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ENHANCING SUSTAINABILITY
IN ENERGY MODELLING:
INTEGRATING KEY
INDICATORS INTO OSeMOSYS
FOR MEDIUM TO LARGE
SCALE ENERGY PLANNING

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SANTIAGO DE COMPOSTELA

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Table of contents

Table of contents.....	ii
Index of Figures.....	iv
Index of Tables.....	v
List of Acronyms	vi
Summary.....	1
Resumen.....	6
Resumo.....	12
Chapter 1. Introduction	18
1.1. Sustainable development.....	19
1.2. Sustainability Assessment	20
1.3. Nexus: A guide to resource management	21
1.4. Climate, Land, Energy, and Water (CLEWs) System Framework	22
1.5. Open Source Energy Modelling System (OSeMOSYS)	24
1.5.1. Core Objective of OSeMOSYS	24
1.5.2. Exploring Energy Scenarios: Leveraging OSeMOSYS for Analysis	25
1.5.3. Reference Energy System.....	25
1.5.4. Structure model of OSeMOSYS.....	26
1.5.5. OSeMOSYS Optimization Function	28
1.6.2. The temporal and spatial range of the case study	33
1.6.3. Electric Demand Side Management	34
1.6.4. Working Hypothesis	34
1.6.5. Post-optimization: Selection of the output results merit variables.....	37
1.7. Developing Insight Through Optimization: Example of Atlantis Standard Economic Optimization (Op_Standard).....	38
1.8. Chapter Conclusions.....	39
Chapter 2. Objectives.....	41
Chapter 3. Methodologies.....	44
Chapter 4. Implementation of the Sustainability Indicators as OSeMOSYS Optimization Functions	49
4.1. Introduction	50
4.2. Sustainability indicators	50
4.3. Embracing the cradle-to-cradle Paradigm towards a holistic TSA.....	53
4.4. Sustainability indicator Dimensional Focus	53
4.4.1. Energetic sustainability indicator (EPBT)	54
4.4.2. Economic sustainability indicator (ITR).....	55
4.4.3. Environmental Sustainability Indicator (IMPcc).....	55
4.5. Integrating Sustainability Indicators into OSeMOSYS Energy Modelling	57
4.6.1. Energetic Sustainability Indicator (EPBT) Implementation.	59
4.6.1.1. Effect of the EPBT in the Atlantis energetic framework	59
4.6.1.2. EPBT Optimization Results Presentation	61
4.6.2. Economic Sustainability Indicator Implementation.....	62
4.6.2.1. Effect of the ITR in the Atlantis energetic framework	63
4.6.2.2. ITR Optimization Results Presentation	65

4.6.3 Environmental Sustainability Implementation	66
4.6.3.1. Effect of the IMPcc in the Atlantis energetic framework	68
4.6.4 Sustainability Index Optimization Function	71
4.6.4.1. Effect of the Sus_Op_index: Optimization Results	72
4.7. Chapter Conclusions.....	74
Chapter 5. Optimizing Sustainability Criteria in Convolution	75
5.1. Introduction	77
5.2. Two-by-Two sustainability indicator convolution	78
5.2.1. Analytic Results.....	78
5.3. Sustainability indicators correlation matrix.....	84
5.3.1. Methodology.....	84
5.3.2. Results	86
5.3.2.1. Correlations matrix coefficients: Energetic production as constraint set	87
5.3.2.2. Correlations matrix coefficients: Energetic production and Emission as constraint set... ..	87
5.3.2.3. Correlations matrix coefficients: Economic cost as constraint set.....	88
5.3.2.4. Correlations matrix coefficients: with Economic cost and energetic production as constraint set.	88
5.3.2.5. Correlations matrix coefficients: Economic Cost and Emission as constraint set.....	88
5.3.3. Decision Table design.....	89
5.4. Chapter Conclusions.....	91
Chapter 6. Decision-making in Sensitive Energy Sectors through the Integration of Sustainability Indicators	93
6.1. Introduction	95
6.2. Sustainability of nuclear energy	95
6.2.1. Sustainability optimization scanning on Nuclear useful lifetime.	98
6.2.2. Energetic optimization results (Op_EPBT)	98
6.2.3. Economic optimization results (Op_ITR).....	100
6.3. Carbon Pricing Mechanisms: Catalysts for Advancing Sustainable Energy Transition	101
6.4. Solar PV sustainability as a function of the climate conditions.....	105
6.4.1. Sustainability of Solar PV as a function of the climate conditions	108
6.5. Chapter Conclusions.....	112
Chapter 7. Conclusions.....	114
To be done.....	117
Appendix A: OSeMOSYS features (Set, Parameters and Variables).	118
Appendix B: Merits Variables.....	120
B.1 Global Energy production.....	120
B.2 Rate of energy production per energy category (RoP).....	120
B.2 Output Costs Components	120
B.3 Output Global Costs and electricity price.....	120
B.3 Output Emissions Component	121
Appendix C: OSeMOSYS Code in GNU MathProg.....	122
References.....	127
Figure Authorship and permission for Reproduction.....	137
Table Authorship and permission for Reproduction.....	139
Diffusion of results	140

Index of Figures

Figure 1.1 The three pillars of sustainability	20
Figure 1.2 Sustainable Development Goals 2030 (SDGs) wedding cake from Azote Images for Stockholm Resilience Centre, 2016. Rockström, J.; Sukhdev, P. How food connects all the SDGs. opening keynote speech at the 2016 EAT Forum	22
Figure 1.3 CLEWs definition and context.....	23
Figure 1.4 Atlantis Reference Energy System	33
Figure 1.5 Atlantis power load considered for the analysis: (a) Daily electricity demand; (a) Annual electricity demand; (b) Percentage of demand per sector.	35
Figure 1.6 Op_Standard: Annual energy production per technology.....	39
Figure 4.1 Lifetime stages diagram	53
Figure 4.2 Variable Cost: Impact of Standard and Extra Costs on Each Technology in the Atlantis RES.	61
Figure 4.3 Op_EPBT: Annual energy production per technology.	62
Figure 4.4 Capital Cost: Impact of Standard and Extra Costs on Each Technology in the Atlantis RES.....	64
Figure 4.5 Op_ITR: Annual energy production per technology	65
Figure 4.6 Emission Cost: Impact of Standard and Extra Costs on Each Technology in the Atlantis RES	69
Figure 4.7 Op_IMPcc: Annual energy production per technology	70
Figure 4.8 Global Cost: Impact of Standard and Extra Costs on Each Technology in the Atlantis RES	72
Figure 4.9 Op_SusIndex: Annual energy production per technology	73
Figure 5. 1 Percentage of variations in comparison to the Op_Standard for renewable energy source category for each sustainable optimization function.	80
Figure 5. 2 Percentage of variations in comparison to the Op_Standard for fossil fuels-based technology for each sustainable optimization function.	80
Figure 5. 3 Percentage of variations in comparison to the Op_Standard for nuclear energy source category for each sustainable optimization function.	81
Figure 5. 4 Percentage of variations of the global emissions level in comparison to the standard optimization function for each sustainable optimization function.	82
Figure 5. 5 Percentage of variations of the global cost features in comparison to the standard optimization function for each sustainable optimization function.....	82
Figure 5. 6 Energy production per technology in 3 optimization function scenarios integrating two-by-two sustainability indicators : a)Op_EPBT_ITR; b) Op_EPBT_IMPcc; c) Op_ITR_IMPcc.....	83
Figure 5.7 Comparison of the person correlation coefficient for each set of constraint between the sustainability indicators.	89
Figure 6.1 Schematic of the nuclear fuel lifetime stages	96
Figure 6.2 Annual energy production per technology, (a): Op_EPBT (nuclear in door-to-door); (b): Op_EPBT (nuclear in cradle-to-door).....	99
Figure 6.3 Annual energy production per technology, (a): Op_ITR (nuclear in door-to-door); (b): Op_ITR (nuclear in cradle-to-door)	100
Figure 6.4 Comparative Analysis of Global Costs and Emissions Relative to Op_Standard: The Impact of Carbon Tax Levels (\$30/t CO ₂ , \$50/t CO ₂ , \$100/t CO ₂ , and \$200/t CO ₂) in Op_IMPcc Optimization.	104
Figure 6.5 Projection of the cumulative PV installed Capacity; in the Graph, CAGR represents the compound annual growth rate.....	105
Figure 6.6 Solar technologies capacity factor for different irradiation levels	107
Figure 6.7 Global Solar CF in line with the Köppen-Geiger climate classification.....	108
Figure 6.8 Percentage of differences of the Op_EPBT against the Op_Standard.....	109
Figure 6.9 Op_EPBT_IMPcc. Yearly distribution of the energetic production differentiated by technologies. (a) PV CF=10%; (b) PV CF=20%; (c) PV CF=30%; (d) CF=40%; (e) CF=50%; (f) CF=60%	111
Figure 6. 10 Contribution rate per Daily type of each energy category for each PV CF at the Op_EPBT_ITR	112

Index of Tables

Table 1.1 Atlantis Time Slice set	33
Table 1.2 Key input parameters: economic cost, emission activity, and useful lifetime	35
Table 1.3 Capacity factor for each technology in each of the defined time slices	36
Table 1.4 Op_Standard: Details of the merit variables	39
Table 4.1 Key environmental indicators relevant to technology sustainability assessment.	51
Table 4.2 Key energetic indicators relevant to technology Sustainability assessment.	51
Table 4.3 Key social indicators relevant to technology sustainability assessment.	52
Table 4.4 Key economic indicators relevant to technology sustainability assessment.	52
Table 4.5 EPBT and FEPBT values associated with the Atlantis technologies.	60
Table 4.6 Op_EPBT; Output optimization results: Details of the merit's variables.	61
Table 4.7 ITR and FITR values associated with the Atlantis technologies	64
Table 4.8 Op_ITR: Details of the merit's variables	65
Table 4.9 FIMPcc values associated with the Atlantis technologies	68
Table 4.10 Op_IMPcc: Details of the merit's variables	70
Table 4.11 Modulation Weight setting associated with the integration of the sustainability indicators.	72
Table 4.12 Op_SusIndex: Details of the merit's variables	73
Table 5.1 Modulation Weight setting associated with the convolution of the sustainability indicators	78
Table 5.2 Details of the merit's variables of the Op_EPBT_ITR, Op_EPBT_IMPcc and Op_ITR_IMPcc	79
Table 5.3 Details of the merit's variables of the Op_Standard, Op_EPBT, Op_ITR, Op_IMPcc and Op_SusIndex	79
Table 5.4 Decision table detailing the behaviour of each indicator across various sets of constraints. (The upward arrows indicate a high influence of the indicators on achieving the proposed goals, whereas the downward arrows suggest the opposite. In the case of In the case of slanted arrows, the influence is not definitive and should be analysed in each specific case)	90
Table 6.1 EPBT, FEPBT ITR, and FITR values associated with the nuclear lifetime Stage.	98
Table 6.2 Modulation Weight setting associated with the different optimization functions under each optimization.	98
Table 6.3 Details of the merit's variables of the Op_EPBT (cradle-to-door) and Op_EPBT (door-to-door)	98
Table 6.4 Details of the merit's variables of the Op_ITR (cradle-to-door) and Op_ITR (door-to-door)	100
Table 6.5 Details of the merit's variables of the Op_IMPcc with emission penalty of \$30, \$50, \$100, and \$200/t CO ₂ eq ...	104
Table 6.6 Detail of the energetic production of the Op_EPBT_ITR for each of the studied PV CF	110
Table A.1 Sets in OSeMOSYS	118
Table A.2 Main parameters and variables	119

List of Acronyms

EPBT	Energetic Payback Time
ITR	Internal Time of Return
NPV	Net Present Value
TSA	Technological Sustainability Assessment
OSeMOSYS	Open Source energy Modelling System
IMPcc	Impact mitigation in term of climate change
OCF_t	Operating Cash Flow at time t
EMat	Energy used for materials extraction.
EManuf	Energy used for manufacturing.
ETrans	Energy used for transportation.
EInst	Energy used for installation.
EEOL	Energy required for dismantling at the end of life.
Ep	Annual energy output
η_t	Technology efficiency
EAgen	Annual energy generation
EO&M	Annual energy demand for operation and maintenance
ULT	Useful lifetime of a technology
MDGs	Millennium development goals
SDGs	Sustainable development goals
CLEWs	Climate-Land-Energy-Water
WEF	Water-Energy-Food
TBL	Tripple bottom line
PJ	Peta-joule
RoP	Rate of Energy production (%)
NGSC	Natural gas steam turbine energy generation technology
DSGC	Diesel Generator energy generation technology
IGCC	Integrated Gasification Coal energy generation technology
HFSC	Heavy Fuel oil energy generation technology
Diesel_Gen	Distributed Diesel energy generation technology
NGCC	NEW Combined Cycle Gas Turbine energy generation technology
Hydro_Dam	Large Hydro energy generation technology
Hydro_Min	Mini Hydro energy generation technology
PV	Photovoltaic Utility Grid energy generation technology
Wind	Wind energy generation technology
Nuclear	Nuclear energy generation technology

Summary

Sustainable development has emerged as a critical global imperative as societies navigate the challenges of modernization and industrialization. It is increasingly acknowledged that balancing these objectives is essential for ensuring a viable and fair future for generations to come. This recognition is particularly evident in the context of addressing climate change through initiatives such as the Millennium Development Goals (MDGs) and the subsequent adoption of the Sustainable Development Goals (SDGs) by the United Nations, which underscore the global commitment to combating poverty and advancing sustainability agendas.

Central to addressing climate change is the urgent imperative to transition towards clean energy systems and embrace sustainable energy planning practices. However, the complexity inherent in energy systems, which comprise interconnected elements such as power generation facilities, transmission networks, and end-user sectors, poses a formidable challenge. Alterations in one component can yield unforeseen consequences throughout the system, further complicating the energy transition process and presenting decision-makers with myriad challenges, particularly in the pursuit of sustainability objectives.

Effective energy planning plays a pivotal role in facilitating the transition towards sustainable energy across diverse scales. This entails the analysis, design, and optimization of strategies, taking into account various factors including energy demand, resource availability, technological options, environmental considerations, and socioeconomic dynamics. The integration of energy modelling tools into planning processes for short, medium, and long-term projections serves to enhance decision-making capabilities, streamline the identification of optimal pathways, and bolster the development of resilient energy systems. A wide array of modelling tools exists for energy planning, providing structured and quantitative insights into diverse energy scenarios. These tools leverage advanced computing capabilities, accommodate multi-objective optimization constraints, and incorporate multiple parameters, thereby expediting the transition to sustainable energy.

Since the adoption of the sustainability paradigm, the imperative to integrate sustainability-based decision-making has become increasingly pronounced. Decision-making processes, particularly in the energy sector, must incorporate sustainability considerations to align with global commitments, such as those outlined in the Paris Agreement. This requires decision-makers to adopt holistic sustainability approaches within their modelling tools that balance immediate outcomes with long-term implications, thereby fostering resilience and adaptability in systems ranging from energy infrastructure to urban planning.

Existing energy modelling tools primarily focus on economic optimization to meet the requirements of economic entities and policymakers leading energy transitions. However, relying solely on economic optimization is insufficient for comprehensive energy planning. Incorporating sustainability criteria into these tools is essential for addressing the multifaceted challenges of energy planning.

Consider a scenario where OSeMOSYS serves as the analytical backbone for assessing the energy dynamics of a medium-sized entity keen on bolstering its sustainability and resilience. In this context, users meticulously input data pertaining to energy demand, available supply options, and prevailing infrastructure constraints. This process allows the modelling of diverse scenarios, each offering insights into their feasibility, cost-effectiveness, and environmental implications across short- and medium-term timeframes.

On a broader scale, such as national or regional energy planning, OSeMOSYS becomes an invaluable tool for transitioning towards cleaner and more sustainable energy systems. By considering a country's unique energy landscape including its resource endowment, energy demand profile, regulatory framework, and socioeconomic context OSeMOSYS enables policymakers to explore diverse pathways for achieving energy security, affordability, and environmental sustainability over the long term. This could involve assessing the optimal mix of energy sources, grid expansion strategies, policy interventions, and investment priorities to align with national development goals and international climate commitments.

The distinction between medium-scale and large-scale energy planning lies in the breadth and complexity of available energy resources, which influence scenario development and optimization strategies. At the medium scale, the focus typically revolves around a limited set of energy resources, where standard optimization techniques often guide decision-making effectively. Parameters such as production limitations or emission constraints are pivotal in shaping optimization outcomes, steering them towards energy trajectories. Conversely, large-scale energy planning encompasses a broader array of energy resources, presenting a more intricate landscape for decision-makers. This complexity is particularly pronounced in sectors deemed sensitive, where strategic choices can have far-reaching societal and environmental implications.

This study aims to address a significant limitation in current energy modelling and transition tools: their inadequate consideration of sustainability criteria. Specifically, it seeks to enhance the capability of OSeMOSYS, by integrating key sustainability indicators into its optimization function. By doing so, the study endeavors to improve the model's capacity to support sustainable energy planning applicable for medium to large scale energy planning, reflecting a broader commitment to the responsible stewardship of natural resources and the well-being of both current and future generations.

The added value of this work lies in the incorporation of widely used sustainability indicators into the OSeMOSYS objective function. Specifically, the sustainability indicators integrated into the model include energetic sustainability, quantified by the Energy Payback Time (EPBT); economic sustainability, measured by the Internal Time of Return (ITR); and environmental sustainability, evaluated through the Impact Mitigation in terms of Climate Change (IMPcc). By incorporating these indicators and their convolution, the model provides a more comprehensive framework for measuring the sustainability of different energy scenarios, guiding decision-making towards more sustainable outcomes.

The incorporation of sustainability indicators into the OSeMOSYS objective function presents a unique challenge, as these indicators are measured in different units. The objective function traditionally encompasses various costs, including investment, maintenance expenses, variable costs, and emissions cost, all expressed in cost units. In contrast, sustainability indicators such as the EPBT and ITR are measured in years, while the IMPcc is quantified in CO₂ equivalent tons. To integrate these indicators seamlessly into the primary objective function in OSeMOSYS, each must be standardized into economic terms.

To address this challenge, the proposed approach converts each sustainability indicator into economic terms and incorporates them as extra cost factors within the objective function. This transformation ensures that the optimization algorithm prioritizes features aligning with sustainability objectives, albeit without directly affecting the overall cost of the optimized energy mix. Although this functionality is not inherent in OSeMOSYS, it has been integrated into the core code to enhance the software's capabilities. This enhancement, while potentially increasing computational demands, aims to provide decision-makers with valuable insights for achieving sustainable energy outcomes.

To evaluate the feasibility of integrating sustainability assessments into OSeMOSYS, the proposed methodology was implemented in a test case study within the Atlantis a pre-built

energy framework. This framework is specifically designed to validate methodologies and facilitate controlled assessments of their reproducibility. The study also aimed to determine the degree of correlation among the sustainability indicators and to demonstrate the utility of the developed methodology by addressing pertinent questions of significant relevance in contemporary discourse.

Atlantis, characterized by a diverse array of technologies, including renewable, non-renewable, and nuclear energies, serves as a robust platform for testing new methodologies and ensuring result reproducibility among OSeMOSYS users. By leveraging this diverse energy landscape, the study effectively showcases the practicality and effectiveness of integrating sustainability indicators into the OSeMOSYS model, thereby providing valuable insights into sustainable energy planning.

After integrating sustainability factors into the optimization function, we assessed the degree to which the convolution of these factors is necessary and sufficient through an analysis of the correlation matrix. Finally, we validated the utility of our work by addressing three critical issues in the actual context of sustainable energy transition: the sustainability level of nuclear technology within the energy system, the efficacy of escalating penalties for carbon emissions, and the sustainability of solar energy as a representative of intermittent production sources based on local resource availability. To address the challenges outlined, the present document is structured as follows:

Chapter 1 provides a comprehensive context analysis, beginning with an exploration of fundamental definitions and principles of sustainable development. It delves into the historical evolution of the concept, tracing its trajectory in response to shifting societal, environmental, and economic paradigms. Emphasis is placed on the multifaceted nature of sustainable development and the diverse perspectives that inform its conceptualization, underscoring the imperative of integrated resource management as the ultimate pathway to ensure sustainability.

Within this chapter, the NEXUS framework approach is discussed, highlighting its significance in addressing sustainability challenges through an integrated lens that considers essential resources holistically. Central to this approach is the Water-Energy-Food (WEF) NEXUS, which underscores the interconnectedness of vital resources and emphasizes the necessity of holistic planning and decision-making for sustainable transitions.

The discussion extends to the development of analytical methods and tools, with particular focus on the Climate-Land-Energy-Water (CLEWs) framework, renowned for its comprehensive approach to managing interconnected systems. Following this, the chapter provides an overview of the OSeMOSYS energy modelling tool, a key tool of the CLEWs framework utilized in this thesis. Details regarding its operational principles, parameters, variables, and the core code of its objective function are elucidated, alongside features such as MoMani, a working interface integral to the study.

Subsequently, the Atlantis energy framework used as case study in this work is introduced, with a focus on the representation of energy technologies and clarification of key input parameters and assumptions defining scenarios. These encompass projections of energy demand, resource availability, and imposed constraints.

Among the multitude of potential outcomes following post-optimization, this thesis focuses on three primary merit variables to present the results. Energetic production delineates the output across renewable technologies, fossil fuels, and nuclear energy sectors. Economic costs encompass three key components: capital costs, fixed costs, and variable costs. Emissions quantify the levels of pollutants released as a result of energy production activities.

The chapter culminates in the presentation of results obtained through post-optimization conducted exclusively through OSeMOSYS's economic optimization function within the Atlantis energetic framework. This segment provides the reader with invaluable insights into

the outcomes of the study, acquainting them with the particular manner of results presentation adopted throughout the thesis.

The significance of the OSeMOSYS's economic optimization function results cannot be overstated, as they serve as a foundational benchmark against which the impacts of novel initiatives are evaluated in the forthcoming feasibility study in Chapter 4. This chapter is dedicated to present the methodology employed in incorporating sustainability indicators as optimization functions within OSeMOSYS. Its objective is to assess the effects of these indicators on energy system optimization. The findings of this chapter are published in the Energy Strategy Reviews journal under the title "Effect of Sustainability Indicators within OSeMOSYS Optimization Transition Scenarios, Volume 54, July 2024, 101448 DOI: <https://doi.org/10.1016/j.esr.2024.101448>.

Beginning with a thorough literature review, the chapter acquaints readers with commonly used sustainability indicators for evaluating energy-related technologies. Subsequently, a detailed overview of the specific sustainability indicators utilized in the study is provided, encompassing EPBT, ITR, and IMPcc. The methodology for incorporating these indicators into the OSeMOSYS optimization objective function as extra costs is outlined, emphasizing the flexibility of the process to accommodate removal when deemed unnecessary.

EPBT is integrated into the Variable cost function by introducing a non-dimensional correction factor, F_{EPBT} , aiming to promote the deployment of technologies with EPBTs below their useful lifetime (ULT). Similarly, ITR is linked to the Capital or Investment Cost function through a non-dimensional correction factor, F_{ITR} , with the objective of promoting technologies with ITRs below their ULT. IMPcc is tied to the Emission Cost function, supplemented by a non-dimensional correction factor, F_{IMPcc} , to incentivize emissions reduction.

This chapter thoroughly examines the impact of sustainability indicators on individual decision-making processes. However, achieving sustainable development sometimes requires a comprehensive consideration of the integrated facets of these indicators. Therefore, an analysis evaluating the convolution of the three sustainability indicators with the aim of uncovering discernible trade-offs among sustainability objectives. This approach reflects efforts to balance and comprehensively fulfil each defined sustainability goal, providing a nuanced understanding of how these indicators interact and influence overall decision-making.

Furthermore, the application of sustainability criteria often leads to increased overall costs. Thus, it is essential to adopt specific sustainability criteria tailored to address specific goals based on the decision-maker's objectives. This approach helps eliminate unnecessary criteria and achieve a better balance between sustainability goals and costs.

Nevertheless, further investigation into the complexities of sustainability assessment is warranted to identify major trade-offs and compromises among sustainability indicators depending on the decision-maker's objectives. Along we identified in Chapter 4 that no single indicator can effectively achieve specific sustainability goals, such as reaching energy neutrality with short payback periods.

Therefore, we have defined and evaluated a sustainable optimization function, termed Op_SusIndex, which integrates multiple indicators to comprehensively assess sustainability. The outcome raises a critical question regarding the operational dynamics of these indicators whether these indicators work independently, capturing unique aspects of sustainability, or if they are interrelated, potentially leading to double counting. This aspect holds particular significance due to the fact that integrating sustainability criteria frequently escalates the overall costs linked with the energy transition process. Chapter 5 aims to address this issue.

In this context, optimizing decision-making holds paramount importance. It is imperative to identify the essential criteria required to attain desired outcomes while mitigating redundant requirements that may exacerbate economic pressures. Therefore, it is crucial to thoroughly

examine and quantify the potential interrelationships between the proposed sustainability indicators.

Our methodology involves several steps. Initially, we will scrutinize the raw data obtained from the preceding chapter to discern overarching trends. Subsequently, we will conduct a more in-depth analysis by quantifying significant effects through a correlation matrix utilizing Pearson's method.

Through this quantitative examination, Pearson coefficients will furnish insights into the degree of correlation between indicators, elucidating the extent of overlap between the effects associated with various facets of sustainable development.

The results are published in the International Journal for Research in Applied Science & Engineering Technology (IJRASET) under the title "Sustainability Indicators Correlation Matrix." Vol 12, 2024; ISSN: 2321-9653, DOI: <https://doi.org/10.22214/ijraset.2024.63572>.

Chapter 6 demonstrates the utility of the developed sustainability approach in addressing the intricate landscape of sensitive energy sectors by assessing their sustainability impact using the indicators within OSeMOSYS. Specifically, three pivotal issues have been examined within the framework of the developed sustainability criteria within OSeMOSYS. These issues carry relevance in both public discourse and political deliberations, encompassing the sustainability assessment of nuclear technology, the efficacy of extensive carbon taxes in incentivizing a transition towards environmentally sustainable practices, the sustainability appraisal of solar photovoltaic technology with respect to the climatic conditions.

The results of each analysis have been published in scientific journals. The sustainability assessment of nuclear energy has been published in the Proceedings of the 2nd International Conference on Water Energy Food and Sustainability (ICoWEFS 2022) (pp. 147-157). DOI: 10.1007/978-3-031-26849-6_16. The evaluation of carbon taxes has been published in the International Journal for Research in Applied Science & Engineering Technology (IJRASET), vol. 11. ISSN: 2321-9653; 2023. DOI: 10.22214/ijraset.2023.55662. Additionally, the examination of solar PV sustainability under different climatic conditions is detailed in another paper published in the International Journal for Research in Applied Science & Engineering Technology (IJRASET), vol. 11. ISSN: 2321-9653; 2023. DOI: 10.22214/ijraset.2023.56000.

The General conclusions (Chapter 7) address the extent to which the initial aims and objectives have been achieved in this thesis and summarizes the main findings and contributions. This conclusion ties together the various elements discussed throughout the work and suggests possible directions for future research or practical applications.

The thesis end with a presentation of the References and the Appendix. The References section lists all the sources and literature cited throughout the research, ensuring proper acknowledgment, and providing readers with a pathway to further explore the study's foundational materials. The Appendix includes supplementary material that supports and enhances the main text, such as detailed data sets, additional methodological information, and extended analysis, offering a deeper understanding of the research findings and methodologies employed.

Resumen

A medida en la que las sociedades se plantean enfrentar la modernización e industrialización como nuevos desafíos, el desarrollo sostenible ha emergido como un imperativo global. Cada vez se reconoce más que llegar al compromiso de equilibrar estos objetivos es esencial para asegurar un futuro viable y justo para las generaciones venideras. Este reconocimiento es particularmente evidente en el contexto de abordar el cambio climático a través de iniciativas como los Objetivos de Desarrollo del Milenio (ODM) y la posterior adopción de los Objetivos de Desarrollo Sostenible (ODS) por parte de las Naciones Unidas, que subrayan el compromiso global de combatir la pobreza y avanzar en las agendas de sostenibilidad.

En la lucha contra el cambio climático es crucial e imperativo el tránsito hacia sistemas de energía limpia que permitan adoptar prácticas de planificación energética sostenible. Sin embargo, la complejidad inherente a los sistemas energéticos, que comprenden elementos interconectados como instalaciones de generación de energía, redes de transmisión y sectores de usuarios finales, constituyen un formidable reto. Las alteraciones en un componente pueden generar consecuencias imprevistas en todo el sistema, complicando aún más el proceso de transición energética y presentando a los tomadores de decisiones numerosos desafíos, especialmente en la consecución de los objetivos de sostenibilidad.

En ese sentido, una adecuada planificación energética, resulta imprescindible para lograr una transición hacia una energía sostenible a diferentes escalas. Esto implica el análisis, diseño y optimización de estrategias, teniendo en cuenta diversos factores, incluyendo la demanda de energía, la disponibilidad de recursos, las opciones tecnológicas, las consideraciones ambientales y las dinámicas socioeconómicas.

La integración de herramientas de modelado energético en los procesos de planificación para proyecciones a corto, mediano y largo plazo mejora las capacidades de toma de decisiones, facilita la identificación de rutas óptimas y refuerza el desarrollo de sistemas energéticos resilientes. Existe una amplia gama de herramientas de modelado para la planificación energética, proporcionando conocimientos estructurados y cuantitativos sobre diversos escenarios energéticos. Estas herramientas aprovechan las capacidades avanzadas de computación, acomodan restricciones de optimización multiobjetivo e incorporan múltiples parámetros, acelerando así la transición hacia una energía sostenible.

Desde la adopción del paradigma de la sostenibilidad, la necesidad de integrar la toma de decisiones basada en la sostenibilidad se ha vuelto cada vez más pronunciada. Los procesos de toma de decisiones, particularmente en el sector energético, deben incorporar consideraciones de sostenibilidad para alinearse con los compromisos globales, como los delineados en el Acuerdo de París. Esto requiere que los tomadores de decisiones adopten enfoques holísticos de sostenibilidad dentro de sus herramientas de modelado que equilibren los resultados inmediatos con las implicaciones a largo plazo, fomentando así la resiliencia y adaptabilidad en sistemas que van desde la infraestructura energética hasta la planificación urbana.

Sin embargo, la mayoría de las herramientas de modelado energético existentes se centran en la optimización económica para satisfacer los requisitos de las entidades económicas y los formuladores de políticas que lideran las transiciones energéticas. Sin embargo, basarse únicamente en la optimización económica es insuficiente para una planificación energética integral. Incorporar criterios de sostenibilidad en estas herramientas es esencial para abordar los desafíos multifacéticos de la planificación energética.

El modelo de planificación del sistema energético de código abierto, OSeMOSYS, es una de las herramientas de modelado energético más utilizadas y es un programa lineal multiperiodo y multirregional. Al igual que otros modelos de sistemas energéticos, su enfoque en la optimización económica tiene como objetivo principal determinar la combinación de tecnologías y generación de energía a largo plazo de menor costo. Esto lo logra incorporando parámetros de restricción específicos, lo que permite a los usuarios guiar y controlar los resultados. Este entorno, facilita estudios estratégicos de energía a través de diversas escalas temporales y espaciales, desde evaluaciones a corto plazo hasta esfuerzos de planificación a largo plazo. Su versatilidad permite un amplio intervalo de aplicabilidad en contextos diversos, desde instalaciones de redes energéticas medianas que sirven a pequeños pueblos o sectores industriales, hasta iniciativas a gran escala que abarcan la planificación de transición energética para ciudades enteras, países o incluso bloques regionales compuestos por múltiples naciones.

El diseño de un sistema de referencia adecuado en la herramienta OSeMOSYS sirve como columna vertebral que permite evaluar diferentes dinámicas energéticas de un sistema/ producto que plantee mejorar su sostenibilidad y resiliencia. En este contexto, los usuarios ingresan meticulosamente datos relacionados con la demanda de energía, las opciones de suministro disponibles y las restricciones de infraestructura prevalecientes. Este proceso permite el modelado de diversos escenarios, cada uno ofreciendo perspectivas sobre su viabilidad, rentabilidad y repercusiones ambientales en horizontes de tiempo a corto, medio y largo plazo.

A cualquier escala, desde la planificación energética nacional, regional o local, OSeMOSYS se convierte en una herramienta invaluable para la transición hacia sistemas energéticos más limpios y sostenibles. Al considerar el paisaje energético único de un país, incluyendo su dotación de recursos, perfil de demanda energética, marco regulatorio y contexto socioeconómico, OSeMOSYS permite a los diseñadores de políticas explorar diversas vías para lograr seguridad energética, asequibilidad y sostenibilidad ambiental a largo plazo. Esto podría implicar la evaluación de la combinación óptima de fuentes de energía, estrategias de expansión de la red, intervenciones políticas y prioridades de inversión para alinearse con los objetivos de desarrollo nacional y los compromisos climáticos internacionales.

La distinción entre la planificación energética a e media y a gran escala radica en la amplitud y complejidad de los recursos energéticos disponibles, que influyen en el desarrollo de escenarios y estrategias de optimización. A escala media, el enfoque generalmente gira en torno a un conjunto limitado de recursos energéticos, donde las técnicas de optimización estándar suelen guiar eficazmente la toma de decisiones. Parámetros como las limitaciones de producción o las restricciones de emisión son fundamentales para dar forma a los resultados de la optimización, orientándolos hacia trayectorias energéticas apropiadas. Por el contrario, la planificación energética a gran escala abarca una gama más amplia de recursos energéticos, presentando un paisaje más intrincado para los tomadores de decisiones. Esta complejidad es particularmente importante en sectores considerados sensibles, donde las opciones estratégicas pueden tener implicaciones sociales y ambientales de largo alcance.

Este estudio tiene como objetivo abordar una limitación significativa en las herramientas actuales de modelado y transición energética: su consideración inadecuada de los criterios de sostenibilidad. Específicamente, busca mejorar la capacidad de OSeMOSYS, integrando indicadores clave de sostenibilidad en su función de optimización. Al hacerlo, el estudio pretende mejorar la capacidad del modelo para apoyar la planificación energética sostenible aplicable a la planificación energética de mediana y gran escala, reflejando un compromiso más amplio con la administración responsable de los recursos naturales y el bienestar de las generaciones presentes y futuras.

