UNIVERSITÀ
DEGLI STUDI
DI PADOVA

Thesis title:

Integrated Modeling and Optimization for Environmental and Social Sustainability in Multi-Energy Systems

Student:

Yasaman Nosrat Tajoddin

Degree:

Master’s Degree in Energy Engineering

Supervisors:

Prof. Andrea Lazzaretto

Prof. George Tsatsaronis

Co-supervisors:

Dr. Gianluca Carraro

M.Sc. Enrico Dal Cin

Academic year 2023-2024

Abstract

The optimization of Multi-Energy Systems (MES) has traditionally been centered around economic objectives and the minimization of operational greenhouse gas emissions (GHG). However, the broader environmental and social impacts of these systems, especially those related to their life cycle and beyond mere GHG emissions, necessitate a more holistic optimization approach. This study introduces a novel and comprehensive objective function, the Inclusive Wealth Index (IWI), for optimizing Multi-Energy Systems. The IWI is defined as the weighted sum of three types of capital—human, natural, and produced—thereby integrating societal and environmental considerations into the optimization process in a comprehensive manner. By conducting a life cycle assessment (LCA) of the technologies and energy carriers within the MES, their implications on human and natural capitals are evaluated, while produced capital is assessed through investments in infrastructure and technology manufacturing, directly influencing economic growth and societal well-being. Utilizing mixed-integer linear programming (MILP) in a Python framework with the Gurobi solver, this research optimizes the design and operation of an MES to both maximize the IWI and reduce overall costs. A reference case is considered, where electricity and heat are supplied through the grid and natural gas boilers, respectively. The optimization of a grid-integrated case study, featuring photovoltaic modules (PV), heat pumps (HP), internal combustion engines (ICE), boilers (BOIL), electrical (EES), and thermal energy storage (TES) demonstrates that focusing solely on cost minimization results in a 46% savings compared to the reference case, yet it adversely impacts the IWI, reducing it to -0.03 points when all capitals are equally weighted. Prioritizing IWI maximization, on the other hand, substantially elevates the index to 0.114 points but incurs costs 42% higher than those associated with the cost-minimization scenario. Through multi-objective optimization that balances cost and IWI objectives, the study reveals that significant enhancements in societal wealth are attainable with low expenses, achieving a notable improvement in IWI of 0.056 points alongside a cost reduction of 41% compared to the reference case, and only 8% higher than the cost-minimization scenario. This research also underscores the critical importance of balanced capital weighting in optimizing MES for sustainable development, paving the way for energy systems that strategically integrate economic, environmental, and social considerations.

Acknowledgment

First, I extend my deepest appreciation to Professor Lazzaretto for his exceptional mentorship and guidance. He generously contributed to the original ideas behind the proposed objective function, central to this thesis. My gratitude also goes out to Professor Tsatsaronis, who supervised my thesis research at Technische Universität Berlin. His guidance and expertise have been fundamental in shaping the direction and outcome of my work. I am equally indebted to Enrico Dal Cin (M.Sc), whose specific role in organizing the equations and structuring the case study of this thesis cannot be overstated. Additionally, I would like to thank Dr. Gianluca Carraro for his constant support and insightful contributions to my research project. Together, these individuals have provided an environment of growth, learning, and discovery, while their expertise and encouragement have been instrumental in navigating the complexities of my work.

To my family—my unwavering foundation of love and support—I owe an immeasurable debt of gratitude, to my father, who instilled in me the value of hard work; to my mother, who nurtured me with unconditional love; to my brother, Ali, and his wife, Sara, for their kindness and support. I am blessed to have you in my life, and your belief in me has been a source of motivation and confidence. A special word of thanks to my sister, Nastaran, who has always been my biggest supporter, my source of motivation, and my inspiration in life. Your encouragement and understanding have been my constant source of strength, and I will always remember that: “Life is not a sprint, but a marathon requiring consistency and resilience.”

Last, but certainly not least, I wish to express my heartfelt thanks to my friends— whose names I hold dear in my heart—you have been my companions through every high and low; and a pillar of support during the demanding times of this thesis.

I am profoundly grateful to each individual who played a pivotal role in this journey, which will forever be cherished and remembered. To all of you, I offer my sincerest gratitude.

Contents

List of Figures

List of Tables

List of Symbols and Abbreviations

IWI	Inclusive Wealth Index
HDI	Human Development Index
GHG	Greenhouse Gas
MES	Multi-energy System
LCA	Life Cycle Assessment
PV	Photovoltaic
HP	Heat Pump
ICE	Internal Combustion Engine
BOIL	Boiler
EES	Electrical Energy Storage
TES	Thermal Energy Storage
GDP	Gross Domestic Product
HC	Human Capital
NC	Natural Capital
PC	Produced Capital
SDG	Sustainable Development Goal
MILP	Mixed-Integer Linear Programming
O&M	Operation and Maintenance
ref	Reference
inv	investment
opr	operation
imp	Imported
exp	Exported
el	electrical
th	thermal
ng	Natural Gas
F	Fuel [m^3]

P	Power [kW_{el}]
Q	Heat [kW_{th}]
n	Lifetime [years]
r	Interest Rate
k	Cost [euro]
C	Capacity [kW] or [kWh]
w_{HC}	Weight of Human Capital
w_{NC}	Weight of Natural Capital
w_{PC}	Weight of Produced Capital
HC^*	Specific Human Capital [$\frac{points}{year}$]
NC^*	Specific Natural Capital [$\frac{points}{year}$]
PC^*	Specific Produced Capital [$\frac{euro}{year}$]
HC	Normalized Human Capital
NC	Normalized Natural Capital
PC	Normalized Produced Capital
hc	Human Capital Coefficient [$\frac{points}{kWh}$] or [$\frac{points}{kW.year}$] or [$\frac{points}{kWh.year}$]
nc	Natural Capital Coefficient $\left[\frac{points}{kWh}\right]$ or [$\frac{points}{kW.year}$] or [$\frac{points}{kWh.year}$]
pc	Produced Capital Coefficient [$\frac{euro}{kWh}$] or [$\frac{euro}{kW.year}$] or [$\frac{euro}{kWh.year}$]

Chapter 1: Introduction

The European Union (EU) is firmly committed to being climate-neutral by 2050, as explained in the European Green Deal [1], which aims to convert the EU into a fair and prosperous society, featuring a modern, resource-efficient, and competitive economy. The goals are achieving net-zero greenhouse gas emissions by 2050, decoupling economic growth from resource use, and ensuring a just and inclusive transition where no person and no place is left behind.

A Multi-Energy System (MES) is an energy infrastructure where multiple energy vectors (such as electricity, heat, cooling, fuels, and transport) interact at different levels (district, city, region) to provide a more efficient, environmentally friendly, and reliable energy system compare to the traditional energy production methods [2]. Optimization models for energy systems play a critical role in analyzing their efficiency and enhancing effectiveness [2]. Traditionally, these models concentrate on economic objectives like minimizing investment and operational costs. In recent years, there has been increased attention on optimizing multi-energy systems beyond merely considering economic aspects by considering the minimization of operational greenhouse gas emissions (GHG) [3]. However, the environmental impact of MES is not limited to greenhouse gas emissions or solely to the operational phase. Given the significant impact of the construction phase of these systems and their critical impact on other environmental sectors beyond greenhouse gas emissions, it is important to consider the whole environmental life cycle assessment (LCA) of these systems while optimizing them [3]. Moreover, it is profoundly important to integrate social aspects into these models. This importance stems from the significant impact of energy modeling on energy policy development, though it remains a significant challenge [4]. While certain research efforts have factored in social considerations, such as employment opportunities and the Human Development Index (HDI), and others have included lifecycle assessments in their optimization analyses (Chapter 3), there still is an absence of a holistic objective function that covers both social and environmental factors comprehensively.

This study's foremost aim is to identify a comprehensive objective function for the design and operation of multi-energy systems, considering the social and whole life cycle environmental aspects, while fulfilling economic growth. Through precise analysis and methodology, this research seeks to quantify these diverse factors into a unified, measurable objective, enabling the optimization of multi-energy systems in a manner that promotes sustainable development, and fills the gap in the current focus of MES optimization. After defining this comprehensive objective function, the goal is to develop a multi-objective function optimization problem based on the mixed-integer linear programming (MILP) method to integrate this objective function for social and life cycle environmental aspects with the traditional yet important objective to minimize the design and operational costs. Thus, the optimal component sizes for the multi-energy system are determined to balance cost efficiency with social and environmental sustainability, as well as economic growth.

Chapter 2: General Issues for a Socially and Environmentally Fair Transition

The term Just Transition originated from 1970s labor movements in response to environmental activism aimed at shifting from a high-carbon to a low-carbon industry. Just Transition was used to address a fair and equitable transition for workers and communities affected by changes caused by energy transition, highlighting the conflict between economic production and environmental conservation [5]. The sociology of energy has an important role in the shift from fossil fuel-based production to renewable energy, addressing issues of equity and justice. Environmental sociology explains that humans and nature are not separate; indeed, they have strong interactions and effects on each other. In “Handbook of Environmental Sociology” [6], the implications of sociology in the environmental context are categorized into four different themes, each highlighting the intersection of sociology with different aspects of environmental concerns. This chapter delves into four critical themes: the intersection of social inequalities with environmental challenges in "Inequality, Political Economy, and Justice"; the multifaceted impacts of climate change on energy, health, and food security in "Climate, Energy, and Health"; the role of culture, governance, and institutions in shaping environmental outcomes in "Culture, Governance, and Institutions"; and the dynamics of population changes, technological advancements, and their environmental implications in "Population, Place, and Possibilities.”

2.1 Inequality, Political Economy and Justice

This theme examines how social inequalities, for example, race, class, and gender, make certain groups more susceptible to environmental problems. For example, concerning consumption, the lifestyles of 10% of the global population account for 50% of global carbon emissions. Additionally, the environmental issues may cause the loss of jobs for people who work in high-polluting industries, making green jobs in renewable energy and other eco-friendly sectors a solution to environmental and economic issues. However, this transition can perpetuate inequalities across race, class, gender, and nationality. For example in solar panel manufacturing, companies often outsource to East Asia, where factories exploit marginalized workers in poor working conditions. The material extraction can result in health risks in the Global South, while the process, including chemical handling by low-income, female, and immigrant workers without adequate safety measures, contributes to several challenges.

This aspect also looks at how global production and trade networks contribute to unequal environmental impacts, emphasizing the need to explore the roles of markets, states, and economies in shaping environmental outcomes. Environmental sociology examines two main theories regarding the relationship between the economy and the environment. The Treadmill theory predicts continuous environmental impacts due to increasing economic production under capitalism unless societal actions dismantle the core structures of capitalism. Ecological Modernization theory, on the other hand, implies a transformation within the system, where corporations, states, and social movements align production with ecological values.

2.2 Climate, Energy and Health

This theme addresses the issues related to energy access, risk, disasters, health implications, and food insecurity rooted in environmental inequalities. Risks from human-made toxins and harmful exposures in air, food, and water are central to environmental health discussions. Environmental justice addresses the distribution of environmental risks, including dangerous waste sites, pollution of air and water, agricultural risks, chemical exposures, and climate change impacts. Additionally, disasters and extreme weather conditions such as floods, heat waves, etc. not only lead to death and health issues but also exacerbate poverty and social issues, particularly in low-to-middle-income countries. It also discusses the sociocultural dynamics of climate change, emphasizing the role of social movements and climate-conscious activists, answering the question "How and why do people come to the conclusions they do regarding climate change?"

Moreover, this aspect focuses on the central role of energy in societies and its impact on power and inequality. Currently, our societies heavily depend on fossil fuels and nuclear energy, which gives significant power and influence to major industries and key figures in these sectors. They play a crucial role in shaping our societies, political systems, economic structures, norms, and the overall health of the planet. There is a phenomenon called "resource curse" or "paradox of plenty," which explains how regions abundant in natural resources, such as fossil fuels, often face increased poverty and unstable governance. The concept of natural resource dependence emphasizes the socio-economic reliance on extractive sectors that lack diversity. These communities experience economic volatility due to boom and bust cycles, hindering long-term stability. The extractive industries can limit other forms of economic development, create spatial stigma, and contribute to a cognitive lock-in, preventing communities from envisioning alternative economic futures.

2.3 Culture, Governance and Institutions

Understanding how culture, governance, and institutions interact is crucial in environmental sociology. It explores how religious beliefs and spiritualities can significantly impact environmental actions. It also introduces Green Criminology (the study of environmental harms, (in) justice, and environmental law and regulation) to study responses to ecologically harmful activities. The theme also examines the connections between war, violence, and environmental damage. Additionally, it sheds light on environmental governance, showcasing the role of the state in shaping environmental outcomes.

A respectful human-animal relationship is also needed, emphasizing an earth-centered perspective, with global justice for animals, humans, and ecosystems. The domestic exploitation of animals for food and fiber to liminal animals facing persecution as pests has direct implications for human and non-human health, environmental issues, and global concerns like climate change.

2.4 Population, Place and Possibilities

Environmental sociology adapts to changes in population, space, and technology. It examines the connections between demographic processes such as birth, death, and migration, and the environment. For example, the displacement caused by a tsunami could result in a decreased desire to have children, as individuals relocate (whether temporarily or permanently) and must secure new jobs and restore their assets. The theme explores the impact of land use changes on the environment and introduces Structural Human Ecology, focusing on evolutionary thinking and risk frameworks. It also connects environmental sociology with science and technology studies, fostering a better understanding of human-environment interactions

The World Health Organization (WHO) [7] identifies climate change (any change in climate over time due to natural and human activities) as the biggest health threat facing humanity, affecting both aspects of nature and human systems. It is estimated that between 2030 and 2050, climate change will cause an additional 250,000 deaths annually. It influences human health, named, clean air, safe drinking water, nutritious food supply, and safe shelter. Climate change can cause death and illness due to air pollution, extreme weather events (heatwaves, storms, and floods), water and food scarcity and safety, vector-borne diseases, animal and human diseases such as zoonoses, water-food illnesses, and mental health problems (anxiety, stress) [8].

- Air Pollution:

Air pollution poses a significant global health risk, causing 4.2 million premature deaths in 2019. Most affected are low- and middle-income countries, with 89% of deaths occurring there. Cardiovascular and respiratory diseases, as well as cancers, result from exposure to fine particulate matter [9].

- Extreme weather events:

The unpredictable rainfall patterns and temperature rise can cause the unavailability of fresh water and a decrease in crop yield, which would increase undernutrition and the risk of diarrheal disease. More frequent floods elevate the chances of waterborne diseases and provide breeding sites for insects that carry and spread diseases, such as malaria. Moreover, heat stress and extreme cold would lead to higher death rates from cardiovascular and respiratory diseases [7]. According to WHO [10], climate change also affects social and economic conditions such as destroying schools and affecting the education of children (e.g. 18000 schools were destroyed in Pakistan due to monsoon-related floods), as well as destroying hospitals and homes, leading to difficulties in accessing health services and separating families, respectively.

- Mental health problems:

The Intergovernmental Panel on Climate Change (IPCC) has reported mental health issues as a consequence of climate change in its sixth Assessment Report. "*Mental health impacts are expected to arise from exposure to extreme weather events, displacement, migration, famine, malnutrition, degradation or destruction of health and social care systems, and climate-related economic and social losses and anxiety and distress associated with worry about climate change"*[11]. Eco-anxiety, a new term in the literature, describes the significant negative emotions—such as worry, guilt, and hopelessness—that awareness of climate change brings, especially to younger populations [12].

In addition to the traditional social sustainability factors such as basic needs, education, equity, employment, human rights, and poverty, climate change can affect soft social sustainability including the sense of place and culture, happiness and quality of life, participation and access, and social mixing and cohesion [13]. The daily well-being of people such as feeling well-rested, worry, sadness, stress, and anger; and the life evaluation estimations (where they stand now and in the future) can also be affected by energy-related consequences. The energy consumption and the ability to heat the house can affect the comfort of people. Moreover, climate change can cause stress and anxiety, while high energy bills can adversely affect the life evaluation estimations of the low-income group of people.

2.5 Conclusions

Chapter two discusses the critical issues surrounding a socially and environmentally fair transition. It introduces the concept of Just Transition, tracing its origins to labor movements in response to the shift from high-carbon to low-carbon industries. The discussion encompasses themes like inequality, political economy, and justice, exploring how social disparities worsen environmental problems. Additionally, it examines climate, energy, and health, emphasizing the disproportionate impacts of environmental risks on marginalized communities. The chapter also explores culture, governance, and institutions, highlighting the role of religious beliefs, green criminology, and environmental governance. Furthermore, it addresses population dynamics, land use changes, and technological advancements, showcasing the complex relationship between human society and the environment. Overall, the chapter emphasizes the urgency of addressing social inequalities and environmental injustices in the transition towards a sustainable future.

Chapter 3: Objective Functions for Optimization of Multi-Energy Systems

Multi-energy systems (MES) refer to integrated systems that manage and optimize the use of various forms of energy, such as electricity, heating, cooling, fuels, and transportation, within a unified framework. These systems are designed to enhance energy efficiency, reduce environmental impact, and improve economic performance compared to traditional energy systems by enabling the optimal interaction between different energy sources and consumption [2].

The optimization of multi-energy systems is crucial for the planning and design of future energy infrastructures, ensuring their feasibility and optimal performance [4]. This process involves selecting objective functions that guide the optimization, fundamentally shaping the outcomes of the system's design and operation. The most common objective functions are the minimization of primary energy consumption, economic costs, and CO_2 emissions. Historically, the economic aspect has been the predominant objective function, focusing on cost minimization and financial viability [14]. However, many authors argued that the modeling and optimization of energy systems lack the involvement of social aspects, despite the significant role of this theme in the planning of multi-energy systems [4] [14]. Furthermore, considering the whole life cycle environmental aspects in the optimization of multi-energy systems is of great importance; however, it is often simplified to solely include greenhouse gas emissions during the operational phase [3].

Recently, some researchers have taken into account the environmental impacts throughout the entire life cycle, alongside some social considerations. These studies typically address economic, environmental, and social objectives separately. Sections 3.1 and 3.2 provide an overview of the studies that considered life cycle environmental aspects and social aspects, respectively.

