the application of LPM, *technical coefficients matrix* $\mathbf{A}(n \times n)$ is introduced as (2.22): each element represents the output flows from process *i*th to process *j*th divided by the total production of *j*th process. In (2.22), $\hat{\mathbf{x}}$ is the matrix with the elements of $\mathbf{x}$ vector at the diagonal and zero elsewhere.
Every balance of system (2.20) must be written in homogeneous units, but different balances may be written with different units. In the latter case, the technical coefficients matrix $\mathbf{A}$ results in hybrid units (*€/€*, *€/kg*, *J/€*, and so on).

$$\mathbf{A}(n \times n) = \mathbf{Z}\hat{\mathbf{x}}^{-1} \qquad \text{with:} \qquad a_{ij} = \mathrm{x}_{\mathrm{ij}} / \mathrm{x}_\mathrm{j}$$
$$\begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} = \begin{bmatrix} \mathrm{x}_{11} & \cdots & \mathrm{x}_{1\mathrm{n}} \\ \vdots & \ddots & \vdots \\ \mathrm{x}_{\mathrm{n}1} & \cdots & \mathrm{x}_{\mathrm{nn}} \end{bmatrix} \cdot \begin{bmatrix} 1/\mathrm{x}_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1/\mathrm{x}_\mathrm{n} \end{bmatrix} \tag{2.22}$$

Introducing definition (2.22), system (2.21) can be rewritten in compact form as (2.23). Accordingly, LPM can be derived in the matrix form (2.24) by simple matrices manipulations: it expresses the total production of each process as a function of technical coefficients and final demands of all the processes.

$$\mathbf{x} = \mathbf{A}\hat{\mathbf{x}}\mathbf{i} + \mathbf{f} \qquad \rightarrow \qquad \mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{f} \tag{2.23}$$

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} \tag{2.24}$$

Each element of the *Leontief inverse matrix* (2.25), also called *total requirements matrix*, represents both the *direct* and *indirect* amount of *i*th product required from *j*th process in order to provide one unit of its final demand [129].

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \tag{2.25}$$

Leontief Cost Model (LCM)

The application of LCM to the system given in Figure 5 requires all the *n* processes to be characterized in terms of exogenous resources or waste emissions, as showed in Figure 6. In the following, LCM is formalized for the application to a system that absorbs *m* kind of exogenous resources releasing *s* kind of wastes. Notice that several kind of exogenous resources and wastes may enter/exit each process.

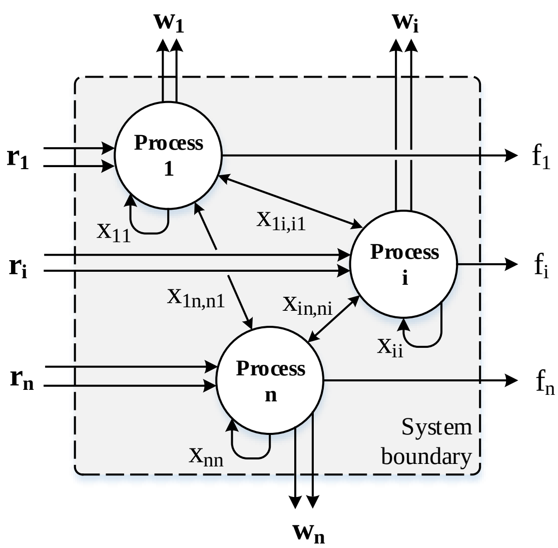

Figure 6. *Flows of inputs and outputs of a system composed by multiple production processes.*

The approach for the evaluation of exogenous resources cost results by collecting *n* cost balances (2.26) into *k* systems of linear equations (2.27), where the subscript *k* refers to the *k*th type of exogenous resource, e.g. energy, materials, working hours, soil, and so on.
For every defined *k*th exogenous resource, every *i*th balance expresses the total cost of *i*th production as the sum of all the cost of inputs to *i*th process (self-consumption and all the other intermediate products consumption) plus the exogenous resources directly absorbed by the process.

$$c_{ki}\mathrm{x}_{\mathrm{i}} = c_{k1}\mathrm{x}_{1\mathrm{i}} + \cdots + c_{kj}\mathrm{x}_{\mathrm{ji}} + \cdots + c_{kn}\mathrm{x}_{\mathrm{ni}} + \mathrm{r}_{\mathrm{ki}} \qquad \rightarrow \qquad c_{ki}\mathrm{x}_{\mathrm{i}} = \sum_{j=1}^{n} c_{kj}\mathrm{x}_{\mathrm{ji}} + \mathrm{r}_{\mathrm{ki}} \tag{2.26}$$

$$\begin{cases} c_{k1}\mathrm{x}_1 = c_{k1}\mathrm{x}_{11} + \cdots + c_{ki}\mathrm{x}_{\mathrm{i}1} + \cdots + c_{kn}\mathrm{x}_{\mathrm{n}1} + \mathrm{r}_{\mathrm{k}1} \\ \vdots \\ c_{ki}\mathrm{x}_{\mathrm{i}} = c_{k1}\mathrm{x}_{1\mathrm{i}} + \cdots + c_{ki}\mathrm{x}_{\mathrm{ii}} + \cdots + c_{kn}\mathrm{x}_{\mathrm{ni}} + \mathrm{r}_{\mathrm{ki}} \\ \vdots \\ c_{kn}\mathrm{x}_{\mathrm{n}} = c_{k1}\mathrm{x}_{1\mathrm{n}} + \cdots + c_{ki}\mathrm{x}_{\mathrm{in}} + \cdots + c_{kn}\mathrm{x}_{\mathrm{nn}} + \mathrm{r}_{\mathrm{kn}} \end{cases} \tag{2.27}$$

As previously introduced by (2.9), every unit of product out of the *i*th process has the same exogenous resources cost: here, for every defined *k*th external resource and for every single *i*th process, the unit cost of product is also constant and results in (2.28).

$$c_{ki} = \text{constant} \tag{2.28}$$

All the exogenous resources inputs are collected in the *exogenous resource matrix* $\mathbf{R}(m \times n)$ (2.29), which represents all the transactions occurring across system boundaries. Every line of matrix **R** is expressed in homogeneous units (*J*, *hours*, *kg*, etc.), and it represents the amount of exogenous resources directly absorbed by each process. Conversely, every column of matrix **R** represents all the different kind of exogenous resources that feed one specific *i*th process.
Notice that, depending on the definition of system's boundaries, these exogenous resources can be *primary* or *secondary* factors of production, according to the classification proposed in chapter 1 (Figure 1).

$$\mathbf{R}(m \times n) = \begin{bmatrix} \underset{\mathrm{m}\times 1}{\mathbf{r_1}} & \cdots & \underset{\mathrm{m}\times 1}{\mathbf{r_n}} \end{bmatrix} \quad \rightarrow \quad \mathbf{R}(m \times n) = \begin{bmatrix} \mathrm{r}_{11} & \cdots & \mathrm{r}_{1\mathrm{n}} \\ \vdots & \ddots & \vdots \\ \mathrm{r}_{\mathrm{m}1} & \cdots & \mathrm{r}_{\mathrm{mn}} \end{bmatrix} \begin{matrix} \text{energy} \\ \text{working hours} \\ \ldots \end{matrix} \tag{2.29}$$

To express the system (2.27) in matrix form, *specific* and *total exogenous resources cost matrices* $\mathbf{c}(n \times m)$ and $\mathbf{C}(n \times m)$ are introduced as (2.30), where each element c_{ij} and C_{ij} represents respectively specific and total costs expressed in terms of the *j*th exogenous resource needed to produce the *i*th unit of final demand.

$$\mathbf{c}(n \times m) = \begin{bmatrix} c_{11} & \cdots & c_{1m} \\ \vdots & \ddots & \vdots \\ c_{n1} & \cdots & c_{nm} \end{bmatrix} \quad ; \quad \mathbf{C}(n \times m) = \begin{bmatrix} C_{11} & \cdots & C_{1m} \\ \vdots & \ddots & \vdots \\ C_{n1} & \cdots & C_{nm} \end{bmatrix} \tag{2.30}$$

According to the above introduced definitions, the system of equation (2.27) can be rewritten in matrix form as (2.31).

$$\hat{\mathbf{x}}\mathbf{c} = \mathbf{Z}^{\mathrm{T}}\mathbf{c} + \mathbf{R}^{\mathrm{T}} \tag{2.31}$$

For the application of LCM, technical coefficient matrix (2.22) is recalled and *intervention matrix* $\mathbf{B}(m \times n)$ (also called *input matrix*) is defined as (2.32). Elements of **B** represent the amount of the *k*th exogenous resource directly required for the production of one unit of *j*th product.

$$\mathbf{B}(m\times n)=\mathbf{R}\hat{\mathbf{x}}^{-1} \qquad \text{with:} \qquad b_{kj}=\mathrm{r}_{\mathrm{kj}}/\mathrm{x}_{\mathrm{j}}$$

$$\begin{bmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{m1} & \cdots & b_{mn} \end{bmatrix} = \begin{bmatrix} \mathrm{r}_{11} & \cdots & \mathrm{r}_{1n} \\ \vdots & \ddots & \vdots \\ \mathrm{r}_{m1} & \cdots & \mathrm{r}_{mn} \end{bmatrix} \cdot \begin{bmatrix} 1/\mathrm{x}_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1/\mathrm{x}_n \end{bmatrix} \tag{2.32}$$

Recalling definitions (2.22) and (2.32), it is possible to express the cost balance (2.31) as a function of technical coefficients matrix and input matrix.

$$\hat{\mathbf{x}}\mathbf{c}=\hat{\mathbf{x}}\mathbf{A}^{\mathrm{T}}\mathbf{c}+\hat{\mathbf{x}}\mathbf{B}^{\mathrm{T}} \tag{2.33}$$

Pre-multiplication of both sides of the system (2.33) by the inverse of the diagonalized total production vector **x** results as follows.

$$\hat{\mathbf{x}}^{-1}\hat{\mathbf{x}}\mathbf{c}=\hat{\mathbf{x}}^{-1}\hat{\mathbf{x}}\mathbf{A}^{\mathrm{T}}\mathbf{c}+\hat{\mathbf{x}}^{-1}\hat{\mathbf{x}}\mathbf{B}^{\mathrm{T}} \quad \rightarrow \quad \mathbf{c}=\mathbf{A}^{\mathrm{T}}\mathbf{c}+\mathbf{B}^{\mathrm{T}} \tag{2.34}$$

To obtain expression (2.33) and (2.34), the following matrix properties need to be recalled:

- Given two generic matrices $\mathbf{X}(\mathrm{n}\times\mathrm{m})$ and $\mathbf{Y}(\mathrm{m}\times\mathrm{r})$, transposition of their product equals the product of the two transposed matrices as follows: $(\mathbf{XY})^{\mathrm{T}}=\mathbf{Y}^{\mathrm{T}}\mathbf{X}^{\mathrm{T}}$
- Given an invertible square matrix **X**, the following identity holds: $\mathbf{XX}^{-1}=\mathbf{X}^{-1}\mathbf{X}=\mathbf{I}_{\mathrm{n}}$
- Given an invertible square matrix **X**, the following identity holds: $(\mathbf{X}^{\mathrm{T}})^{-1}=(\mathbf{X}^{-1})^{\mathrm{T}}$

LCM is finally obtained manipulating expression (2.34): specific costs of each product represent both the _*direct*_ and _*indirect*_ exogenous resources contributions required to fulfill a unit of final demand.

$$\mathbf{I}\mathbf{c}-\mathbf{A}^{\mathrm{T}}\mathbf{c}=\mathbf{B}^{\mathrm{T}} \quad \rightarrow \quad \mathbf{c}=\left(\mathbf{I}-\mathbf{A}^{\mathrm{T}}\right)^{-1}\mathbf{B}^{\mathrm{T}} \quad \rightarrow \quad \mathbf{c}=\left[\left(\mathbf{I}-\mathbf{A}\right)^{-1}\right]^{\mathrm{T}}\mathbf{B}^{\mathrm{T}} \tag{2.35}$$

Therefore, specific and total costs of the final demand can be expressed in compact form as follows, recalling definition of Leontief Inverse matrix (2.25).

$$\mathbf{c}=\left(\mathbf{BL}\right)^{\mathrm{T}} \tag{2.36}$$

$$\mathbf{C}=\hat{\mathbf{f}}\,\mathbf{c} \quad \rightarrow \quad \mathbf{C}=\hat{\mathbf{f}}\left(\mathbf{BL}\right)^{\mathrm{T}} \tag{2.37}$$

Notice that elements of total cost matrix **C** obviously differs from the elements of the exogenous resources matrix **R**: this because the cost can be naively interpreted as the *allocation* of exogenous resources among all the production of final demand.
Because the cost is a *conservative* quantity, the sum of the exogenous resources absorbed by the system equals the sum of the total costs of its products, as showed by relation (2.38).

$$\left.\begin{array}{l} \mathbf{R}(m\times n)\cdot\mathbf{i}(n\times 1)=\mathbf{R}_{\mathbf{tot}}(m\times 1) \\ \left[\mathbf{i}(1\times n)\cdot\mathbf{C}(n\times m)\right]^{\mathrm{T}}=\mathbf{C}_{\mathbf{tot}}(m\times 1) \end{array}\right\} \quad \mathbf{R}_{\mathbf{tot}}=\mathbf{C}_{\mathbf{tot}} \tag{2.38}$$

Moreover, if the *m* different resources are measured in a unique numeraire (e.g. different kind of fossil fuels all measured in *Joules*) relation (2.38) can be further extended and the total conservation results as the equality between two scalars:

$$\left.\begin{aligned} \mathbf{i}(1\times m)\cdot\mathbf{R_{tot}}(m\times 1) = C_{tot} \\ \mathbf{i}(1\times m)\cdot\mathbf{C_{tot}}(m\times 1) = R_{tot} \end{aligned}\right\} \quad R_{tot} = C_{tot} \tag{2.39}$$

For the sake of completeness, the specific and total costs expressed in terms of exogenous emissions can be also evaluated, introducing the *exogenous waste matrix* (2.40) and the *output matrix* (2.41).

$$\mathbf{W}(s\times n) = \begin{bmatrix} \mathrm{w}_{11} & \cdots & \mathrm{w}_{1n} \\ \vdots & \ddots & \vdots \\ \mathrm{w}_{s1} & \cdots & \mathrm{w}_{sn} \end{bmatrix} \quad \begin{matrix} \mathrm{CO_2} \\ \mathrm{NO_X} \\ \ldots \end{matrix} \tag{2.40}$$

$$\mathbf{G} = \mathbf{W}\hat{\mathbf{x}}^{-1} \qquad \text{with:} \quad g_{kj} = \mathrm{w_{kj}}/\mathrm{x_j} \tag{2.41}$$

In (2.41), subscript *k* refers to the *k*th type of waste released through the system control volume to the environment. Specific and total costs, in terms of environmental emissions, per unit of final demand result respectively as follows.

$$\mathbf{c} = (\mathbf{GL})^{\mathrm{T}} \tag{2.42}$$

$$\mathbf{C} = \hat{\mathbf{f}}\,\mathbf{c} \quad \rightarrow \quad \mathbf{C} = \hat{\mathbf{f}}\,(\mathbf{GL})^{\mathrm{T}} \tag{2.43}$$

Relation (2.38) also holds between total cost (2.43) and exogenous waste matrices (2.40).
Notice that exogenous resources matrix **R** and waste matrix **W** are also known as *Environmental Satellite matrices* [24, 193].

Exogenous resources cost breakdown

As suggested by *Wiedmann* et al. in [215], a detailed insight in the cost structure for each product of the final demand can be obtained if the Leontief matrix is pre-multiplied by the diagonalized vector of each *i*th exogenous resource category. Considering one single *i*th exogenous resource the following relation can be written.

$$\underline{\mathbf{c}}(n\times n) = \left\{diag\left[row_i(\mathbf{B})\right]\cdot\mathbf{L}\right\}^{\mathrm{T}} \quad \rightarrow \quad \underline{\mathbf{C}}(n\times n) = \hat{\mathbf{f}}\cdot\underline{\mathbf{c}} \tag{2.44}$$

In (2.44), each *j*th element of the *i*th row of both $\underline{\mathbf{c}}(\mathrm{n}\times\mathrm{n})$ and $\underline{\mathbf{C}}(\mathrm{n}\times\mathrm{n})$ represents direct and indirect exogenous resources cost contributions (respectively specific and total) of the *j*th process to the *i*th final demand. Therefore, it is possible to identify the processes that largely contribute to the exogenous resources cost of each product of the final demand.

2.2.3. Assumptions of the Leontief IO model

Application of LPM and LCM to a generic production system is performed according to the following assumptions [4, 120, 136, 191]:

1. **Process characterization.** As stated in paragraph 2.2.1, every productive process must produce one single kind of useful product, measured with one specific metric. However, it can absorb flows of different products from other processes and different kind exogenous resources. As an instance, if one single process produces different kind of chemical reactants, IO table requires these products to be measured in one single metric (e.g. *kg* or *€* of "reactants");
2. **Technical coefficients.** Leontief IO model works with *constant returns to scale*. This assumption implies that process technology does not change in a specific time frame. In practice, technical coefficients and input coefficients are assumed as constant values, resulting in linear production functions: if the output level of a certain process changes, the input requirements (both intermediate products and exogenous resources) will change in a proportional way. This can be considered a reasonable assumption in most cases: given a car production process, if the required final demand of cars increase, steel required by the process will also proportionally increase and vice-versa. Obviously, the accuracy of IOA predictions will be lower as the changes in final demand increases;
3. **Exogenous resource elasticity.** Since the production activity is invoked to meet the final demand, the Leontief IO model is also known as *demand driven model* [129]. In this perspective, IOA assumes supply of exogenous resources as infinite and perfectly elastic. The demand driven model suits the behavior of human productive systems so far, in which the level of production is driven by the final demand level more than the availability of exogenous resources. When the level of production is limited by the input of exogenous resources, as happens in ecological systems, the so-called *Ghosh* model, or *supply driven model*, can be adopted. Deep discussion about *Ghosh* model can be found in literature [45, 73];
4. **Aggregation of processes.** Practical compilation of IOTs for large systems, such as economic systems or supply chains, requires a certain degree of aggregation. For this reason, sometimes it could happen that processes operating in different places are grouped together in one *virtual* sector (e.g. the steel production sector of a national economy is formed by all the steel productive plants operating within the considered nation).

2.2.4. Metric based classification of IOTs

Different kind of Input – Output tables can be found in literature. Commonly, IOTs are classified according to the metric adopted for characterize productive processes: *monetary*, *physical* or *hybrid* units.

Monetary Input – Output Table (MIOT)

As its name suggests, transaction matrix, final demand vector and total production vector are entirely expressed by means of monetary values. Tables compiled in monetary values are almost exclusively adopted to describe and to analyze national economies, rather than small productive systems. For this reason, the acronym MIOT is here referred always to a monetary IOT of a national economy. MIOTs are compiled according to international rules defined by *System of National Accounts* (SNA) [105] and classifies productive activities according to the *International Standard Industrial Classification of all economic activities* (ISIC) standard [198].

In general, MIOTs present and clarify all the economic activities being performed for a specific country, pointing out how many goods and services produced by a certain industry in a given year are distributed among the industry itself, other industries, households, etc. The major drawback of

MIOTs consists in the approximation of product flows with their monetary equivalents, which makes results affected by variation in products prices.
Because of the crucial role covered by MIOTs in the evaluation of the *primary* exogenous resources cost of products, a deeper discussion about them is presented in section 4.2;

Physical Input – Output Table (PIOT)

In this IOT, all the entries are measured in physical units, such as mass or pieces. *Material Flows Analysis* (MFA) and IOA find a meeting point in PIOTs, that are able to describe material and resource flows within the sectors of the given system [122]. Even if PIOTs are usually adopted to analyze small productive system, these tables was defined also for the following economies: Netherlands, Germany, Denmark, Italy and Finland. Furthermore, a preliminary PIOT for the European Union is based on information from the German and Danish PIOT, scaled up to EU levels. Because of the difficulties in finding required data, these PIOTs are outdated, with lack of information and represent few sectors only [96].
Even if PIOTs seem the best tables for resources cost assessment, it suffers from a great number of limitations. Firstly, flows are counted in a single unit of measurement, usually tons: in this way, immaterial products or flows of materials with a high environmental impact cannot be taken into account (usually co-products). Furthermore, a major methodological weakness is related to a not standardized methods for their compilation [172, 214]. Finally, compiling PIOTs is time-intensive and the data are not always available for all the economic sectors under consideration. The evidence of this drawbacks is the limited number of PIOTs available in literature.

Comparison between MIOT and PIOT

Recently, several publications have performed theoretical comparison among PIOT and MIOT in order to define the best way for the application of Leontief models.
The most important difference between PIOT and MIOT is the purpose by which the two tables are designed: PIOT has a purely environmental purpose, whereas MIOT is mainly adopted to have a detailed picture of all economic activities within the economy and to perform various economic performance analysis [74].
If both PIOT and MIOT are formulated for the same system with the same number of processes, and if each process sell his products at one unique price, it should be theoretically possible to derive one table from the other one (and vice-versa) simply multiplying (or dividing) each entry in the table by its monetary price. In other words, *PIOT* and *MIOT are mutually connected by the price of products* [65, 214]. However, this operation results practically unviable, mainly due to the price inequality of products: every productive sector usually sell his products to other sectors at different prices, thus a matrix of products prices (rather than a vector) need to be identified. Nevertheless, process aggregation makes prices identification a difficult task, introducing large uncertainties in IO models. A deeper discussion about the use of monetary or physical units as metric for IOTs can be found in literature [74, 98, 167, 214].

Hybrid units Input – Output Table (HIOT)

In recent years, some specialists have called for the development of *hybrid* tables with the aim to describe both physical and monetary flows within a given economy: this tables are based on the idea that every sector should have the unit of measurement that best represents the output of that sector [97]. HIOTs requires to build a dual accounting, both in physical and monetary terms, in order to merge these two approaches from the macro-economic point of view. In past decades, construction of HIOTs was constrained because of limited availability of several monetary and physical data.

Nowadays, current data on both physical and economic dimension are mostly available and the account can be performed. In literature, *Konijn* et al. [110] and *Hoekstra* [95] used both physical and monetary units in one IOT, introducing the mixed-unit input-output model. Recently, a study about mixed units model for a hybrid energy IOA was proposed by *Mayer* [124].
HIOTs could play an important role in modeling materials and energy flows, solving both the price inhomogeneity typical of MIOTs and the pitfalls of single-mass unit of PIOTs [104]. Efforts in HIOTs development are focused on the expansion of the IOA impact evaluation, including different kind of products able to model social, environmental and economic dimensions of sustainability in order to understand relationship between consumption activities and *wellbeing*. For instance, a HIOT was implemented trying to take into account monetary transactions, physical flows of resources and working hours as three potential sustainability indicators [130].

2.2.5. Meaning of the Leontief Inverse coefficients

The fundamental step for the solution of the IO system of equations (2.24) and (2.35) consists in the derivation of the Leontief Inverse matrix. The Leontief Inverse coefficient defined in (2.8) was obtained solving the production balance (2.6); alternatively, it can be obtained by considering the *power series approximation*, which allows to make clear its very economic meaning.

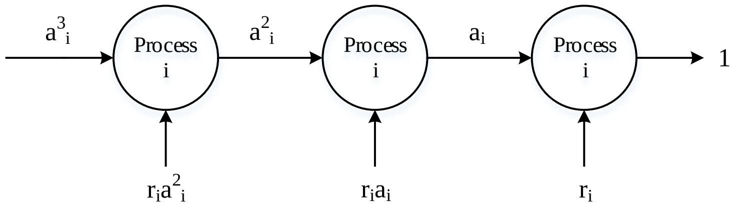

Figure 7. *Meaning of the Leontief Inverse Coefficient.*

With reference to Figure 7, the production of one unit of final demand by *i*th process requires self-consumption of the *i*th product quantified as a_i, and absorbs a certain amount of exogenous resources r_i. Again, self-consumption of *i*th product has to be produced in addition to the original unit by *i*th process. This imply another self-consumption of *i*th product quantified as a_i^2 and other indirect consumption of $r_i a_i$ exogenous resources. This looping process ends up in the sum of the so called power series:

$$\underbrace{1}_{\substack{direct\\requirement}} + \underbrace{a_i + a_i^2 + a_i^3 + \cdots}_{\substack{indirect\\requirements}} = \sum_{t=0}^{+\infty} a_i^t = (1 - a_i)^{-1} \tag{2.45}$$

Intuitively, it follows that the *i*th process of Figure 4 can be defined as *productive* only if the net output is positive, that is, only if the following condition is respected.

$$x_{ii} < x_i \quad ; \quad 0 < a_i < 1 \quad ; \quad l_i > 1 \tag{2.46}$$

Relation (2.46) is the necessary and sufficient condition to assess the productivity of the *i*th process and thus for the convergence of the power series (2.45).
The concept expressed by power series (2.45) can be extended for the generic production system described in paragraph 2.2.2 composed by *n* processes. Considering the system showed in Figure 6, the total amount of products required by each *i*th sector to fulfill its final demand results in an infinite

series of increasingly smaller contributions: mathematically, the infinite limit of the power series approaches the Leontief Inverse matrix, as suggested by (2.47) and showed in Figure 8. In other words, Leontief Inverse matrix represent the asymptote to which the power series converges.
Relation (2.47) reveals its usefulness in a computational perspective: as will be practically showed in chapter 6, the matrix inversion process could be very difficult from the numerical viewpoint, especially in case of large and dense matrices [80, 152, 212]. Therefore, obtaining the Leontief Inverse matrix using (2.47) could be a smart shortcoming to avoid numerical problems.

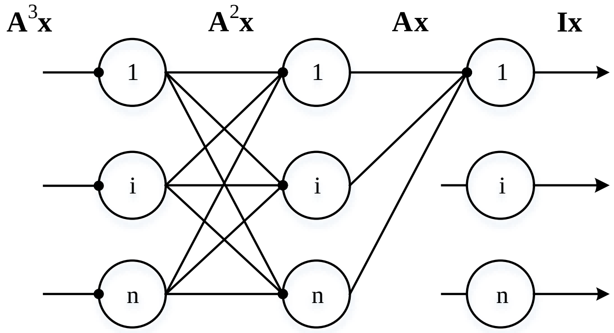

Figure 8. *Meaning of the Leontief Inverse Matrix.*

$$\underbrace{\mathbf{I}}_{\substack{direct\\ requirement}} + \underbrace{\mathbf{A}+\mathbf{AA}+\mathbf{AAA}+\cdots}_{\substack{indirect\\ requirement}} = \sum_{t=0}^{+\infty}\mathbf{A}^t = \left(\mathbf{I}-\mathbf{A}\right)^{-1} \tag{2.47}$$

To assess the convergence of the power series (2.47), that is, to determine whether the system is productive or not, two cases can be distinguished:

- **MIOT.** If all the entries in the IOT are measured in terms of monetary value, the sufficient conditions are that (1) technical coefficients matrix A is a non-negative matrix and (2) the row sums of A are less than one [143, 213]:

$$\sum_{i=1}^{n}\left|A_{ij}\right| < 1 \qquad \forall\ j\text{th columns} \tag{2.48}$$

- **PIOT and HIOT.** If the entries of the IOT are measured in physical or mixed units, condition (2.48) may be no longer respected and does not give relevant information about system productivity. Therefore, literature suggests that the power series converges if the *spectral radius* is less than one [143, 210]:

$$\rho(A) = \left\{\max\left(\left|\lambda\right|\right)\ \forall\ \text{eigenvalues of } A\right\} < 1 \tag{2.49}$$

2.2.6. Data organization and application of IOA

This paragraph provides graphical aided guidelines for the setup of an *Input – Output table* (IOT) of a generic productive system and for the application of LPM and LCM. Finally, the analytical potential of IOA is discussed.

Application guidelines

Practical transposition of the LCA guidelines listed in section 2.1.2 are here proposed for the application of IOA. Considering the nomenclature presented in paragraph 2.1.1, in order to perform exogenous resources accountings, the following steps are required:

1. **Functional Unit and objective**. *C*onsists in the clear definition of both the final demand of the analysis and the kind of exogenous resources that has to be evaluated. For instance, the objective of IOA could be the evaluation of electric energy required by a firm to produce one specific plastic bag, or the evaluation of primary fossil fuels required by each sector of a national economy to produce their products;

2. **Temporal and spatial boundaries**. This second step consists in the definition of temporal and spatial extension of the considered system. Different life cycle phases (production, use, dismantling) and spatial boundaries can be arbitrarily defined and both these choices largely affects the final results. Spatial boundaries defines the upstream processes included in the analysis: in the example of the plastic bag, defining them as the factory's boundaries will exclude all the upstream electric energy consumptions from the accounting;

   Process characterization. In this phase, every productive process has to be defined and characterized, and the two following conditions have to be met. Methodological details about this phase can be retrieved in [170].

   a. Each production process must produce only one kind of product, measured with one single metric;
   b. Every production process must delivers inputs to, or receives outputs from, other processes;

3. **IOT compilation and application of LPM and LCM.** In this phase, IOTs are compiled and both LPM and LCM are applied according to relations (2.24) and (2.36);

4. **Uncertainty analysis.** Input data to IOA could be affected by uncertainties that propagate through Leontief's models till final results: for this reason, uncertainty analysis is obviously important. This issue has been addressed in cost accounting and LCA disciplines by many authors [86-88]. The widely adopted approach has been developed under the name of *Marginal Analysis* or *Perturbation Analysis* [89]: uncertainties of results by IOA can be measured by introducing numerical perturbations in technical coefficients and input matrices, and determining how such perturbations affect the cost of products. Finally, statistical treatment and post-processing of the obtained results must be performed.

Setup of Input Output table and application of LPM and LCM

For the purpose of practical applications of IOA, let's consider the generic system depicted in Figure 6, formed by n productive processes, producing n different products and absorbing m different kind of exogenous resources.
Before staring IOA, it is required to identify a reference time frame for system analysis: usually, one year is considered.

IOTs must be compiled according to results of thermodynamic or numerical model of the considered system, or through a data collection process. Input – Output table of the system is given in Figure 9: IO analysis requires to know all values in such matrices.

From / To	1 … n	Final demand	Total production
Process 1 … Process n	Transaction matrix $\mathbf{Z}(n \times n)$	$\mathbf{f}(n \times 1)$	$\mathbf{x}(n \times 1)$
Resource 1 … Resource m	Exogenous Resources matrix $\mathbf{R}(m \times n)$		

Figure 9. *Input Output table for generic n-process system augmented with exogenous resources matrix.*

From / To	1 … n	Final demand	Total production
Process 1 … Process n	Technical coefficients matrix $\mathbf{A}(n \times n) = \mathbf{Z}\hat{\mathbf{x}}^{-1}$	$\mathbf{f}(n \times 1)$	$\mathbf{x}(n \times 1)$
Resource 1 … Resource m	Intervention matrix $\mathbf{B}(m \times n) = \mathbf{R}\,\hat{\mathbf{x}}^{-1}$		

Figure 10. *Technical coefficients and input matrices.*

From / To	Processes 1 … n		Resources 1 … m	Resources 1 … m
Process 1 … Process n	Leontief inverse matrix $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$		Specific cost matrix $\mathbf{c} = (\mathbf{BL})^{\mathrm{T}}$	Total cost Matrix $\mathbf{C} = \hat{\mathbf{f}}\,\mathbf{c}$
Total				Total cost vector $\mathbf{C}_{\mathbf{tot}} = \mathbf{i}(1 \times n)\mathbf{C}$

Figure 11. *Derivation of Leontief Inverse matrix and application of LCM .*

Rows of transaction matrix $\mathbf{Z}(n \times n)$ represent products out of *i*th process received as inputs to *j*th process. Elements in final demand vector $\mathbf{f}(n \times 1)$ represent the net useful output of each *i*th process, whereas each element of the exogenous resource matrix $\mathbf{R}(m \times n)$ represents the *k*th

exogenous resource absorbed by the *i*th process. It is worth to remark that final demand represents the purpose of the whole system, i.e. the reason because consumption of exogenous resources takes place.
To obtain the IOT in a useful shape for practical applications of LPM and LCM, transaction matrix and exogenous resources matrix presented in Figure 9 need to be respectively converted in technical coefficients matrix $\mathbf{A}(n \times n)$ and input matrix $\mathbf{B}(m \times n)$, as showed in Figure 10. Finally, Figure 11 reports the essential relations required for the derivation of specific and total costs of the final demand.

The analytical potential of IOA in Environmental Impact Assessment

The main two useful application of Leontief Production and Cost models are here listed and described. A deeper theoretical discussion with applications was performed by *Nakamura* and *Kondo* in [136].

- **Final demand shock effects.** Given the IOT of a generic system in the form of Figure 10, application of LPM and LCM reveal how a change in final demand respectively affect total production and total exogenous resources cost:

$$\Delta\mathbf{x} = \mathbf{L}\,\Delta\mathbf{f} \qquad ; \qquad \Delta\mathbf{C} = \Delta\hat{\mathbf{f}}\left(\mathbf{B}\,\mathbf{L}\right)^{\mathrm{T}} \tag{2.50}$$

  Notice that relation (2.50) assumes constant values for technical coefficients and input matrices by hypothesis. By consequence, coefficients of Leontief Inverse and specific cost matrices are constant. In this perspective, both LPM and LCM assume linear behavior for every process: thus, as introduced in paragraph 2.2.3, the evaluation of total production and environmental burdens represents here an estimation of the real values. The smaller the imposed final demand changes, the more accurate and reliable will be the results of relation (2.50).
- **Technological shock effects.** Changes in technology of one or more productive processes of a same system result in a change in both technical coefficient matrix (from $\mathbf{A}$ to $\bar{\mathbf{A}}$) and input matrix (from $\mathbf{B}$ to $\bar{\mathbf{B}}$). As a consequence, also Leontief Inverse matrix changes from $\mathbf{L}$ to $\bar{\mathbf{L}}$. Applying LPM and LCM to this new system configuration, keeping constant the final demand, it is possible to estimate the effects that a change in technology has in total production (2.51) and exogenous resources cost (2.52).

$$\Delta\mathbf{x} = \left(\mathbf{L} - \bar{\mathbf{L}}\right)\mathbf{f} \tag{2.51}$$

$$\Delta\mathbf{c} = \left(\mathbf{B}\mathbf{L}\right)^{\mathrm{T}} - \left(\bar{\mathbf{B}}\bar{\mathbf{L}}\right)^{\mathrm{T}} \quad \rightarrow \quad \Delta\mathbf{C} = \hat{\mathbf{f}}\left[\left(\mathbf{B}\mathbf{L}\right)^{\mathrm{T}} - \left(\bar{\mathbf{B}}\bar{\mathbf{L}}\right)^{\mathrm{T}}\right] \tag{2.52}$$

2.2.7. Practical example

According to the application guidelines defined in paragraph 2.2.6, IOA is here practically applied to a simple productive system.

Functional unit and objective. The objective of the analysis is the evaluation of the electric energy cost of 100 plastic bags.
Temporal and spatial boundaries. The analysis focuses on the evaluation of the exogenous resources cost from the producer perspective. Therefore, the production of bags is the only phase

considered. Spatial boundaries are limited to the production process of the bags, and encompasses three productive processes: *Bags production* (1), *Plastic production* (2) and *Heat production* (3). Other life cycle phases, as well as the other upstream/downstream processes out the boundaries, are excluded from the analysis.

Process characterization. System structure and characterization of each productive process is showed in Figure 12. Every process produces one single output measured in one single unit, receiving one or more inputs from other processes and from outside the system (electric energy, the exogenous resource).