El valor añadido de este trabajo radica en la incorporación de indicadores de sostenibilidad en la función objetivo de OSeMOSYS. Específicamente, los indicadores de sostenibilidad integrados en el modelo incluyen la sostenibilidad energética, cuantificada por el Tiempo de

Recuperación Energética (EPBT); la sostenibilidad económica, medida por la Tasa Interna de Retorno (ITR); y la sostenibilidad ambiental, evaluada a través de la Mitigación del Impacto en términos de Cambio Climático (IMPcc). Al incorporar estos indicadores que son los más comúnmente utilizados y su convolución, el modelo proporciona un marco más integral para medir la sostenibilidad de diferentes escenarios energéticos, guiando la toma de decisiones hacia resultados más sostenibles.

La incorporación de indicadores de sostenibilidad en la función objetivo de OSeMOSYS presenta un desafío único, ya que estos indicadores se miden en unidades diferentes. La función objetivo tradicionalmente abarca varios costos, incluidos los de inversión, mantenimiento, costos variables y emisiones, todos expresados en unidades monetarias. En contraste, los indicadores de sostenibilidad como el EPBT y la ITR se miden en años, mientras que el IMPcc se cuantifica en toneladas equivalentes de CO₂. Para integrar estos indicadores de manera fluida en la función objetivo-primaria en OSeMOSYS, cada uno debe estandarizarse en términos económicos.

Para abordar esta propuesta, el enfoque propuesto convierte cada indicador de sostenibilidad en términos económicos y los incorpora como factores de costo adicionales dentro de la función objetivo. Esta transformación asegura que el algoritmo de optimización priorice características que se alineen con los objetivos de sostenibilidad, aunque sin afectar directamente el costo total de la combinación de energía optimizada. Si bien esta funcionalidad no es inherente a OSeMOSYS, se ha integrado en el código central para mejorar las capacidades del software. Esta mejora, aunque potencialmente aumenta las demandas computacionales, tiene como objetivo proporcionar a los tomadores de decisiones conocimientos valiosos para lograr resultados energéticos sostenibles.

Para evaluar la viabilidad de integrar evaluaciones de sostenibilidad en OSeMOSYS, la metodología propuesta se implementó en un estudio de caso dentro del marco energético preconstruido de Atlantis. Este marco está diseñado específicamente para validar metodologías y facilitar evaluaciones controladas de su reproducibilidad. El estudio también tenía como objetivo determinar el grado de correlación entre los indicadores de sostenibilidad y demostrar la utilidad de la metodología desarrollada al abordar preguntas pertinentes de gran relevancia en el discurso contemporáneo.

Atlantis, caracterizado por una diversa gama de tecnologías, incluidas las energías renovables, fósiles y nucleares, sirve como una robusta plataforma para nuevas metodologías y asegurar la reproducibilidad de resultados entre los usuarios de OSeMOSYS. Al aprovechar la amplia matriz energética, el estudio muestra efectivamente la practicidad y efectividad de integrar indicadores de sostenibilidad en el modelo OSeMOSYS, proporcionando así conocimientos valiosos para la planificación energética sostenible.

Después de integrar los factores de sostenibilidad en la función de optimización de OSeMOSYS y realizar un análisis basado en el marco energético de Atlantis, el modelo proporciona el escenario con la mezcla de tecnologías energéticas que aseguran el menor coste global. Además de los costes económicos detallados, el modelo proporciona información sobre producción energética por tecnología, y las emisiones de CO₂ asociadas. El trabajo realizado, permite la evaluación de los efectos de incluir criterios de sostenibilidad y resaltar el valor de la metodología propuesta para abordar estos factores.

En resumen, al integrar parámetros de sostenibilidad en la optimización energética, se puede lograr una transición más equilibrada y sostenible hacia sistemas de energía limpia. Esta integración no solo facilita la planificación energética efectiva, sino que también asegura que las decisiones tomadas hoy contribuyan a un futuro más sostenible y resiliente para las generaciones futuras.

Después de integrar los factores de sostenibilidad en la función de optimización, evaluamos el grado de correlación entre los indicadores de sostenibilidad en estudio mediante un análisis de la matriz de correlación. Finalmente, validamos la utilidad de nuestro trabajo al abordar tres cuestiones críticas en el contexto actual de la transición energética sostenible: el nivel de sostenibilidad de la tecnología nuclear dentro del sistema energético, la eficacia del aumento de las sanciones por emisiones de carbono y la sostenibilidad de la energía solar como representante de fuentes de producción intermitentes basadas en la disponibilidad de recursos locales. Para abordar los desafíos descritos, el presente documento está estructurado de la siguiente manera:

El Capítulo 1 proporciona un análisis contextual integral, comenzando con una exploración de las definiciones y principios fundamentales del desarrollo sostenible. Se profundiza en la evolución histórica del concepto, trazando su trayectoria en respuesta a los cambiantes paradigmas sociales, ambientales y económicos. Se enfatiza la naturaleza multifacética del desarrollo sostenible y las diversas perspectivas que informan su conceptualización, subrayando el imperativo de la gestión integrada de recursos como el camino final para asegurar la sostenibilidad.

Dentro de este capítulo, se introduce el enfoque del marco NEXUS, destacando su importancia en abordar los desafíos de sostenibilidad a través de una visión integrada que considera los recursos esenciales de manera holística. Central en este enfoque es el NEXUS Agua-Energía-Alimentos (WEF), que subraya la interconexión de los recursos vitales y enfatiza la necesidad de una planificación y toma de decisiones integrales para transiciones sostenibles.

La discusión se extiende al desarrollo de métodos y herramientas analíticas, con particular enfoque en el marco Climate-Land-Energy-Water (CLEWs), reconocido por su enfoque global en la gestión de sistemas interconectados. A continuación, el capítulo proporciona una visión general de la herramienta de modelado energético OSeMOSYS, una herramienta clave del marco CLEWs utilizada en esta tesis. Se introducen los principios operativos, parámetros, variables y el código central de su función objetivo, junto con características como MoMani, una interfaz de trabajo amigable para el estudio.

Subsecuentemente, se introduce el marco energético de Atlantis utilizado como estudio de caso en este trabajo, con un enfoque en la representación de tecnologías energéticas y la definición de los parámetros de entrada clave e hipótesis de trabajo que permiten definir los escenarios. Estos abarcan proyecciones de demanda de energía, disponibilidad de recursos y restricciones impuestas.

Entre la multitud de posibles resultados posteriores a la optimización, esta tesis se centra en tres variables de mérito principales para presentar los resultados. La producción energética diferenciada en la producción a través de tecnologías renovables, combustibles fósiles y fuentes de energía nuclear. Los costos económicos abarcan, que tres componentes clave: costos de capital, costos fijos y costos variables. Las emisiones cuantifican los niveles de contaminantes liberados como resultado de las actividades de producción de energía.

El capítulo culmina con la presentación de los resultados obtenidos a través de la post-optimización realizada exclusivamente a través de la función de optimización económica de OSeMOSYS dentro del marco energético de Atlantis. Este segmento proporciona al lector perspectivas valiosas sobre los resultados del estudio, familiarizándolos con la particular manera de presentación de resultados adoptada a lo largo de la tesis.

La importancia de los resultados de la función de optimización económica de OSeMOSYS no puede ser subestimada, ya que sirven como un punto de referencia fundamental contra el cual se evalúan los impactos de nuevas iniciativas en el estudio de viabilidad descrito en el Capítulo 4. Este capítulo está dedicado a desarrollar la metodología empleada en la incorporación de indicadores de sostenibilidad como funciones de optimización dentro de OSeMOSYS. Su objetivo es evaluar los efectos de estos indicadores en la optimización del

sistema energético. Los resultados de este capítulo se han publicado en la revista *Energy Strategy Reviews* bajo el título "Effect of Sustainability Indicator within OSeMOSYS Optimization Transition Scenarios" Volume 54, July 2024, 101448 DOI: <https://doi.org/10.1016/j.esr.2024.101448>.

Comenzando con una revisión exhaustiva de la literatura, el capítulo familiariza a los lectores con los indicadores de sostenibilidad comúnmente utilizados para evaluar tecnologías relacionadas con la energía. Posteriormente, se proporciona una visión general detallada de los indicadores de sostenibilidad específicos utilizados en el estudio, que abarcan EPBT, ITR e IMPcc. Se describe la metodología para incorporar estos indicadores en la función objetivo de optimización de OSeMOSYS como costos adicionales, enfatizando la flexibilidad del proceso para acomodar su eliminación cuando se considere innecesario. El EPBT se integra en la función de costo variable mediante la introducción de un factor de corrección no dimensional, F_{EPBT} , con el objetivo de promover el despliegue de tecnologías con EPBT por debajo de su vida útil (ULT). De manera similar, el ITR se vincula a la función de costo de capital o inversión a través de un factor de corrección no dimensional, F_{ITR} , con el objetivo de promover tecnologías con ITR por debajo de su ULT. El IMPcc se vincula a la función de costo de emisión, complementado por un factor de corrección no dimensional, F_{IMPcc} , para incentivar la reducción de emisiones.

Este capítulo examina a fondo el impacto de los indicadores de sostenibilidad en los procesos individuales de toma de decisiones. Sin embargo, lograr el desarrollo sostenible a veces requiere una consideración integral de las facetas integradas de estos indicadores. Por lo tanto, se realiza un análisis que evalúa la convolución de los tres indicadores de sostenibilidad con el objetivo de descubrir compensaciones discernibles entre los objetivos de sostenibilidad. Este enfoque refleja los esfuerzos para equilibrar y cumplir integralmente cada objetivo de sostenibilidad definido, proporcionando una comprensión matizada de cómo estos indicadores interactúan e influyen en la toma de decisiones en general.

Además, la aplicación de criterios de sostenibilidad a menudo conduce a un aumento de los costos generales. Por lo tanto, es esencial adoptar criterios de sostenibilidad específicos adaptados para abordar objetivos específicos en función de los objetivos del tomador de decisiones. Este enfoque ayuda a eliminar criterios innecesarios y a lograr un mejor equilibrio entre los objetivos de sostenibilidad y los costos.

No obstante, se justifica una mayor investigación sobre las complejidades de la evaluación de sostenibilidad para identificar las principales compensaciones y compromisos entre los indicadores de sostenibilidad en función de los objetivos del tomador de decisiones. En el Capítulo 4 se identificó que ningún indicador único puede lograr de manera efectiva objetivos de sostenibilidad específicos, como alcanzar la neutralidad energética con períodos de recuperación cortos.

Por lo tanto, hemos definido y evaluado una función de optimización sostenible, denominada OP_SusIndex, que integra múltiples indicadores para evaluar integralmente la sostenibilidad. El resultado plantea una pregunta crítica sobre la dinámica operativa de estos indicadores si estos indicadores funcionan de manera independiente, capturando aspectos únicos de la sostenibilidad, o si están interrelacionados, lo que podría llevar a un doble conteo. Este aspecto es de particular importancia debido a que la integración de criterios de sostenibilidad frecuentemente incrementa los costos generales asociados con el proceso de transición energética. El Capítulo 5 tiene como objetivo abordar esta cuestión.

En este contexto, la optimización de la toma de decisiones tiene una importancia primordial. Es imperativo identificar los criterios esenciales necesarios para alcanzar los resultados deseados, al tiempo que se mitigan los requisitos redundantes que pueden aumentar las presiones económicas. Por lo tanto, es crucial examinar y cuantificar minuciosamente las posibles interrelaciones entre los indicadores de sostenibilidad propuestos.

Nuestra metodología implica varios pasos. Inicialmente, examinaremos los datos en bruto obtenidos del capítulo anterior para discernir las tendencias generales. Posteriormente, realizaremos un análisis más profundo cuantificando los efectos significativos a través de una matriz de correlación utilizando el método de Pearson.

A través de este examen cuantitativo, los coeficientes de Pearson proporcionarán conocimientos sobre el grado de correlación entre los indicadores, elucidando el alcance de la superposición entre los efectos asociados con diversas facetas del desarrollo sostenible.

Los resultados se publican en el *International Journal for Research in Applied Science & Engineering Technology* (IJRASET) bajo el título "Sustainability Indicators Correlation Matrix." Vol 12, 2024; ISSN: 2321-9653, DOI: <https://doi.org/10.22214/ijraset.2024.63572>.

El Capítulo 6 demuestra la utilidad del enfoque de sostenibilidad desarrollado para abordar el intrincado paisaje de sectores energéticos sensibles al evaluar su impacto de sostenibilidad utilizando los indicadores dentro de OSeMOSYS. Específicamente, se han examinado tres cuestiones fundamentales dentro del marco de los criterios de sostenibilidad desarrollados en OSeMOSYS. Estas cuestiones tienen relevancia tanto en el discurso público como en las deliberaciones políticas, abarcando la evaluación de la sostenibilidad de la tecnología nuclear, la eficacia de los impuestos extensivos al carbono para incentivar una transición hacia prácticas ambientalmente sostenibles y la evaluación de la sostenibilidad de la tecnología solar fotovoltaica con respecto a las condiciones climáticas.

Los resultados de cada análisis se han publicado en revistas científicas. La evaluación de la sostenibilidad de la energía nuclear se ha publicado en las Actas de la 2ª Conferencia Internacional sobre Agua, Energía, Alimentos y Sostenibilidad (ICoWEFS 2022) (pp. 147-157). DOI: 10.1007/978-3-031-26849-6_16. La evaluación de los impuestos al carbono se ha publicado en la revista *International Journal for Research in Applied Science & Engineering Technology* (IJRASET), vol. 11. ISSN: 2321-9653; 2023. DOI: 10.22214/ijraset.2023.55662. Además, el examen de la sostenibilidad de la energía solar fotovoltaica bajo diferentes condiciones climáticas se detalla en otro artículo publicado en la revista *International Journal for Research in Applied Science & Engineering Technology* (IJRASET), vol. 11. ISSN: 2321-9653; 2023. DOI: 10.22214/ijraset.2023.56000.

Las conclusiones generales (Capítulo 7) abordan hasta qué punto se han logrado los objetivos iniciales y se resumen los principales hallazgos y contribuciones. Esta conclusión vincula los diversos elementos discutidos a lo largo del trabajo y sugiere posibles direcciones para futuras investigaciones o aplicaciones prácticas.

La tesis finaliza con la presentación de las Referencias y el Apéndice. La sección de Referencias enumera todas las fuentes y la literatura citada a lo largo de la investigación, asegurando el debido reconocimiento y proporcionando a los lectores un camino para explorar más a fondo los materiales fundamentales del estudio. El Apéndice incluye material suplementario que apoya y mejora el texto principal, como conjuntos de datos detallados, información metodológica adicional y análisis extendidos, ofreciendo una comprensión más profunda de los hallazgos de la investigación y las metodologías empleadas.

Resumo

Coas sociedades enfrontando os desafíos da modernización e industrialización, o desenvolvemento sostible emerxeu como un imperativo global. Cada vez se recoñece máis a necesidade de equilibrar estes obxectivos para asegurar un futuro viable e xusto para as xeracións vindeiras. Este recoñecemento é particularmente evidente no contexto de abordar o cambio climático a través de iniciativas como os Obxectivos de Desenvolvemento do Milenio (ODM) e a posterior adopción dos Obxectivos de Desenvolvemento Sostible (ODS) por parte das Nacións Unidas, que subliñan o compromiso global de combater a pobreza e avanzar nas axendas de sostibilidade.

Na loita contra o cambio climático, é crucial e imperativo o tránsito cara a sistemas de enerxía limpa que permitan adoptar prácticas de planificación enerxética sostible. Non obstante, a complexidade inherente aos sistemas enerxéticos, que comprenden elementos interconectados como instalacións de xeración de enerxía, redes de transmisión e sectores de usuarios finais, constitúe un formidable reto. As alteracións nun compoñente poden xerar consecuencias imprevistas en todo o sistema, complicando aínda máis o proceso de transición enerxética e presentando aos tomadores de decisión numerosos desafíos, especialmente na consecución dos obxectivos de sostibilidade.

Nese sentido, unha adecuada planificación enerxética resulta imprescindible para lograr unha transición cara a unha enerxía sostible a diferentes escalas. Isto implica a análise, deseño e optimización de estratexias, tendo en conta diversos factores, incluíndo a demanda de enerxía, a dispoñibilidade de recursos, as opcións tecnolóxicas, as consideracións ambientais e as dinámicas socioeconómicas.

A integración de ferramentas de modelado enerxético nos procesos de planificación para proxeccións a curto, mediano e longo prazo mellora as capacidades de toma de decisións, facilita a identificación de rutas óptimas e reforza o desenvolvemento de sistemas enerxéticos resilientes. Existe unha ampla gama de ferramentas de modelado para a planificación enerxética, proporcionando coñecementos estruturados e cuantitativos sobre diversos escenarios enerxéticos. Estas ferramentas aproveitan as capacidades avanzadas de computación, acomodan restricións de optimización multiobxectivo e incorporan múltiples parámetros, acelerando así a transición cara a unha enerxía sostible.

Dende a adopción do paradigma da sostibilidade, a necesidade de integrar a toma de decisións baseada na sostibilidade volveuse cada vez máis pronunciada. Os procesos de toma de decisións, particularmente no sector enerxético, deben incorporar consideracións de sostibilidade para aliñarse cos compromisos globais, como os delineados no Acordo de París. Isto require que os tomadores de decisión adopten enfoques holísticos de sostibilidade dentro das súas ferramentas de modelado que equilibren os resultados inmediatos coas implicacións a longo prazo, fomentando así a resiliencia e adaptabilidade en sistemas que van dende a infraestrutura enerxética ata a planificación urbana.

A maioría das ferramentas de modelado enerxético existentes céntranse na optimización económica para satisfacer os requisitos das entidades económicas e os formuladores de políticas que lideran as transicións enerxéticas. Non obstante, basearse unicamente na optimización económica é insuficiente para unha planificación enerxética integral. Incorporar criterios de sostibilidade nestas ferramentas é esencial para abordar os desafíos multifacéticos da planificación enerxética.

O modelo de planificación do sistema enerxético de código aberto, OSeMOSYS, é unha das ferramentas de modelado enerxético máis utilizadas e é un programa lineal multiperiodo e multirrexional. Ao igual que outros modelos de sistemas enerxéticos, o seu enfoque na optimización económica ten como obxectivo principal determinar a combinación de tecnoloxías e xeración de enerxía a longo prazo de menor custo. Isto lógrase incorporando parámetros de restrición específicos, permitindo aos usuarios guiar e controlar os resultados.

Este entorno facilita estudos estratéxicos de enerxía a través de diversas escalas temporais e espaciais, dende avaliacións a curto prazo ata esforzos de planificación a longo prazo. A súa versatilidade permite unha ampla aplicabilidade en contextos diversos, dende instalacións de redes enerxéticas medianas que serven a pequenos pobos ou sectores industriais, ata iniciativas a gran escala que abarcan a planificación de transición enerxética para cidades enteiras, países ou incluso bloques rexionais compostos por múltiples nacións.

O deseño dun sistema de referencia adecuado na ferramenta OSeMOSYS serve como columna vertebral que permite avaliar diferentes dinámicas enerxéticas dun sistema/produto que plantexa mellorar a súa sostibilidade e resiliencia. Neste contexto, os usuarios ingresan meticulosamente datos relacionados coa demanda de enerxía, as opcións de subministración dispoñibles e as restricións de infraestrutura prevalecentes. Este proceso permite o modelado de diversos escenarios, cada un ofrecendo perspectivas sobre a súa viabilidade, rendibilidade e repercusións ambientais en horizontes de tempo a curto, medio e longo prazo.

A calquera escala, dende a planificación enerxética nacional, rexional ou local, OSeMOSYS convértese nunha ferramenta invaluable para a transición cara a sistemas enerxéticos máis limpos e sostibles. Ao considerar o paisaxe enerxético único dun país, incluíndo a súa dotación de recursos, perfil de demanda enerxética, marco regulatorio e contexto socioeconómico, OSeMOSYS permite aos deseñadores de políticas explorar diversas vías para lograr seguridade enerxética, accesibilidade e sostibilidade ambiental a longo prazo. Isto podería implicar a avaliación da combinación óptima de fontes de enerxía, estratexias de expansión da rede, intervencións políticas e prioridades de investimento para aliñarse cos obxectivos de desenvolvemento nacional e os compromisos climáticos internacionais.

A distinción entre a planificación enerxética a media e a gran escala radica na amplitude e complexidade dos recursos enerxéticos dispoñibles, que inflúen no desenvolvemento de escenarios e estratexias de optimización. A escala media, o enfoque xeralmente xira en torno a un conxunto limitado de recursos enerxéticos, onde as técnicas de optimización estándar adoitan guiar eficazmente a toma de decisións. Parámetros como as limitacións de produción ou as restricións de emisión son fundamentais para dar forma aos resultados da optimización, orientándoos cara a traxectorias enerxéticas apropiadas. Pola contra, a planificación enerxética a gran escala abarca unha gama máis ampla de recursos enerxéticos, presentando un paisaxe máis intricado para os tomadores de decisión. Esta complexidade é particularmente importante en sectores considerados sensíbles, onde as opcións estratéxicas poden ter implicacións sociais e ambientais de longo alcance.

Este estudo ten como obxectivo abordar unha limitación significativa nas ferramentas actuais de modelado e transición enerxética: a súa consideración inadecuada dos criterios de sostibilidade. Especificamente, busca mellorar a capacidade de OSeMOSYS, integrando indicadores clave de sostibilidade na súa función de optimización. Ao facelo, o estudo pretende mellorar a capacidade do modelo para apoiar a planificación enerxética sostible aplicable á planificación enerxética de mediana e gran escala, reflectindo un compromiso máis amplo coa administración responsable dos recursos naturais e o benestar das xeracións presentes e futuras.

O valor engadido deste traballo radica na incorporación de indicadores de sostibilidade na función obxectivo de OSeMOSYS. Especificamente, os indicadores de sostibilidade integrados no modelo inclúen a sostibilidade enerxética, cuantificada polo Tempo de Recuperación Enerxética (EPBT); a sostibilidade económica, medida pola Tasa Interna de Retorno (ITR); e a

sostibilidade ambiental, avaliada a través da Mitigación do Impacto en termos de Cambio Climático (IMPcc). Ao incorporar estes indicadores que son os máis comunmente utilizados e a súa convolución, o modelo proporciona un marco máis integral para medir a sostibilidade de diferentes escenarios enerxéticos, guiando a toma de decisións cara a resultados máis sostibles.

A incorporación de indicadores de sostibilidade na función obxectivo de OSeMOSYS presenta un desafío único, xa que estes indicadores mídense en unidades diferentes. A función obxectivo tradicionalmente abarca varios custos, incluíndo os de investimento, mantemento, custos variables e emisións, todos expresados en unidades monetarias. En contraste, os indicadores de sostibilidade como o EPBT e a ITR mídense en anos, mentres que o IMPcc se cuantifica en toneladas equivalentes de CO₂. Para integrar estes indicadores de maneira fluída na función obxectivo primaria en OSeMOSYS, cada un debe estandarizarse en termos económicos.

Para abordar esta proposta, o enfoque proposto converte cada indicador de sostibilidade en termos económicos e os incorpora como factores de custo adicionais dentro da función obxectivo. Esta transformación asegura que o algoritmo de optimización priorice características que se aliñen cos obxectivos de sostibilidade, aínda que sen afectar directamente o custo total da combinación de enerxía optimizada. Aínda que esta funcionalidade non é inherente a OSeMOSYS, foi integrada no código central para mellorar as capacidades do software. Esta mellora, aínda que potencialmente aumente as demandas computacionais, pretende proporcionar aos tomadores de decisións información valiosa para lograr resultados enerxéticos sostibles.

Para avaliar a viabilidade de integrar avaliacións de sustentabilidade en OSeMOSYS, a metodoloxía proposta foi implementada nun estudo de caso dentro do marco enerxético pre-construído de Atlantis. Este marco está especificamente deseñado para validar metodoloxías e facilitar avaliacións controladas da súa reproducibilidade. O estudo tamén tiña como obxectivo determinar o grao de correlación entre os indicadores de sustentabilidade e demostrar a utilidade da metodoloxía desenvolvida abordando cuestións pertinentes de relevancia significativa no discurso contemporáneo.

Atlantis, caracterizado por unha ampla gama de tecnoloxías, incluíndo enerxías renovables, non renovables e nucleares, serve como unha plataforma robusta para probar novas metodoloxías e asegurar a reproducibilidade dos resultados entre os usuarios de OSeMOSYS. Aproveitando esta diversa paisaxe enerxética, o estudo amosa efectivamente a practicidade e efectividade de integrar indicadores de sustentabilidade no modelo OSeMOSYS, proporcionando información valiosa sobre a planificación enerxética sostible.

Despois de integrar factores de sustentabilidade na función de optimización, avaliamos o grao en que a convolución destes factores é necesaria e suficiente a través dunha análise da matriz de correlación. Finalmente, validamos a utilidade do noso traballo abordando tres cuestións críticas no contexto actual da transición enerxética sostible: o nivel de sustentabilidade da tecnoloxía nuclear dentro do sistema enerxético, a eficacia do aumento das penalizacións por emisións de carbono e a sustentabilidade da enerxía solar como representante de fontes de produción intermitentes baseadas na dispoñibilidade de recursos locais. Para abordar os desafíos expostos, o presente documento estrutúrase da seguinte maneira:

O capítulo 1 proporciona unha análise contextual completa, comezando cunha exploración das definicións e principios fundamentais do desenvolvemento sustentable. Examínase a evolución histórica do concepto, rastrexando a súa traxectoria en resposta aos paradigmas sociais, ambientais e económicos cambiantes. Enfásese na natureza multifacética do desenvolvemento sustentable e nas diversas perspectivas que informan a súa conceptualización, subliñando a importancia da xestión integrada de recursos como a vía definitiva para asegurar a sustentabilidade.

Dentro deste capítulo, elúcidase o enfoque do marco NEXUS, destacando a súa importancia para abordar os desafíos de sustentabilidade a través dunha lente integrada que considera os recursos esenciais de forma holística. Central neste enfoque é o NEXUS Auga-Enerxía-Alimentos (WEF), que subliña a interconexión de recursos vitais e enfatiza a necesidade dunha planificación e toma de decisións holísticas para transicións sostibles.

A discusión exténdese ao desenvolvemento de métodos e ferramentas analíticas, con especial atención ao marco Clima-Terra-Enerxía-Auga (CLEWs), coñecido polo seu enfoque integral para xestionar sistemas interconectados. A continuación, o capítulo proporciona unha visión xeral da ferramenta de modelado enerxético OSeMOSYS, unha ferramenta clave do marco CLEWs utilizada nesta tese. Elúcídanse os seus principios operativos, parámetros, variables e o código central da súa función obxectivo, xunto a características como MoMani, unha interface de traballo integral para o estudo.

Subsecuentemente, preséntase o marco enerxético de Atlantis utilizado como estudo de caso neste traballo, cun enfoque na representación das tecnoloxías enerxéticas e a elucidación dos parámetros de entrada e suposicións clave que definen os escenarios. Estes abarcan proxeccións de demanda enerxética, dispoñibilidade de recursos e restricións impostas.

Entre a multitude de posibles resultados tras a optimización, esta tese céntrase en tres variables principais de mérito para presentar os resultados. A produción enerxética delinea a saída a través de tecnoloxías renovables, combustibles fósiles e sectores de enerxía nuclear. Os custos económicos abranguen tres compoñentes clave: custos de capital, custos fixos e custos variables. As emisións cuantifican os niveis de contaminantes liberados como resultado das actividades de produción enerxética.

O capítulo culmina coa presentación dos resultados obtidos a través da post-optimización realizada exclusivamente mediante a función de optimización económica de OSeMOSYS dentro do marco enerxético de Atlantis. Este segmento proporciona ao lector unha visión inestimable dos resultados do estudo, familiarizándoo co particular xeito de presentación dos resultados adoptado ao longo da tese.

A importancia dos resultados da función de optimización económica de OSeMOSYS non pode ser subestimada, xa que serven como un punto de referencia fundamental contra o cal se avalían os impactos das novas iniciativas no estudo de viabilidade que se desenvolve no capítulo 4. Este capítulo dedícase a elucidar a metodoloxía empregada para incorporar os indicadores de sustentabilidade como funcións de optimización dentro de OSeMOSYS. O seu obxectivo é avaliar os efectos destes indicadores na optimización do sistema enerxético. Os achados deste capítulo está publicado na revista *Energy Strategy Reviews* baixo o título "Effect of Sustainability Indicators within OSeMOSYS Optimization Transition Scenarios" Volume 54, July 2024, 101448 DOI: <https://doi.org/10.1016/j.esr.2024.101448>.

Comezando cunha revisión exhaustiva da literatura, o capítulo familiariza aos lectores cos indicadores de sustentabilidade comúns utilizados para avaliar tecnoloxías relacionadas coa enerxía. Posteriormente, proporciónase unha visión detallada dos indicadores de sustentabilidade específicos empregados no estudo, incluíndo EPBT, ITR e IMPcc. Delínase a metodoloxía para incorporar estes indicadores na función obxectivo de optimización de OSeMOSYS como custos adicionais, enfatizando a flexibilidade do proceso para acomodar a súa eliminación cando se considere innecesaria.

O EPBT intégrase na función de custo variable mediante a introdución dun factor de corrección non-dimensional, F_{EPBT} , que pretende promover o despregamento de tecnoloxías con EPBT inferiores á súa vida útil (ULT). Do mesmo xeito, o ITR vincúlase á función de custo de capital ou de investimento a través dun factor de corrección non-dimensional, F_{ITR} , co obxectivo de promover tecnoloxías con ITR inferiores á súa ULT. O IMPcc relaciónase co custo das emisións, complementado por un factor de corrección non-dimensional, F_{IMPcc} , para incentivar a redución das emisións.

Este capítulo examina exhaustivamente o impacto dos indicadores de sustentabilidade nos procesos de toma de decisións individuais. Non obstante, lograr o desenvolvemento sostible ás veces require unha consideración integral das facetas integradas destes indicadores. Polo tanto, realízase unha análise que avalía a convolución dos tres indicadores de sustentabilidade co obxectivo de descubrir compensacións discernibles entre os obxectivos de sustentabilidade. Este enfoque reflicte esforzos para equilibrar e cumprir de xeito integral cada obxectivo de sustentabilidade definido, proporcionando unha comprensión matizada de como estes indicadores interactúan e inflúen na toma de decisións global.

Ademais, a aplicación de criterios de sustentabilidade a miúdo leva a un aumento dos custos globais. Así, é esencial adoptar criterios de sustentabilidade específicos adaptados para abordar obxectivos concretos baseados nos obxectivos do tomador de decisións. Este enfoque axuda a eliminar criterios innecesarios e lograr un mellor equilibrio entre os obxectivos de sustentabilidade e os custos.

Non obstante, é necesario continuar investigando as complexidades da avaliación da sustentabilidade para identificar os principais compromisos e compensacións entre os indicadores de sustentabilidade segundo os obxectivos do tomador de decisións. Identificamos no capítulo 4 que ningún indicador único pode alcanzar de forma efectiva obxectivos específicos de sustentabilidade, como acadar a neutralidade enerxética con períodos de retorno curtos.

Polo tanto, definimos e avaliamos unha función de optimización sostible, denominada OP_SusIndex, que integra múltiples indicadores para avaliar de forma integral a sustentabilidade. O resultado plantexa unha pregunta crítica sobre a dinámica operativa destes indicadores: se estes indicadores funcionan de forma independente, capturando aspectos únicos da sustentabilidade, ou se están interrelacionados, potencialmente levando a unha dobre contaxe. Este aspecto ten particular relevancia debido ao feito de que a integración de criterios de sustentabilidade frecuentemente eleva os custos globais vinculados ao proceso de transición enerxética. O capítulo 5 ten como obxectivo abordar esta cuestión.

Neste contexto, a optimización da toma de decisións ten unha importancia primordial. É imperativo identificar os criterios esenciais necesarios para acadar os resultados desexados ao tempo que se mitigan os requisitos redundantes que poden aumentar as presións económicas. Polo tanto, é crucial examinar minuciosamente e cuantificar as posibles interrelacións entre os indicadores de sustentabilidade propostos.

A nosa metodoloxía implica varios pasos. Inicialmente, examinaremos os datos brutos obtidos do capítulo anterior para discernir tendencias xerais. Posteriormente, realizaremos unha análise máis profunda cuantificando os efectos significativos a través dunha matriz de correlación utilizando o método de Pearson.

A través desta análise cuantitativa, os coeficientes de Pearson proporcionarán información sobre o grao de correlación entre os indicadores, elucidando a medida en que os efectos asociados con varios aspectos do desenvolvemento sostible se solapan. Os resultados publicanse no International Journal for Research in Applied Science & Engineering Technology (IJRASET) baixo o título "Sustainability Indicators Correlation Matrix." Vol 12, 2024; ISSN: 2321-9653, DOI: <https://doi.org/10.22214/ijraset.2024.63572>.

O capítulo 6 demostra a utilidade do enfoque de sustentabilidade desenvolvido ao abordar o panorama intricado dos sectores enerxéticos sensibles mediante a avaliación do seu impacto en sustentabilidade utilizando os indicadores dentro de OSeMOSYS. Especificamente, examináronse tres cuestións fundamentais dentro do marco dos criterios de sustentabilidade desenvolvidos en OSeMOSYS. Estas cuestións teñen relevancia tanto no discurso público como nas deliberacións políticas, abarcan a avaliación da sustentabilidade da tecnoloxía nuclear, a eficacia de impostos de carbono elevados para incentivar unha transición cara a

prácticas ambientalmente sostibles, e a avaliación da sustentabilidade da tecnoloxía solar fotovoltaica con respecto ás condicións climáticas.

Os resultados de cada análise foron publicados en revistas científicas. A avaliación da sustentabilidade da enerxía nuclear foi publicada nos Proceedings of the 2nd International Conference on Water Energy Food and Sustainability (ICoWEFS 2022) (pp. 147-157). DOI: 10.1007/978-3-031-26849-6_16. A avaliación dos impostos sobre o carbono foi publicada na International Journal for Research in Applied Science & Engineering Technology (IJRASET), vol. 11. ISSN: 2321-9653; 2023. DOI: 10.22214/ijraset.2023.55662. Ademais, a avaliación da sustentabilidade da enerxía solar fotovoltaica baixo diferentes condicións climáticas detállase noutra publicación na International Journal for Research in Applied Science & Engineering Technology (IJRASET), vol. 11. ISSN: 2321-9653; 2023. DOI: 10.22214/ijraset.2023.56000.

As conclusións xerais (Capítulo 7) abordan o grao en que se alcanzaron os obxectivos iniciais desta tese e resumen os principais achados e contribucións. Esta conclusión vincula os diversos elementos discutidos ao longo do traballo e suxire posibles direccións para futuras investigacións ou aplicacións prácticas.