3.1 Life Cycle Environmental Consideration in the Optimization of MES

Many studies on MES often neglect or only briefly account for the operational greenhouse gas (GHG) emissions, ignoring the emissions throughout the entire lifecycle of the system; However, the construction phase of technologies involved in MES, for example, construction of a new conventional powerplant or producing photovoltaic modules, have a significant role on environmental impacts. Furthermore, focusing only on GHG emissions of technologies involved in the multi-energy system neglects other crucial environmental impacts [3]. Hence, it is essential to consider the whole life cycle assessment of the energy carriers and technologies involved in the multi-energy systems to model and optimize them.

In 2005, A. Hugo and E.N. Pistikopoulos [15] defined a mixed-integer linear programming model to optimize the supply chain of chemical production, using multi-objective functions to consider life cycle assessment as well as economic considerations. In the field of energy systems, L. Gerber et al. [16] used a multi-objective optimization to minimize the investment and operational costs as well as minimize the life cycle emissions in kg CO_2 equivalent. However, the environmental aspect of multi-energy systems is not limited to greenhouse gas emissions. To solve this issue, C. Reinert et al. [17] [18] developed an open-source MILP multi-objective optimization approach to minimize both total annualized system costs and annual climate impact, using midpoint impact categories from life cycle assessments based on the Ecoinvent database. T. Terlouw et al. [3] proposed a MILP method to optimize multi-energy systems considering costs and life cycle assessment, using the IPCC 2021 GWP100 and Environmental Footprint (EF) method. Their results show that the construction of technologies makes up 80% contribution to the overall life cycle environmental impact (such as ozone depletion, and human toxicity), showcasing the importance of considering the whole life cycle assessment in optimizing multi-energy systems.

3.2 Social Aspects in the Optimization of MES

Regarding the social aspects, the most common objective function in the literature is maximizing job creation or human development index (HDI)[1]. For instance, Dufo-Lopez et al. [19] optimized an off-grid multi-energy system including photovoltaic modules, wind turbines, diesel engines, and batteries to minimize total net present cost while maximizing human development index (HDI) and job creation. They considered the dependency of HDI on electricity consumption so that by producing electricity in the off-grid multi-energy system, the grid would have excess energy that can be used by extra businesses or services, so the HDI would increase. In another study, Z. Ullah et al. [20] used Homer to optimize a hybrid system composed of photovoltaic, wind, hydro, biomass, and battery based on five criteria, total life cycle cost, capacity shortage, greenhouse gas emission, job creation potential, and required land area. Furthermore, R Hassan et al. [21] optimized their model by minimizing the cost of energy, as well as considering the lifetime equivalent CO_2 emissions (as an environmental objective), and job creation (as a social objective). Additionally, I. Mariuzzo et al. [22] considered total annualized cost, life cycle, and operational CO_2 emissions and introduced a social objective related to "Social Comfort" associated with shiftable and adjustable loads (demand-side management). Similarly and in a more comprehensive study, T.Adefarati et al. [23] optimized a grid-integrated multi-energy system composed of wind turbines, fuel cells, and photovoltaic modules to minimize lifecycle costs, life cycle emission of greenhouse gases (CO_2, SO_2, and NOx sources), and monetary value of energy purchased from the utility grid, while maximizing the Human Development Index (HDI), job creation (JC), and monetary values of energy obtained from renewable energy sources. While these studies take into account certain social aspects, like job creation and the Human Development Index, as well as lifecycle greenhouse gas emissions, they fall short in two key areas: they lack a comprehensive objective function and fail to address broader environmental impacts of Multi-Energy Systems (MES) beyond just greenhouse gas emissions.

[1] According to Our World in Data: **"***The Human Development Index (HDI) is an index that measures key dimensions of human development. The three key dimensions are:*

1. *A long and healthy life – measured by life expectancy.*
2. *Access to education – measured by expected years of schooling of children at school-entry age and mean years of schooling of the adult population.*
3. *A decent standard of living – measured by Gross National Income per capita adjusted for the price level of the country."*

3.3 Conclusions

Chapter 3 explores optimizing Multi-Energy Systems (MES) while questioning the traditional emphasis on economic objectives, advocating for broader considerations including lifecycle environmental impacts and social factors. Even though some studies incorporate job creation and the Human Development Index (HDI) as social aspects and some consider life cycle assessment in the optimization problem, a comprehensive objective function encompassing all environmental and social dimensions remains lacking. The chapter calls for an integrated approach to fully address both environmental life cycle impacts and social aspects in the optimization of multi-energy systems (MES).

Chapter 4: Inclusive Wealth Index as Objective Function for Sustainable Development

This chapter presents a comprehensive exploration of sustainability, emphasizing the need to balance economic growth with environmental preservation and social equity. It starts by defining sustainability and the United Nations' Sustainable Development Goals (SDGs), focusing on the concept's complexity and its essentiality for future generations. Questioning the traditional GDP metric, the chapter argues for a comprehensive approach to measure a country's growth, by introducing the Inclusive Wealth Index (IWI) [24], a superior metric that captures natural, human, and produced capital. This index, reflecting a more accurate picture of national well-being, challenges conventional economic indicators by incorporating environmental and social dimensions into the assessment of a country's health and progress towards sustainability. Through a detailed examination of the components of the IWI and their interrelations, the narrative highlights the necessity of integrating ecological and human factors into economic planning and policy-making. This chapter not only offers a critical analysis of current practices but also proposes a visionary framework for achieving a sustainable future, introducing a measurable factor for a shift in how we evaluate success and well-being.

4.1 The Definition of Sustainability and Sustainable Development Goals

Sustainable development aims to integrate environmental and developmental concerns into a unified framework, addressing the trade-offs between global economic growth and the social and ecological aspects of this growth [25]. Sustainable development tends to achieve a balance between economic, environmental, and social aspects as can be seen in Fig. 1. Our Common Future,' a report by the World Commission on Environment and Development, states that sustainable development enables meeting current needs without hindering future generations' ability to meet theirs [26]. The concept of sustainable development suggests the existence of constraints - not unyielding barriers, but rather limitations dictated by current technological capabilities and societal structures on environmental resources, as well as the capacity of the biosphere to mitigate the impacts of human endeavors.

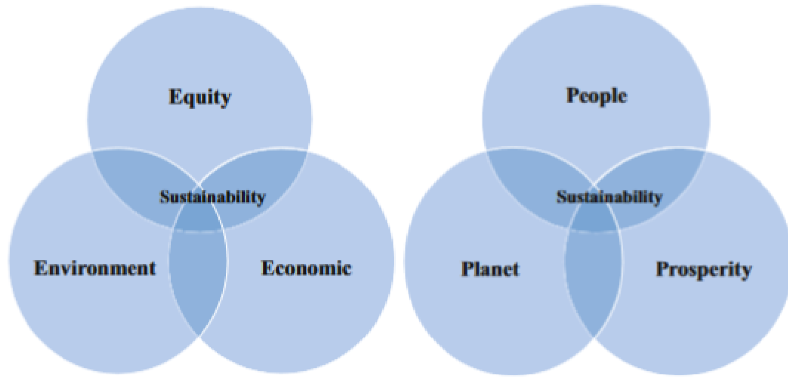

Fig. 1 The definition of sustainability derived directly from "Handbook of Environmental Sociology" [6]

The United Nations' 2030 Agenda for Sustainable Development adopted 17 sustainable development goals (SDGs) that represent a global effort to address various challenges, including poverty, health, education, inequality, economic growth, climate change, and environmental preservation. These goals, as shown in Fig. 2, can be summarized as i) end poverty, ii) protect the environment. iii) ensure prosperity for all, and call for collaboration among countries to work together towards a more sustainable and equitable future [27]. As indicated in the seventh sustainable development goal, the energy transition requires achieving a climate-neutral economy ensuring access to affordable, reliable, sustainable, and modern energy for all.

Fig. 2 Sustainable development goals, source: United Nations

4.2 Moving Beyond GDP

One of the 2050 net-zero goals in the European Green Deal is to decouple production growth from resource use. The traditional way of showing the economic performance of a country is by measuring Gross Domestic Product (GDP). GDP measures the total market value of all final goods and services produced within a country in a given period, excluding the value of imports [28]. The emissions are referred to as greenhouse gas emissions. Greenhouse gases (GHGs) are a group of gases that cause climate change and global warming. They are reported in carbon dioxide (or CO2) equivalents so that it is easy to compare or report the total contribution to global warming. Mainly, greenhouse gases consist of seven groups: carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), Sulphur hexafluoride (SF6), and nitrogen trifluoride (NF3) [29]. Fig. 3 shows the EU's GHG emissions targets by 2030 and carbon neutrality by 2050.

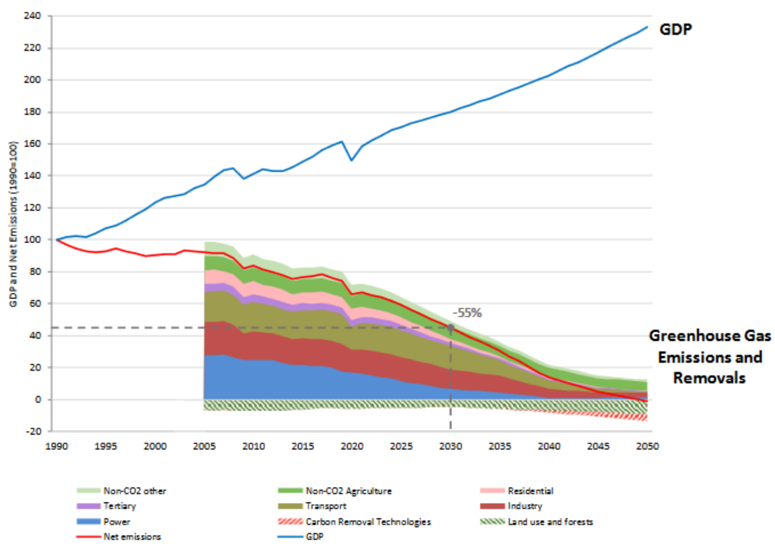

Fig. 3 European Union 2050 target to decouple economic growth from greenhouse gas emissions [30]

As of today, many countries still heavily rely on fossil fuels for their GDP, highlighting a direct correlation between greenhouse gas emissions (measured in kg CO_2 equivalent) and economic growth. However, there is a growing recognition of the need to reduce our carbon footprint and mitigate the climate impact of our activities. One approach that various nations have adopted is carbon pricing. Carbon pricing involves implementing measures such as taxing the carbon content of fossil fuels or regulating CO_2 emissions through emissions trading systems (ETS). However, there are concerns that such regulations could be perceived as a hindrance to a country's economic growth [31]. For instance, the significant portion of energy costs within industries' total expenses has raised fears of deindustrialization in Europe, as it may prompt industries to relocate to countries with lower energy prices [32].

This would raise the question of whether GDP is a good way of measuring growth for a country. While combatting climate change should not slow down economic growth, this evaluation of a country's health measuring environmental degradation and economic growth as two different factors lack necessary considerations and the impact of these two on each other. As L.Forni explains [33], GDP is not a good measure to evaluate the health of a country since it does not evaluate the decrease in natural capital such as emissions and industrial waste that were needed to achieve that level of GDP. Thus, we need a tool to evaluate the health of a country considering both environmental and economic aspects in one measure. GDP alone cannot measure the progress towards sustainable development.

4.3 Introduction to the Inclusive Wealth Index

Dasgupta in "*The Economics of Biodiversity: The Dasgupta Review*" [24] defines nature as "*our most precious asset*" that should be also counted to measure the well-being of a country. He challenges traditional economic thinking by emphasizing the interdependent relationship between the economy and the natural world. Since GDP alone does not measure the costs of environmental destruction and depreciation of overall assets. We need a tool that considers people, the planet, and prosperity, the three pillars of sustainable development. In this context, a well-being economy prioritizes just and inclusive sustainable well-being for both humans and nature, in contrast to the current focus on just GDP growth.

Dasgupta explains the sustainable development theorem as: "*Intergenerational well-being increases over a period of time if and only if inclusive wealth increases over that same period of time. This theorem defines inclusive wealth as the right measure of progress towards sustainable development, not GDP nor HDI*."

Unlike the HDI, which aggregates GDP per capita, life expectancy, and literacy into a linear measure, the IWI encompasses not only produced and human capital but also natural capital, accounting for biodiversity loss and environmental degradation. This holistic approach ensures that growth in produced and human capital is balanced against the depreciation of natural capital, reflecting a nation's true wealth and sustainability [24].

A country's inclusive wealth is the social value (not money) of all its capital assets, including natural capital, human capital, and produced capital.

Fig. 4 shows the interactions between all these three capitals.

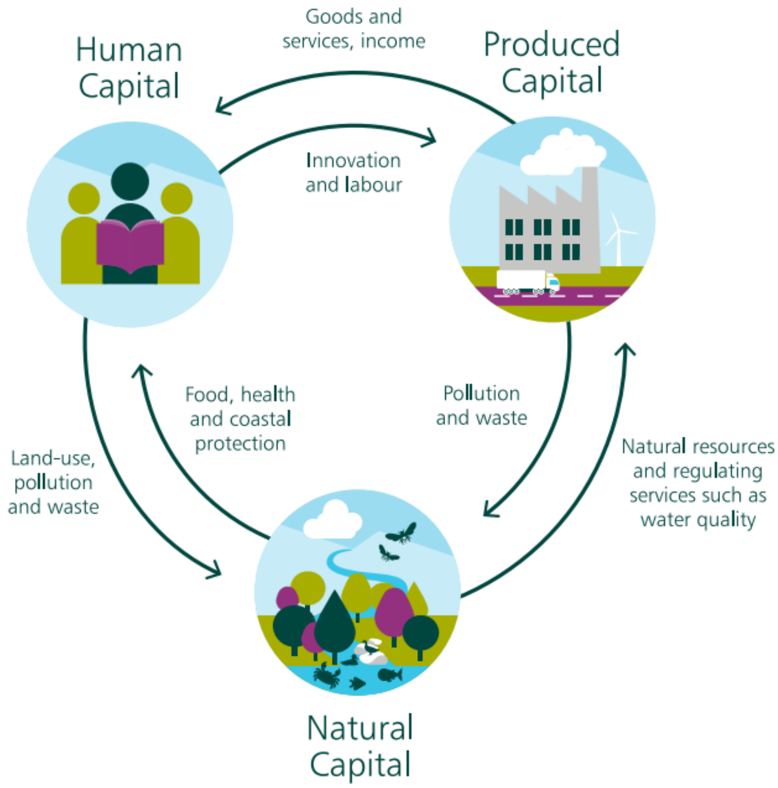

Fig. 4 Interaction between the three capitals, source: The Dasgupta review [24]

An economy's inclusive wealth accounts for the calculated value of its asset stocks. These assets are typically categorized as (i) manufactured capital, encompassing infrastructure like roads, buildings, and machinery; (ii) human capital, encompassing knowledge, abilities, education, and skills; and (iii) natural capital, including resources such as forests, agricultural land, water bodies, ecosystems like rivers and estuaries, and subsoil reserves like soil nutrients. Inclusive wealth, unlike income which is a flow, represents the total value of an economy's manufactured, human, and natural capital. While income is more static, wealth provides a dynamic view of an economy's resources. In a stable economy, income and wealth may align, but in changing economies, they can indicate different directions of growth or decline [34]. Fig. 5 is a schematic representation of the composition of the Inclusive Wealth Index.

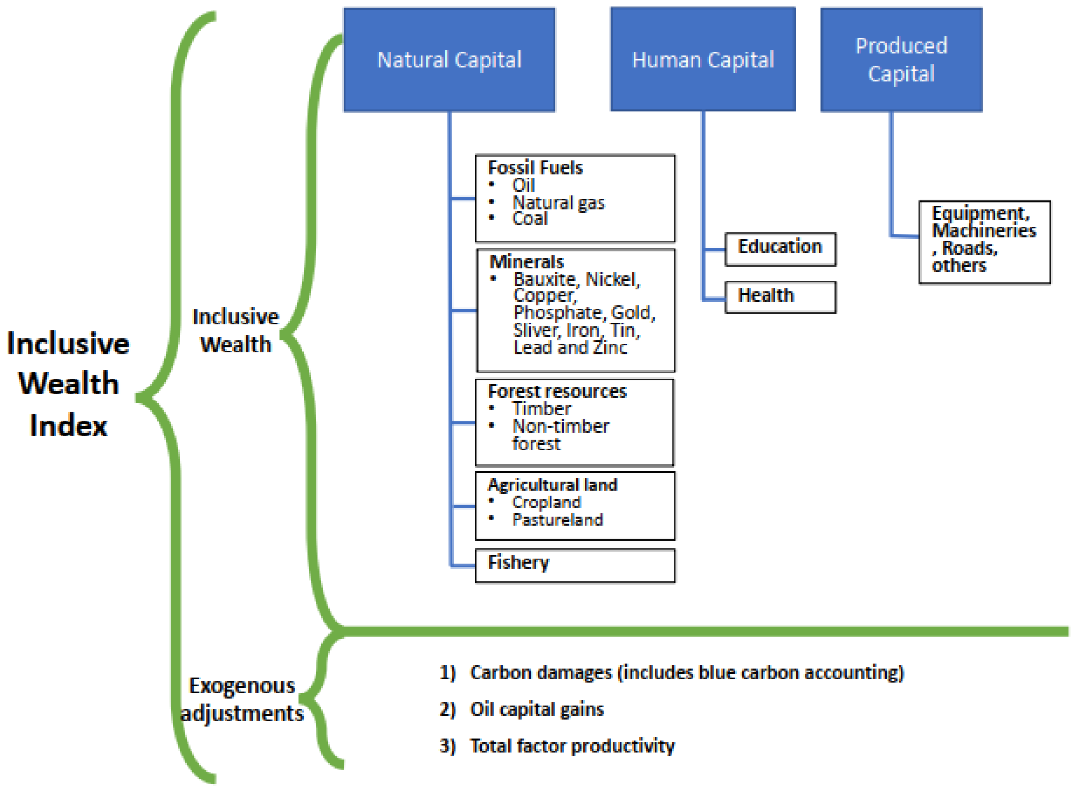

Fig. 5 Schematic representation of the Inclusive Wealth Index, source: Inclusive Wealth Report 2023 [35]

In sustainable development, there is a concept called "non-declining capital." This idea is viewed through two lenses: "weak sustainability" and "strong sustainability." Strong sustainability suggests that different types of capital (like human, natural, or economic) cannot be easily replaced, asserting that certain natural assets, such as biodiversity or clean air, cannot simply be replaced by human-made capital or technological innovations. However, weak sustainability allows for more flexibility, explaining that various forms of capital—be it human, natural, or economic—can, to some extent, be substituted for one another. For example, technological advancements could potentially offset the depletion of natural resources [6]. Inclusive wealth is based on the weak sustainability theorem so different forms of capital (natural, human, and produced) define the total inclusive wealth. This means that to be sustainable, we do not require to be sustainable in each capital but to be sustainable in the overall contribution of all three capitals [35].