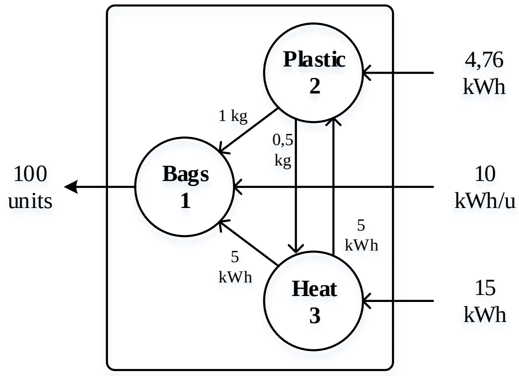

Figure 12. *Plastic bags productive system.*

IOT compilation and application of LPM and LCM. Values reported in Figure 12 can be arranged in an PIOT, defining transaction and exogenous resources matrices **Z** and **R**, final demand and total production vectors **f** and **x**. Once technical coefficient and input matrices **A** and **B** are evaluated, LPM and LCM can be applied according to the approach defined in paragraph 2.2.6. Notice that in this simple example both exogenous resources and costs are vectors.

				1	**2**	**3**	**f**	**x**
Z	Bag	units	1	-	-	-	100	100
	Plastic	kg	2	1,0	-	0,5	0	1,5
	Heat	kWh	3	5,0	5,0	-	0	10
R	Electricity	kWh	1	10	7	15		

				1	2	3	**f**	**x**
A	Bag	units	1	-	-	-	100	100
	Plastic	kg	2	0,01	-	0,05	0	1,5
	Heat	kWh	3	0,05	3,33	-	0	10
B	Electricity	kWh	1	0,10	4,67	1,50		

				1	2	3	**c** kWh/ …	**C** kWh
L	Bag	units	1	1,00	0,00	0,00	0,32	32
	Plastic	kg	2	0,02	1,20	0,06	11,60	0
	Heat	kWh	3	0,10	4,00	1,20	2,08	0
	Total							32

Table 1. *Results of the IOA of the Plastic bags productive system.*

Results of the analysis are showed in Table 1: the electricity cost of one single plastic bag results as 0,32 kWh/unit and the total cost is 32 kWh. Is worth to note that the latter is three times greater than the direct electricity consumption (10 kWh) of plastic bag production process.

Since final demand is formed by plastic bags only, specific costs of the other products have not a practical meaning: all the exogenous electricity requirements will be charged on plastic bags only.
Because row sum of the total cost vector equals the column sum of the exogenous resources (32 kWh of electricity), identity (2.38) is respected and results of IOA are correct.
Due to the simplicity of the given example, the evaluation of the electricity cost is straightforward. Advantages in using IOA become relevant for the analysis of more complex systems, with large number of components, multiple kind of goods and services produced and exogenous resources required.

2.3. Process Analysis

One alternative method to evaluate its exogenous resources consumption is the so-called *Process Analysis* (PA). This method was first defined by *International Federation of Institutes for Advanced Study* (IFIAS) in 1974 to overcome the problem due to different and not standardized approaches for the evaluation of primary energy requirements of products [100]. Once the final demand and the objective of the analysis have been defined, evaluation of the primary energy requirements through PA consists in tracing back the upstream structure of its supply chains according to scheme depicted in Figure 13, identifying every upstream contribution to primary energy taken from the environment level by level.

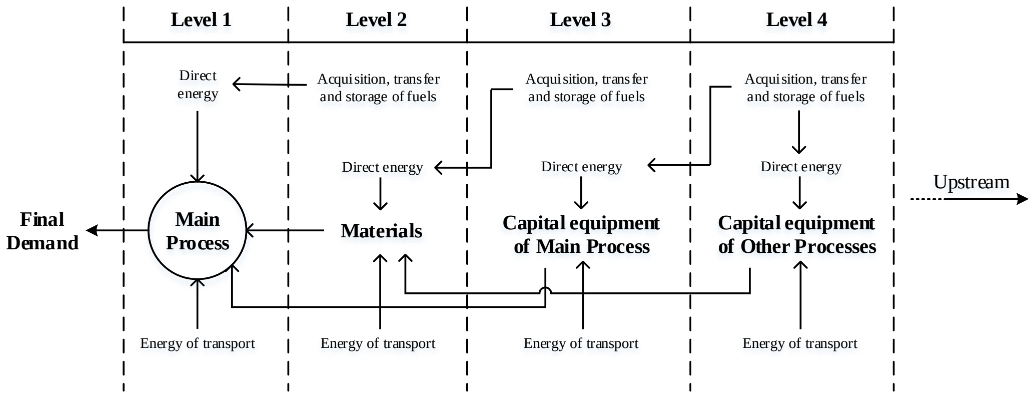

Figure 13. *IFIAS scheme for primary energy cost analysis of goods and services.*

Detailed definition and application of PA for the evaluation of primary energy cost of products has been carried out by *Trelorar* [191] and *Wilting* [216]. These studies reveal that complexity of the network and data requirements increase exponentially as the levels of the analysis increase but, at the same time, primary energy requirements decrease level by level until reaching negligible contributions to primary energy cost [26].
During the last decades, large number of researchers and organizations have worked to develop specific process model for LCA analysis [41, 99, 106] aimed at evaluating primary resources cost of specific products and systems. For this purpose, different commercial software were developed, such as *Simapro*® or *GaBi*® [33, 163], and process models were collected in commercial databases, such as *Ecoinvent* [68].
Process models are mainly focused of the evaluation of *primary* cost related to specific case studies: except for few methodological discussions [31, 91, 169, 170, 184], agreement about the best theoretical formalization of PA as a resource cost accounting method is still non existent.

2.3.1. Definition and formalization of PA method

In order to apply PA to a generic productive system, the following practical transposition of the LCA guidelines listed in section 2.1.2 are proposed. These guidelines are very similar to the ones proposed for the application of IOA in paragraph 2.2.6: definition of functional unit (1), temporal and spatial boundaries (2) and characterization of each process (3) is then performed in the same way and with the same rules of IOA. After these first steps, practical application of PA are:

1. **Process flow diagram.** Consist in the development of a process tree similar to the one presented in Figure 13, and in the accounting of total production and total exogenous resources consumption by each process. As showed in paragraph 2.3.2 and underlined by *Consoli* et al., this calculation process results in an infinite geometric progression if the considered system have *internal loops of intermediate products*. In this case, an iterative approach is required [31];
2. **Resources cost evaluation and definition of cut-off criteria.** As the levels of the process flow diagram increase, required iterations also increase: result approaches the exact solution and the convergence speed become slower. Therefore, cut-off criteria are required to stop the calculations.

These steps of PA can be mathematically formalized through linear algebra [129, 169]. The application of PA to a generic system formed by n production processes results in the calculation of total production $\mathbf{x}$ and total exogenous resources cost $\mathbf{C}$ required to produce the final demand $\mathbf{f}$, as showed by relations (2.53) and (2.54).

$$\mathbf{x} = \mathbf{x}_D + \mathbf{x}_I \quad \rightarrow \quad \mathbf{x} = \mathbf{I} \cdot \mathbf{f} + \mathbf{A} \cdot \mathbf{f} + \mathbf{AA} \cdot \mathbf{f} + \mathbf{AAA} \cdot \mathbf{f} + \cdots \tag{2.53}$$

$$C = C_D + C_I \quad \rightarrow \quad C = \mathbf{b} \cdot \mathbf{I} \cdot \mathbf{f} + \mathbf{b} \cdot \left(\mathbf{A} \cdot \mathbf{f} + \mathbf{AA} \cdot \mathbf{f} + \mathbf{AAA} \cdot \mathbf{f} + \cdots \right) \tag{2.54}$$

As for IOA, technical coefficients are collected in the square matrix $\mathbf{A}$ and represents the direct flows of the ith product directly required for the production of a unit of the jth product. In a similar fashion, input coefficients are collected in a row vector $\mathbf{b}$ and represent the amount of exogenous resources directly required by ith process to produce one unit of product.
Every term of *rhs* of (2.53) and (2.54) serve to evaluate production and exogenous resources cost of each level of the developed process flow diagram: the first addend is the direct contribution (subscript D), whereas the sum of other addends represents the indirect contribution (subscript I).
Not surprisingly, equation (2.53) coincides with the *power series approximation* (2.47), commonly used to interpret the Leontief inverse matrix in Input – Output analysis. Therefore, it can be said that *a strong theoretical relation exists between Process Analysis and Input – Output analysis: indeed, PA and IOA converges to the same results*.
The model introduced in this paragraph is general and can be adapted to every kind of productive system, ranging from small system, supply chains or even national economies [216].

2.3.2. Practical example

In this paragraph, PA is applied to the simple system of Figure 12, analyzed in paragraph 2.2.7 trough IOA. The application of PA has the same objective, temporal and spatial extension of IOA.

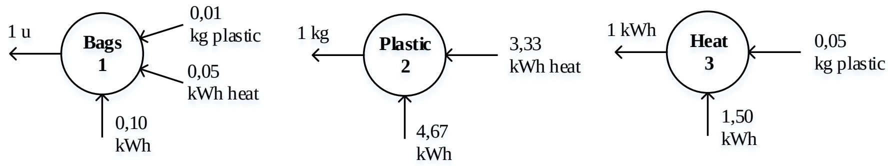

Figure 14. *Unit Process characterization.*

Figure 14 resumes process characterization for the considered system: endogenous and exogenous inputs to each process are expressed per unit of production. This representation results useful in order to draw the process flow diagram showed in Figure 15, in which the amount of products exchanged by all the processes are visible in the *tree structure* typical of process models.

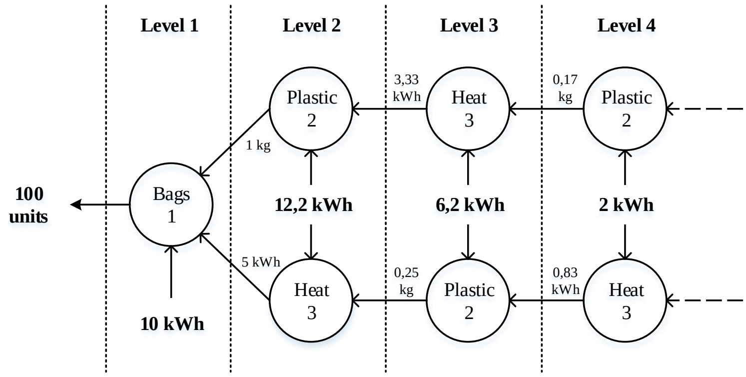

Figure 15. *Direct and Indirect contributions to total production and exogenous resources cost.*

If all the data presented in Figure 14 and Figure 15 are available, system can be considered fully characterized and it is possible to apply the last two step of PA.
The direct electric energy requirements are already known from the data: the process 1 produces 100 bags absorbing 0,1 kWh per bag and thus resulting in 10 kWh of direct electric energy consumption. In order to assess the indirect contributions to total electricity consumption, which are hidden in the Bags process 1, further levels of the process flow diagram are considered according to (2.53) and (2.54).

Level	No	Name	Units	0	1	2	3	4	5	6
Production	1	Bags	u	100	0,00	0,00	0,00	0,00	0,00	0,00
	2	Plastic	kg	0	1,00	0,25	0,17	0,04	0,03	0,01
	3	Heat	kWh	0	5,00	3,33	0,83	0,56	0,14	0,09
Cost	**C**	**Electricity**	**kWh**	**10,0**	**12,2**	**6,2**	**2,0**	**1,0**	**0,3**	**0,2**
Cumulative cost	$\mathbf{C_{cum}}$	**Electricity**	**kWh**	**10,0**	**22,2**	**28,3**	**30,4**	**31,4**	**31,7**	**31,9**

Table 2. *Results of the process analysis.*

In Table 2 results of PA are reported: indirect contributions to total production and cost have been traced till level 6. The analysis is complete since the numerical difference of indirect contributions of levels 5 and 6 are very small: exogenous resources cost of 100 bags turns out to be 31,9 kWh.
However, this could not always be adopted as the only convergence criteria: in has been demonstrated that, especially for the analysis of large systems, diminishing the amount of exogenous resources required for each stage provide no guarantee that the sum of that single negligible contributions is also negligible [22].

2.4. Discussion

In the following, some crucial aspects in PA and IOA are highlighted. Further discussions can be found in literature [91, 92, 129, 169].

2.4.1. Mathematical equivalency between PA and IOA

From the literature review about resources cost accounting techniques, PA and IOA methods emerges as two distinct approaches used for different purposes: in general, PA is used to account for the primary resources required in specific productive processes, whereas IOA is used almost exclusively for economic and environmental impact analysis of national productive sectors.
Not surprisingly, theoretical description of PA and IOA models presented in this chapter reveals that once the objective of the analysis (i.e. the final demand) and the boundaries of the productive system have been univocally defined, *application of PA converges to IOA trough the power series approximation (2.47)* [170]. *It follows that any productive system can be* <u>*always*</u> *described and analyzed by means of IOA, which is a better formalized method with respect to PA*. However, if the analyzed system is very simple (formed by few productive processes) and does not present any loop of endogenous products, PA approach results to be simpler than IOA.

2.4.2. Drawbacks of resources accounting methods

Based on the methodological review above presented, the following features of the analyzed resources accounting methods emerged, which are essential for the final choice of the accounting method in the current research.

- **Immaterial services.** Both PA and IOA are typically focused on productive processes with material outputs. Therefore, production of immaterial services is usually neglected, even in methodological discussions, mainly because of difficulties in its characterization, making the resources accounting not fully comprehensive [191]. As will be showed in chapter 4, this problem could be efficiently solved through a smart choice of system boundaries;
- **Small inputs.** Especially when large productive systems are considered (i.e. in case of primary resource cost evaluation), both PA and IOA mainly focuses on relevant flows of products, avoiding small inputs. Literature shows that the environmental burdens linked to such negligible inputs could be non-negligible [91, 115];
- **Working hours.** The role of human labor in resources consumption is a controversial and largely debated topic in environmental impact analysis: in principle, production of one working hour required by one specific productive process requires consumption of goods and services in turn, causing additional environmental impact. Literature states that such contributions would result negligible [18] but a numerical proof of this statement has not been given yet;
- **Allocation method.** Is not always possible to define production processes with only one product: when multiple output products are produced, the cost of inputs to the process need to be allocated according to one specific criterion [56];
- **Boundaries definition.** Every application of both PA and IOA requires to draw the system and to collect data from scratch. This makes results of the analysis strongly dependent by analyst's choices, making two different analyses of a same product not comparable. This is particularly true in the evaluation of *primary* resource cost, for which the analyzed system can be formed by a very large number of processes.

In conclusion, IOA emerges as simpler and well formalized with respect to PA. Therefore, it is adopted here as the suited technique for resources cost accounting purposes. With reference to the emerging needs of environmental impact analysis highlighted in the first chapter, the method of IOA is formalized in following chapters in order to:

- Develop a reproducible, standard and simple method for the evaluation of *primary* energy-resources cost of products;
- Develop a reproducible, standard and simple method for the analysis and optimization of of *energy conversion systems*;
- Clarify the role that *working hours* produced by workers and absorbed by productive processes have on primary resources cost of products.

3.
Accounting for Energy-resources use by thermodynamics

This chapter investigates the role played by thermodynamics in energy-resources cost accountings. Specifically, the main achievements of this chapter are summarized below.

- A general overview about *Life Cycle methods based on thermodynamics* is provided. A taxonomy of the methods is finally proposed;
- Definition of processes for thermodynamic based characterization of *non-renewable energy-resources* for the purpose of Input – Output analysis is provided.

3.1. Thermodynamic-based Life Cycle methods in literature

Primary energy-resources are essential in order to sustain all the economic activities. Various kind of natural resources may be involved in production processes and transformed through them causing environmental impact: emissions to air, depletion of fossil fuels, raw materials consumption, land occupation, water use etc. Account for all of these resources is certainly important to evaluate the possible future scenarios in a sustainable perspective. However, in order to carry out a rigorous analysis, it is necessary to implement methods that comply with the basic scientific laws such as the *First* and the *Second Laws* of thermodynamics [196]. In this context, energy, entropy generation and exergy are numeraires that allow to take into account a huge number of resources compared to other resource accounting methods. This paragraph aims at providing a general overview about the most commonly used thermodynamics based methods that seek to quantify resources requirements over the life cycle of a generic productive system. Because of the huge literature produced in recent years about exergy based methods, special attention is devoted to such techniques and their taxonomy is finally proposed.

3.1.1. Energy based methods

Early applications of thermodynamic concepts to LC based analysis were proposed as two different methodologies contemporarily and independently developed: *Net-energy* and *Emergy* analyses.

Net – energy analysis. The concept of *Net Energy Analysis* or *Cumulative Energy Consumption* (CEnC) refers to the primary energy required to produce a good or service, considering direct and indirect contributions among its production chain [28]. In the early 1970s, these studies were the first concerning a LCA view and, usually, they account for non-renewable fossil fuels only. The objectives of these analysis are the calculation of the total primary energy intensity of products (also called *energy cost*) and the *Energy Return on Investment* (EROI), defined as the ratio of the energy delivered by a process to the energy used directly and indirectly in that process [29]. Rough versions of Process Analysis and Input – Output Analysis described in chapter 2 were formulated and used in order to evaluate such indexes.
Emergy analysis. At about the same time, a very original line of thought was devised by *Odum* in its Emergy method: they adopted an embodied energy paradigm, but measured all types of primary

energy requirements by a conventional equivalent amount of solar radiation [102, 140, 141]. In contrast to other methods, Emergy has its own unit of measure: the *emjoule* (also called *solar emjoule*), to emphasize that primary solar energy contributions are taken into account. As the exergy, Emergy is able to account different and various forms of resources and it is able to consider the different quality of the energy flows [85] thanks to the concept of *transformity* (or *transformation ratio*), which are defined as *the solar Emergy required to make one Joule of a service or product*. Detailed calculations of transformities for many different products are available in literature.
Emergy is also able to take into account economic inputs and human resources, by introducing the ground-breaking idea that human work and monetary circulation in a society are in fact supported by the cumulative amount of Emergy that the society could avail itself of. Based on this hypothesis, calculation of an *Emergy/money ratio* was proposed [194].
The Emergy analysis differs from traditional accounting approaches, establishing its own accounting rules [19]. As for all the accounting methods, Emergy analysis suffers from uncertainties, especially in the quantification of the transformities; moreover, Emergy analysis has allocation problems mostly related to co-products. In any case, Emergy analysis appears as the first attempt to unify the processes that occur in ecosystems and human activities [85].

3.1.2. Entropy based methods

The use of *entropy* in system analysis and optimization has a history that can be traced back to the early beginning of Thermodynamics [109]. The concept of entropy was introduced to describe the lost of work potential occurring in any energy conversion process, and only recently entropy analysis has been used to assess the overall resource consumption of one generic system. Two entropy based method emerges from literature as the state of the art: *Entropy Generation Minimization* (EGM) and *Cumulative Entropy production*.

Entropy Generation Minimization. The EMG method, introduced by *Bejan* in [11, 12], aims at evaluate the Second Law efficiency of a given energy conversion system, revealing the source of inefficiencies by identifying the large amount of entropy generations within the system and thus providing useful information for thermodynamic optimization. This method is designed to improve systems at a very detailed level: for such reason, it requires to know details about the geometrical setup of the system and the thermodynamic properties of the flows of matter and energy that cross its boundaries. However, since the boundaries defined by EGM are restricted to specific processes, its results exclude the sources of inefficiencies in supply chains: in order to fully assess the overall effects of optimizations at the process level, a different approach is then required [8].
Cumulative Entropy production. Differently from EGM, the approach proposed by *Reisemann* consists in extending the boundaries of entropy analysis at the level of production and consumption systems that span several plants and regions. It is not so much aimed at optimizing the design of specific systems, but at assessing the resource consumption accompanying the economic production and consumption of goods in a Life Cycle perspective [75, 76].

3.1.3. Exergy based methods

Exergy based methods for system analysis have been largely deepened in literature, as demonstrated by the huge number of scientific articles and books published every year. For such reason, the current paragraph devotes special attention to exergy and exergy based methods.

The concept of exergy

Exergy is defined by literature as *the amount of useful work extractable from a generic system when it is brought to equilibrium with its reference environment through a series of reversible processes in which the system can only interact with such environment* [112, 131, 132]. Definition of reference environmental conditions is therefore an implicit prerequisite for the evaluation of exergy, which can be defined as a property of both the system and the environment.

Notice that if the system is closed with respect to its reference environment, the final equilibrium state is called *Environmental State* (subscript 0), and implies a complete thermo-mechanical equilibrium ($T = T_0, p = p_0$). Once the environmental state has been reached, the chemical and/or phase composition of the system may be different from that of the environment and material exchanges may take place until the system reaches another thermodynamic state called *Dead State* (subscript 00), described by both thermo-mechanical and chemical equilibrium ($T = T_0, p = p_0, \mu_i = \mu_{i,0}$).

The generalized exergy balance, analytically formulated among others by *Bejan* [13], can be derived by combining energy and entropy balances and results as follows:

$$\frac{dEx}{dt} = \sum_j \dot{E}x_{W,j}^{\leftarrow} + \sum_k \dot{E}x_{Q,j}^{\leftarrow} + \sum_q \dot{m}_q^{\leftarrow} ex_q - \dot{E}x_D \tag{3.1}$$

Notice that, since exergy – like entropy – is not conserved, the word *balance* is not strictly appropriate: indeed, the term $\dot{E}x_D$ in (3.1) is a virtual term introduced with the purpose of closing the balance, and does not correspond to any physical flux.

Following the classification proposed by *Kotas* , definitions of *internal exergy* (3.2), *exergy of work and heat interactions* (3.3) and *exergy of bulk flow* (3.4) are introduced. Exergy of bulk flow (3.4) can be expressed as the sum of four components: *potential* (pt), *kinetic* (kn), *physical* (ph) and *chemical* (ch) exergy.

$$Ex = E - T_0 S + p_0 V \tag{3.2}$$

$$\dot{E}x_W^{\leftarrow} = \dot{W}^{\leftarrow} \qquad \dot{E}x_Q^{\leftarrow} = \dot{Q}^{\leftarrow}\left(1 - T_0/T_k\right) \tag{3.3}$$

$$ex = \underbrace{g\left(z - z_0\right)}_{ex_{pt}} + \underbrace{\frac{1}{2}\left(w^2 - w_0^2\right)}_{ex_{kn}} + \underbrace{h - h_0 - T_0\left(s - s_0\right)}_{ex_{ph}} + \underbrace{\sum_i \left(g_{i,0} - g_{i,00}\right) y_i}_{ex_{ch}} \tag{3.4}$$

Finally, the exergy destruction term $\dot{E}x_D$ represents the irreversible (i.e. irrecoverable) loss of work capacity experienced by the system during a thermodynamic process, and it is evaluated through the so-called *Gouy-Stodola* theorem [112]:

$$\dot{E}x_D = \dot{W} - \dot{W}_{rev} = T_0 \cdot \dot{S}_{gen} \tag{3.5}$$

Because of its features, exergy is widely recognized by literature as a convenient tool for system analysis and optimization and as a suited indicator for quantification of resource consumption.

Exergy based methods: brief literature review

In recent years, standard exergy analysis, described by *Kotas*, *Moran* and *Sciubba* in [111, 131], has been developed extending temporal and spatial boundaries of the analyzed system and by considering many different contributions in terms of exogenous resources [166]. Therefore, all the

methods proposed by literature and briefly described below have their roots in standard exergy analysis. Moreover, all these methods are classified by literature in the broad category collectively know as *Thermoeconomics*, defined as the discipline that merges *Thermodynamic principles* with *Cost accounting methods* [149].
The word *Thermoeconomics* was coined in 1961 by *Tribus* [62], and further fundamental developments were made by *El-Sayed* and *Evans* [57] in US and by *Elsner*, *Fratzscher*, *Beyer* and *Brodjansky* in Europe [58]. Later, in the '80s, *Gaggioli* extended the application of the theory to encompass a broader set of energy-intensive systems [69]. Recently, *Tsatsaronis* [192] and *Valero et al.* [123, 202-205], were able to produce a complete and elegant formalization of the method, that is now known as *Exergy Cost theory*. For a review of the developments of the theory and of its applications, see [14, 59, 158, 208].

Cumulative Exergy Consumption (CExC). Also called *Cumulative Exergy Demand* (CExD), this method was initially proposed by *Szargut* and *Morris* in 1986 [177, 179]. It is similar to Cumulative Energy Consumption, but, instead of energy, it uses the exergy as the numeraire. CExC expands the analysis boundary by considering all the industrial processes needed to convert both renewable and non-renewable natural resources into the desired industrial goods or services [84]. The use of exergy as the only numeraire allows to take into account not only energy flows that cross system boundary, but also other types of primary resources, such as water, metals and minerals [17]. Temporal and spatial boundaries are usually defined by CExC in order to account for the primary resources requirements of the production phase of a good or service [180, 182].
Thermo-Ecological Cost (TEC). Based on CExC concept, *Szargut* and *Stanek* introduced TEC as the cumulative consumption of non-renewable exergy of primary resources (fossil fuels) required for the production phase of the considered good or service [180].
Cumulative Exergy Extraction from Natural Environment (CEENE). As for CExC, this method accounts for renewable and non-renewable resources, including water, minerals and metals extraction and also quantifying the exergy cost due to land occupation, as described in [44]. From a purely ecological perspective, when land is occupied, the ecosystem is deprived of the solar exergy necessary to sustain its natural cycles. Therefore, cumulative land use is taken into account as a solar exergy contribution.
Exergetic Life Cycle Assessment (ELCA). A life cycle extension of the above introduced methods was proposed by *Cornelissen* in 1997 through ELCA [34, 35, 148]. This approach extend temporal and spatial boundary of CExC analysis, evaluating materials and energy requirements for all the LC phases of the considered system by means of their exergy equivalents.
Moreover, a further extension of the ELCA approach, called *Zero-ELCA*, was proposed by the same author in order to include the impact due to pollutant emissions into the primary exergy cost of the considered product through the primary exergy requirements of emission abatement processes [94, 148, 222].
Industrial/Ecological Cumulative Exergy Consumption (ICEC/ECEC). Other developments of CExC method were proposed by *Ukiwide* and *Bakshi* [84] named ICEC and ECEC. The former considers only the non-renewable natural resources requirements (expressed by means of exergy) of the analyzed productive process, and is then very close to the TEC method. A complementary result is then obtained through the ECEC method, which adds to the ICEC result also the exergy consumed by ecological processes to produce primary flows of energy, materials and to dissipate the emissions. Notice that, differently from *all* the other method described in this section, ICEC/ECEC method is explicitly formalized by means of the same mathematics of Input-Output analysis [196].

ECEC method is conceptually close to the Emergy method, trying to expand the boundary over the ecosystem processes. Furthermore, practical applications of the methods are performed in a similar way [84, 195, 220, 221]:

- ECEC uses an analogous concept of *transformity*, called *Ecological Cumulative Degree of Perfection* (ECDP), to express the ratio between the exergy and the embodied exergy of products;
- Economic activities are also taken into account by means of a factor that express the cumulative exergy required to sustain monetary circulation.

Even if ECEC approach has the advantage of using exergy as the numeraire, its formulation suffers from the same problems of Emergy analysis, mainly related to the allocation of exergy cost and to uncertainties caused by the lack of data for most of the processes that occur within ecological systems. Moreover, the formulation of this method do not encompasses all the life cycle of the system: exergy requirements due to disposal of the product and the influence of recycling are not taken into account [196].

Extended Exergy Accounting (EEA). This method was conceived by *Sciubba* in 1998 [154]. EEA can be considered a further extension of the CExC method: similarly to ELCA, EEA consists in the evaluation of primary exergy requirements of the whole life cycle of a given system [155]. Another fundamental difference between EEA and other methods is that it proposes to include the side-effects that externalities have on primary exergy requirements: human labor, capital and environmental pollution. An extensive review of EEA was carried out by the author in [149].

With reference to relation (3.6), once the *i*th system has been defined, its Extended Exergy can be evaluated as the sum of the following two contributes, considered for each of the *j*th phases of the life – cycle of the system.

- Primary exergy requirements of materials and energy flows, considering renewable and non-renewable resources. The way to take into account these contributions is the same as CExC;
- Primary Exergy requirements caused by externalities E_{ext}, including labor E_L, capital E_K and environmental remediation costs E_O.

$$EE_i = \int_{t=LC_i} \left(CExC_i + E_{ext} \right)_j dt \qquad \rightarrow \qquad E_{ext} = E_L + E_K + E_O \tag{3.6}$$

The environmental remediation costs E_O are evaluated as the additional Extended Exergy expenses required by real pollutants treatment processes, in a similar manner as introduced in the Zero-LCA approach. On the other hand, evaluation of labor and capital externalities requires the introduction of the following two *postulates*.

1. *In any society, a portion of the gross global influx of exergy resources E_{in} is used to sustain the workers who generate labor.*

   According to this postulate, *Sciubba* states that the exergy cost of one working hour can be *estimated* as the ratio as the ratio between the fraction of exergy converted into labor E_L and the total number of hours cumulatively produced by the society in the same time frame:

$$E_{L,i} = ee_{L,i} \cdot N_{wh,i} \qquad \rightarrow \qquad ee_{L,i} = \left(\frac{HDI_i}{HDI_o} \right) \cdot ex_{surv} \cdot \frac{N_{h,i}}{N_{wh,i}} \tag{3.7}$$

In relation (3.7), HDI_i and HDI_0 are respectively the Human Development Index of the considered country and of the reference pre-industrial society (about 0,055); e_{surv} represents the minimum exergy amount required for the metabolic survival of an individual (about $1{,}05 \cdot 10^7\ J/p \cdot day$) and $N_{h,i}/N_{wh,i}$ is the ratio between the cumulative amount of living hours and working hours of the ith country.

2. *The amount of exergy required to generate the net monetary circulation within a society is proportional to the amount of exergy embodied into labor.*
   This postulate establish a links between the working hours circulation and the monetary circulation within a specific ith country. This allows to evaluate the exergy embodied in one monetary unit through the following relation:

$$E_{K,i} = E_{L,i} \cdot \left(\frac{M_{f,i}}{S_i} \right) \quad \rightarrow \quad ee_{K,i} = E_{L,i} \cdot \left(\frac{M_{f,i}}{S_i} \right) \cdot \frac{1}{M2} \tag{3.8}$$

According to relation (3.8), the exergy embodied in monetary circulation $E_{K,i}$ is related to $E_{L,i}$ through the ratio between the monetary circulation due to financial activities $M_{f,i}$ and the gross cumulative wages S. The exergy cost of one monetary unit is then evaluated dividing $E_{K,i}$ by the total monetary circulation within the considered country $M2$.

Additional details and a derivation of the above introduced relations can be found in literature [42, 149, 156, 157, 159, 183].

Exergy based methods: a tentative taxonomy

The outcome of the literature analysis is represented by the taxonomy of Exergy based methods proposed in Figure 16.

Category	Type	CExC (CExD)	TEC	CEENE	ELCA	Zero ELCA	ICEC	ECEC	EEA
Primary factors	Fossil fuels (NR)	●	●	●	●	●	●		●
	Nuclear (NR)	●	●	●	●	●	●		●
	Kinetic	●		●	●	●			●
	Solar	●		●	●	●		●	●
	Potential	●		●	●	●			●
	Biomass (NR)	●	●	●	●	●	●		●
	Biomass	●		●	●	●			●
	Water	●		●	●	●			●
	Metals (NR)	●		●	●	●		●	●
	Minerals (NR)	●		●	●	●		●	●
	Land use			●					
Secondary factors	Energy carriers	●	●	●	●	●	●	●	●
	Goods and services	●	●	●	●	●	●	●	●
	Monetary capitals						●	●	●
	Working hours								●
Life Cycle phases	Costruction	●	●	●	●	●	●	●	●
	Operation			●	●	●			●
	Disposal			●	●	●			●
	Production of NR resources							●	
	Environmental remediation					●			●

Figure 16. *Taxonomy for the analyzed exergy based methods.*

Classification of the methods is performed according to three main categories:

- *Primary factors* category identifies all the natural resources that are taken into account by each method. Notice that this first category include the same natural resources adopted by the standard *Life Cycle Impact Assessment* (LCIA) [33, 77];
- *Secondary factors* category identifies the products for which the respective exergy cost is taken into account by the analysis method;
- *Life Cycle phases* category identifies the LC phases included by the analysis. Notice that the sub-category named *Production of NR resources* refers to the extension of spatial and temporal boundaries of the method in order to account for the primary resources required by the environment to produce the non-renewable resources (only for ECEC method).

Detailed treatment of all the exergy based methods is out of the scope of the thesis [8, 150, 166]. The fundamental element that emerges from literature is that research efforts related to thermodynamic system analysis seems to be generally focused on the development of Life Cycle exergy based methods for the quantification of primary natural resources consumption.
Finally, literature highlights that even if the temporal and spatial domains and the primary factors included in the evaluation are clearly defined for all the analyzed methods, practical cost accounting techniques are not properly and univocally established, making applications of such methods very difficult and arbitrary.

3.2. Thermodynamic characterization of non-renewable energy-resources for IOA

Based on the emerging needs of Environmental Impact Analysis emerged in chapter 1 and on the outcomes of chapters 2 related to cost accounting methods, author propose here to establish Input – Output analysis as a unified method for the purpose of *non-renewable energy-resources* cost accounting. According to the objective of the thesis highlighted in chapter 1, this section focuses on characterization processes of non-renewable energy-resources (fossil fuels), considered as exogenous resources in Leontief models.
In principle, exogenous resources matrix can be simply compiled by measuring fossil fuels through their *mass* or *volume* (e.g. *tons* of raw coal, Nm^3 of natural gas, etc.). However, different fuels are usually characterized by different physical and thermodynamic properties, making column elements of exogenous resources matrix non-additive. To overcome this issue, literature suggests to characterize energy-resources by means of the thermodynamic effects they generate through a defined reference depletion process [79]:

- Heat or Entropy generation caused by a **spontaneous** (i.e. irreversible) **depletion process**;
- Mechanical work produced through a **reversible depletion process**.

All these quantities can be derived by manipulating standard *energy balance* (3.9) and *entropy* balance (3.10).

$$\frac{dE}{dt} = \sum_j \dot{W}_j^{\leftarrow} + \dot{Q}_0^{\leftarrow} + \sum_k \dot{Q}_k^{\leftarrow} + \sum_q \dot{m}_q^{\leftarrow} \left(gz + \frac{w^2}{2} + h \right)_q \tag{3.9}$$

$$\frac{dS}{dt} = \frac{\dot{Q}_0^{\leftarrow}}{T_0} + \sum_k \frac{\dot{Q}_k^{\leftarrow}}{T_k} + \sum_q \dot{m}_q^{\leftarrow} s_q + \dot{S}_{gen} \tag{3.10}$$

As will be showed below, apart for the definition of one specific *depletion process* (reversible or irreversible), this characterization method *always* requires definition of one *reference environment*: usually, *Standard State* is assumed for such purpose as a temperature T_0 of *298,15 K* (*25 °C*), pressure P_0 of *100,0 kPa* and a chemical composition of reference air, oceans and earth crust defined by *Szargut et al.* [181].

3.2.1. Spontaneous depletion process

Let us consider the combustion chamber of Figure 17, such that:

1. The system operates at steady state;
2. Flows of *fuel* (*f*), *stoichiometric dry air* (*a*) and *flue gases* (*fg*) are entering/exiting the combustion chamber at environmental temperature T_0 and pressure p_0;
3. The inlet dry air (*a*) provides theoretical amount of oxygen for the complete combustion of the fuel;
4. Apart from the bulk flow interactions, the system exchange heat $\dot{Q}_0^{\rightarrow}$ with the environment, crossing an ideal boundaries at temperature T_0.