A tese remata cunha presentación das Referencias e do Apéndice. A sección de Referencias enumera todas as fontes e literatura citadas ao longo da investigación, asegurando un recoñecemento adecuado e proporcionando aos lectores un camiño para explorar máis a fondo os materiais fundamentais do estudo. O Apéndice inclúe material complementario que apoia e mellora o texto principal, como conxuntos de datos detallados, información metodolóxica adicional e análises extensas, ofrecendo unha comprensión máis profunda dos achados da investigación e das metodoloxías empregadas.

Chapter 1. Introduction

The purpose of this chapter is to offer a comprehensive overview of the contextual framework that supports the main objective of this thesis. This objective is to incorporate sustainable development criteria by exclusively employing sustainability indicators within an energy modelling tool. The ultimate objective is to direct long-term energy planning towards a sustainable path.

To commence, this chapter begins by defining sustainable development and exploring its historical context, evolution, and treatment in assessments. This foundational section provides a thorough understanding of the term, tracing its origins and evolution in response to changing societal, environmental, and economic paradigms. The chapter also delves into the multifaceted nature of sustainable development and the diverse perspectives that inform its conceptualization. This comprehensive overview offers valuable insight into the complexities involved in assessing sustainable development and its crucial role in contemporary discourse and decision-making.

A dedicated section within the chapter is devoted to the NEXUS paradigm, which represents a transformative approach to sustainable development [1]. The NEXUS is a framework that emphasizes the need to address sustainability challenges by taking an integrated approach and considering essential resources together [2]. This approach recognizes the interconnectedness between different domains and requires a holistic approach to resource management [3]. The Water-Energy-Food (WEF) NEXUS is a key framework for navigating these complex interconnections [4]. By acknowledging the interdependence between these systems, the NEXUS approach emphasizes the importance of integrated planning and decision-making [5]. This perspective enables more efficient resource allocation and identifies synergies and trade-offs across different sectors [6]. Ultimately, incorporating the NEXUS concept holds great promise for enhancing resilience and sustainability in development initiatives [7].

Also part, a detailed discussion on the Climate, Land, Energy, and Water Systems (CLEWs) framework, which is an important nexus tool [8]. CLEWs use various modelling tools to manage and analyze data related to interconnected systems, allowing for the integration of different components and consideration of interdependencies between systems within sectoral models [9]. In this study, OSeMOSYS, a CLEWs energy modelling tool, is the main focus due to its flexibility in accommodating new energy modelling initiatives [10]. It has been employed in this thesis to incorporate the sustainability criteria directly into its core code to guide energy planning towards a sustainable trajectory.

Following a comprehensive discussion on OSeMOSYS, including its operational principles, parameters, variables, and the core code of its objective function [11], along with associated features such as MoMani, a working interface utilized in this study [12], the subsequent section introduces the Atlantis energy framework used as a case study employed to assess the feasibility of the developed methodology [13]. The focus is directed towards elucidating the representation of energy technologies and delineating the key parameters and assumptions that delineate a scenario. These encompass projections of energy demand, availability of resources, and constraints imposed.

To conclude the chapter, an illustrative example showcasing the presentation of OSeMOSYS results post-optimization is provided. The presentation of the Atlantis outcomes of the Standard optimization is of particular significance, exclusively conducted through OSeMOSYS's

economic optimization module. This presentation holds considerable importance, serving as the baseline against which the results of novel initiatives can be compared and evaluated.

1.1. Sustainable development

Sustainable development is a comprehensive framework designed to address current societal requirements while safeguarding the capacity of future generations to meet their own needs [14]. This entails harmonizing economic advancement, environmental conservation, and social equity to foster a sustainable and prosperous future for all individuals [15].

Sustainable development has historical origins intertwined with environmental and social apprehensions that gained momentum during the 20th century. This period witnessed heightened awareness as industrialization and economic expansion exerted palpable effects on both natural ecosystems and human societies [16].

Although the term "sustainable development" was not formalized until a later epoch, the seeds of such principles were sown in the 19th century. During this time, conservation and environmental protection movements emerged in response to the escalating environmental degradation resulting from rapid industrialization [17].

During the 1960s, there was a noticeable rise in awareness about environmental issues. This surge was influenced by significant events such as the release of Rachel Carson's book "Silent Spring" in 1962. Carson's book brought attention to the harmful effects of pesticides like DDT on both animals and humans [18].

However, it wasn't until 1972 that a major milestone in global environmental consciousness was reached. In that year, the first United Nations Conference on the Human Environment took place in Stockholm. This conference led to the establishment of the United Nations Environment Program (UNEP) [19].

The momentum continued, and in 1987, the World Commission on Environment and Development (WCED) was formed, chaired by Gro Harlem Brundtland. The commission produced a groundbreaking report called "Our Common Future," also known as the Brundtland Report. It was within this report that the modern concept of sustainable development emerged [14].

Subsequently, the Earth Summit held in Rio de Janeiro in 1992 marked a pivotal moment in global environmental policy. This event saw the issuance of the Rio Declaration on Environment and Development, alongside Agenda 21, a comprehensive action plan outlining strategies for sustainable development [20].

Moving into the new millennium, the United Nations adopted the Millennium Development Goals (MDGs) in 2000. These goals encompassed specific targets related to poverty reduction, health and education improvement, gender equality, and environmental sustainability [21]. In 2015, the MDGs were succeeded by the Sustainable Development Goals (SDGs), offering a more expansive and ambitious framework to address global challenges [22].

Throughout this historical trajectory, sustainable development has evolved from being primarily an environmental concern to a broader concept acknowledging the intricate links between the environment, economy, and society. It seeks to reconcile economic advancement with environmental preservation and social equity [15].

Various approaches to sustainable development have emerged, each emphasizing different aspects and strategies. Common approaches include the green economy, sustainable human development, intergenerational justice, and the triple bottom line (TBL). These approaches are not mutually exclusive and often complement one another [23].

The TBL approach, devised by John Elkington in the 1990s, represents a significant paradigm shift in how businesses and societies evaluate their performance. It suggests that success should not be solely measured by economic profits but also by considering social and environmental impacts. This entails incorporating sustainability principles into decision-making processes to

ensure progress across three main dimensions: environmental, social, and economic [23](as illustrated in Figure 1.1). It's essential to implement practices that are economically feasible, socially fair, and environmentally sound. The TBL recognizes the interconnectedness of these dimensions and strives to find a balance among them to promote sustainable development in the long run [15].

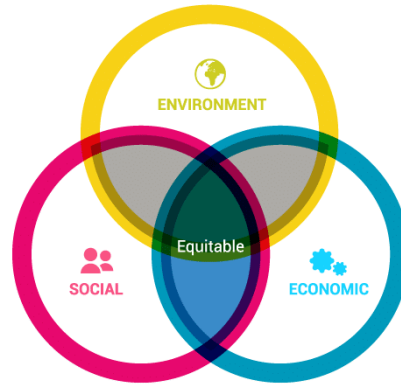


Figure 1.1 The three pillars of sustainability
This figure is reproduced from the following reference [24]

While profitability remains crucial for organizations (the economic bottom line), the Triple Bottom Line (TBL) underscores the importance of considering broader impacts on both people and the planet when formulating business strategies [23]. Incorporating TBL principles into corporate management and decision-making processes is essential for effectively tackling global challenges and fostering a more sustainable and equitable future [25]. Currently, the TBL approach is widely embraced as a framework for sustainable development [15].

However, establishing successful sustainable development models is complex. It necessitates the integration of policies and practices that balance economic, social, and environmental needs to ensure a prosperous and just future for current and upcoming generations [16]. This requires coordinated decision-making across all levels, from individual to governmental, while considering the economic, social, and environmental consequences of actions [15].

It is crucial to carefully evaluate available options to maximize long-term benefits while minimizing adverse impacts [16]. Integrated assessments of resource systems and objectives, coupled with interdisciplinary practices and analysis of decision impacts on various systems, are invaluable in facilitating integrated decision-making and advancing sustainable development goals [26].

1.2. Sustainability Assessment

The Triple Bottom Line (TBL) framework encompasses three dimensions economic, social, and environmental offering a broad approach to assessing overall sustainability. This framework's expansive scope allows it to be applied to organizations, projects, policies, and other initiatives [23]. Sustainability assessments typically begin with defining objectives and criteria for what constitutes sustainable development within a specific context or system [27]. These objectives serve as benchmarks against which the performance and impacts of actions or policies are measured [28]. Methods for assessing sustainability encompass a broad spectrum, spanning qualitative analyses to quantitative assessments.[29]

For instance, sustainability assessments often embrace stakeholder engagement and participatory methodologies to integrate a diverse array of perspectives and values into decision-making processes, thereby fostering inclusivity and transparency in sustainability efforts [30]. Through systematic evaluation, stakeholders can pinpoint improvement areas,

monitor progress over time, and make well-informed decisions to advance toward a more sustainable future [30].

In contrast, Life Cycle Assessment (LCA) primarily targets environmental impacts throughout the life cycle of a specific product or process. LCA is more specific, focusing on individual products, processes, or services [31]. Similarly, Cost-Benefit Analysis (CBA) examines the economic feasibility of projects or policies by weighing their costs and benefits over time [32]. Social Impact Assessments (SIA) delve into the societal implications of development initiatives or policies on communities [33].

Despite their differing approaches and methods, TBL and LCA can be complementary in sustainability assessments. For instance, an organization can utilize the TBL framework to evaluate its overall performance across economic, social, and environmental dimensions, while employing LCA to conduct detailed analyses of the environmental impacts of specific products or processes. This integrated approach provides a more comprehensive and nuanced understanding of sustainability.

One widely adopted strategy in sustainability assessment involves the utilization of sustainability indicators, which comprise both quantitative and qualitative measures providing insights into the state or trends of specific aspects pertinent to sustainability [34]. However, the selection and application of these indicators necessitate meticulous consideration of their relevance, reliability, and comprehensiveness to ensure robust and accurate assessments [34].

In the realm of energy, sustainability indicators encompass an array of parameters, including resource consumption, pollution levels, social equity, and economic prosperity [35]. They facilitate the monitoring and evaluation of progress toward sustainability objectives, thereby enabling evidence-based decision-making and policy formulation [35]. Among the myriads of existing sustainability indicators, prominent ones in the energy sector include Energy Payback Time (EPBT) from an energetic perspective, Internal Time of Return (ITR) from an economic standpoint, and Environmental Impact (IMPcc) [36].

These indicators are particularly salient within the cradle-to-cradle paradigm, enabling the tracking of each technology's impact from raw material extraction to end-of-life [31]. Their significance is underscored in this study, as they serve as pivotal tools for assessing the sustainability of energy mix systems within the context of energy modelling. The subsequent chapter delves into a comprehensive discussion of EPBT, ITR, and IMPcc.

1.3. Nexus: A guide to resource management

During the 2012 Bonn conference, where the progress of the Millennium Development Goals (MDGs) was evaluated and the subsequent Sustainable Development Goals (SDGs) for the following 15 years were formulated, a significant issue contributing to the failure to achieve the set targets became apparent: the reliance on isolated solutions [37]. This highlighted the urgent need to comprehensively explore the intricate connections between the envisioned goals, leading to the development of robust methodologies, tools, and collaborative frameworks to address the forthcoming challenges of sustainable development [37]. This holistic approach came to be known as NEXUS Networks or the NEXUS of things.

The SDGs embody the NEXUS approach, showcasing the intricate links between their 17 goals and measurement indicators [38]. Rockström and Sukhdew's "wedding cake" analogy, illustrated in Figure 1.2, highlights the evolution of the SDGs' vision, moving from a human-centric focus on "zero hunger" to a more comprehensive emphasis on resource management and governance [39]. Notably, the Water-Energy-Land NEXUS brings forward pioneering concepts that have gained prominence in discussions on Water-Energy-Food (WEF) interactions [40].

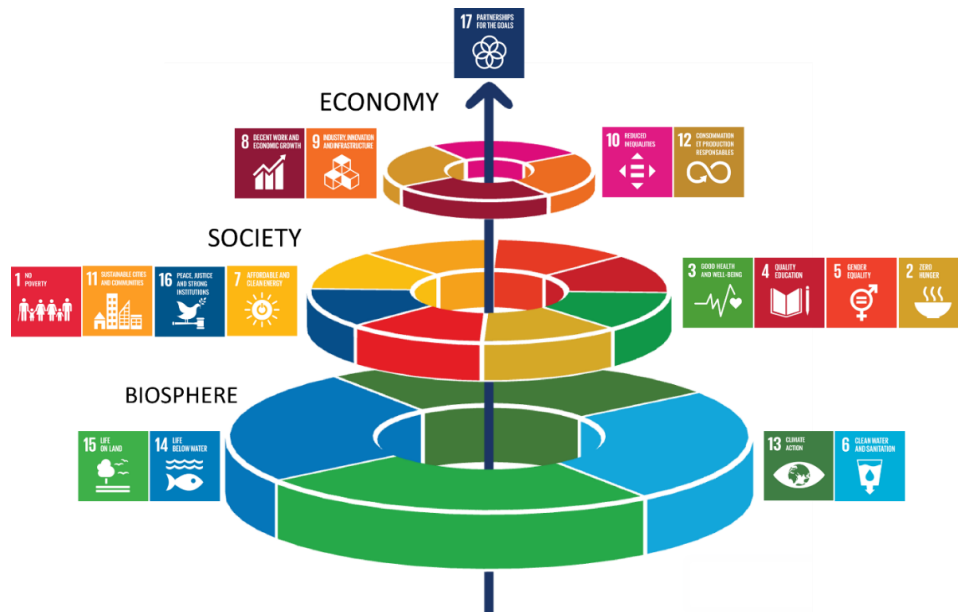


Figure 1.2 Sustainable Development Goals 2030 (SDGs) wedding cake from Azote Images for Stockholm Resilience Centre, 2016. Rockström, J.; Sukhdev, P. How food connects all the SDGs. opening keynote speech at the 2016 EAT Forum

This figure is reproduced from the following reference [41].

The NEXUS framework offers practical methods for examining how different systems are interconnected, allowing for the development of plans that promote sustainable transitions through better resource management [40]. Over the years, the NEXUS framework has undergone considerable evolution. Initially conceived as a response to the growing recognition of how various goals and aspirations are linked, it has now matured into a widely embraced methodology centered on the effective management of essential resources [42]. This evolution has been marked by significant advancements in research, the integration of policies, and the crafting of solutions tailored to specific contexts to address emerging challenges. This is particularly pertinent in light of increasing apprehensions surrounding climate change and the need for resilience [42].

During its early stages, approximately from 2012 onwards, the NEXUS approach initially focused on highlighting the complex relationships between different systems within a conceptual framework [43]. However, as time advanced, there was a notable shift towards developing analytical methods aimed at systematically assessing these interconnections. This evolution gave rise to several tools and frameworks, including the FAO-WEF approach, the WEF NEXUS Tool, the TBNA methodology, and Climate-Land-Energy-Water (CLEWs) systems, all of which played crucial roles in enhancing our understanding and management of interconnected systems [40]. In this study, we will utilize the CLEWs framework.

These initiatives, by promoting a holistic approach to managing resources, especially in the areas of energy, water, and climate resilience, are essential for driving advancements towards a sustainable future [3]. They offer crucial guidance for addressing intricate challenges and moving forward with sustainable development objectives, benefiting communities both locally and globally [3].

1.4. Climate, Land, Energy, and Water (CLEWs) System Framework

The CLEWs framework, developed by the International Atomic Energy Agency (IAEA), stands out as an advanced tool for evaluating biofuel supply chains, offering applications that reach beyond its original purpose [44], [45]. Since its introduction, it has emerged as a fundamental resource for academia, governmental policymaking, and international collaborations [46]. Initially tested in Mauritius in 2012 through collaborative efforts involving

multiple institutions, this methodology offers a detailed analysis of the complex interactions between the climate and vital resource systems, including energy, water, and land use [47].

Figure 1.3 serves as a visual representation of the core principles of the CLEWs framework, highlighting its emphasis on essential resources and boundary conditions [46]. This framework facilitates both qualitative and quantitative investigations, providing a structured, data-driven method crucial for understanding the intricate dynamics within integrated systems[8]. Additionally, its flexibility across various geographic scales, ranging from global to regional, national, and urban levels, underscores its effectiveness in conducting thorough resource assessments and tackling sustainability challenges from a holistic standpoint [8].

Given the intricate nature of these analyses, the importance of employing suitable modelling tools and comparative analysis methods cannot be overstated [47]. Ongoing advancements in these tools empower users to manage and analyze data related to CLEW systems effectively. This facilitates the integration of diverse components and the consideration of interdependencies between systems within sectoral models.

Such integration not only enhances coherence and consistency in analyses but also enables a deeper comprehension of the complex relationships and feedback loops among climatic, terrestrial, energy, and water elements [48]. Consequently, these modelling tools play a crucial role in tackling a wide array of challenges, from initiatives aimed at decarbonization to promoting international collaboration in resource management and navigating intricate energy transitions[47] .

Among the diverse array of CLEWs modelling tools available, Integrated Assessment Models (IAMs) emerge as notable examples, such as GCAM [49], MESSAGE-GLOBIOM [50], [51], and IMAGE [52]. However, these models require robust quantification, leading to the development of sectoral models focusing on water, energy, and land use. By considering various climate scenarios, these models offer insights into critical pressure points and strategies to mitigate adverse impacts [50], [52].

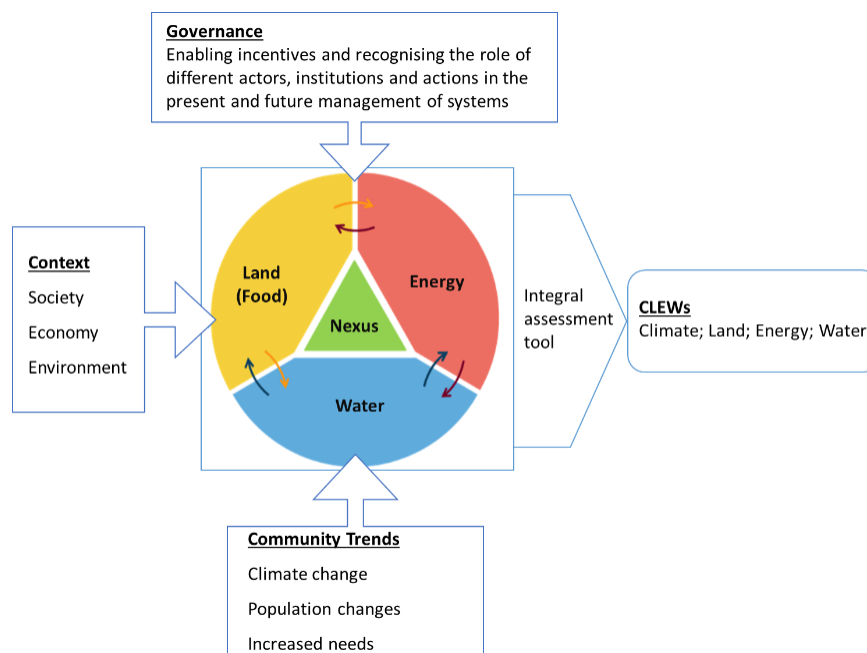


Figure 1.3 CLEWs definition and context
This figure is reproduced from the following reference [46]

For instance, specialized water-related modelling tools like WEAP (Water Evaluation and Planning) and MODFLOW provide essential insights into water management within CLEW systems [53], [54]. In the domain of land-use modelling, the MOLAND tool enables spatial

land-use modelling at regional and national scales, often employed for scenario analysis and policy assessment in land-use planning and management [55].

Conversely, LEAM (Land Evaluation and Allocation Model) offers a comprehensive approach, integrating economic, environmental, and social factors to inform land-use decision-making processes [56]. On the other hand, tools like LEAP (Long-range Energy Alternatives Planning) and OSeMOSYS (Open Source Energy Modelling System) focus on supporting energy system assessment and planning for energy transitions [10], [57]

The decision to utilize a particular software tool hinges upon several critical factors, notably the specific objectives of the modelling endeavor, the scale at which the analysis is conducted, and the accessibility of requisite data and expertise. In this context, the OSeMOSYS modelling tool has been chosen to align with the objectives outlined in this study.

1.5. Open Source Energy Modelling System (OSeMOSYS)

OSeMOSYS represents a tool that highlights the collaborative nature of the energy systems research community. Drawing on various perspectives and expertise, it serves as a transformative toolset that enables evidence-based decision-making and policy formulation for energy transitions. Its strategic capacity expansion tool is designed for national or regional-level energy planning [10].

The inception of OSeMOSYS in 2007 marked a significant milestone in the development of computational tools for energy systems analysis. This framework has since undergone continuous refinement, with contributions from a diverse range of organizations and scholars with expertise in energy systems research. This collaborative approach has resulted in a robust and versatile modelling platform that can tackle the complex challenges of the energy landscape [10].

By 2016, OSeMOSYS had matured into three distinct branches, each tailored to meet specific analytical demands and operational contexts within the energy domain. The foundational variant, originating from the UCL Energy Institute, embodies the core principles and methodologies of the model's conceptual framework. In parallel, a specialized iteration was developed by the Stockholm Environment Institute (SEI) in partnership with the World Bank, catering to the unique requirements of international development projects and policy formulation initiatives [10].

Furthermore, the Royal Institute of Technology in Stockholm's Department of Energy Systems Analysis (KTH-dESA) undertook a comprehensive re-factoring of OSeMOSYS, resulting in a refined version that prioritizes computational efficiency and methodological robustness. This re-factored variant has become the preferred standard for global applications in energetic modelling due to its superior performance and versatility in capturing the complex interplay of variables within energy systems dynamics [10], [58].

1.5.1. Core Objective of OSeMOSYS

The primary goal of OSeMOSYS is to identify the most cost-efficient energy service system that meets all energy service demands while adhering to several constraints, including technological, environmental, social, and political aspects. This tool encompasses various sectors, including heat, electricity, and transportation, to provide a comprehensive energy planning approach that can be tailored to specific spatial and temporal domains and scales [10], [58], [59].

OSeMOSYS stands out for its notable features, each contributing to its effectiveness as a tool for comprehensive energy system analysis. One key aspect is its transparent integration of resource availability, system transformation, and end-use dynamics. By openly incorporating

data on available resources and considering how systems evolve, OSeMOSYS provides a clear understanding of the factors shaping the energy mix [10], [13], [58] .

Furthermore, the model's inclusion of alternative competing technologies across all supply sectors ensures a thorough examination of diverse options, fostering informed decision-making. Another strength lies in its consistent treatment of both primary and secondary energy resources, ensuring an ideal representation of the full spectrum of energy sources [10], [58], [60].

Additionally, OSeMOSYS excels in its detailed accounting of energy service demands among various consumer groups, offering insights into specific sectoral needs and consumption patterns. Operating on a single time-step basis, usually on an annual basis, facilitates granular analysis of energy system dynamics within each period [13], [60], [61].

Last but not least, the model's ability to generate least-cost trajectories over multi-decade time horizons equips offers valuable long-term planning insights enabling the navigation into complex energy landscapes with clarity and precision [10], [58].

1.5.2. Exploring Energy Scenarios: Leveraging OSeMOSYS for Analysis

Beyond its primary focus on cost optimization, OSeMOSYS stands out for its flexibility and adaptability, allowing users to pursue a diverse array of objectives within energy planning and policy analysis. Through its flexible framework, users can define scenarios tailored to diverse goals, reflecting the nuanced landscape of energy challenges [10].

A scenario is a coherent representation of the future used to explore and understand possible developments and outcomes. In various fields such as strategic planning, scientific research, policy-making, and fictional storytelling, scenarios are powerful tools for analyzing and preparing for different future situations. Essentially, a scenario is a structured narrative that describes how certain factors, events, or conditions could evolve in the future, typically based on assumptions and projections [62].

Energy scenarios are shaped by specific objectives, assumptions, and inputs chosen by users, and serve as for addressing pertinent questions and navigating complex policy dilemmas. Whether the focus is on bolstering environmental resilience, enhancing equitable access to energy resources, or pursuing other socio-economic imperatives, OSeMOSYS offers a platform for scenario analysis that empowers stakeholders to chart informed pathways forward [10], [58].

1.5.3. Reference Energy System

Energy scenarios developed using OSeMOSYS indeed often begin with an existing Reference Energy System (RES) as the foundational framework [10], [12], [58]. The RES serves as a detailed representation of the current state of the energy system, encompassing various aspects such as energy infrastructure, technologies, fuels, energy demand, and policy frameworks.

It essentially maps out the entire energy or electricity system, providing a comprehensive overview of the existing landscape and it should be flexible enough to include future system extensions. By starting with the RES, users can establish a baseline from which to build and explore different future scenarios. This baseline serves as a reference point for understanding the current dynamics and constraints within the energy system [63].

A comprehensive RES overview illustrates how energy is generated, transmitted, converted, and consumed within the system, facilitating energy sector analysis, decision-making, and policy formulation [63], [64]. Its main components typically include:

 *Energy Supply Technologies: Power plants, renewable energy sources (e.g., solar, wind, hydro), nuclear reactors, and other energy generation forms.*

- ✚ *Energy Conversion Technologies: Devices or processes converting primary energy sources into usable energy forms, such as electricity, heat, or transportation fuels.*
- ✚ *Energy Demand Sectors: Representing energy-consuming sectors like residential, commercial, industrial, transportation, and agriculture.*
- ✚ *Fuel Types: Different fuels used within the system, including fossil fuels (coal, oil, natural gas), biofuels, hydrogen, and electricity.*
- ✚ *Infrastructure and Transmission: Essential components for energy transfer and distribution, such as Fuel transportation, transmission lines, distribution networks, storage facilities, and grid interconnections.*

1.5.4. Structure model of OSeMOSYS

Within OSeMOSYS energy system planning, users possess the ability to define and adapt technology and fuel parameters based on unique characteristics, data availability, and regional variances. In this context, the term “Parameter” represents a numerical input designated by the user, whereas “Variable” signifies the calculated output quantity of a model [10], [58].

The term “Technology” encompasses a wide variety of power plants and assets involved in energy conversion processes. This includes power plants fuelled by coal, natural gas, nuclear, or renewable sources, refineries, transmission lines, distribution networks, heating systems, and end-use appliances. This versatility enables the model to accurately capture the complexity of energy systems and their interactions [10], [60].

The term "Fuels" encompasses all energy sources and vectors used in electricity supply, including primary resources like natural gas, coal, and oil, as well as electricity and reserve capacity. By considering various energy vectors, the model can effectively analyze energy flows and conversions across different sectors and applications [10], [60].

OSeMOSYS employs a transfer function to capture the essence of each technology. This function outlines the conversion of inputs, such as fuel or resources, into outputs, such as electricity or heat. So far, OSeMOSYS encompasses a rich array of input parameters and output variables essential for conducting comprehensive energy system analyses [10], [58], [60].

The foundational elements of OSeMOSYS are its input parameters, which define the model's parameters, constraints, and assumptions. These parameters cover a wide range of factors that are essential for energy planning and policy analysis [58], [63], [64]. For example:

- ✚ *Energy demand projections: Provide insights into future energy needs across different sectors and regions.*
- ✚ *Input parameters: Include technology costs and performance characteristics, such as capital and operational costs, efficiency, and capacity factors, which inform energy technologies' economic viability and operational characteristics.*
- ✚ *Policy targets and constraints: Such as renewable energy mandates, emissions reduction goals, and other regulatory requirements, shape the modelling of policy scenarios.*
- ✚ *Parameters related to fuel availability: Provide essential information about the availability, cost, and accessibility of different energy sources. In contrast, economic parameters like discount rates and inflation rates help assess the financial implications of energy investments and policies.*
- ✚ *Inclusion of emission activity rates for technologies: Enables the modelling of environmental impacts and facilitates the evaluation of emissions reduction strategies.*

The Capacity Factor (CF) is an essential input parameter in energy modelling and analysis, providing valuable insight into a power plant or technology's efficiency over a given period [10], [64]. As represented by Equation 1.1, the CF of technology is the ratio of actual output

during a specific period, as defined in Equation 1.2, to the maximum possible output if the technology operated continuously at full capacity. It measures the technology's ability to generate power consistently and efficiently over time [65].

$$CF = \frac{\text{Actual Output}}{\text{Maximum Possible Output}} \times 100\% \quad (\text{Eq. 1.1})$$

$$\text{Actual Output} = \text{Input Energy} \times \eta \quad (\text{Eq. 1.2})$$

Where:

Actual Output [KWh]: The actual amount of energy produced by the technology over a specific period or during a specific time slice (t).

Maximum Possible Output [MWh]: The maximum amount of energy that could be produced if the technology operated at full capacity continuously during the same period.

Input Energy: The total energy input into the system. This could be in the form of fuel, electricity, irradiation, etc.

η : The efficiency of the technology, expressed as a decimal or percentage. It represents the ratio of useful output energy to the total input energy.

In OSeMOSYS, the CF value is between 0 and 1 indicating the proportion of the maximum potential energy production that was realized [64]. A CF of 1 would mean the plant operated at full capacity, generating its maximum energy output, while a CF of 0 would mean the plant generated no energy at all. This normalization allows for easier comparison and integration of the CF values across different technologies, periods, and scenarios within the energy modelling framework.

On the other hand, OSeMOSYS generates a plethora of output variables that provide insights into the optimized energetic configurations [60]. These outputs provide a detailed breakdown of the contribution of each technology to the overall energy mix, shedding light on the role of different energy sources in meeting demand over time. In addition, typical examples include:

- ✚ *Capacity additions* for each energy technology, offering guidance on investment priorities and infrastructure development needs.
- ✚ *Economic features* such as capital costs, variable costs, and fixed costs associated with energy provision enabling users to assess the financial implications of different scenarios and identify cost-effective strategies for energy planning and investment.
- ✚ *Emissions trajectories* are also generated, allowing users to evaluate the environmental impacts of different energy scenarios and assess progress towards decarbonization goals.

Appendix A in the accompanying documentation provided with OSeMOSYS [66] offers a list of default sets of input parameters and output variables widely utilized in this thesis. With an extensive range of input parameters and output variables available, OSeMOSYS empowers users to conduct in-depth analyses and obtain strategic insights into the complexities of energy systems. These features enable nuanced examinations of multiple scenarios, aiding informed decision-making in energy planning and policy formulation [10].

The structure of OSeMOSYS allows for breaking down the annual demand into representative time slices parameter. These slices determine the time resolution of the model and reflect the time split of each modelled year. Separating high-demand times from low-demand times, also known as demand shifting or demand-side management, is a crucial strategy for optimizing energy storage costs, improving system reliability, and maximizing energy system efficiency[10], [58], [64].

To save computation time, these time slices are often grouped into aggregate seasons such as "summer," "winter," and "spring" that are specific to the region being considered. Each season is associated with its demand levels. These seasons may be further subdivided into "day types," such as workdays and weekends. Additionally, each day may be further divided based on demand levels, such as into day and night [64].

OSeMOSYS generates a single optimized energy mix for a particular scenario. This mix is the most cost-effective allocation of energy resources, technologies, and investments that fulfil the required energy demand and policy objectives. The reason for producing a single energy mix is that the model uses an optimization process to find the cheapest solution that meets energy demands and objectives. OSeMOSYS assumes that a centralized decision-making entity selects energy technologies and resources based on complete knowledge about future conditions and competitive market dynamics [10], [67].

Although utilizing a single energetic mix can aid in simplifying result interpretation and decision-making, it's crucial to acknowledge that the actual energy landscape is frequently marked by diversity and complexity. Various factors, like regional variances, technological advancements, policy interventions, and market dynamics, can influence the optimal energy mix in practice. Consequently, even though OSeMOSYS offers beneficial perspectives into potential pathways for energy planning and policy formulation, users must approach its results with caution and account for the model's assumptions and limitations when applying them to final decision-making [10].

1.5.5. OSeMOSYS Optimization Function

As said previously (Section 1.5.1.), OSeMOSYS aims to minimize the total costs involved in energy supply while meeting specified constraints and objectives. The Total cost refers to the aggregate cost associated with supplying energy to meet the specified demand while adhering to various constraints and objectives. It encompasses the OSeMOSYS input cost components including the Capital, Fixed, Variable, and Emission Costs [10], [68].

From a mathematical standpoint, the primary objective of OSeMOSYS lies in the minimization of total costs, a goal encapsulated within an optimization function typically formulated as an objective function representing the Total costs incurred over the model period [58], [68], [69].

Equation 1.3 serves as a representation of OSeMOSYS's objective optimization function, herein referred to as Standard Optimization (Op_Standard). This specific nomenclature (Op_Standard) is chosen deliberately to align with the default optimization function inherent to OSeMOSYS, which predominantly emphasizes economic optimization.

Consequently, Op_Standard serves as a fundamental benchmark for assessing the economic efficacy of the energy system under analysis. The mathematical structure delineating the optimized TotalCost is succinctly expressed through Equation 1.4.

$$\text{Op_Standard} = \text{Min} \sum_{r,y} \text{Total_Cost}_{r,y} \quad (\text{Eq 1.3})$$

$$\text{Total_Cost}_{r,y} = \text{Capital_Cost}_{r,t,y} + \text{Variable_Cost}_{r,t,y} + \text{Fixed_Cost}_{r,t,y} + \text{Emission_Cost}_y \quad (\text{Eq 1.4})$$

Where:

r, y, and t: Represent respectively the region in which occurs the modelling, each annual time frame of the modelling, and the technologies included in the RES.

Op_Standard: Is standard OSeMOSYS objective function ensuring strict economic optimization.

Total_Cost [\$]: This is the total or global cost of the system along the time interval under study.

Capital_Cost [\$ /MW]: Represent the Capital Cost of each technology in the RES for each corresponding year. These are the upfront investment costs required to build or install energy generation, transmission, and distribution infrastructure.

Variable_Costs[\$ /MWh]: Represent the Variable Cost of each technology in the RES for each corresponding year. These are costs that vary with the level of operation and energy production or consumption, such as fuel costs for thermal power plants or variable operation and maintenance costs.

Fixed_Costs [\$/MW]: Represent the Fixed Cost of each technology in the RES for each corresponding year. These are costs that remain constant regardless of the level of energy production or consumption, such as fixed operation and maintenance costs, insurance premiums, and administrative expenses.

Emission_Cost [\$]: Represent the Emission Cost for each corresponding year.