While traditional measures like GDP may show significant economic growth over time, the Inclusive Wealth Index provides a more comprehensive picture by considering natural, human, and produced capital together. For instance, despite impressive GDP growth rates in countries like the USA, India, and China from 1990 to 2010, the Inclusive Wealth Index reveals a more modest increase in overall wealth. This discrepancy underscores the importance of assessing the sustainability and long-term impact of economic growth. As nations strive for sustainable development, the Inclusive Wealth Index offers a valuable tool for quantifying and tracking progress beyond purely economic metrics, ensuring a more holistic understanding of national wealth and well-being [36].

The Inclusive Wealth Index is a multi-purpose tool and has gained traction as a tool for measuring sustainable development, aligning with the United Nations' focus on social and environmental progress beyond GDP. Fig. 6 shows how inclusive wealth can target different sustainable development goals of the United Nations [37].

Fig. 6 The sustainable development goals indications in Inclusive Wealth Index [37]

4.4 Description of the Inclusive Wealth Index Components: Human, Natural, and Produced Capitals

In the following, each capital is explained in more detail according to the Dasgupta review [24] and inclusive wealth report 2023 [35].

4.4.1 Human Capital

Human capital, the main source of global wealth, comprises 54% of the total inclusive wealth., according to the Inclusive Wealth Index Report 2023. It represents the collective human potential that contributes to the well-being and productivity of a nation. It is measured in levels of health, education, skills, and abilities. Human capital recognizes that investments in healthcare, education, and other forms of human development are crucial for sustainable development and economic prosperity. By valuing human capital alongside natural and produced capital in measures of inclusive wealth, societies can better understand the true wealth and resilience of their economies, fostering policies that promote human development and ensure long-term prosperity.

In report 2023, human capital is calculated by gender, including both health and education, with education levels based on expected years of schooling. The shadow price of human capital is determined by expected years of work, reflecting the remaining years of compensation for education in the labor market.

4.4.2 Natural Capital

The world's natural capital comprises renewable (such as agricultural land, forests, and fisheries), and non-renewable resources (like fossil fuels and minerals), which has decreased by more than 28% on average over the last three decades. While renewable capital has shown slight growth in recent years, there are disparities in the distribution of growth among different countries. For instance, agricultural land has seen varied growth rates across nations, with some experiencing positive trends while others face a decline. Similarly, forests and fisheries are important resources, but their depletion in certain countries threatens sustainable development. Fossil fuels and minerals, though diminishing, play significant roles in energy systems and economic development. Overexploitation has led to a substantial decline in global natural capital, with implications for future generations. The rate of natural capital depreciation has been, on average, five times greater in developing countries than in the rich Organization for Economic Cooperation and Development (OECD) economies

Recognizing the value of natural capital and incorporating it into policymaking is crucial for sustainable development efforts worldwide. Nature does not work like a financial investment that tries to maximize its productivity. Instead, it operates differently in various places, depending on things like weather and available resources. It does not aim to be super productive everywhere all the time, which means urgent action is needed to limit further degradation and ensure the viability of natural resources for present and future generations.

Limited research has directly linked a country's natural capital wealth to income and wealth inequality within that country, but experts argue that resource-rich nations often face exacerbated inequality and slower human capital development. The concept of 'Dutch Disease' suggests that heavy reliance on natural resource exports can harm other sectors of the economy. Despite rapid economic growth, this expansion has come at the expense of biodiversity and climate stability due to the underpricing and overexploitation of natural capital.

4.4.3 Produced Capital

Produced capital, as a component of the Inclusive Wealth Index, encompasses the tangible assets and infrastructure created through human activity, including buildings, machinery, infrastructure, and technological advancements. It represents the physical capital stock that contributes to economic production and productivity. Produced capital plays a critical role in economic development and growth by providing the means of production and facilitating the transformation of inputs into goods and services. It encompasses both private and public sector investments in physical infrastructure such as roads, bridges, factories, and utilities, as well as intangible assets like intellectual property and organizational capital. In the 2023 report, produced capital is measured as the total sum of investments, by considering the capital depreciation incurred each period.

Investments in produced capital are essential for increasing efficiency, promoting innovation, and enhancing competitiveness in economies. For instance, advancements in technology and machinery can lead to higher levels of productivity and output, driving economic growth over time. However, it's important to note that while produced capital contributes significantly to economic activity, its sustainability and long-term impact are influenced by factors such as resource depletion, environmental degradation, and technological obsolescence. Therefore, managing and maintaining produced capital in a sustainable manner is crucial for ensuring continued economic development and well-being.

4.5 Weight of Different Capitals in the Inclusive Wealth Index

As Dasgupta explains [24], the accounting prices of different types of capital, which may not always align with market prices, gauge the societal value of goods, services, or assets. Inclusive wealth, then, refers to the overall social value of a nation's capital assets, considering their worth not only to present individuals but also to future generations.

The ratio of the capitals' shadow prices determines their substitutability degree and the degree of transformation across the capitals in a given country. A country may convert some of its stocks to other types of capital to increase their inclusive wealth, which shows the importance of the weight of each capital and its contribution to overall inclusive wealth. In some cases, there may be little to no substitution possibilities between key forms of natural capital and produced capital, or for substitution between any other forms of capital.

The Dasgupta review [24] offers insights into calculating these shadow prices, particularly for non-market capital like natural resources, which presents challenges due to the absence of market prices. While natural capital depletion is critical and irreversible, existing indicators often underestimate natural capital depletion. For example in countries with serious depletion and deterioration of resources and environment, the wealth change may be positive due to their economic growth, highlighting the need for accurate estimation of shadow prices to construct a comprehensive sustainability indicator. In some countries, if the shadow price of natural capital is considered higher, they may experience negative sustainability, or their inclusive wealth would be lower. Taxes based on accounting prices can serve as effective instruments for reducing environmentally damaging activities. Moreover, urgent action is needed to address perverse subsidies, which distort economic incentives and hinder sustainable development efforts. Valuing natural capital at accounting prices is expected to stimulate green investment, leading to greater returns on human capital and employment opportunities.

The distribution of inclusive wealth across countries varies, with each nation possessing different proportions of capital types. For instance, when two countries deplete the same amount of natural resources, the one with a greater share of natural capital will witness a more significant decline in overall wealth. Developing nations often rely more heavily on natural resources for their wealth compared to wealthier developed countries. Consequently, for sustainable development, developing countries should aim for greater growth in the produced and human capital relative to the typical developed nation [35].

The composition of different capitals has changed since 1992, as can be seen in Fig. 7. From 1992 to 2009, inclusive wealth was composed of 25 % natural, 53% human, and 22% produced capital, while from 2010 to 2019, this share was 18% natural, 54% human and 28% produced capital.

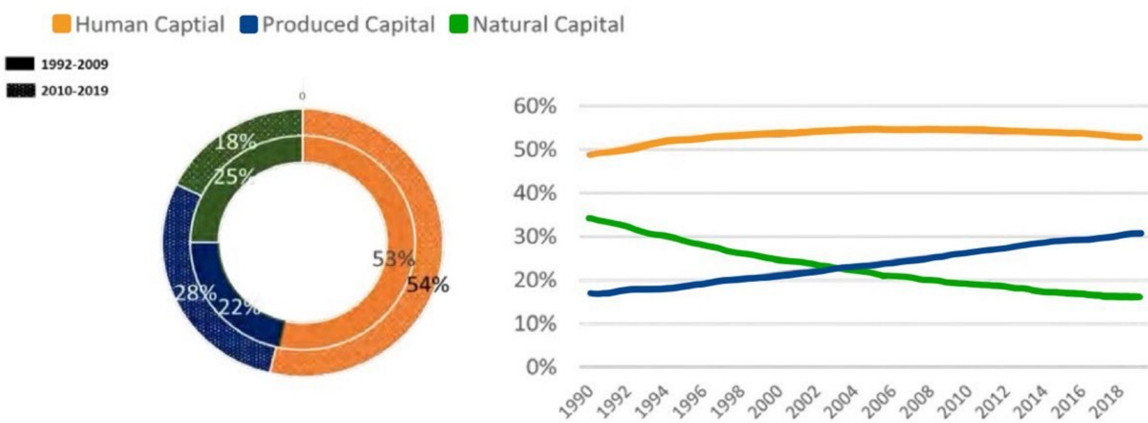

Fig. 7 Developments in the composition of wealth by capital, 1990–2019 [35]

4.6 Conclusions

This chapter introduces a new indicator for measuring sustainability, emphasizing the delicate balance between economic growth, environmental protection, and social equity. It introduces the concept of sustainability and the United Nations' Sustainable Development Goals (SDGs), showing their significance for the well-being of future generations. This chapter goes beyond the use of Gross Domestic Product (GDP) as a singular measure of growth, proposing instead the Inclusive Wealth Index (IWI) as a more comprehensive metric that encapsulates natural, human, and produced capital. This innovative index challenges traditional economic indicators by considering environmental and social dimensions in the evaluation of a nation's prosperity and sustainability progress. Through an in-depth analysis of the IWI's components and their interactions, the chapter underscores the transition towards evaluating national health in a manner that genuinely reflects ecology and social fairness beyond GDP.

Chapter 5: General Methodology for the Optimization of Multi-Energy Systems

In this chapter, the methodology to optimize multi-energy systems is explored throughout their design and operation phases, with an emphasis on maximizing the Inclusive Wealth Index (IWI). Our methodology utilizes a Mixed-Integer Linear Programming (MILP) approach, executed in Python with the Gurobi solver. The aim is to enhance the Inclusive Wealth Index of our multi-energy system, considering the three pillars of IWI: human, natural, and produced capitals. Initially, a single-objective optimization problem is defined to maximize the Inclusive Wealth Index, followed by a traditional cost-minimization approach, for comparison. Subsequently, we introduce a multi-objective optimization problem that aims to simultaneously increase the Inclusive Wealth Index and minimize costs, in both the design and operation phases. The optimization's decision-making variables focus on the capacities of the technologies (energy conversion and storage plants) within the multi-energy system. For precise quantification of the natural and human capital, a life cycle assessment with SimaPro is performed, utilizing the Ecoinvent database. Produced capital is also considered as infrastructure and manufacturing process investments. This study endeavors to go beyond mere economic efficiency, focusing instead on a holistic optimization of multi-energy systems that balances environmental, social, and economic sustainability. This comprehensive approach not only embraces broader sustainability goals but also marks a significant step towards establishing a framework for achieving comprehensive optimization within the multi-energy systems field.

5.1 Mixed-Integer Linear Programming (MILP)

The design and operation optimization challenge is structured within a Mixed-Integer Linear Programming (MILP) framework within the Python interface using the Gurobi solver. The MILP method is a powerful mathematical optimization technique used to solve decision-making problems under constraints. The key characteristic of MILP is its ability to handle linear equations and inequalities as constraints and optimize a linear objective function, subject to these constraints. The aim of our optimization involves determining the optimal size of the components—namely, the technologies within the multi-energy system.

Initially, a single-objective function optimization is conducted to maximize the Inclusive Wealth Index (IWI) of our multi-energy system. Following this, another round of single-objective optimization is performed, this time to minimize costs as done by E. Dal Cin et al. [38] and compare the resulting IWI value with that of the first model. Finally, a multi-objective function optimization is performed to optimize the system with two objective functions, maximizing inclusive wealth and minimizing investment and operation costs. By utilizing Pareto optimization techniques, a set of solutions is generated, known as the Pareto frontier, which represents the trade-offs between these objectives.

When dealing with multi-objective optimization problems, such as maximizing the Inclusive Wealth Index while minimizing costs, a direct approach using Gurobi might not be straightforward due to its inherent limitations in handling multiple objectives simultaneously. Thus, the epsilon constraint method is used to solve this limitation. The epsilon constraint method is a technique used to convert a multi-objective optimization problem into a series of single-objective problems. Setting one objective as the primary goal and transforming the others into constraints with specified bounds (epsilon values), allows for the exploration of the trade-offs between objectives. The modeling of components and the corresponding equations are based on the methodology proposed by E. Dal Cin et al. [39] for modeling and optimization of multi-energy systems.

5.2 Objective Functions and Units of Measurement

Our objective functions are twofold: the first seeks to maximize the Inclusive Wealth Index (IWI), symbolized as f' in Equation (1), while the second aims at minimizing the overall investment and operation costs, associated with the system, denoted by $f"$ in Equation (2). By setting these objectives, our multi-energy system's design and operation are aimed at aligning with broader environmental, social, and economic sustainability targets.

$$f' = max(IWI) \tag{1}$$

$$f" = \min(cost) \tag{2}$$

The Inclusive Wealth Index (IWI) combines human capital (HC), natural capital (NC), and produced capital (PC), each weighted appropriately (w_{HC} , w_{NC} and w_{PC}respectively). These capitals are quantified in points, relative to the capitals of a reference case as defined in Chapter 6. Thus, the IWI is also expressed in points and can be categorized and calculated following the formula explained by Dasgupta [24] as in Equation (3).

$$IWI = w_{HC}HC + w_{NC}NC + w_{PC}PC \tag{3}$$

As explained by Dasgupta [24] and inclusive wealth reports [34] [35], the inclusive wealth of countries is calculated as the annual change in percentage, referring to a temporal difference. However, our study adapts the IWI concept to specific case scenarios rather than temporal changes. By comparing to a reference scenario, the calculation of HC, NC, and PC is adjusted to reflect their relative contributions to IWI based on the reference case (ref). Moreover, the weights of the capitals are defined knowing that $w_{HC} + w_{NC} + w_{PC} = 1$. This adjustment allows us to calculate IWI in a more straightforward and simplified way.

In the calculation of IWI, initially, a reference scenario is established for human, natural, and produced capitals. Then the values from our case study are compared and normalized to this reference scenario. This normalization helps in focusing the optimization on enhancing the IWI relative to the reference scenario's baseline of zero. This means that each capital's change in value reflects an improvement or deterioration relative to this baseline. In more detail, the IWI is increased by reducing damages (for human and natural capital) and increasing investments (for produced capital). For more clarification:

- If $HC^* < HC^*_{ref}$ the human capital increases in relative terms (the damage to human health is less than in the reference case). The assumption here is that HC is intended as an impact on human health rather than a positive contribution;
- If $NC^* < NC^*_{ref}$, the natural capital increases in relative terms (the damage to nature is less than in the reference case). The assumption here is that NC is intended as a negative environmental impact rather than a "regeneration" of natural resources;
- If $PC^* > PC^*_{ref}$, the produced capital increases in relative terms.

This normalization process aids in centering the optimization efforts on improving the IWI relative to a baseline of zero established by the reference scenario. The values of the three capitals can be translated into *Points* normalized to the reference system as stated in Equation (4), (5), and (6) to define the final objective function (Equation (3)) in relative terms. In these equations, * means that this value is presented in its specific unit of measurement (before normalization).

$$HC = \frac{HC^*_{ref} - HC^*}{HC^*_{ref}} \tag{4}$$

$$NC = \frac{NC^*_{ref} - NC^*}{NC^*_{ref}} \tag{5}$$

$$PC = \frac{PC^* - PC^*_{ref}}{PC^*_{ref}} \tag{6}$$

Thus, the reference case's normalized capitals and its Inclusive Wealth Index are zero by definition, as presented in Equations (7), (8), (9), and (10).

$$HC_{ref} = \frac{HC^*_{ref} - HC^*_{ref}}{HC^*_{ref}} = 0 \tag{7}$$

$$NC_{ref} = \frac{NC^*_{ref} - NC^*_{ref}}{NC^*_{ref}} = 0 \tag{8}$$

$$PC_{ref} = \frac{PC^*_{ref} - PC^*_{ref}}{PC^*_{ref}} = 0 \tag{9}$$

$$IWI_{ref} = w_{HC}\, HC_{ref} + w_{NC} NC_{ref} + w_{PC}\, PC_{ref} = 0 \tag{10}$$

As measuring inclusive wealth for our multi-energy system is different from measuring the inclusive wealth of a whole country during a year, an interpretation should be done to identify how these three capitals can be measured for our study. As explained in Table 1, human capital and natural capital are measured with a life cycle assessment (LCA), intended as avoided damages rather than capital improvements; while produced capital, which means roads, buildings, machines, and equipment, is simply the investments according to Inclusive Wealth Report 2023 [35]. The reason for this choice is that investing in manufacturing, roads, and infrastructure catalyzes broad economic growth, directly impacting job creation and societal well-being. Moreover, enhancements in manufacturing elevate efficiency and innovation, enhancing competitiveness and productivity, while road and infrastructure developments smooth logistics and connectivity, attracting further investments. This cascading effect generates employment, stimulates local economies, and enhances living standards by improving access to services and fostering community development. Ultimately, this impacts on society's progress and quality of life.

Table 1 Interpretation and localization of different capitals within the Inclusive Wealth Index (IWI) in the context of multi-energy systems

capital	human capital	natural Capital	produced capital
explanation	Avoided damage to human health	Avoided damage to fishery, ecosystem, and natural resources	manufacturing, roads, and machinery
method of measurement	human health endpoint damage assessment in life cycle assessment	ecosystems and resources endpoint damage assessments in life cycle assessment	investments

The proposed objective function (IWI) would target six sustainable development goals proposed by United Nations, as explained in Table 2.

Table 2 The sustainable development goals indications in the current study

sustainable development goal	factor included in the current study	implication in capitals
3 GOOD HEALTH AND WELL-BEING	endpoint impact human health	Human capital
6 CLEAN WATER AND SANITATION	water use, freshwater ecotoxicity, and freshwater eutrophiciation	Human capital, Natural capital
13 CLIMATE ACTION	global warming, land use, water use, acidification, ozone depletion	Human capital, Natural capital
14 LIFE BELOW WATER	marine ecotoxicity, marine eutrophiciation	Natural capital
15 LIFE ON LAND	global warming, land use, water use, acidification, trop. Ozone, terrestrial ecotoxicity, terrestrial acidification	Natural capital
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	investments	Produced capital

5.3 Life Cycle Assessment: Goal, Scope, Method and Functional Unit

To calculate the specific values of human and natural capitals (hc and nc) a life cycle assessment (LCA) is done using SimaPro version 9.5.0.1 based on the Ecoinvent database. The method is ReCiPe2016 due to its advantage in reporting the results in three endpoint impact categories, which can be interpreted as two capitals (human and natural capitals) of the Inclusive Wealth Index (IWI). It should be mentioned that the system is more sustainable if the damage assessments are lower. Among three perspectives (individualist (I), hierarchist (H), and egalitarian (E)), the hierarchist one is chosen as it is based on the most common policy principles. The endpoint damage assessments of the method ReCiPe2016 are analyzed. These damage assessments are described in Table 3 according to the SimaPro database manual [40]. It s important to note that while CO_2's direct impact might seem most closely related to human health, as is shown in Fig. 8, ReCiPe2016's comprehensive approach ensures that the wide-ranging consequences of CO_2 emissions and other pollutants are evaluated across both human health and ecosystems. Thus, CO_2 emissions in the current study are included in both human and natural capitals.