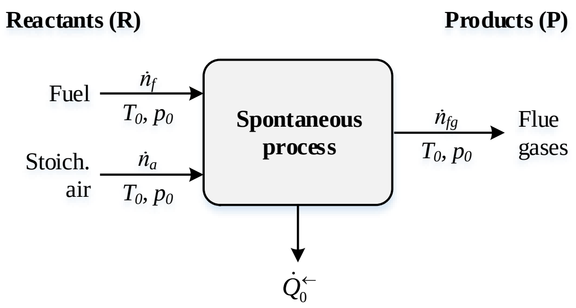

Figure 17. *Steady state spontaneous process used for the evaluation of Heating Value and Entropy generation of fossil fuels.*

According to these hypotheses, application of the energy balance (3.10) allows to evaluate the amount of heat produced by combustion of a mole or mass unit of fuel delivered to the environment $q_0^{\rightarrow}$, expressed by (3.11): literature refers to such quantity as the *Heating Value* of the fuel. It is worth to remark that the heat is delivered to the environment through an ideal surface at temperature T_0.

$$\dot{Q}_0^{\rightarrow} = \left(\dot{H}_R - \dot{H}_P\right)_{T_0, p_0} \quad \rightarrow \quad q_0^{\rightarrow} = HV = \frac{\dot{Q}_0^{\rightarrow}}{\dot{n}_f} \tag{3.11}$$

Since the process is defined as *spontaneous* (i.e. *irreversible*), application of combined energy and entropy balance (3.10) lead to the evaluation of the maximum amount of entropy that could be generated by depletion of a mole or mass unit of fuel (3.12).

$$\begin{cases} \dot{Q}_0^{\rightarrow} = \left(\dot{H}_R - \dot{H}_P\right)_{T_0,p_0} \\ \dfrac{\dot{Q}_0^{\leftarrow}}{T_0} + \left(\dot{S}_R - \dot{S}_P\right)_{T_0,p_0} + \dot{S}_{gen} = 0 \end{cases} \rightarrow \quad \dot{S}_{gen} = \frac{\dot{Q}_0^{\leftarrow}}{T_0} - \left(\dot{S}_R - \dot{S}_P\right) \quad \rightarrow \quad s_{gen} = \frac{\dot{S}_{gen}^{\rightarrow}}{\dot{n}_f} \tag{3.12}$$

3.2.2. Reversible depletion process

The combustion chamber of Figure 18 is considered, according to the same hypotheses above introduced. In this case, fuel is depleted according to a reversible process: the entropy generation term in balance (3.10) is set to zero, the system exchange heat $\dot{Q}_0^{\rightarrow}$ with the environment through an ideal surface at temperature T_0 and produces mechanical work $\dot{W}_{rev}^{\rightarrow}$.

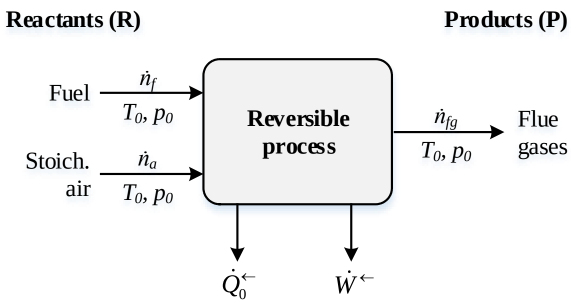

Figure 18. *Sketch of the steady state reversible process used for the evaluation of Exergy of fossil fuel.*

Because the outlet flow stream is in temperature and pressure equality with the reference environment at standard conditions, $w_{rev}^{\rightarrow}$ represent the *availability*, or *exergy*, of the mole or mass unit of the considered fuel and it is expressed by relation (3.13).

$$\begin{cases} \dot{Q}_0^{\leftarrow} + \dot{W}^{\leftarrow} + \left(\dot{H}_R - \dot{H}_P\right)_{T_0,p_0} = 0 \\ \dfrac{\dot{Q}_0^{\leftarrow}}{T_0} + \left(\dot{S}_R - \dot{S}_P\right)_{T_0,p_0} = 0 \end{cases} \rightarrow \quad \dot{W}_{rev}^{\rightarrow} = \dot{E}x^{\rightarrow} = \dot{H}_R - \dot{H}_P - T_0 \cdot \left(\dot{S}_R - \dot{S}_P\right) \tag{3.13}$$

Before calculating *Heating Value HV*, *Entropy Generation* s_{gen} or *Chemical Exergy* ex_{ch} of primary fuels, it is required to define specific models and assumptions for the calculation of enthalpy and entropy of material flows entering and exiting the ideal reactors of Figure 17 and Figure 18.

3.3. Discussion

Exergy allows to homogenously account for the quantity and quality of bulk flows and energy interactions, referring them to a reversible thermodynamic exploitation process. Moreover, exergy seems to be characterized by lower sensibility to environmental conditions with respect to entropy generations. For these reasons, exergy has been accepted by scientific community as the most suited metric to account for natural resources consumption, and has been assumed as the quantitative basis for Industrial Ecology [8, 160]. Recently, also the *International Reference Life Cycle Data System* (ILCD) refers to exergy as *the best and most mature midpoint indicator to account for resources consumption* [127].

However, it has to be remarked that the interpretation of exergy as a measure of a substance's thermodynamic value makes sense only for substances that are somehow used to drive a process. Indeed, the absolute exergy value of substances has relevance only when they are used are used energetically (which includes, e.g., driving a chemical reaction). In case of substances that are used non-energetically (e.g., by providing structure or by conducting heat and electricity), their exergy content has no practical relevance. However, for substances or materials that are used in a cascading way, the relevance of their exergy content might, however, come into play in a later-use phase [75, 76, 160]. Finally, exergy does not give information about the scarcity of resources.

What emerges from the current chapter is that many exergy based methods have been proposed in recent literature to account for natural resources requirements of productive processes and energy conversion systems. However, all the presented methods are not clearly and univocally defined from the methodological viewpoint.

For these reasons, exergy is adopted in the following chapters for the characterization of non-renewable energy-resources within the comprehensive framework of Input – Output analysis.

3.3.1. The exergy of common fossil fuels

Detailed analytical methods for the calculation of chemical exergy of organic and inorganic substances were developed by *Szargut et al.* [133, 175, 176, 178], *Kotas* [113], *Gyftopoulos* and *Beretta* [79], *Moran* and *Shapiro* [132].

Thermophysical properties of *gaseous fuels*, either pure or as a mixture, can be easily derived through the ideal or real gas models: for this reason, evaluation of standard chemical exergy of gaseous fuels can be performed starting from the analytical expression (3.13). This is not the case of complex *liquid* and *solid fuels* (e.g. coal, oil or biomass), for which literature has developed specific correlations. Among others, *Song et al.* propose one unified correlation for estimating specific standard chemical exergy of solid and liquid fuels [162]:

$$ex_{ch}\left(T_0, p_0\right) = 363{,}439\boldsymbol{C} + 1075{,}633\boldsymbol{H} - 86{,}308\boldsymbol{O} + 4{,}147\boldsymbol{N} + 190{,}798\boldsymbol{S} - 21{,}1\boldsymbol{A} \qquad (3.14)$$

Given the weight content, in percentage, of carbon ($27{,}33\% \le \boldsymbol{C} \le 89{,}10\%$), hydrogen ($2{,}46\% \le \boldsymbol{H} \le 14{,}00\%$), oxygen ($1{,}10\% \le \boldsymbol{O} \le 46{,}92\%$), nitrogen ($0{,}00\% \le \boldsymbol{N} \le 9{,}27\%$), sulphur ($0{,}01\% \le \boldsymbol{S} \le 5{,}54\%$) and ash ($0{,}00\% \le \boldsymbol{A} \le 51{,}96\%$) of the fuel, correlation (3.14) returns its chemical exergy expressed in kJ/kg. Such correlation is applicable to coal, biomass, petroleum, shale oil, oil from tar sands, crude benzol, synthetic liquid fuels made from coal or biomass. In Table 3, average Heating Value and chemical exergy of the common primary non-renewable fossil fuels are reported.

The so-called *Szargut factor* β defined by (3.15) is the ratio between Chemical Exergy and Heating Values of the fuel.

$$\beta = \frac{ex_{ch}}{HV} \qquad (3.15)$$

In the following chapters, values given in Table 3 will be used as the reference for primary fossil fuels characterization.

Impact category	R-NR	Resource	Units	HV	ex_{ch}	β
Fossil	NR	Coal, brown, in ground	MJ / kg	9,9	10,3	1,04
		Coal, hard, unspecified, in ground	MJ / kg	19,1	19,7	1,03
		Gas, mine, off-gas, process, coal mining	MJ / m3	39,8	37,4	0,94
		Gas, mine, off-gas, process, coal mining	MJ / kg	49,8	46,8	0,94
		Gas, natural, in ground	MJ / m3	38,3	36	0,94
		Oil, crude, in ground	MJ / kg	45,8	46,5	1,02
		Peat, in ground	MJ / kg	9,8	10,3	1,05
Nuclear	NR	Uranium, in ground	MJ / kg	560000	560000	1,00
Biomass	R-NR	Wood, hard, standing	MJ / m3	12740	13377	1,05
		Wood, soft, standing	MJ / m3	9180	9639	1,05
		Wood, unspecified, standing	MJ / m3	10960	11508	1,05

***Table 3.** Heating Value and Exergy of the common non-renewable fuels. Biomass category can be classified as renewable or non-renewable.*

3.3.2. The role of reference environment

One of the most debated issues related to thermodynamic characterization of energy-resources concerns the influence that *environmental reference conditions* have on the calculation of Heating Value, Entropy generation or Chemical exergy of fossil fuels. Indeed, the real environment is far from equilibrium and involves in changings of its properties – especially its temperature – that are functions of seasons and geographical location.
As can be inferred from the previous section, thermodynamic characterization of fossil fuels requires the definition of one reference depletion process: therefore, definition of one reference environment is required in turn. Indeed, exploitation of one resource can be seen as the extraction of thermodynamic utility (heat or work) through an ideal process that brought the resource in physical and chemical equilibrium with the environment. The (wrong) assumption that the environment is in equilibrium at constant temperature, pressure and chemical composition is thus necessary in order make characterization of fuels feasible. It is worth to remark that <u>*all*</u> the thermodynamic numeraires introduced in previous section are affected by this assumption.
Once a reference environment has been defined (here, the *Standard State:* $T_{ref} = 25°C$, $p_{ref} = 1\ bar$, denoted by the superscript °), the question about the influence that a change in environmental temperature T_0 has on the *numerical* values of Heating Value, Entropy generation and Chemical exergy of fossil fuels arise. As an example, this paragraph evaluate how such values are sensible to a change in environmental temperature between $-10\ °C$ and $50\ °C$ for *1 kmol* of pure methane (CH_4) that is involved in a stoichiometric combustion reaction:

$$CH_4 + 2\left(O_2 + 3{,}76 N_2\right) \rightarrow CO_2 + 2H_2O + 7{,}52 N_2 \tag{3.16}$$

Molar values of *enthalpy* and *absolute entropy* for any given pure substance at the environmental temperature and pressure can be evaluated according to the following relations [132]:

$$\begin{aligned} \bar{h}\left(T_0, p_0\right) &= \bar{h}_f^{\circ} + \left[\bar{h}\left(T_0, p_0\right) - \bar{h}\left(T_{ref}, p_{ref}\right)\right] \\ \bar{s}\left(T_0, p_0\right) &= \bar{s}^{\circ} + \left[\bar{s}\left(T_0, p_0\right) - \bar{s}\left(T_{ref}, p_{ref}\right)\right] \end{aligned} \tag{3.17}$$

Assuming *ideal gas* behavior, the above introduced relations can be rewritten as (3.18), where $R = 8{,}314\ kJ/kmolK$ is the universal gas constant and $\bar{c}_p$ is the molar isobaric heat capacity, evaluated according to the *NASA* polynomial expressions [132] and $\bar{h}_f^o$ is the molar enthalpy of formation.

$$\begin{aligned} \bar{h}\left(T_0, p_0\right) &= \bar{h}_f^o + \bar{c}_p\left(T_0 - T_{ref}\right) \\ \bar{s}\left(T_0, p_0\right) &= \bar{s}^o + \bar{c}_p \ln\frac{T_0}{T_{ref}} - R\ln\frac{p_0}{p_{ref}} \end{aligned} \tag{3.18}$$

Enthalpy and entropy of a ideal mixture of ideal gases results as (3.19), where y_i denotes the molar composition of the mixture.

$$\begin{aligned} \bar{h}_{mix}\left(T_0, p_0\right) &= \sum_i y_i \cdot \bar{h}_i\left(T_0, p_0\right) \\ \bar{s}_{mix}\left(T_0, p_0\right) &= \sum_i y_i \cdot \bar{s}_i\left(T_0, p_0\right) - R\cdot\sum_i y_i \cdot \ln y_i \end{aligned} \tag{3.19}$$

Heating Value (3.11), *Entropy generation* (3.12) and *Chemical exergy* (3.13) of *1 kmol* of pure methane can be thus evaluated as functions of the environmental temperature T_0 through the following relations:

$$HV\left(T_0, p_0\right) = \Delta h_r^o + \sum_R\left[\nu_i \bar{c}_{p,i}\left(T_0 - T_{ref}\right)\right]_R - \sum_P\left[\nu_j \bar{c}_{p,j}\left(T_0 - T_{ref}\right)\right]_P \tag{3.20}$$

$$\bar{s}_{gen}\left(T_0, p_0\right) = \frac{HV\left(T_0, p_0\right)}{T_0} - \left[\sum_i \nu_i \cdot \bar{s}_i\left(T_0, p_0\right) - R\cdot\sum_i \nu_i \cdot \ln y_i\right]_{R-P} \tag{3.21}$$

$$\overline{ex}_{ch}\left(T_0, p_0\right) = HV\left(T_0, p_0\right) - T_0\left[\sum_i \nu_i \cdot \bar{s}_i\left(T_0, p_0\right) - R\cdot\sum_i \nu_i \cdot \ln y_i\right]_{R-P} \tag{3.22}$$

Where P and R respectively refers to *products* and *reactants*, and ν are the stoichiometric coefficients of reaction (3.16).

For practical reasons, fossil fuels are usually characterized at *Standard State*. However, according to these relations, it can be said that Heating Value, Entropy generation and Chemical exergy of ideal gas mixtures of fossil fuels are all sensible to changes in the environmental temperature, as showed in Table 4.

T_0	HV	ΔHV	s_{gen}	Δs_{gen}	ex_{ch}	Δex_{ch}
°C	*MJ/kg*	%	*MJ/kgK*	%	*MJ/kg*	%
-10	50,03	0,04	196,52	12,81	51,71	-0,43
-5	50,03	0,04	192,97	10,77	51,75	-0,37
5	50,02	0,03	186,27	6,92	51,81	-0,25
15	50,02	0,01	180,03	3,34	51,87	-0,12
25 (ref)	**50,01**	**-**	**174,20**	**-**	**51,94**	**-**
40	50,00	-0,02	166,17	-4,61	52,04	0,19
50	50,00	-0,03	161,23	-7,45	52,10	0,31

Table 4. *Sensitivity of Heating Value, Entropy generation and Chemical exergy of methane to the environmental temperature.*

Considering the case of methane, Entropy generation results in a stronger dependence with respect to Heating value or Chemical exergy, as depicted in Figure 19. Relative differences (Δ, in percentage) between results obtained at T_0 and at T_{ref} are shown in Table 4. Heating Value and Chemical exergy are not sensible to environmental temperature variation, whereas Entropy generation undergoes in relevant changes.

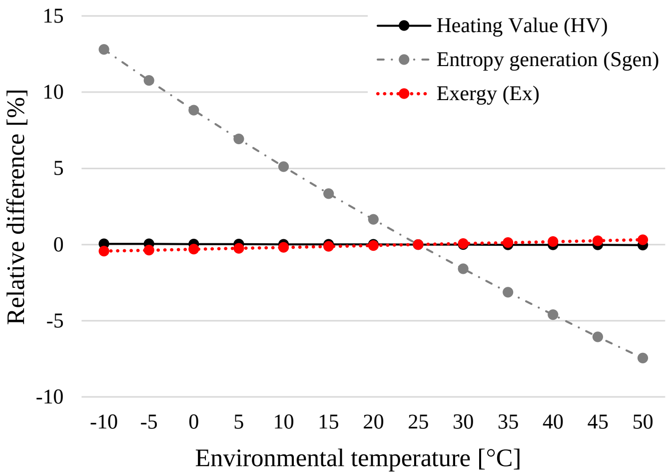

Figure 19. *Sensitivity of Heating Value, Entropy generation and Chemical exergy of methane to the environmental temperature.*

Intuitively, using IOA for the evaluation of primary cost of goods and services in terms of fossil fuels depletion requires to compile the exogenous resources matrix by means of Heating Value, Entropy generation or Chemical exergy of fossil fuels. However, due to the assumption of *process aggregation* (paragraph 2.2.3), it may happen that productive processes operating in different geographical locations (with different environmental temperatures) are ideally aggregated in one single process: therefore, using entropy generation to characterize gaseous fossil fuels may produce errors in estimating the cost of products. However, further investigations are required before extending such theoretical results to all the fossil fuels.

4.
Exergy based Input – Output Analysis, a novel formulation

In this research, *Input – Output analysis* and *Exergy based methods* are recognized as the most suited tools to address all the issues emerged from literature, highlighted in paragraph 1.2. Drawbacks of both the methods introduced in previous chapters can be solved by coupling them into the innovative joint approach of *Exergy based Input – Output analysis* (ExIO). This chapter focuses on the following main activities:

1. Definition of the ExIO analysis as a tool for the evaluation of *primary exergy cost* of goods and services of a given economy based on national *Monetary Input – Output Tables* (MIOTs);
2. Formalization of a *Hybrid* Input – Output technique in order to increase *accuracy* of results, evaluating primary exergy cost of detailed products;
3. Formalization of a procedure for *Thermoeconomic analysis* and *Design Evaluation* of energy systems, introducing specific indicators aimed at optimize the primary exergy cost of energy conversion systems.

4.1. Benefits in coupling Input – Output and exergy analyses

The introduction of exergy within the mathematical framework of Input – Output Analysis can be performed in two ways:

1. **Characterization of exogenous resources matrix only.** In this case, Exogenous Resources matrix is defined by means of exergy, whereas Transaction matrix and Final Demand vector are defined in monetary, physical or hybrid units. Therefore, application of Leontief Cost Model results in the evaluation of the primary exergy cost of goods and services of a generic production system in a more meaningful theoretical way with respect to other standard numeraires. Because the heating value and the exergy of fossil fuels results very close to each other [78, 112], energy and exergy costs of products will result numerically similar;
2. **Characterization of both exogenous resource matrix and input – output table.** Exergy is adopted as both numeraire and metric in Leontief's Models. This practice allows to perform Thermoeconomic analysis and Design Evaluation of the considered energy conversion system, locating and quantifying the exergy destructions and their relative costs, thus giving a better thermodynamic insight on the considered system.

4.2. Evaluating primary exergy cost through national MIOTs

As discussed in section 2.2, the application of Leontief Cost Model to a defined productive system result in specific and total costs of its final demand in terms of exogenous resources inputs. However, in modern economies, the inputs to one generic system are rarely taken directly from the environment: most likely, they are products of other systems as well. For this reason, the evaluation of *primary* resources consumption through IOA requires in principle to extend the boundaries of IO table of the system till all the exogenous inputs are directly taken from the environment, as shown in Figure 20.

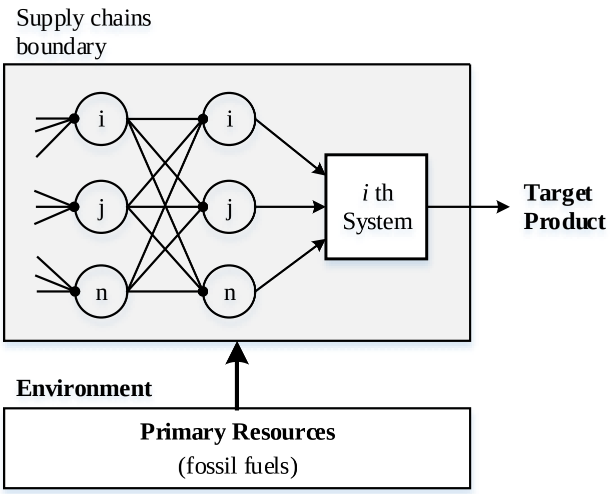

Figure 20. *Extension of system IOT to account for primary exogenous resources.*

Compile IO tables from scratch, encompassing all the supply chains of the considered system, could be a very difficult and expansive way to evaluate primary energy-resources consumption. Moreover, due to the arbitrariness in the selection of the control volume, this practice could lead to difficulties in comparing different IO analysis of a same product. It follows that rules for definition of the system's boundaries and a convenient and standardized representation of the supply chains need to be established. In order to reach such goal, literature suggests to rely on *Monetary Input – Output Tables* (MIOTs) of national economies [91, 92, 103]. Indeed, MIOTs provide a *standard*, *largely available* and *constantly updated* classification of all the economic and productive activities within a country. Thus, once a MIOT of a given country is considered and exogenous resources matrix has defined as the exergy of primary fossil fuels entering the economy, calculation of the exergy cost of national products can be performed applying both LPM and PCM.

However, this approach presents some flaws: (1) *specific assumptions are needed to treat the problem of import and export trade flows* and (2) *the economic activities are usually represented with high level of aggregation*. Both these issues may turn in low accuracy of results.

4.2.1. Monetary Input Output tables of national economies

Input – Output analysis was originally conceived with the fundamental purpose to analyze the interdependence of economic sectors within a certain nation [46, 120]. Nowadays, developments of the basic IOA framework initially set by Leontief in late 1930s are key components of many economic analysis and IO analysis is one of the most applied methods in economics [10, 129].

The MIOT of one given nation has the same structure of the IOT described in paragraph 2.2.2: all the economic and productive activities are subdivided into different *productive sectors*, or *segments*, that produce goods or services for intermediate consumption and for final demand [129]. MIOTs may be compiled according to different degree of aggregation, depending on data availability and on the purpose of IOA: producing sectors may be represented as whole industrial activities (e.g.

“manufacturing sector”), specific production industries (e.g. “steel production”) or even much smaller categories (e.g. “production of steel nails and spikes”).
As its name suggests, MIOT is compiled exclusively in monetary values. With respect to physical or hybrid units, describing products trades within a national economy using monetary values is considered as the most rational choice for many practical reasons:

- Products of national economies are, except for few cases like *Developing Countries* (DCs), composed by a very large number of both material and immaterial products as output of each productive sector. It is then very difficult to find a unique physical unit suited to account for each sectors, especially in case of high level of aggregation;
- Products trades within a country are periodically collected by means of their monetary equivalents rather than physical units: compiling an IOT in physical or even hybrid units could be then a very challenging task;
- MIOTs are constantly updated and compiled according to defined standards. Such tables are largely used for many kind of economic analyses, and their main purpose is not related to environmental accounts, which are defined in literature as a part of the “satellite accounts” [193].

The structure of MIOT of a generic national economy in a defined time frame (usually one year) is presented in Figure 21: the economy is ideally divided into distinct sectors, represented by one row and one column, according to one specific standard protocol such as the *Statistical Classification of Economic Activities in the European Community* (NACE, adopted in the European context) [61] or the *International Standard Industrial Classification of All Economic Activities* (ISIC) [49]. All the direct relations among each sector constitutes the *national transaction matrix*, in which every line represents the products sales of one sector to other sectors and every column represents the products that one sector purchases from other sectors.

	1	**…**	**n**	**Final demand**				**Total output**
Sector 1	x_{11}	$\cdots$	x_{1n}	h_1	i_1	g_1	e_1	x_1
…	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
Sector n	x_{n1}	$\cdots$	x_{nn}	h_n	i_n	g_n	e_n	x_n
Value added	l_1	$\cdots$	l_n	l_H	l_I	l_G	l_E	L
	n_1	$\cdots$	n_n	n_H	n_I	n_G	n_E	N
Imports	m_1	$\cdots$	m_n	m_H	m_I	m_G	m_E	M
Total outlays	x_1	$\cdots$	x_n	H	I	G	E	

Figure 21. *MIOT of a generic national economy. Adapted from [129].*

With reference to Figure 21, in addition to transaction matrix **Z**, final demand **f** matrix and total output vector **x** (shaded squares), MIOTs are also formed by value added matrix **v** and imports matrix **m**. Components of the final demand matrix, given by expression (4.1), represent *household purchases* (h_i), *purchases for (private) investment purposes* (i_i), *government purchases* (g_i) (federal, public, and local), and *exports* (e_i), each of one referred to the *i*th productive sector.

$$\mathbf{f}\left(n\times 4\right)=\left[\mathbf{f_H}\quad \mathbf{f_I}\quad \mathbf{f_G}\quad \mathbf{f_E}\right]\quad \rightarrow \quad \mathbf{f}=\begin{bmatrix} h_i & i_i & g_i & e_i \\ \vdots & \vdots & \vdots & \vdots \\ h_n & i_n & g_n & e_n \end{bmatrix} \tag{4.1}$$

Value added **v**, given by expression (4.2), is composed by payments for labor compensation (l_i) and government services (taxes), interests on invested capitals, land, entrepreneurship profit and other minor voices (n_i). Value added can be generated by the producing sectors expenses ($\mathbf{v_Z}$) or directly by household and govern outlays ($\mathbf{v_f}$).

$$\mathbf{v}=\left[\mathbf{v_Z}\,|\,\mathbf{v_f}\right]=\left[\begin{array}{ccc|cccc} l_1 & \cdots & l_n & l_H & l_I & l_G & l_E \\ n_1 & \cdots & n_n & n_H & n_I & n_G & n_E \end{array}\right] \tag{4.2}$$

In a similar way, total imported products **m** from other economies, vector (4.3), can be expressed as the sum of imported products by producing sectors ($\mathbf{m_Z}$) or by household and govern ($\mathbf{m_f}$).

$$\mathbf{m}=\left[\mathbf{m_Z}\,|\,\mathbf{m_f}\right]=\left[m_1\quad \cdots \quad m_n\,|\,m_H\quad m_I\quad m_G\quad m_E\right] \tag{4.3}$$

For each *i*th productive sectors of an *n* sectors economy, it is possible to write the economic production balance (4.4) that accounts for the distribution of *i*th products to other sectors and to final demand.

$$x_i=\sum_{j=1}^{n} x_{ij}+f_i \qquad \textit{with}:\quad f_i=h_i+i_i+g_i+e_i \tag{4.4}$$

Considering the endogenous production only (without consider goods or services imports), *total output* of every sector can be evaluated through expression (4.4) and can be rewritten in matrix form as showed in (4.5). In (4.5), vector **x** represents the economic value produced by each sector in the considered time window.

$$\mathbf{x}=\mathbf{Z}\mathbf{i}+\mathbf{f}\,\mathbf{i}$$

$$\begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}=\begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nn} \end{bmatrix}\cdot \mathbf{i}\left(n\times 1\right)+\begin{bmatrix} h_i & i_i & g_i & e_i \\ \vdots & \vdots & \vdots & \vdots \\ h_n & i_n & g_n & e_n \end{bmatrix}\cdot \mathbf{i}\left(4\times 1\right) \tag{4.5}$$

The *total outlays* of the *i*th sector are defined as the sum of products value from other sectors, value added and imports and result as the row sum of the corresponding matrices, expressed by relation (4.6).

$$\mathbf{x}^T=\mathbf{Z}^T\mathbf{i}+\mathbf{v_Z}^T\,\mathbf{i}+\mathbf{m_Z}^T$$

$$\begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}=\begin{bmatrix} x_{11} & \cdots & x_{n1} \\ \vdots & \ddots & \vdots \\ x_{1n} & \cdots & x_{nn} \end{bmatrix}\cdot \mathbf{i}\left(n\times 1\right)+\begin{bmatrix} l_1 & n_1 \\ \vdots & \vdots \\ l_n & n_n \end{bmatrix}\cdot \mathbf{i}\left(2\times 1\right)+\begin{bmatrix} m_1 \\ \vdots \\ m_n \end{bmatrix} \tag{4.6}$$

In MIOTs, the equality between total output and total outlays holds: for every *i*th sector, the economic output produced equals the sum of purchases, value added and imports. This equality could be extended to all the economy introducing total value added L + N and total imports M (as column sum), and the total domestic final demand H + I + G and total exports E (as row sum). In this perspective, relation (4.7) expresses the *circular* nature of the economy [129], in which total value of output equals the total value of outlays and the economy is said to be balanced.

$$\mathbf{i}(n\times1)\cdot\mathbf{x}+\mathrm{L}+\mathrm{N}+\mathrm{M}=\mathbf{i}(n\times1)\cdot\mathbf{x}+\mathrm{H}+\mathrm{I}+\mathrm{G}+\mathrm{E}=\mathrm{X} \quad (4.7)$$

If MIOT's boundary is defined as the country's border, the total amount of endogenous final demand plus the value added directly generated by household and govern outlays is the monetary aggregate known as *Gross Domestic Product* (GDP); on the other hand, *Gross National Product* (GNI) results if the MIOT includes all the products produced by all the enterprises owned by a country's citizens (no matter where they are). In other words, GDP defines its scope according to location, while GNI defines its scope according to ownership [105]. Notice that imported goods are not included in the evaluation of *GP*, as showed by (4.8).

$$GP=\mathbf{i}(1\times n)\cdot\left\{\begin{bmatrix}\mathbf{f}\\ \hline \mathbf{v_z}\end{bmatrix}\left[(n+2)\times1\right]\cdot\mathbf{i}(4\times1)\right\} \quad \rightarrow \quad GP=\begin{cases}GDP\\ GNP\end{cases} \quad (4.8)$$

A large number of nations routinely publish their MIOTs according to internationally agreed standard set of recommendations of the *System of National Accounts* (SNA), which describes macroeconomic accounts in the context of internationally agreed concepts, definitions and rules [138]. Further details about the possible uses of MIOTs for economic and statistic purposes are out of the scope of this research and are can be found in literature [105, 129].

Notice that MIOTs encompasses all the economic activities of the considered economy, and the ISIC classification defines *Mining and Quarrying* sector as the interface between the economy and the environment, that is the sector in which primary non-renewable fossil fuels enter the economy [198].

In conclusion, MIOTs provide available, constantly updated and standardized data sources for the application of both Leontief Production and Cost Models. For these reasons, use of MIOTs is recognized by the literature as the most convenient, reliable and simple way for the evaluation of primary resources cost of products [64, 92].

4.2.2. Treatment of imported products in national MIOTs

Because of economic trades of products among countries, national economies are in practice not fully closed economies and the problem of import treatment arise. Indeed, due to trade flows of products, the primary exergy cost of final demand does not consists only in the exergy directly extracted by the considered economy, but also includes the exergy cost required to extract, process and transport imported products [21].

Specifically, application of LPM and LCM to an economy described by its MIOT (endogenous production plus imports) and by its exogenous resources matrix (primary fuels extracted within the country) may produce inaccurate results because of two main reasons:

- *Imported products* comes into a country from an unknown production process: specific assumptions are needed to estimate their primary exergy cost;

- *Exported products* could be part of both intermediate consumption or final demand of other countries, whereas the MIOT of a given country usually consider exported products as part of the final demand only.

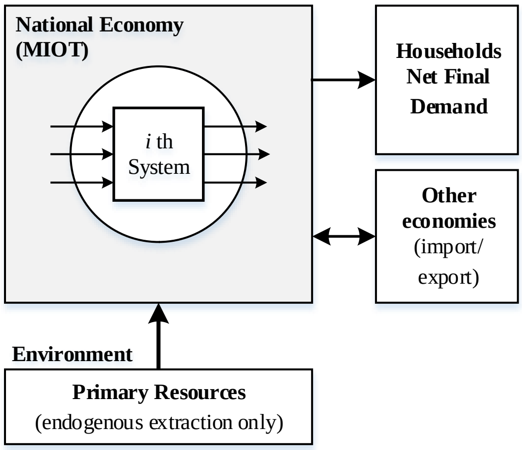

Figure 22. *Boundaries of national economies described by MIOTs. Notice the flows of imported/exported products.*

For the sake of exogenous resources accounting, it is convenient to distinguish between imports that are also endogenously produced, or *competitive imports* (subscript *c*), and those that are not domestically produced, or *noncompetitive imports* (subscript *nc*. Relation (4.3) can be rewritten and expanded according to these definitions as (4.9).

$$\mathbf{m}=\left[\begin{array}{c|c}\mathbf{m_{c,Z}} & \mathbf{m_{c,f}}\\ \hline \mathbf{m_{nc,Z}} & \mathbf{m_{nc,f}}\end{array}\right]=\left[\begin{array}{ccc|cccc} \mathrm{m}_{c,11} & \cdots & \mathrm{m}_{c,1n} & \mathrm{m}_{c,Hi} & \mathrm{m}_{c,Ii} & \mathrm{m}_{c,Gi} & \mathrm{m}_{c,Ei}\\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots\\ \mathrm{m}_{c,n1} & \cdots & \mathrm{m}_{c,nn} & \mathrm{m}_{c,Hn} & \mathrm{m}_{c,In} & \mathrm{m}_{c,Gn} & \mathrm{m}_{c,En}\\ \hline \mathrm{m}_{nc,1} & \cdots & \mathrm{m}_{nc,n} & \mathrm{m}_{nc,H} & \mathrm{m}_{nc,I} & \mathrm{m}_{nc,G} & \mathrm{m}_{nc,E}\end{array}\right] \tag{4.9}$$

Noncompetitive imports are usually internalized in one category of *competitive* imports: this assumption is realistic for large economies, for which all imported products are also endogenously produced and for which one standard classification of all economic activities is adopted [21, 136]. In this case, import matrix (4.9) can be simplified as (4.10).

$$\mathbf{m}=\left[\mathbf{m_Z}\,|\,\mathbf{m_f}\right]=\left[\begin{array}{ccc|cccc} \mathrm{m}_{c,11} & \cdots & \mathrm{m}_{c,1n} & \mathrm{m}_{c,Hi} & \mathrm{m}_{c,Ii} & \mathrm{m}_{c,Gi} & \mathrm{m}_{c,Ei}\\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots\\ \mathrm{m}_{c,n1} & \cdots & \mathrm{m}_{c,nn} & \mathrm{m}_{c,Hn} & \mathrm{m}_{c,In} & \mathrm{m}_{c,Gn} & \mathrm{m}_{c,En}\end{array}\right] \tag{4.10}$$

In the following, imports will be considered as competitive only and three import/export treatment methods are introduced. In chapter 6, such techniques are applied to different economies and results are compared.

Method a: internalization of imports with constant Input matrix

The simplest method to estimate the primary exergy cost of the final demand of a given economy through MIOTs is to consider imports as if they were endogenously produced, i.e. produced with the same efficiency of endogenous products. One reason to justify this assumption is to note that imported products would require this amount of natural resources if they were manufactured within the considered economy [21].

Practical application of this method requires to evaluate the input matrix as the amount of the exogenous resources required for the production of one unit of the *endogenous* production only, as showed in (4.11). Usually, primary fossil fuels enter the considered economy through *Mining and Quarrying sector* [49].

$$\mathbf{B_a} = \mathbf{R_a}\,\hat{\mathbf{x}}_{\mathbf{end}}^{-1} \tag{4.11}$$

Where $\mathbf{R_a}$ is the exogenous resource matrix (2.29) formed only by resources that are extracted within the considered country (that is, endogenously produced). Total production vector $\mathbf{x_{end}}$ results from the production balance (4.5): the *end* subscript is used in (4.11) to emphasize the endogenous nature of total production.