The Emission Cost accounts for the monetary cost associated with emissions of pollutants or greenhouse gases and is factored into the optimization process based on whether emission penalties per unit of emission are applied [70]. This parameter plays a crucial role in addressing environmental concerns within the optimization framework. Equation 1.5 gives the mathematical formulation of the emission cost, encompassing both emission penalties and the Rate of emission activity of technologies within the RES per unit of activity.

$$\text{Emission_Cost}_y = \sum_y \text{Emission_Penalty}_{r,e,y} \times \text{Emiss_Rate}_{r,t,e,y} \quad (\text{Eq 1.5})$$

Where:

e: Represents the GHG considered for the study.

Emission_penalty [\$/t CO₂ eq]: The cost penalty per unit of emission, typically in monetary units.

Emission_Rate [t CO₂ eq]: The emission rate of technologies in the RES, representing the amount of pollutants or greenhouse gases emitted per unit of activity such as energy production or consumption.

Despite its many variations, OSeMOSYS remains a cohesive reference framework with unique features and capabilities. Since its conceptualization dates to 2008, its principles framework was comprehensively outlined in a published article in 2011. Originally developed using GNU MathProg, OSeMOSYS underwent a transformative shift, transitioning exclusively to GAMS (General Algebraic Modelling System) [10], [58].

Characterized by approximately seven hundred lines of text, the code of OSeMOSYS within GAMS architecture assumes the semblance of algebraic expressions, thereby enhancing clarity and facilitating comprehension [58]. To expand accessibility to a wider range of user and coder communities, parallel versions of the code were created in both GAMS and Python and were seamlessly integrated with the GNU Linear Programming Kit (GLPK) [71].

GLPK serves as an open-source solver adept in resolving linear programming and mixed-integer linear programming problems [71]. Equipped with a suite of tools and libraries, GLPK streamlines the construction, solution, and analysis of linear programming models, thereby extending its utility across various domains, including operations research, optimization, economics, and engineering. Leveraging GLPK, users can efficiently convert models into matrices, identify optimal solutions, and generate numerical outputs, thus enhancing the strategic capacity expansion and energy planning capabilities of OSeMOSYS [58].

Functioning as a deterministic, linear optimization model tailored for long-term planning, OSeMOSYS incorporates mixed-integer linear programming to optimize discrete functions, such as power plant capacity expansion [10], [13], [58]. Notably, OSeMOSYS is characterized by a modular structure, comprising distinct code blocks that can be readily modified to accommodate the specific requirements of users [58].

This modular approach renders OSeMOSYS versatile, enabling its application across diverse contexts, irrespective of scale, complexity, or objectives [13], [60], [71]. Consequently, OSeMOSYS has been leveraged in numerous studies, where its inherent flexibility has been instrumental in devising novel analytical approaches. A comprehensive review of the literature reveals that authors have harnessed the adaptability of OSeMOSYS to establish innovative methodologies and address a myriad of research questions.

The research conducted by A. Dhakouani et al. [68], illuminates the Tunisian power system as a pertinent case study to elucidate the integration of power reliability as a pivotal optimization component within the OSeMOSYS framework. Their investigation highlights the intricate dynamics at play, wherein energy-efficient measures, and peak clipping strategies,

while effective in reducing energy demand and peak loads, paradoxically present challenges to power system reliability. Additionally, the study reveals that a significant increase in renewable energy deployment, although essential in reducing carbon emissions, may concurrently create reliability concerns within the power system. This nuanced understanding emphasizes the importance of comprehensive energy planning strategies that reconcile sustainability goals with reliability targets, providing valuable insights for navigating the complexities of Tunisian energy transitions.

G. Godinez-Zamora et al. [72] provide a comprehensive guide to achieving net-zero emissions in Costa Rica's National Decarbonization Plan, using OSeMOSYS as a key analytical tool. Their research indicates that achieving this ambitious goal will require significant investment in renewable energy infrastructure by 2050. However, the study also reveals that these investments can be offset by substantial reductions in operating costs, making a shift toward deep decarbonization achievable. The findings highlight the importance of integrating renewable energy into sustainable development plans, while also emphasizing the economic viability of such initiatives within the context of Costa Rica's decarbonization efforts.

In response to shocks evaluated through the lens of OSeMOSYS flexibility J. Augutis et al. [69], have developed a methodological optimization framework to evaluate energy generation technologies through the lens of OSeMOSYS flexibility. Their study focuses on energy security considerations and assesses the resilience of the energy system against disturbances. The findings reveal that gas technology is the dominant component of the energy mix within this framework due to its stability and resilience to shocks. On the other hand, nuclear technology exhibits a comparatively lower level of stability and experiences a decline in market share as renewable energies gain prominence. This detailed analysis highlights the complex interplay between technological choices, energy security imperatives, and market dynamics. It provides valuable insights for policymakers and stakeholders as they navigate the intricacies of energy transition pathways.

In their study, T. Niet et al. [73] have expanded the analytical abilities of OSeMOSYS by introducing a stochastic risk structure into its optimization model. This modification is designed to alleviate the natural uncertainty surrounding emissions from energy generation technologies. The integration of this stochastic framework provides a nuanced assessment of risk within energy planning and decision-making processes, which enhances the model's ability to account for variability and unpredictability in emissions outcomes. By refining this methodology, policymakers and stakeholders can gain a more comprehensive understanding of the potential risks associated with various energy pathways, allowing them to make informed decisions that prioritize resilience and sustainability in the face of uncertain environmental factors.

In their research, P. de Moura et al.[59], conducted research utilizing OSeMOSYS to investigate the potential for power system interconnection operations and cross-border trade in renewable energy generation between Brazil and its South American neighbors. The study analyses the intricate dynamics of energy diplomacy, assessing the bargaining power of each participating country using the Shapley value concept. Leveraging the analytical capabilities of OSeMOSYS, the authors provide insights into the economic and strategic implications of regional energy integration and shed light on the opportunities and challenges inherent in fostering collaborative approaches to renewable energy deployment and cross-border energy trade. This comprehensive examination contributes to the discourse surrounding sustainable energy transitions and emphasizes the importance of multilateral cooperation in advancing regional energy security and resilience agendas.

As part of the thesis development and extra academic activities, OSeMOSYS has been instrumental in developing energy plans for several medium-sized case studies. These endeavors include published research that highlights strategic initiatives aimed at decarbonizing the industrial park of Bemibre [67]. By utilizing OSeMOSYS, we have outlined pathways to optimize energy consumption, create job opportunities, minimize carbon emissions, and enhance the overall sustainability profile of the industrial park. These efforts serve as tangible examples of how OSeMOSYS can be applied in real-world contexts, guiding decision-makers towards more informed and impactful energy planning strategies.

Since its inception, OSeMOSYS has evolved significantly, undergoing various enhancements aimed at improving simulation conditions and expanding its capabilities. One key area of improvement has been the optimization algorithms used within OSeMOSYS [58], [70]. Efforts have been made to refine the timing techniques employed during the optimization process, resulting in more efficient and accurate simulations. These enhancements have helped to streamline model execution and improve the reliability of results [10], [13].

Additionally, OSeMOSYS has seen the integration of new coding blocks to represent various aspects of the energy system better. For example, storage capabilities have been added to model the role of energy storage technologies in balancing supply and demand. Short-term flexibility options have also been incorporated to capture the dynamics of energy generation and consumption in response to changing conditions [10], [58].

Furthermore, enhancements have been made to model interconnections between different regions or energy markets, allowing for a more comprehensive analysis of energy systems at a regional or global scale. These improvements enable OSeMOSYS to better account for cross-border energy flows and the impacts of regional policies and infrastructure investments [58].

1.5.6. Model Management Infrastructure OSeMOSYS Interface

OSeMOSYS offers a variety of user-friendly interfaces designed to optimize model execution and improve accessibility across different computational environments. These interfaces, including Otoole, Osinda, ClicSand, Notepad++, and MoMani (Model Management Interface), provide intuitive tools for setting up model inputs, running simulations, and analyzing results. By simplifying the integration of OSeMOSYS into decision-making processes, these interfaces enhance its usability, adaptability, and accessibility, empowering researchers, policymakers, and stakeholders to tackle complex energy system challenges with accuracy and efficiency within a user-centric framework [74].

While OSeMOSYS applications can be created and run within an interface, for this work, we have chosen MoMani, a browser-based open-source and free interface that allows for creating models and visualizing results, available in both online and desktop versions. MoMani is tailored specifically for OSeMOSYS, offering users a comprehensive platform for creating, managing, and executing energy system models. This interface provides a user-friendly environment that simplifies the often-complex process of model development and result visualization [64].

The selection of MoMani is driven by its capability to streamline data manipulation and alleviate the requirement for extensive manual coding within the modelling process. By offering functionalities to modify, add, or delete equations, MoMani simplifies the customization of OSeMOSYS models according to specific research or policy objectives [58], [64].

Moreover, MoMani facilitates the seamless operation of OSeMOSYS, enabling users to execute simulations, design scenarios, and analyze results within a unified interface. Its user-friendly design provides an intuitive platform to edit and update any aspect of the modelling process, ranging from the fundamental mathematical equations underlying OSeMOSYS to the

visualization of output data. Through MoMani's interactive visualization tools, users can explore and analyze model results with clarity and interactivity, empowering informed decision-making and facilitating a deeper understanding of complex energy system dynamics [64].

1.6. Methodology: Case study Atlantis power mix scenario.

MoManI incorporates Atlantis as one of its pre-built energy frameworks, specifically designed to validate methodologies and facilitate controlled assessments of their reproducibility. Atlantis is highly regarded within the scientific community for its role as the primary experimental energetic setup framework for testing and validating the feasibility of newly developed methods within OSeMOSYS [64].

Atlantis is distinguished by its comprehensive and well-structured design, which incorporates various power generation technologies, including renewables, non-renewables, and nuclear power. This diversity allows for a thorough examination of developed approaches and makes it easier to reproduce results [64].

This diversity not only facilitates a thorough examination of developed approaches but also allows for the exploration of different scenarios and policy designs. Researchers can analyze how various combinations of energy sources affect system reliability, environmental sustainability, and economic viability. Furthermore, it provides a platform for assessing the applicability of methodologies to different contexts and the actuality of their outcomes in real-world settings.

In this thesis, the selection of Atlantis to evaluate and confirm the feasibility and reproducibility of the developed contributions within OSeMOSYS appears to be a logical and rigorous choice. It demonstrates a commitment to ensuring the reliability and validity of the developed methodologies.

1.6.1. Atlantis Model Mapping

The report on the Atlantis energy framework outlines the operation of five power plants, each fueled by a specific imported resource [64]. These include a large hydropower plant, a single-cycle steam turbine fueled by natural gas, another single-cycle steam turbine fueled by heavy fuel oil, a diesel-fed gas turbine, and a coal-based integrated gasification combined cycle facility.

As we approach the four-year mark since the initial modelling period, the Atlantis framework is expanding, underscoring the importance of exploring the feasibility of integrating new technologies to improve the energy system's efficiency. These technologies include wind turbines with a maximum annual energetic production capacity of 555 GWh, mini hydro power plants (less than 1 MW of annual installed capacity), grid-connected PV systems for commercial use, a light water reactor-based nuclear power plant, and new combined cycle power plants powered by natural gas.

The depiction of the Atlantis RES in Figure 1.4 presents a comprehensive framework consisting of five main energy levels: Resources, Primary, Secondary, Tertiary, and Final energy. This hierarchical structure illustrates the flow of energy horizontally from the initial resource extraction and utilization on the far left to the final energy consumption on the far right.

Each level involves distinct processes of energy transformation and distribution, facilitated by various technologies represented as blocks. The lines connecting these blocks symbolize energy carriers such as coal, natural gas, and electricity, highlighting the diverse sources utilized throughout the energy value chain.

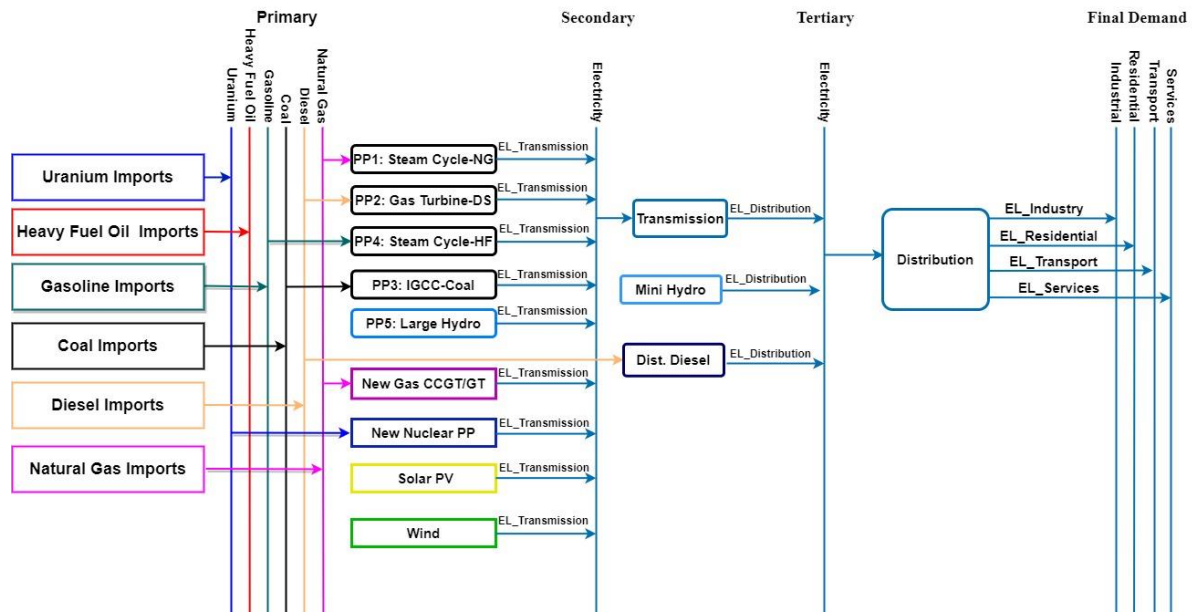


Figure 1.4 Atlantis Reference Energy System
This figure is reproduced from the following reference [64]

Moreover, the segmentation of final energy demand into different sectors, including industry, services, residential, and transportation, underscores the multifaceted nature of energy consumption patterns. This visualization aids in understanding the intricate interactions within the energy system, facilitating modelling, optimization, and result analysis.

The categorization of energy demand into various sectors, namely industry, services, residential, and transportation, highlights the complex nature of energy consumption habits. This detailed classification provides a deeper insight into the usage of energy across different aspects of these sectors, thereby facilitating the identification of specific areas for improvement. This, in turn, enhances the potential for modelling, optimization, and outcome analysis within the Atlantis RES.

1.6.2. The temporal and spatial range of the case study

The concept of time slices as discussed in (Section 1.5.4) reveals the division of each modelled year into segments, providing the model with a specific temporal resolution to accurately represent the yearly demand. In this study, the period under consideration spans from 2024 to 2050, and the yearly electricity consumption is distributed across six time slices.

Table 1.1 Atlantis Time Slice set

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Season	Time slice	Year split	Hour per time slice	Number of months per season
Intermediate	ID	0.1667	16	3
	IN	0.0833	8	
Summer	SD	0.1667	16	3
	SN	0.0833	8	
Winter	WD	0.3333	16	6
	WN	0.1667	8	

Atlantis has defined six time slices as ID, IN, SD, SN, WD, and WN, representing three seasons (Intermediate, Summer, and Winter) and two daily types (Days and Nights) [70]. The assumption made by Atlantis is that these year splits will remain constant and unchanging over

time. The specific parameters for Atlantis' year split hypothesis for each season are detailed in Table 1.1

1.6.3. Electric Demand Side Management

Figure 1.5 provides a comprehensive overview of the annual electricity demand, the daily distribution profile, and the sectoral composition, aiding in understanding the demand landscape utilized in this study. The electricity demand within the Atlantis framework is distributed across four key sectors: industry, residential, services, and transport. Notably, residential demand represents the largest share, followed by industry, services, and transport, as depicted in Figure 1.5 (c).

While the annual electricity demand highlights a gradual increase over time [75], as illustrated in Figure 1.5 (b), the daily distribution is modeled with a consistent pattern across the daily types. Specifically, daytime demand is estimated to be double that of nighttime demand Figure 1.5 (a). These assumptions are fundamental components of the Atlantis model [64], although it is acknowledged that they may not fully capture the intricacies of real-world electricity demand management.

It is essential to acknowledge and retain these assumptions within the study's framework. The primary objective of this research is to evaluate the sustainability of different generation technologies, rather than delve into the complexities of electricity demand dynamics. Thus, maintaining the existing electricity demand profile within the Atlantis model ensures consistency and enables meaningful comparisons in sustainability assessments.

Energy losses in electrical transmission and distribution systems are important considerations for analyzing power delivery efficiency. Transmission lines transport electricity over long distances from power plants to substations or between substations [76]. These lines typically operate at high voltages to minimize energy losses during transmission. On the other hand, distribution networks deliver electricity from substations to end-users, such as residential, commercial, and industrial customers. These networks operate at lower voltages compared to transmission lines and cover shorter distances.

In the case of Atlantis, only a small amount (2%) of the electricity is lost as heat during the long-distance transmission phase. In comparison, a larger proportion (5%) of energy is lost during the distribution phase compared to the transmission phase [64].

1.6.4. Working Hypothesis

Table 1.2 presents the essential input parameters for the Atlantis technologies utilized in this study. These parameters encompass crucial aspects such as the cost components, emission activity per unit of energy production, and the useful lifetime (ULT) of each technology. These input data are derived from the Atlantis default parameters [64], and serve as the foundation for our analysis.

The technical and economic input data employed in Atlantis were sourced from IRENA reports and IEA-Energy Systems Analysis Program-Technology briefs (E01, E02, E03, E06, E10, and E11). Nonetheless, it was discovered that certain default input parameters were not optimally configured and, as a result, were modified to offer a more accurate depiction.

The variable costs and emissions per unit of activity are derived from authoritative sources such as IRENA [77], [78] and the World Bank reports for each technology [79] to estimate the variable costs and for emissions [80], [81]. They serve as crucial inputs for our analysis, providing a robust foundation for evaluating the economic and environmental aspects of energy generation technologies.

Among the parameters that have been adjusted in the model, include the maximum annual output of the large hydroelectric plant, which has been constrained to 555×10^3 MWh, deviating from the usual unrestricted production.

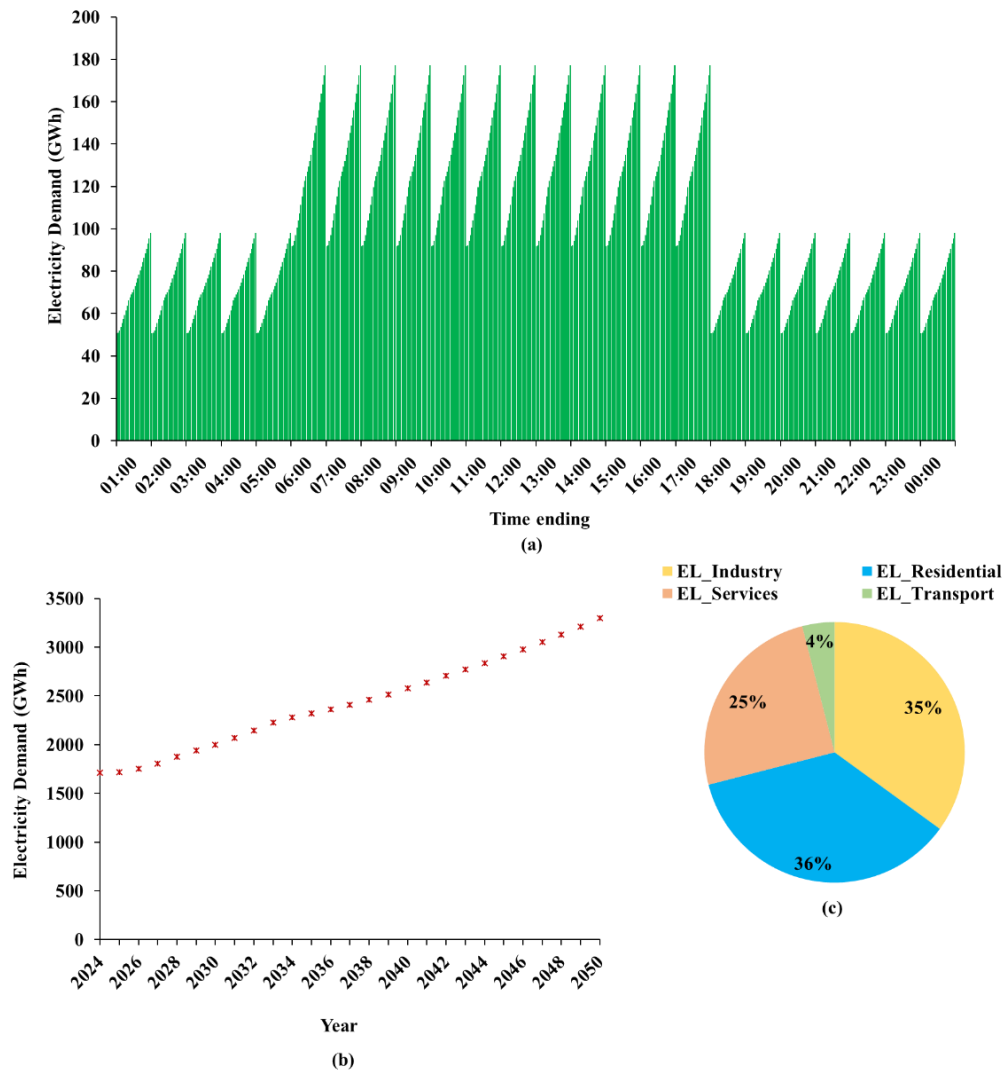


Figure 1.5 Atlantis power load considered for the analysis: (a) Daily electricity demand; (a) Annual electricity demand; (b) Percentage of demand per sector.

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Table 1.2 Key input parameters: economic cost, emission activity, and useful lifetime

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Technologies	Variable Cost (\$/MWh)	Fixed Cost (\$/MW)	Capital Cost (\$/MW)	Emission activity ratio (CO ₂ /MWh)	Useful Lifetime (Year)
Natural Gas (NGSC)	86.51	4.40×10 ⁴	2.30×10 ⁶	0.475	30
Diesel Generator (DSGC)	80.90	3.60×10 ⁴	9.00×10 ⁵	0.694	30
Integrated Gasification Coal (IGCC)	41.65	1.48×10 ⁵	3.70×10 ⁶	0.964	30
Heavy oil (HFSC)	108.74	5.00×10 ⁴	2.30×10 ⁶	0.730	35
Large Hydro (Hydro Dam)	0	6.00×10 ⁴	4.00×10 ⁶	0.694	35
Mini Hydro (Hydro_Min)	0	6.50×10 ⁴	4.50×10 ⁶	0.363	50
Distributed Diesel (Diesel_Gen)	80.86	5.50×10 ⁴	1.07×10 ⁶	0	40
Photovoltaic Utility Grid (PV_UTL)	0	0	2.00×10 ⁶	0	25
Wind	0	0	1.85×10 ⁶	0	25
NEW Combined Cycle Gas Turbine (NGCC)	58.17	4.40×10 ⁴	1.10×10 ⁶	0	35
Nuclear	22.01	0	3.00×10 ⁶	0.014	50

Table 1.3 Capacity factor for each technology in each of the defined time slices
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Category	Technology	Capacity Factor (CF)					
		Time Slice					
		ID	IN	SD	SN	WD	WN
Fossil Fuels	NGSC	1	1	1	1	1	1
	DSGC	1	1	1	1	1	1
	IGCC	1	1	1	1	1	1
	HFSC	1	1	1	1	1	1
	Diesel_Gen	1	1	1	1	1	1
	NGCC	1	1	1	1	1	1
Renewable Energy	Hydro Dam	0.45	0.45	0.34	0.34	0.50	0.50
	Hydro_Min	0.40	0.40	0.34	0.34	0.56	0.56
	PV	0.35	0	0.35	0	0.35	0
	Wind	0.25	0.25	0.25	0.25	0.25	0.25
Nuclear	Nuclear	1	1	1	1	1	1

The Capacity Factor employed for each technology aligns with the predefined settings in the Atlantis default configuration [64], as detailed in Table 1.3 across each time slice. Notably, an adjustment has been made specifically for the solar photovoltaic (PV) system to ensure a capacity factor (CF) of 35%, deviating from the customary 15% in the default configuration.

Considerable attention is dedicated to the treatment of technologies' Useful Lifetime (ULT) within the OSeMOSYS optimization framework (See Table 1.2). While certain technologies may necessitate complete replacement at the end of their operational lifespan such as photovoltaic (PV) systems or diesel generators among others [82], particularly those entailing extensive civil structures like hydroelectric dams or intricate thermal installations like nuclear or gas power plants, may exhibit prolonged operational lifespans beyond those listed in Table 1.2.

The ULT estimations in Table 1.2, notably for technologies featuring substantial civil structures such as Hydro_Dam, Nuclear HFSC, NGCC, and NGSC, align with the concept of the Ageing Factor. This factor denotes the gradual material degradation over time due to operational conditions. For instance, nuclear plants are typically presumed to have operational lifespans of up to 50 years, while thermal power plants or hydroelectric facilities may be estimated to operate for around 30 years [83].

It's essential to distinguish between the estimated lifespans of individual components and the overall structural integrity of power generation facilities. Thermal power plants typically incur material replacement costs for major components like turbines, boilers, and generators. Research conducted by the International Energy Agency (IEA) indicates that these replacement costs usually range from 15% to 20% of the total investment required to construct a new plant [84].

In the case of nuclear power plants, the cost of material replacement is influenced by various factors, including reactor vessel and steam generator replacements. According to a report by the U.S. Nuclear Regulatory Commission (NRC) [85], replacing major components in existing nuclear facilities can account for 10% to 20% of the total investment cost of building a new nuclear plant.

On the other hand, hydroelectric power plants tend to have lower material replacement costs due to simpler technology and fewer safety concerns compared to thermal and nuclear facilities. Studies conducted by the IRENA estimate that replacing major components in hydroelectric plants constitutes approximately 10% to 15% of the total investment cost of constructing a new hydroelectric facility [86].

This distinction underscores the significant discrepancy between the lifespans of individual components and the overarching operational lifespan of power generation facilities, underscoring the necessity of integrating factors of investment cost strategies for technologies featuring substantial civil structures. However, complexities may arise within OSeMOSYS configurations when addressing the conclusion of the operational lifetime of large-scale installations. Instead of solely considering the costs linked to replacing degraded materials, the post-ULT investment cost is often calculated as if constructing an entirely new plant.

This disparity in cost estimation methodologies warrants further examination to ensure the precise representation of investment requirements within the optimization framework. While this specific weakness within OSeMOSYS remains unaddressed within the framework and scope of this study, it merits explicit acknowledgment for consideration in future research endeavors.

1.6.5. Post-optimization: Selection of the output results merit variables

Among the various output variables that result from OSeMOSYS optimization, the selection of merit variables holds paramount importance, notably encompassing energetic production, economic costs, and emissions. These variables serve as pivotal benchmarks for presenting the outcome of a single scenario analyzed within this thesis to facilitate comparative assessments across diverse scenarios.

The rationale behind the preference for these specific variables stems from contemporary trends observed among policymakers within the energy sector. Notably, there exists an escalating concern surrounding the optimal production rate, characterized by an intricately balanced energetic mix. This balance is crucial for assessing the proportional contribution of each technology in the energy landscape, particularly in endeavors aimed at mitigating emissions amidst the prevailing context of global warming. Additionally, the consideration of economic and financial impacts is imperative, given their significant ramifications on energy transitions and overarching policy frameworks.

The chosen merit variables, selected for analysis, are scrutinized as integral components within the defined temporal framework ranging from 2024 to 2050. This temporal delineation holds significant relevance, particularly in the context of assessing a diverse spectrum of energy sources, exemplified by the case of Atlantis RES. The systematic examination of these merit variables serves to elucidate their intrinsic importance and influence within the specified timeframe, thereby enhancing the rigour and comprehensiveness of the analytical process.

The process of categorizing technologies serves to streamline analytical procedures, fostering clarity and facilitating comparative assessments of their performance. Therefore, within the framework of this study, Atlantis technologies are systematically classified into distinct categories for comprehensive evaluation. The Atlantis technologies are categorized as follows:

- ✚ *The Renewable Energy category includes solar PV, wind, large, and mini hydro.*
- ✚ *The Fossil Fuels energy category includes NGCC, NGSC, IGCC, HFSC, DSGC, and Diesel_Gen.*
- ✚ *The Nuclear category is considered separately to further explore its sustainability.*

For each optimization scenario, the presentation of results will encompass the following components:

- ✚ *A schematic portrayal delineating the annual energy production trends per technology, aimed at highlighting the competitive edge of various technologies.*

- ✚ *The determination of global energy production within each energy category entails the comprehensive summation of energy production attributed to individual technologies belonging to respective categories throughout the entire duration under examination.*
- ✚ *The cost analysis comprises three principal components: Global Capital Cost, Global Variable Cost, and Global Fixed Cost, each contributing to the overall economic assessment.*
- ✚ *The estimation of global emissions involves the meticulous consideration of annual emissions corresponding to the energy mix across the entirety of the study period. This approach ensures a comprehensive evaluation of environmental impact over time of the corresponding scenario.*

In addition, to delve deeply into the ramifications of optimization on energetic contribution, economic considerations, and environmental impact, a set of merit variables has been defined, comprising:

- ✚ *The Rate of Production (RoP %) serves as a variable to quantify the proportion of energy contribution attributed to each predefined energy category within the overall energy mix.*
- ✚ *The Global Cost per Unit of Energy Production, which offers a comprehensive assessment of the net present cost associated with electricity generation for each unit of energy produced across the entirety of the energy mix throughout the entire study period.*
- ✚ *The Residual Electricity Price (R_{price}), denoting the prevailing electricity tariff, thereby capturing the economic implications of energy production.*
- ✚ *The Global Emissions per Unit of Energy Produced, a variable that accounts for the aggregate emissions stemming from the energy mix per unit of energy generated over the entire duration under consideration, thus providing insights into the environmental footprint associated with energy production.*

Detailed mathematical formulations of the defined merit variables are provided in Appendix B.

1.7. Developing Insight Through Optimization: Example of Atlantis Standard Economic Optimization (Op_Standard)

The standard economic optimization (Op_Standard), utilizes the default OSeMOSYS optimization function, with a primary focus on economic considerations. The findings from the Atlantis Op_Standard, presented in this section, carry substantial significance as they establish the baseline optimization against which the outcomes of subsequent initiatives, discussed in forthcoming chapters, can be compared.

Figure 1.6 illustrates the annual energy production trend observed in Op_Standard. Among the technologies considered, Hydro_Min, Nuclear, Wind, Solar, and IGCC demonstrate considerable potential in terms of economic viability. In contrast, DSGC emerges as economically inefficient. Furthermore, Hydro_Dam, NGSC, and HFSC exhibit a lack of economic competitiveness, particularly evident from 2027 onwards, coinciding with the commencement of network expansion.

The detailed breakdown of merit variables resulting from Op_Standard is provided in Table 1.4. Notably, Op_Standard delineates an energy composition predominantly reliant on renewable sources, which collectively contribute up to 60% of the total energy output. The remaining 40% is divided between nuclear and fossil fuel-based generation, as depicted in Table 1.4.

It is worth highlighting that the Rate of Production for nuclear energy exhibits economic competitiveness equivalent to that of the fossil fuel category, each representing a 20% share. This allocation corresponds to a cumulative emission of ten to the power of six tons over the 26-year study period.

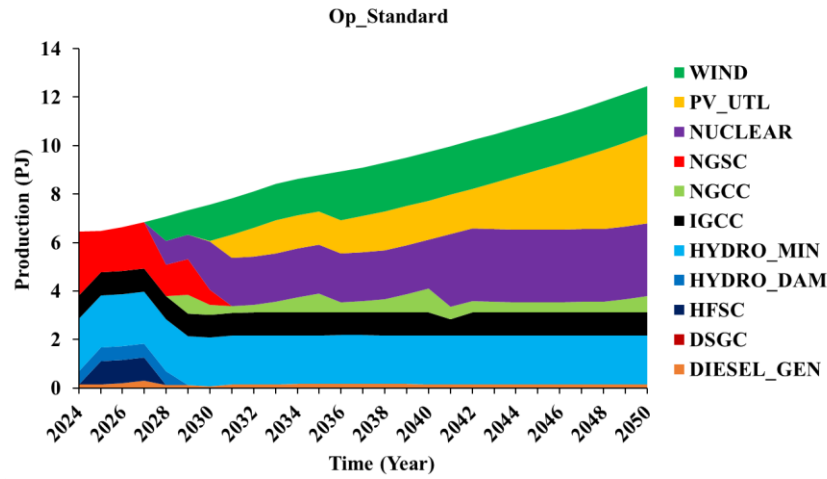


Figure 1.6 Op_Standard: Annual energy production per technology
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Table 1.4 Op_Standard: Details of the merit variables
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Energetic trend	Global Energy Production (MWh)	Renewable Energy	38594×10^3
		Fossil Fuels	14238×10^3
		Nuclear	15012×10^3
	RoP (%)	Renewable Energy	57
		Fossil Fuels	21
		Nuclear	22
Economic trend	Economic Cost features (\$)	Capital Cost	1867×10^6
		Variable Cost	2882×10^6
		Fixed Cost	773×10^6
	Economic Cost per unit of energy production (\$/MWh)	Global Cost	80.09/MWh
		Residual Price	53.01/MWh
Emissions trend	Global Emissions (t CO ₂)		11.05×10^6
	Global Emissions per unit of energy production (t CO ₂ /MWh)		0.160

In terms of economic implications, the electricity price remains fixed at a rate 30% lower than the global cost, attributable to a significant disparity in capital investment costs, which are notably $\$1788 \times 10^6$ lower than operational and maintenance expenses.

1.8. Chapter Conclusions

In this chapter, we explored the intricacies of OSeMOSYS, highlighting its operational principles, parameters, variables, and the core optimization functions that form its foundation. OSeMOSYS stands out as a robust tool for comprehensive energy system analysis, offering transparency in resource availability, system transformation, and end-use dynamics. Its ability to incorporate alternative competing technologies across all supply sectors and its consistent treatment of both primary and secondary energy resources make it indispensable for informed decision-making in energy planning and policy formulation.

We also examined the model's detailed accounting of energy service demands across various consumer groups, emphasizing its utility in sectoral analysis and consumption pattern insights.

The capacity to generate least-cost trajectories over extended time horizons provides valuable long-term planning insights, essential for navigating complex energy landscapes.