Table 3 The endpoint damage assessments of method ReCiPe2016 considered in the current study for calculation of human and natural capitals

Endpoint impact	Human Health	Ecosystems	Resources
unit	[DALY]	[species.year]	[USD2013]
definition	Disability Adjusted Life Years: The summation of the number of years of life lost and the number of years lived with a disability.	The loss of species over a specific area within a defined time period (year).	The surplus costs of future resource production over an infinite timeframe (assuming a constant annual production rate), with a consideration of a 3% discount rate. Fossil resource scarcity does not have constant mid-to-endpoint factors but individual factors for each substance.
capital assumed in the current study	Human Capital	Natural Capital	Natural Capital

Fig. 8 shows the details of how different midpoint impact categories are included in each end-point damage assessment in method ReCiPe2016 which is used in the current study.

The concept of functional unit (FU), as explained in the context of life cycle assessments, underscores the importance of ensuring comparability between products by equating them based on their ability to perform the same function. This notion encompasses both quantitative and qualitative aspects, detailing the scope, quantity, duration, and quality of the function served [41]. In the present study, the functional unit applied to energy carriers is measured per 1 kWh, while for components, it is assessed per 1 kW.year. For thermal and electrical storage systems, the functional unit is considered in terms of capacity, quantified as kWh.year. Further elaboration on how each carrier or technology is analyzed within these parameters can be found in the detailed case study presented in Chapter 6.

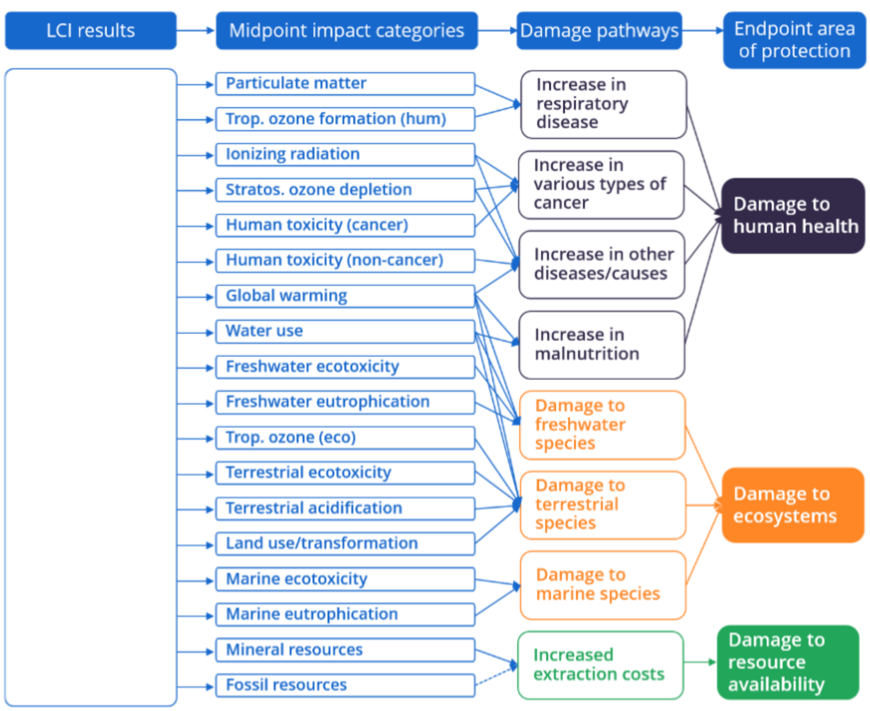

Fig. 8 The relations between midpoint impact categories and endpoint damage assessments in ReCiPe 2016 [40]

5.4 Conclusions

Chapter five explores the optimization methodology for multi-energy systems, targeting both design and operation phases with a focus on maximizing the Inclusive Wealth Index (IWI). Utilizing a Mixed-Integer Linear Programming (MILP) framework implemented via Python with the Gurobi solver, this chapter outlines a dual-objective approach: maximizing IWI while minimizing system costs. These objectives, aimed at fostering environmental, social, and economic sustainability, leverage decision-making variables related to technology capacities within the energy system. This chapter explains the calculation of IWI by normalizing the three capitals - human, natural, and produced - by comparing them to reference scenarios. This process aids in quantifying improvements or regressions in the system's inclusive wealth relative to a reference case with an IWI of zero. Key to this methodology is the precise quantification of human, natural, and produced capitals through life cycle assessments (LCA), alongside investment considerations, which is an innovative approach to address the Inclusive Wealth Index within the framework of multi-energy systems. Human capital and natural capital are assessed through LCA using endpoint damage assessments of method ReCiPe 2016 (H) based on the Ecoinvent database, while produced capital is gauged through investments. This methodological framework sets the stage for aligning the multi-energy system with the United Nations' sustainable development goals, underscoring the study's commitment to advancing societal progress and quality of life through strategic investments in infrastructure and technological innovation.

Chapter 6: Reference Case and Case Study: Definition and Numerical Modeling

This chapter explores a specific scenario situated in Padua, Italy, characterized by a cluster of users with both electrical and thermal energy requirements. It takes into account weather conditions and demand profiles pertinent to this location. The baseline scenario involves users obtaining electricity directly from the power grid and generating heat through the combustion of natural gas in boilers. The focus of our case study is a comprehensive multi-energy system, incorporating photovoltaic cells (PV), an internal combustion engine (ICE) for the simultaneous production of electricity and heat, boiler (BOIL), air-water heat pumps (HP), electrical energy storage (EES) that are lithium-ion batteries and thermal energy storage (TES) that are supposed to be water tanks. In this chapter, the assumptions and numerical model of the reference case and case study are explained in detail. It is noteworthy that the electricity and heat demands are equal in both reference case and case study, and the existing grid infrastructure (transmission lines and transformation infrastructure) and natural gas distribution system are presumed to be ideal. The chapter will further present the input data of the optimization problem, namely the techno-economic values and the specific capital of the Inclusive Wealth Index (IWI) for the proposed components of the multi-energy system. The optimization timeframe spans one year, with the valuation of natural, human, and produced capital expressed in one year per unit of component's capacity (in kW or kWh) and kWh for energy carriers.

6.1 Reference Case

The reference system (ref) is an end user (or aggregation of end users) that provides its given electricity and heat demand by the power grid and gas boilers, respectively. (Fig. 9)

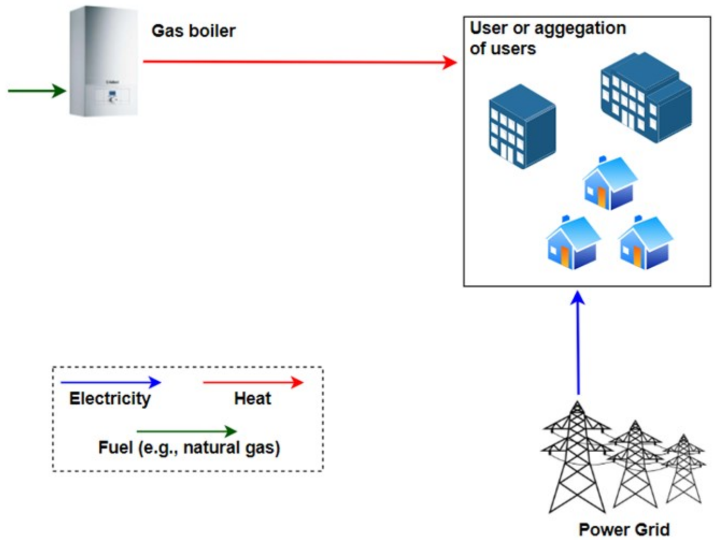

Fig. 9 The schematic representation of the reference case

In the reference case, it is assumed that electricity is solely supplied by the grid, with the existing infrastructure of the grid and transformation system; Thus these elements do not contribute to the capitals of the reference case. However, this scenario includes the construction and operation of power plants for electricity production, as well as accounting for losses incurred during the distribution and transformation of electricity. Additionally, the total heat demand is met through the combustion of natural gas within a boiler. While the boiler unit is factored into the calculations, it is presupposed that the natural gas distribution network is pre-existing within the system and, as such, does not add to the capitals of the reference case.

The different capitals for our reference case can be calculated as presented in Equation (11), Equation (12), and Equation (13). These reference capitals are calculated by defining the electrical power imported from the grid ($P_{el,ref,t}^{imp}$) as the electrical demand and the heat produced by the boiler ($Q_{BOIL,ref,t}$) as the heat demand, being $\Delta t = 1\ hour$ and the unit of demand in kW, the final values expressed in kWh. The factors hc_{el} , nc_{el} and pc_{el} represent specific human, natural, and produced capitals of electrical power imported from the grid. These values are reported as specific values, being hc_{el}^{imp} and nc_{el}^{imp} points per kWh (the damage assessment results of the LCA) and pc_{el}^{imp} euro per kWh. Similarly for the heat produced by burning natural gas inside the boiler, $hc_{heat,BOIL}$, $nc_{heat,BOIL}$ and $pc_{heat,BOIL}$ are the specific values of human, natural, and produced capitals, respectively, given in the same units. Then these values are summed during one year, being T = 8760 hours. The boiler is supposed as a reference unit that can provide all our heat demand throughout the year, being $C_{BOIL,ref}$ the capacity of the reference boiler in kW. The efficiency of the boiler is included in the calculation of its capacity. The specific values of human and natural capital for the boiler, $hc_{BOIL,}$ and nc_{BOIL} are expressed in points per kW.year, while the specific value of produced capital pc_{BOIL} is expressed in euros per kW.year. The symbol * means that the corresponding capital is expressed in its specific unit of measurement (per point for HC and NC and per euro for PC).

$$HC^{*}_{ref} = hc_{BOIL}C_{BOIL,ref} + \sum_{t\in T} \Delta t\left(hc^{imp}_{el}P^{imp}_{el,ref,t} + hc_{heat,BOIL}Q_{BOIL,ref,t}\right) \quad (11)$$

$$NC^{*}_{ref} = nc_{BOIL}C_{BOIL,ref} + \sum_{t\in T} \Delta t\left(nc^{imp}_{el}P^{imp}_{el,ref,t} + nc_{heat,BOIL}Q_{BOIL,ref,t}\right) \quad (12)$$

$$PC^{*}_{ref} = pc_{BOIL}C_{BOIL,ref} + \sum_{t\in T} \Delta t\left(pc^{imp}_{el}P^{imp}_{el,ref,t} + pc_{heat,BOIL}Q_{BOIL,ref,t}\right) \quad (13)$$

6.2 Case Study

Our case study, as shown in Fig. 10, outlines a grid-integrated multi-energy system (MES) designed to provide both thermal energy and electric power to the end users with heat and electric demand as the reference case. This system includes traditional power grid and gas boilers, along with additional components:

- Photovoltaic (PV) cells to produce electricity (mounted mono-crystalline silicone modules)
- The air-water heat pump (HP) for heat production
- Combined-heat and power internal combustion engine (ICE) fueled by natural gas for both electricity and heat production
- Thermal energy storage (TES) system (water tank)
- Electrical energy storage (EES) system (lithium-ion battery)

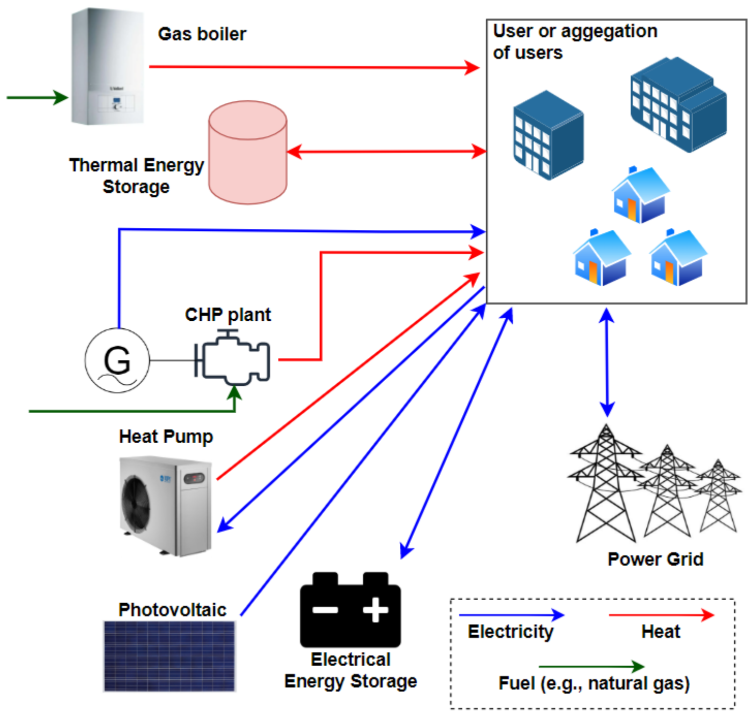

Fig. 10 The schematic representation of the case study

The human capital (HC), natural capital (NC), and produced capital (PC) of our case study are calculated as expressed in Equation (14), Equation (15), and Equation (16), respectively. These equations are composed of an infrastructure contribution (time-independent) and an operational contribution (time-dependent) part. The specific coefficients referring to the time-independent quantities take into account the life cycle of a technology until its startup, and they are multiplied by the capacities of the components. Whereas the coefficients referring to the time-dependent quantities take into account the life cycle impact of the energy streams during the system operation. The capacities C_{PV}, C_{HP} and C_{ICE} are the sizes of the corresponding components expressed in kW. The capacities for thermal C_{TES} and electrical C_{EES} storages are expressed in kWh. Thus, the specific values hc and nc (damage assessment of LCA) are points per kW.year, and values of pc are euros per kW.year for PV, HP, and ICE; while hc and nc are points per kWh.year, and pc values are euros per kWh.year for TES and EES.

Regarding the time-dependent part of the equations, the specific values of capitals are expressed per kWh, while the heat produced by the boiler ($Q_{BOIL,t}$), and in the internal combustion engine ($Q_{ICE,t}$) are in kWh thermal. Moreover, the electrical power imported from the grid ($P_{el,t}^{imp}$), and the electricity produced in ICE ($P_{ICE,t}$) are in kWh electrical. The value of Δt is one hour while T is one year (8760 hours) so the units would be the same for both time-dependent and time-independent parts of the equations. The symbol * means that the corresponding capital is expressed in its specific unit of measurement.

It is crucial to highlight that the electricity exported ($P_{el,t}^{exp}$) is not included in the calculation of the inclusive wealth index, yet it plays a significant role in the energy balances of Equation (17) and determining cost calculations of Equation (21). This apparent discrepancy arises from how the natural capital, human capital, and produced capital associated with the exported electricity are factored into the calculations of the multi-energy system components responsible for generating this energy. Nonetheless, the financial gains from selling the exported electricity to the grid are taken into account in the cost assessments.

$$HC^* = hc_{PV}C_{PV} + hc_{HP}C_{HP} + hc_{ICE}C_{ICE} + hc_{BOIL}C_{BOIL} + hc_{TES}C_{TES} + hc_{EES}C_{EES} + \\ + \sum_{t \in T} \Delta t \left[hc_{heat,BOIL}Q_{BOIL,t} + hc_{heat,ICE}Q_{ICE,t} + hc_{el,ICE}P_{ICE,t} + hc_{el}^{imp}P_{el,t}^{imp} \right] \tag{14}$$

$$NC^* = nc_{PV}C_{PV} + nc_{HP}C_{HP} + nc_{ICE}C_{ICE} + nc_{BOIL}C_{BOIL} + nc_{TES}C_{TES} + nc_{EES}C_{EES} + \\ + \sum_{t \in T} \Delta t \left[nc_{heat,BOIL}Q_{BOIL,t} + nc_{heat,ICE}Q_{ICE,t} + nc_{el,ICE}P_{ICE,t} + nc_{el}^{imp}P_{el,t}^{imp} \right] \tag{15}$$

$$PC^* = pc_{PV}C_{PV} + pc_{HP}C_{HP} + pc_{ICE}C_{ICE} + pc_{BOIL}C_{BOIL} + pc_{TES}C_{TES} + pc_{EES}C_{EES} + \\ + \sum_{t \in T} \Delta t \left[pc_{heat,BOIL}Q_{BOIL,t} + pc_{heat,ICE}Q_{ICE,t} + pc_{el,ICE}P_{ICE,t} + pc_{el}^{imp}P_{el,t}^{imp} \right] \tag{16}$$

The constraints on the system for the optimization model are composed of the energy balances and the characteristic equations of the components, as explained by E. Dal Cin et al. [39]. For the electricity and heat balances, Equation (17) and Equation (18) can be written, respectively. In these equations, $Dem_{el,t}$ stands for electrical demand in kW_{el} and $Dem_{th,t}$ is thermal demand in kW_{th}, while P stands for electricity in kW_{el}, and Q demonstrates heat in kW_{th}.

$$-Dem_{el,t} + P_{el,t}^{imp} + P_{PV,t} + P_{ICE,t} - P_{HP,t} + P_{discharge,EES,t} - P_{charge,EES,t} - P_{el,t}^{exp} = 0 \quad (17)$$

$$-Dem_{th,t} + Q_{ICE,t} + Q_{BOIL,t} + Q_{HP,t} + Q_{discharge,TES,t} - Q_{charge,TES,t} = 0 \quad (18)$$

The overall cost of the case study, as shown in Equation(19), is composed of the investment ($cost_{inv}$) and operational costs ($cost_{opr}$), as explained in Equation(20) and Equation(21). The index k stands for cost in euros, while n is the lifetime of the component in years, being r the interest rate (in the current study it is assumed to be 0.05), and C stands for the capacity of the component.

$$cost = cost_{inv} + \ cost_{opr} \quad (19)$$

$$cost_{inv} = \sum_{i \in \{PV,ICE,BOIL,HP,TES,EES\}} \frac{r \times (1+r)^{n_i}}{(1+r)^{n_i} - 1} + O\&M_{fix,i}) \times k_{inv,i} \times C_i \quad (20)$$

$$cost_{opr} = \sum_{t \in T} \Delta t\big[\big(F_{BOIL,t} + F_{ICE,t}\big)k_{ng} + k_{el}^{imp} P_{PG,t}^{imp} - k_{el}^{exp} P_{el,t}^{exp}\big] \quad (21)$$

The techno-economic characteristics of the components are defined in Table 4 based on the technology data sheet provided by the Danish Energy Agency [42] [43]. It should be mentioned that the output of PV is considered AC, so the cost of the inverter and relevant costs are considered for residential users, both in cost calculation and investments (produced capital), as well as the life cycle assessment. The cost and also life cycle analysis consider PV modules, inverter, balance of system, and installation.