Total intermediate production $\tilde{\mathbf{Z}}$, final demand $\tilde{\mathbf{f}}$ and total production $\tilde{\mathbf{x}}$ are then computed as the matrix sum between the endogenous production and the imported products, as follows.

$$\begin{gathered} \left[\tilde{\mathbf{Z}} \middle| \tilde{\mathbf{f}}\right] = \left[\mathbf{Z} \middle| \mathbf{f}\right] + \left[\mathbf{m_Z} \middle| \mathbf{m_f}\right] \\ \tilde{\mathbf{x}} = \tilde{\mathbf{Z}}\,\mathbf{i} + \tilde{\mathbf{f}}\,\mathbf{i} \end{gathered} \tag{4.12}$$

Calculation of total and specific cost of production results from the application of LPM and LCM according to the procedure described in paragraph 2.2.2.

$$\tilde{\mathbf{A}} = \tilde{\mathbf{Z}}\hat{\tilde{\mathbf{x}}}^{-1} \quad \rightarrow \quad \tilde{\mathbf{L}} = \left(\mathbf{I} - \tilde{\mathbf{A}}\right)^{-1} \quad \rightarrow \quad \tilde{\mathbf{x}} = \tilde{\mathbf{L}}\,\tilde{\mathbf{f}} \tag{4.13}$$

$$\tilde{\mathbf{c}}_{\mathbf{a}} = \left(\tilde{\mathbf{L}}\,\tilde{\mathbf{B}}_{\mathbf{a}}\right)^{\mathrm{T}} \quad ; \quad \tilde{\mathbf{C}}_{\mathbf{a}} = \hat{\tilde{\mathbf{f}}}\,\tilde{\mathbf{c}}_{\mathbf{a}} \tag{4.14}$$

It is worth to notice that in *method a* the equality (2.38) between the estimated total cost of products $\tilde{\mathbf{C}}_{\mathbf{a}}$ and the real amount of natural resources extracted within the country is no longer respected: such difference increases as the share of imported products increases with respect to total endogenous production.

$$\left.\begin{aligned} \mathbf{R_a}(m \times n) \cdot \mathbf{i}(n \times 1) &= \mathbf{R_{a,tot}}(m \times 1) \\ \left[\mathbf{i}(1 \times n) \cdot \tilde{\mathbf{C}}_{\mathbf{a}}(n \times m)\right]^{\mathrm{T}} &= \tilde{\mathbf{C}}_{\mathbf{a,tot}}(m \times 1) \end{aligned}\right\} \quad \mathbf{R_{a,tot}} \neq \tilde{\mathbf{C}}_{\mathbf{a,tot}} \tag{4.15}$$

Method b: internalization of imports estimating the Exogenous resources matrix

As *method a*, *method b* also consists in the internalization of exogenous imports: total intermediate production, total final demand and total production (4.12) are the same as *method a*. Since technical coefficient matrix $\tilde{\mathbf{A}}$ and Leontief Inverse matrix $\tilde{\mathbf{L}}$ are here defined as in (4.13), application of LPM gives the same results as *method a*. What makes *method b* different is the definition of the exogenous resources and input matrices: fossil fuels extracted within the country and imported from other economies are both considered as primary exogenous resources, and these contributions should be carefully allocated among the different productive sectors of the economy in which they actually enter. Input matrix is then evaluated according to relation (4.16).

$$\mathbf{B_b} = \mathbf{R_b}\,\hat{\mathbf{x}}_{\mathbf{end}}^{-1} \tag{4.16}$$

Considering the intermediate production matrix, final demand and total production vectors (4.12), also used in *method a*, application of LCM results as follows.

$$\tilde{\mathbf{c}}_{\mathbf{b}} = \left(\tilde{\mathbf{L}}\,\tilde{\mathbf{B}}_{\mathbf{b}}\right)^{\mathrm{T}} \quad ; \quad \tilde{\mathbf{C}}_{\mathbf{b}} = \hat{\tilde{\mathbf{f}}}\,\tilde{\mathbf{c}}_{\mathbf{b}} \tag{4.17}$$

Also with this method, total cost of production and total exogenous resources are not equal.

$$\left.\begin{aligned} &\mathbf{R_b}\left(m\times n\right)\cdot\mathbf{i}\left(n\times 1\right) = \mathbf{R_{b,tot}}\left(m\times 1\right) \\ &\left[\mathbf{i}\left(1\times n\right)\cdot\tilde{\mathbf{C}}_{\mathbf{b}}\left(n\times m\right)\right]^{\mathrm{T}} = \tilde{\mathbf{C}}_{\mathbf{b,tot}}\left(m\times 1\right) \end{aligned}\right\} \quad \mathbf{R_{b,tot}} \neq \tilde{\mathbf{C}}_{\mathbf{b,tot}} \tag{4.18}$$

Method c: inversion of the World Input – Output Table (WIOT)

From the theoretical standpoint, treatment of imported/exported products in a not approximated way requires to define system boundaries in order to encompass all the supply chains that are directly and indirectly feeding the considered country, thus removing all the hypotheses on imported/exported products.

One practical method to pursue this objective consists in the aggregation of national MIOTs till the exogenous flows coming inside the aggregated system is formed only by primary fossil fuels directly extracted from natural environment, and to distinguish among the exported products that are part of the intermediate consumption or the final demand for each economy, resulting in a system closed with respect to trade flows. This practice results in the so-called *Regional models* [101, 217] and especially in the *Global Model* or *World Model* [54, 67, 118, 119].

To make a parallelism: as embodied cost of products is known if all direct interactions among producing sector are known – i.e. number of unknowns equals number of equations in system of equations (2.27) –, so the embodied cost of imported products among countries is known if all the direct products exchanges among countries are known and only primary resources enters each economy.

The first IO model of the world economy was conceived and implemented by Leontief to analyze scenarios about future economic development [118]. Further updates and refinements were performed by *Leontief* [121] and *Duchin* [48] to evaluate possible alternative scenarios by means of emissions, energy use and mineral extraction. Many applications of multi-regional and World input – output models are analyzed in details in [129].

Starting from the same assumptions of IO framework (paragraph 2.2.3), the general production balance (2.21) can be extended treating each one of the World country as a single producing sector according to the following conditions:

- The entire World economy can be subdivided in N national economies: each economy is represented by a MIOT. All the MIOTs are characterized by the same sectors and with the same level of aggregation;
- Destination and amount of exported products is known for all the countries;
- All quantities are expressed in the same unit of value (*€*, *USD*, etc.) defined at producer's price;
- The amount of primary exogenous resources directly extracted by each economy is known;

For a given time period, the total production balance for each of the *i*th economies (2.21) can be expressed by tracing the destination of its exported products $\mathbf{e_i}$ and considering them as part of intermediate consumption of the other *N-1* economies, as expressed by relation (4.19).

$$\mathbf{x_i} = \left[\mathbf{Z_i i}(n\times1)+\mathbf{e_i}\right]+\left(\mathbf{f_i}-\mathbf{e_i}\right) \qquad with: \;\; \mathbf{e_i} = \left(\sum_{j=1}^{N-1}\mathbf{E_{ij}}\right)\mathbf{i}(n\times1) \tag{4.19}$$

Relation (4.19) can be extended to all the *N* World economies, writing the *World production balance* showed by (4.20).

$$\mathbf{x_W} = \mathbf{Z_W i_W} + \mathbf{f_W i_{f,W}}$$

$$\begin{bmatrix} \mathbf{x_1} \\ \vdots \\ \mathbf{x_j} \\ \vdots \\ \mathbf{x_N} \end{bmatrix} = \begin{bmatrix} \mathbf{Z_1} & \cdots & \mathbf{E_{1j}} & \cdots & \mathbf{E_{1N}} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathbf{E_{j1}} & \cdots & \mathbf{Z_j} & \cdots & \mathbf{E_{jN}} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathbf{E_{N1}} & \cdots & \mathbf{E_{Nj}} & \cdots & \mathbf{Z_N} \end{bmatrix} \cdot \underset{n_{tot}\times1}{\mathbf{i_W}} + \begin{bmatrix} \mathbf{f_{11}} & \cdots & \mathbf{f_{1j}} & \cdots & \mathbf{f_{1N}} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathbf{f_{j1}} & \cdots & \mathbf{f_j} & \cdots & \mathbf{f_{jN}} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathbf{f_{N1}} & \cdots & \mathbf{f_{Nj}} & \cdots & \mathbf{f_N} \end{bmatrix}_{\mathbf{Net}} \cdot \underset{4\cdot N\times1}{\mathbf{i_{f,W}}} \tag{4.20}$$

Where *World transaction matrix* $\mathbf{Z_W}(n_{tot} \times n_{tot})$ can be expressed as the sum between the *World intermediate consumption matrix* $\mathbf{Z_{I,W}}(n_{tot} \times n_{tot})$ and the *World trade matrix* $\mathbf{E_{T,W}}(n_{tot} \times n_{tot})$, as presented by relation (4.21).

$$\mathbf{Z_W} = \mathbf{Z_{I,W}} + \mathbf{E_{T,W}}$$

$$\mathbf{Z_{I,W}} = \bigoplus_{i=1}^{N}\mathbf{Z_i}\,(n\times n) = \begin{bmatrix} \mathbf{Z_1} & - & - \\ - & \mathbf{Z_i} & - \\ - & - & \mathbf{Z_N} \end{bmatrix} \quad ; \quad \mathbf{E_{T,W}} = \begin{bmatrix} - & \mathbf{E_{1j}} & \mathbf{E_{1N}} \\ \mathbf{E_{j1}} & - & \mathbf{E_{jN}} \\ \mathbf{E_{1N}} & \mathbf{E_{Nj}} & - \end{bmatrix} \tag{4.21}$$

As shown by relation (4.21) Diagonal elements of the *World Transaction matrix* $\mathrm{Z_W}$ are composed by the direct sum of the transaction matrices of each *j*th country $\mathrm{Z_i}$, whereas extra-diagonal elements defines the interrelation among countries: $\mathrm{E_{ij}}$ represents the exported products from the *i*th country to the *j*th country. Notice that World total production vector $\mathbf{x_W}$ and World summation vector $\mathbf{i_W}$ results as column vectors of length $\mathrm{n_{tot}}$, resulting by the product between the number of producing sectors of one country *n* and the number of total countries *N*.

$$n_{tot} = n \cdot N \tag{4.22}$$

Every element of the *World final demand matrix* $f_{W,ij}$ expresses the output if the ith economy delivered to the jth country as final demand only. The column sum of $\mathbf{f_W}$ thus results as the total final demand of each country's sector diminished by the amount of exported products delivered as intermediate consumption for other economies. *World technical coefficients* and *World Leontief Inverse* matrices are derived in the same way as relations (2.22) and (2.25) as follows.

$$\mathbf{A_W} = \mathbf{Z_W}\mathbf{\hat{x}_W}^{-1} \tag{4.23}$$

$$\mathbf{L_W} = \left(\mathbf{I_W} - \mathbf{A_W}\right)^{-1} \tag{4.24}$$

The *World Identity matrix* $\mathbf{I_W}$ results as the direct sum of *N* standard identity matrices (4.25).

$$\mathbf{I_W} = \bigoplus_{i=1}^{N} \mathbf{I}(n) = \begin{bmatrix} \mathbf{I}_n & - & - \\ - & \mathbf{I}_n & - \\ - & - & \mathbf{I}_n \end{bmatrix} \tag{4.25}$$

Therefore, Leontief Production Model results as follows:

$$\mathbf{x_W} = \left(\mathbf{I_W} - \mathbf{A_W}\right)^{-1} \mathbf{f_W}\,\mathbf{i_{f,W}} \quad \rightarrow \quad \mathbf{x_W} = \mathbf{L_W}\mathbf{f_W}\,\mathbf{i_{f,W}} \tag{4.26}$$

World exogenous resources matrix $\mathbf{R_W}$ results as bordered matrix formed by exogenous resources matrices of each country; evaluation of *World input matrix* $\mathbf{B_W}$ is then straightforward. Both matrices are defined as $m \times n_{tot}$.

$$\mathbf{R_W} = \left[\mathbf{R_1} \quad \cdots \quad \mathbf{R_i} \quad \cdots \quad \mathbf{R_N}\right] \quad \rightarrow \quad \mathbf{B_W} = \mathbf{R_W}\,\hat{\mathbf{x}}_{\mathbf{W}}^{-1} \tag{4.27}$$

Finally, application of Leontief Cost Model (4.28) returns specific cost matrix $\mathbf{c_W}$ and total cost matrix $\mathbf{C_W}$, both of $n_{tot} \times m$ dimensions.

$$\mathbf{c_W} = \left(\mathbf{B_W}\mathbf{L_W}\right)^{\mathrm{T}} \quad ; \quad \mathbf{C_W} = diag\left(\mathbf{f_W}\mathbf{i_{f,W}}\right)\mathbf{c_W} \tag{4.28}$$

Notice that, since no assumptions were made for imports/export treatment, the equality (4.29) between total cost of World production and the total amount of natural resources absorbed by the World economy holds. Notice that in (4.29) all the *m* kind of resources must be measured in homogeneous units.

$$\left.\begin{aligned} \mathbf{i}(1\times m)\cdot\mathbf{R_W}\left(m\times n_{tot}\right)\cdot\mathbf{i}\left(n_{tot}\times 1\right) &= R_{W,tot} \\ \mathbf{i}(1\times m)\cdot\left[\mathbf{i}\left(1\times n_{tot}\right)\cdot\mathbf{C_W}\left(n_{tot}\times m\right)\right]^{\mathrm{T}} &= C_{W,tot} \end{aligned}\right\} \quad R_{W,tot} = C_{W,tot} \tag{4.29}$$

Advantages and drawbacks of import/export treatment methods

IO framework can be used to study both single economies in isolation (nations or regions), aggregates regions or even the entire World economy: the latter practice allows to make explicit the economic connections among countries or regions in the model.
Choice of import/export treatment method is crucial in order to make results of different Exergy based Input – Output analysis applied to a same economy comparable to each other. Moreover, as results of the case studies presented in chapter 6 will show, this choice could largely affects results of the analysis and these changes are strictly dependent by the structure and the characteristics of the analyzed economy. For these reasons, import/export treatment method should be carefully chosen. In the following, main advantages and drawbacks of each methods are listed:

Method a:

- Simple application: no specific assumptions are needed to estimate exogenous resources matrix;
- Only MIOT of the analyzed economy is required;

- Results can be affected by relevant uncertainties, especially in economies strongly dependent by imported/exported products;
- It is not applicable if the considered economy does not extract primary fuels;
- Since exports are part of final demand, specific exergy costs of products results underestimated with respect to real values;

Method b:

- Only MIOT of the analyzed country is required;
- Nowadays, that national economies are strongly connected by flows of imported and exported products. Therefore, evaluation of primary exergy cost of products with *method a* could produce very inaccurate results, especially with economies strongly based on imports. Moreover, if the considered country do not even extract primary fossil fuels, the exogenous resources matrix is empty and application of *method a* is no longer possible.
- It requires specific assumptions in order to allocate imported fossil fuels over the different producing sectors of the economy: definition of exogenous resources matrix is critical and results of different IOA obtained with this method could be not comparable;
- Exergy cost involved in extraction, process and transport of imported fuels are neglected;
- Application of LCM results in a double accounting of the imported fossil fuels, thus specific exergy cost of products results overestimated with respect to results of method a;
- Since exports are part of final demand, specific exergy costs of products results underestimated with respect to real values also in this case;

Method c:

- It allows to analyze and to understand the trade relationships between countries;
- It allows to determine the real amount of primary exergy involved in national production, thus revealing the international resources dependencies among regions;
- No assumptions on imported/exported products are made, thus results can be seen as exact, at least from a theoretical point of view;
- Application of shocks on final demand or technology can reveal its effects on other World economies;
- IO table of all countries must have the same producing sectors in order to be included (as diagonal blocks) in the World transaction matrix [142];
- Large amount of data are required, then results could be affected by large uncertainties;
- Compilation of World IOT is very complicated because all countries exports must be identified and properly allocated in the extra-diagonal matrices of the World transaction matrix;

Because *method a* is widely adopted in literature, in the following imported goods are treated with such method, unless otherwise stated.

4.3. Increase accuracy of results based on Hybrid Exergy based IO Analysis

As can be inferred from section 4.2, MIOTs provide available and constantly updated data sources for the evaluation of primary exergy cost of products. Apart from import treatment method, which can significantly affects quality of results, one of the major problems of this approach resides in the high aggregation level of MIOTs, which makes hard to distinguish among the cost of different outputs produced by the same sector. Such high aggregation level of MIOTs causes low accuracy of results: for example, the production of 1 € of the ISIC sector no. 3110 *Manufacture of electric motors, generators and transformers* [198] has the same environmental burdens, whether it is 1 € of motor, generator, transformer or any other product or service out of any firm of the considered economy.

If the analyst's objective is to evaluate the primary exergy cost of one specific product or process, standard ExIO analysis is no longer adequate mainly due to its coarse sector aggregation [174]. To overcome this problem, a different approach based on the so-called *Hybrid Input – Output* methods can be used [170, 173]. Using this approach, aggregation of the sector is selectively gained to adequate level for the considered process or product using detailed process specific information, while the supply chains still covers the entire economy represented by national MIOTs [137, 174].

Literature occasionally defines Hybrid IO methods as a *mix* between Process Analysis and Input – Output analysis [92, 170]. Since mathematical equivalency between PA and IOA has been showed in paragraph 2.4.1, this definition is likely to be misleading. Differently from literature, the term *hybrid* is here used to define the source of data: products cost is computed within the analytical framework of IO analysis, relying on data given by both MIOT's datasets and specific survey of the detailed product analyzed [92, 170].

4.3.1. Hybrid Exergy based Input – Output analysis: general formulation

The Hybrid model is presented here as a part of the general framework of Exergy based Input – Output analysis. It is defined as an alternative general formalization of the Hybrid models suggested by *Suh et al.* [170], *Joshi* [90, 103] and *Ferrao et al.* [64]. The algebraic formulation of Leontief Production and Cost models for the Hybrid model works in a similar way of the standard IO model, defining a new transaction matrix that includes the national MIOT (*background system*, or supply chains) linked to the IO table of the specific production process for which a detailed analysis is required (*foreground system*). With reference to Figure 23, generalized formulation of the Hybrid model is presented below.

Given a specific national economy represented by a MIOT, it can always be expressed as an *Hybrid system H* composed by the *National economy N* (background system) and by a *Productive system S* (foreground system) operating within one specific *j*th producing sector of the considered national economy. Therefore, for a given time period, usually a year, the total production balance of the Hybrid system *H*, can be expressed by relation (4.30).

$$\mathbf{x_H} = \mathbf{Z_H i} + \mathbf{f_H}$$

$$\begin{bmatrix} \mathbf{\bar{x}_N} \\ \mathbf{x_S} \end{bmatrix} = \begin{bmatrix} \mathbf{\bar{Z}_N} & \mathbf{E_{NS}} \\ \mathbf{E_{SN}} & \mathbf{Z_S} \end{bmatrix} \cdot \mathbf{i}\left[\left(n+s\right)\times 1\right] + \begin{bmatrix} \mathbf{\bar{f}_N} \\ \mathbf{f_S} \end{bmatrix} \cdot \mathbf{i}\left(4\times 1\right) \tag{4.30}$$

Where $\mathbf{x_H}[(n+s)\times 1]$ is the *hybrid total production vector*, $\mathbf{Z_H}[(n+s)\times(n+s)]$ and $\mathbf{f_H}[(n+s)\times 4]$ are respectively the *hybrid transaction* and the *hybrid final demand matrices*. Notice that the above introduced hybrid vector and matrices may be defined in mixed units: indeed, IOT of the foreground system *S* could be defined in physical, monetary or even hybrid units.

Since the foreground system *S* operates inside a given national economy *N*, production balance (4.30) must be representative of the total production of the national economy *N*, defined by (2.21). Therefore, the aforementioned vector and matrices have to be carefully defined in order to avoid double accounting errors in results of LPM and LCM: in other words, the productive system have to be *extracted* from the national economy in which it operates.

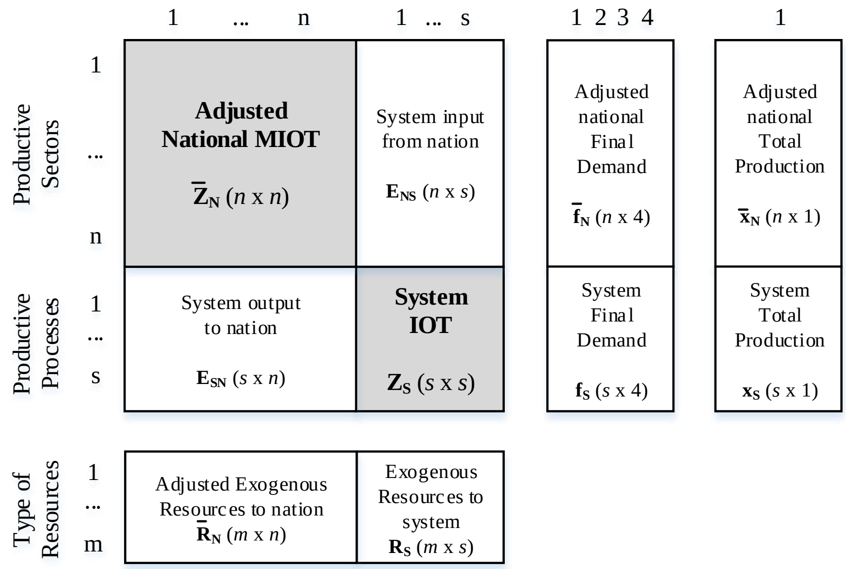

Figure 23. *Input Output table for Hybrid Analysis.*

With reference to Figure 23, the hybrid balance (4.30) is then composed by the following terms:

- $\bar{\mathbf{Z}}_{\mathbf{N}}$, $\bar{\mathbf{f}}_{\mathbf{N}}$, $\bar{\mathbf{x}}_{\mathbf{N}}$ *Adjusted* National transactions, final demand and total production;
- $\mathbf{Z}_{\mathbf{S}}$, $\mathbf{f}_{\mathbf{S}}$, $\mathbf{x}_{\mathbf{S}}$ System transactions, final demand and total production;
- $\mathbf{E}_{\mathbf{NS}}$ *Upstream cutoff matrix*, defining outputs from Nation to System;
- $\mathbf{E}_{\mathbf{SN}}$ *Downstream cutoff matrix*, defining outputs from System to Nation;

Each element of *upstream cutoff matrix* $\mathbf{E}_{\mathbf{NS}}$ represents the amount of product that goes from one specific sector of the national economy to one specific process of the considered system. Because each of the lines in IOTs must be expressed in homogeneous units, quantities in $\mathbf{E}_{\mathbf{NS}}$ must be defined in monetary units at producer's price. Conversely, each element of *downstream cutoff matrix* $\mathbf{E}_{\mathbf{SN}}$ represents the amount of product directed from one process of the system to one sector of the national economy and must be expressed in the same unit of the corresponding productive process.
Once the *j*th sector of the national economy in which the system operates and the upstream cutoff matrix $\mathbf{E}_{\mathbf{NS}}$ are known, the adjusted National transaction matrix $\bar{\mathbf{Z}}_{\mathbf{N}}$ can be derived subtracting total products absorbed by *S* (column sum of matrix $\mathbf{E}_{\mathbf{NS}}$) from the intermediate inputs of the *j*th sector of *N* ($\mathbf{Z}_{\mathbf{N,c:j}}$ indicates the *j*th column of $\mathbf{Z}_{\mathbf{N}}$), as showed in relation (4.31).

$$\bar{\mathbf{Z}}_{\mathrm{N}} \quad \rightarrow \quad \bar{\mathbf{Z}}_{\mathrm{N},c:j} = \mathbf{Z}_{\mathrm{N},c:j}\left(n\times1\right)-\left[\mathbf{E}_{\mathrm{NS}}\left(n\times s\right)\cdot\mathbf{i}\left(s\times1\right)\right] \qquad (4.31)$$

Similarly, if the system *S* produces goods or services for the final demand, the national adjusted final demand matrix $\bar{\mathbf{f}}_{\mathbf{N}}$ have to be derived subtracting total products produced by the *S* from the final demand of *j*th sector ($\mathbf{f}_{\mathbf{N,r:j}}$ indicates the *j*th row of $\mathbf{f}_{\mathbf{N}}$ matrix), as showed in (4.32).

$$\bar{\mathbf{f}}_{\mathbf{N}} \quad \rightarrow \quad \bar{\mathbf{f}}_{\mathrm{N},r:j} = \mathbf{f}_{\mathrm{N},r:j}(1\times 4) - \left\{\mathbf{i}(1\times s)\cdot\left[\hat{\mathbf{p}}_{\mathbf{S}}(s\times s)\cdot\mathbf{f}_{\mathbf{S}}(s\times 4)\right]\right\} \tag{4.32}$$

Because final demand matrices of *N* and *S* may be expressed in non-homogeneous units, final demand matrix of system *S* have to be pre-multiplied by the *S average product's price vector* $\mathbf{p_S}(s \times 1)$.
The evaluation of the *adjusted total production vector* is straightforward and results by (4.33). Notice that because system *S* operates within the nation *N*, total intermediate production of the nation remains constant. Therefore, its total production may change only if the system *S* produces products for final demand purposes.

$$\bar{\mathbf{x}}_{\mathbf{N}} = \left[\bar{\mathbf{Z}}_{\mathbf{N}} \quad \mathbf{E}_{\mathbf{NS}}\right]\cdot\mathbf{i}\left[(n+s)\times 1\right] + \bar{\mathbf{f}}_{\mathbf{N}}\cdot\mathbf{i}(4\times 1) \tag{4.33}$$

Once the hybrid IOT has been defined, practical application of IOA continues as usual, defining of hybrid technical coefficient matrix and hybrid Leontief Inverse matrix (4.34) and applying of Leontief Production Model (4.35). Both hybrid technical coefficient and Leontief Inverse matrices are defined as square matrices of $(n + s)$ rows and columns.

$$\mathbf{A_H} = \mathbf{Z_H}\hat{\mathbf{x}}_{\mathbf{H}}^{-1} \quad \rightarrow \quad \mathbf{L_H} = (\mathbf{I_H} - \mathbf{A_H})^{-1} \tag{4.34}$$

$$\mathbf{x_H} = (\mathbf{I_H} - \mathbf{A_H})^{-1}\mathbf{f_H} \quad \rightarrow \quad \mathbf{x_H} = \mathbf{L_H}\mathbf{f_H} \tag{4.35}$$

Evaluation of the primary exergy cost of the hybrid final demand requires definition of *hybrid exogenous resources matrix* and *hybrid input matrix* as in relation (4.36). Both these matrices are defined as $[m \times (n + s)]$ rows and columns.

$$\mathbf{R_H} = \left[\bar{\mathbf{R}}_{\mathbf{N}} \middle| \mathbf{R_S}\right] \quad \rightarrow \quad \mathbf{B_H} = \mathbf{R_H}\,\hat{\mathbf{x}}_{\mathbf{H}}^{-1} \tag{4.36}$$

If the system *S* absorbs primary resources, before applying (4.36) it is required to evaluate the *adjusted exogenous resources matrix* $\bar{\mathbf{R}}_{\mathbf{H}}$ subtracting the exogenous resources absorbed by *S* from the exogenous resources absorbed by *j*th sector in which *S* operates.

$$\bar{\mathbf{R}}_{\mathbf{N}} \quad \rightarrow \quad \mathbf{R}_{\mathrm{N},c:j}(m\times 1) - \left[\mathbf{R_S}(m\times s)\cdot\mathbf{i}(s\times 1)\right] \tag{4.37}$$

Finally, evaluation of both specific and total primary exergy cost of the hybrid final demand results from the application of Leontief Cost Model. In relation (4.38), specific and total costs matrices can be seen as formed by the cost matrices of national products augmented by the cost matrices of system products.

$$\mathbf{c_H} = \left[\frac{\mathbf{c}_{\mathbf{H,N}}(n\times m)}{\mathbf{c}_{\mathbf{H,S}}(s\times m)}\right] = (\mathbf{B_H}\,\mathbf{L_H})^{\mathrm{T}} \;; \quad \mathbf{C_H} = \left[\frac{\mathbf{C}_{\mathbf{H,N}}(n\times m)}{\mathbf{C}_{\mathbf{H,S}}(s\times m)}\right] = \hat{\mathbf{f}}_{\mathbf{H}}\,\mathbf{c_H} \tag{4.38}$$

The Hybrid Exergy based Input – Output analysis, here presented in its general formulation, is useful if the aim of the analyst is to increase the accuracy of the results given by IOA based on national MIOTs. For instance, since primary exergy cost of the final demand delivered by the energy sector does not distinguish among generating electricity using a 50-years old coal plant and using a new

combined cycle plant, H-ExIO can be used to split the energy sector into many different generating technologies, returning more detailed and meaningful results.
Finally, if the size of the System and the Nation are very different in terms of total production, application of H-ExIO analysis could be performed even without adjusting national transaction and final demand matrices: because the system *S* is not mathematically extracted from national economy *N*, this practice results in a double accounting error.

4.3.2. H-ExIO: final demand approach

If the objective of the analyst consists in the evaluation of the total primary exergy cost of products out of one *specific system S* rather than to increase the accuracy of all the results of IOA, application of the general H-ExIO model above formalized is not adequate and have to be modified.
Indeed, application of the standard H-ExIO model above descripted results in specific and total primary exergy costs of the final demand produced by both the nation *N* and the system *S*. Therefore, if the products of system *S* are required for intermediate consumption only, their total primary exergy cost results equal to zero while their specific costs represent the primary exergy requirements of *one marginal unit* of each product delivered as final demand.
With reference to the hybrid system depicted in Figure 23, the hybrid production balance (4.30) is formulated as (4.39): system *S* absorbs all the required inputs from the nation *N* through the upstream cutoff matrix $\mathbf{E_{NS}}$, and deliver <u>*all*</u> of its products as final demand only, precisely as *household purchases*. In this approach, downstream cutoff matrix $\mathbf{E_{SN}}$ become a part of the final demand matrix of the system *S*.

$$\mathbf{x_H} = \tilde{\mathbf{Z}}_\mathbf{H}\mathbf{i} + \tilde{\mathbf{f}}_\mathbf{H}$$

$$\begin{bmatrix} \bar{\mathbf{x}}_\mathbf{N} \\ \mathbf{x_S} \end{bmatrix} = \underbrace{\begin{bmatrix} \bar{\mathbf{Z}}_\mathbf{N} & \mathbf{E_{NS}} \\ - & \mathbf{Z_S} \end{bmatrix} \cdot \mathbf{i}\left[(n+s)\times 1\right]}_{\tilde{\mathbf{Z}}_\mathbf{H}\mathbf{i}} + \underbrace{\begin{bmatrix} \bar{\mathbf{f}}_\mathbf{N} \\ \mathbf{f_S} \end{bmatrix} \cdot \mathbf{i}(4\times 1) + \begin{bmatrix} \mathbf{0}(n\times 1) \\ \mathbf{E_{SN}} \cdot \mathbf{i}(n\times 1) \end{bmatrix}}_{\tilde{\mathbf{f}}_\mathbf{H}} \quad (4.39)$$

Adjusted national transaction matrix $\bar{\mathbf{Z}}_\mathbf{N}$ and hybrid exogenous resources matrix $\bar{\mathbf{R}}_\mathbf{H}$ are still evaluates according to (4.31) and to (4.37). Adjusted national final demand matrix $\bar{\mathbf{f}}_\mathbf{N}$ is evaluated through (4.40), where $\mathbf{p_S}(s \times 1)$ still represents *average product's price vector*.

$$\bar{\mathbf{f}}_{\mathbf{N},r:j} = \underset{1\times 4}{\mathbf{f}_{\mathbf{N},r:j}} - \left\{ \underset{1\times s}{\mathbf{i}} \cdot \left[\underset{s\times s}{\hat{\mathbf{p}}_\mathbf{S}} \cdot \left(\underset{s\times 4}{\mathbf{f_S}} + \left[\mathbf{E_{SN}} \cdot \underset{n\times 1}{\mathbf{i}} \middle| \underset{s\times 3}{\mathbf{0}} \right] \right) \right] \right\} \quad (4.40)$$

Total adjusted national production $\bar{\mathbf{x}}_\mathbf{N}$ remains constant and can be still evaluated through (4.33). Therefore, total hybrid production vector $\mathbf{x_H}$ is equal to the one defined in (4.33).
Once *modified* hybrid transaction matrix $\tilde{\mathbf{Z}}_\mathbf{H}$ and final demand matrix $\tilde{\mathbf{f}}_\mathbf{H}$ have been evaluated, application of LPM and LCM follows according to relations (4.34), (4.35) and (4.38).
The approach here formalized is theoretically introduced as *Model II* by *Joshi* [103], *Final Demand Approach* by *Miller and Blair* [129] and *Input – Output Hybrid method* by *Suh and Huppes* [89, 170].
Because System's products could actually feed National interindustry production, rather than final demand, this practice results in an underestimation of the specific and total costs of the National products. Specifically, the more the size of the analyzed System and the Nation are different (in

terms of total production), the more this assumption is acceptable and it does not significantly affects the accuracy of results.
In the following, this modified H-ExIO analysis is called *Final Demand approach*.

4.3.3. H-ExIO as a tool for Life Cycle Assessment

The Final Demand approach formalized in the previous paragraph is adopted to evaluate the primary exergy cost of a defined final demand produced by a system in a given time period. However, this exergy cost does not encompass all the primary exergy requirements of the considered final demand. Indeed, such evaluation should take into account the primary exergy expenses due to all the life cycle phases of the productive system: production, operation and disposal.
As stated in section 2.1.2, the procedure of LCA requires a careful definition of both the *purpose* and the *boundaries* (spatial and temporal) of the considered system before starting any further environmental impact analysis.

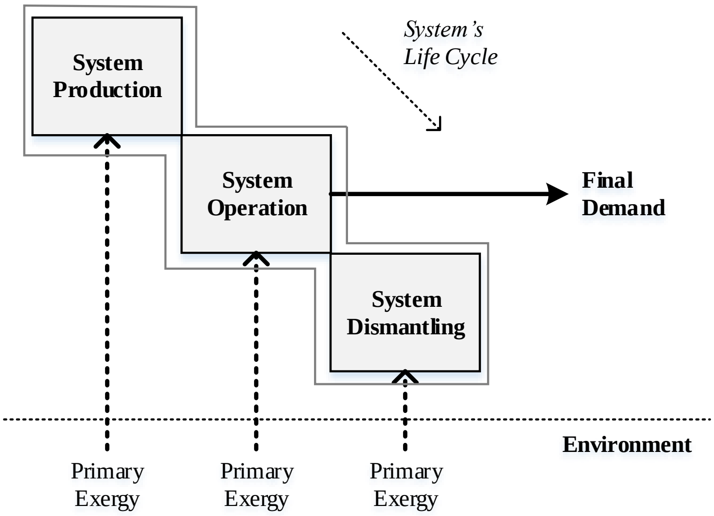

Figure 24. *Life Cycle phases of a generic productive system.*

Once the *foreground system S*, its *life cycle phases* and its *final demand* have been defined, the analysis proceed with the evaluation of the primary exergy requirements for each of the LC-phases of the foreground system (Figure 24). If a LC-phase lasts more than a year, the analyst should carefully split this phase and use different MIOTs (if available) to characterize the background system (this usually happens with *operation* phase). The exergy requirements of all the LC-phases are then summed up as in (4.41) and specific costs are finally obtained by a proper *allocation* of the total cost $\mathbf{C}_{\mathbf{S,LC}}$ on the final demand of system *S*.

$$\mathbf{C}_{\mathbf{S,LC}} = \mathbf{C}_{\mathbf{S,construction}} + \mathbf{C}_{\mathbf{S,operation}} + \mathbf{C}_{\mathbf{S,disposal}} \tag{4.41}$$

If the LC of the analyzed system is developed in future years, the most recent MIOT can be adopted to characterize the background system: this turns out to be the only viable practice to perform an H-ExIO analysis.
Finally, if the analyzed system produces exergy during its operative phase, the *Net-primary exergy cost* can be evaluated as the difference between the total primary exergy cost given by (4.41) and

the total amount of exergy produced by the system: the use of H-ExIO method for LCA and Thermoeconomic analysis of energy conversion systems is discussed in the following section.