Further, the chapter introduced the Atlantis energy framework, used as a case study to assess the feasibility of the developed methodology (in Chapter 2). This framework exemplifies the application of OSeMOSYS in real-world scenarios, highlighting the importance of detailed parameter and assumption delineation in scenario development.

A key aspect of this chapter is the discussion of sustainable development, tracing its evolution from environmental and social concerns to a broader concept integrating economic advancement, environmental preservation, and social equity. This historical perspective underscores the need for balanced development approaches, aligning with contemporary global goals such as the Sustainable Development Goals (SDGs).

By systematically categorizing technologies and scrutinizing merit variables within a defined temporal framework, we ensured a rigorous and comprehensive analytical process. This approach not only enhances the clarity of comparative assessments but also fosters a deeper understanding of the intrinsic importance and influence of various energy sources over time.

In conclusion, this chapter provides a foundational understanding of OSeMOSYS and its application in energy system optimization, setting the stage for subsequent chapters that will delve deeper into the practical outcomes and implications of using this model in diverse energy scenarios. Through detailed analyses and case studies, we aim to elucidate the pathways toward sustainable and cost-effective energy solutions, contributing to the broader discourse on sustainable development and energy policy

Chapter 2. Objectives

The primary objective of this thesis is to address a significant limitation in current energy modelling and transition tools: their inadequate consideration of sustainability criteria. Specifically, this study aims to enhance the Open Source Energy Modeling System (OSeMOSYS) by integrating key sustainability indicators into its optimization function.

This enhancement seeks to improve the model's capacity to support medium to large-scale sustainable energy planning, reflecting a broader commitment to the responsible stewardship of natural resources and the well-being of both current and future generations.

The objectives of this work lie in the incorporation of widely used sustainability indicators into the OSeMOSYS objective function. The sustainability indicators integrated into the model include:

-  **Energetic Sustainability Indicator**, quantified by the Energy Payback Time (EPBT).
-  **Economic Sustainability Indicator**, measured by the Internal Time of Return (ITR).
-  **Environmental Sustainability Indicator**, evaluated through the Impact Mitigation in terms of Climate Change (IMPcc).

By incorporating these indicators and their convolution, the model provides a more comprehensive framework for measuring the sustainability of different energy scenarios, thereby guiding decision-making towards more sustainable outcomes.

Integrating these sustainability indicators into the OSeMOSYS objective function presents a unique challenge, as these indicators are measured in different units. The traditional objective function encompasses various costs, including investment, maintenance expenses, variable costs, and emissions costs, all expressed in monetary terms.

In contrast, sustainability indicators such as EPBT and ITR are measured in years, while IMPcc is quantified in CO₂ equivalent tons. To integrate these indicators seamlessly into the primary objective function in OSeMOSYS, each must be standardized into economic terms.

The proposed approach converts each sustainability indicator into economic terms and incorporates them as extra cost factors within the objective function. This transformation ensures that the optimization algorithm prioritizes features aligning with sustainability objectives, albeit without directly affecting the overall cost of the optimized energy mix.

Although this functionality is not inherent in OSeMOSYS, it has been integrated into the core code to enhance the software's capabilities. This enhancement, while potentially increasing computational demands, aims to provide decision-makers with valuable insights for achieving sustainable energy outcomes.

To evaluate the feasibility of integrating sustainability assessments into OSeMOSYS, the proposed methodology was implemented in a test case study using the Atlantis energy framework. This pre-built framework as detailed in Chapter 1 is specifically designed to validate methodologies and facilitate controlled assessments of their reproducibility.

After integrating sustainability factors into the optimization function, the study assessed the degree to which the convolution of these factors is necessary and sufficient through an analysis of the correlation matrix. Given that the incorporation of sustainability criteria generally increases the overall costs associated with the energy transition process, it raises the question of whether the proposed indicators operate independently, capturing unique dimensions of sustainability, or if they are interrelated, potentially leading to double counting.

Under these circumstances, optimizing decision-making is imperative by identifying the essential criteria necessary to achieve desired outcomes while avoiding redundant requirements that increase economic pressure.

Continuing from this point, an objective is formalised aiming to quantify the effects of mutual interaction among indicators through the construction of correlation matrices using the Pearson method. This entails evaluating pivotal variables such as prices, energy consumption, and emissions, and comparing them against established benchmarks. Through this quantitative analysis, Pearson coefficients will furnish the degree of correlation between the indicators, elucidating the extent of overlap between the effects associated with various facets of sustainable development. Consequently, the study can fine-tune the weighting assigned to each indicator in alignment with its objectives.

This sustainability-centric approach not only fosters informed decision-making but also addresses the complex challenges inherent to energy planning processes, particularly demonstrating effectiveness in navigating sensitive energy concerns. The utility of the methodology was validated by addressing three critical issues in the context of sustainable energy transition: the sustainability level of nuclear technology within the energy system, the efficacy of escalating penalties for carbon emissions, and the sustainability of solar energy as a representative of intermittent production sources based on local resource availability.

These sensitivities, which frequently serve as the focal point of discourse, encompass a spectrum of pivotal issues. Navigating sensitive concerns in decision-making poses perennial challenges for stakeholders, particularly when sustainability outcomes are paramount. Therefore, as an ultimate activity of the thesis, the aim is to seek the utility of the developed sustainability approach in addressing such complexities.

Specifically, the study investigates the sustainability discourse surrounding nuclear energy by examining various aspects such as energetic and economic sustainability metrics, as well as the complex landscape of nuclear waste management. Despite its low-emission status, nuclear energy is examined through these various lenses to gain a comprehensive understanding of its overall impact.

Similarly, the narrative progresses to investigate the implications of increased emissions penalties in terms of environmental sustainability indicators. It weighs the potential environmental benefits of lower carbon emissions against the economic costs associated with carbon taxes. This analysis aims to illuminate the intricate trade-offs inherent in such policy deliberations.

Furthermore, the study examines the case in favour of renewable energy technologies, with a particular focus on solar photovoltaic (PV) systems. It delves into the intricacies of the climatic dependencies that characterize these technologies, demonstrating how geographical variables

can influence both energetic and economic sustainability indicators. Such a detailed examination emphasizes the importance of considering local circumstances when planning and implementing renewable energy projects.

In conclusion, this thesis's objectives demonstrate that integrating sustainability indicators into OSeMOSYS significantly enhances its capacity to support sustainable energy planning. By considering economic, energetic, and environmental factors holistically, the research contributes to the development of resilient and sustainable energy systems.

Chapter 3. Methodologies

The methodology adopted in this thesis establishes a framework for the integration of sustainability indicators within the OSeMOSYS modelling framework. This methodological approach is designed to ensure a comprehensive evaluation of economic, energetic, and environmental factors, thereby enhancing the capability for informed decision-making in sustainable energy planning. The methodology encompasses the following key components:

Conceptual Framework

- The study utilizes the Climate-Land-Energy-Water (CLEWs) framework, which is known for managing interconnected systems comprehensively.
- The OSeMOSYS (Open Source Energy Modelling System) energy modelling tool is a key component of this framework, used extensively in the thesis for economic optimization and scenario analysis.

Case Study: Atlantis Energy Framework

- The Atlantis framework is selected for its comprehensive representation of energy technologies and structured design, making it suitable for validating methodologies.
- The framework includes various power generation technologies such as renewables, non-renewables, and nuclear power, allowing for diverse scenario analysis and policy assessment.

Sustainability Indicators

- The methodology focuses on integrating sustainability indicators into the OSeMOSYS optimization function.
- Three primary sustainability indicators are considered: Energetic Production (EPBT), Investment to Output Ratio (ITR), and Emission Reduction Potential (IMPcc).
- These indicators are converted into economic terms and incorporated as additional cost factors to balance sustainability and cost considerations.

Analytical Tools and Post-Optimization

- The thesis emphasizes post-optimization analysis using OSeMOSYS's economic optimization function within the Atlantis framework.
- Key variables analyzed include energetic production, economic costs (capital, fixed, and variable), and emissions.

Integration of Sustainability Indicators

- Each sustainability indicator is integrated into the cost functions within OSeMOSYS using non-dimensional correction factors to incentivize desired outcomes:
 - **EPBT**: Integrated into the Variable cost function to promote technologies with lower energy payback times.
 - **ITR**: Linked to the Capital cost function to favour technologies with better investment-to-output ratios.
 - **IMPcc**: Incorporated into the Emission cost function to encourage emission reductions.

Validation and Results Presentation

- The results of the optimization and the impact of sustainability indicators are validated through scenarios and their reproducibility is assessed.
- The findings and insights gained are published in a peer-reviewed journal, demonstrating the applicability and utility of the developed methodologies.

To achieve the objectives outlined in the preceding chapter, this doctoral thesis is structured into self-contained chapters, each developed autonomously. Each chapter conducts an exhaustive review of existing literature, specifies its objectives, outlines the methodology employed, elaborates on the progression of research, analyzes results comprehensively, and draws pertinent conclusions. To effectively address the goals, outlined in the thesis, the document is organized into seven distinct chapters.

In Chapter 1, an introduction is provided, where it contextualizes and justifies the work. The chapter discusses the historical context of sustainable development, integrating perspectives on economic advancement, environmental preservation, and social equity. It aligns the study with contemporary global goals, such as the Sustainable Development Goals (SDGs).

The chapter provides an overview of the OSeMOSYS model, detailing its operational principles, parameters, variables, and core optimization functions. The focus is on elucidating the model's capacity to comprehensively analyze energy systems by considering resource availability, system transformation, and end-use dynamics.

This chapter also introduces the Atlantis energy framework, used as a case study to assess the feasibility of the developed methodology. The Atlantis framework allows for an examination of parameter and assumption delineation in scenario development and systematically categorizes and scrutinizes technologies within a defined temporal framework to ensure a comprehensive analysis by introducing the input data parameters used in the thesis. The chapter details the representation of energy technologies and clarifies key input parameters and assumptions that define the scenarios.

Post-optimization analysis of the standard optimisation function of OSeMOSYS focuses on three primary merit variables: energetic production, economic costs, and emissions. Results obtained through OSeMOSYS's economic optimization function are presented in detail, providing insights into the outcomes of the study. The chapter benchmarks the significance of these results against novel initiatives evaluated in the feasibility study.

Chapter 2 identifies the study objectives, whereas Chapter 3 outlines the methodology undertaken in developing the thesis.

Chapter 4 titled "Implementation of the Sustainability Indicators as OSeMOSYS Optimization Functions.", details the methodology used to integrate sustainability indicators into the OSeMOSYS energy modelling framework. The chapter begins by introducing commonly used sustainability indicators for energy-related technologies. It then provides a comprehensive overview of the specific sustainability indicators employed in the study, followed by the approach used to incorporate these indicators into the OSeMOSYS optimization objective function as an extra cost.

 The chapter elaborates on three main sustainability indicators:

- **Energetic Sustainability Indicator (EPBT):** The Energy Pay-Back Time (EPBT) measures the time required for an energy system to produce the amount of energy consumed during its production phase.

- **Economic Sustainability Indicator (ITR):** The Internal Rate of Return (ITR) is an economic indicator that reflects the profitability of investments in energy technologies.
- **Environmental Sustainability Indicator (IMPcc):** The Environmental Performance Cost Correction (IMPcc) focuses on emissions mitigation and incorporates environmental costs into the energy modelling framework.

✚ The integration of sustainability indicators into the OSeMOSYS framework involves several steps:

- **Modifying the Objective Function:** The sustainability indicators are included as additional cost factors in the OSeMOSYS optimization function. This modification allows the model to prioritize sustainable solutions by incorporating the indicators as constraints in the optimization process.
- **Use of Correction Factors:** For each indicator, a correction factor is introduced to adjust the objective function. These factors represent the additional costs associated with each sustainability aspect.

✚ Detailed Implementation Steps:

- **Energetic Sustainability Indicator (EPBT):**
 - The EPBT is integrated by converting it into an economic cost factor.
 - A non-dimensional correction factor, F_{EPBT} , is introduced as an additional cost term. This factor is the ratio of EPBT to the Useful Lifetime Time (ULT) of each technology.
 - The objective is to promote technologies with shorter EPBTs relative to their ULTs.
- **Economic Sustainability Indicator (ITR):**
 - Similar to the EPBT, the ITR is integrated into the optimization function through an economic adjustment.
 - A non-dimensional correction factor, F_{ITR} , is introduced as an additional cost term. This factor is the ratio of ITR to the Useful Lifetime Time (ULT) of each technology.
 - The objective is to promote technologies with shorter ITRs relative to their ULTs.
 - The implementation involves incorporating ITR-related costs to reflect the profitability of different energy technologies.
- **Environmental Sustainability Indicator (IMPcc):**
 - The IMPcc is integrated by including environmental costs associated with emissions mitigation.
 - The emission cost parameter is a key variable for this integration, aligning with the IMPcc's focus on environmental sustainability.

After the integration, the chapter discusses the validation of the methodology by evaluating the feasibility of replicating sustainability indicators within the Atlantis energy framework. The results of the optimization process are presented, highlighting the impact of each sustainability indicator. The assessment involves comparing the optimized results with those from a standard economic optimization scenario, ensuring a comprehensive analysis of the impact of sustainability considerations.

The methodology presented in Chapter 4 systematically incorporates sustainability criteria into the OSeMOSYS energy modelling framework. This approach enhances the model's capability to evaluate and prioritize sustainable energy solutions, providing a robust tool for energy planning and policy analysis.

Chapter 5 of the thesis titled "Optimizing Sustainability Criteria in Convolution" focuses on integrating various sustainability indicators to create a comprehensive optimization model. It provides a structured approach to integrating and optimizing sustainability criteria within the energy transition process, using a combination of convolution, paired indicator analysis, and correlation assessments to guide decision-making.

The methodology used in this chapter involves several key steps. This includes defining a sustainable optimization function (OP_SusIndex) by integrating the sustainability indicators into a convolution model. This model is designed to address the multifaceted nature of sustainable development by combining economic, energy, and environmental factors. The methodology then involves pairing the sustainability indicators in two-by-two combinations to analyze their combined effects. This is achieved through the following optimization functions:

- **Op_EPBT_ITR**: Integrates energetic and economic sustainability criteria.
- **Op_EPBT IMPcc**: Integrates energetic and environmental sustainability criteria.
- **Op_ITR_IMPcc**: Integrates economic and environmental sustainability criteria.

Each combination is analyzed to understand the synergies and trade-offs between different sustainability objectives.

The methodology includes setting modulation weights for each paired combination to prioritize specific sustainability indicators. These weights are critical for guiding the optimization process. These weights help to balance the contributions of each indicator in the convolution process.

To ensure a thorough evaluation, the methodology involves constructing correlation matrices using the Pearson method. This step quantifies the mutual interactions between the indicators and identifies potential redundancies or double counting. By analyzing these interactions, the methodology aims to refine the decision-making process and ensure that each indicator captures unique aspects of sustainability.

The Atlantis energy framework and the OSeMOSYS are used to implement the convolution approach. The optimization process includes assessing the sustainability indicators through paired convolutions to evaluate their combined effects on energy planning and sustainability goals. This involves running simulations and analyzing the results to identify the most sustainable energy transition pathways.

Finally, the methodology includes analyzing the results of the paired convolutions. Tables and decision matrices are used to present the outcomes, facilitating a comparative evaluation of the different optimization scenarios. This step helps to identify the best strategies for achieving sustainability goals while considering economic, energy, and environmental trade-offs.

Chapter 6 of the thesis titled "Decision-making in Sensitive Energy Sectors through the Integration of Sustainability Indicators" details the methodology used to integrate sustainability indicators into the OSeMOSYS framework. This chapter focuses on demonstrating the viability of integrating sustainability indicators into decision-making processes within sensitive energy sectors. This approach helps in addressing the complex challenges inherent to energy planning, especially in sensitive contexts.

Sustainability of Nuclear Energy:

- **Sustainability Optimization Scanning on Nuclear Useful Lifetime:** The methodology includes a comprehensive assessment of the nuclear energy sector by evaluating its sustainability through various metrics. This involves scanning the optimization of nuclear energy's useful lifetime to understand its energetic

and economic sustainability, as well as the challenges associated with nuclear waste management.

- **Energetic Optimization Results (Op_EPBT):** The energetic sustainability indicator (EPBT) is implemented and analyzed. This involves assessing the energy payback time and the overall energetic sustainability of nuclear energy.
- **Economic Optimization Results (Op_ITR):** The economic sustainability indicator (ITR) is also analyzed. This includes evaluating the investment-to-return ratio and the economic feasibility of nuclear energy projects.

✚ **Carbon Pricing Mechanisms:**

- The methodology examines the implications of increased emissions penalties through environmental sustainability indicators. This analysis weighs the potential benefits of reduced carbon emissions against the economic costs associated with carbon taxes. It aims to elucidate the trade-offs involved in such policy decisions.

✚ **Sustainability of Solar PV as a Function of Climate Conditions:**

- The methodology includes a detailed analysis of solar photovoltaic (PV) systems, focusing on their sustainability based on climatic conditions. This involves assessing how geographical and climatic variables affect the energetic and economic sustainability of PV technology.
- **Integration of Sustainability Criteria:** The integration of both energetic requirements and initial investment requirements is analyzed to determine the sustainability of various technologies. The methodology emphasizes the importance of considering local circumstances when planning and implementing renewable energy projects.
- **Challenges and Solutions:** The methodology also highlights the challenges associated with the integration of renewable energy, such as the intermittency of PV technology. It underscores the necessity of complementary measures like storage systems to ensure reliability and sustainability.

✚ **Optimization and Decision-making:**

- The chapter emphasizes the need to reevaluate the weighting assigned to different sustainability indicators within optimization functions. By prioritizing optimization objectives that promote sustainability, decision-makers can achieve a more comprehensive understanding of each indicator's behaviour concerning output variables such as energy production sources, economic costs, and emissions.

The insights gained from the methodology facilitate the prioritization of sustainability in decision-making processes. The methodology developed for integrating sustainability indicators into the OSeMOSYS framework offers valuable support to decision-makers, particularly in navigating critical energy challenges. This detailed methodology is crucial for understanding how sustainability indicators can be effectively integrated into energy sector decision-making, particularly in sensitive and complex contexts.

Ultimately, Chapter 7 concludes the thesis by summarizing key findings and conclusions drawn from the comprehensive methodologies developed throughout the document. This structured approach not only advances theoretical knowledge but also offers practical tools for policymakers and stakeholders navigating the complexities of sustainable energy planning and policy analysis.

Chapter 4. Implementation of the Sustainability Indicators as OSeMOSYS Optimization Functions

This chapter partially reproduces content from the following publication, which was derived from research conducted by the doctoral candidate during the thesis development period:

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4.1. Introduction

The opening segment of this chapter familiarizes readers with the commonly used sustainability indicators for assessing energy-related technologies. Following this, it offers a comprehensive overview of the specific sustainability indicators employed in the study. Furthermore, it outlines the approach utilized to incorporate these indicators into the OSeMOSYS optimization objective function as an extra cost.

While not initially part of OSeMOSYS, these sustainability indicators have been incorporated into the core code as an optimizing constraint, providing added value to the model's ability to evaluate sustainability aspects. This integration may increase computational complexity, but it significantly enhances the model's capabilities.

It should be noted that users have the flexibility to exclude these components from the code if they are not deemed necessary for their specific analyses or applications. This adaptability showcases the versatility of the modelling framework and its ability to accommodate a diverse range of sustainability assessment needs and preferences [60].

Following a thorough explanation of our process for integrating sustainability indicators into the OSeMOSYS code, the chapter proceeds to a subsection focused on methodology validation. To achieve this, we evaluate the feasibility of replicating sustainability indicators within the Atlantis energy framework.

The subsequent analysis delves into the detailed presentation of the resulting impact post-optimization within the Atlantis framework. This critical validation stage ensures that the methodology effectively captures and reflects the sustainability implications of different energy technologies within the context of a representative energy system such as Atlantis.

4.2. Sustainability indicators

Sustainability estimators, also referred to as indicators are useful tools for evaluating and tracking the impacts and progress of energy generation technologies towards sustainable development goals [87]. They quantitatively or qualitatively measure various dimensions, providing a comprehensive understanding of the environmental, social, and economic aspects of sustainability [34].

They help to identify areas for improvement and action, such as reducing greenhouse gas emissions, preserving biodiversity, and addressing inequality[88]. By monitoring these indicators regularly, stakeholders can determine if they are moving closer to or further away from their sustainability goals [89]. This helps anticipate future challenges and take proactive measures to mitigate negative impacts, contributing to advancing sustainable development and creating a more resilient and equitable future [90].

Clear and accessible sustainability indicators aid in conveying complex information in a meaningful manner, promoting understanding and engagement [35]. Existing sustainability indicators cover a broad range of domains and can be classified, in the context of Technology Sustainability Assessment (TSA), into environmental, social, economic, and energetic indicators [29].

The environmental indicators are crucial for evaluating the environmental impacts and sustainability performance of energetic systems. These indicators focus on assessing how technology affects the natural environment, including air, water, land, biodiversity, and climate [88]. Table 4.1 lists some key environmental indicators relevant to TSA.

The energetic sustainability indicators are essential for evaluating the energy efficiency, resource utilization, and overall sustainability performance of energy technologies. These indicators focus on assessing how energy technologies contribute to sustainable energy production, distribution, and consumption [91]. Table 4.2 highlights some key energetic sustainability indicators relevant to TSA.

In the context of TSA, social indicators play a crucial role in evaluating the social impacts and implications of technological innovations and systems. These indicators focus on assessing how technology affects human well-being, equity, and social dynamics [92]. Social sustainability indicators examples are listed in Table 4.3.

The economic indicators play a crucial role in evaluating the economic viability, efficiency, and impacts of energy technologies. These indicators focus on assessing the economic aspects of energy production, distribution, and consumption, as well as the broader economic implications of energy systems [88]. Table 4.4 lists some key economic indicators relevant to TSA.

Table 4.1 Key environmental indicators relevant to technology sustainability assessment.
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Context	Index	Description
Climate Change Mitigation	Impact Mitigation in term of Climate Change (IMPcc)	Quantifies the reduction in emissions of greenhouse gases (e.g., CO ₂ , CH ₄ , NO ₂) achieved through mitigation measures, typically expressed in equivalent tons of carbon dioxide (t CO ₂ eq), associated with the life cycle of a technology, including manufacturing, operation, and disposal phases [93].
Resource Use	Material and Water Consumption	Quantifies the amount of raw materials, minerals, water, and other resources used in the production, operation, and disposal of a technology. This approach identifies opportunities for resource efficiency, waste reduction, and circular economy to minimize environmental footprint [94].
Pollution and Emissions	Air and Water Quality	Measures the emissions of pollutants and contaminants, such as particulate matter, nitrogen oxides (NO _x), sulfur dioxide (SO ₂), volatile organic compounds (VOCs), heavy metals, and other hazardous substances, from technology operations and waste streams. Assessing air and water quality impacts helps mitigate environmental pollution and protect human health and ecosystems [95].
Biodiversity Conservation	Habitat Impact	Assesses the direct and indirect impacts of technology on biodiversity and ecosystems, including habitat destruction, fragmentation, and degradation. Technologies that minimize habitat disturbance and promote biodiversity conservation contribute to ecological sustainability and resilience [96].
Waste Generation and Management	Waste Generation Rate	Quantifies the amount of solid, liquid, and hazardous waste generated by technology processes and operations, as well as the effectiveness of waste management practices, such as recycling, reuse, and treatment. Minimizing waste generation and promoting sustainable waste management practices reduce environmental pollution and resource depletion [97].

Table 4.2 Key energetic indicators relevant to technology Sustainability assessment.
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Context	Index	Description
Energy Efficiency	Energy Conversion Efficiency	Measures the efficiency of converting primary energy sources into useful energy services, such as electricity, heat, or mechanical work. Higher energy conversion efficiency indicates greater energy productivity and reduced resource consumption and environmental impacts [91].
Energy Security	Energy Independence Index	Assesses the degree of energy independence and resilience of energy systems by measuring reliance on imported energy sources, geopolitical risks, and supply chain vulnerabilities. Enhancing energy security reduces dependency on fossil fuel imports and mitigates risks associated with energy disruptions [98].
Resource Efficiency	Energy Payback Time (EPBT)	Measure the time that it takes for the technology to produce the total energy consumed throughout the lifecycle reflecting its overall energy efficiency and resource utilization. Quicker EPBT values indicate greater energy yield relative to the energy invested in production and operation, contributing to overall energy system sustainability [99].
Grid Integration and Smart Grids	Grid Stability and Reliability	Assesses the stability, reliability, and resilience of electricity grids in accommodating variable energy sources, managing demand-side fluctuations, and ensuring uninterrupted supply to consumers. Smart grid technologies and grid modernization efforts improve grid flexibility and optimize energy flows [100].

Table 4.3 Key social indicators relevant to technology sustainability assessment.*This Table is personal reproduction*

Context	Index	Description
Equitable Access	Access to Technology	Measures the extent to which technology is accessible and affordable to all segments of society, including marginalized and underserved communities. Disparities in access can exacerbate existing inequalities and hinder social inclusion [101].
Community Engagement and Participation	Stakeholder Engagement,	Measures the extent to which communities and stakeholders are involved in decision-making processes related to technology development, implementation, and governance. Meaningful engagement fosters trust, accountability, and social license for technological innovations [102].
Skills Development	Literacy Rates	Assesses the level of skills among individuals and communities, including the ability to access, understand, and use of technology effectively and responsibly. Strengthening literacy empowers people to fully participate in society and benefit from technological advancements [103].
Worker Rights and Job Displacement	Job Displacement Rate	Measures the impact of technology adoption on employment patterns, job displacement, and labour market dynamics. This includes considerations such as automation, outsourcing, gig economy practices, and worker rights protections. Ensuring equitable labour outcomes and social protections is essential for mitigating adverse effects on workers [104].
Cultural Preservation and Diversity	Cultural Heritage Preservation	Evaluates the preservation and promotion of cultural diversity, heritage, and identity in the face of technological change. This includes considerations such as the digital preservation of cultural artefacts, indigenous knowledge systems, and linguistic diversity. Respecting and protecting cultural rights and identities is critical for maintaining social cohesion and resilience [105].

Table 4.4 Key economic indicators relevant to technology sustainability assessment.*This Table is personal reproduction*

Context	Index	Description
Cost-effectiveness	Levelized Cost of Energy (LCOE)	Measures the average lifetime cost of electricity generation from a particular energy technology, considering factors such as capital costs, operating costs, fuel costs, and project lifetime. Lower LCOE values indicate greater cost-effectiveness and competitiveness of the technology compared to other energy sources [106].
Investment and Financing	Investment Flows	Tracks the flow of investments and financial resources into energy technology projects, including funding from public sources, private investors, development banks, and other financial institutions. Understanding investment trends helps assess market confidence, attractiveness, and barriers to financing energy projects [107].
Employment and Economic Growth	Job Creation Potential	Estimates the potential for job creation and economic growth associated with the deployment and operation of energy technologies, including direct employment in manufacturing, construction, installation, and operation, as well as indirect and induced effects on related industries and sectors [108].
Resource Efficiency	Internal time of return from Investment (ITR)	Measures the time that takes for a technology to recoup the initial investment or the capital cost reflecting its overall energy efficiency and resource utilization. Rapid ITR values indicate greater energy yield relative to the energy invested in production and operation, contributing to overall energy system sustainability [109].
Cost Externalities	External Costs	Quantifies the external environmental and social costs associated with energy production and consumption, such as air pollution, greenhouse gas emissions, public health impacts, and ecosystem degradation. Integrating external costs into economic assessments helps internalize environmental and social considerations and promotes more sustainable energy choices [110].
Price Stability	Energy Price Volatility	Measures the variability and volatility of energy prices over time, including fluctuations in fuel prices, electricity tariffs, and energy commodity markets. Price stability is important for energy security, investment planning, and economic competitiveness, particularly for energy-intensive industries and vulnerable consumers [111].
Market Integration and Competition	Market Integration Index	Assesses the degree of market integration and competition within energy markets, including electricity markets, energy trading platforms, and renewable energy certificate markets. A more integrated and competitive market environment promotes efficiency, innovation, and consumer choice, driving down costs and accelerating the adoption of sustainable energy technologies [112].

4.3. Embracing the cradle-to-cradle Paradigm towards a holistic TSA

In the context of TSA utilizing sustainability indicators, the approach adopts a comprehensive perspective over the entire life cycle stage of a technology, often referred to as the cradle-to-cradle paradigm [113]. This entails the consideration of every phase within the technology's lifespan [114], encompassing associated processes and supply chains. This holistic approach is illustrated in Figure 4.1, which depicts the lifetime stage of an energy generation technology. By scrutinizing each stage of the lifetime, from initial resource extraction to end-of-life disposal or recycling (circular economy), the TSA methodology ensures a thorough assessment of the sustainability implications across the entirety of the technology's lifespan [115].

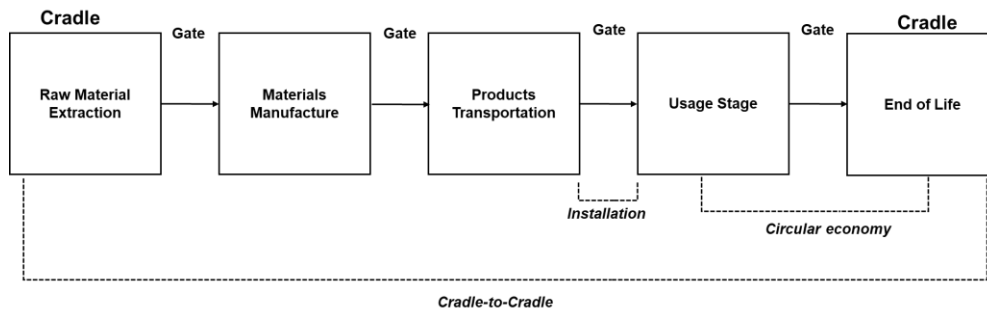


Figure 4.1 Lifetime stages diagram

This Figure is reproduced from the following reference [116]

While a sustainability indicator can provide valuable insights into the cradle-to-cradle, it may be limited in scope if it only examines specific stages. For example, a cradle-to-door assessment evaluates the process from raw material extraction to the point of leaving the factory gate but does not include use, reuse, recycling, or disposal stages. Another approach is the door-to-door assessment, which evaluates a specific stage or segment of the lifetime, typically from one production gate to the next [117].

4.4. Sustainability indicator Dimensional Focus

While there are numerous sustainability indicators available for each dimension at different levels used during a TSA within the cradle-to-cradle paradigm, this work focuses only on the environmental, economic, and energetic dimensions [118]. More in detail, the three most popular and widely used sustainability indicators because they provide a comprehensive assessment of energy-related sustainability aspects [119], [120], [121], [122], are selected and then incorporated into OSeMOSYS. The selected sustainability indicators are:

- ✚ The *IMP_{cc}* (Input Mitigation Potential in terms of climate change) from an environmental sustainability perspective. *IMP_{cc}* measures the potential of an energy technology to mitigate climate change impacts by reducing greenhouse gas emissions.
- ✚ The *ITR* (Internal Time of Return), from the economic sustainability criteria. *ITR* assesses the time it takes for an energy technology to recover its initial investment costs through energy generation.
- ✚ *EPBT* (Energy Payback Time), from the energetic sustainability criteria. *EPBT* evaluates the time it takes for an energy technology to generate as much energy as was expended during its production and operation phases.

Besides they offer quantitative metrics, allowing for precise measurement and comparison of different energy technologies. This quantitative nature enhances the credibility and reliability of assessments, making them valuable tools for decision-making [123].

In addition, these indicators are directly relevant to policy goals and targets related to energy efficiency, renewable energy deployment, and climate change mitigation. Governments, regulatory agencies, and international organizations often use these indicators to evaluate the effectiveness of policies and initiatives aimed at promoting sustainable energy solutions [124].

Furthermore, they have been recognized and standardized by international organizations, such as the International Energy Agency (IEA), the International Organization for Standardization (ISO) [125], and the Intergovernmental Panel on Climate Change (IPCC). This standardization enhances their credibility and facilitates their adoption and implementation across different countries and regions.

The exclusion of social dimensions in this work is primarily due to the inherent challenges associated with quantifying social indicators compared to environmental and economic factors. Social indicators often involve qualitative or semi-quantitative data, making them more subjective and difficult to measure consistently across different contexts [126]. Additionally, social impacts can be highly context-dependent and influenced by cultural, political, and institutional factors, further complicating their quantification and comparability [127].

While some efforts have been made to develop quantitative social indicators, such as those related to employment generation have already been implemented in OSeMOSYS by Asma et al. [128], these metrics may not capture the full spectrum of social impacts or adequately reflect diverse stakeholder perspectives. As a result, this work has chosen to focus on the more quantifiable dimensions of environmental, energetic, and economic sustainability.

Furthermore, the decision to exclude social dimensions may also be influenced by the scope and objectives of the study. In some cases, researchers may prioritize specific aspects of sustainability based on the relevance to their research questions, available data, or the intended audience. In this instance, the focus on environmental, energetic, and economic dimensions may align with the goals of the study or the capabilities of the analytical tools being used, such as OSeMOSYS.

It's important to note that while social dimensions are not explicitly addressed in this work, they remain integral to holistic sustainability assessments. Future research may explore ways to incorporate social indicators more effectively or develop innovative methodologies for quantifying social impacts in energy sustainability assessments.

4.4.1. Energetic sustainability indicator (EPBT)

The EPBT pertains to the duration it takes for an energy system to yield an equivalent quantity of energy that was expended during its production and setup stages. In simpler terms, it gauges the number of years necessary for the energy generated by the system to balance out the energy utilized in its manufacturing, conveyance, installation, and dismantling [129], [130].

The EPBT [Year] as defined in Equation 4.1, is given by dividing the total energy invested, E_{inv} , [MWh] throughout the system's life cycle by the annual energy output, E_{out} , [MWh] [130]. The E_{inv} is the addition of the energy used for materials extraction, E_{Mat} , [MWh], manufacturing, E_{Manuf} , [MWh], transportation, E_{Trans} , [MWh] and installation, E_{Inst} , [MWh] as well as the energy required for dismantling at the end of life, E_{EOL} , [MWh].