Table 4 Techno-economic characteristics of the components in the case study [42] [43]

Technology	Quantity	Unit	Value
PV	InvestmentCost	€/kWp	1240
	O&Mcost,fix	%Inv./y	1.08
	Lifetime	y	35
ICE	InvestmentCost	€/kWel	1010
	O&Mcost,fix	%Inv./y	1.026
	O&Mcost,var	€/kWhel	0.005742
	Lifetime	y	25
	MinLoad	%MaxLoad	50
BOIL	InvestmentCost	€/kWth	60
	O&Mcost,fix	%Inv./y	3.455
	Lifetime	y	25
	EfficiencyTh	.	0.97
HP	InvestmentCost	€/kWth	1520
	O&Mcost,fix	%Inv./y	0.139
	Lifetime	y	25
	MinLoad	%MaxLoad	25
TES	InvestmentCost	€/kWh	420
	O&Mcost,fix	%Inv./y	4.047
	Lifetime	y	30
	RoundTripEfficiency	.	0.98
	SelfDischarge	%SOC/hour	2.1
	OutputCapacity	kW/kWh	6.6
	InputCapacity	kW/kWh	6.6
EES	InvestmentCost	€/kWh	1110
	O&Mcost,fix	%Inv./y	0.0513
	Lifetime	y	20
	RoundTripEfficiency		0.91
	SelfDischarge	%SOC/hour	0.00416
	OutputCapacity	kW/kWh	3
	InputCapacity	kW/kWh	0.5

The cost of the energy carriers, namely imported electricity from the grid k_{el}^{imp} , exported electricity to the grid k_{el}^{exp}, and the cost of natural gas (k_{ng}) are given in Table 5.

Table 5 The cost of the electricity and natural gas used in the current study [44] [45] [46]

<table>
<tr><th>Carrier</th><th>description</th><th>Quantity</th><th>Unit</th><th>Value</th></tr>
<tr><td rowspan="2">Electricity</td><td rowspan="2">All taxes and levies included; Consumption from 2 500 kWh to 4 999 kWh - band DC, first half of year 2023</td><td>cost for households</td><td>€/MWh</td><td>378.2</td></tr>
<tr><td>sell price</td><td>€/MWh</td><td>61</td></tr>
<tr><td>Natural Gas</td><td>All taxes and levies included; Consumption from 20 GJ to 199 GJ - band D2, first half of year 2023</td><td>cost for households</td><td>€/MWh</td><td>98.1</td></tr>
</table>

6.3 Inventories of Life Cycle Assessment

6.3.1 Energy Carriers

To conduct the Life Cycle Assessment (LCA) of Italy's electricity grid, the country's energy mix is calculated based on a functional unit output of 1 kWh. This analysis utilizes data from the International Energy Agency regarding Italy's energy mix for the year 2022 [47] as presented in Table 6.

Table 6 The values of electricity generated by source in Italy in the year 2022 [47]

Electricity generation, 2022	Value [GWh]	Share in 1 kWh
Coal	27543	0.09627
Oil	15554	0.05437
Natural gas	138615	0.48451
Biofuels	15175	0.05304
Waste	4628	0.01618
Hydro	30086	0.10516
Geothermal	5816	0.02033
Solar PV	28121	0.09829
Wind	20558	0.07186

The analysis focuses on 1 kWh of high-voltage output electricity generated by power plants, explicitly excluding infrastructure components such as transmission lines and the high-to-medium and high-to-low voltage transformation systems from the system boundary. Instead, the assessment incorporates transformation and transmission losses directly associated with electricity delivery from the grid, quantified as 5.9% of the total electricity demand. This figure is based on 2021 data from Terna [48].

In conducting a life cycle assessment (LCA) of the cogeneration unit (ICE) and boiler, it is crucial to differentiate between the impacts of the infrastructure (the engine or boiler) and the operation phase, which is time-dependent. The inventory data in SimaPro for both heat from boilers and internal combustion engines (ICE), as well as electricity generated by ICE, are reported on a per 1 kWh basis, inclusive of the infrastructure component. To isolate and evaluate the operational impacts of these units accurately, it is necessary to subtract the unit's impact from the overall results. This adjustment ensures that the analysis focuses solely on the time-dependent operational phase. This process involves considering the production volume of the unit as defined within the SimaPro database, and the values for these calculations is thoroughly detailed in Table 7. This approach allows for a more precise assessment of the environmental performance of the operational phase of ICE and boiler, free from the embedded impacts of their manufacturing and installation. The complete inventory of the carriers and the units used in SimaPro are presented in Table 8.

Table 7 The production volume of the components associated with energy carriers, used for subtracting the contribution of infrastructure from LCA of energy carriers' operation

Infrastructure of the energy carrier	Production Volume in kWh (based on SimaPro)	Value of $\frac{piece}{kWh}$
ICE heat	2.66E+10	3.76E-11
ICE elelectriciy	14762611111	6.77E-11
boiler	2.40E+11	4.16E-12

Table 8 Detailed processes and values used in LCA for energy carriers

Energy carrier	Unit per	Process	value inserted in SimaPro	Unit in SimaPro
grid electricity	kWh	Electricity, high voltage {IT}| electricity production, hydro, run-of-river | Cut-off, U	0.105161	kWh
		Electricity, high voltage {RoW}| ethanol production from wood | Cut-off, U	0.053042	kWh
		Electricity, high voltage {IT}| electricity production, lignite | Cut-off, U	0.096272	kWh
		Electricity, high voltage {IT}| electricity production, oil | Cut-off, U	0.054366	kWh
		Electricity, high voltage {IT}| electricity production, natural gas, combined cycle power plant | Cut-off, U	0.484505	kWh
		Electricity, high voltage {IT}| electricity production, deep geothermal | Cut-off, U	0.020329	kWh
		Electricity, for reuse in municipal waste incineration only {IT}| treatment of municipal solid waste, incineration | Cut-off, U	0.016176	kWh
		Electricity, high voltage {IT}| electricity production, wind, >3MW turbine, onshore | Cut-off, U	0.071857	kWh
		Electricity, low voltage {IT}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Cut-off, U	0.09829	kWh
Heat from Boiler (infrastructure included)	kWh	Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler condensing modulating <100kW | Cut-off, U	1	kWh
Heat from ICE (infrastructure included)	kWh	Heat, central or small-scale, natural gas {Europe without Switzerland}| heat and power co-generation, natural gas, 50kW electrical, lean burn | Cut-off, U	1	kWh
Electricity from ICE (infrastructure included)	kWh	Electricity, low voltage {Europe without Switzerland}| heat and power co-generation, natural gas, 50kW electrical, lean burn | Cut-off, U	1	kWh
Infrastructure of heat from Boiler	kWh	Gas boiler {RER}| production | Cut-off, U	4.16E-12	piece
Infrastructure of heat from ICE	kWh	Heat and power co-generation unit, 50kW electrical, components for heat only {RER}| construction | Cut-off, U	3.76E-11	piece
	kWh	Heat and power co-generation unit, 50kW electrical, common components for heat+electricity {RER}| construction | Cut-off, U	3.76E-11	piece
Infrastructure of electricity from ICE	kWh	Heat and power co-generation unit, 50kW electrical, components for electricity only {RER}| construction | Cut-off, U	6.77E-11	piece
	kWh	Heat and power co-generation unit, 50kW electrical, common components for heat+electricity {RER}| construction | Cut-off, U	6.77E-11	piece

After doing the LCA using the endpoint impact categories of method ReCiPe2016 (H), the results would be as presented in Table 9.

Table 9 The weighted results of the LCA for energy carriers

Energy carrier/Infrastructure	Human health [Pt]	Ecosystems [Pt]	Resources [Pt]
Generation of electricity (Grid)	0.022188847	0.000530789	0.000281924
losses of the electricity in Grid	0.001309142	3.13166E-05	1.66335E-05
Total electricity from Grid considering losses	0.023497989	0.000562106	0.000298558
heat from ICE, infrastructure included	0.002256018	0.000101495	9.6334E-05
infrastructure of heat from ICE	8.46649E-08	2.21632E-09	6.01783E-10
heat from ICE, without infrastructure	0.002255934	0.000101492	9.63334E-05
electricity from ICE, infrastructure included	0.013768496	0.000619422	0.000587927
infrastructure of electricity from ICE	1.56509E-07	3.91121E-09	1.00734E-09
electricity from ICE, without infrastructure	0.013768339	0.000619418	0.000587926
heat from boiler, infrastructure included	0.004913442	0.000216981	0.000223931
infrastructure of heat from boiler	2.38674E-10	3.62742E-12	8.61812E-13
heat from boiler, without infrastructure	0.004913442	0.000216981	0.000223931

6.3.2 Energy Conversion and Storage Units

To have the same desired units for our technologies, some calculations have been done using their characteristics (lifetime from Table 4 and capacities from the process description in SimaPro). For technologies like PV, HP, and ICE, the unit in LCA is per piece, while it is favorable to have human and natural capitals expressed in points per $kW\ .year$. Thus, Equation (22) has been used.

$$conversion\, unit\ for\ PV, HP\ and\ ICE = \frac{1\,piece}{capacity\ in\ kW\ \times\ lifetime\ in\ years}\quad \left[\frac{piece}{kW\ .year}\right] \tag{22}$$

With regards to EES, the Lithium-ion battery of PowerWall 2 manufactured by Tesla has been used (Table 10). Since the functional unit for life cycle assessment is expressed in kg, and ourdesired unit for natural and human capitals is in points per $h\,.\,year$, Equation (23) has been used.

$$conversion\ unit\ for\ EES = \frac{wight\ of\ battery\ in\ \ kg}{capacity\ in\ kWh\ \times\ life\ time\ in\ years}\ \left[\frac{kg}{kWh\,.\,year}\right] \tag{23}$$

Similarly for TES (water tank), using the charecteristics presented in Table 10, Equation (24) can be presented for the conversion of units.

$$conversion\ unit\ for\ TES = \frac{1\ piece}{specific\ energy\ storage\ density\ \frac{kWh}{liter}\ \times\ capacity\ in\ \ liter\ \ \times\ life\ time\ in\ years}\ \left[\frac{piece}{kWh\,.\,year}\right] \tag{24}$$

Table 10 Additional characteristics required for the unit conversion of storage units

Storage unit	characteristics	value
TES (water tank) [49]	Specific energy storage density [kWh/m³]	80
	Capacity of one unit in SimaPro [liter]	2000
	Lifetime [years]	30
EES (lithium-ion battery) [50] [51]	Weight [kg]	114
	Energy density [kWh/kg]	0.1184
	Capacity of one unit [kWh]	13.5
	Lifetime [years]	10

After doing these conversions, the processes and the units would be as expressed in Table 11 to be able to do the life cycle assessment. The results of the LCA for the components are presented in Table 12.

Table 11 Detailed processes and values used in LCA for different technologies

Technology	Unit per	Process	converting the units	value inserted in SimaPro	Unit in SimaPro
PV	kW.year	Photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof {RoW}| photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof | Cut-off, U	$\frac{1\ piece}{3\ kWp\ \times 20\ years} = 0.016666$	0.016666	piece
ICE	kW.year	Heat and power co-generation unit, 50kW electrical, components for heat only {RER}| construction | Cut-off, U	$\frac{1\ piece}{50\ kW\ \times 25\ years} = 0.0008$	0.0008	piece
	kW.year	Heat and power co-generation unit, 50kW electrical, components for electricity only {RER}| construction | Cut-off, U		0.0008	piece
	kW.year	Heat and power co-generation unit, 50kW electrical, common components for heat+electricity {RER}| construction | Cut-off, U		0.0008	piece
Boiler	kW.year	Gas boiler {RER}| production | Cut-off, U	$\frac{1\ piece}{10\ kW\ \times 25\ years} = 0.004$	0.004	piece
HP	kW.year	Heat pump, 30kW {RER}| production | Cut-off, U	$\frac{1\ piece}{30\ kW\ \times 25\ years} = 0.0013$	0.0013	piece
TES	kWh.year	Heat storage, 2000l {RoW}| production | Cut-off, U	$\frac{1\ piece}{0.08 \frac{kWh}{liter} \times 2000\ liters \times 30\ years} = 0.00020833$	0.000208333	piece
EES	kWh.year	Battery, Li-ion, rechargeable, prismatic {GLO}| production | Cut-off, U	$\frac{114\ \ kg}{13.5\ kWh\ \times\ 10\ years} = 0.8444$	0.8444	kg

Table 12 The weighted results of the LCA for components

Technology	Human health [Pt]	Ecosystems [Pt]	Resources [Pt]
PV	9.086759	0.212691	0.054965
ICE	2.300226173	0.055846394	0.014794428
Boiler	0.229494043	0.003487906	0.000828665
HP	0.544518794	0.009790999	0.001335554
TES	0.01779764	0.000316734	9.30325E-05
EES	1.131053	0.017168	0.003700

6.4 Human, Natural and Produced Capitals for Energy Carriers and Components

In our life cycle assessment, the human and natural capitals of energy carriers and components are calculated. Human capital reflects health impacts, calculated as weighted points using the ReCiPe 2016 method. Natural capital sums up ecosystem and resource damages similarly, while produced capital is represented by monetary investments in euros. Annual investments in technologies are calculated based on their lifetimes, providing a streamlined view of our environmental assessment's financial and ecological aspects. The values of capitals for various energy carriers and technologies are detailed in Table 13 for energy carriers and Table 14 for the components. In the tables provided, higher values for human and natural capitals indicate greater damage, which, in turn, suggests a decrease in the total inclusive wealth index. Conversely, higher figures for produced capital signal an increase in the inclusive wealth index. This reflects the direct relationship between produced capital and overall wealth, as opposed to the inverse relationship seen with human and natural capitals.

As previously detailed in subsection 6.2, exported electricity is excluded from capital considerations, yet it is integrated within energy balances. However, its economic significance is acknowledged and reflected in cost calculations, underscoring its financial contribution.

Additionally, when the value of produced capital for internal combustion engines (ICE) is calculated— that is, the economic value they create through generating both heat and electricity —specific formulas are used. These formulas distinguish between the costs of producing heat and electricity from ICE, taking into account the price of natural gas per kWh. This price includes all the initial investments, ensuring that the economic contribution of ICE is accurately reflected in generating energy.

Table 13 Specific human, natural and produced capital coefficients for energy carriers, their units and values

carrier	coefficient	unit	value
Imported Electricity	hc_{el}^{imp}	$\frac{points}{kWh}$	0.0234980
	nc_{el}^{imp}	$\frac{points}{kWh}$	0.0008607
	pc_{el}^{imp}	$\frac{euro}{kWh}$	0.3782000
Heat generated in boiler	$hc_{heat,BOIL}$	$\frac{points}{kWh}$	0.0049134
	$nc_{heat,BOIL}$	$\frac{points}{kWh}$	0.0004409
	$pc_{heat,BOIL}$	$\frac{euro}{kWh}$	0.1011340
Heat generated in ICE	$hc_{heat,ICE}$	$\frac{points}{kWh}$	0.0022559
	$nc_{heat,ICE}$	$\frac{points}{kWh}$	0.0001978
	$pc_{heat,ICE}$	$\frac{euro}{kWh}$	0.0533051
Electricity generated in ICE	$hc_{el,ICE}$	$\frac{points}{kWh}$	0.0137683
	$nc_{el,ICE}$	$\frac{points}{kWh}$	0.0012073
	$pc_{el,ICE}$	$\frac{euro}{kWh}$	0.0447949

Table 14 Specific human, natural and produced capital coefficients for components, their units and values

Technology	coefficient	unit	value
PV	hc_{PV}	$\frac{points}{kW.year}$	9.0867591
	nc_{PV}	$\frac{points}{kW.year}$	0.2676557
	pc_{PV}	$\frac{euro}{kW.year}$	62.0000000
HP	hc_{HP}	$\frac{points}{kW.year}$	0.5445188
	nc_{HP}	$\frac{points}{kW.year}$	0.0111266
	pc_{HP}	$\frac{euro}{kW.year}$	60.8000000
ICE	hc_{ICE}	$\frac{points}{kW.year}$	2.3002262
	nc_{ICE}	$\frac{points}{kW.year}$	0.0706408
	pc_{ICE}	$\frac{euro}{kW.year}$	40.4000000
BOILER	hc_{BOIL}	$\frac{points}{kW.year}$	0.2294940
	nc_{BOIL}	$\frac{points}{kW.year}$	0.0043166
	pc_{BOIL}	$\frac{euro}{kW.year}$	2.4000000
TES	hc_{TES}	$\frac{points}{kWh.year}$	0.0177976
	nc_{TES}	$\frac{points}{kWh.year}$	0.0004098
	pc_{TES}	$\frac{euro}{kWh.year}$	14.0000000
EES	hc_{EES}	$\frac{points}{kWh.year}$	1.131053063
	nc_{EES}	$\frac{points}{kWh.year}$	0.020868042
	pc_{EES}	$\frac{euro}{kWh.year}$	111

6.5 Conclusions

Chapter 6 explores the details of the reference case and case study, focusing on a cluster of users in Padua, Italy with electrical and thermal energy needs. This outlines a baseline scenario where electricity is sourced from the grid and heat is generated through natural gas combustion. A grid-connected multi-energy system featuring photovoltaic cells (PV), internal combustion engines (ICE), boiler (BOIL), air-water heat pumps (HP), and both electrical (EES) and thermal (TES) energy storage units forms the core of our case study. The chapter comprehensively details the numerical modeling and assumptions underlying both the reference and case study scenarios, ensuring equal electricity and heat demands across both. Detailed equations calculate the impacts on human, natural, and produced capitals (three components of the Inclusive Wealth Index), distinguishing between infrastructure (time-independent) and operational (time-dependent) contributions. Techno-economic data, LCA inventories, and LCA results of both energy carriers and components are explained in detail, highlighting the measurement of natural and human capitals based on the end-point damage assessments of LCA. Concluding this chapter, specific capital values for system components are provided, laying the groundwork for an optimization analysis spanning a year. The reference case, which relies on grid-supplied electricity and gas boilers for heat, establishes a baseline for comparing the impacts of different capitals calculated using specific equations. This sets the stage for a comprehensive evaluation of the environmental, social, and economic performance of the proposed multi-energy system.