4.4. Thermoeconomic Design Evaluation of energy systems

If H-ExIO is used for the analysis of energy conversion systems, it is possible to compile the foreground IOT and the exogenous resources matrix by means of exergy. In this way, exergy is adopted as both numeraire and metric in Leontief Production and Cost Models: in addition to the evaluation of specific and total exergy cost of products, the so-called *Thermoeconomic Design Evaluation* process can be performed, allowing to evaluate the *exergy costs of exergy destructions* and thus giving a better thermodynamic insight of the considered energy conversion system. This practice has been originally conceived, formalized and applied by *Valero and colleagues* through many publications and can be considered the state of the art in the field of *Thermoeconomics* [2, 66, 187, 188, 200, 201, 208, 209].
Nevertheless, the evaluation of non-renewable energy resources through the approach proposed by Valero takes into account only direct exergy required by the considered system, disregarding all the indirect exergy requirements associated to goods and services for which the exergy content cannot be defined. This may lead to misleading results, especially in the following two cases:

- Life Cycle of *complex energy systems*, such as Fuel Cells or chemical processing plants, may require large amounts of goods and services that are not quantifiable by means of exergy but that cause additional indirect exergy requirements;
- Operation of *renewable energy systems* does not directly absorb non-renewable fuels, but non negligible consumptions of fossil fuels may occur in their supply chains.

As will be showed in chapter 6, productive sectors of the economy that are closer to the environment (e.g. the energy sector) present small contributions of indirect exergy cost with respect to direct contributions. Therefore, if the analyzed energy system directly absorbs non-renewable fuels, the indirect requirements of supply chains may be smaller compared to the direct ones. However, literature clearly states that this conclusion may be false, so a quantitative check is always required for every specific case [22].
In the following, the approach of *standard Thermoeconomic analysis* is briefly introduced and reformulated through the IO mathematics as the *Thermoeconomic Input – Output analysis*. The novel approach of *Hybrid Exergy based Input – Output analysis* is finally proposed.

4.4.1. Standard Thermoeconomic analysis

Let us consider one generic energy system formed by n processes operating in a defined time frame (as in Figure 6). First step for the application of *Thermoeconomic analysis* (TA) is to define the system of linear equations (4.42) for each *i*th process.

$$\begin{cases} a: \quad Ex_{R,i} = Ex_{P,i} + Ex_{L,i} + Ex_{D,i} \\ b: \quad C_{R,i} = C_{P,i} \\ c: \quad C_{j,i} = c_{j,i} \cdot Ex_{j,i} \end{cases} \tag{4.42}$$

a. *Exergy accounting:* all the flows of exergy that cross the process boundaries are classified according to *Resource - Product - Loss* paradigm (RPL), based on their economic purpose. Further details and rules for the application of the RPL paradigm are given in literature [14, 145, 206]. Notice that the *exergy functional efficiency* of the process can be evaluated according to (4.43);

$$\eta_{ex,\mathrm{i}} = \frac{Ex_{P,i}}{Ex_{R,i}} \tag{4.43}$$

b. *Cost balance:* it express the conservation of total cost between resources and products of the process. It can be defined in any kind of units, according to the purpose of TA, e.g. *J* of exergy, *kg* of CO_2, € of monetary value, and so on. Specifically, if total costs are expressed by means of exergy, application of TA takes the name of *Exergy Cost analysis*. Differently, if total cost is measured in monetary value, TA is called *Exergo-economic Cost analysis* [206, 207].
c. *Constitutive relation:* it expresses the total cost of the *j*th contribution C_{ji} as the product between its exergy Ex_{ji} and its specific cost per exergy unit c_{ji}.

In the following, cost balance *b* is expressed by means of exergy. For each of the *i*th systems of equations (4.42), combination of relations *b* and *c* allows to rewrite the cost balance as follows:

$$c_{R,i}Ex_{R,i} = c_{P,i}Ex_{P,i} + c_{L,i}Ex_{L,i} \tag{4.44}$$

According to cost accounting practice, the cost should be allocated on useful products only, that is, specific cost of losses is assumed as zero. the specific exergy cost of product can be evaluated as follows:

$$c_{\mathrm{P},i} = c_{R,i}\frac{Ex_{R,i}}{Ex_{P,i}} + \cancel{c_{L,i}\frac{Ex_{L,i}}{Ex_{P,i}}} \tag{4.45}$$

Substituting the exergy balance *a* into the cost balance (4.44), the *cost structure* of the product is obtained:

$$Ex_{R,i} = Ex_{P,i} + Ex_{(L+D)i} \quad \rightarrow \quad \begin{cases} c_{\mathrm{P},i} = c_{R,i} + c_{R,i}\dfrac{Ex_{(L+D)i}}{Ex_{P,i}} \\ c_{\mathrm{P},i} = c_{R,i} + c_{P,i}\dfrac{Ex_{(L+D)i}}{Ex_{R,i}} \end{cases} \tag{4.46}$$

Relation (4.46) reveals that the exergy cost of products is the sum of two components: the exergy cost of resources and the exergy cost increase caused by irreversibilities (exergy loss and destruction). The latter can be evaluated assuming that the component works at constant rate of *product* or *resource*: in the first case additional irreversibilities will cause additional resource consumption, whereas in the second case additional irreversibilities will cause a loss in the product.

$$C_{(L+D)i} \quad \rightarrow \quad \begin{cases} C_{(L+D)i} = c_{R,i}Ex_{(L+D)i} \\ C_{(L+D)i} = c_{P,i}Ex_{(L+D)i} \end{cases} \tag{4.47}$$

In order to obtain the specific exergy cost of product (and its structure) and the cost of exergy loss and destruction for all the n components of the system, it is required to solve a system of n linear equations in the form of (4.44).
Especially for complex systems, it may happen that the number of components n is smaller than the number of connections among components m. For such reason, the system of linear equations results undetermined and a number $r = m - n$ of *auxiliary relations* are required. More details about this topic can be found in literature [145, 206].
The two main purposes of standard Thermoeconomic analysis are:

- *Cost assessment*: consists in the evaluation of the specific and total costs of products and their respective structures, as showed by (4.45) and (4.46);
- *Design Evaluation*: consists in the evaluation and the optimization of the *cost of exergy loss and destruction*, which represent the amount of additional resources (or alternatively, products losses) caused by the irreversibilities.

In standard exergy analysis of productive systems composed by multiple processes, as in Figure 6, evaluation of exergy destructions caused by each process serves to identify the most relevant thermodynamic inefficiencies within the system, thus providing useful information for a further *thermodynamic* optimizations. In a different manner, Design Evaluation (DE) is useful to understand how such thermodynamic inefficiencies are related to the direct and indirect resource requirements of the *i*th process, thus giving a better insight on the role of thermodynamic inefficiencies on the cost formation process of the system's products.
Further methodological aspects are required for the application of TA to energy systems: definition of the *Fuel-Product structure*, definition of *auxiliary relations*, concept of *Junction ratios* and further details of the *Thermoeconomic indexes*. These concepts are not relevant for the purpose of this section and can be retrieved in literature [2, 14, 192, 201, 208, 209].

4.4.2. Thermoeconomic Input – Output analysis

Definition of IO model for exergy cost analysis

As introduced in the beginning of the current section, standard Thermoeconomic analysis was reformulated by *Valero* and colleagues through the Input – Output mathematics and takes the name of *Thermoeconomic Input – Output analysis* (TIOA). In this paragraph, an alternative formalization of TIOA is proposed, in order to provide the proper structure for the evaluation of *primary* exergy costs through the hybrid approach formulated in paragraph 4.4.3.
Any energy system can be represented as a set of components linked to each other and to the environment by physical flows expressed by means of exergy. As for traditional Thermoeconomic analysis, these contributions can be classified according to their *economic* purpose as *Resources*, *Products* or *Losses* (RPL criterion). This classification allows to distinguish among:

- *Productive components (P)*: whose main purpose is to generate a useful product;
- *Dissipative components (D)*: whose are responsible for the generation of losses and residues that are not considered as useful product of the system;

The energy system introduced in previous paragraph is then composed by a total number of components $n = n_P + n_D$. For ease of mathematical notation, the set of productive components

$P = \{1, \dots, n_P\}$ and the set of dissipative components $D = \{n_P + 1, \dots, n\}$ can be defined. For this system, the exergy balance (4.48) can be written.

$$\mathbf{x_{ex}}(n\times 1) = \mathbf{Z_{ex}}(n\times n)\mathbf{i}(n\times 1) + \mathbf{w_{ex}}(n\times 1) \tag{4.48}$$

Elements of the *Transaction matrix* $\mathbf{Z_{ex}}(n \times n)$, also called *Resource – Product table* (RP table), represent the amount of exergy produced by ith component and fueled as a resource to jth component. Notice that the elements of $\mathbf{Z_{ex}}$ are easy to calculate as long as a single component and/or a single stream are considered. However, in case the products of more than one component are used concurrently by more than one other component, a rational pattern is compulsory in order to allocate the total product to each user component, consistently with their respective resources. This task is accomplished through the introduction of the so-called *exergy junction ratios* r, which allocate the product of each producing component to each user component proportionally to the exergy these last use as a resource. More details can be retrieved in literature [199].

$$\mathbf{Z_{ex}}(n\times n) = \left|Ex_{ij}\right| \qquad i, j \in P \cup D \tag{4.49}$$

The amount of exergy provided to the environment from productive and dissipative components is respectively collected in the *final demand vector* $\mathbf{f}(n_P \times 1)$ and in the *residue vector* $\mathbf{g}(n_D \times 1)$: these vectors define the *system output vector* $\mathbf{w_{ex}}(n \times 1)$ according to (4.50).

$$\mathbf{w_{ex}} = \begin{bmatrix}\mathbf{f}\\ \mathbf{g}\end{bmatrix} \quad \rightarrow \begin{cases}\mathbf{f}(n_P\times 1) = \left|Ex_{i0}\right| & i\in P\\ \mathbf{g}(n_D\times 1) = \left|Ex_{j0}\right| & j\in D\end{cases} \tag{4.50}$$

The *exogenous resource vector* $\mathbf{R_{ex}}(n \times 1)$ collects the amount of exergy directly fueled to each component from the environment.

$$\mathbf{R_{ex}} = \left|Ex_{0i}\right| \qquad i\in P\cup D \tag{4.51}$$

Technical coefficients matrix $\mathbf{A_{ex}}(n \times n)$ and *input vector* $\mathbf{B_{ex}}(n \times 1)$ are defined according to standard IOA as follows.

$$\mathbf{A_{ex}} = \mathbf{Z_{ex}} \cdot \mathbf{\hat{x}_{ex}}^{-1} \qquad \rightarrow \qquad \left|\mathbf{A_{ex}}\right|_{ij} = \frac{\left|\mathbf{Z_{ex}}\right|_{ij}}{\left|\mathbf{x_{ex}}\right|_{j}} = \frac{Ex_{ij}}{Ex_{P,j}} = a_{ex,ij} \tag{4.52}$$

$$\mathbf{B_{ex}} = \mathbf{R_{ex}} \cdot \mathbf{\hat{x}_{ex}}^{-1} \qquad \rightarrow \left|\mathbf{B_{ex}}\right|_{i} = \frac{\left|\mathbf{R_{ex}}\right|_{i}}{\left|\mathbf{x_{ex}}\right|_{i}} = \frac{Ex_{0i}}{Ex_{P,i}} = b_{ex,ij} \tag{4.53}$$

Thanks to the introduced definitions, it is possible to evaluate the specific and total exergy cost of both system products and residues through LPM and LCM, according to (4.54), where $\mathbf{c_{ex}}(n \times 1)$ is the *specific cost vector*, $\mathbf{C_{ex}}(n \times 1)$ is the *total exergy cost vector*, and $\mathbf{L_{ex}}(n \times n)$ is the *Leontief inverse matrix*.

$$\mathbf{L_{ex}} = \left(\mathbf{I} - \mathbf{A_{ex}}\right)^{-1} \quad \rightarrow \quad \begin{cases}\mathbf{c_{ex}} = \left(\mathbf{B_{ex}}\mathbf{L_{ex}}\right)^{\mathrm{T}}\\ \mathbf{C_{ex}} = \mathbf{\hat{w}_{ex}} \cdot \mathbf{c_{ex}}\end{cases} \tag{4.54}$$

Notice that relation (4.54) is just a compact and smart way to solve the system of equations composed by the n cost balances defined as (4.44).

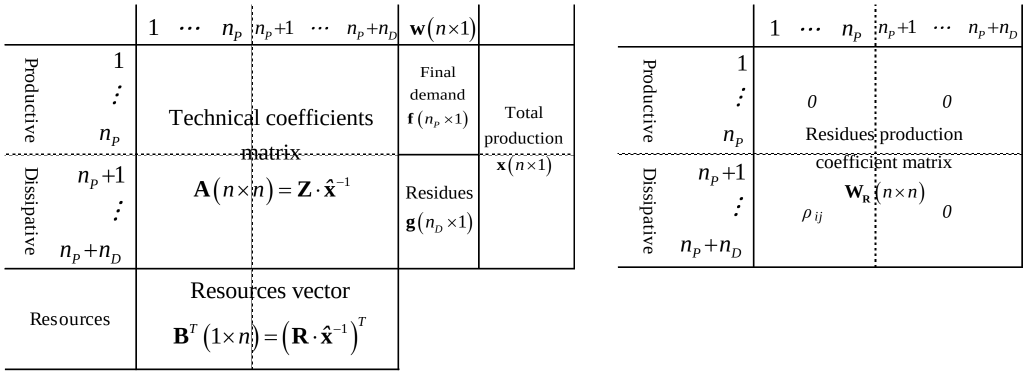

Figure 25. *IOT for the Thermoeconomic IO analysis and residues production coefficient matrix. Subscripts "ex" are omitted for simplicity.*

In TIOA, the flows of residues (losses) are part of the system output vector $\mathbf{w_{ex}}$: application of LCM returns positive exergy costs also for them. However, according to cost accounting practice, cost of residues should be reallocated to <u>*useful products only*</u>. This could be done through the proportionality criterion proposed by Valero and colleagues: *the cost of residue of the jth dissipative component is allocated to all the productive components that feed it, in proportion to the amount of exergy they deliver to j* [187]. This is expressed by the *residues cost distribution ratios* ψ_{ji}, defined as the ratio between the exergy delivered from the *i*th productive component to the *j*th dissipative component over the total resource of the *j*th dissipative component.

$$\psi_{ji} = \frac{Ex_{ij}}{Ex_{R,j}} \quad \rightarrow \quad \sum_{i \in P} \psi_{ji} = 1 \quad \forall i \in P, j \in D \tag{4.55}$$

According to this definition, the exergy cost of the product out of the *i*th productive component is expressed as the sum of three contributions: the exergy directly taken from the environment, the exergy costs of products absorbed by other productive components and the fraction of exergy cost of losses absorbed from of the *j*th dissipative components.

$$c_i Ex_{P,i} = Ex_{0i} + \sum_{j \in P} c_j Ex_{P,ji} + \sum_{j \in D} \left(\psi_{ji} c_j Ex_{L,j} \right) \tag{4.56}$$

Rearranging (4.56), the following expression is obtained:

$$c_i = \kappa_{0i} + \sum_{j \in P} c_j \kappa_{ji} + \sum_{j \in D} \left(\psi_{ji} c_j \frac{Ex_{P,j}}{Ex_{P,\mathrm{i}}} \right) \tag{4.57}$$

Residues production coefficients ρ_{ji} can be finally defined and arranged in the *residue production coefficient matrix* $\mathbf{W_R}(n \times n)$ as follows. Figure 25 shows IOT for the Thermoeconomic IO analysis and residues production coefficient matrix.

$$\mathbf{W_{ex,R}} = \left|\rho_{ji}\right| \quad \rightarrow \quad \rho_{ji} = \begin{cases} 0 & j \in P \\ \psi_{ji} \dfrac{Ex_{P,j}}{Ex_{P,\mathrm{i}}} & j \in D \end{cases} \tag{4.58}$$

Finally, in parallel to (4.54), LPM and LCM can be rewritten to account for the reallocation of residues costs as follows:

$$\mathbf{\breve{L}_{ex}} = \left(\mathbf{I} - \mathbf{\breve{A}_{ex}}\right)^{-1} = \left(\mathbf{I} - \mathbf{A_{ex}} - \mathbf{W_{ex,R}}\right)^{-1} \quad \rightarrow \quad \begin{cases} \mathbf{\breve{c}_{ex}} = \left(\mathbf{\breve{L}_{ex}B_{ex}}\right)^{\mathrm{T}} \\ \mathbf{\breve{C}_{ex}} = \mathbf{\hat{w}_{ex}} \cdot \mathbf{\breve{c}_{ex}} \end{cases} \tag{4.59}$$

Design evaluation

The so-called *Design evaluation* is described by literature as an iterative optimization process that aims at reduce the final cost of system's products. The optimization is supported by a set of indicators used to identify the component in which the irreversibilities and the margin of thermodynamic improvements are relevant.

- *Exergy destruction and losses*: reveals location and magnitude of irreversibilities within each component.

$$Ex_{D,i} + Ex_{L,i} = Ex_{R,i} - Ex_{P,i} \quad \rightarrow \quad \mathbf{Ex_{L+D}} = \left(\mathbf{i}_{1\times n} \cdot \mathbf{Z_{ex}}\right)^{\mathrm{T}} - \mathbf{Z_{ex}} \cdot \mathbf{i}_{n\times 1} \tag{4.60}$$

- *Exergy cost of exergy destructions and losses* $\mathbf{C_{ex,D+L}}$ reveals the impact of thermodynamic inefficiency in terms of exogenous resources. Notice that the hypothesis the system is operating with constant product output has been made.

$$\mathbf{\breve{C}_{ex,D}} = \mathbf{\hat{Ex}_{L+D}} \cdot \mathbf{\breve{c}_{ex}} \tag{4.61}$$

- *Relative cost difference* r_i represents the increase in the cost of product due to thermodynamic inefficiencies within a component: it is evaluated by means of exergy efficiency defined in (4.43) and it reveals practical margin of improvement of each component.

$$r_i = \frac{\breve{c}_i - \breve{c}_{R,i}}{\breve{c}_{R,i}} = \frac{1 - \eta_{ex,i}}{\eta_{ex,i}} \tag{4.62}$$

Design Evaluation process is traditionally performed iteratively, focusing on components with the highest values of $\mathbf{\breve{C}_{ex,D,i}}$ and r_i. Further details can be retrieved in literature [14, 145].
The IO approach introduced in this paragraph is recognized to be an efficient and compact way to perform Thermoeconomic analysis of energy system and it is widely adopted in literature.

4.4.3. Hybrid Exergy based IO approach

Definition of IO model for primary exergy cost analysis

Hybrid Exergy based Input – Output analysis reveals all of its potential if exergy is adopted for the characterization of both the *exogenous resources matrix* and the *foreground system S*. This allows to extend the boundaries of the considered system S including also the indirect primary exergy requirements due to the supply chains of the system (National economy, or background system). Indeed, if H-ExIO is applied for the analysis of energy systems, it is possible to evaluate the ***primary*** *exergy cost* of system products and the *primary exergy cost of exergy destructions* of system's products.

According to this purpose, H-ExIO can be applied according to the same rules introduced in section 4.3; the only difference consists in the definition of the technical coefficient matrix of the energy system, which needs to take into account the reallocation of the residues' costs according to the procedure described in the previous paragraph.

Design evaluation

The hybrid approach above introduced, in a dual way with respect to standard Thermoeconomic IO analysis, leads to the definition of a set of indicators for the application of the Design Evaluation procedure. These novel indicators provide improved information about the total environmental impact of the system in terms of primary resources consumption in a Life-Cycle perspective.

More specifically The above introduced indicators should be used to evaluate whether changes in design of one considered technology, performed according to the standard design evaluation of TIOA, provides overall benefits in terms of primary fossil fuels requirements in a LC perspective.

- *Net primary resource cost* C_{NET} is defined as the cumulative net amount of primary exergy required for *construction* (C), *operation* (O) and *disposal* (D) phases, as shown in (4.63). Since the system produces exergy during one year of operation, the net exergy cost of such phase for one year $c_{O,net}$ is evaluated as the difference between primary exergy cost of final demand and the total amount of exergy produced by the system.

$$\begin{gathered} C_{NET} = \underbrace{C_C}_{Construction} + \underbrace{C_{O,net}}_{Operation} + \underbrace{C_D}_{Disposal} \\ C_{O,net} = LT \cdot c_{O,net} \end{gathered} \tag{4.63}$$

  Value of $c_{O,net}$ has to be multiplied by the years of expected operation of the system LT. Net primary exergy cost C_{NET} is expected to be relevant for traditional fossil-fueled systems; conversely, this values may result small, even negative, in case of systems based on renewable energy sources;

- If values of C_{NET} are negative, the system produces a net amount of exergy. therefore, the *Exergy Return on Investment ExROI* can be evaluated as the ratio between C_{NET} and the primary exergy cost of construction phase C_C, as shown by (4.64). In practical terms, *ExROI* quantifies how many times the investment is paid back by system net exergy production.

$$ExROI = \frac{|C_{NET}|}{C_C} \tag{4.64}$$

- *Levelized Exergy Cost of Electricity (LExCOE)*, in analogy with economic practice, can be defined as the ratio between the sum of all the exergy expenditures bore throughout the entire lifetime of the plant, and the total amount of electricity concurrently produced, as shown in (4.65), where E^{-} represents the yearly exergy outlay for operating the plant, and E^{+} is the yearly net electrical generation of the plant, in homogeneous units.

$$LExCOE = \frac{|C_C + C_D| + \sum_{i=1}^{LT} Ex_i^{-}}{\sum_{i=1}^{LT} Ex_i^{+}} \tag{4.65}$$

4.5. Practical applications

In this section, practical application of the ExIO framework is illustrated through the following fours examples:

1. Evaluation of the primary exergy cost of final demand produced by the Italian economy in 2005;
2. Application of the H-ExIO analysis for increase detail of the Italian MIOT of 2005 disaggregating the energy sector from the primary sector;
3. Application of H-ExIO analysis (Final Demand approach) for the evaluation of primary exergy cost of the final demand produced by one energy system;
4. Thermoeconomic analysis and Design Evaluation of energy systems: comparison among standard IO analysis and H-ExIO approach;

4.5.1. ExIO analysis of one national economy

In this paragraph, IO technique is applied to the *Italian economy* of *2005* with the following objectives:

- Evaluation of specific and total primary exergy costs of final demand produced by each sector of the economy;
- Evaluation of the effects that a change in the final demand have on total production and primary exergy cost of each sector;

The symmetric Italian MIOT compiled by the *Istituto nazionale di Statistica* (ISTAT) (*http://www.istat.it/*) is here considered. The table collects transactions of products among 59 sectors of the Italian economy in 2005. For the sake of simplicity, the productive sectors are aggregated into the *Primary*, *Secondary* and *Tertiary* sector, according to ISIC standard classification of economic activities [198].

Primary exergy cost of final demand produced by each of the considered sectors is evaluated in terms of primary consumption of *coal*, *crude oil* and *natural gas* expressed by means of their exergy equivalents. Imported products are treated as if they are produced by the Italian economy with constant input matrix, according to *method a* described in paragraph 4.2.2. Therefore, exogenous resources matrix only includes endogenous extraction of primary raw fuels, retrieved in *International Energy Agency* database (IEA, *http://www.iea.org*).

				1	2	3	f	x	x_{end}
Z	Primary	M€	**1**	27.777	82.705	13.189	52.744	176.415	127.684
	Secondary	M€	**2**	28.563	742.798	132.626	1.017.350	1.921.337	1.654.347
	Tertiary	M€	**3**	6.869	214.614	183.922	634.834	1.040.239	1.010.554
R	Coal	ktoe	**1**	1.429	-	-			
	Crude Oil	ktoe	**2**	10.016	-	-			
	Natural Gas	ktoe	**3**	6.478	-	-			

Table 5. *Input Output table of the Italian economy in 2005.*

With reference to Figure 9 and Figure 10, MIOT and exogenous resources matrix are presented in Table 5. Notice that transaction matrix **Z** and final demand vector **f** includes contributions of imported products form other economies, considered as only competitive imports.

Once technical coefficients **A** and input matrices **B** are evaluated, total production and primary exergy cost of the final demand are evaluated through the application of LPM and LCM. Notice that input matrix **B** is evaluated according to method a – expressed by relation (4.11) – thus considering only the endogenous total production $\mathbf{x_{end}}$. Evaluation of primary exergy cost of the final demand is performed as showed in Figure 11, and results are reported in Table 6.

			c_{coal}	c_{oil}	c_{ng}	**c**
Primary	1	kgoe/100€	1,35	9,46	6,12	**16,93**
Secondary	2	kgoe/100€	0,10	0,71	0,46	**1,27**
Tertiary	3	kgoe/100€	0,04	0,26	0,17	**0,46**

			C_{coal}	C_{oil}	C_{ng}	**C**
Primary	1	ktoe	712	4.989	3.226	**8.927**
Secondary	2	ktoe	1.031	7.227	4.674	**12.931**
Tertiary	3	ktoe	232	1.623	1.050	**2.905**
Total		ktoe	1.974	13.839	8.950	**24.763**

Table 6. *Results of ExIO analysis of the Italian economy in 2005.*

For the sake of clarity, specific energy cost of products is evaluated per 100 € of products. Since coal, crude oil and natural gas are all measured in homogeneous units (*oil equivalent*), column sum of specific and total cost matrices results as the direct and indirect exergy requirements of each sector.

It is worth to note that, as relation (4.15) suggests, the primary exergy cost of production (*24.763 ktoe*) is greater that the total endogenous resource extraction (*17.922 ktoe*): indeed, the former represents the primary exergy that should endogenously be extracted in order to sustain its total production (including production of imported goods).

Furthermore, assuming that an increases Δf of the Italian final demand (i.e. the *Gross Domestic Product*) is forecasted for year 2006, the effect that such change may have on total production and total cost can be estimated through the application of the *shock analysis* (2.50).

			LPM	LCM			
		Δf	Δx	ΔC_{coal}	ΔC_{oil}	ΔC_{ng}	ΔC
		M€	M€	ktoe	ktoe	ktoe	ktoe
Primary	1	**0,5**	1,1	0,7	4,7	3,1	**8,5**
Secondary	2	**3,0**	6,9	0,3	2,1	1,4	**3,8**
Tertiary	3	**6,0**	8,3	0,2	1,5	1,0	**2,7**
Total		**9,5**	**16,2**	**1,2**	**8,4**	**5,4**	**15,0**

Table 7. *Reaction of the Italian economy in 2005 to a final demand shock.*

As reported by Table 7, a final demand shock Δf of *9,5 M€* would result in an increase of total production and primary resources requirements respectively of *16,2 M€* and *15 ktoe*.

4.5.2. Hybrid ExIO analysis (1): increase accuracy of results

The Hybrid ExIO model described in paragraph 4.3.1 is here used to increase the primary exergy cost accuracy of the final demand produced by the Italian economy previously analyzed. Specifically, the sector of *Electricity, Gas and Water supply* is disaggregated from the *Primary* sector.

				1	2	3	4	f	x
Z	Primary	M€	1	4.565	54.995	3.056	**12.407**	27.428	102.451
	Secondary	M€	2	13.552	742.798	132.626	**15.011**	1.017.350	1.921.337
	Tertiary	M€	3	2.479	214.614	183.922	**4.391**	634.834	1.040.239
	Electricity, Gas, Water	**M€**	**4**	**1.190**	**27.710**	**10.133**	**9.615**	**25.315**	**73.963**
R	Coal	ktoe	1	1.429	-	-	-		
	Crude Oil	ktoe	2	10.016	-	-	-		
	Natural Gas	ktoe	3	6.478	-	-	-		

Table 8. *Application of H-ExIO for Electricity, Gas, Water supply sector disaggregation.*

Results of previous paragraph are obtained with very low accuracy: indeed, all kind of goods and services are produced by the Primary sector with the same specific exergy cost: 1 € of both electricity or fertilizers results in the same primary exergy requirements. The productive sector named *Electricity, Gas and Water supply*, included within the Primary sector [198], results in a primary exergy cost of *15,3* kg_{oe} every *100€* of final demand. The accuracy of such estimation can be increased by disaggregating the Primary sector, as showed in Table 8, according to the procedure presented in 4.3.1.
In the hybrid IOT, primary sector represent all output products from primary sectors except for the *Electricity, Gas and Water Supply* products. Results of H-ExIO are reported in Table 9.
The following comments can be made:

- It is important to notice that, due to the extremely high aggregation level of the adopted MIOTs, all the results of these case studies are rough average estimations of primary exergy cost of national products. Therefore, such example are useful only to show how the ExIO method can be practically applied;
- Primary exergy costs of final demand out of the Electricity, Gas and Water Supply sector (*6,95* kg_{oe}*/100€*) and Primary sector (*33,65* kg_{oe}*/100€*) result very different: the number of sectors in IOT greatly affects the accuracy of results;
- Specific exergy costs of Primary, Secondary and Tertiary sectors are changed with respect previous calculation: this because Electricity, Gas and Water Supply sector have relevant

size in terms of total production. Therefore, its disaggregation contributes to increasing the accuracy of results;

- Total primary exergy requirements of Italian production (*32.595 ktoe*) is different with respect to the value calculated in the previous example (*24.763 ktoe*, from paragraph 4.5.1). This is due to the fact that disaggregation of MIOT influences both the productive structure and the efficiency of the considered economy with respect to the previous case. Specifically, this huge difference in primary exergy requirements can be justified by the large size of the Electric, Gas, Water that has been disaggregated by the three sector MIOT: indeed, Table 5 and Table 8 represent different very different structures of the same Italian economy.

			c_{coal}	c_{oil}	c_{ng}	c
Primary	kgoe/100€	1	2,68	18,80	12,16	33,65
Secondary	kgoe/100€	2	0,15	1,02	0,66	1,82
Tertiary	kgoe/100€	3	0,04	0,27	0,18	0,48
Electricity, Gas, Water	kgoe/100€	**4**	**0,55**	**3,88**	**2,51**	**6,95**

			C_{coal}	C_{oil}	C_{ng}	C
Primary	ktoe	1	736	5.158	3.336	9.229
Secondary	ktoe	2	1.477	10.357	6.698	18.533
Tertiary	ktoe	3	245	1.719	1.111	3.075
Electricity, Gas, Water	ktoe	**4**	**140**	**983**	**636**	**1.758**
Total	ktoe		2.598	18.216	11.781	32.595

Table 9. *Results of H-ExIO analysis.*

Form this example, it follows that the definition of MIOT aggregation is crucial for the application of LPM and LCM: different level of aggregation could return very different estimation of primary exergy costs. In other words, the more the MIOT is detailed, the more accurate will be the representation of national economy.

4.5.3. Hybrid ExIO analysis (2): final demand approach

The simple chemical production system showed in Figure 26 is here analyzed.
The system is composed by two distinct productive processes: *Energy Production* (*a*) and *Chemicals Production* (*b*) and operates within the *Secondary sector* of the Italian economy in 2005 analyzed in previous paragraph. The aim of the analysis is to evaluate the primary exergy invoked by the *operation phase* of the system in order to produce its products. Because such products are actually used for intermediate consumption of the nation, H-ExIO analysis have to be performed according to the *Final Demand approach* described in paragraph 4.3.2.
The background system is constituted by the national MIOT aggregated in three sector introduced in previous paragraph, whereas the foreground system is given by the PIOT of the system *S*, compiled by means of exergy as showed in Table 10. Because national MIOT is referred to a time frame of one year, the same time frame is also adopted for characterization of the system *S*.
IOT of the hybrid system is showed in Table 10. Process *a* produces thermal energy for self-consumption and for process *b*, resulting in a total exergy production of *3150 MWh per year*. On the other hand, process *b* produced chemical products (measured in ton) for self-consumption, for process *a* and also for the final demand, resulting in a total production of *2250 MWh per year* of chemicals.

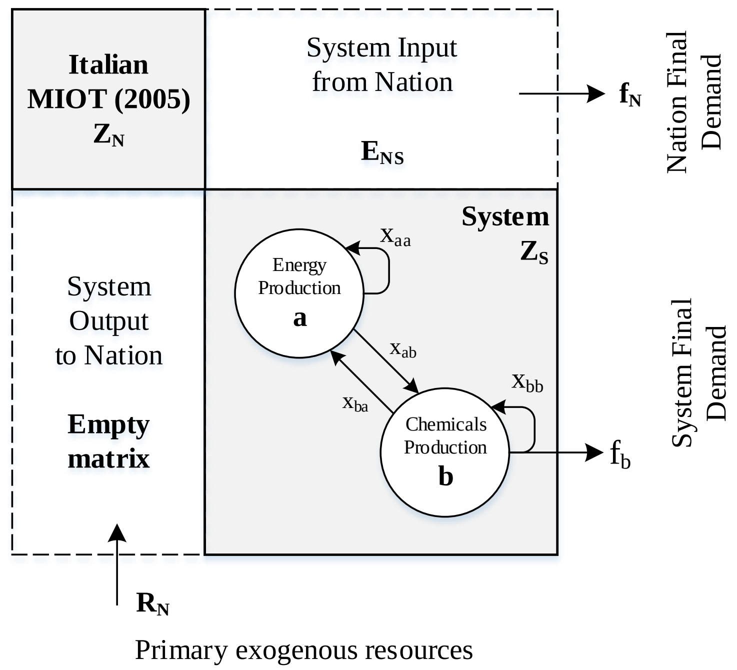

Figure 26. *Chemicals production plant S formed by two productive processes and operating in the Italian economy of 2005.*

Notice that system *S* does not absorb exogenous resource directly from the environment but it is fed by the Italian economy. The flows of products invoked by productive processes *a* and *b* from all the three sectors of the Italian economy are represented by the upstream cutoff matrix. Transaction matrix and Exogenous Resources vector are respectively converted into Technical Coefficient matrix and Input vector according to procedure showed in Figure 10.