The annual energy output, E_p , [MWh] is determined by the technology efficiency, η_t , and the annual energy generation, E_{Agen} , [MWh/Year] and annual energy demand for operation and maintenance, $E_{O\&M}$, [MWh]. A shorter EPBT indicates that the system can repay its energy debt more quickly, making it more energy-efficient and sustainable.

$$EPBT = \frac{E_{inv}}{E_{out}} = \frac{E_{Mat} + E_{Manuf} + E_{Trans} + E_{Inst} + E_{EOL}}{\eta_t \times E_{Agen} - E_{O\&M}} \left(\frac{MWh}{MWh/year} \right) \quad (Eq\ 4.1)$$

The assessment of Technological Performance within the TSA entails a comprehensive examination of how effectively a technology fulfils its intended function and evolves. This evaluation encompasses various parameters such as efficiency, reliability, durability, innovation, and technological advancements. Central to this assessment is the concept of EPBT, which serves as a focal point for gauging the production efficiency of a system throughout its entire lifetime [131].

Efficiency emerges as a pivotal factor influencing a technology's EPBT, as it directly influences the ratio of energy output generated to the energy input required across all stages of the technology's lifetime stage, including production, installation, operation, and decommissioning. Consequently, technologies characterized by higher efficiency levels tend to exhibit shorter EPBTs, thereby enabling them to repay their energy debt and contribute to sustainable energy transitions more rapidly [132].

The EPBT of technologies can differ significantly based on their design, manufacturing, and operation. For example, the amount of sunlight or wind available at the installation site can greatly affect the energy output and overall efficiency of solar panels and wind turbines, respectively. Areas with abundant solar irradiance or consistent winds typically see greater energy yields from these technologies, resulting in increased efficiency and rapid EPBT [133].

4.4.2. Economic sustainability indicator (ITR)

The ITR [Year] is a widely used economic indicator that determines the financial feasibility and desirability of an investment or project over the years [130], [134]. It is calculated as the discount rate at which the net present value, NPV, [\$] of cash flows from the investment reaches zero, as shown in Equation 4.2.

The NPV represents the disparity between the present value of cash inflows and outflows over a designated period. Essentially, the ITR indicates the duration of time it takes for an investment to produce a return, accounting for the timing and size of cash flows throughout the project's lifespan [134].

$$NPV = \sum_{t=0}^n \frac{OCF_t}{(1 + ITR)^t} = 0 \quad (\text{Eq 4.2})$$

Where OCF_t [\$/Year] represents the operating cash flow at time t , and n is the number of periods in years.

The ITR is a valuable metric for evaluating the profitability and appeal of an investment opportunity. A quicker ITR suggests a more desirable investment, indicating a greater return on the initial investment. Like the EPBT, this metric is influenced by both internal factors like technology design, manufacturing, and operation, as well as external factors such as resource availability [134], [135].

4.4.3. Environmental Sustainability Indicator (IMPcc)

The Mitigation Potential for Climate Change (IMPcc) is a commonly referenced metric when evaluating environmental sustainability. It serves as a gauge for measuring the effectiveness of climate change mitigation efforts, as well as the ability of specific actions, strategies, or technologies to decrease the input of resources, emissions, or other harmful elements into a given system or process [130], [136].

The IMPcc focuses on the reduction of greenhouse gas (GHG) emissions throughout the lifespan of a technology. This measurement considers the potential global warming impact of emitted gases and considers a variety of gases including CO₂, SO₂, NO_x, CH₄, and more [123], [136].

$$IMP_{cc} = \frac{CC_{Mat} + CC_{Manuf} + CC_{Trans} + CC_{Inst} + CC_{EOL} + CC_{O\&M}}{CC_{agen}} \left(\frac{t \text{ CO}_2 \text{ eq}}{\text{MWh}} \right) \quad (\text{Eq 4.3})$$

Equation 4.3 demonstrates the IMP_{cc} calculation for an energy system in the cradle-to-cradle philosophy [130]. This approach considers the system's entire lifetime, from the extraction of raw materials and manufacturing to usage and disposal, to reduce environmental impacts and promote sustainability. CC_{agen} , in Equation 4.3, represents the annual electricity generation (in MWh). The remaining impacts on climate change, measured in (t CO₂ eq), are denoted by CC_{Mat} for raw material extraction, CC_{Manuf} for technology system manufacturing, CC_{trans} for material transportation during the system's lifespan, CC_{Inst} for impacts during installation, CC_{EOL} for end-of-life management, and $CC_{O\&M}$ for impact associated with operation and maintenance processes.

A SWOT analysis of the IMP_{cc} reveals several key insights into its strengths, weaknesses, opportunities, and threats. The IMP_{cc} demonstrates several strengths in its environmental sustainability assessment. It employs a comprehensive approach, focusing on quantifying and mitigating environmental impacts related to climate change, including greenhouse gas emissions reduction and ecosystem conservation [123]. Additionally, IMP_{cc} benefits from its comprehensive approach, considering various mitigation and adaptation strategies to address climate change impacts holistically likely utilizing measurable metrics related to greenhouse gas emissions reduction, renewable energy adoption, carbon sequestration, etc., providing clear indicators of progress [137].

However, IMP_{cc} also faces challenges and limitations in its environmental sustainability assessments. One such challenge is the complexity and interconnectedness of environmental issues, which may make it difficult to accurately measure and attribute impacts to specific interventions. Additionally, uncertainties in climate modelling and data availability can pose challenges to conducting robust environmental assessments and projecting future impacts accurately [127]. Addressing these challenges requires ongoing research, monitoring, and refinement of methodologies to improve the accuracy and reliability of environmental sustainability indicators [103].

Despite these challenges, opportunities exist for IMP_{cc} to leverage technological innovation, capacity building, and ecosystem-based approaches to enhance its environmental sustainability assessment. Threats, including climate change impacts, policy instability, natural resource scarcity, and global inequities, pose challenges to achieving environmental sustainability within IMP_{cc} [138].

By capitalizing on its strengths, addressing weaknesses, seizing opportunities, and mitigating threats, IMP_{cc} can enhance its effectiveness in promoting environmental sustainability and combating climate change.

4.4.4. Sustainability Index

Achieving a sustainable energy design or transition depends on various user objectives, including energetic, economic, and environmental goals [129]. For example, when a power company or energy agency must produce a sustainable transition plan with comprehensive decarbonization as the key limitation, environmental sustainability should be a top priority.

Conversely, if the goal is economic sustainability, the economic sustainability ITR indicator should be considered. The EPBT metric should be referenced when striving to achieve energetic sustainability.

The integration of all sustainability estimators into a single unit of measure is highly valuable when attempting to achieve multiple sustainability objectives. This approach simplifies the evaluation process by eliminating the need to consider and weigh multiple indicators separately, allowing for a direct sum and a numerical value for the sustainability index.

The Sustainability Index represents a compromise between economic, energy, and environmental aspects, streamlining the assessment process and enhancing usability [129]. Equation 4.4 outlines the sustainability index's characteristics.

$$\text{Sustainability}_{\text{Index}} = \text{EPBT} \odot \text{ITR} \odot \text{IMPcc} \quad (\text{Eq 4.4})$$

4.5. Integrating Sustainability Indicators into OSeMOSYS Energy Modelling

As the scope and objectives of energy modelling become more ambitious, the modelling becomes more complex [128]. Therefore, when planning an energy mix with an application as in the current instance of integrating sustainability indicators, the use of strong modelling tools is essential.

Of the numerous modelling tools available, OSeMOSYS [58] seems to be suitable for this purpose. This is mainly because of its flexibility in modifying and adapting the source code to the specific characteristics of the energy system to be analyzed enabling the development of methodologies that adhere to the user's optimization restrictions, merging different blocks into a common model [10].

Two options were available to enable the inclusion process, the configuration of the full objective function or the adjustment of the current objective function of OSeMOSYS. The latter option is typically more conservative being thus adopted in this application where sustainability indicators are included as an extra cost.

The implementation of the sustainability metrics as an extra cost in the OSeMOSYS optimization function is an artificial factor that introduces a deliberate bias toward sustainable outcomes. Although it may be tempting to label this as an "artificial" factor, it is important to note that this consideration is critical in driving the optimization algorithm to prioritize cost-effective and sustainable solutions.

The proposed methodology offers a systematic and comprehensive solution to incorporating sustainability criteria into energy modelling optimization. One of the key challenges is the integration of sustainability indicators into an objective function primarily focused on economic factors. It is crucial to recognize that the optimization function in OSeMOSYS aims to capture the comprehensive costs of the energy mix, including implementation, maintenance, production, and emissions.

Notably, sustainability indicators such as EPBT and ITR are measured in years, while IMPcc is quantified in CO₂ equivalent tons. To address this discrepancy, the proposed approach standardizes each indicator into economic terms, allowing their seamless integration into the primary objective function. This involves converting the metrics of EPBT, ITR, and IMPcc into equivalent economic costs, treating them as extra cost factors within the optimization function.

The extra cost represents one factor for each sustainability index, with a specific cost in line with the sustainability objective considered among the traditional costs (variable, capital, fixed, and emissions costs). Though it is an incremental factor imposed on the optimization process. The inclusion of this extra cost incentivizes the optimization process to minimize the total cost to be calculated, considering both traditional costs and the extra cost associated with the sustainability index, resulting in output characteristics that prioritize the most cost-effective and sustainable solutions.

It should be noted that the inclusion of the extra cost influences the optimization algorithm to prioritize features that contribute to higher levels of sustainability objectives. Despite the influence on feature selection, the extra cost associated with sustainability doesn't directly impact the output cost of the features resulting from the optimization process.

The output costs serve as a dependable and consistent portrayal of the cost trend for the energy mix, derived from the post-optimization assessments encompassing capital and operational expenses. This ensures that the optimization process doesn't artificially inflate or deflate the

cost estimates but rather provides solutions that balance sustainability considerations with the economic realities of technology implementation. By maintaining this correlation between output and technology costs, the optimization process provides accurate and reliable results, enhancing the credibility of sustainable solutions.

The process of including all the estimators is simple and achieved by following a step-by-step method to develop a comprehensive model that integrates the sustainability indicators into a unified framework, facilitating analysis and decision-making regarding the system's sustainability. This has involved formulating a hypothesis that serves as an approximation with the primary aspect of converting sustainability indicators (energetic, economic, and environmental sustainability) into economic cost weights.

The step involves defining the relationships between these indicators and the economic costs of the Optimization Function of OSeMOSYS. Each term OSeMOSYS objective function (Equation 1.3) is scrutinized, considering the underlying sustainability criteria. This examination is crucial for ensuring that the equation accurately reflects the sustainability considerations and contributes effectively to the overall model, therefore:

- ✚ *EPBT is found to be related to the function of the Variable or Production Cost. The Variable cost parameters represent expenditures that fluctuate in tandem with the scale of energy production. Within OSeMOSYS, optimizing these variable costs is paramount for fostering efficient and economically sustainable energy generation practices. Given its alignment with the production phase, the EPBT profile, quantifying the duration for a technology to offset the energy consumed throughout its lifecycle, naturally dovetails with the variable cost parameter. Consequently, integrating EPBT into the OSeMOSYS optimization algorithm through the variable cost parameter emerges as an optimal approach.*
- ✚ *ITR is found to be related to the function of the Capital or Investment Cost. The integration of ITR into the optimization algorithm involves configuring the investment cost parameters, also known as capital cost parameters in OSeMOSYS. This integration is essential as ITR is inherently associated with capital costs, serving as a metric to gauge the duration required to recoup the initial investment.*
- ✚ *IMPcc is found to be related to the function of the Emission Cost. The emission cost parameter in OSeMOSYS serves as a crucial financial indicator, directly linked to the interplay between energy production, resulting emissions, imposed penalties, and the overarching objective function guiding the optimization process. This parameter can be strategically leveraged to encourage emission reductions or conversely, to impose penalties on activities generating significant emissions. Given its pivotal role in environmental sustainability assessments, the emission cost parameter becomes a key variable for integrating the IMPcc indicator, which focuses on emissions mitigation, into the optimization framework.*

The implementation process of the sustainability indicators as an extra cost into OSeMOSYS has led to draft a research paper [139] . This paper present also the effect of the sustainability index applied using the Atlantis energetic framework.

4.6. Implementation process

This section describes how each indicator is integrated into the OSeMOSYS optimization function. Appendix C presents the complete OSeMOSYS code, including the modifications made to incorporate the sustainability estimators.

Following each integration, the effects of the corresponding sustainability estimator in the optimization function are presented using the Atlantis energetic framework.

The assessment of each sustainability indicator after optimization involves an examination of the merit variables outlined in the preceding chapter (Section 1.6.5). The discussion of the results is guided by a methodical comparison with the outcomes obtained from the Op_Standard scenario, as detailed in Chapter 1, section 1.7. This systematic approach ensures a comprehensive analysis of the impact of integrating sustainability considerations within the energy modelling framework.

4.6.1. Energetic Sustainability Indicator (EPBT) Implementation.

The integration of EPBT into the optimization function poses a significant challenge, requiring the conversion of an energetic variable into an economic cost factor. The foundational premise is that the long-term sustainability of an energy generation technology hinges on its EPBT being shorter than its Useful Lifetime Time (ULT).

To address this, we adopt a first-order approximation, assuming a uniform recovery process over the technology's lifespan. This implies that additional yearly production, evenly distributed, is necessary to offset the energy consumed during the implementation phase (cradle-to-cradle), thereby increasing the technology's variable cost.

To formalize this adjustment, we introduce a non-dimensional correction factor, F_{EPBT} , as an additional cost term (Equation 4.5). This factor represents the ratio of EPBT to ULT for each technology within the studied RES. The objective is to promote the deployment of technologies with EPBTs below their ULT.

The OSeMOSYS code inherently includes ULT as a default parameter, while EPBT is a newly introduced parameter specific to each technology and region. Consequently, the optimization process prioritizes sustainable trends with minimal F_{EPBT} .

Equation 4.6 presents the adjusted variable cost term in the OSeMOSYS optimization function, incorporating the F_{EPBT} extra cost to account for energetic sustainability (Variable_Cost_{r,t,y}^{Sus}).

$$F_{EPBT_{r,t}} = \left(\frac{EPBT}{ULT} \right)_{r,t} \quad (\text{Eq 4.5})$$

$$\text{Variable_Cost}_{r,t,y}^{\text{Sus}} = \sum_{r,y,t} \text{VarCost}_{r,y,t} \left(1 + F_{EPBT_{r,t}} \times W_{EPBT} \right) \quad (\text{Eq 4.6})$$

The modulation weight W_{EPBT} serves as an artificial parameter deliberately introduced to provide the flexibility of potentially disabling the energetic sustainability correction within the optimization process.

For clarification, OSeMOSYS does not calculate the EPBT of each technology included in the analysis. Instead, the user typically needs to input the EPBT as parameter data for the different technologies under consideration.

4.6.1.1. Effect of the EPBT in the Atlantis energetic framework

The assessment of EPBT for energy generation technologies is a complex undertaking, necessitating consideration of a multitude of factors. This entails tracing the entire lifetime of each technology, which encompasses the extraction of raw materials, manufacturing, installation, operation, and eventual dismantlement.

Critical factors influencing EPBT estimation include geographical considerations, especially pertinent for renewable energy technologies reliant on natural resources. Additionally, factors such as energy intensity during manufacturing, transportation distances, and energy output during operation play significant roles in determining EPBT values.

This study is limited in its scope, refraining from an exhaustive examination of the intricacies of the life-cycle processes associated with each technology. Furthermore, it does not directly address the nuances of regional variations in the EPBT of each technology.

Our approach involves the curation of a comprehensive compilation of EPBT data sourced from extensive literature reviews, integrated with insights obtained from country-specific case studies. By synthesizing this diverse array of information, we derived a mean value intended to serve as an initial estimation for evaluating the potential impact of the developed methodology on the energetic sustainability of the Atlantis.

Table 4.5 provides a concise summary of reported EPBT values for various energy generation technologies used in Atlantis RES. We have included the reference of literature from where values of EPBT were derived and used to estimate the energetic sustainability indicator in brackets. Additionally, the table includes the corresponding F_{EPBT} for each technology, facilitating a comprehensive understanding of the energetic sustainability implications within the RES. The ULT for each technology employed in the F_{EPBT} computation was sourced from the default data provided by Atlantis, as delineated in Table 1.2.

Table 4.5 EPBT and F_{EPBT} values associated with the Atlantis technologies.
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Category	Technology	EPBT (Year)	F_{EPBT}
Fossil Fuels	NGSC	8.17 [140], [141], [142]	0.272
	DSGC	12.68 [141], [142]	0.423
	IGCC	12.93 [140]	0.431
	HFSC	29.33 [141], [142]	0.838
	Diesel_Gen	12.68 [141], [142]	0.317
	NGCC	8.17 [140], [141], [142]	0.233
Renewable Energy	Hydro Dam	7.2 [140], [143]	0.206
	Hydro_Min	3.63 [140], [143], [144]	0.073
	PV	3 [140], [144], [145], [146]	0.120
	Wind	10.32 [140]	0.413
Nuclear	Nuclear	80 [140], [147]	1.6

Figure 4.2 depicts the variable cost per unit of energy produced by each technology within the Atlantis RES, juxtaposed with their respective extra costs attributed to the F_{EPBT} impact. A notable observation emerges renewable energy technologies (the two hydro technologies, solar and wind) remain unaffected by this extra cost, given their lack of variable or fuel expenses during electricity production. Consequently, the optimization strategy for these technologies primarily revolves around maintenance investment and efficiency enhancements to address their intermittent nature.

In contrast, nuclear technology emerges as the least economically competitive, with its corresponding extra variable costs surpassing even the standard uranium costs by at least 35%. This discrepancy likely arises from the substantial energy requirements during recurrent nuclear mining operations and power plant civil construction, making it challenging to recoup these investments within a single operational lifespan.

Fossil fuel technologies exhibit varying degrees of extra costs, rendering them less competitive compared to renewable counterparts. Notably, HFSC incurs the highest fuel costs within the RES, coupled with extra costs exceeding those of other technologies' standard fuel expenses. Consequently, HFSC may prove unsustainable from an energetic sustainability standpoint. Conversely, gas technologies (NGCC and NGSC) and IGCC experience comparatively lower impacts, with extra costs accounting for approximately 60% of the difference compared to their standard costs, whereas HFSC's difference is approximately 10%.

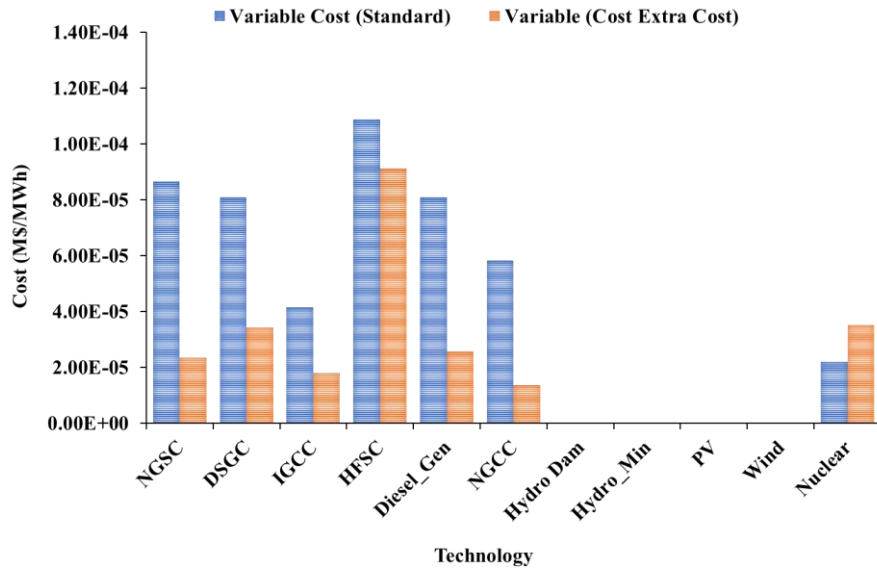


Figure 4.2 Variable Cost: Impact of Standard and Extra Costs on Each Technology in the Atlantis RES.
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4.6.1.2. EPBT Optimization Results Presentation

The derived merit variables following the implementation of the optimization function, encompassing the energetic sustainability estimator denoted as "Op_EPBT," are presented in Table 4.6. Additionally, Figure 4.3 provides a representation of the annual energy production for the competitive technologies emphasizing as the results the impact of Op_EPBT.

Table 4.6 Op_EPBT; Output optimization results: Details of the merit's variables.
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Energetic trend	Global Energy Production (MWh)	Renewable Energy	53221×10 ³
		Fossil Fuels	15774×10 ³
		Nuclear	0
	RoP (%)	Renewable Energy	77
		Fossil Fuels	23
		Nuclear	0
Economic trend	Economic Cost features (M\$)	Capital Cost	3530
		Variable Cost	1607
		Fixed Cost	1465
	Economic Cost per unit of energy production (\$/MWh)	Global Cost	95.76
		Residual Price	44.56
Emissions trend	Global Emissions (t CO ₂)		9.20×10 ⁶
	Global Emissions per unit of energy production (t CO ₂ /MWh)		0.133

Upon closer examination, the influence of EPBT on nuclear energy deployment becomes apparent, as is not illustrated among the competitive technologies in Figure 4.3. Notably, the substantial impact of EPBT on nuclear technology is evident from the observed nuclear F_{EPBT} . This underscores the significance of considering nuclear EPBT within the cradle-to-cradle paradigm, wherein factors such as energy consumption for waste management post-decommissioning are accounted for. Consequently, this reaffirms the unsustainable nature of nuclear energy production within the cradle-to-cradle framework, particularly concerning energetic sustainability criteria. Chapter 6 will undertake a more comprehensive analysis of the sustainability aspects associated with nuclear energy, considering its various life stages.

The observed impact of EPBT, leading to the unsustainability of nuclear energy in the Op_EPBT scenario, stands in stark contrast to its competence in the Op_Standard approach.

Consequently, this trend towards nuclear unsustainability prompts a heightened reliance on renewable energy sources and, to a lesser extent, fossil fuels to address the intermittency inherent in renewable energy sources.

Remarkably, the impact of the energetic sustainability criteria serves to incentivize the deployment of renewable energy sources, proving to be even more economically effective than the Op_Standard approach. Specifically, as can be seen in Table 4.6, renewable energy sources exhibit a 20% increase in contribution within the Op_EPBT scenario compared to the Standard optimization. However, fossil fuels continue to hold a substantial share, representing 23% of the total energy output.

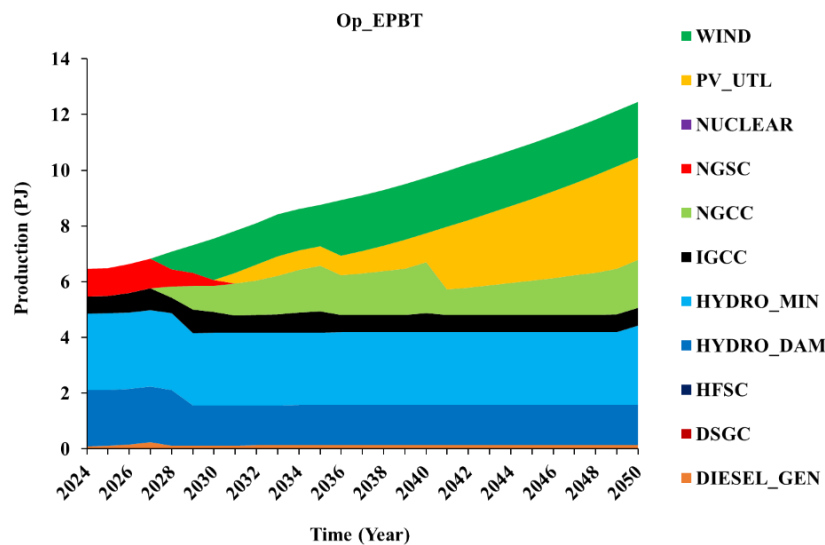


Figure 4. 3 Op_EPBT: Annual energy production per technology.
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Continuing our focus on Table 4.6, particularly on emissions, the comparison between the energetic sustainability criteria trend and the Standard optimization reveals that Op_EPBT results in a reduction of approximately 2×10^6 tons of CO₂ emissions compared to Op_Standard. However, it's important to note that this reduction, while significant, does not surpass the threshold of 20%.

The economic analysis reveals that the energetic sustainability-based results, characterized by significant deployments of renewable energy, incurs a substantial investment cost approximately double that of the investment cost observed in the Op_Standard scenario. However, this shift is accompanied by a decrease in fuel costs, attributable to the no reliance on nuclear energy. Consequently, despite the heightened investment costs, the Op_EPBT trend exhibits an overall or global cost of nearly \$16/MWh, representing a minimum 13% increase compared to the Op_Standard scenario.

Interestingly, despite the higher global cost, the Op_EPBT scenario results in electricity price per MWh being cheaper than the Op_Standard by approximately \$8/MWh. This translates to a minimum 20% decrease in electricity price, highlighting the cost-saving potential associated with the adoption of renewable energy sources despite the initial investment outlay.

4.6.2. Economic Sustainability Indicator Implementation

The integration of the economic sustainability indicator mirrors the approach detailed in the preceding section. Given its direct correlation with the initial investment, the associated additional cost naturally impacts the capital cost term of the OSeMOSYS objective function. This involves imposing an extra cost on the investment cost based on the ITR and the ULT.

A first-order hypothesis is defined to translate ITR into economic terms. It is assumed that investment recovery occurs uniformly throughout the evaluated technology's lifespan. The underlying concept posits that each technology must generate surplus energy annually, evenly distributed to offset the initial investment, thereby significantly augmenting the technology's capital cost. The overarching aim is to ensure that each technology within the energy mix can recover its initial investment outlay.

Furthermore, sustainability is intrinsically linked to the operational lifespan of each system, underscoring the importance of expeditious capital investment recovery for enhancing economic sustainability. Therefore, to incorporate ITR into an economic cost weight, a correction factor, F_{ITR} , is established as shown in Equation 4.7 as the ratio between the ITR of each technology considered in the studied energetic mix and its corresponding useful lifetime. This serves as a preliminary approximation method.

The introduction of ITR as a new input parameter within OSeMOSYS is contingent upon technology and region. Subsequently, post-optimization, every technology in the energy mix should ideally recoup its initial investment. Hence, prioritizing the sustainable trend with technologies having the lowest F_{ITR} .

Equation 4.8 illustrates the capital cost term in the OSeMOSYS optimization function, adjusted by the F_{ITR} extra-cost factor, accounting for economic sustainability ($Capital_Cost_{r,t,y}^{Sus}$). The economic sustainability correction can be overridden using the additional modulation weight W_{ITR} .

$$F_{ITR_{r,t}} = \left(\frac{ITR}{ULT} \right)_{r,t} \quad (Eq\ 4.7)$$

$$Capital_Cost_{r,t,y}^{Sus} = \sum_{r,t,y} CapCost_{y,t} \left(1 + F_{ITR_{r,t}} \times W_{ITR} \right) \quad (Eq\ 4.8)$$

Consistent with the approach observed for EPBT, it's essential to note that OSeMOSYS lacks built-in functionality to compute the ITR for each technology under examination. Rather, users are tasked with providing the ITR as parameter data for the array of technologies being assessed.

4.6.2.1. Effect of the ITR in the Atlantis energetic framework

The process of estimating a technology's ITR is complex and requires a thorough consideration of various factors throughout its entire lifecycle, from raw material extraction to technology dismantling. Key factors that impact ITR estimation include geographical and energy efficiency [148].

To create a comprehensive compilation of ITR data for this study, literature reviews and country-specific case studies were conducted, and a mean value was derived from synthesizing this information. This initial estimate provides insight into the potential impact of the developed methodology on the energetic sustainability of Atlantis.

Table 4.7 offers a concise overview of reported ITR values for energy generation technologies used in Atlantis RES, along with references to the literature sources. Additionally, the table provides corresponding F_{ITR} values for each technology, offering insights into the energetic sustainability implications within the RES. The ULT for each technology employed in the F_{ITR} computation was sourced from the default data provided by Atlantis, as delineated in Table 1. 2.

Figure 4.4 illustrates the Capital Investment Cost per unit of capacity for each technology deployed in the Atlantis RES, juxtaposed with their respective additional costs attributed to the F_{ITR} impact. Certainly, it is evident that Hydro_Dam and nuclear technologies incur significantly higher extra costs compared to their standard investment outlays. The Hydro_Dam incurs an extra cost double the standard investment cost, while nuclear technology

sees a 30% higher difference. This may affect their competitiveness during the optimization process when economic sustainability criteria are considered. This disparity can be attributed to the inclusion of ITR considerations within the cradle-to-cradle framework, accounting for the extensive civil construction expenditures associated with these technologies. Furthermore, the ULT assessments address the dynamic ageing processes of materials, rather than solely focusing on the static structural integrity of civil components. This nuanced discussion is extensively explored in Chapter 1, Section 1.6.4.

Table 4.7 ITR and F_{ITR} values associated with the Atlantis technologies
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Category	Technology	ITR (Year)	F_{ITR}
Fossil Fuels	NGSC	11.7 [149], [150], [151], [152]	0.390
	DSGC	14.7 [151], [152], [153]	0.490
	IGCC	30 [151], [154]	1
	HFSC	14.7 [152], [155]	0.420
	Diesel_Gen	14.8 [151], [153]	0.370
	NGCC	11.9 [149], [150], [151], [152]	0.340
Renewable Energy	Hydro Dam	84 [156], [157]	2.400
	Hydro_Min	35 [156], [157]	0.700
	PV	2 [151], [152], [153], [158], [159]	0.080
	Wind	10 [151], [152], [153], [156], [160]	0.400
Nuclear	Nuclear	75 [151], [152], [161]	1.5

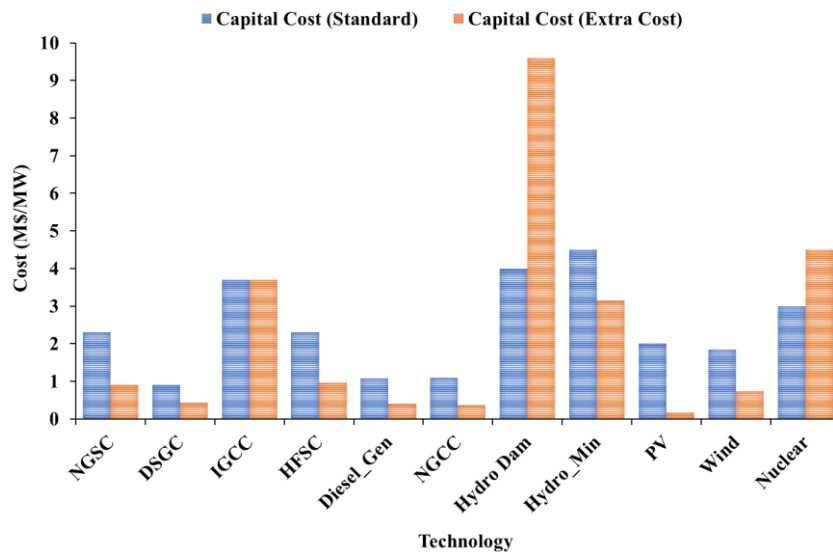


Figure 4.4 Capital Cost: Impact of Standard and Extra Costs on Each Technology in the Atlantis RES
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Conversely, solar and wind energy technologies within the renewable energy category demonstrate minimal impact, indicating their economic viability. Among fossil fuel technologies, NGCC and Diesel_Gen exhibit relatively lower extra costs, while others show varying degrees of enhancement in their extra costs. For instance, IGCC's extra cost remains comparable to its standard cost, suggesting its economic resilience within the optimization framework

4.6.2.2. ITR Optimization Results Presentation

The computed merit variables after the execution of the optimization function, which integrates the economic sustainability estimator labelled as "Op_ITR," are outlined in Table 4.8. Furthermore, Figure 4.5 provides a representation of the annual energy production for the competitive technologies emphasizing as the results the impact of the economic sustainability criteria.

Table 4.8 Op_ITR: Details of the merit's variables
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Energetic trend	Global Energy Production (MWh)	Renewable Energy	21372×10^3
		Fossil Fuels	47571×10^3
		Nuclear	0
	RoP (%)	Renewable Energy	31
		Fossil Fuels	69
		Nuclear	0
Economic trend	Economic Cost features (M\$)	Capital Cost	2859
		Variable Cost	4201
		Fixed Cost	1108
	Economic Cost per unit of energy production (\$/MWh)	Global Cost	118.48
		Residual Price	77
Emissions trend	Global Emissions (t CO ₂)		22.27×10^6
	Global Emissions per unit of energy production (t CO ₂ /MWh)		0.323

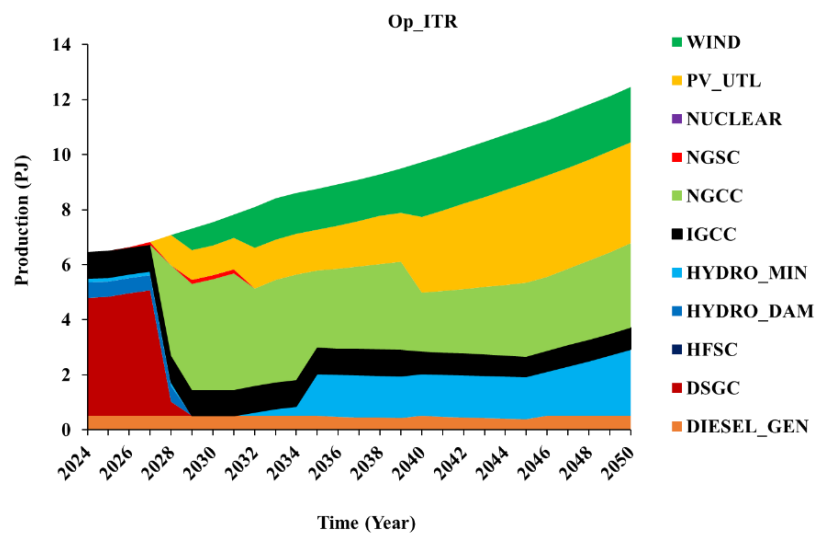


Figure 4. 5 Op_ITR: Annual energy production per technology
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The similarity between economic sustainability indicators and energetic criteria is conspicuous, particularly in the context of nuclear energy technology. This is highlighted by the discernible absence of nuclear technology among the competitive options in terms of economic sustainability (Figure 4.5). The inhibition of nuclear energy deployment, evidenced by its elevated F_{ITR} induced extra costs shown in Figure 4.4, underscores its economic impracticality within a cradle-to-cradle framework. Similarly, Hydro_Dam encounters constraints within the Op_ITR framework due to its prolonged economic recovery duration, rendering it economically unsustainable in this context.

In contrast to standard optimization approaches, economical based sustainability criteria prioritize the deployment of fossil fuel technologies such as NGCC, Diesel_Gen, and IGCC, as depicted in Figure 4.5. Despite some renewable energy deployments (Solar PV, Wind, and

Mini_Hydro) being present, their global contribution only amounts to 30%, marking a 20% decrease compared to Op_Standard's renewable contribution (See Table 4.8).