Chapter 7: Results of Design and Operation Optimization

This chapter provides detailed results of the design and operation optimization of our Multi-Energy System (MES), aiming to enhance the Inclusive Wealth Index (IWI) while also minimizing costs. Initially, the MES is optimized to reduce costs, focusing on strategically allocating system capacities for economic efficiency, and then we calculate the IWI based on the results of this solution. Subsequently, the focus shifts towards maximizing the Inclusive Wealth Index. This approach showcases the potential for enhancement of the IWI, exploring the importance of the weights of capitals in the final results. In the end, a multi-objective function design and operation optimization is conducted, which seeks a balanced approach to maximizing IWI and minimizing costs. This section highlights the interactions between cost efficiency and wealth enhancement. This comprehensive examination provides the suitability of the introduced objective function (maximizing Inclusive Wealth Index) in optimizing multi-energy systems.

7.1 Single-Objective: Cost Minimization

In the single-objective scenario focused on cost minimization, the system adjusts its design and operation to achieve the lowest possible financial outlay while maintaining a balance in energy production and consumption. The objective here is not to maximize the Inclusive Wealth Index (IWI) but to ensure the most cost-effective use of resources. The result is presented in Fig. 11.

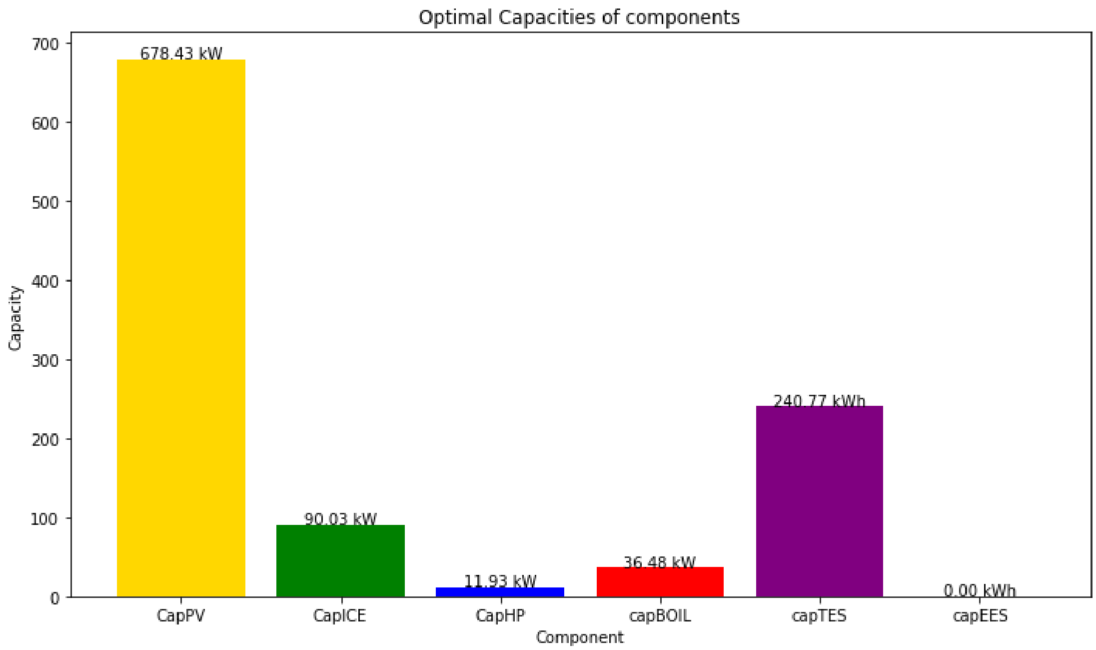

Fig. 11 The results of minimizing design and operation costs

The optimal capacities allocated for the energy components show a clear prioritization of photovoltaic cells and the system's reliance on solar power. Boilers with small capacity of 36.48 kW, indicate a reduced dependency on traditional heating methods. In detail, the results are presented in Table 15.

Table 15 Optimal values of the components' capacities for minimizing the costs

PV [kW]	ICE [kW]	HP [kW]	TES [kWh]	EES [kWh]	BOILER [kW]
678.43	90.034	11.927	240.768	0	36.48

Moreover, as can be seen in Table 16, the system manages to minimize expenditure to approximately €183352 which represents a significant saving (around 46% saving) when compared to the reference cost of approximately €337907. If IWI is calculated using the weight factors equally distributed between capitals, $w_{HC} = 0.333$, $w_{NC} = 0.333$, and $w_{PC} = 0.334$, total IWI would be -0.03161 points, with diverse contributions from various forms of capital. These different contributions are highlighted by the positive input from human and natural capitals, contrasting with the negative impact from produced capital.

Table 16 The results of single objective cost minimization and calculation of IWI using the weights $w_{HC} = 0.333$, $w_{NC} = 0.333$, and $w_{PC} = 0.334$

Costs [euro]	Annual electricity imports [kWh]	Anuual electricity exports [kWh]	Contribution of human capital [points]	Contribution of natural capital [points]	Contribution of produced capital [points]	Total IWI [points]
183352	146004.6	562671.2	0.1066(-337.39%)	0.0622 (-196.95%)	-0.2005(634.33%)	-0.03161

The percentages reported in brackets in Table 16 are the ratio between the value of each capital, which includes the corresponding weight, and the total IWI as represented in Equation (3). In the current optimization scenario, the system impressively exports approximately 563 MWh of electricity annually. This is significant when compared to the annual electricity demand of the local community, which is about 809 MWh, underscoring the system's efficiency in not only meeting internal energy needs but also generating a surplus for sale. However, the Inclusive Wealth Index (IWI) for this scenario is marginally lower than the reference case, registering at around -0.03161. The important reason for this low value is the substantial negative impact of produced capital, which is around -0.2 points. This suggests that cost-saving strategies have an adverse effect on the produced capital. This is anticipated, as cost reductions often lead to decreased investments in infrastructure and industry, which are crucial for manufacturing and employment and are categorized as produced capital in our analysis.

Conversely, human capital sees a positive contribution of 0.1 points, implying that cost minimization strategies may benefit human capital, which is also higher than the contribution of natural capital, which is around 0.06 points. The system's independence from grid electricity imports causes less damage to human health, the ecosystem and resources, leading to a positive influence on the IWI. In the reference case, which assumes a zero IWI, electricity and heat demands are met entirely through the grid and boilers.

The role of photovoltaic (PV) cells within the IWI is substantial. By lessening grid electricity dependence, the system reduces reliance on the country's conventional energy mix, yielding better environmental impacts for human and natural capitals. Yet, this reduction in electricity imports can adversely affect produced capital due to potential declines in sectoral investments. This could result in a downturn in produced capital and related job losses, particularly within industries like natural gas which are key components of Italy's energy mix. On the other hand, investments in the production of system components like PV, ICE, TES, EES and HP have a favorable impact on the IWI. Such investments can spur economic growth in the sector, enhance manufacturing capabilities, and create job opportunities. However, it is worth noting that the increase in produced capital from advancements in these technologies with the capacities suggested by the cost minimization optimization is less than what would be achieved through the reference case of using grid electricity and natural gas boilers.

Overall, this solution effectively demonstrates the system's proficiency in reducing overall costs, encompassing both investment and operational expenditures. However, this cost minimization is evidenced by a lower Inclusive Wealth Index (IWI) when compared to the baseline scenario, primarily due to a reduction in produced capital. Furthermore, while utilizing the components of the Multi Energy System (MES) positively affects natural and human capitals, the produced capital of these MES components is less than the one that the reference case would bring, resulting in unfavorable IWI outcomes. Consequently, this shows a need to balance cost efficiencies with maximizing the Inclusive Wealth Index.

7.2 Single-Objective: Maximization of Inclusive Wealth Index (IWI)

This section explores optimizing a multi-energy system to only maximize the Inclusive Wealth Index (IWI) for the user with the heat and electricity demand as in section 7.1. In our initial approach to optimize the multi-energy system for the maximum enhancement of the Inclusive Wealth Index, the allocation weights for capitals are considered equal as specified in Section 7.1: $w_{HC} = 0.333$, $w_{NC} = 0.333$, and $w_{PC} = 0.334$. This model yields an optimal Inclusive Wealth Index value of 0.11406 points, with the outcomes depicted in Fig. 12.

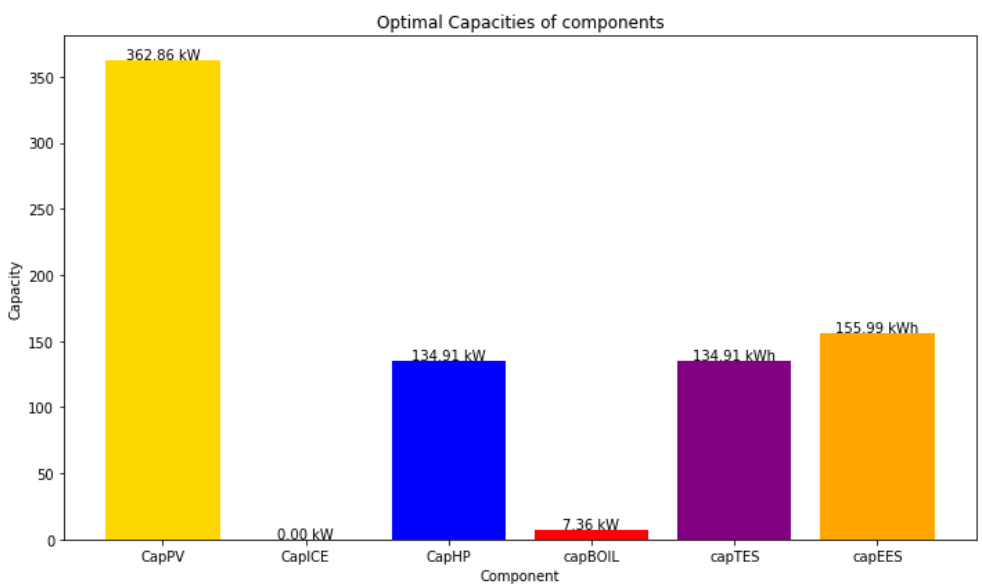

Fig. 12 The results of maximizing IWI using weight factors $w_{HC} = 0.333$, $w_{NC} = 0.333$, and $w_{PC} = 0.334$

The analysis, as detailed in Table 17, underscores a significant emphasis on specific energy components—namely, Photovoltaic cells (PV), Heat Pumps (HP), Thermal Energy Storage (TES), and Electrical Energy Storage (EES). This contrasts with the considerably lower capacity allocated to boilers (BOIL) at 7.36 kW, and the complete absence of capacity for Internal Combustion Engines (ICE). It is important to note that the capacities of HP, TES and EES reach their upper bound. The upper bound capacities for HP and TES are considered 10% higher than the maximum community's thermal demand and the upper bound capacity of EES is 10% higher than the maximum community's electrical demand, while other components do not have any upper bounds for their capacities.

Table 17 Optimal values of the components' capacities for maximizing the Inclusive Wealth Index, $w_{HC} = 0.333$, $w_{NC} = 0.333$, *and* $w_{PC} = 0.334$

PV [kW]	ICE [kW]	HP [kW]	TES [kWh]	EES [kWh]	BOILER [kW]
362.8585	0	134.913	134.913	155.991	7.3594

The significant focus on PV, HP, TES, and EES can be attributed to the system's aim to enhance IWI by leveraging components with minimal environmental impact—those causing lesser harm to natural and human capitals—while simultaneously offering significant investment value and enhanced produced capital.

In this scenario, the allocated capacity for Photovoltaic (PV) systems is about 46% lower than its optimal capacity identified in the cost-minimization scenario. Consequently, this adjustment leads to a reduced export of electricity to the grid (around 97 MWh annual exported electricity), as compared to the scenario prioritizing cost minimization. This underscores the economic benefit of selling produced electricity to the grid as a significant advantage of PV systems, overshadowing their environmental and social benefits.

Moreover, as presented in Table 18, the aim of IWI maximization is achieved with significant costs, approximately 42% higher than those associated with cost-minimization scenarios; However, overall costs are still about 23% lower than the reference cost at €337907. In the current allocation of weights, a great positive impact on human and natural capitals can be seen, accompanied by a negative impact on produced capital. This result suggests that the benefits to both human and natural capitals are higher than the damage to produced capital, which would overall result in the sustainable development of the community compared to the reference case. However, the higher costs highlight the need to guide the system toward a more balanced optimization, integrating a multi-objective function that encompasses both cost minimization and IWI maximization. Such an approach promises to align more closely with sustainable development goals, ensuring a balance between economic efficiency, environmental preservation, and social well-being.

Table 18 The results of single objective maximizing of IWI using weight factors $w_{HC} = 0.333$, $w_{NC} = 0.333$, *and* $w_{PC} = 0.334$, and calculation of costs

Costs [euro]	Annual electricity imports [kWh]	Annual electricity exports [kWh]	Contribution of human capital [points]	Contribution of natural capital [points]	Contribution of produced capital [points]	Total IWI [points]
261153.755	481815.41	96679.92	0.0919(80.58%)	0.1263 (110.74%)	-0.104 (-91.32%)	0.11406

Given that the values of the weights were initially set as equal and chosen arbitrarily, the optimization problem thus far has not fully explored the varied contributions of different capitals to the overall Inclusive Wealth Index (IWI). To better accommodate the diverse potentials and scales of the system and to more accurately reflect the distinct impacts of each type of capital on the IWI, we have undertaken the optimization of maximizing the Inclusive Wealth Index with varied weightings for the capitals (Table 19). This adjustment allows for a more tailored approach to optimizing the system, recognizing the unique value and role of each capital in contributing to the overall wealth.

Across various weight allocations, with the exception of the scenario prioritizing produced capital, the contribution of produced capital to the overall inclusive wealth is consistently negative. However, when we increase the weight of produced capital to 0.6, the model would result in an unbounded model. This outcome is logical, considering that an intense emphasis on produced capital is likely to raise the system's capacities to their utmost by maximizing investments in production, potentially leading the system towards being unbounded. Furthermore, allocating a greater weight to human capital results in a reduction in imported electricity from the grid, showcasing the negative impacts of depending on grid electricity for human capital enhancement. In the analysis of weight allocations, the Inclusive Wealth Index (IWI) reaches its peak when emphasis is placed on natural capital. Specifically, under this prioritization of natural capital, the optimal capacity for Internal Combustion Engines (ICE) drops to zero, indicating a complete shift away from them. Meanwhile, the capacity allocated for boilers is minimal (0.386 kW), with an increase in the optimal capacity designated for Photovoltaic (PV) systems. This outcome highlights the superiority of PV cells in enhancing natural capital, given their environmentally friendly nature. On the contrary, components reliant on natural gas, such as ICE and boilers, are shown to adversely affect natural capital, which encompasses ecosystems and natural resources. Moreover, the optimal capacities for HP, TES and EES reach their upper bound amount in all the studied weight allocations.

Table 19 The optimal values and results of maximizing the Inclusive Wealth Index using different values for the weight of capitals

	$w_{HC} = 0.333$ $w_{NC} = 0.333$ $w_{PC} = 0.334$	$w_{HC} = 0.6$ $w_{NC} = 0.2$ $w_{PC} = 0.2$	$w_{HC} = 0.2$ $w_{NC} = 0.6$ $w_{PC} = 0.2$	$w_{HC} = 0.2$ $w_{NC} = 0.2$ $w_{PC} = 0.6$
PV [kW]	362.8585	369.609	394.266	model unbounded
ICE [kW]	0	67.130	0	
HP [kW]	134.913	134.913	134.913	
BOIL [kW]	7.3594	1.161	0.386	
TES [kWh]	134.913	134.913	134.913	
EES [kWh]	155.991	155.991	155.991	
Total IWI [points]	0.11406	0.209	0.2238	
Contribution of HC (%)	80.58%	123.65%	25.10%	
Contribution of NC (%)	110.74%	29.98%	103.92%	
Contribution of PC (%)	-91.32%	-53.63%	-29.02%	
Total imported elelctricity [kWh]	481815.4	193162.11	466447.33	
Total exported elelctricity [kWh]	96679.92	103138.93	124544.26	
Total costs [euro]	261153.755	212062.2	256662.98	

Reviewing Table 19 reveals that certain outcomes, though theoretically beneficial, diverge from practical sustainability objectives. Notably, the system amplifies the storage capacities of TES and EES for IWI maximization across all weight allocations. This trend is due to the lower adverse impacts of them on both human and natural capitals, while raising the produced capital, driven by growth in manufacturing and employment opportunities.

Overall, the analysis reveals the interactions between environmental benefits, capital investments, and the reaching the goal of inclusive wealth maximization. It demonstrates that a correct application of weights is crucial for guiding the system towards broader sustainability goals. Moreover, the higher costs to achieve high values of IWI highlight the need to guide the system toward a more balanced optimization, integrating a multi-objective function that encompasses both cost minimization and IWI maximization. Such an approach promises to align more closely with sustainable development goals, ensuring a balance between economic efficiency, environmental preservation, and social well-being.

7.3 Multi-Objective Optimization of Costs and Inclusive Wealth Index

In this section for design and operation optimization of the multi-energy system, our approach aims at achieving a balance between maximizing the Inclusive Wealth Index (IWI) and minimizing costs. The objectives are to keep the costs at a low level while achieving a high IWI value. The optimization is done using the same weight for each capital: $\mathrm{w_{HC}} = 0.333, \mathrm{w_{NC}} = 0.333, \mathrm{w_{PC}} = 0.334$.

Fig. 13 showcases the Pareto front in the context of a multi-objective optimization problem, focusing on the balance between reducing costs and maximizing the Inclusive Wealth Index (IWI), with an equal weighting applied to human, natural, and produced capital.