				1	2	3	**a**	**b**	f	x
Z	Primary	M€	1	27.777	82.703	13.189	**2**	**-**	52.744	176.415
	Secondary	M€	2	28.563	742.788	132.626	**5**	**5**	1.017.350	1.921.337
	Tertiary	M€	3	6.869	214.601	183.922	**10**	**3**	634.834	1.040.239
	energy production	**MWh**	**a**	-	-	-	**150**	**3000**	**-**	**3.150**
	chemicals production	**MWh**	**b**	-	-	-	**200**	**50**	**2.000**	**2.250**
R	Coal	ktoe	1	1.429	-	-	-	-		
	Crude Oil	ktoe	2	10.016	-	-	-	-		
	Natural Gas	ktoe	3	6.478	-	-	-	-		

Table 10. *Application of H-ExIO for the analysis of the chemical production plant.*

Results of the application of LPM and LCM are showed in Table 11. Because the analyzed system is relatively small with respect to the whole national economy (in terms of total production), specific and total exergy costs of product out of each national sector remains almost the same as in paragraph 4.5.1 (Table 6). Notice that even if a specific cost has been evaluated for both *a* and *b*, all the primary exergy costs are charged on the final demand of process *b*.

			c_{coal}	c_{oil}	c_{ng}	c
Primary	1	kgoe/100€	1,35	9,46	6,12	16,93
Secondary	2	kgoe/100€	0,10	0,71	0,46	1,27
Tertiary	3	kgoe/100€	0,04	0,26	0,17	0,46
energy production	**a**	**toe/toe**	**0,15**	**1,08**	**0,70**	**1,94**
chemicals production	**b**	**toe/toe**	**0,24**	**1,71**	**1,10**	**3,05**

			C_{coal}	C_{oil}	C_{ng}	C
Primary	1	ktoe	712	4.989	3.226	32.766
Secondary	2	ktoe	1.031	7.226	4.673	47.462
Tertiary	3	ktoe	232	1.623	1.050	10.661
energy production	**a**	**ktoe**	**-**	**-**	**-**	**-**
chemicals production	**b**	**ktoe**	**0,04**	**0,29**	**0,19**	**1,54**
Total			1.974	13.839	8.950	90.892

Table 11. *Results of H-ExIO analysis.*

4.5.4. Thermoeconomic Design Evaluation of energy conversion systems

In this paragraph, *Thermoeconomic Design Evaluation* (DE) of the chemicals production plant introduced in previous section performed according to the procedure described in section 4.4.

A first approach consists in the application of the *standard Thermoeconomic Input – Output analysis* (TIOA): the IOT of the productive system *S* is coupled with a new exogenous resources vector, defined by all the exergy contributions directly absorbed by the system *S*. These contributions are all assumed to be non-renewable refined fuels. The IOT of the system, together with its technical coefficients and input matrices, is showed in Table 12.

				a	b	f	x
Z	energy production	MWh	a	150	3.000	-	3.150
	chemicals production	MWh	b	200	50	2.000	2.250
R	exergy	MWh	1	4.000	200		

Table 12. *Input Output table of the chemical production system S.*

Specific exergy costs of the final demand result by the application of the procedure described in paragraph 4.4.2. In the second approach, *Hybrid Exergy based Input – Output analysis* (H-ExIO) is applied according to the procedure described in paragraph 4.4.3, assuming that the chemicals production system is part of the Italian economy of 2005.

Thermoeconomic IO		$\mathbf{Ex_{D,i}}$	$\mathbf{c_{ex,i}}$	$\mathbf{C_{ex,i}}$	$\mathbf{C_{ex,D,i}}$
		kgoe	J/J	kgoe	kgoe
energy production	**a**	103	1,47	-	152
chemicals production	**b**	86	2,10	361	181
total	**tot**	**189**	**n.d.**	**361**	**n.d.**

Hybrid - ExIO		$\mathbf{Ex}_{D,i}$	$\mathbf{c}_{ex,i}$	$\mathbf{C}_{ex,i}$	$\mathbf{C}_{ex,D,i}$
		kgoe	J/J	kgoe	kgoe
energy production	**a**	103	1,94	-	200
chemicals production	**b**	86	3,05	1.542	263
total	**tot**	**189**	**n.d.**	**1.542**	**n.d.**

Table 13. *Results of standard Thermoeconomic IOA approach and H-ExIO approach.*

Results of the two approaches are showed in Table 13. The following comments can be made:

- Exergy destruction caused by each productive process is derived through the foreground system IOT of Table 13. Therefore, it is constant for the two adopted approaches;
- Specific exergy costs of products obtained with the H-ExIO approach are greater than the ones obtained with Thermoeconomic IOA. This differences result because H-ExIO includes the indirect primary exergy costs caused within the supply chains that are not neglected by TIOA;
- The total exergy cost of final demand returned by H-ExIO approach results more than 4 times greater with respect to the result of TIOA, revealing that the indirect exergy contributions are a non negligible portion of the total system requirements;
- Both exergy and *primary* exergy costs of exergy destructions suggest that the more relevant thermodynamic inefficiencies are located in the chemical production process.

5. Evaluation of the primary exergy cost of human labor: Bioeconomic ExIO analysis

This chapter focuses on the role that *working hours* produced by workers have in the formation of primary exergy cost of goods and services. After a brief review about the main approaches provided by literature, the innovative method of *Bioeconomic Exergy based Input – Output analysis* (B-ExIO) is proposed and discussed in this chapter. B-ExIO model is applied for the analysis of many national economies in section 6.1.

5.1. The role of human labor in Environmental Impact Analysis

One of the most controversial topic in environmental impact analysis discipline concerns the primary resources requirements of human labor [219]. Indeed, production activities of *all* the economic and productive systems require a *direct* and *indirect* amount of working hours to be productive. Once the considered system have been characterized, total exogenous resource cost of its final demand can be evaluated in terms of working hours through standard IOA, by collecting direct working hours required of each process as one line in the exogenous resources matrix (2.29). This practice is of great importance in social accountings and led to the definition of a *labor theory of value*, according to which the values of commodities are proportional to the labor needed to produce them, a classic economic idea introduced by *Petty* [51]. The study of human labor is performed by many disciplines, ranging from economics to social sciences. Human labor is treated here as one factor of production, as intended by *Solow* [5]: social or moral values of labor on which every society is based is out of the scope of the work.
Both *Environmental* and *Economics* disciplines are involved in the debate concerning the treatment of labor as a factor of production [7]:

- *Economists* regards human labor as an independent primary input, and thus exclude goods and services invoked by workers (for instance food, clothes, education etc.) from the cost of production. In this view, human labor results as an independent input to the economic system: it is required for the production of all the goods and services of a country, but its creation lies outside the domain of the analyst. It follows that accounting for the cost of labor as part of the cost of the production of the economy would results as a double counting;
- *Ecologists* recognize that workers are able to produce working hours only because of primary energy-resources consumption that sustain the whole productive system, thus claim to evaluate and to include primary energy-resources cost of working hours in the cost of goods and services production. In evidence of this fact, *Ayres* states that *human labor* and *capitals*[1] have to be considered as *intermediate* rather than independent inputs, because primary energy-resources are required to produce both of them [6]. Indeed, the consumption of working hours of a process does not reflect the cost of complementary

[1] Capitals are here defined, according to their classic economic meaning, as already-produced durable goods or any non-financial asset that is used in production of goods or services.

capitals indirectly required to produce them, i.e. its associated primary energy-resources cost. Classic economic paradigms do not take into account for food, clothing, housing and other workers' consumption – nor their education and training – as part of the cost of production, although it does count the energy consumed by labor-saving machines in the production process. For such reason, *Ayres* claims for inconsistency in the classic economic paradigm [7].

As a matter of fact, it is evident that the total working hours requirements of a product need to be produced by workers that, in turn, spend their salaries buying goods and services required for supporting their life, causing additional direct and indirect resources consumption that should be properly taken into account. Despite the role of working hours is recognized to be crucial in social accountings and in planning economic policies, the environmental implications that working hours requirements have on primary resources cost of products have not been clarified yet [144]. Evaluation of environmental burdens caused by working hours consumption is referred in the following as *working hours internalization*.

5.2. Working hours internalization: literature review

Although large theoretical debates can be found in literature about the role of labor in economy and ecology, few authors focuses on the issue of working hours internalization from a methodological viewpoint. This is mainly due to the following reasons:

- Definition of a *working hours productive process* is extremely difficult and subjected to a great arbitrariness [191, 216];
- Literature states that contribution of working hours is expected to be negligible in the context of primary energy-resources cost of most products of developed economies [18]. However, numerical proof of this statement has not been already given;

In the following paragraphs, two methods for the evaluation of the effect that human labor has on primary resources consumption are described and discussed: *Extended Exergy Accounting (EEA)* and *Closed Input – Output model*. In section 5.3, an innovative method developed by the author and based on Input – Output analysis is proposed and named *Bioeconomic ExIO model*.

5.2.1. Extended Exergy Accounting

The Extended Exergy Accounting (EEA) has been described in section 3.1 as part of the broad discipline of Thermoeconomics. EEA is the only exergy based method that explicitly addresses the link between human labor and its primary resources requirements; however, according to its last literature review provided by the author [149] and with reference to the theoretical description given in paragraph 3.1.3, the following drawbacks are identified:

- EEA is a relatively young methodology which still needs further validation and the inclusion of some supporting tools before it may become a standard within engineering analysis. Therefore, EEA requires a real standardization and formalization: detailed and univocal definition of the method for the evaluation of primary extended exergy cost of products need to be made;

- Evaluation of the extended exergy cost of goods and services results as the sum between their Cumulative Exergy Costs (CExC) and the exergy equivalents of labor, capitals and environmental impact, as showed by relation (3.6). However, the sum the CExC of all the products in the considered economy in a given time window would result in the total primary exergy consumption of the economy: therefore, adding any other contribution to the CExC of the considered product (i.e. exergy equivalents of working hours) seems to result a double accounting error.

5.2.2. Fully closed Input – Output model

Several attempts have been made to include households sector as an endogenous factor in Input – Output analysis. For instance, *Costanza* tried to include households and government expenditure within the transaction matrix, with the aim of looking for a correlation between primary energy cost and economic price of products out of the US economy [36]; in economics, *Appelbaum* tried to integrate household structure and industrial structure through an extension of traditional IOA [3] and efforts along these lines can be found in *Duchin*'s publications [55].
All these methods are based on the so-called Closed IO model, which consists in the internalization of final demand and added value matrices $\mathbf{f_N}$ and $\mathbf{v_N}$ into national transaction matrix $\mathbf{Z_N}$, as showed by relation (5.1). Notice that:

- Rows and columns of Final demand and added value matrices are properly aggregated to make the final closed transaction matrix $\mathbf{Z_C}$ a square matrix;
- For the sake of simplicity, imported products are not considered in balance (5.1);

$$\mathbf{x_C} = \mathbf{Z_C i}$$

$$\begin{bmatrix} \mathbf{x_N} + \mathbf{f_N} \cdot \mathbf{i}(4\times1) \\ v_\mathrm{N} \end{bmatrix} = \begin{bmatrix} \mathbf{Z_N} & \mathbf{f_N} \cdot \mathbf{i}(4\times1) \\ \mathbf{i}(4\times1)\cdot \mathbf{v_{Z,N}} & \mathbf{v_{f,N}} \cdot \mathbf{i}(4\times1) \end{bmatrix} \cdot \mathbf{i}\left[(n+1)\times1\right] \tag{5.1}$$

Once the final demand and the added value are included in the transaction matrix, the input – output model will reduce to relation (5.2).

$$\mathbf{A_C} = \mathbf{Z_C}\hat{\mathbf{x}}_\mathbf{C}^{-1} \quad \rightarrow \quad \mathbf{x_C} = \mathbf{A_C x_C} \quad \rightarrow \quad (\mathbf{I} - \mathbf{A_C})\mathbf{x_C} = \mathbf{0} \tag{5.2}$$

In the perspective of a fully closed model, the final demand of the economic system is not defined: it is not possible to evaluate the effect of a change in the final demand (shock analysis), nor to evaluate the cost of production in terms of exogenous resources consumption. Closed model allows only to understand and to analyze the effects introduced by a change in the technical coefficients matrix $\mathbf{A_C}$ [135].

5.3. Bioeconomic ExIO model

In this section, novel method of *Bioeconomic ExIO analysis* is introduced and formalized in order to overcome the methodological drawbacks of other methods highlighted in previous paragraph.

5.3.1. Theoretical description of the method

With reference to Figure 27, application of standard ExIO model to a given national economy N can be practically performed according to the rules introduced in section 4.2.2. Environment provides primary resources to the economy, which in turn produces goods and services in order to fulfill the final demand **f** required by households. The productive process of the given economy can be defined as a *circular process* [129]: the final demand that sustain *all* the household activities is compensated by an opposite flow of working hours that sustain the economic production.

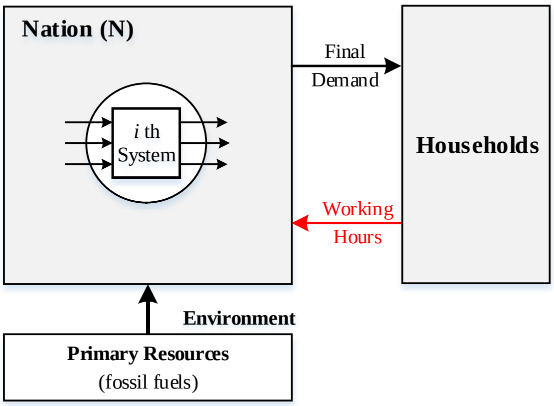

Figure 27. *Representation of the circular nature of the economic process in the ExIO model.*

In this perspective, boundaries of ExIO analysis are defined as the border of the considered economy. Therefore, the ideal production process of working hours is defined *outside* system boundaries: primary resources are then allocated on the total final demand and working hours result to be as like as another exogenous resource, completely uncorrelated from primary resources consumption.

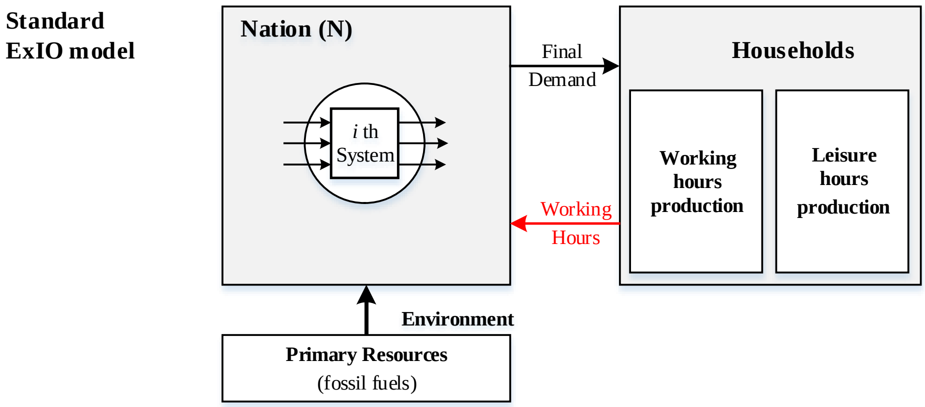

Figure 28. *Total final demand can be shared among the working hours and the leisure hours productive processes.*

According to *Neoclassical theories of Labor Supply* [107], *Bioeconomic ExIO model* (B-ExIO) assumes that the total final demand of households is produced with two main purposes: sustaining *working hours production* (1) and sustaining *leisure time production* (2, i.e. all the other activities except for working hours production). Therefore, according to Figure 28, household sector can be ideally divided into two distinct productive processes: the former requires a certain amount of the total final demand and produce working hours; the latter works as a perfect sink, absorbing the remaining portion of the final demand in order to sustain all the leisure activities of the households. Once a quantitative criterion to share the total demand among these two productive processes has been established, traditional ExIO boundaries can be extended in order to internalize the *working hours production process* as a new sector of the economy, as showed in Figure 29: this new sector receives goods and services from other productive sectors and returns working hours as its unique output. The evaluation of specific and total cost of the net final demand result, as usual, through the application of Leontief's models.

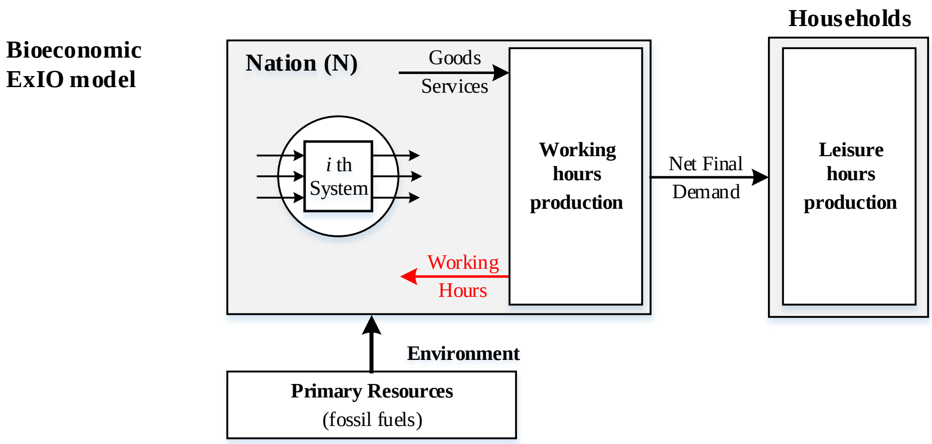

Figure 29. *Total final demand can be shared among the working hours and the leisure hours productive processes.*

Notice that the proposed B-ExIO approach is similar to the fully closed IO model described in paragraph 5.2.2.

As a last note, the term "*Bioeconomic*" is an explicit reference to the *Bioeconomic paradigm*, proposed by *Nicholas Georgescu-Roegen* as an alternative to *Neoclassical economic paradigm* [125]. In one of his publications, *Georgescu-Roegen* discusses about the purpose of the economic production and the role of human labor through one example:

> *«[...] we should cure ourselves of what I have been calling "the circumdrome of the shaving machine", which is to shave oneself faster so as to have more time to work on a machine that shaves faster so as to have more time to work on a machine that shaves still faster, and so on ad infinitum. This change will call for a great deal of recanting on the part of all those professions which have lured man into this empty infinite regress. We must come to realize that an important prerequisite for a good life is a substantial amount of leisure spent in an intelligent manner»* [71].

While traditional economic paradigm considers the maximization of the final demand (i.e. the shaving machines) as the final purpose of the economic systems, *Georgescu-Roegen* claims that the role of labor should be taken into account in the definition of the objective of the economic production in order to avoid the *"circumdrome of the shaving machine"*. The ultimate purpose of Bioeconomic ExIO analysis is to make a step forward in this direction.

In the next two sections, two fundamental elements for the applications of the B-ExIO method are introduced and discussed:

- Definition of *quantitative criterion* required to evaluate the portion of the final demand that is devoted working hours activities;
- Definition of the B-ExIO model by introducing the new sector of working hours production through the *Hybrid IO approach* described in section 4.3.

5.3.2. Goods and services required by working hours production process

The amount goods and services required by workers is clearly a part of the total final demand of households. For instance, let's consider a worker of the *machinery and equipment sector*, who drives his personal car to reach his workplace: because fuel consumption and car production are part of the household final demand, both of them are characterized by a primary exergy cost. For this reason, such contributions are not taken into account in the primary exergy cost evaluation of the products of *machinery and equipment sector*. In addition to car and fuel consumption, the considered worker requires many other products of the final demand in order to support its working activities: clothes, food, manufactured products, and so on.

Therefore, it could be said that the portion of the total final demand devoted to support the national productive system (i.e. to produce working hours) should not be considered as the useful product of the economy.

$$\mathbf{f}\left(n\times 4\right)=\left[\mathbf{f_H}+\mathbf{f_I}+\mathbf{f_G}+\mathbf{f_E}\right] \tag{5.3}$$

As a result, the part of the total final demand f (5.3) devoted to households consumptions $\mathbf{f_H}$ can be expressed as the sum of products consumption for working activities $\mathbf{f_{H,W}}$ and product consumption for leisure activities $\mathbf{f_{H,L}}$.

$$\mathbf{f_H}\left(n\times 1\right)=\mathbf{f_{H,W}}+\mathbf{f_{H,L}} \tag{5.4}$$

Working and leisure contributions to total final demand are very difficult to estimate because of the following reasons:

- Final demand of household sector is used by both workers and non-workers;
- Workers use final demand products during working time and leisure time;
- Not all the workers require the same amount of final demand: workers with higher income level usually result in higher consumption of goods and services;
- Goods and services required in one specific year can be used by workers in a time window different than the considered year.

A first rough estimation of these two contributions can be performed according to a *proportionality assumption*: considering the *i*th producing sector of the economy, the ratio between final demand devoted to sustain working hours production $\mathrm{f_{H,W,i}}$ for the *i*th sector and total households final demand $\mathrm{f_{H,tot}}$ equals the ratio between the amount of hours devoted to working activities $\mathrm{h_{W,i}}$ and total hours lived by the entire population $\mathrm{h_{tot}}$, as showed by relation (5.5).

$$\frac{\mathrm{f_{H,W,i}}}{\mathrm{f_{H,tot}}}=\frac{\mathrm{h_{W,i}}}{\mathrm{h_{tot}}} \qquad \rightarrow \qquad \mathrm{f_{W,i}}=\mathrm{f_{H,tot}}\cdot\frac{\mathrm{h_{W,i}}}{\mathrm{h_{tot}}} \tag{5.5}$$

The total final demand of households $f_{H,tot}$ and the total hours lived by the entire population h_{tot} can be respectively determined from relations (5.6) and (5.7), in which N_{pop} is the total population of the considered country. Required data for working hours employed in each productive sector are usually collected by national bureaus of statistics or can be estimated according to literature [211].

$$f_{H,tot} = \mathbf{i}(1\times n)\cdot \mathbf{f_H}(n\times 1) \tag{5.6}$$

$$h_{tot} = N_{pop}\cdot 8760\ {}^{h}\!/_{y} \tag{5.7}$$

Relation (5.5) can be rewritten in matrix form as (5.8) introducing the *working hour requirements vector* $\mathbf{h_W}(n\times 1)$. The net final demand that feed leisure hours produced by population can be evaluate as the difference between total final demand of households and final demand of workers.

$$\mathbf{f_{H,W}} = \mathbf{i}(1\times n)\cdot \mathrm{f}_{\mathbf{H}}(n\times 1)\cdot \frac{\mathbf{h_W}(n\times 1)}{h_{tot}} \tag{5.8}$$

$$\mathbf{f_{H,L}} = \mathbf{f_H} - \mathbf{f_{H,W}} \tag{5.9}$$

With reference to Figure 28, once the total final demand has been shared in its two components, two new distinct productive processes can now be identified according to the proportionality hypothesis above introduced.

5.3.3. Internalization of working hours in primary exergy cost analysis

From the previous section, working hours produced by households are recognized to be a factors of production: workers require a part of the total final demand in order to support the productive system. Therefore, because of such circular nature of economic production, human labor has to be regarded as endogenous in the input – output model.

Figure 29 shows how the boundaries of ExIO model can be extended in order to encompass the Working hours productive process, making endogenous its exchanges of products and working hours with the economy. Once a method for treatment of imported products has been defined according to the guidelines provided in paragraph 4.2.2, the mathematical model of B-ExIO is described by means of the Hybrid IO model introduced in section 4.3: the production balance of the national economy N composed by *n* productive sectors is now given by (5.10).

$$\mathbf{x_B} = \mathbf{Z_B}\mathbf{i} + \mathbf{f_B}$$

$$\underbrace{\begin{bmatrix}\mathbf{x_N}\\ h_{W,tot}\end{bmatrix}}_{\substack{Total\\Production\\ \mathbf{x_B}}} = \underbrace{\begin{bmatrix}\mathbf{Z_N} & \mathbf{f_{H,W}}\\ \mathbf{h_W^T} & -\end{bmatrix}\cdot \mathbf{i}\big[(n+1)\times 1\big]}_{\substack{Intermediate\\Requirements\\ \mathbf{Z_B}}} + \underbrace{\begin{bmatrix}\mathbf{f_H}-\mathbf{f_{H,W}}\\ -\end{bmatrix} + \begin{bmatrix}\mathbf{f_I}+\mathbf{f_G}+\mathbf{f_E}\\ -\end{bmatrix}\cdot \mathbf{i}(3\times 1)}_{\substack{Net-Final\ Demand\\ \mathbf{f_B}}} \tag{5.10}$$

Where $\mathbf{x_B}[(n+1)\times 1]$ is the *Bioeconomic total production vector*, $\mathbf{Z_B}[(n+1)\times(n+1)]$ and $\mathbf{f_B}[(n+1)\times 4]$ are respectively the *Bioeconomic transaction* and the *Bioeconomic final demand matrices*. Notice that the above introduced vector and matrices are defined in hybrid units: indeed, Bioeconomic transaction matrix is defined in monetary units except for its last line, which is compiled in terms of *hours*.

In the Bioeconomic ExIO model, the hybrid system (5.10) is defined here aggregating the new Working hours production process to the national MIOT: since the sector has not been extracted

from the MIOT, the latter does not need to be adjusted as in the standard hybrid IO model presented in section 4.3.
According to Figure 23, the hybrid balance (4.30) is then composed by the following terms:

- $\mathbf{Z_B}$, $\mathbf{f_B}$, $\mathbf{x_B}$ Bioeconomic system's transactions, final demand and total production;
- $\mathbf{Z_N}$, $\mathbf{x_N}$ System transactions matrix (MIOT) and total production vector;
- $\mathbf{f_H}$, $\mathbf{f_I}$, $\mathbf{f_G}$, $\mathbf{f_E}$ Final demand of *Households*, *Investments*, *Govern*, *Exports*;
- $\mathbf{f_{H,W}}$ Final demand of the Working hours productive process;
- $\mathbf{h_W}$ working hour requirements vector;

The Bioeconomic balance (5.10) shows that the Working hours productive process provides working hours to all the other productive sectors but does not invoke any self consumption: the Bioeconomic system's transactions matrix $\mathbf{Z_B}$ is then compiled with a zero in the appropriate position.
Once the Bioeconomic system (5.10) has been defined, practical application of IOA continues as usual, defining technical coefficient matrix and Leontief Inverse matrix (5.11), and applying Leontief Production Model (5.12). Technical coefficients, Leontief Inverse and Identity matrices are defined as square matrices in hybrid units of $(n + 1)$ rows and columns.

$$\mathbf{A_B} = \mathbf{Z_B}\hat{\mathbf{x}}_\mathbf{B}^{-1} \quad \rightarrow \quad \mathbf{L_B} = \left(\mathbf{I_B} - \mathbf{A_B}\right)^{-1} \tag{5.11}$$

$$\mathbf{x_B} = \left(\mathbf{I_B} - \mathbf{A_B}\right)^{-1}\mathbf{f_B} \quad \rightarrow \quad \mathbf{x_B} = \mathbf{L_B}\mathbf{f_B} \tag{5.12}$$

Evaluation of the primary exergy cost of the Bioeconomic final demand requires definition of *Bioeconomic exogenous resources* and *input matrices* as in relation (5.13). Both these matrices are defined as $[m \times (n + 1)]$ rows and columns, according to the assumption that the Working hours productive process does not absorb any direct primary resource.

$$\mathbf{R_B} = \left[\mathbf{R_N} \,|\, \mathbf{0}\right] \quad \rightarrow \quad \mathbf{B_B} = \mathbf{R_B}\,\hat{\mathbf{x}}_\mathbf{B}^{-1} \tag{5.13}$$

Finally, evaluation of both specific and total primary exergy cost of the Bioeconomic final demand results from the application of Leontief Cost Model as in relation (5.14). Because the final demand of the Working hours production process is zero, the total cost of working hours also result as zero and their specific cost represents the cost of one working hour produced by the economy as a *marginal unit*.

$$\mathbf{c_B} = \left(\mathbf{B_B}\,\mathbf{L_B}\right)^{\mathrm{T}} \quad ; \quad \mathbf{C_B} = \hat{\mathbf{f}}_\mathbf{B}\,\mathbf{c_B} \tag{5.14}$$

It is noteworthy that once both the treatment method for imported/exported products and the national exogenous resource matrix $\mathbf{R_N}$ have been defined, the equality between the row sum of total exogenous resources cost obtained with *standard ExIO model* $\mathbf{C_{std,tot}}$ and *Bioeconomic ExIO model* $\mathbf{C_{B,tot}}$ holds, as showed by relation (5.15).

$$\left.\begin{array}{l} \mathbf{i}\left[1\times(n+1)\right]\cdot\mathbf{C_{std}}\left[(n+1)\times m\right] = \mathbf{C_{std,tot}}\left(1\times m\right) \\ \mathbf{i}\left[1\times(n+1)\right]\cdot\mathbf{C_B}\left[(n+1)\times m\right] = \mathbf{C_{B,tot}}\left(1\times m\right) \end{array}\right\} \quad \mathbf{C_{std,tot}}\left(1\times m\right) = \mathbf{C_{B,tot}}\left(1\times m\right) \tag{5.15}$$

On the other hand, specific costs of goods and services returned by the models may differ because of two main reasons:

- The internalization of the Working hours production process in Bioeconomic model results in a different allocation of exogenous resources on the final demand;
- Part of the total final demand of the standard ExIO model is *endogenized* by the Bioeconomic ExIO model: because of identity (5.15), this practice results in higher specific costs of products.

Because detailed data about working hours and leisure hours of the population are available at national level only, the B-ExIO model can be applied only for the analysis of primary resources cost of national production. Furthermore, the B-ExIO balance (5.10) can be further extended to increase accuracy of results according to the Hybrid approach describe in section 4.3.

5.4. Practical application: B-ExIO analysis of national economy

In this section, the Italian economy of 2005 analyzed in paragraph 4.5.1 is considered. This time, the economy is schematized as 15 sectors, according to the ISIC standard classification of economic activities [198]. The objective of this paragraph is to evaluate specific and total primary exergy costs of final demand produced by each sector of the economy through *standard* and *Bioeconomic* ExIO analyses. Finally, results are compared in order to determine the influence that Working hours production sector has on the primary exergy cost of national products.
In order to make results of B-ExIO comparable with standard ExIO model, primary exergy cost of the final demand is evaluated in terms of consumption of non-renewable fossil fuels expressed by means of their exergy equivalents, and imported products are treated according to *method a* described in paragraph 4.2.2.

Italian economy, 2005, 15 sectors		$h_{w,i}$	$h_{w,i}/h_{tot}$	$f_{tot,i}$	$f_{H,i}$	$f_{W,i}$
		Mh	%	M€	M€	M€
Agriculture, Hunting, Forestry and Fishing	1	986	0,19	26541	21719	1530
Mining and Quarrying	2	62	0,01	887	161	97
Manufacturing	3	6862	1,35	618608	234503	10653
Electricity, Gas and Water Supply	4	205	0,04	25315	23934	319
Construction	5	1966	0,39	136891	7404	3052
Wholesale and retail trade; household goods …	6	3102	0,61	169103	121701	4816
Hotels and Restaurants	7	1651	0,33	77526	76178	2563
Transport, storage and communication	8	2219	0,44	92748	66877	3444
Financial Intermediation	9	815	0,16	35140	31211	1264
Real estate, renting and business activities	10	2725	0,54	175658	129254	4230
Public Admin and Defence; …	11	2088	0,41	116887	908	3242
Education	12	1775	0,35	67598	9840	2756
Health and Social Work	13	2037	0,40	105141	18606	3163
Other Community, Social and Personal Services	14	1092	0,22	44929	34071	1695
Private Households with Employed Persons	15	2453	0,48	11955	11955	3808
Total		**30039**	**5,92**	**1704927**	**788324**	**46632**

Table 14. *Data required to compile input – output table for B-ExIO analysis.*

Total population of Italy in 2005 is estimated as *57,97 Millions*; according to relation (5.7), it is then possible to evaluate the total amount of hours lived by the population h_{tot} (about *507000 Mh*).

In Table 14 fundamental data are reported for all the 15 sectors of the economy: the amount of working hours required $h_{W,i}$, the fraction of working hours with respect to the total hours lived by population $h_{W,i}/h_{tot}$, the total final demand produced $f_{tot,i}$, the total demand of households $f_{H,i}$ and the amount of final demand that sustain working hours production process $f_{W,i}$.
Once the amount of final demand devoted to working hours production process has been identified, according to relation (5.8), the B-ExIO production balance (5.10) can be written and LPM and LCM applied. Results of *standard* and *Bioeconomic* ExIO analyses are visible in table Table 15: relative difference ε among the costs obtained with the two models are showed for each sector in percentage.

Italian economy, 2005, 15 sectors		***ExIO***	***B-ExIO***		***ExIO***	***B-ExIO***	
		c_i	c_i	**ε**	C_i	C_i	**ε**
		kgoe/100€	kgoe/100€	**%**	ktoe	ktoe	**%**
Agriculture, Hunting, Forestry and Fishing	1	2,04	2,20	**7,5**	542	549	**1,3**
Mining and Quarrying	2	203,13	203,15	**0,0**	1802	1606	**-10,9**
Manufacturing	3	9,08	9,18	**1,0**	56185	55787	**-0,7**
Electricity, Gas and Water Supply	4	40,54	40,59	**0,1**	10262	10147	**-1,1**
Construction	5	4,62	4,74	**2,8**	6319	6348	**0,5**
Wholesale and retail trade; household goods …	6	2,62	2,73	**4,1**	4427	4477	**1,1**
Hotels and Restaurants	7	3,17	3,33	**4,9**	2458	2494	**1,4**
Transport, storage and communication	8	2,14	2,25	**5,2**	1985	2011	**1,3**
Financial Intermediation	9	0,73	0,81	**11,2**	257	276	**7,2**
Real estate, renting and business activities	10	1,04	1,11	**6,6**	1830	1903	**4,0**
Public Admin and Defence; …	11	1,48	1,62	**10,0**	1725	1845	**6,9**
Education	12	0,59	0,76	**30,5**	396	496	**25,1**
Health and Social Work	13	1,76	1,92	**9,0**	1848	1955	**5,7**
Other Community, Social and Personal Services	14	1,90	2,04	**7,6**	853	883	**3,5**
Private Households with Employed Persons	15	0,00	1,40	**nd**	0	114	**nd**
Working hours production process	**16**	**nd**	**6,84**	**nd**	**nd**	**0**	**nd**
Total					**90892**	**90892**	

Table 15. *Results of standard and Bioeconomic ExIO applied to Italian economy in 2005.*

The following comments can be made:

- The total exergy cost of production of standard and Bioeconomic models are equal (*90892 ktoe*): this can be established as a check for a correct application of the B-ExIO model;
- As expected, primary exergy costs of total production C_i of the same ith sector are different: sectors that requires less amount of working hours, like *Mining and Quarrying*, result in smaller primary exergy cost C_i. Likewise, tertiary and services sectors results in higher primary exergy costs;
- Because of the reduction in the final demand of the national economy, specific exergy costs of *all* of its products c_i evaluated through B-ExIO result higher with respect to standard model. Again, such increases are higher for products out of the tertiary sectors (e.g. *Education*, *Financial Intermediation*, etc.);
- Working hours production process is characterized by a specific exergy cost of *6,84 kgoe/100€*, that is the cost of one working hours produced as final demand (i.e. marginal cost). This value can be used as a reference for the primary resources intensity of human labor for all the given economies. However, since working hours are not part of the final demand, total primary exergy cost of the working hours production sector is zero: this means that B-ExIO model results in a reallocation of exogenous resources among all the productive sectors of the economy.

6.
Case studies: applications of the Exergy based IO framework

The general objective of this chapter is to show how the framework of ExIO can be practically applied for the evaluation of primary fossil fuel requirements of systems, goods and services, highlighting the relevance that these results have for Environmental Impact Analysis discipline.
Specifically, ExIO framework is applied for the analysis of the following case studies:

- *ExIO analysis of national economies*. Exergy based IO analysis is applied to different World countries. Standard and Bioeconomic ExIO analyses are performed, evaluating the primary exergy cost of products. Analyses are performed according to all the import treatment methods described in paragraph 4.2 and results are finally compared;
- *Thermoeconomic IOA and H-ExIO of a Waste to Energy power plant.* Primary exergy cost of WtE products are evaluated and compared with results obtained according to traditional exergy cost analysis. Design Evaluation is performed and results are discussed;
- *ExIO analysis of alternative solutions: Manual dishwashing VS Dishwasher.* Standard and Bioeconomic ExIO models are applied for the comparative evaluation of alternative dishwashing practice in a Life Cycle perspective.