In contrast, fossil fuels hold a dominant 70% share of the global energy mix, demonstrating a twofold increase in economic competitiveness for swiftly recovering initial investment costs compared to Op_Standard. However, this heightened economic efficiency comes at a significant environmental cost, as fossil fuels emerge as the most pollution-intensive sustainability indicator, with emission trends as can be seen in Table 4.8 approximately double those observed in Op_Standard.

In analyzing the impact of Op_ITR on economic costs, it's evident that a notable increase in the Global Cost has been observed, surpassing the proposed standard economic solutions trend by nearly \$40/MWh. This uptick can be attributed to the substantial presence of fossil fuels within the energy mix. Consequently, the corresponding fuel costs aggregated over the entire period were found to be significantly higher, with a disparity of M\$ 3913 compared to the standard trend. This translates to a higher electricity price of \$77/MWh, contrasted with the estimated \$53/MWh in the Op_Standard trend.

4.6.3 Environmental Sustainability Implementation

So far, to address environmental concerns, OSeMOSYS employs different energy modelling techniques and is commonly employed hence targeting a lower feasible emission in the tendency. Among these approaches is an alternative to controlling emission activity, which is to be set by employing the emission limitation parameter [10].

Furthermore, there is the possibility of instituting a carbon tax (emission penalty) on the emitted greenhouse gases, which is currently used by several legislation and countries as a policy to mitigate high levels of carbon emissions [70]. Plus, the technological limitation parameter under the activity constraints can be considered as a focused methodology at inhibiting the contribution of highly emitting technology to the tendency, which could act as a further strategy for achieving this endeavor.

The approach established in this work adheres to the pre-existing strategy such as the consideration of the emission penalty but differs in its technical form. The peculiarity of this methodology lies in how it incorporates the environmental sustainability indicator directly into the OSeMOSYS algorithm optimization function straight forward as an extra cost. As an effect, from a technical standpoint, this will alter the objective function structure slightly by upgrading the emission cost, but the preservation of its initial configuration makes it an optimization constraint.

As in the previous cases, the main challenge is to convert the IMPcc into an economic cost weight. However, as no tabulated values of IMPcc are immediately available, the matching emissions per unit of energy produced also called emission activity ratio in OSeMOSYS code EmissRate, [t CO₂eq] represents the carbon content per unit of energy produced for a given technology. These values are essential for accurately representing the carbon intensity of energy consumption and for evaluating different energy scenarios in terms of their carbon emissions and environmental impact.

The consideration of the emission activity ratio as the main element to include the IMPcc as extra cost probably becomes a limit of this methodology because the EmissRate value estimates only the GHG during the production phase (gate-to-gate) rather than the cradle-to-cradle paradigm. This will make, for example, renewable energy sources like wind and solar with minimal or no carbon emission rate because typically they produce electricity with minimal or no carbon emissions. On the other hand, fossil fuels like coal and natural gas have higher EmissRate values due to the carbon content associated with their combustion.

However, due to values based on available data or estimates for the technologies or fuels being modelled during the production phase, the EmissRate is considered to build a first order

to conceptualize the actual purpose by converting the effect of EmissRate being the IMPcc indicator as an extra cost by modifying the Emission_Cost so far detailed in Equation 1.5.

The approach used is to gauge EmissRate for each technology relative to the mean of the emission rate of all technologies considered in the energetic mix, MeEmissRate [t CO₂ eq]. The MeEmissRate serves as a reference point for comparing the emissions of individual technologies.

A modulating emission factor F_{IMPcc} is defined (Equation 4.9) for each technology as the ratio between each technology EmissRate and the MeErsEmissRate aiming to evaluate how emissive a technology is in comparison with the remaining technologies in the system forcing the deployment of non-emissive technologies.

$$F_{IMPcc} = \frac{EmissRate_t}{MeErsEmissRate} \quad (Eq\ 4.9)$$

The F_{IMPcc} permits values in the range (F_{IMPcc} ≥ 0) and leads to non-linear changes in the Emission Cost structure which means that the relationship between the F_{IMPcc} value and the associated costs is not linear. Instead, it varies in a non-linear manner, potentially leading to more pronounced cost differences between technologies with different emission profiles.

This implies that the technology is penalized for emitting carbon, and as a result, it incurs higher related costs. Therefore, low-emission technologies with low carbon content or those that emit minimal pollutants will have a lower F_{IMPcc} value and consequently face reduced related emission costs. Conversely, high-polluting technologies with high carbon content or those that emit significant pollutants will have a higher F_{IMPcc} value. This leads to increased related emission costs due to the emission penalty associated with their higher carbon emissions.

The emissions cost, which has been improved by the IMPcc estimator via the F_{IMPcc} correction, is expressed in Equation 4.10 as (Emiss_Cost_y^{Sus}). As in the previous case, the environmental sustainability correction can be disabled with the additional modulation weight W_{IMPcc}.

$$Emiss_Cost_y^{Sus} = \sum_t EmissionPenalty_{r,e,y} \times EmissRate_{r,t,e,m,y} \times F_{IMPcc} \times W_{IMPcc} \quad (Eq\ 4.10)$$

The main aim of this approach is to differentiate between technologies based on their emission profiles, particularly to incentivize low-emission technologies and disincentivize high-emission ones thus leading toward a decision focused on crediting low-emission technologies and penalizing high-polluting ones based on their carbon content. While the F_{IMPcc} parameter can have a significant impact on the costs and incentives for technologies with distinct emission profiles, still affects technologies with emission rates close to MeEmissRate (F_{IMPcc} ≈ 1) despite having no direct effect on associated costs.

In OSeMOSYS, the integration of the IMPcc indicator involves a nuanced approach centered on adjusting the F_{IMPcc} and Emiss_Cost_y^{Sus} parameters. Rather than directly incorporating the F_{IMPcc} parameter into the existing emission cost, a distinct emission cost feature is introduced. This new feature operates in tandem with the original emission cost parameter, both of which are linked to a common activator called the IMPcc_Activator. This activator serves as a control mechanism, regulating the activation of the duplicated emission cost feature containing the F_{IMPcc} parameter.

The value of the IMPcc_Activator parameter determines whether the duplicated emission cost feature, incorporating the F_{IMPcc} parameter, is activated or not. This activation mechanism allows for the selective application of the emission cost adjustments based on the F_{IMPcc} parameter. The activation mechanism is as follows:

- ✚ If the $IMPcc_Activator = 1$, then $Emission_Cost_y = Emiss_Cost_y^{Sus}$
- ✚ If the $IMPcc_Activator = 0$, then $Emission_Cost_y \neq (Emiss_Cost_y^{Sus} = 0)$

The methodology delineated herein constitutes a foundational strategy within the broader discourse of addressing environmental considerations in energy modelling, notably within the OSeMOSYS framework. Its principal objective is to discern among various technologies based on their emission profiles, thereby fostering the adoption of low-emission technologies while discouraging the utilization of high-emission ones.

The implementation of IMPcc within the OSeMOSYS framework presents distinct challenges compared to EPBT and ITR due to the absence of directly applicable tabular values. The key difference between IMPcc and EPBT/ITR lies in their operational mechanisms. While F_{EPBT} and F_{ITR} are seamlessly integrated as extra costs within Variable and Capital costs, respectively, by utilizing direct tabular values representing EPBT and ITR, IMPcc's integration into the Emission Cost hinges on emissions activity ratios.

It's worth noting that the developed methodology within the IMPcc evaluates technology emission activity exclusively within the energy production phase, which may serve as a limitation. Limit includes also Because of the commutative operation within the $Emission_Cost_y^{Sus}$ feature the emission penalty must be nonzero. This penalty ensures that adjustments made by " F_{IMPcc} " have a meaningful impact on emissions-related costs.

In OSeMOSYS, it's a common practice to assign small nonzero values (such as 0.00001) to input parameters that should not be nil. Assigning small nonzero values to parameters in this case, such as emission penalties, could inhibit the effectiveness of the F_{IMPcc} parameter [64]. This is because these small values might not adequately represent the actual impact of emissions on costs. To ensure that the adjustments made by the F_{IMPcc} parameter interact effectively with emission costs, it's essential to apply the IMPcc factor in the context of an emission penalty. This means that the F_{IMPcc} adjustments should be based on meaningful penalties associated with emissions, rather than arbitrarily small values.

4.6.3.1. Effect of the IMPcc in the Atlantis energetic framework

The central element of the IMPcc approach developed within OSeMOSYS is the F_{IMPcc} . Table 4.9 presents the F_{IMPcc} values assigned to each technology within the Atlantis RES. The calculation of F_{IMPcc} relies on input emission data ($Emiss_Rate$) provided in Chapter 1, as detailed in Table 1.2. From this data, the mean emission rate value of the Atlantis RES is determined ($MeErsEmissRate = 0.358 \text{ t CO}_2/\text{MWh}$).

Table 4. 9 F_{IMPcc} values associated with the Atlantis technologies
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Category	Technology	F_{IMPcc}
Fossil Fuels	NGSC	1.17
	DSGC	1.71
	IGCC	2.37
	HFSC	1.80
	Diesel_Gen	1.71
	NGCC	0.89
Renewable Energy	Hydro Dam	0
	Hydro_Min	0
	PV	0
	Wind	0
Nuclear	Nuclear	0.04

Figure 4.6 presents the Emission Cost per unit of energy produced across various technologies within the Atlantis RES, along with the additional costs attributed to the F_{IMPcc} impact. Notably, renewable technologies entail no emission costs, given their non-emissive nature during energy generation. Consequently, optimization strategies for these technologies predominantly focus on addressing other pertinent costs and enhancing efficiency to mitigate their intermittent operational characteristics. Similarly, nuclear energy exhibits negligible emissions and, consequently, incurs minimal emission costs.

Conversely, fossil fuel technologies involve emission costs and are significantly affected by additional expenses. While gas technologies, particularly NGCC, are minimally impacted by extra costs, other components within the fossil fuel category demonstrate a different scenario, rendering them environmentally unsustainable.

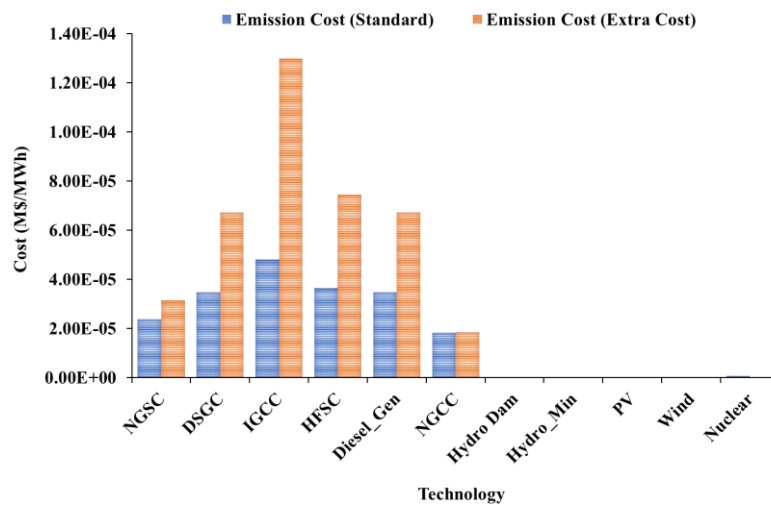


Figure 4.6 Emission Cost: Impact of Standard and Extra Costs on Each Technology in the Atlantis RES
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4.6.3.2. IMPcc Optimization Results Presentation

At this juncture of the study, the IMPcc methodology introduces a critical parameter related to emission penalties. Given the variable nature of regulations and community standards governing emissions, we have established a preliminary working hypothesis for these penalties. Specifically, we have set the emission penalty at \$50 per ton of CO₂, aligning with regulatory frameworks observed within the European Union (EU) [162], [163].

In Chapter 6, analysis will be conducted to explore the impact of various carbon tax levels, as stipulated by EU legislation [162], on the efficacy of the IMPcc approach. This examination will shed light on the sensitivity of the IMPcc methodology to evolving regulatory environments and provide valuable insights into its operational viability.

Table 4.10 offers a comprehensive assessment of the IMPcc's impact, delineating the merit variables post-execution, while Figure 4.7 illustrates the annual energy generation per technology.

The implementation of the environmental sustainability criteria heralds a notable shift towards renewable energy sources. As evidenced in Table 4.10, these sources constitute a substantial portion, accounting for at least 70% of the overall energy mix, while fossil fuel utilization remains marginal, comprising less than 10% of the total energy mix, primarily dominated by gas technology, with a minimal contribution from Diesel_Gen. This contribution underscores their capacity to complement the intermittent nature of renewable energy sources, thereby ensuring grid stability and reliability.

This disparity stems from the pronounced impact of the extra cost on fossil fuel technologies as depicted in Figure 4.6, which indicates a higher level of emissivity compared to the mean emission rate (MeErEmissRate). Notably, technologies such as IGCC and HFSC are particularly affected by the F_{IMPcc} , rendering them noncompetitive within the energy mix (Figure 4.7).

Table 4.10 Op_IMPcc: Details of the merit's variables

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Energetic trend	Global Energy Production (MWh)	Renewable Energy	49762×10^3
		Fossil Fuels	4381×10^3
		Nuclear	14826×10^3
	RoP (%)	Renewable Energy	72
		Fossil Fuels	6
		Nuclear	22
Economic trend	Economic Cost features (M\$)	Capital Cost	3456
		Variable Cost	1379
		Fixed Cost	1362
	Economic Cost per unit of energy production (\$/MWh)	Global Cost	89.90
		Residual Price	39.76
Emissions trend	Global Emissions (t CO ₂)		2.33×10^6
	Global Emissions per unit of energy production (t CO ₂ /MWh)		0.034

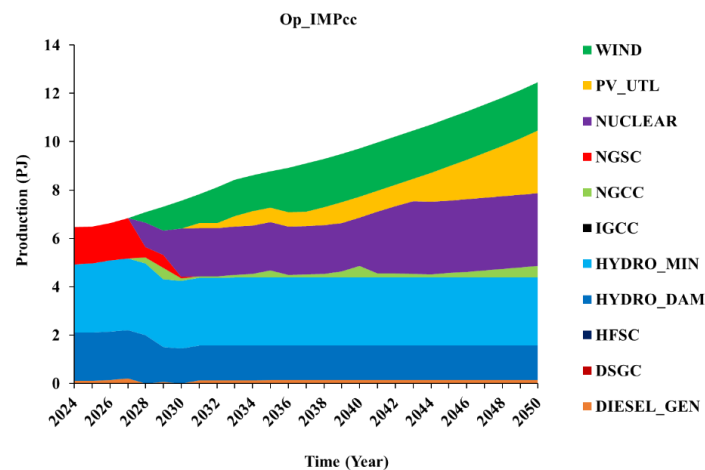


Figure 4.7 Op_IMPcc: Annual energy production per technology

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Nuclear energy, renowned for its minimal greenhouse gas emissions [164], is regarded as a sustainable option from an environmental standpoint. Its pollution-free nature during the generation phase significantly contributes to the observed trends, prompting some policymakers to categorize it as a green technology.

The environmental sustainability-based decision-making approach has successfully facilitated a significant transition from renewable energy sources to fossil fuels, resulting in a noteworthy reduction in global emissions. In comparison to the baseline scenario established by the Op_Standard approach, emission trends have plummeted by up to 80%.

The economic analysis of the Op_IMPcc scenario unveils significant insights into the energetic mix of technologies deployed. Notably, the dominance of renewable energy sources in this approach, constituting 70% of the energetic mix, contributes to a substantial increase in capital investment costs. Specifically, the IMPcc optimization exhibits a notable disparity, amounting to $\$1589 \times 10^6$ more in capital investment costs compared to the Op_Standard scenario.

This heightened investment cost translates to a 10% increase in the overall global cost in the sustainable environment scenario when juxtaposed with the Standard optimization. Conversely, despite the elevated capital investment costs, the Option under environmental sustainability criteria yields electricity prices that are 25% lower than those resulting from the Standard optimization. This considerable reduction in electricity prices can be attributed to the lower variable costs associated with the environment scenario, which are twice as low as those of the Standard optimization.

However, while a drastic decrease in variable costs, expected to be around 70%, is anticipated due to the reduced reliance on fossil fuels in the Op_IMPcc scenario (constituting only 6% of the mix compared to 21% in the Op_Standard), the actual decrease is only 50%. This discrepancy can be elucidated by considering the influence of nuclear energy within the mix and its corresponding fuel cost.

4.6.4 Sustainability Index Optimization Function

Equation 4.11 defines the sustainable optimization function integrated into OSeMOSYS called sustainability optimization index, *Sus_Op_index*, in compliance with sustainability criteria. The sustainability optimization functions can be run either as single functions or in convolutions (either paired or integrated), following the user's preferences.

$$\text{Sus_Op_index} = \sum_y \left(\text{Variable_Cost}_{r,t,y}^{\text{Sus}} + \text{FixCost}_y + \text{Capital_Cost}_{r,t,y}^{\text{Sus}} + \text{Emiss_Cost}_y^{\text{Sus}} \right) \quad (\text{Eq 4.11})$$

The comprehensive evaluation of sustainable development encompasses the utilization of modulation weights, as delineated by Equation 4.6, Equation 4.8, and Equation 4.10. These modulation weights serve as activators, with a value of 1 signifying the activation of the corresponding sustainability index and 0 indicating its deactivation. This approach allows for the adjustment of prioritization among different aspects of sustainable development through the modulation weights.

Thus far, our discussion has primarily focused on the single effects of each sustainability index within the Atlantis energy framework. However, with the introduction of the *Sus_Op_index*, we embark on a more holistic approach that integrates multiple sustainability indicators. This entails examining how various sustainability factors collectively impact the overall sustainability of the energy system.

By amalgamating economic, environmental, and energetic considerations, this optimization strategy facilitates the formulation of comprehensive strategies that strike a balance between conflicting objectives and enhance overall sustainability. Through this approach, we gain insights into the synergies and trade-offs inherent in sustainability objectives.

The *Sus_Op_index* plays a pivotal role in optimizing the overall associated cost, prioritizing technologies with minimal extra global costs incurred from various components. Figure 4.8 illustrates the Global Cost and the corresponding extra Global Cost for each technology within the Atlantis RES.

In the renewable energy category, both PV and wind technologies exhibit minimal impact from extra costs, notably exempt from both emission and fuel-related expenses. Conversely, within the fossil fuels category, NGSC, NGCC, and Diesel_Gen is less affected by extra costs. However, technologies such as HFSC and IGCC face significant impacts, resulting in elevated extra global costs.

Of particular note are nuclear and Hydro_Dam technologies, which experience substantial impacts, surpassing their standard costs. This can be attributed to factors such as civil infrastructure and waste management, especially notable in the case of nuclear technology.

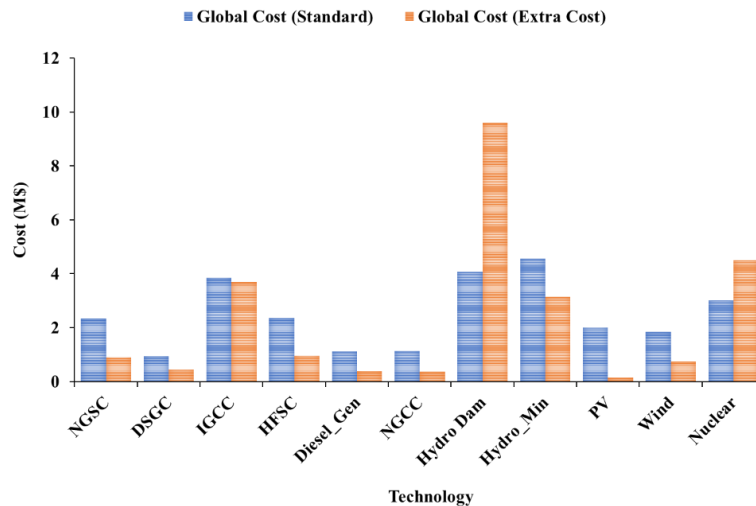


Figure 4.8 Global Cost: Impact of Standard and Extra Costs on Each Technology in the Atlantis RES
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4.6.4.1. Effect of the Sus_Op_index: Optimization Results

The integrated sustainable optimization process relies on the Op_SusIndex, indicating that the modulation weight for each sustainability index is activated. Table 4.11 furnishes details regarding the modulation weights utilized to prioritize the Op_SusIndex optimization.

Table 4.11 Modulation Weight setting associated with the integration of the sustainability indicators.
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Integrated Sustainability Criteria Optimization function	
Op_SusIndex	$\text{Sus_Op_index with } \begin{cases} W_{EPBT} = 1 \\ W_{ITR} = 1 \\ W_{IMPcc} = 1 \end{cases}$

Table 4.12 offers a comprehensive assessment of the outcomes derived from Op_SusIndex, delineating the merit variables obtained post-optimization. Conversely, Figure 4.9 provides a visual representation of the annual energy production resulting from the integration of sustainability criteria, as denoted by Op_SusIndex.

The tabulated data illustrates a balanced representation of both renewable and fossil fuel technologies. However, nuclear energy and Hydro_Dam technologies are notably hindered, indicating a reduced emphasis on their deployment within the optimized energy system.

The obtained results whether from Table 4.12 or the graphical representation (Figure 4.9) illuminates the inherent trade-offs between sustainability criteria, exemplified by the curtailment of nuclear production due to the cradle-to-cradle implications of both ITR and EPBT. This initial trade-off underscores the complex interplay between sustainability objectives.

Furthermore, the Op_SusIndex facilitates a comprehensive deployment of renewable energy sources, constituting 47% of the total energy mix, as delineated in Table 4.12. This strategic deployment aims to align with both environmental and energetic criteria, albeit exhibiting a reduction of 30% and 10% in renewable energy share compared to Op_IMPcc and Op_EPBT, respectively.

While environmental indicators advocate for increased renewable energy deployment, their effectiveness in curbing fossil fuel utilization is constrained by the intermittent nature of renewable sources. Consequently, fossil fuel deployment remains inevitable, ensuring not only a swift economic return on investment, in line with economic sustainability objectives, but also

addressing the intermittent nature of renewable energy sources. Notably, fossil fuels account for a 6% higher capacity deployment compared to renewable energy sources, as evident in Table 4.12.

Table 4.12 Op_SusIndex: Details of the merit's variables
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Energetic trend	Global Energy Production (MWh)	Renewable Energy	32772×10^3
		Fossil Fuels	36222×10^3
		Nuclear	0
	RoP (%)	Renewable Energy	47
		Fossil Fuels	53
		Nuclear	0
Economic trend	Economic Cost features (M\$)	Capital Cost	2238
		Variable Cost	3431
		Fixed Cost	1029
	Economic Cost per unit of energy production (\$/MWh)	Global Cost	97.16
		Residual Price	64.70
Emissions trend	Global Emissions (t CO ₂)		14.30×10^6
	Global Emissions per unit of energy production (t CO ₂ /MWh)		0.207

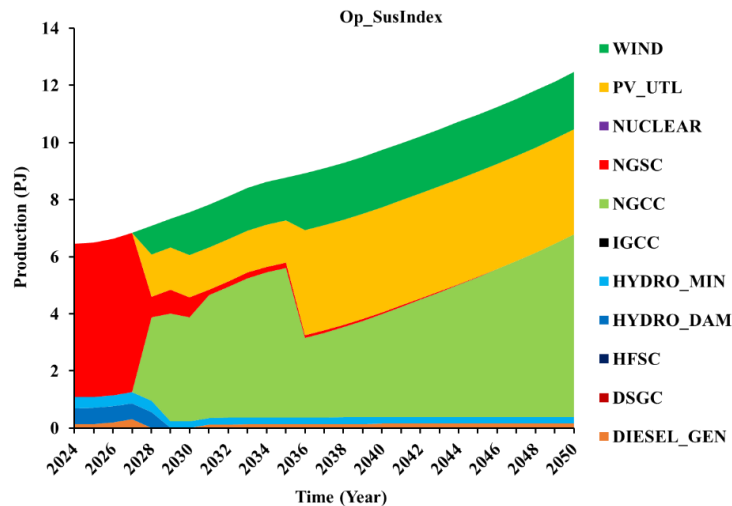


Figure 4.9 Op_SusIndex: Annual energy production per technology
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The economic cost profile is intricately linked to the output trends, with significant impacts arising from the integration of sustainability indicators. A comparative analysis with the Standard optimization reveals notable increases across all cost components, underscoring the trade-offs inherent in sustainability integration.

Primarily, the investment cost within the Op_SusIndex exhibits a disparity of M\$ 371 relatives to the Op_Standard. This escalation is emblematic of the strategic emphasis on sustainable practices, necessitating higher initial capital outlays. Furthermore, the heightened deployment of fossil fuels within the Op_SusIndex contributes to an increased variable cost over the long term, amounting to M\$ 549 compared to the Op_Standard output variable cost.

These increments in cost components reverberate throughout the overall economic landscape, impacting both the global cost and electricity price. To be more specific, the implementation of the Op_SusIndex results in a \$15.75/MWh increase in global cost and a \$10/MWh increase in electricity prices compared to the Op_Standard. These findings emphasize the intricate economic consequences of incorporating sustainability measures and underscore the

importance of conducting thorough cost-benefit analyses when pursuing energy optimization initiatives.

In terms of emissions mitigation, it's noteworthy that the Op_SusIndex output trend showcases a concerning divergence from the Op_Standard, registering an 18% increase in emissions. Specifically, this equates to a gap of 0.047 t CO₂/MWh, attributable to the pronounced reliance on fossil fuels within its energetic mix.

4.7. Chapter Conclusions

This chapter delineates the methodology employed to integrate sustainability indicators, namely EPBT, ITR, and IMPcc, within the OSeMOSYS framework. The feasibility of each sustainability criterion is validated within the Atlantis energetic framework, and the ensuing results are analyzed, focusing on merit variables encompassing energy production, economic aspects, and emissions activities. These results are juxtaposed with those of the Standard optimization function, serving as the baseline scenario.

Primarily, the analysis reveals that energetic based sustainability decision prioritizes renewable energy over fossil fuels, while also making it in the energetic mix to alter the intermittent nature of renewable sources while constraining the deployment of nuclear technologies due to sustainability concerns. This aligns with the economic sustainability goal, which favours fossil fuels to expedite investment return, albeit at the cost of heightened emissions. Notably, while decision making based with both energetic and economic sustainability goal discourage nuclear deployment, they diverge regarding emission mitigation, with Op_EPBT exhibiting a favourable reduction in emissions due to its emphasis on renewable solutions.

Environmental based sustainability decision predominantly endorses non-emissive solutions, notably renewable energy, and nuclear power, albeit with variations. Op_IMPcc trend includes nuclear technology, distinguishing it from energetic and economic sustainability trend. Despite differences in nuclear deployment, environmental and energetic sustainability trends positively contribute to emission reduction, particularly owing to their extensive deployment of renewable solutions.

Concerning economic costs, Op_IMPcc and Op_EPBT trends exhibit similarities, driven by heightened investment costs and reduced fuel costs attributable to increased renewable deployment. Conversely, Op_ITR demonstrates an opposite trend, incurring higher costs due to extensive fossil fuel utilization. Similarly, in terms of global costs and electricity prices, both EPBT and IMPcc trends remain comparable, whereas ITR trends surpass them by twofold.

Last but not least, the integration of sustainability indices within an integrated approach presents a versatile framework capable of accommodating multiple sustainability metrics simultaneously. An initial analysis of combining the three indicators within the Op_SusIndex within such an integrated optimization approach reveals a discernible trade-off among sustainability objectives within the resultant output trend. This trade-off reflects an endeavour to balance and fulfil each of the defined sustainability goals comprehensively.

As a partial conclusion, the congruence observed among the output variables of each sustainability trend suggests an increase in global cost and the presence of similarities within certain trend. Moreover, the potential for integrating and evaluating the convolution among the sustainability indices provides an opportunity to amplify this interrelation. The forthcoming chapter will prioritize conducting paired convolutions to delve deeper into the similarities levels and provide a comprehensive understanding of their implication.

Chapter 5. Optimizing Sustainability Criteria in Convolution

This chapter partially reproduces content from the following publications, which were derived from research conducted by the doctoral candidate during the thesis development period:

Publications 1:

- Title: Sustainability Indicators Correlation Matrix
- Authors: Mahamat Habib Bechir, M. Darío Ferreira, A. López Agüera.
- Journal: International Journal for Research in Applied Science & Engineering Technology (Ijraset).
- ISSN: 2321-9653
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Publications 2:

- Title: Environmental Sustainability Impact as Optimization Function of OSeMOSYS Energetic Modelling System
- Authors: Mahamat Habib Bechir and A. López Agüera.
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5.1. Introduction

In the previous chapter, we analyzed how sustainability indicators influence individual decision-making processes. Our findings indicate that the inclusion of sustainability criteria in modelling an energy transition process helps identify the most sustainable options and can yield multiple solutions.

However, sustainable development requires a multifaceted approach, integrating economic, energy, and environmental factors [129], [165]. We discovered in the previous chapter that no single indicator can effectively address specific sustainability goals, such as achieving energy neutrality with short payback periods. Consequently, we defined a sustainable optimization function (OP_SusIndex) that encompasses an integrated convolution of a set of sustainability indicators.

Given that the incorporation of sustainability criteria generally increases the overall costs associated with the energy transition process, it raises the question of whether the proposed indicators operate independently, capturing unique dimensions of sustainability, or if they are interrelated, potentially leading to double counting.

Under these circumstances, optimizing decision-making is imperative by identifying the essential criteria necessary to achieve desired outcomes while avoiding redundant requirements that increase economic pressure. It is crucial, therefore, to examine and quantify the possible interrelationships between the proposed sustainability indicators and understand how one sustainability indicator might modulate another [34]. This chapter aims to address these concerns.

Utilizing the Atlantis energy framework alongside the established sustainability methodology within OSeMOSYS, we employ an integrated strategy to assess sustainability indicators through paired convolution during optimization. This approach involves pairing indicators to evaluate their combined effects, unveiling synergies, and identifying potential trade-offs in sustainability objectives.

To ensure consistency and facilitate the study, as well as to identify and assess the general trends observed in the previous chapter, we adhere to the predefined working hypotheses outlined in detail in Chapter 2, sections 2.3.1, 2.3.2, and 2.3.3. These sections respectively cover the feasibility analyses of Op_EPBT, Op_ITR, and Op_IMPcc respectively the optimization under the energetic, economic and environmental sustainability criteria.

Continuing from this point, we formalize our observations by quantifying the effects of mutual interaction among indicators through the construction of correlation matrices using the Pearson method. This entails evaluating pivotal variables such as prices, energy consumption, and emissions, and comparing them against established benchmarks.

Through this quantitative analysis, Pearson coefficients [166], will furnish us with the degree of correlation between the indicators, elucidating the extent of overlap between the effects associated with various facets of sustainable development. Consequently, we can fine-tune the weighting assigned to each indicator in alignment with our objectives.

The potential need for modulation underscores the crucial role of the weighting factors introduced in Chapter 2 (section 2.2.4), while remaining aligned with user goals. Consequently, these modulation factors (W_j , where $j = \text{EPBT, ITR and IMPcc}$) could be defined as a function of the correlation coefficients, moving beyond the binary form defined in the previous chapter.

The findings highlight the importance of accurately weighting sustainability indicators to optimize decision-making processes in energy transitions, ensuring that sustainability objectives are met without unnecessary economic burden. This approach paves the way for more refined and holistic energy planning methodologies, aligning with broader sustainability goals. The present work could serve as a roadmap for future investigations.

5.2. Two-by-Two sustainability indicator convolution

The investigation encompasses three distinct optimizations, each targeting specific sustainability facets:

- ✚ Optimization integrating the convolution of the energetic and economic sustainability criteria (*Op_EPBT_ITR*).
- ✚ Optimization integrating the convolution of the energetic and environmental sustainability criteria (*Op_EPBT_IMPcc*).
- ✚ Optimization integrating the convolution of the economic and environmental sustainability criteria (*Op_ITR_IMPcc*).

In each optimization application where IMPcc is implicated, the corresponding emission penalty is fixed at \$50/t CO₂ eq. This value is consistent with the penalty rate established to confirm the feasibility of IMPcc in Chapter 4 (section 4.6.3.2).

Table 5.1 provides insights into the modulation weights assigned to prioritize each optimization, guiding towards a comprehensive understanding of sustainability dynamics within energy planning and optimization frameworks.

Table 5 1 Modulation Weight setting associated with the convolution of the sustainability indicators
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Paired Tandem Optimization Function	Modulation Weight in the Sus_Op_index
Op_EPBT_ITR	Sus_Op_index with $\begin{cases} W_{EPBT} = 1 \\ W_{ITR} = 1 \\ W_{IMPcc} = 0 \end{cases}$
Op_EPBT_IMPcc	Sus_Op_index with $\begin{cases} W_{EPBT} = 1 \\ W_{ITR} = 0 \\ W_{IMPcc} = 1 \end{cases}$
Op_ITR_IMPcc	Sus_Op_index with $\begin{cases} W_{EPBT} = 0 \\ W_{ITR} = 1 \\ W_{IMPcc} = 1 \end{cases}$

5.2.1. Analytic Results

Table 5.2 documents the post-optimization results of the paired convolution of sustainability indicators. The table provides an overview of the merit variables derived from each of the paired convolution optimization processes.

In Table 5.3, we present the results obtained in the previous chapter, detailing the outcomes of applying sustainability indicators individually, in convolution (*Op_SusIndex*), and without the application of sustainability indicators (*Op_Standard*). This summary facilitates a more straightforward comparative analysis of the optimization effects, with those tabulated in Table 5.2.

Through the evaluation of the convolution among sustainability indicators, the first observation underscores the interconnected nature of sustainability criteria, where improvements in one indicator can modulate or exert feedback loops that influence another indicator.

To investigate the nature of the interrelation whether it involves modulation or double counting between the sustainability indicators, we conducted an analytical study of each merit variable trend. This unbiased comparative study involved analyzing the outcomes of each merit variable for sustainable optimization scenarios applied both singularly and in convolution and comparing these to the corresponding trend variables in the standard optimization

(Op_Standard). The Op_Standard serves as a reference point for this analysis, allowing us to discern the unique contributions and interactions of each sustainability indicator.