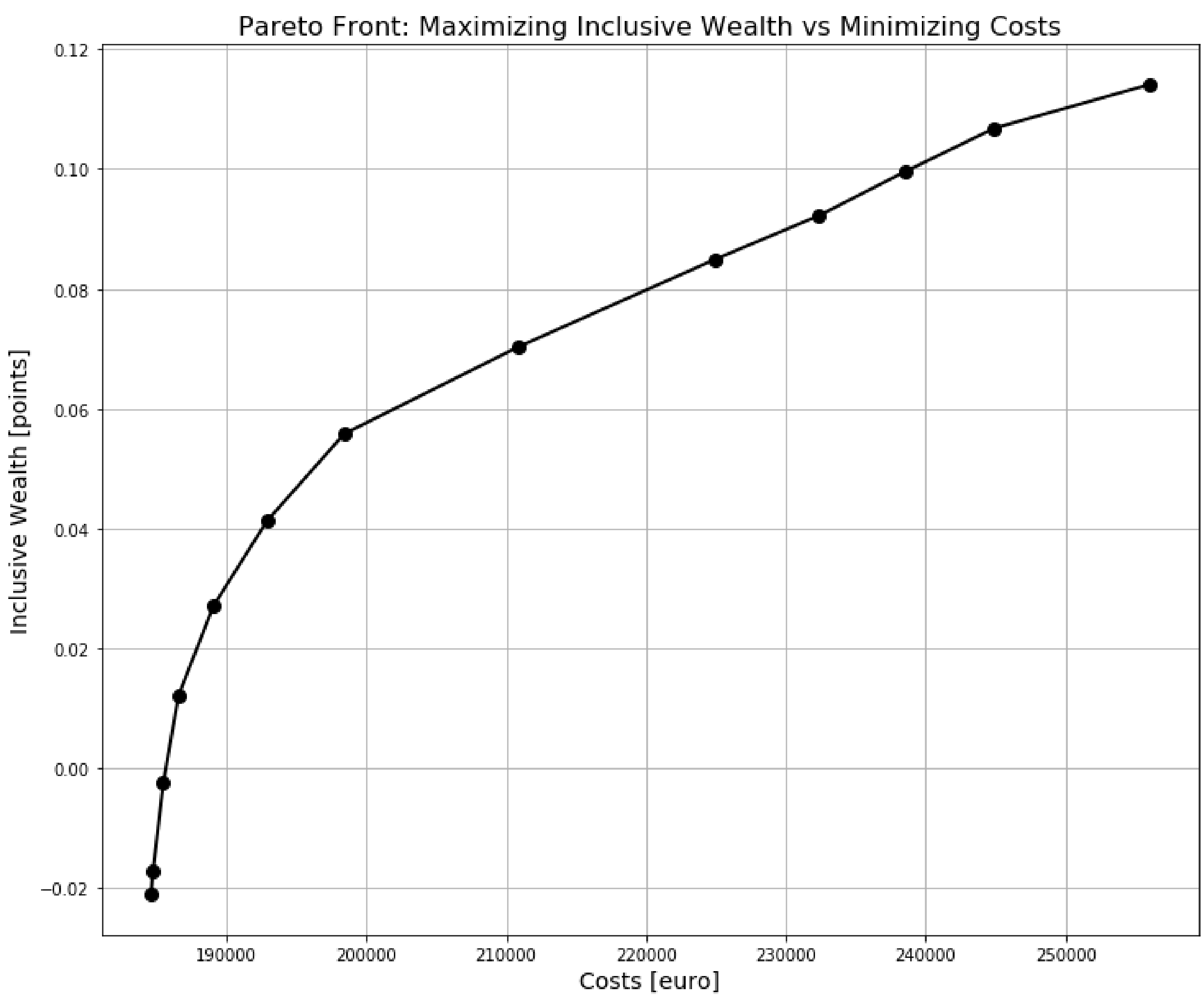

Fig. 13 The Pareto front of multi-objective optimization, reducing costs and maximizing IWI, $w_{HC} = 0.333$, $w_{NC} = 0.333$, $w_{PC} = 0.334$

Fig. 13 effectively illustrates the trade-offs between the objectives of cost minimization and wealth maximization. It is evident that at lower cost levels, increments in IWI can be achieved with relatively modest increases in expenditure. As the costs increase, the rate of increase in IWI becomes less significant. This pattern suggests that initial investments are highly efficient in enhancing IWI, but beyond a certain threshold, the cost of additional improvements in IWI becomes significantly higher. The values of costs, IWI, and the capacities of each component are detailed in Table 20.

Table 20 The detailed costs, IWI, and capacities for the different points of Pareto front for the multi-objective optimization, reducing costs and maximizing IWI, $w_{HC} = 0.333$, $w_{NC} = 0.333$, $w_{PC} = 0.334$

No.	Cost [euro]	IWI [point]	PV [kW]	ICE [kW]	BOIL [kW]	HP [kW]	TES [kWh]	EES [kWh]
1	183352.1	-0.03161	678.43	90.034	36.48	11.927	240.768	0
2	184757.9	-0.01704	695.01	73.814	29.529	35.458	134.913	0
3	185495.8	-0.00247	574.19	72.207	36.655	29.583	134.913	0
4	186574.3	0.01209	462.92	68.229	27.606	31.441	118.267	1.107
5	189072.7	0.02707	460.52	62.077	31.772	37.627	70.039	37.558
6	192892.3	0.04122	499.36	61.072	31.843	36.630	48.981	127.92
7	198427	0.05579	446.45	61.072	4.046	50.259	60.873	155.99
8	210924.5	0.07036	437.66	56.415	2.359	67.646	132.438	155.99
9	224970.5	0.08492	437.66	46.733	14.952	67.646	132.438	155.99
10	232378.3	0.09221	437.66	32.905	30.573	67.646	132.438	155.99
11	238488.9	0.09949	461.35	0.000	76.125	59.757	87.969	155.99
12	244907.9	0.10677	427.66	0.000	43.771	69.633	132.438	155.99
13	261153.7	0.11406	362.86	0.000	7.3594	134.91	134.913	155.99

The initial data points reveal a negative IWI value, which gradually increases as costs rise. This pattern suggests that the optimization process progressively moves from a state of wealth reduction to wealth generation while optimizing across various technologies. The capacity of the internal combustion engine (ICE) diminishes to zero as the optimization goes to higher values of IWI, showcasing the higher damage impact of ICE on human and natural capitals. As costs and IWI continue to increase, we observe a substantial allocation towards heat pumps (HP), thermal energy storage (TES), and electrical energy storage (EES), culminating in maximum capacities for these components.

The composition of IWI and the values of different capitals at every point are detailed in Table 21. It is important to note that in this table, the weights are included in the contribution values of each capital.

Table 21 The detailed composition of IWI for the different points of Pareto front for the multi-objective optimization, reducing costs and maximizing IWI, w_HC=0.333,w_NC=0.333, w_PC=0.334

Point Number	Inclusive Wealth [points]	HC contribution [points]	NC contribution [points]	PC contribution [points]
1	-0.03161	0.1066	0.0622	-0.2005
2	-0.01704	0.10152	0.072591	-0.19115
3	-0.00247	0.11403	0.078081	-0.19459
4	0.012092	0.124813	0.084346	-0.19707
5	0.027066	0.127191	0.092872	-0.193
6	0.041225	0.131362	0.101006	-0.19114
7	0.055792	0.136913	0.107774	-0.18889
8	0.070359	0.130576	0.114195	-0.17441
9	0.084925	0.116672	0.119687	-0.15143
10	0.092208	0.109544	0.121926	-0.13926
11	0.099492	0.097815	0.121873	-0.1202
12	0.106775	0.096496	0.126662	-0.11638
13	0.114058	0.093702	0.129168	-0.10881

Table 21 illustrates that the initial segments of the Pareto front (points 1-3) are characterized by lower costs and IWI values, alongside high negative contributions from produced capital. In all the points of the Pareto front, the total costs are lower than the one for the reference case. A favorable result occurs between the 4th and 7th data points, marking a strategic shift towards increasing IWI while keeping the costs lower than 200 thousand euros. This suggests a balanced advancement across the Inclusive Wealth Index and total costs, enabled by the strategic integration of technologies like HP, TES and EES. This equilibrium is particularly apparent in data point 7, where costs remain below the 200 thousand euro threshold, yet IWI achieves around 0.056 points, meaning a 5.6% improvement from the IWI of the reference case. Furthermore, the 7^{th} data point shows a significant increase in human and natural capitals, 13.7% and 10.7% improvement with respect to the reference case, respectively; while the negative contribution of produced capital can be compensated. We achieve this IWI at a cost of approximately €198427, which is roughly 41% lower than the reference scenario cost of €337,907, and only 8% higher than the minimum cost achievable by only minimization of costs. This data point demonstrates that a relatively modest rise in expenditure from the minimum cost scenario can result in a significant enhancement of the Inclusive Wealth Index.

Past the 7th data point, increased costs and IWI are achieved with lower contributions of human capital and a marginal increase in natural capital. This shows that the model favors a strategy to boost produced capital at the expense of human capital. This approach effectively raises the IWI, bringing the value of IWI to 0.114 points, while costs (€255991.4) are still lower than the costs of the reference case. This shows that it is possible to improve wealth substantially with modest financial input, which is an ideal scenario for our MES aiming to be efficient and sustainable.

Overall, the Pareto front for our multi-objective function optimization demonstrates that achieving higher values of the Inclusive Wealth Index (IWI) requires higher costs than the cost minimization scenario. There is a range of efficient solutions where IWI can be maximized relative to the cost. Decision-makers might use this graph to identify a balance point where the increase in wealth justifies the associated costs, bearing in mind that beyond this point, the pursuit of greater wealth becomes significantly more expensive. Furthermore, given that adjusting these weights can significantly alter the IWI and the contributions from each type of capital, it is important to carefully consider the weight factors assigned to different capitals, highlighting their critical role in guiding sustainable decision-making and optimizing outcomes.

Chapter 8: Critical Remarks

The analysis of the multi-energy system optimization for enhancing the Inclusive Wealth Index (IWI) while minimizing costs reveals several critical insights:

1. **Single objective optimization of MES for minimizing the investment and operation costs:**

- A significant cost reduction of 46%, achieving an overall annual cost of €183,352 compared to the annual reference case costs of €337,907.
- The system prioritizes photovoltaic (PV) technology for cost optimization, leading to a substantial production of excess electricity. Consequently, a high amount of electricity, totaling 563 MWh annually, is exported to the grid, from the MES of the community with an annual electricity demand of 809 MWh.
- A noticeable adverse impact on the value of the Inclusive Wealth Index (IWI), decreasing it by -0.03161 points while setting equal weight allocation for capitals.
- The negative values of IWI are primarily due to the high negative contribution of produced capital.
- Both human and natural capitals contribute positively to the IWI.

2. **Single objective optimization of MES for maximizing the Inclusive Wealth Index (IWI):**

- The novel objective function to maximize IWI marks a considerable progression beyond mere cost minimization, emphasizing a comprehensive approach to sustainability.
- The allocation of varied weights to different types of capital in the calculation of IWI significantly modifies both the IWI and associated costs.
- Achieving a high value of IWI 0.11406 points while considering the equal weight allocation between capitals, mostly due to the positive contribution of human and natural capitals.
- The total annual cost to achieve IWI=0.11406 points is 261153 euros.
- The allocated capacity for Photovoltaic (PV) systems is about 46% lower than its optimal capacity identified in the cost-minimization scenario.
- The complete absence of ICE and the low optimal capacity of the boiler suggests the high damage of the operation of these components on both human and natural capitals.
- Prioritizing human capital leads to a reduction in electricity imports.

- A focus on Heat Pumps (HP), Thermal Energy Storage (TES), and Electrical Energy Storage (EES) is favored due to their lower damage to human and natural capitals, while contributing positively to the produced capital.

3. Multi-objective optimization of MES for minimizing the costs and maximizing the Inclusive Wealth Index:

- Pareto front shows that achieving higher values of the Inclusive Wealth Index (IWI) needs increased costs. This trade-off highlights the cost implications of enhancing community wealth through the MES.
- Initial investments prove highly efficient in boosting IWI. However, after surpassing a certain cost threshold, the expense of further improvements in IWI increases considerably.
- With an equal weight allocation across capitals, a balanced and beneficial impact is observed. Specifically, between IWI values of 0.012 and 0.056 points, with high values of human and natural capitals can be achieved, while keeping the costs lower than 200000 euro.
- We can improve IWI to 0.056 points, meaning a 5.6% improvement from the IWI of the reference case, with a significant increase in human (13.7%) and natural (10.7%) capitals at a cost of approximately €198427, which is approximately 41% lower than the reference scenario cost of €337,907, and only 8% higher than the minimum cost achievable by only minimization of costs.
- As the IWI optimization target exceeds 0.092 points, the reliance on internal combustion engines (ICE) is eliminated, signifying a shift towards more sustainable energy sources.

Chapter 9: Conclusions and Future Work

This thesis aimed at redefining the optimization of Multi-Energy Systems (MES), with the primary objective to develop a comprehensive objective function that integrates social, environmental (spanning the entire lifecycle), and economic dimensions to facilitate sustainable development through the design and operation of MES. By leveraging the novel objective function, the Inclusive Wealth Index (IWI), this study aimed to encapsulate human, natural, and produced capitals into a unified optimization framework, moving beyond traditional cost minimization strategies to employ a holistic approach to sustainability. This approach not only adheres to economic principles but also significantly contributes to environmental sustainability and social well-being, reflecting practical insights for policymakers and engineers aiming to shift towards integrating broader sustainability goals in energy system optimization.

The methodology adopted a Mixed-Integer Linear Programming (MILP) approach, utilizing the Gurobi solver within Python. This method allowed for the detailed analysis and optimization of the system's component capacities, focusing on maximizing the IWI while also considering cost minimization. Our approach involved conducting a detailed life cycle assessment (LCA) for each component and energy carrier within the MES to quantify their impacts on human and natural capitals, while investments in these technologies were considered as produced capital, reflecting economic growth and societal well-being.

The optimization process demonstrated significant findings. Initially, the single-objective optimization aimed at minimizing investment and operational costs resulted in a significant cost reduction of 46% compared to the reference scenario. However, this was at the expense of a minor decline in the Inclusive Wealth Index (IWI), which decreased to -0.03 points. In this scenario, while human and natural capitals contributed positively to the IWI, the overall negative value of IWI was due to the substantial negative impact of produced capital. This is understandable, considering that produced capital encompasses investments in infrastructure and manufacturing, which are minimized in cost-reduction strategies. Furthermore, in pursuing cost minimization, the system demonstrated a preference for a higher allocation of photovoltaic (PV) cell capacity over other components. This strategic prioritization led to the exportation of a significant amount of electricity to the grid, approximately 70% of the community's total electricity demand.
In contrast, the single-objective optimization for maximizing the Inclusive Wealth Index (IWI) showed a different aspect of sustainable development. By prioritizing the IWI, the optimization yielded a notable improvement in the value of IWI, achieving a value of 0.114 points for the equal weight allocation of capitals. This strategy underscored

the vital role of human and natural capitals in enhancing societal wealth, combined with 42% higher costs (€261153) than those associated with the cost-minimization scenario (€183352). Notably, this optimization approach resulted in a more than 46% reduction in the allocated capacity for photovoltaic (PV) systems compared to their optimal capacity identified in the cost-minimization scenario. Despite the higher costs, this strategy emphasized investments in Heat Pumps (HP), Thermal Energy Storage (TES), and Electrical Energy Storage (EES) due to their minimal operational damage to human and natural capitals combined with positive values of produced capital. The diverse weight allocations among the different types of capital significantly influenced the outcomes, indicating that strategic emphasis on certain capitals can yield substantial gains in the IWI with comparatively modest increases in costs. For instance, adjusting the weights of different capitals to $\mathrm{w_{HC}} = 0.2$, $\mathrm{w_{NC}} = 0.6$, $\mathrm{w_{PC}} = 0.2$ demonstrated a holistic improvement in achieving a maximum IWI of 0.2238 points at a lower cost of €256663. This approach, while highlighting the potential for substantial enhancement of the IWI, also underscores the complexity and costs associated with shifting towards a more sustainable energy system.

The exploration of multi-objective optimization, balancing the goals of minimizing costs and maximizing the Inclusive Wealth Index (IWI), revealed an understanding of the trade-offs inherent in sustainable energy system design. The Pareto front analysis highlighted a continuum of efficient solutions, illustrating that initial investments could significantly enhance the IWI at relatively low additional costs. However, beyond a certain threshold, the cost of further improvements in the IWI escalated, indicating a higher contribution of produced capital. This optimization strategy allowed for the identification of a balanced solution, where an IWI increase of 0.056 points with high positive contributions of human (13.7%) and natural (10.7%) capitals was achievable at a cost approximately 41% lower than the reference scenario. Such a balance suggests that with strategic planning and allocation of resources, it is possible to simultaneously address economic efficiency and enhance societal wealth. Moreover, the capacity for internal combustion engines (ICE) diminished to zero in optimizations favoring higher IWI values, underscoring a preference for sustainable components that mitigate operational damage to both human and natural capitals. This multi-objective approach fosters a comprehensive perspective, guiding the transition towards more sustainable energy systems by illustrating the complex interplay between cost efficiency and the enhancement of inclusive wealth.

Overall, this thesis contributes a novel perspective to the optimization of Multi-Energy Systems by integrating the Inclusive Wealth Index, thus offering a comprehensive framework that balances economic, environmental, and social objectives. Through mathematical analysis, it reveals the trade-offs between cost minimization and wealth maximization, demonstrating that while significant cost savings can be achieved, they can come at the expense of a slight reduction in IWI. Conversely, prioritizing the IWI fosters substantial improvements in societal wealth, combined with higher associated costs. This study underscores the importance of strategic weight allocation among human, natural, and produced capitals in influencing the optimization outcomes, advocating for a balanced consideration of these factors to achieve optimal sustainability results. Additionally, the research highlights the pivotal role of renewable energy components in contributing to a more sustainable and inclusive wealth generation. Ultimately, this thesis illuminates the potential and challenges of integrating the IWI into MES optimization, laying the groundwork for future research and practical applications aimed at advancing the transition towards more sustainable and inclusive energy systems.