6.1. ExIO analysis of national economies

6.1.1. Source of data and main assumptions

The ExIO framework described in chapter 4 is here applied for the analysis of different World's national economies. In order to make the results of the analysis comparable, productive sectors of the adopted MIOTs must be defined with the same aggregation level and compiled according to a unified standard. For such reasons, the *World Input Output Database* (WIOD) is here adopted as the only source of MIOTs [185] (*http://www.wiod.org/*). The WIOD database is public and free of charge; it covers 27 European countries and 13 other major World countries, providing annual data for the period from 1995 to 2009. All the MIOTs are *symmetric industry-by-industry* tables as showed in Figure 21 (paragraph 4.2.1), with an aggregation level of *35 economic branches* listed in Table 16, according to the *Statistical Classification of Economic Activities in the European Community* (NACE rev. 1, which correspond to the ISIC rev. 3) [61]. All the MIOTs are compiled in *USD* at *current basic price*: these values for gross outputs and intermediate inputs have been properly harmonized across countries. All data in the WIOD are obtained from official national statistics and are consistent with the *System of National Accounts* [138].
Furthermore, WIOD database collects additional data related to *Socio-economic accounts* and *Environmental accounts*. For the purpose of ExIO analysis, only working hours requirements of each economic sector and fossil fuels endogenous extraction (raw coal, crude oil, natural gas, expressed in *tons*) are considered [70]. Data about fossil fuels extraction are properly converted in exergy terms by means of their exergy equivalents, defined in paragraph 3.1.3. Other ancillary data (TPES, GPD and so on) are taken from *World Bank* and *International Energy Agency* (IEA) databases.

No.	NACE code	Name
1	AtB	Agriculture, Hunting, Forestry and Fishing
2	C	Mining and Quarrying
3	15t16	Food, Beverages and Tobacco
4	17t18	Textiles and Textile Products
5	19	Leather, Leather and Footwear
6	20	Wood and Products of Wood and Cork
7	21t22	Pulp, Paper, Paper , Printing and Publishing
8	23	Coke, Refined Petroleum and Nuclear Fuel
9	24	Chemicals and Chemical Products
10	25	Rubber and Plastics
11	26	Other Non-Metallic Mineral
12	27t28	Basic Metals and Fabricated Metal
13	29	Machinery, Nec
14	30t33	Electrical and Optical Equipment
15	34t35	Transport Equipment
16	36t37	Manufacturing, Nec; Recycling
17	E	Electricity, Gas and Water Supply
18	F	Construction
19	50	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
20	51	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
21	52	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
22	H	Hotels and Restaurants
23	60	Inland Transport
24	61	Water Transport
25	62	Air Transport
26	63	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
27	64	Post and Telecommunications
28	J	Financial Intermediation
29	70	Real Estate Activities
30	71t74	Renting of M&Eq and Other Business Activities
31	L	Public Admin and Defence; Compulsory Social Security
32	M	Education
33	N	Health and Social Work
34	O	Other Community, Social and Personal Services
35	P	Private Households with Employed Persons

Table 16. *Economic activities considered in MIOTs.*

ExIO method is here applied for the analysis of the 35 countries listed in Table 17: algorithms for the application of Leontief models are developed in *Matlab®* environment. The analyzed countries are selected on the basis of data quality and availability, according to their economic importance (they cover more than 80% of the World GDP). Application of ExIO through the *import treatment method c* (paragraph 4.2.2) is performed on the *World Input Output Table* (WIOT) provided by WIOD database. Because the analyzed 35 economies do not cover all the countries in the World, it is worth to notice that the fictitious economy named *Rest of the World* (RoW) is considered in order (1) to capture all the World trade flows and (2) to respect the identity between total World outlays and total World outputs, as in relation (4.7).
Additional details about compilation of MIOTs and WIOT can be retrieved in literature [47, 185].
Notice that all the ExIO analyses are performed for the *reference year 2005*.

Country Name	Country Code	no	Population [Millions]	GDP [BUSD]	TPES [$Mtoe_{en}$]	Fossil production [$Mtoe_{ex}$]	$f_{fuel,imp}$	$f_{prod,imp}$
Australia	AUS	1	20,39	693,7	113,5	365,5	0,11	0,08
Austria	AUT	2	8,23	305,0	33,8	2,5	0,92	0,12
Bulgaria	BGR	3	7,74	28,9	19,9	20,1	0,74	0,14
Brazil	BRA	4	186,14	882,2	215,3	105,2	0,33	0,03
Canada	CAN	5	32,31	1164,2	272,2	341,4	0,20	0,10
China	CHN	6	1303,72	2256,9	1775,7	1916,9	0,11	0,04
Czech Republic	CZE	7	10,21	130,1	44,9	51,1	0,46	0,11
Germany	DEU	8	82,47	2766,3	335,2	185,9	0,78	0,10
Denmark	DNK	9	5,42	257,7	18,9	29,9	0,32	0,10
Spain	ESP	10	43,65	1130,8	141,9	16,3	0,95	0,09
Estonia	EST	11	1,35	13,9	5,2	10,9	0,39	0,15
Finland	FIN	12	5,25	195,8	34,3	7,3	0,92	0,08
France	FRA	13	63,18	2136,6	270,7	2,5	0,99	0,08
United Kingdom	GBR	14	60,40	2321,4	222,6	211,8	0,41	0,09
Greece	GRC	15	11,09	240,1	30,2	56,6	0,77	0,10
Hungary	HUN	16	10,09	110,3	27,6	12,6	0,80	0,12
Indonesia	IDN	17	224,48	285,9	179,5	238,3	0,16	0,05
India	IND	18	1127,14	834,2	539,4	410,7	0,40	0,05
Ireland	IRL	19	4,16	202,6	14,3	3,7	0,92	0,09
Italy	ITA	20	57,97	1786,3	183,9	17,9	0,92	0,07
Japan	JPN	21	127,77	4571,9	520,5	3,6	0,99	0,04
Korea, Rep.	KOR	22	48,14	898,1	210,2	2,8	0,99	0,06
Lithuania	LTU	23	3,32	26,1	8,8	0,6	0,98	0,14
Latvia	LVA	24	2,24	16,0	4,5	0,6	1,00	0,15
Mexico	MEX	25	110,73	866,3	170,3	245,4	0,12	0,07
Netherlands	NLD	26	16,32	638,5	78,8	74,7	0,73	0,09
Poland	POL	27	38,17	303,9	92,4	132,8	0,33	0,09
Romania	ROU	28	21,32	99,2	38,7	25,3	0,44	0,11
Russian Federation	RUS	29	143,11	764,0	651,7	1234,8	0,02	0,09
Slovak Republic	SVK	30	5,37	61,3	18,8	2,2	0,94	0,14
Slovenia	SVN	31	2,00	35,7	7,3	3,7	0,80	0,14
Sweden	SWE	32	9,03	370,6	51,6	0,4	0,63	0,09
Turkey	TUR	33	67,74	483,0	84,4	55,3	0,83	0,06
Taiwan	TWN	34	23,43	481,4	104,7	0,5	1,00	0,10
United States	USA	35	295,52	13095,4	2318,9	1586,0	0,39	0,05

Table 17. *Base data of the considered countries. Year 2005.*

Table 17 reports the relevant data for the analyzed countries: *resident population*, *Gross Domestic Product* (GDP), *Total Primary Energy Supply* (TPES), *total fossil fuels production* (extraction plus imports). Furthermore, the fraction of the exergy of imported fuels with respect the exergy of the total fuels production ($f_{fuel,imp}$) and the fraction of imported products over the total GDP ($f_{prod,imp}$) are also reported to highlight the fuels and products dependency of each country.

6.1.2. About the choice of the import treatment method

Since national economies are connected through trades of imported and exported products, the first step for the application of ExIO analysis is to define one of follow import treatment methods (paragraph 4.2.2):

- *Method a:* internalization of imports with constant Input matrix;
- *Method b:* internalization of imports estimating the Exogenous resources matrix;

- *Method c:* inversion of the World Input Output Table.

If uncertainties in WIOT compilation are ignored, application of *method c* returns theoretically exact values of the primary exergy costs (no assumptions are made for treatment of imported/exported products). Therefore, results of *method c* are assumed here as the reference in order to compare and to evaluate results obtained through *methods a* and *b*.
In general, application of *method c* is possible only if MIOTs for all the World's economies are (1) available, (2) defined according to the same standard and (3) defined with the same aggregation level. Since only few national MIOTs are available with high level of disaggregation, application of method c is not feasible if a detailed analysis is required. Therefore, the common practice is to apply ExIO using *methods a* or *b*. However, because these methods work in a very different manner, a careful choice among them have to be made.

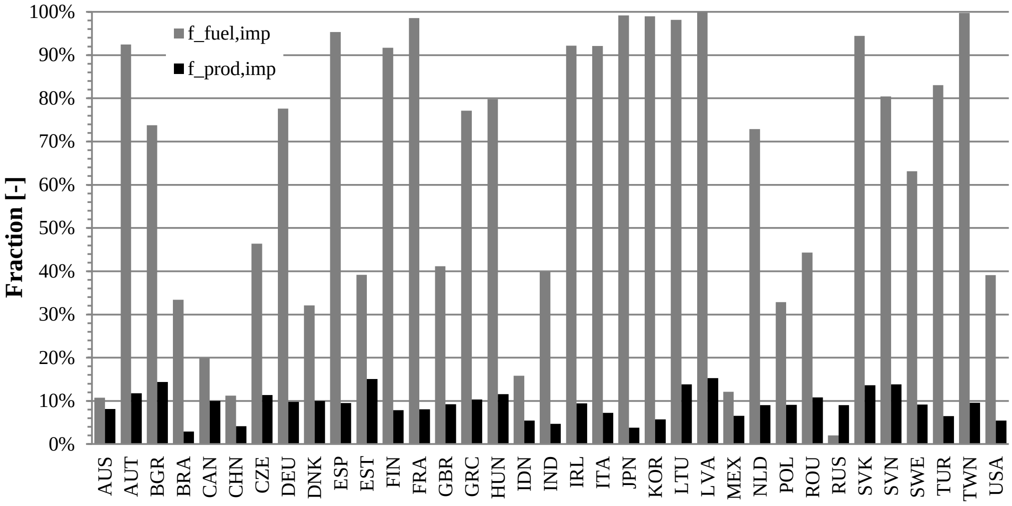

Figure 30. *Fraction of GDP due to imports of products (black) and fraction of fossil total exergy imported with respect to total exergy consumption (production + imports, grey).*

Values of $f_{fuel,imp}$ and $f_{prod,imp}$ are plotted in Figure 30. Since all the imported products of the analyzed economies are less than 20% of GDP (black bars), application of ExIO according to methods a or b should not lead to large uncertainties in results. On the other hand, the fossil fuel dependency (grey bars) results very large for many countries (including Italy): in such cases, *method a* may cause distortions of the input coefficients, and results of *method b* are expected to be more accurate.

6.1.3. Efficient algorithm for World Leontief Inverse evaluation

Application of Leontief Production and Cost Models to WIOT requires the evaluation of the World Leontief Inverse matrix $\mathbf{L_W}$ starting from a World technical coefficients matrix of order *1296*. It is well established by literature that application of *direct* inversion methods to such systems are considerably slower and less accurate with respect to *indirect* method [212].
Evaluation of the World Leontief Inverse can be performed iteratively through the *Power Series approximation* (6.1), introduced in section 2.2.5. Starting from such expression, the algorithm reported in Figure 31 is applied and results a more efficient and accurate method with respect direct methods.

$$\mathbf{L_W} = \left(\mathbf{I_W} - \mathbf{A_W}\right)^{-1} \quad \rightarrow \quad \mathbf{L_W} = \sum_{t=0}^{+\infty} \mathbf{A_W^i} = \mathbf{I_W} + \mathbf{A_W} + \mathbf{A_W}\mathbf{A_W} + \cdots \tag{6.1}$$

Convergence criterion for the developed algorithm has been assumed as the difference between the total exergy extracted by all the countries ($R_{W,tot}$) and the total primary exergy cost of production ($C_{W,tot}$), evaluated according to (4.29). With reference to the right hand side of Figure 31, such difference results less than *1 Mtoe* after after the 16th iteration, and convergence is then reached after about 2 minutes of calculation.

$$
\begin{aligned}
&\mathbf{L_W} = \mathbf{I_W} \\
&i = 0 \\
&\qquad \textit{while } \left(R_{W,tot} - C_{W,tot}\right) > \text{eps} \\
&\qquad\qquad i = i + 1 \\
&\qquad\qquad \mathbf{L_W} = \mathbf{L_W} + \mathbf{A_W}^{i} \\
&\qquad\qquad \mathbf{C_{W,t}} = \left[\mathbf{i} \cdot \hat{\mathbf{f}}_\mathbf{W} \left(\mathbf{B_W L_W}\right)^{\mathrm{T}}\right]^{\mathrm{T}} \\
&\qquad \textit{end}
\end{aligned}
$$

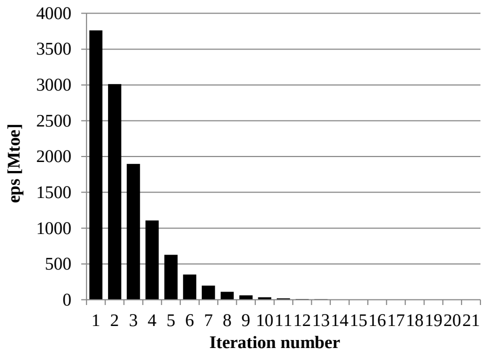

Figure 31. *Algorithm used for the iterative evaluation of the World Leontief Inverse matrix (left side) and values of* eps *resulting after every iteration (right side).*

Differently with respect to method c, application of methods a or b implies the evaluation of Leontief inverse starting from Technical coefficient matrix of order 35, and therefore standard direct inversion methods can be adopted.
In depth analysis of efficient algorithms and numerical methods applied to LCA and IOA can be retrieved in the works of *Peters* [143] and *Suh and Heijungs* [89]

6.1.4. Standard ExIO analysis of national economies

In the following, the economies listed in Table 17 are analyzed according to the standard ExIO model presented in section 4.2, through the application of all the import treatment methods introduced in paragraph 4.2.2.

Application of method c

Figure 32 shows the *primary exergy cost* of the whole net final demand of each economy, resulting from the application of LPM and LCM to the WIOT, and expressed as total quantities (*Mtoe*) and per capita (*toe/p*).
Notice that, differently from other standard indicators such as *Total Primary Energy Supply* (TPES), the total primary exergy cost of the *i*th economy $C_{ex,i}$ showed in Figure 32 represents the total primary fossil fuels *embodied* in the *i*th total final demand: therefore, the amount of fossil fuels required by other countries to produce goods or services delivered to the *i*th economy are also included.

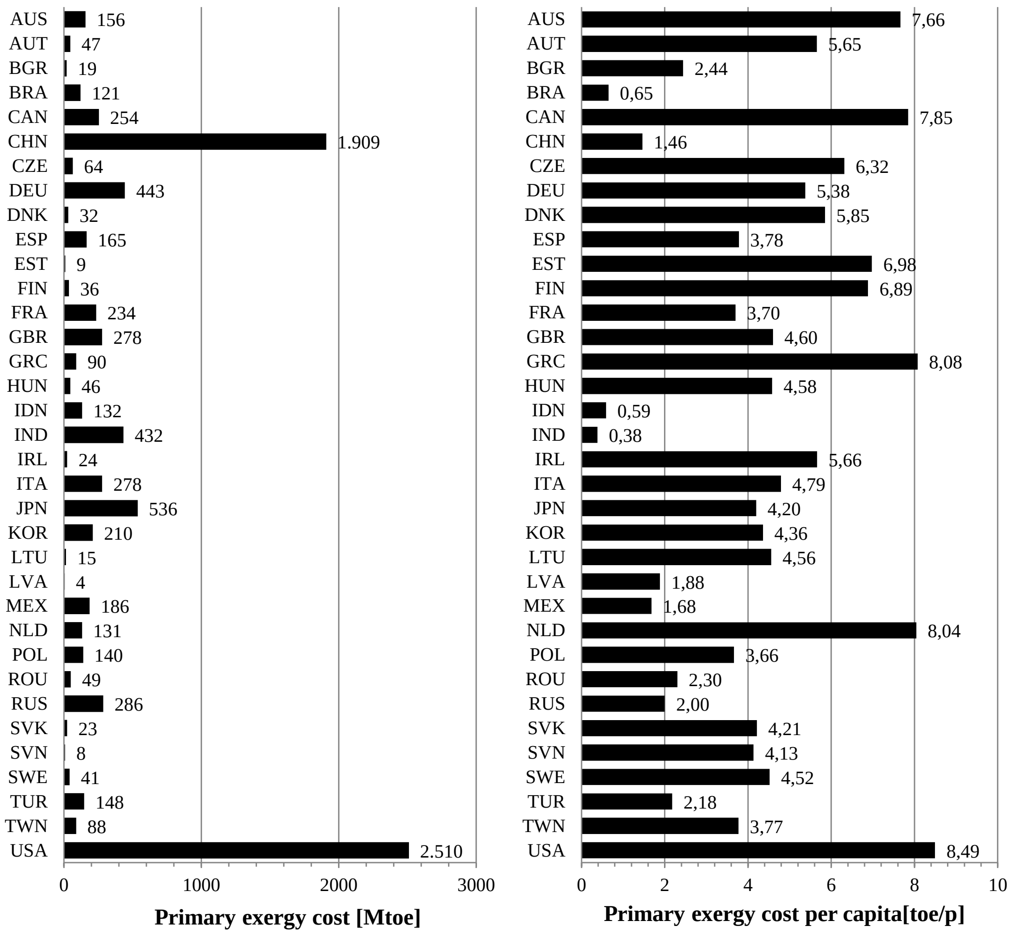

Figure 32. *Exergy cost of total production for each country with method c. Results are in total (left) and per capita (right).*

Results obtained through the Input – Output analysis of WIOT allows to investigate and to understand how trade flows across the World economies influence the formation process of the exergy costs of products.

Furthermore, the *direct* and *indirect* fossil fuels dependency can be quantitatively evaluated: Figure 33 shows the *net exergy requirements* $C_{ex,net,i}$ of each *i*th country, calculated as the difference between the *primary exergy cost* $C_{ex,i}$ of total production and the *total endogenous fossil fuels extraction* $Ex_{extr,i}$, according to relation (6.2). Values of fuel extraction are taken from *International Energy Agency* (IEA) database and properly converted into their exergy equivalents according to section 3.2.

$$C_{ex,net,i} = C_{ex,i} - Ex_{extr,i} \tag{6.2}$$

The analysis of net exergy requirements $C_{ex,net,i}$ (Figure 33) lead to the following comments:

- Positive values of $C_{ex,net,i}$ reveal that the direct and indirect fossil fuels requirements of the *i*th economy is greater than the its endogenous fossil fuels extraction: the larger the $C_{ex,net,i}$, the more *hidden and strong* is the fossil fuel dependency of the economy. Indeed, it may happen that economies which export large amount of fossil fuels are actually consuming a larger quantity of them because of the imports of goods or services (e.g. the USA);

- Conversely, a negative value of $C_{ex,net,i}$ reveals that the ith economy produces large amounts of fossil fuels that are devoted to sustain the *intermediate production* of other economies rather than its own final demand. This is especially the case of *Australia*, *Canada* and *Russia*;

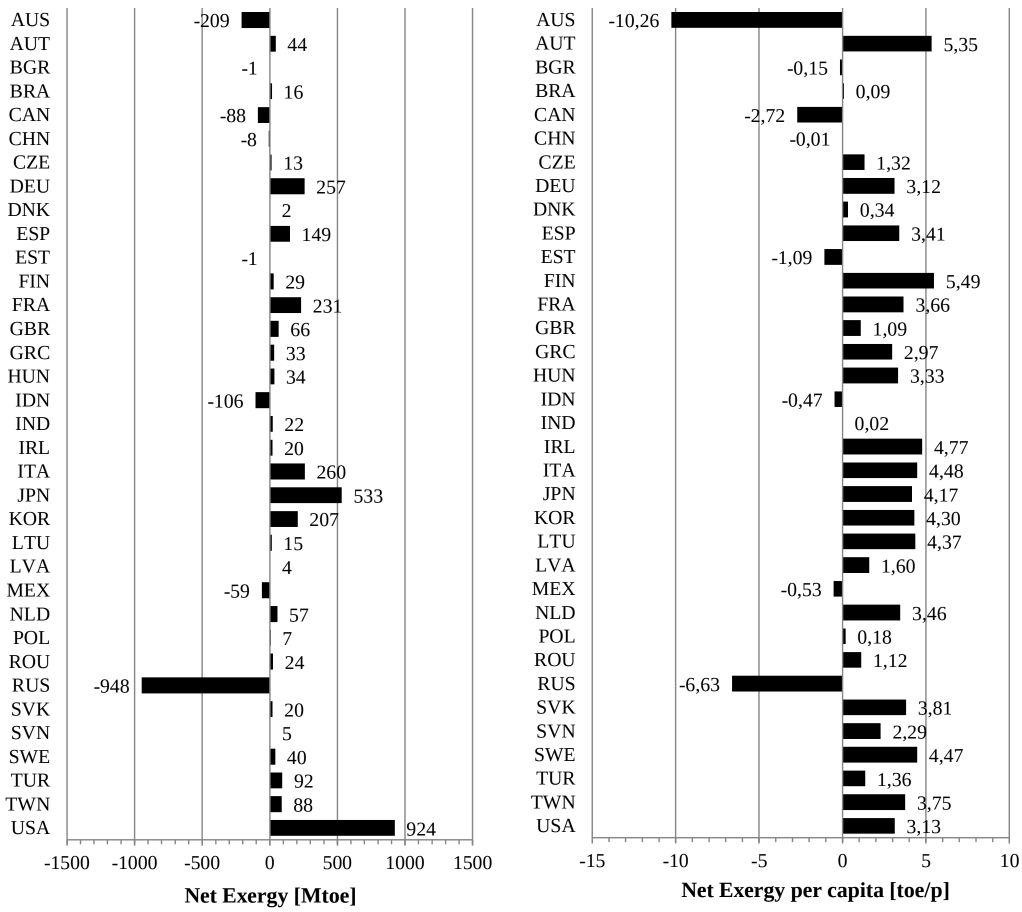

Figure 33. *Net exergy cost balance for each country. Total results (left) and specific results per capita (right).*

Application of methods a and b: comparison with method c

Once ExIO analysis has been applied according to *methods a* and *b*, the obtained results need to be compared with the ones obtained with *method c*, assumed as the reference for the present case study. This is necessary in order to check the validity of the import treatment method.

Figure 34 reports the relative difference between total primary exergy costs $C_{ex,i}$ obtained according to *method a* (black bars) and *method b* (grey bars) with respect to *method c*:

$$\varepsilon_{a-c,i} = \frac{C_{ex,a,i} - C_{ex,c,i}}{C_{ex,c,i}} \qquad ; \qquad \varepsilon_{b-c,i} = \frac{C_{ex,b,i} - C_{ex,c,i}}{C_{ex,c,i}} \tag{6.3}$$

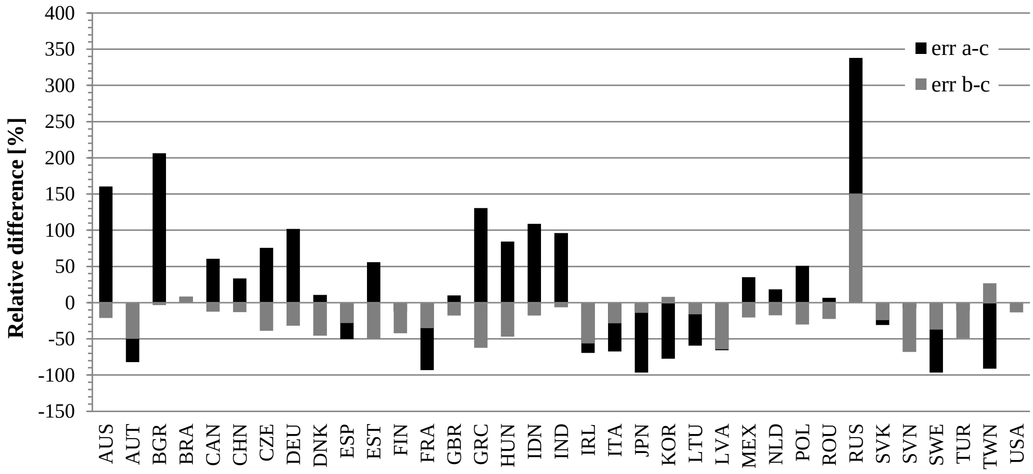

Figure 34. *Deviation of results of models a and b with respect to model c.*

With reference to Figure 34, the following considerations can be made:

- Higher values of $\varepsilon_{a-c,i}$ and $\varepsilon_{b-c,i}$ occur for economies with larger fraction of both *imported* or *exported* products;
- Standard deviation of results of *method a* results as *4,1* toe_{ex}/p, whereas the standard deviation of results of *method b* is *1,9* toe_{ex}/p: therefore, the latter gives more accurate results on average;
- On average, *method b* underestimates values of exergy costs (negative values of ε): this may happen because the additional exergy contributions required to produce, refine and transport the imported fuels are neglected;
- Values returned by *method a* are sensible to the amount and the type of products imported or exported by the economy. If goods and services imported in the given economy are produced by one other economy with a different technological level, results will be respectively overestimated or underestimated;

Primary exergy cost of goods and services: focus on the Italian economy

As an example, Figure 35 reports exergy cost of products (in $kg_{oe}/100€$) out of the 35 sectors of the Italian economy in 2005, evaluated with all the above introduced import treatment methods (notice that the radar graphs are in logarithmic scale). The following comments can be made:

- Specific costs obtained according to *method c* are always higher with respect to *methods a* and *b*. This is motivated by the fact that the final demand defined by *method c* is lower with respect to other methods (fluxes of exported products that feed the intermediate consumption of other countries are included in the World Transaction matrix);
- Since *method c* does not make hypothesis on imported and exported products, primary exergy costs evaluated with this method can be considered as the reference costs for further comparisons and for LCA analysis;
- On average, results obtained with *method b* are more accurate than the results obtained with *method a* (i.e. they are more similar to results obtained with *method c*). This is mainly due to the fact that with *method a* all the exogenous resources are ideally entering the economy

through *sector c* only (*mining and quarrying*), whereas in *method b* imported fuels are directly allocated on the producing sector through which they are actually entering the economy;

- According to all the import treatment methods, sectors *C* (*Mining and Quarrying*), 23 (*Coke, Refined Petroleum and Nuclear Fuel*) and *E* (*Electricity, Gas and Water Supply*) present the higher exergy costs. This results is reasonable, because such sectors are directly involved in the extraction and conversion of energy and then constitute the interface between the economy and the environment;

Code	a	b	c
AtB	2,61	6,11	11,96
C	163,57	2,33	188,24
15t16	2,81	7,01	13,55
17t18	2,39	6,66	13,73
19	1,86	4,60	10,91
20	2,41	5,39	13,46
21t22	3,22	7,74	14,48
23	79,72	180,38	274,90
24	3,69	9,50	27,31
25	3,14	7,26	19,68
26	16,66	19,31	43,34
27t28	4,88	12,84	28,88
29	2,58	6,46	17,51
30t33	1,86	4,57	15,15
34t35	1,87	4,26	17,71
36t37	2,57	5,48	16,39
E	34,66	79,01	109,05
F	4,76	6,21	15,79
50	2,25	5,28	10,07
51	2,41	4,95	9,76
52	3,27	7,35	11,80
H	2,33	6,00	9,18
60	4,88	11,35	18,81
61	3,38	7,52	14,25
62	5,63	12,60	30,38
63	2,53	5,63	10,76
64	1,71	3,98	7,23
J	0,80	1,93	3,25
70	0,43	1,07	1,52
71t74	1,66	3,83	6,99
L	1,39	3,57	5,36
M	0,58	1,63	1,93
N	1,37	3,49	6,49
O	1,88	4,55	7,73
P	0,00	0,00	0,00

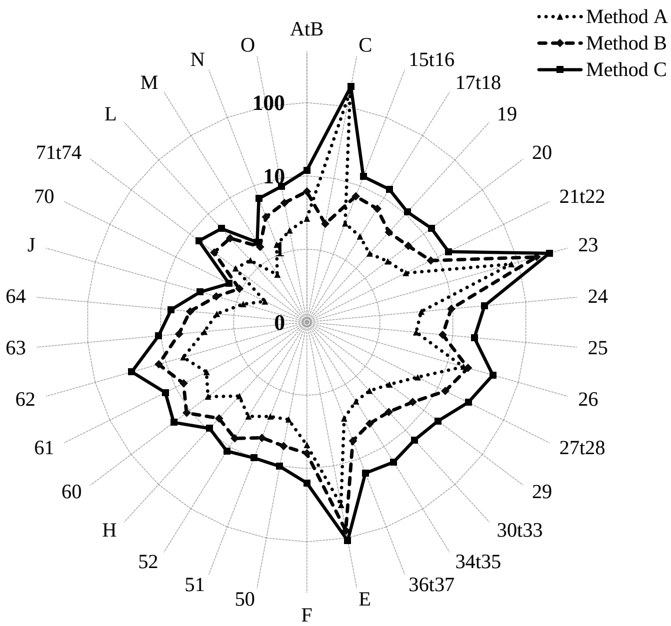

Figure 35. *Specific exergy cost of goods and services of the 2005 Italian economy, derived with models a, b and c. Graph is in logarithmic scale and values are expressed in kg_{oe}/100€.*

Finally, ExIO analysis allows to derive the total primary exergy costs of goods and service produced by the analyzed economy and also allows to evaluate the *direct* and *indirect* contributions to such total costs according to the power series approximation (2.47). Figure 36 shows these two contributions for the Italian economy in 2005, evaluated according to the import treatment *method a*. As can be inferred from the figure, fossil fuels are *directly* required in large quantity by only few sectors: *C* (*Mining and Quarrying*), *23* (*Coke, Refined Petroleum and Nuclear Fuel*), *E* (*Electricity, Gas and Water Supply*) and *F* (*Construction*). For this reason, traditional thermodynamic analyses and optimizations are focused on processes and systems that are part of these sectors.

However, Figure 36 also shows that *indirect* requirements of fossil fuels takes places in all the other sectors of the economy: the amount of such indirect requirements is represented by the area between black and grey lines. Therefore, according to these results, relevant savings of primary fossil fuels can be obtained also through the optimization of such other sectors of the economy: *application of ExIO analysis allows to extend the traditional concept of energy saving also to unusual and unsuspected fields of applications.*

Code	C_dir ktoe	C_ind ktoe	C_tot ktoe
AtB	11	852	863
C	1797	9	1805
15t16	82	2828	2910
17t18	30	1695	1725
19	11	524	535
20	4	158	162
21t22	105	640	746
23	25659	1717	27376
24	388	2178	2566
25	23	694	717
26	1585	1015	2600
27t28	1121	1991	3111
29	131	2976	3107
30t33	55	1357	1412
34t35	49	1620	1668
36t37	95	1010	1106
E	8513	2403	10916
F	2004	6097	8101
50	36	1101	1137
51	194	1716	1910
52	313	2320	2632
H	35	2211	2245
60	19	2208	2227
61	3	270	272
62	5	558	563
63	20	598	618
64	11	455	466
J	8	342	349
70	31	655	686
71t74	47	960	1007
L	40	1981	2021
M	8	482	489
N	37	1752	1788
O	35	1019	1054
P	0	0	0

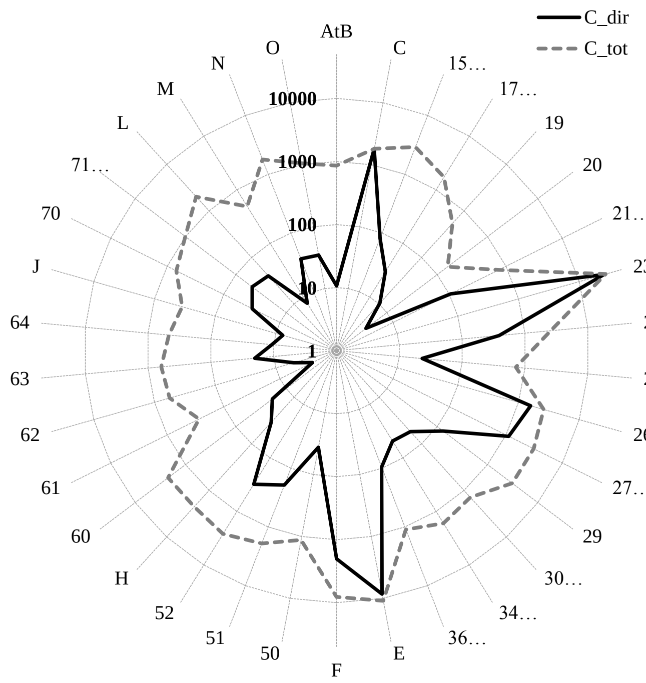

Figure 36. *Direct (black) and Total (grey) contributions of the primary* ***e****xergy cost of products (ktoe) for the 2005 Italian economy. Import are treated with model a. Graphic in logarithmic scale.*

6.1.5. Bioeconomic ExIO analysis of national economies

In this last paragraph, the *Bioeconomic ExIO analysis* is applied to all the countries listed in Table 17. In this case, imported products are treated according to method 1.

As stated in section 5.3, working hours are interpreted by the *B-ExIO analysis* as intermediate consumptions: they do not have an exergy cost, but they contribute to the generation of the exergy cost of goods and services. Because of this reason, specific exergy costs of one working hour delivered by each country as the final demand can be seen as the marginal amounts of primary required to produce one working hour.

Considering one country, the *total* primary exergy cost of production evaluated according to B-ExIO and standard ExIO models are equal. On the other hand, as stated in paragraph 5.3.3, the primary exergy costs of each productive sector undergoes a reallocation based on the amount of working hours required by each sector of the economy. Indeed, Figure 37 shown the relative difference between specific and total primary exergy costs of Italian products (respectively on left and right side of the figure).

Based on the obtained results, the following comments can be made:

- According to the B-ExIO model, a part of the final demand of the economy is internalized in the transaction matrix: since the amount of primary exergy absorbed by the economy remains constant, specific exergy costs of products results higher for the B-ExIO analysis (left side of Figure 37);
- As a consequence of the previous statement, total exergy cost of products out of all the sectors change. Specifically, sectors that require a large amounts of working hours (*tertiary*

sectors) will results in higher primary exergy costs. On the other hand, the opposite phenomenon occurs for the less working hours intensive sectors.