The findings of the current study call for further investigations into the dynamic interplay between different capitals, and the impact of varying weight allocations. Furthermore, some improvements in the definition of different capitals can be studied. For instance, expanding the definition and calculation of human capital within the Inclusive Wealth Index (IWI) to include education, job creation, and gender inclusivity, as well as addressing downstream lifecycle impacts of energy technologies in all the capitals and cost allocation. Specifically:

- Education and Job Creation: Expanding the human capital component of the IWI to include factors such as education and job creation, leveraging job creation metrics per MW for different energy technologies as in [21], together with the educational impacts associated with training and skill development required for these technologies. This will provide a deeper insight into the social benefits and workforce development potential of Multi-Energy Systems (MES).

- Downstream Processes and Lifecycle Costs: It is critical to extend cost allocation to include end-of-life management and recycling costs beyond the design and operational phase, especially for technologies like photovoltaic cells. For instance, research indicates that the significant costs associated with recycling photovoltaic (PV) cells deter many countries from undertaking this process [52] , which would diminish the environmental benefits of PV technology and their significant impact on increasing IWI. This comprehensive approach will help in assessing the true environmental and economic impact of energy technologies over their entire lifecycle.

- Gender Gap in the Energy Sector: Analyzing the gender distribution within the energy sector workforce, noting the differences between traditional and renewable energy sectors. For instance, while only 22% of workers in the oil industry are women, this figure increases to 32% within renewable technologies [53]. This perspective can enrich the human capital evaluation by highlighting social inclusivity and equality.

- Adjustment of Constraints for Realistic Investments: Refining the optimization model's constraints to account for the values of investments in renewable technologies. This allows the model to align the produced capital component more closely with achievable economic growth according to the budget of the country.

- Application of Planetary Boundaries to Environmental Factors: Implementing constraints based on planetary boundaries for environmental factors [54], particularly for the life cycle assessment aspects tied to human and natural capitals can be studied. This approach would ensure that the optimization process respects ecological limits, contributing to sustainable development goals.

Additionally, future studies should explore the dynamic adjustment of the weights for human, natural, and produced capitals to balance economic efficiency with environmental and social sustainability, ensuring that the optimization of multi-energy systems aligns with broad sustainability goals.

References

[1] European Commission, "The European Green Deal," *COM(2019) 640 Final. Brussels*, 2019.

[2] P. Mancarella, "MES (multi-energy systems): An overview of concepts and evaluation models," *Energy*, vol. 65, pp. 1–17, 2014.

[3] T. Terlouw, P. Gabrielli, T. AlSkaif, C. Bauer, R. McKenna, and M. Mazzotti, "Optimal economic and environmental design of multi-energy systems," *Appl. Energy*, vol. 347, no. June, p. 121374, 2023.

[4] O. Vågerö and M. Zeyringer, "Can we optimise for justice? Reviewing the inclusion of energy justice in energy system optimisation models," *Energy Res. Soc. Sci.*, vol. 95, no. December 2022, p. 102913, 2023.

[5] B. Wilgosh, A. H. Sorman, and I. Barcena, "When two movements collide: Learning from labour and environmental struggles for future Just Transitions," *Futures*, vol. 137, no. December 2021, 2022.

[6] B. Schaefer Caniglia, A. Jorgenson, S. A. Malin, L. Peek, D. N. Pellow, and X. Huang, Eds., *Handbook of Environmental Sociology*. Springer International Publishing, 2021.

[7] World Health Organization (WHO), "Protecting Health from Climate Change," 2016.

[8] World Health Organization (WHO), "Review of IPCC Evidence 2022, climate change, health, and well-being," 2022.

[9] World Health Organization (WHO), "Ambient (outdoor) air pollution." [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health.

[10] WHO Climate Change and Health Unit, "Climate Change, Health,& Intergenerational Equity," pp. 1–6, 2022.

[11] IPCC - Working Group II, "Fact sheet-Health - IPCC Sixth Assessment Report," pp. 7–8, 2023.

[12] T. Léger-Goodes, C. Malboeuf-Hurtubise, T. Mastine, M. Généreux, P. O. Paradis, and C. Camden, "Eco-anxiety in children: A scoping review of the mental health impacts of the awareness of climate change," *Front. Psychol.*, vol. 13, 2022.

[13] A. Colantonio, "Social sustainability: a review and critique of traditional versus emerging themes and assessment methods," *Sue-Mot Conf. 2009 Second Int. Conf. Whole Life Urban Sustain. Its Assess.*, pp. 865–885, 2009.

[14] M. Fodstad *et al.*, "Next frontiers in energy system modelling: A review on challenges and the state of the art,"

Renew. Sustain. Energy Rev., vol. 160, no. December 2021, p. 112246, 2022.

[15] A. Hugo and E. N. Pistikopoulos, “Environmentally conscious long-range planning and design of supply chain networks,” *J. Clean. Prod.*, vol. 13, no. 15, pp. 1471–1491, 2005.

[16] L. Gerber, S. Fazlollahi, and F. Maréchal, “A systematic methodology for the environomic design and synthesis of energy systems combining process integration, Life Cycle Assessment and industrial ecology,” *Comput. Chem. Eng.*, vol. 59, pp. 2–16, 2013.

[17] C. Reinert *et al.*, *Combining optimization and life cycle assessment: Design of low-carbon multi-energy systems in the SecMOD framework*, vol. 51. Elsevier Masson SAS, 2022.

[18] C. Reinert, N. Nolzen, J. Frohmann, D. Tillmanns, and A. Bardow, “Design of low-carbon multi-energy systems in the SecMOD framework by combining MILP optimization and life-cycle assessment,” *Comput. Chem. Eng.*, vol. 172, no. January, p. 108176, 2023.

[19] R. Dufo-López, I. R. Cristóbal-Monreal, and J. M. Yusta, “Optimisation of PV-wind-diesel-battery stand-alone systems to minimise cost and maximise human development index and job creation,” *Renew. Energy*, vol. 94, pp. 280–293, 2016.

[20] Z. Ullah, M. R. Elkadeem, K. M. Kotb, I. B. M. Taha, and S. Wang, “Multi-criteria decision-making model for optimal planning of on/off grid hybrid solar, wind, hydro, biomass clean electricity supply,” *Renew. Energy*, vol. 179, pp. 885–910, 2021.

[21] R. Hassan, B. K. Das, and M. Hasan, “Integrated off-grid hybrid renewable energy system optimization based on economic, environmental, and social indicators for sustainable development,” *Energy*, vol. 250, p. 123823, 2022.

[22] I. Mariuzzo, D. Fioriti, E. Guerrazzi, D. Thomopulos, and M. Raugi, “Multi-objective planning method for renewable energy communities with economic, environmental and social goals,” *Int. J. Electr. Power Energy Syst.*, vol. 153, no. March, p. 109331, 2023.

[23] T. Adefarati, R. C. Bansal, T. Shongwe, R. Naidoo, M. Bettayeb, and A. K. Onaolapo, “Optimal energy management, technical, economic, social, political and environmental benefit analysis of a grid-connected PV/WT/FC hybrid energy system,” *Energy Convers. Manag.*, vol. 292, no. June, p. 117390, 2023.

[24] P. Dasgupta, *The Economics of Biodiversity : the Dasgupta Review.*, vol. 28, no. 1. 2021.

[25] S. F. Bernstein, *THE COMPROMISE OF LIBERAL ENVIRONMENTALEM*, vol. 699, no. 499. 2001.

[26] G. H. Brundtland, “Our Common Future: Report of the World Commission on Environment and Development,”

United Nations Gen. Assem. Doc. A/42/427, 1987.

[27] United Nations, “Transforming Our World: The 2030 Agenda for Sustainable Development. Resolution Adopted by the General Assembly on 25 September 2015,” *A/RES/70/1*, 2015.

[28] eurostat, “Glossary:Gross domestic product (GDP).” [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Gross_domestic_product_(GDP).

[29] eurostat, “Glossary:Greenhouse gas (GHG).” [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Greenhouse_gas_(GHG).

[30] Europen Commission, “Stepping up Europe’s 2030 climate ambition Investing in a climate-neutral future for the benefit of our people,” *J. Chem. Inf. Model.*, vol. 53, no. 9, pp. 1–25, 2020.

[31] I. PARRY, “Five Things to Know about Carbon Pricing.” [Online]. Available: https://www.imf.org/en/Publications/fandd/issues/2021/09/five-things-to-know-about-carbon-pricing-parry.

[32] M. Grömling, M. Koenen, G. Kunath, T. Obst, and S. Parthie, “Deindustrialisation - A European Assessment,” *Intereconomics*, vol. 58, no. 4, pp. 209–214, 2023.

[33] L. Forni, *Net Zero*. Il Mulino, 2023.

[34] S. Managi and P. Kumar, “Inclusive Wealth Report 2018 (Open Access): Measuring Progress Towards Sustainability,” pp. 3–52, 2018.

[35] UNEP (UN Environment Programme), “INCLUSIVE WEALTH REPORT 2023,” 2023.

[36] American Association for the Advancement of Science (AAAS), “Inclusive Wealth Index shows more than half of countries ‘consuming beyond their means.’” [Online]. Available: https://www.eurekalert.org/news-releases/873578.

[37] P. Dasgupta, S. Managi, and P. Kumar, “The inclusive wealth index and sustainable development goals,” *Sustain. Sci.*, vol. 17, no. 3, pp. 899–903, 2022.

[38] E. Dal Cin, G. Carraro, A. Lazzaretto, and G. Tsatsaronis, “Optimization of the Design and Operation of Multi-Energy Systems Integrated With Energy Networks: Retrofit Design Problem,” *Proc. ASME 2023 Int. Mech. Eng. Congr. Expo.*, 2023.

[39] E. Dal Cin, G. Carraro, A. Lazzaretto, and G. Tsatsaronis, “Optimizing the Retrofit Design and Operation of Multi-Energy Systems Integrated With Energy Networks,” *J. Energy Resour. Technol. Trans. ASME*, vol. 146, no. 4, 2024.

[40] Pré, “Simapro Database Manual,” 2023.

[41] PRé Sustainability, “SimaPro Tutorial,” *SimaPro*, no. 5.3, p. 89, 2023.

[42] DEA - Danish Energy Agency, “Technology Data sheet for Electricity and district heating production updated February 2024.” [Online]. Available: https://ens.dk/en/our-services/technology-catalogues.

[43] DEA - Danish Energy Agency, “datasheet for energy storage, updated September 2023.”

[44] Eurostat, “Electricity prices for household consumers - bi-annual data (from 2007 onwards).” [Online]. Available: https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_204__custom_10713435/default/table?lang=en.

[45] European Commission, Rademaekers, K., Smith, M., Demurtas, A. et al., “Study on energy prices, costs and their impact on industry and households – Final report,” *Publ. Off.*, 2020.

[46] Eurostat, “Gas prices for household consumers - bi-annual data (from 2007 onwards).”

[47] Internationl Energy Agency (IEA), “Energy system of Italy.” [Online]. Available: https://www.iea.org/countries/italy.

[48] Terna S.p.A., “Dati statistici sull’energia elettrica in Italia - 2021,” pp. 5–9, 2022.

[49] IEA Technology Collaboration Programmes, “Sensible Heat Storage for Low Temperatures (up to 150 °C).” [Online]. Available: https://iea-es.org/fact-sheet_sensible-water/.

[50] “Tesla Powerwall 2 datasheet.” [Online]. Available: https://digitalassets.tesla.com/tesla-contents/image/upload/powerwall-2-ac-datasheet-en-na_001.

[51] “Powerwall Waranty.” [Online]. Available: https://static1.squarespace.com/static/655ca2b0f826bb7b2b4dfe90/t/656883d60072797e4f0ff843/1701348310916/Powerwall_2_AC_Warranty_AUS-NZ.pdf.

[52] R. Deng, N. L. Chang, Z. Ouyang, and C. M. Chong, “A techno-economic review of silicon photovoltaic module recycling,” *Renew. Sustain. Energy Rev.*, vol. 109, no. January, pp. 532–550, 2019.

[53] IRENA (International Renewable Energy Agency), *Renewable Energy: A Gender Perspective*. 2019.

[54] S. Sala, E. Crenna, M. Secchi, and E. Sanyé-Mengual, “Environmental sustainability of European production and consumption assessed against planetary boundaries,” *J. Environ. Manage.*, vol. 269, no. May, 2020.

Appendix: The Inventories and Results of LCA

Calculation:	Compare
Results:	Impact assessment
Product 1:	0.105161 kWh Electricity, high voltage {IT}| electricity production, hydro, run-of-river | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 2:	0.053042 kWh Electricity, high voltage {RoW}| ethanol production from wood | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 3:	0.096272 kWh Electricity, high voltage {IT}| electricity production, lignite | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 4:	0.054366 kWh Electricity, high voltage {IT}| electricity production, oil | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 5:	0.484505 kWh Electricity, high voltage {IT}| electricity production, natural gas, combined cycle power plant | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 6:	0.020329 kWh Electricity, high voltage {IT}| electricity production, deep geothermal | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 7:	0.016176 kWh Electricity, for reuse in municipal waste incineration only {IT}| treatment of municipal solid waste, incineration | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 8:	0.071857 kWh Electricity, high voltage {IT}| electricity production, wind, >3MW turbine, onshore | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 9:	0.09829 kWh Electricity, low voltage {IT}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 10:	1 kWh Heat, central or small-scale, natural gas {Europe without Switzerland}| heat and power co-generation, natural gas, 50kW electrical, lean burn | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 11:	1 kWh Electricity, low voltage {Europe without Switzerland}| heat and power co-generation, natural gas, 50kW electrical, lean burn | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 12:	1 kWh Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler condensing modulating <100kW | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 13:	0.0095238 p Photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof {RoW}| photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 14:	0.0008 p Heat and power co-generation unit, 50kW electrical, components for heat only {RER}| construction | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 15:	0.0008 p Heat and power co-generation unit, 50kW electrical, components for electricity only {RER}| construction | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 16:	0.0008 p Heat and power co-generation unit, 50kW electrical, common components for heat+electricity {RER}| construction | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 17:	0.004 p Gas boiler {RER}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 18:	0.001333333 p Heat pump, 30kW {RER}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 19:	0.000208333 p Heat storage, 2000l {RoW}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 20:	0.4222 kg Battery, Li-ion, rechargeable, prismatic {GLO}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 21:	4.16E-12 p Gas boiler {RER}| production | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 22:	6.77E-11 p Heat and power co-generation unit, 50kW electrical, components for electricity only {RER}| construction | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 23:	6.77E-11 p Heat and power co-generation unit, 50kW electrical, common components for heat+electricity {RER}| construction | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 24:	3.76E-11 p Heat and power co-generation unit, 50kW electrical, components for heat only {RER}| construction | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Product 25:	3.76E-11 p Heat and power co-generation unit, 50kW electrical, common components for heat+electricity {RER}| construction | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit)
Method:	ReCiPe 2016 Endpoint (H) V1.07 / World (2010) H/A
Indicator:	Weighting

Damage category	Total	Human health	Ecosystems	Resources
Unit	Pt	Pt	Pt	Pt
Electricity, high voltage {IT}| electricity production, hydro, run-of-river | Cut-off, U	2.65859E-05	2.57863E-05	5.9269E-07	2.06889E-07
Electricity, high voltage {RoW}| ethanol production from wood | Cut-off, U	0.000458327	0.000397943	5.46243E-05	5.7592E-06
Electricity, high voltage {IT}| electricity production, lignite | Cut-off, U	0.014380476	0.014203764	0.000175662	1.05024E-06
Electricity, high voltage {IT}| electricity production, oil | Cut-off, U	0.002689508	0.002550061	8.16121E-05	5.7835E-05
Electricity, high voltage {IT}| electricity production, natural gas, combined cycle power plant | Cut-off, U	0.004639082	0.004232511	0.000194211	0.00021236
Electricity, high voltage {IT}| electricity production, deep geothermal | Cut-off, U	7.97407E-05	7.72714E-05	1.97132E-06	4.9802E-07
Electricity, high voltage {IT}| electricity production, wind, >3MW turbine, onshore | Cut-off, U	0.000263977	0.000257954	4.91352E-06	1.10914E-06
Electricity, low voltage {IT}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | Cut-off, U	0.000463864	0.000443556	1.7202E-05	3.10531E-06
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat and power co-generation, natural gas, 50kW electrical, lean burn | Cut-off, U	0.002453847	0.002256018	0.000101495	9.6334E-05
Electricity, low voltage {Europe without Switzerland}| heat and power co-generation, natural gas, 50kW electrical, lean burn | Cut-off, U	0.014975845	0.013768496	0.000619422	0.000587927
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler condensing modulating <100kW | Cut-off, U	0.005354355	0.004913442	0.000216981	0.000223931
Photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof {RoW}| photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof | Cut-off, U	5.34537986	5.192433764	0.121537551	0.031408545
Heat and power co-generation unit, 50kW electrical, components for heat only {RER}| construction | Cut-off, U	0.463307772	0.450788715	0.009628249	0.002890808
Heat and power co-generation unit, 50kW electrical, components for electricity only {RER}| construction | Cut-off, U	0.509527369	0.498846094	0.008690745	0.00199053
Heat and power co-generation unit, 50kW electrical, common components for heat+electricity {RER}| construction | Cut-off, U	1.398031853	1.350591363	0.037527401	0.009913089
Gas boiler {RER}| production | Cut-off, U	0.233810614	0.229494043	0.003487906	0.000828665
Heat pump, 30kW {RER}| production | Cut-off, U	0.555645348	0.544518794	0.009790999	0.001335554
Heat storage, 2000l {RoW}| production | Cut-off, U	0.018207406	0.01779764	0.000316734	9.30325E-05
Battery, Li-ion, rechargeable, prismatic {GLO}| production | Cut-off, U	0.575960552	0.565526532	0.008583798	0.001850223
Gas boiler {RER}| production | Cut-off, U	2.43163E-10	2.38674E-10	3.62742E-12	8.61812E-13
Heat and power co-generation unit, 50kW electrical, components for electricity only {RER}| construction | Cut-off, U	4.31188E-08	4.22149E-08	7.35454E-10	1.68449E-10
Heat and power co-generation unit, 50kW electrical, common components for heat+electricity {RER}| construction | Cut-off, U	1.18308E-07	1.14294E-07	3.17576E-09	8.38895E-10
Heat and power co-generation unit, 50kW electrical, components for heat only {RER}| construction | Cut-off, U	2.17755E-08	2.11871E-08	4.52528E-10	1.35868E-10
Heat and power co-generation unit, 50kW electrical, common components for heat+electricity {RER}| construction | Cut-off, U	6.57075E-08	6.34778E-08	1.76379E-09	4.65915E-10