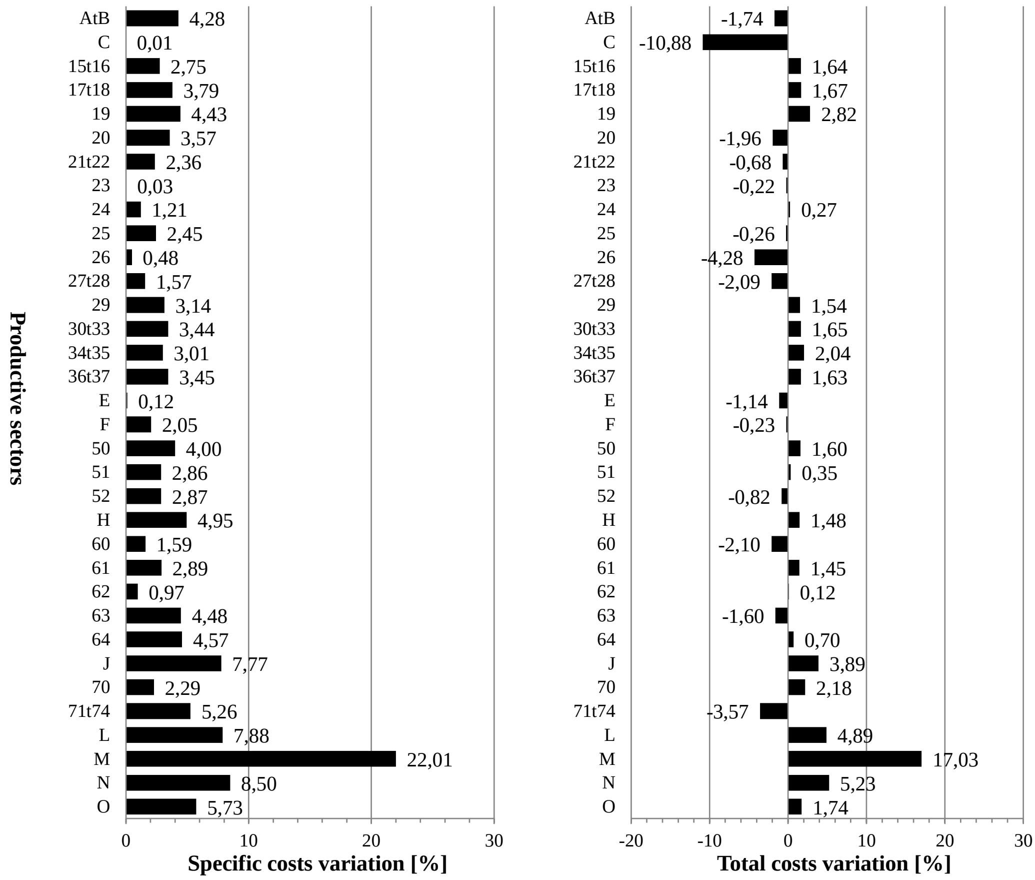

Figure 37. *Relative difference between primary exergy costs of the Italian products evaluated with ExIO and B-ExIO (model a for import treatment)*

6.2. TIOA and Hybrid-ExIO analysis of a Waste-to-Energy power plant

In this section, Standard and Hybrid Thermoeconomic Input–Output Analysis formalized in section 4.4 is applied for the analysis of the *Tecnoborgo Waste-to-Energy (WtE) power plant*, located in the city of *Piacenza*, in northern *Italy*. The objectives of the case study are:

- Evaluation of specific and total exergy costs of products, and identification of *critical* components through the evaluation of Thermoeconomic indexes according to the procedure introduced in paragraph 4.4.2;
- Evaluation of specific and total *primary* exergy cost of system products and assessment of system performances in a Life Cycle perspective, according to the Hybrid ExIO method introduced in paragraph 4.4.3.

6.2.1. WtE plant description

The facility is endowed with two waste treatment lines, comprising an air-cooled downward reverse-reciprocating grate (*Martin grate*) with a counter-flow combustion chamber. Both lines produce superheated steam which is expanded in a single Rankine steam cycle, producing about *10 MW* net electricity. The Flue-Gas Treatment (FGT) sections apply a Dry Process, featuring a Selective Catalytic Reactor (SCR) with NH_3-solution, an Electro-Static Precipitator (ESP), a $NaHCO_3$/Lime and Activated Carbon reacting section, and a Fabric Filter (FF). The simplified physical structure of the plant is shown in Figure 38, and it has been modeled and simulated with *ThermoFlow ThermoFlex*®. More details about *WtE* technology and the analyzed power plant can be retrieved in literature [16].

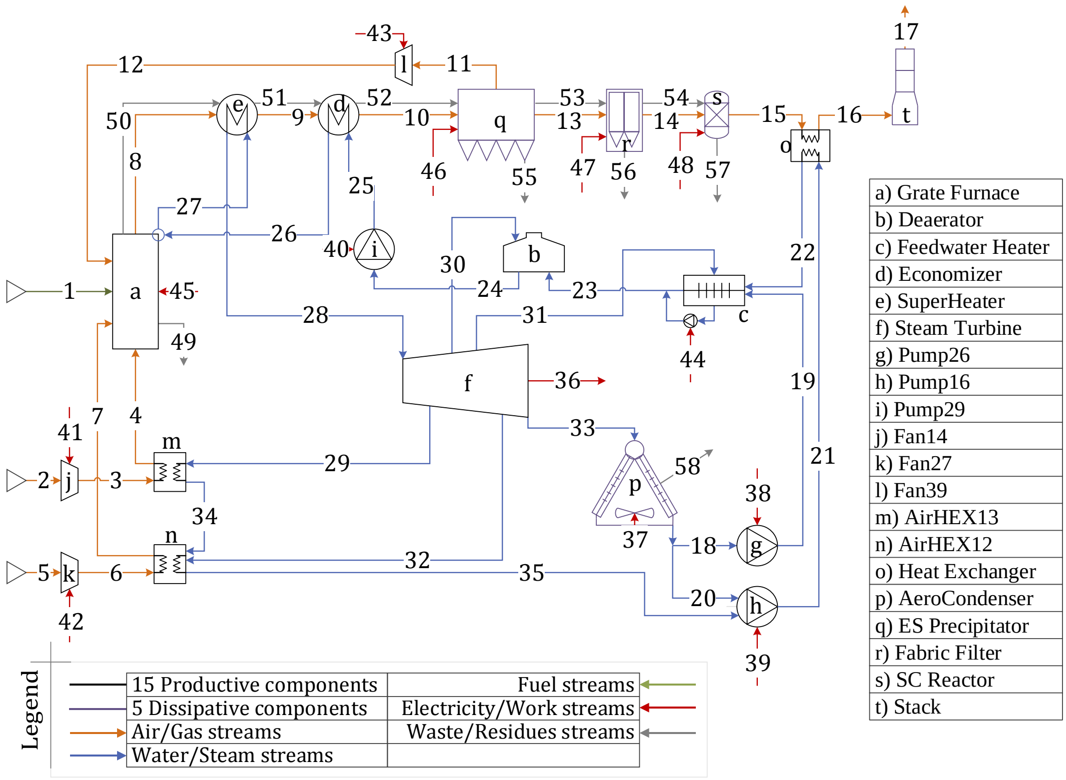

Figure 38. *Physical layout of the Waste-to-Energy power plant under study.*

Obviously, definition of the model for Thermodynamic and Thermoeconomic Analyses does not resemble the physical structure of the power plant: aggregation level of the model is defined according to economic cost data availability [145].

Description	Parameter	Units	Value
Feedstock flow rate	$\dot{m}_1$	kg/s	4,2
Lower Heating Value of the waste	LHV	MJ/kg	10,8
Estimated chemical exergy of the waste	E^{CH}	MJ/kg	12,9
Steam turbine inlet pressure	p_{in}^{ST}	bar	40
Steam turbine inlet termperature	T_{in}^{ST}	$°C$	390
Exhaust Gas Recirculation ratio	EGR	–	15%

Table 18. *Main thermodynamic parameters of the Waste-to-Energy power plant under study.*

The plant is designed to treat 120'000 t/year of waste, mainly *Municipal Solid Waste* (MSW), plus small fractions of *Clinical Waste* (CW) and *Sewage Sludge* (SS), which result in an average Lower Heating Value of $10{,}8\,MJ/kg$ [24]; chemical exergy has been estimated in $12{,}9\,MJ/kg$ according to [162]. Other main design parameters are collected in Table 18.

6.2.2. Standard Exergy Cost analysis: Thermoeconomic IO analysis

The thermodynamic model of the WtE plant here considered is composed by 20 components, connected to each other, to the environment and to the Italian economy by flows of exergy. All the flows entering and exiting each component are classified according their purpose as Resource, Product or Loss as showed in Table 19; practical definition of such categories is performed as described in literature [145, 206-208]. For each component, the exergy balance and exergy efficiency can be written: the amount of exergy resources equals the sum of products, losses and exergy destructions.
This practice allows to distinguish among *productive* and *dissipative* processes [6]:

- *Productive*: whose main purpose is to generate a useful product;
- *Dissipative*: which do not generate any final product, but are responsible for disposing of the residues created during production (condensers, filters, SCRs, stacks, etc.).

		Component	Resource	[kW]	Product	[kW]	η[%]
Productive	a)	**Grate Furnace**	*1+4+7+12+45*	55540,3	*8+(27-26)+49*	28196,3	50,8
	b)	**Deaerator**	*30*	668,3	*24-23*	607,9	91,0
	c)	**Feedwater Heater**	*31+44*	352,1	*23-(22+19)*	300,5	85,3
	d)	**Economizer**	*9-10*	3363,4	*26-25*	2827,4	84,1
	e)	**SuperHeater**	*8-9*	3871,2	*28-27*	3238,8	83,7
	f)	**Steam Turbine**	*28-(29+…+33)*	13810,3	*36+…+48*	10811,1	78,3
	g)	**Pump26**	*38*	4,4	*19-18*	2,6	58,2
	h)	**Pump16**	*39*	4,8	*2-(20+35)*	2,8	58,5
	i)	**Pump29**	*40*	115,5	*25-24*	77,7	67,3
	j)	**Fan14**	*41*	66,7	*3-2*	49,5	74,2
	k)	**Fan27**	*42*	44,8	*6-5*	323,0	73,6
	l)	**Fan39**	*43*	9,4	*12-11*	7,2	76,1
	m)	**AirHEX13**	*29-34*	682,7	*4-3*	332,2	48,7
	n)	**AirHEX12**	*32+34-35*	156,1	*7-6*	76,8	49,2
	o)	**Heat Exchanger**	*15-16*	165,0	*22-21*	78,2	47,4
Dissipative	p)	**AeroCondenser**	*33-(18+20)+ 37*	4832,4	*58*	4710,0	97,5
	q)	**ES Precipitator**	*10-(11+13)+46+52-53*	338,8	*55*	250,0	73,8
	r)	**Fabric Filter**	*13-14+47+53-54*	72,7	*56*	0,8	1,1
	s)	**SC Reactor**	*14-15+48+54*	53,3	*57*	0,2	0,3
	t)	**Stack**	*16*	5871,2	*17*	5865,7	99,9

Table 19. *Resource–Product classification for each component of the plant.*

Subsequently, these quantities are collected in the *exergy Input – Output table* (also called *Resource-Product table*) showed in Table 20. To understand the definition of the exergy IOT, it is necessary to identify origin and destination of every exergy flow, underlying where the resource and product of each component are respectively produced and utilized. Notice that exogenous resources input consists only in the exergy of the waste, while useful products consists in electric energy and bottom ashes. All the other outputs are classified as dissipations, such as rejected heat, dusts and fly-ashes, and chemical residues.

Component		a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	p	q	Rr	s	t	
	Ref	R_a	R_b	R_c	R_d	R_e	R_f	R_g	R_h	R_i	R_j	R_k	R_l	R_m	R_n	R_o	R_p	R_q	R_r	R_s	R_t	**W**
a	P_a	1083	434	229	3363	3871	8976	-	-	-	-	-	-	444	101	165	3061	272	46	53	5871	476
b	P_b	-	20	10	-	-	412	-	-	-	-	-	-	20	5	-	141	-	-	-	-	-
c	P_c	-	10	5	-	-	204	-	-	-	-	-	-	10	2	-	69	-	-	-	-	-
d	P_d	-	93	49	-	-	1916	-	-	-	-	-	-	95	22	-	653	-	-	-	-	-
e	P_e	-	106	56	-	-	2195	-	-	-	-	-	-	108	25	-	749	-	-	-	-	-
f	P_f	83	-	0	-	-	-	4	5	116	67	45	9	-	-	-	122	67	26	0	-	10267
g	P_g	-	0	0	-	-	2	-	-	-	-	-	-	0	0	-	1	-	-	-	-	-
h	P_h	-	0	0	-	-	2	-	-	-	-	-	-	0	0	-	1	-	-	-	-	-
i	P_i	-	3	1	-	-	53	-	-	-	-	-	-	3	1	-	18	-	-	-	-	-
j	P_j	49	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
k	P_k	33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
l	P_l	7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
m	P_m	332	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
n	P_n	77	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
o	P_o	-	3	1	-	-	53	-	-	-	-	-	-	3	1	-	18	-	-	-	-	-
p	P_p	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	4710
q	P_q	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	250
r	P_r	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1
s	P_s	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0
t	P_t	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5866
	R	53877	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	

Table 20. *Exergy Input - Output Table of the system.*

As showed in Table 20, WtE plant is composed by 15 productive components and 5 dissipative components. For this system, the *exergy production balance* (4.48) is defined: elements of the Exergy Input - Output Table $\mathbf{Z}_{\mathbf{WtE}}$ represents the amount of exergy produced by *i*th component and fueled as a resource to *j*th component. Definition of *exergy junction ratios* is required in this case to overcome the problem of allocating the product of multiple components as a resource of other components: further details about such procedure are given in literature [201, 208, 209].
Exergy costs, exergy destruction and exergy cost of exergy destructions are reported in Table 21.

Productive components	$\boldsymbol{c}[-]$	$\boldsymbol{C}[\boldsymbol{kW}]$	$\dot{\boldsymbol{D}}[\boldsymbol{kW}]$	$\boldsymbol{C_{Ex,D}}[\boldsymbol{kW}]$	$\boldsymbol{r}$
a) Grate Furnace	3,3	1587,8	27093,1	90354,2	0,97
b) Deaerator	5,2	-	60,4	315,9	0,10
c) Feedwater Heater	5,5	-	51,7	284,9	0,17
d) Economizer	4,9	-	536,0	2616,2	0,19
e) SuperHeater	4,9	-	632,4	3099,0	0,20
f) Steam Turbine	5,1	52288,8	2999,2	15274,2	0,28
g) Pump26	9,7	-	1,8	17,8	0,72
h) Pump16	9,6	-	0,0	0,0	0,71
i) Pump29	8,5	-	37,8	320,6	0,49
j) Fan14	6,9	-	17,2	118,4	0,35
k) Fan27	6,9	-	11,8	81,8	0,36
l) Fan39	6,7	-	2,3	15,0	0,31
m) AirHEX13	8,1	-	350,5	2828,3	1,06
n) AirHEX12	8,0	-	79,4	633,9	1,03
o) Heat Exchanger	8,0	-	86,8	690,0	1,11

Table 21. *Results of the standard exergy cost evaluation procedure*.

Based on the obtained results, the following consideration can be made:

- Total exergy costs can be evaluated for products that are part of the final demand (bottom ashes and electric energy). Specific exergy costs are evaluated for all the components and represent the marginal cost of products delivered as final demand;

- Cost of products out of dissipative components results null, as a consequence of the reallocation procedure presented in paragraph 4.4.2. Notice that, for such components, specific costs have no practical meaning;
- Exergy destruction are higher for grate furnace and steam turbine, revealing the sources of thermodynamic inefficiencies within the plant;
- Since exergy cost of exergy destructions, with reference also to Figure 39, are evaluated at the specific cost of the product, they provide a measure of the loss of exergy production due to thermodynamic inefficiencies of components. Also in this case, relevance of grate furnace and steam turbine is confirmed;
- Values of the relative cost difference show that there are practical margins of thermodynamic improvements for many components, especially for grate furnace, air pre-heaters, and general heat exchangers.

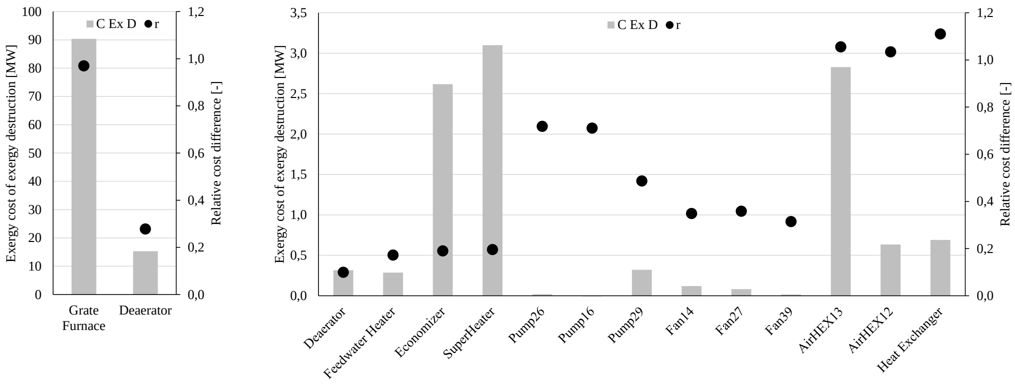

Figure 39. *Exergy cost of exergy destruction and relative cost difference for the WtE plant.*

6.2.3. Primary Exergy Cost analysis: Hybrid ExIO analysis

An Economic Analysis has been carried out following the procedure suggested by [32, 134, 186], in order to devise input data for the application of H-ExIO. More specifically, these data are arranged in the Upstream Cut-off matrix, as described in paragraph 4.4.3.

In a LC approach, three different Hybrid IOTs have been defined. Table for *Construction phase* is determined through the *Total Capital Investment* (TCI) of the plant; table for *Operation phase* is compiled assuming a prospected lifetime of 25 years at nominal operative conditions and *Dismantling phase* is neglected due to lack and uncertainties of data. Hybrid IOTs are compiled as follows:

- To determine the primary exergy cost of constructing the energy system, the Total Capital Investment provides the connection between national economy and the plant: Purchased Equipment Cost, Delivery, Installation, Piping, Buildings, Land and Yard Improvements, Electrical Systems, Instrumentation and Control, plus other Non-Manufacturing costs (Engineering, Legal expenses, Contingencies, etc.). The physical system is accounted then as a single component, provided as one unit of final demand; therefore, Downstream Cut-off matrix results empty, and national final demand needs no correction. Conversely, the Italian MIOT needs to be adjusted, extracting the Upstream Cut-off matrix, in order to avoid double counting;
- To estimate the yearly primary exergy cost of operating the power plant, economic cost for operation and maintenance of each component are used to compile the Upstream Cut-off matrix. The main terms include Raw Materials, Labor, Utilities, Maintenance,

Depreciation, Taxes, etc. Moreover, national final demand of electric energy has been corrected to account for the power plant contribution.

The direct and indirect expenditures in terms of fossil fuel exergy for owning and operating the WtE plant are determined on yearly basis and reported in . The net benefit arisen from electricity generation is computed and cumulated over the entire LC of the plant, to obtain the previously defined Primary Resource Cost C_{net}. The ratio between this cost and the construction requirement provides the Exergy Return On Investment of the energy system.

Parameter	Units	Value
$\boldsymbol{C_C}$	*ktoe*	1,40
$\boldsymbol{E^-}$	*ktoe/y*	0,005
$\boldsymbol{E^+}$	*ktoe/y*	7,062
$\boldsymbol{C_O}$	*ktoe/y*	7,017
$\boldsymbol{C_{net}}$	*ktoe*	174,03
$\boldsymbol{ExROI}$	-	124,02
$\boldsymbol{LExCOE}$	-	0,014

Table 22. *Results of the Hybrid Exergy based IO analysis.*

These results confirm the strong potential of Waste-to-Energy technology with respect to fossil fuel savings. Indeed, the analyzed system is able to produce a net amount of exergy about 124 times with respect to the primary fossil fuel exergy required for its construction, as shown by the value of ExROI. In a different perspective, $LExCOE$ shows that in order to produce 1 toe of electric exergy, WtE requires only 0,014 toe of primary fossil exergy.

However, it must be remarked that the H-ExIO analysis of power plants should be used to evaluate whether changes in design of one considered technology, performed according to the standard design evaluation of Thermoeconomic analysis, provides overall benefits in terms of primary fossil fuels requirements in a LC perspective.

In conclusion, from a theoretical viewpoint, H-ExIO reveals to be a simple, standardized and promising technique to perform LCA of energy systems. Furthermore, it provides useful indicators to assess their real thermodynamic performances. Practical application of H-ExIO reveals that WtE technology operating in the Italian context has a strong potential from a resource-saving standpoint.

6.3. ExIO analysis of alternative solutions: Manual dishwashing VS Dishwasher

In the evaluation of environmental impact of economic activities, the primary fossil fuels requirements of household appliances is under close scrutiny. Dishwashers are used to substitute or supplement manual dishwashing, so the question arises about the environmental effects not only of automatic but also of manual dishwashing. Indeed, while on the water consumption there is a clear advantage of using a dishwasher, evaluation of primary energy-resources requirements is more complex: energy-resource cost of energy, detergents and water should to be taken into account as well [15, 147].

To investigate this issue, this section presents results of Hybrid-ExIO analysis applied to evaluate and to compare primary exergy costs of *manual dishwashing* (MW) and *dishwasher* (DW) in a Life Cycle perspective. Since different amount of working hours are involved in such alternatives, this

case study is suited as a test for the novel *Bioeconomic* ExIO models, introduced in chapter 5. Results of both standard and Bioeconomic ExIO models are finally compared to assess the relevance of working hours in terms of primary exergy requirements.
The analysis has been carried out in the Italian context, and it is based on data retrieved in literature [20, 165] and in the European regulations [60], collected in Table 23 and Table 25.

	Units	Manual Washing (MW)	Dishwasher (DW)
Reference year	*y*	2005	
Place settings	*no/day*	12	
Days	*d/y*	300	
Years	*y*	10	
Labor time	*min/wash*	100	15
Water	*l/wash*	150	15
Electric energy	*kWh/wash*	0	1,5
Natural gas	*kWh/wash*	3,5	0
Detergents	*g/wash*	50	30

Table 23. *Average assumptions for manual dishwashing and dishwasher.*

The analysis is based on the Italian MIOT of 2005 only. According to average data found in literature, it has assumed a washing requirements of 12 place settings per day, for a total number of 300 days per year and a total time window of 10 years. Labor time, water, energy and detergents requirements are also estimate as average values.
The ExIO analysis has been carried out according to the *final demand approach*, described in paragraph 4.3.2: according to such model, the analyzed systems receive inputs from the Italian economy, and deliver *all* of their outputs as final demand (i.e. the Italian economy do not receive back any system's product).
The primary exergy cost of products absorbed by the system from the sectors of the economy are reported in Table 24 for standard and Bioeconomic models.

Primary exergy costs (ITALY 2005)	Code	Units	c_{ex}	$c_{ex,B}$
Chemicals and Chemical Products	24	$kg_{oe}/€$	0,32	0,32
Machinery, Nec	29	$kg_{oe}/€$	0,08	0,08
Manufacturing, Nec; Recycling	36t37	$kg_{oe}/€$	0,07	0,07
Electricity, Gas and Water Supply	E	$kg_{oe}/€$	1,39	1,39
Labor	Lab	kg_{oe}/h	-	0,04

Table 24. *Specific primary exergy cost of national products required by the analyzed system.*

Average economic price of inputs to the analyzed systems, required to compile the upstream cutoff matrix $\mathbf{E_{NS}}$, can be inferred from Table 25.

	Units	Economic cost
Dishwasher	*€*	1100
Water	$€/m^3$	1
Natural gas	*€/MWh*	74
Electricity	*€/kWh*	0,2
Detergents	*€/kg*	7

Table 25. *Specific economic prices of materials and energy required by the system.*

Before applying ExIO models, data of Table 25 allows to perform a comparison of the two alternatives from the purely economic standpoint: total economic cost of dishwashing is then evaluated over 10 years for the two alternatives, leading to results showed in Figure 40. From this first rough evaluation, total economic cost of dishwashing results to be comprised between 2000 € and 2500 €, and manual dishwashing seems to be less expansive with respect to dishwasher. This because the water and detergents savings are not greater than the investment cost required to owing, operating and dispose the dishwasher.

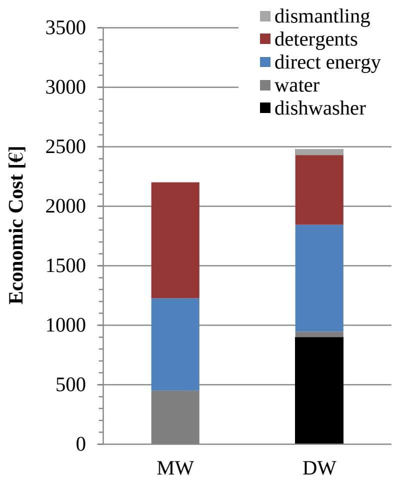

Figure 40. *Economic cost of the analyzed alternatives.*

Results of economic and ExIO analyses are reported in Table 26: in both cases, manual dishwashing results as the most primary exergy intensive solution.

	Manual dishwashing			Dishwasher		
Cathegory	C_{eco}	C_{ex}	$C_{ex,B}$	C_{eco}	C_{ex}	$C_{ex,B}$
	€	kg_{oe}	kg_{oe}	€	kg_{oe}	kg_{oe}
Dishwasher	-	-	-	900	28	29
Water	450	156	156	45	16	16
Direc energy	777	269	270	900	312	312
Detergents	975	36	36	585	22	22
Dismantling	-	-	-	50	1	1
Labor	-	-	312	-	-	47
Total	**2202**	**461**	**774**	**2480**	**379**	**427**

Table 26. *Results of the analysis.*

As showed by Figure 41, Standard ExIO model results in small difference between MW and DW solutions, whereas such difference is emphasized according to the Bioeconomic model. Specifically, the following considerations can be made:

- Primary exergy costs of direct energy requirements (natural gas for MW and electric energy for DW) are comparable, as well as the cost of detergents. Primary exergy cost of dishwasher (including its dismantling) and water use results in a very small contribution for DW;
- Both model results in substantial difference in exergy cost of water for the two alternatives;

- Primary exergy cost of products do not change significantly between standard and Bioeconomic models;
- Considering results of B-ExIO model, the contribution of working hours to the primary exergy cost is relevant for manual dishwashing, causing almost a doubling of the cost with respect to standard model. As expected, dishwasher solution does not change significantly;
- Because the analyzed alternatives do not produce any exergy output, it is not possible to evaluate the performance indexes introduced in paragraph 4.4.3;
- Since the analysis has been carried out using only the Italian MIOT of 2005, and since constant average input data has been considered to model the whole Life Cycle of the analyzed alternatives, the evaluation of uncertainties should be carried out to confirm the validity of results.

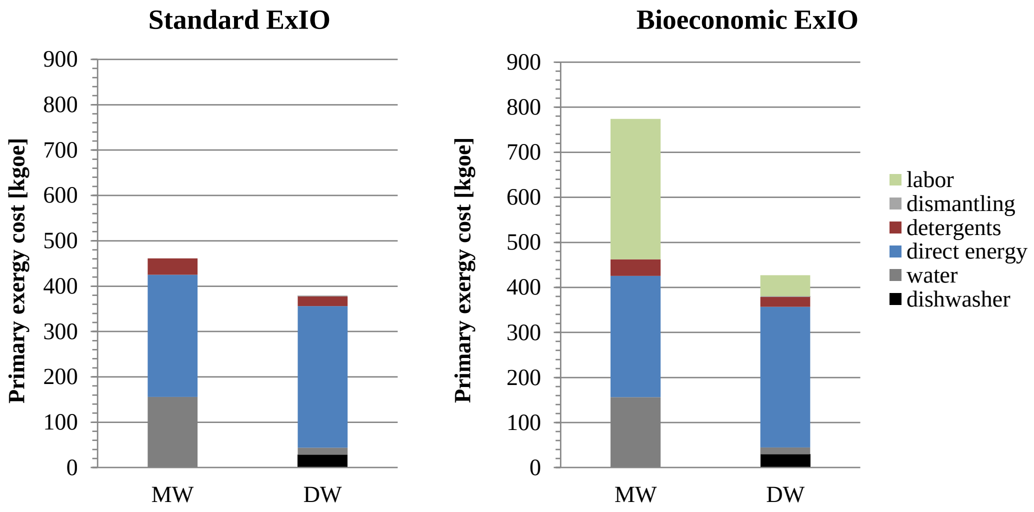

Figure 41. *Exergy cost (standard and Bioeconomic model) of products involved in the case study.*

Notice that in paragraph 5.3.3 is clearly stated that working hours contribute to the generation of the exergy cost of products, but they do not have a primary exergy cost because they are not product of the society. This seems to be in contrast with the obtained B-ExIO results, in which exergy cost of working hours is different than zero. This results can be justified because because the final demand approach as been used, and thus working hours requirements are considered as a part of the final demand required to owing and operating the two considered alternatives.
In conclusion, both economic and standard ExIO analyses do not results in significant differences between MW and DW from the point of view of economic cost and primary exergy cost. However, Bioeconomic ExIO model is capable to capture the primary exergy requirements of working hours, revealing the strong benefits that could be obtained from dishwashers in primary fossil fuels savings.

Conclusions

Thanks to the case studies presented in the previous chapter, advantages and drawbacks of the ExIO framework are here highlighted, and possible further research paths in the field of energy-resources accounting discipline are proposed. Finally, a general overview about the main achievements of the research are remarked.

Advantages, drawbacks and further research paths of ExIO

The ExIO framework have been developed to deal with the main issues emerged from literature, that becomes the specific objectives of the research.

Identification of a standardized accounting method. As extensively showed in chapter 4, mathematical formulation of ExIO is based on Input – Output *analysis*, which establishes standard rules for the definition of time and space boundaries of any analyzed system or product, encompassing its whole Life Cycle. The approach relies on *Monetary Input Output tables of national economies*, that are freely available, constantly updated and compiled according to international standards. As confirmed by the case studies (chapter 6), the ExIO framework avoids extensive data mining processes and makes evaluation of primary energy-resources cost of products *reproducible* and *reliable*. Moreover, application of such technique results to be *simpler* and *faster* than other traditional process based LC based methods. Moreover, the following main considerations can be made:

- The use of MIOTs requires suited hypotheses for the treatment of imported and exported trade flows among countries, and *three different methods* have been proposed to face this issue. As showed by practical applications of ExIO to the case study of paragraph 6.1.4, the choice of import treatment method is critical and could largely affect the accuracy of results. Moreover, a formally correct treatment of trade flows relies on the World IO table (method c), which can be compiled only for higher aggregation of productive sectors and hardly it can be thus adopted for traditional LCA analysis of products;
- MIOTs are affected by uncertainties that negatively influences the quality and the accuracy of results obtained from ExIO: the problem of uncertainties propagation thus arise. Due to the mathematical structure of ExIO, uncertainty analysis could be efficiently performed by means of *Perturbation Theory*: this issue has not been addressed in this thesis and it may be considered as one of the possible further research paths;
- Another critical issue that emerges from ExIO analysis consists in the low accuracy of results. To overcome this problem, the *Hybrid-ExIO approach* has been proposed and completely formalized to selectively extract the analyzed system from its respective productive sector. This method results very useful in order to perform LCA analysis of small systems, as showed by the analyses of WtE plant and dish cleaning options in chapter 6, but it requires detailed monetary costs of system's components as input data that may be hardly available.

Energy-resources characterization. With respect to the other thermodynamic-based metrics, exergy represents the real usefulness of energy-resources, resulting as the most meaningful indicator for energy-resources accounting purpose. Moreover, exergy of fossil fuels seems to be less sensible to the conditions of reference environment with respect to the entropy generations. For such reasons, the ExIO approach accounts for the primary energy-resources requirements assuming *exergy* as the sole numeraire. With respect to the other exergy based LC methods emerging from the literature review (chapter 3), the ExIO framework results to be unambiguously formalized.

Evaluation of efficiency of energy systems in a Life Cycle perspective. The most important advantage that emerges from ExIO analysis resides in the opportunity to perform Thermoeconomic analysis and design evaluation of energy conversion systems. Indeed, application of the Hybrid-ExIO approach allows to define quantitative criteria and suited indicators in order to *identify* and to *minimize* the primary fossil fuels requirements of system's products in a Life Cycle perspective. Specifically, the H-ExIO analysis should be used to evaluate whether changes in design of one considered technology provides overall benefits in terms of primary fossil fuels requirements.
This technique has been tested in the Thermoeconomic analysis of a Waste to Energy power plant operating in the Italian context (chapter 6), revealing the great benefit of such technology from the in saving primary fossil fuels.
From the methodological standpoint, H-ExIO suffers of the same flaws above listed, but reveals to be a simple, standardized and promising technique to perform LCA of energy systems. More applications of H-ExIO, especially to renewable energy systems, may be useful to test and to validate the method.

Role of working hours. The *Bioeconomic ExIO analysis* has been proposed as a *partially closed* Input – Output model to account for the effect that *working hours* requirements due to goods and services production have on primary fossil fuels consumption. As results from the analysis of the Italian economy, the partial internalization of the final demand performed by the model cause a reallocation of the primary fossil fuels requirements among all the productive sectors: this allows to take into account for the additional goods and services consumption required to feed workers that produce working hours, causing an increase of the total exergy costs of products out of tertiary with respect to other less working hours intensive sectors.
Moreover, Standard ExIO and Bioeconomic ExIO have been used to compare manual dishwashing and dishwasher practices within the Italian context, evaluating the total primary exergy requirements of both solutions in a LC perspective.
From the methodological standpoint, the amount of final demand products that are actually feeding the working hours production process is determined according to a simple proportionality hypothesis, introduced in chapter 5. Further research is required in order to test this hypothesis or to propose a more refined criteria.

Final achievements of the research

As stated in the introductive chapter, political initiatives as well as research efforts are facing the issue of the increasingly scarcity of fossil fuels by promoting a rational use of energy through the so-called *energy saving* practice. As can be inferred from the literature and from the results obtained in this thesis, production of goods and services in modern economies may cause relevant *indirect* fossil fuels requirements that are ignored by traditional thermodynamics based methods. Without a proper evaluation of the *overall* resource consumption of one specific productive system, capable to include also the indirect supply chains requirements and externalities effects, misleading results may be obtained and wrong political and technological decisions may be taken.
Therefore, the *Exergy based Input – Output analysis* (ExIO) has been developed in this thesis with the aim to provide analysts and policymakers with a comprehensive and useful framework for the evaluation of primary energy-resources requirements of goods and services, and for Thermoeconomic analysis of energy conversion systems in a Life Cycle perspective.

List of author's publications

Publications on International Journal (ISI):

1. Rocco M, Colombo E, Sciubba E. *Advances in exergy analysis: a novel assessment of the Extended Exergy Accounting method*. Applied Energy. 2014;113:1405-20.

2. Cassetti G, Rocco MV, Colombo E. *Exergy based methods for economic and risk design optimization of energy systems: Application to a gas turbine*. Energy. 2014.

3. Colombo E, Rocco MV, Toro C, Sciubba E. *An exergy-based approach to the joint economic and environmental impact assessment of possible photovoltaic scenarios: A case study at a regional level in Italy*. Ecological Modelling. 2014.

Publications on International Conference Proceedings:

1. Rocco M, Taranto F, Colombo E. *Energy and Exergy Life Cycle Assessment of different anti-erosion systems*. Proceedings of the VII Convegno Scientifico della Rete Italiana LCA: "Life Cycle Assessment e ottimizzazione ambientale: esempi applicativi e sviluppi metodologici". 2013.

2. Rocco M, Toro C. *Exergy Based Methods For Economic And Environmental Analysis Applied To A 320 MW Combined Cycle Power Plant*. Proceedings of the 12th Joint European Thermodynamics Conference, JETC 2013, Eds M Pilotelli and GP Beretta 2013.

3. Colombo E, Rocco M, Gardumi F, Cassetti G, Barbieri J. *Exergy as a measure of oil well potential*. Proceedings of the 31st UIT National Heat Transfer Conference, Como (Italy), June, 25-27, 2013, Eds L Vitali and P Gramazio 2013.

4. Cassetti G, Rocco M, Colombo E. *Exergy based methods for economic and environmental design optimization of energy systems*. Proceedings of the 26th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. 2013.

5. Colombo E, Rocco MV, Toro C, Sciubba E. *An exergy-based approach to the joint economic and environmental impact assessment of possible photovoltaic scenarios: A case study at a regional level in Italy*. Proceedings of ecos 2014 - the 27th International conference on Efficiency, cost, optimization, simulation and environmental impact of energy systems 2014.

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