Table 5. 2 Details of the merit's variables of the Op_EPBT_ITR, Op_EPBT_IMPcc and Op_ITR_IMPcc
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Merits variables		Op_EPBT_ITR	Op_EPBT_IMPcc	Op_ITR_IMPcc
Global Energy Production (MWh)	Renewable	31003×10 ³	55790×10 ³	30063×10 ³
	Fossil Fuels	37990×10 ³	4429×10 ³	27045×10 ³
	Nuclear	0	8877×10 ³	11885×10 ³
ROP (%)	Renewable	45%	81%	47%
	Fossil Fuels	55%	6%	53%
	Nuclear	0	13%	17%
Economic Cost features (M\$)	Capital Cost	2158	3855	2268
	Variable Cost	3320	1177	3123
	Fixed Cost	994	1444	939
Economic Cost (\$/MWh)	Global Cost	93.87	93.93	97.16
	Residual Price	62.57	38.02	64.70
Global Emissions (t CO ₂)		19.02×10 ⁶	2.20×10 ⁶	11.22×10 ⁶
Global Emissions (t CO ₂ /MWh)		0.276	0.032	0.163

Table 5. 3 Details of the merit's variables of the Op_Standard, Op_EPBT, Op_ITR, Op_IMPcc and Op_SusIndex
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Merits variables		Op_Standard	Op_EPBT	Op_ITR	Op_IMPcc	Op_SusIndex
Global Energy Production (MWh)	Renewable	38594 ×10 ³	53221×10 ³	21372×10 ³	49762×10 ³	32772×10 ³
	Fossil Fuels	14238 ×10 ³	15774×10 ³	47571×10 ³	4381×10 ³	36222×10 ³
	Nuclear	15012 ×10 ³	0	0	14826	0
ROP (%)	Renewable	57	77	31	72	47
	Fossil Fuels	21	23	69	6	53
	Nuclear	22	0	0	22	0
Economic Cost features (M\$)	Capital Cost	1867×10 ⁶	3530	2859	3456	2238
	Variable Cost	2882×10 ⁶	1607	4201	1379	3431
	Fixed Cost	773×10 ⁶	1465	1108	1362	1029
Economic Cost (\$/MWh)	Global Cost	80.09	95.76	118.48	89.90	97.16
	Residual Price	53.01	44.56	77	39.76	64.70
Global Emissions (t CO ₂)		11.05×10 ⁶	9.20×10 ⁶	22.27×10 ⁶	2.33×10 ⁶	14.30×10 ⁶
Global Emissions (t CO ₂ /MWh)		0.160	0.133	0.323	0.034	0.207

In Figure 5.1, the percentage deviation from Op_Standard within the renewable energy category is presented for each sustainable optimization function. The observation indicates that economic sustainability considerations result in 25% less renewable energy deployment compared to the standard. However, this effect is modulated when combined with EPBT and/or IMPcc, reducing the difference to at least 10% when convoluted with Op_ITR.

Notably, an increased rate of renewable energy deployment is observed when sustainability is measured by a quick energetic time of recovery. The combination of EPBT with environmental sustainability which follows a similar trend, further amplifies the increase in renewable energy deployment compared to when these indicators are applied individually. This positive interrelation or feedback loop is evident in the Op_EPBT_IMPcc trend shown in Figure 5.1.

In Figure 5.2, the fossil fuel trend demonstrates an inverse trajectory to the renewable energy category, where economic sustainability promotes its deployment. As illustrated in Figure 5.2,

there is a negative interrelation with both EPBT and IMPcc; their presence modulates the impact of economic sustainability on fossil fuel deployment.

While EPBT and IMPcc exhibit a positive relationship in renewable energy deployment, this does not hold for fossil fuel-based technologies. Although environmental sustainability goals (IMPcc) inhibit fossil fuel deployment, Op_EPBT however shows some tolerance toward it. Thus, when EPBT is combined with IMPcc, its tolerance toward fossil fuels deployment is moderated, indicating a divergence between these indicators.

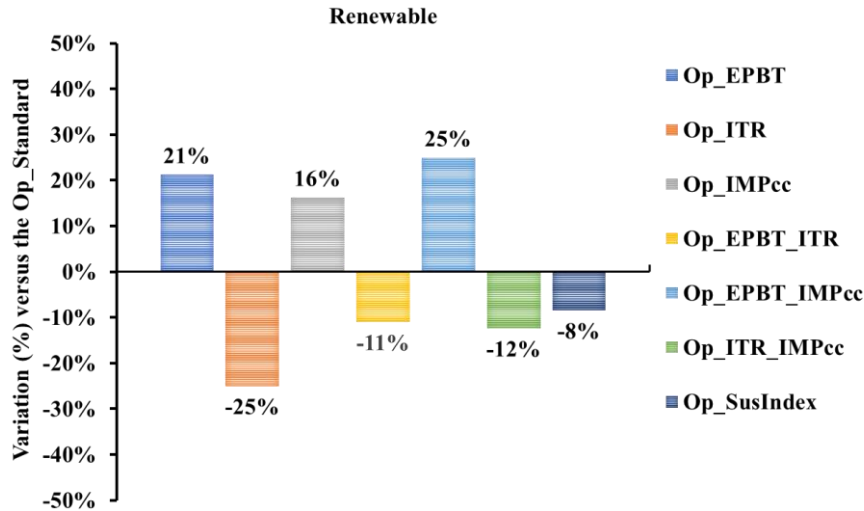


Figure 5. 1 Percentage of variations in comparison to the Op_Standard for renewable energy source category for each sustainable optimization function.

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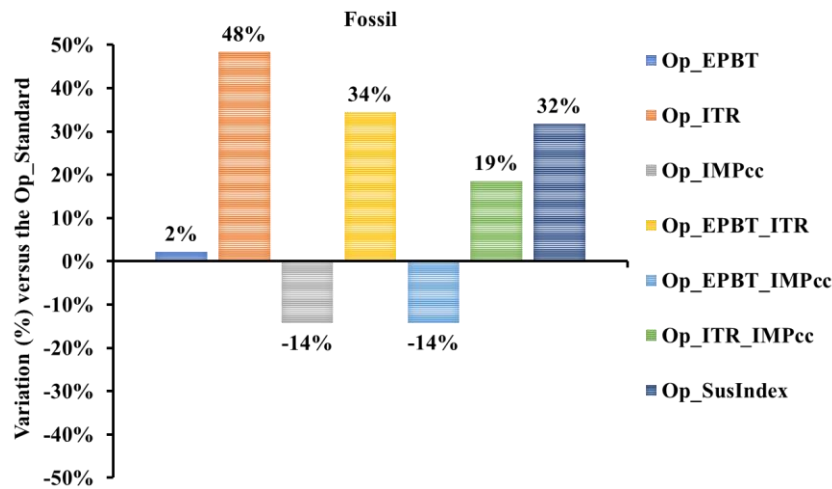


Figure 5. 2 Percentage of variations in comparison to the Op_Standard for fossil fuels-based technology for each sustainable optimization function.

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In the context of nuclear energy, as illustrated in Figure 5.3, both Op_ITR and Op_EPBT distinctly exclude this technology from their respective trends, a pattern that persists even in their joint optimization, thus fostering a convergent relationship between them.

However, Op_IMPcc includes nuclear energy in its deployment strategy due to its perception as a non-pollutant feature within the IMPcc framework (this will be discussed in the next chapter), resulting in a sustained reliance on nuclear production similar to that of Op_Standard. The influence of IMPcc on nuclear deployment is modulated when combined with either EPBT

or ITR, as shown in Figure 5.3, indicating a divergence among these indicators regarding nuclear energy.

Conversely, nuclear energy deployment is restrained when IMPcc is applied in conjunction with both EPBT and ITR (Op_SusIndex) confirming their divergence between IMPcc and both EPBT and ITR in nuclear deployment. This restraint is primarily due to the strict considerations of nuclear waste management inherent in both energetic and economic sustainability criteria (this will be addressed in the next chapter).

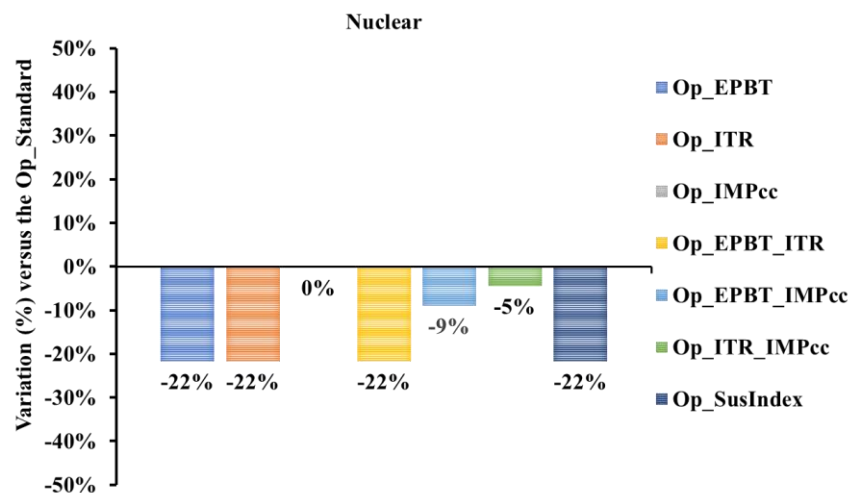


Figure 5. 3 Percentage of variations in comparison to the Op_Standard for nuclear energy source category for each sustainable optimization function.
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Figure 5.4 illustrates the percentage variations in global emissions trends for each sustainable optimization function compared to the standard optimization function. Notably, both Op_IMPcc and Op_ITR exhibit contrasting behaviours. The environmental goal, represented by IMPcc, is associated with substantial emissions decrease of at least 75%. Conversely, when rapid economic return on initial investments is prioritized, emissions tend to increase at a similar magnitude. This dichotomy evidences their negative interrelation; despite the modulating effect of ITR on IMPcc, there is no significant overall change compared to the standard, suggesting that each indicator operates independently within their convolution.

Regarding the energetic sustainability criterion (EPBT), a distinct emissions reduction is observed when it is applied singularly, as depicted in Figure 5.4. However, this reduction appears to be a circumstantial effect rather than a robust trend. When EPBT is combined with the other indicators, it does not exert a substantial influence on the emissions trend, instead adopting the characteristics of the indicators it is paired with. This suggests that EPBT behaves more as a follower indicator, positively interrelating with the dominant sustainability criteria it is associated with.

Figure 5.5 presents an accumulative diagram plotting the percentage variations in cost features relative to the standard optimization function for each sustainable optimization approach. Notably, the systematic integration of any sustainability indicator results in a corresponding rise in global costs, with Op_ITR presenting the most expensive scenarios, nearly doubling the global cost compared to Op_Standard. Conversely, Op_IMPcc emerges as the more economical option, necessitating only a modest 10% increase in global costs relative to Op_Standard. Furthermore, the residual electricity price decreases by up to 25% below that of Op_Standard, although this requires an initial investment cost 80% higher than Op_Standard.

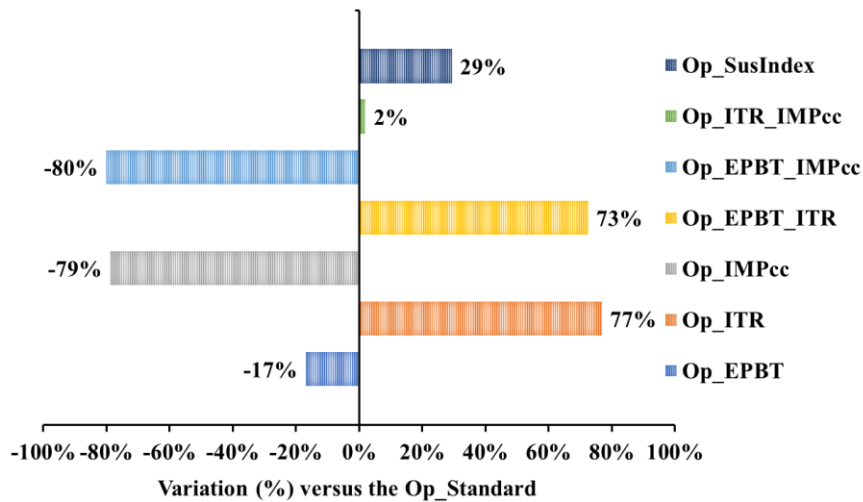


Figure 5. 4 Percentage of variations of the global emissions level in comparison to the standard optimization function for each sustainable optimization function.
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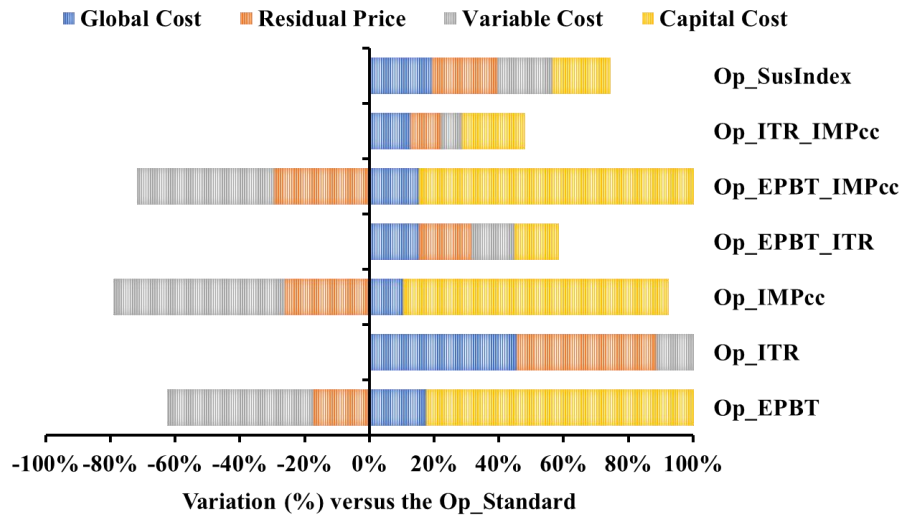


Figure 5. 5 Percentage of variations of the global cost features in comparison to the standard optimization function for each sustainable optimization function
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The optimization of both environmental and economic criteria invariably leads to an increase in investment costs due to a high reliance on the more expensive renewable solutions and a consequent decrease in variable or fuel costs. This trend is opposite to that of ITR, which relies on fossil fuel-based technologies and is therefore associated with high fuel costs and lower investment costs. The residual cost trend similarly shows a decrease under energy and environmental sustainability criteria, while it increases within the economic sustainability criteria optimization.

Analyzing the cost trends further, Op_ITR modulates the cost trends of both EPBT and IMPcc, particularly for capital and residual costs when combined with ITR. This indicates a positive interrelation between EPBT and IMPcc, both of which are negatively interrelated with ITR, except in the context of global costs, which increase under any sustainable optimization scenario.

So far, we have analytically evidenced the interrelation between the sustainability indicators. The results from paired convolution optimization have been critical in achieving this aim. Given these analytical findings, it is also important to explore the impact of these paired convolution optimizations on energy production trends. This can be visualized in Figure 5.6, which plots the annual energy production by technology, illustrating the output results of the paired optimization functions.

The analysis of decision-making scenarios targeting both improved energy payback time and long-term environmental solutions, as depicted in Figure 5.6(c), offers key insights into the mutual dependence of sustainability indicators and their impacts on energy production trends. Notably, the prominence of renewable energy sources is evident, with hydroelectric technologies, Solar PV, and wind emerging as sustainable energy sources within the Op_EPBT_IMPcc scenario. This highlights the synergistic effect of combining environmental sustainability with energy efficiency metrics.

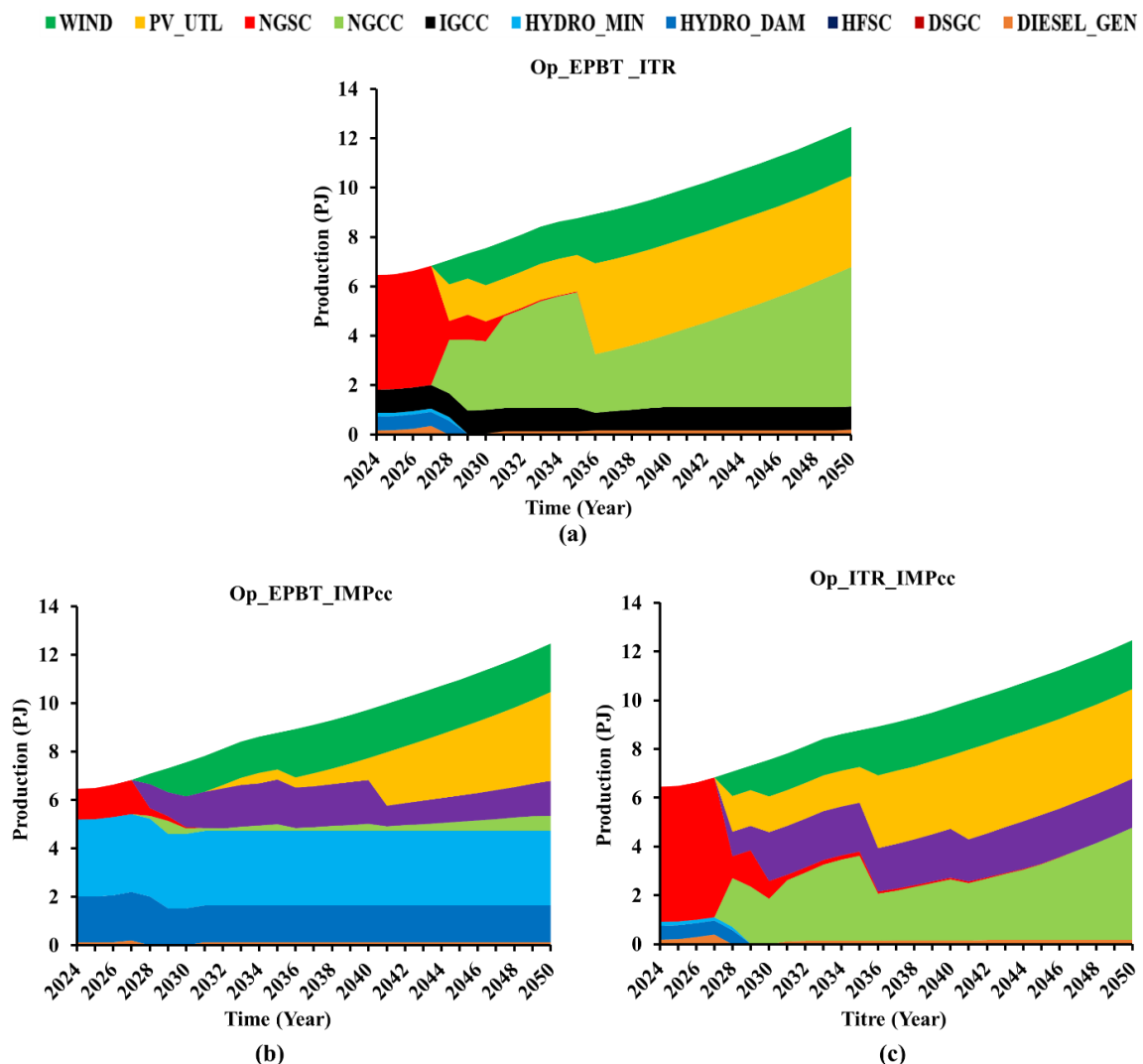


Figure 5. 6 Energy production per technology in 3 optimization function scenarios integrating two-by-two sustainability indicators : a)Op_EPBT_ITR; b) Op_EPBT_IMPcc; c) Op_ITR_IMPcc
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However, this synergistic effect does not extend to the deployment of nuclear energy, which remains limited despite being modulated by the energy payback time indicator. Additionally, fossil fuel usage, primarily driven by natural gas with a marginal contribution from diesel generators, reflects the influence of the energy payback time (EPBT) indicator. This usage is

further modulated by the environmental impact indicator, illustrating a nuanced balance between reducing fossil fuel dependency and integrating environmental sustainability considerations.

The prioritization of economic returns consistently results in an energy mix heavily reliant on fossil fuels, particularly natural gas, and coal, especially when energy payback time requirements are considered (Figure 5.6(a)). However, this relationship becomes more complex when environmental goals are taken into account, as the economic benefits are significantly influenced by environmental impacts. Consequently, only natural gas combined cycle technology remains viable for achieving the desired economic outcomes (Figure 5.6(b)).

In summary, the influence of each sustainability indicator on the others has been clearly demonstrated, revealing a complex interplay among these indicators when considered in pairs. This intricate behavior, involving a two-by-two convolution, will be quantified in the following section.

5.3. Sustainability indicators correlation matrix

It is crucial when conducting multivariate analysis, such as in this specific instance involving sustainability indicators and therefore by examining the correlations it is possible to identify which variables are related and which are not. Generally, when multiple variables are being analysed, their correlations are displayed as coefficients in a table or matrix. This is known as a correlation matrix a statistical tool that elucidates the strength and direction of relationships between multiple variables [167].

In the preceding section, we established the presence of a correlation among sustainability indicators through the analysis of their outcome results. In this section, our objective is to deepen our understanding of the robustness of this correlation using the correlation matrix approach [168]. This approach entails constructing a table wherein correlation coefficients for various pairs of variables are systematically arranged, showcasing the respective values. This tabular arrangement facilitates the comprehension of the interaction and interdependence among variables [166], [167], [168].

By employing this method, we seek to provide comprehensive insights into the intricate interplay among these sustainability indicators. Such insights hold significant value, offering valuable guidance for policymakers, businesses, and society at large in their pursuit of sustainable development.

5.3.1. Methodology

We employ the Pearson method to assess the correlation among energy-economic and environmental sustainability indices [166]. Through this method, we construct correlation matrices that elucidate the linear connections among all variables under consideration. These matrices serve to unveil patterns and connections between the energy-economic and environmental dimensions of sustainable development, offering a deeper insight into their interplay within the sphere of sustainability.

However, in our multidimensional study encompassing numerous merits variables, the correlation matrix isn't a static, singular entity. Instead, it functions as a dynamic tool to evaluate the strength and direction of relationships among multiple variables simultaneously, within a defined set of relevant constraints. To this end, we've identified distinct constraint sets based on merit variables, which can be applied either individually or collectively during the analysis process. By employing these constraint sets, we refine datasets to create subsets that adhere to specific conditions or criteria, enabling focused analysis on particular aspects or relationships within the data.

Thus, we generate a correlation matrix for each subset, resulting in a unique matrix for each set of constraints. Specifically, our set of constraints pertains to the outcome optimization

results conducted with OSeMOSYS, comprising merit variables such as energy production, economic costs, and output emissions.

As part of our working hypothesis, the energy production feature set encompasses three categories or subsets: renewable energy, fossil fuels, and nuclear energy. Similarly, economic costs are subdivided into subset of capital costs, fixed costs, and variable costs. Meanwhile, output emissions constitute a single set for analysis. By delineating these subsets, we can undertake a comprehensive examination of the correlation dynamics across various dimensions of sustainability.

The correlation matrix for sustainability indicators (SI_CorrMtxSet) is delineated in Equation 5.1. Each cell within this matrix represents the Pearson correlation coefficient (Cc) between two specific sustainability indicators, offering insights into the magnitude and direction of their linear relationship.

$$SI_CorrMtx^{Set} = \begin{bmatrix} Cc_{EPBT_EPBT}^{Set} & Cc_{EPBT_ITR}^{Set} & Cc_{EPBT_IMPcc}^{Set} \\ Cc_{ITR_EPBT}^{Set} & Cc_{ITR_ITR}^{Set} & Cc_{ITR_IMPcc}^{Set} \\ Cc_{IMPcc_EPBT}^{Set} & Cc_{IMPcc_ITR}^{Set} & Cc_{IMPcc_IMPcc}^{Set} \end{bmatrix} \quad (Eq. 5.1)$$

Where:

Set: Represents the set of constrain defined. It indicates the output data variables that make up the dataset for analysis; in OSeMOSYS this can include costs, emissions, and energetic production among others.

$Cc_{EPBT_EPBT}^{Set}$: The correlation coefficient between the indicator EPBT and EPBT.

$Cc_{ITR_ITR}^{Set}$: The correlation coefficient between the indicator ITR and ITR.

$Cc_{IMPcc_IMPcc}^{Set}$: The correlation coefficient between the indicator IMPcc and IMPcc.

$Cc_{EPBT_ITR}^{Set}$: The correlation coefficient between the indicator EPBT and ITR.

$Cc_{EPBT_IMPcc}^{Set}$: The correlation coefficient between the indicator EPBT and IMPcc.

$Cc_{IMPcc_ITR}^{Set}$: The correlation coefficient between the indicator IMPcc and ITR.

The Pearson coefficient is computed [169] by dividing the covariance of the two variables by the product of their standard deviations. Esteemed for its intuitive interpretation and ability to capture linear associations between variables, a value of Cc nearing 1 indicates a robust positive correlation, while a value near -1 suggests a strong negative correlation. Conversely, a value approximating 0 indicates an absence of correlation [170]. The correlation coefficient for a pair of sustainability indicators under defined constraints can be calculated using Equation 5.2.

$$Cc_{X_Y}^{set} = \frac{Nr^{Set} \sum (XY) - (\sum X \sum Y)}{\sqrt{(Nr^{Set} \sum X^2 - (\sum X)^2)(Nr^{Set} \sum Y^2 - (\sum Y)^2)}} \quad (Eq. 5.2)$$

Where:

$Cc_{X_Y}^{Set}$: correlation coefficient between variable X and Y (in this case it represents the sustainability indices)

$\sum XY$: sum of the product of each pair of corresponding sets of constraints of the two variables

$\sum X$: sum of the sets of constraints of the first parameter

$\sum Y$: sum of the sets of constraints of the second parameter

Nr^{Set} : Number of sets of constraints defined before that are applied.

The application of this methodology necessitates the implementation of a systematic analysis of correlation matrices derived from a multitude of sets of constraints. This approach facilitates comparisons and enables the identification of disparities or similarities in the relationships among sustainability indicators. Such an endeavour fosters a deeper comprehension of the intricate relationships between sustainability indicators across diverse contexts [167], [169]. By analysing the results, discernible patterns and dependencies among sustainability indicators

emerge, thereby contributing to informed decision-making and the formulation of effective policies.

Prior to computing the Pearson coefficients, data preprocessing plays a crucial role in standardizing or normalizing units and potentially transforming variables to adhere to a normal distribution. In this context, we have employed the standard deviation method, a fundamental technique utilized to standardize the scale of variables within a dataset. This method involves adjusting the distribution of each variable to possess a mean of zero and a standard deviation of one, thereby promoting fair and accurate comparisons across diverse metrics. Such normalization is instrumental in enhancing the interpretability and effectiveness of subsequent analyses, particularly in scenarios where variables exhibit disparate scales and units. For a comprehensive understanding of the standard deviation method, detailed documentation can be found in works such as Kotsiantis et al [171].

5.3.2. Results

The considered sets of constraints utilized to generate the correlation matrices encompass three primary dimensions: i) Ep (comprising categorized energy production sources, including renewable, fossil, and nuclear), ii) Ec (encompassing economic cost, which includes capital investment, fixed and variable costs), and iii) Em (emissions).

These constraints correspond to the output merit variables derived from the optimization results of sustainability indicators as detailed in Table 5.3.

In assessing the level of correlation among sustainability indicators, it has been observed that the response varies depending on the merit variables considered. This observation has been corroborated in our research paper [172], dedicated to the correlation matrix between sustainability indicators. To enhance clarity, an analytical evaluation is proposed through the construction of correlation matrices, wherein sets of constraints are applied individually and in combination.

Notably, the application of all constraints simultaneously does not yield informative decision-making insights, as the corresponding correlation matrix suggests an interdependence among the variables' constraints as represented in Equation 5.3, this correlation matrix includes the joint application of EC, EP, and EM constraints. Specifically, the analysis reveals no correlation between economic and energy sustainability criteria, while environmental sustainability demonstrates a clear negative correlation with economic sustainability. Conversely, energy and environmental sustainability exhibit a correlation exceeding 80%.

$$SI_CorrMtx^{EP\&EC\&EM} = \begin{bmatrix} 1 & 0.05 & 0.82 \\ 0.05 & 1 & -0.42 \\ 0.82 & -0.42 & 1 \end{bmatrix} \quad (\text{Eq. 5.3})$$

Moreover, our examination reveals a multifaceted (fivefold) interrelation among the variables, encompassing renewable and fossil fuel production, emissions, variable costs, and investment costs. Specifically, emissions exhibit intricate connections not only with the distribution of renewable energy sources or fossil fuels in the energy mix but also with capital investment.

This relationship is exemplified within the context of Op_IMPcc, where despite a substantial proportion of renewable sources, the trend showcases lower CO₂ emissions but entails higher investment costs. In contrast, Op_ITR, prioritizing swift investment payback, often favors fossil fuels over renewable energy, despite their minimal capital investment requirements. However, this approach incurs higher variable costs and results in extensive CO₂ emissions.

5.3.2.1. Correlations matrix coefficients: Energetic production as constraint set.

To delve deeper into this matter, correlation matrices are evaluated with a more straightforward set selection. That is when focusing specifically on energy production where in this analysis, the set of constraints utilized comprises the three distinct categories of energy production: renewable energy, fossil energy, and nuclear energy. Equation 5.4 illustrates the resulting correlation matrix, revealing discernible directional relationships among sustainability indicators. The findings demonstrate a robust correlation of at least 80% between EPBT and IMPcc. This positive correlation primarily emanates from both indicators advocating for the widespread adoption of renewable energy production.

However, the correlation between ITR and EPBT, while positive, is not particularly robust, standing at 23%. This modest correlation can be attributed to their differing approaches to energy production, with the exception of fossil fuel category production. Additionally, both indicators exhibit no reliance on nuclear energy compared to fossil fuels and renewables, contributing to their similarity in this aspect.

$$SI_CorrMtx^{EP} = \begin{bmatrix} 1 & 0.23 & 0.86 \\ 0.23 & 1 & -0.29 \\ 0.86 & -0.29 & 1 \end{bmatrix} \quad (Eq.5.4)$$

Furthermore, economic, and environmental sustainability indicators exhibit an anticorrelation of 29%. This disparity can be elucidated by the notable differences in renewable and fossil production between these indicators. Op_IMPcc restricts polluting technology alternatives to a mere 6% of the energy mix, while the higher incorporation of renewable energy necessitates increased capital investment costs. This stands in contrast to Op_ITR, where half of the energy generation is derived from fossil fuels, thereby prioritizing quicker economic returns over environmental sustainability considerations.

5.3.2.2. Correlations matrix coefficients: Energetic production and Emission as constraint set.

The inclusion of emissions as set of constraint alongside energy production categories set yields a significant impact on the correlation matrix, denoted as $SI_CorrMtx^{EP\&EM}$, as delineated in Equation 5.5. Notably, the correlation coefficient associated with ITR undergoes a notable transformation due to this inclusion. This shift in correlation arises from each trend aligning with the triangular interrelation between emissions performance and the dependency on fossil fuels and renewable energy sources, as elucidated in detailed analyses presented in Figures 5.1, 5.2, and 5.3.

$$SI_CorrMtx^{EP\&EM} = \begin{bmatrix} 1 & -0.01 & 0.74 \\ -0.01 & 1 & -0.67 \\ 0.74 & -0.67 & 1 \end{bmatrix} \quad (Eq.5.5)$$

Specifically, ITR exhibits a noteworthy change in correlation behavior, being either uncorrelated or even anticorrelated with EPBT when the emission is set as a constraint. This shift in correlation is reminiscent of the behavior observed with IMPcc, where the degree of anticorrelation is exacerbated compared to when only energy production is considered as the constraint.

On the other hand, EPBT and IMPcc continue to display a robust correlation, driven by their shared emphasis on promoting renewable energy production. However, it's worth noting that

the reliability of Op_EPBT, with 30% of fossil fuels in its energetic mix, contributes to a higher emissions level compared to Op_IMPcc (refer to Figure 3.4), resulting in a decline of the correlation level by 12% when emissions are included as constraints alongside energy production. This nuanced observation underscores the intricate dynamics at play when considering emissions alongside energy production in correlation analyses.

5.3.2.3. Correlations matrix coefficients: Economic cost as constraint set.

The correlation matrix shown in Equation 5.6 denoted as SI_CorrMtx^{EC} focuses on the economic cost component set and at the same time serves to affirm the intricate relationships among sustainability indicators in the economic trend (refer to Figure 5.5). As anticipated, a robust correlation emerges between EPBT and IMPcc, with the correlation coefficient reaching its maximum value, indicative of parallel economic and renewable energy trends.

$$\text{SI_CorrMtx}^{\text{EC}} = \begin{bmatrix} 1 & 0.14 & 1 \\ 0.14 & 1 & 0.08 \\ 1 & 0.08 & 1 \end{bmatrix} \quad (\text{Eq. 5.6})$$

However, the ITR indicator, characterized by contrasting trends, displays a positive correlation with EPBT, albeit not particularly strong, with a correlation coefficient of approximately 15%. Notably, it exhibits a clear lack of correlation with IMPcc, underscoring the divergence in their respective economic and energy trajectories.

5.3.2.4. Correlations matrix coefficients: with Economic cost and energetic production as constraint set.

The incorporation of the energetic production set of constraints alongside the economic cost set does not yield a substantial impact on the correlation matrix, designated as SI_CorrMtx^{EC&EP}, in comparison to the SI_CorrMtx^{EC}. As shown in Equation 5.7, the addition of the energy production constraint leads to a slight decrease in the correlation strength between EPBT and IMPcc, albeit they still maintain a robust correlation. However, there is no noteworthy alteration in the correlation between ITR and IMPcc, with their corresponding correlation coefficient standing at 17%. Moreover, the relationship between ITR and IMPcc persists as an anticorrelation, indicating a divergence in their economic and energy trends.

$$\text{SI_CorrMtx}^{\text{EC\&EP}} = \begin{bmatrix} 1 & 0.17 & 0.91 \\ 0.17 & 1 & -0.11 \\ 0.91 & -0.11 & 1 \end{bmatrix} \quad (\text{Eq.5.7})$$

5.3.2.5. Correlations matrix coefficients: Economic Cost and Emission as constraint set.

Equation 5.8 delineates the correlation matrix, denoted as SI_CorrMtx^{EC&EM}, which examines the relationship between sustainability indicators under the constraint grouping of economic cost and emissions. A notable observation is that the inclusion of emissions trends, which vary among individual indicators (refer to Figure 3.4), exerts a significant influence on the current correlation matrix.

$$SI_CorrMtx^{EC\&EP} = \begin{bmatrix} 1 & -0.02 & 0.85 \\ -0.02 & 1 & -0.39 \\ 0.85 & -0.39 & 1 \end{bmatrix} \quad (Eq.5.8)$$

Specifically, ITR demonstrates an anticorrelation with both EPBT and IMPcc, exacerbated by their disparate trends in emissions and costs. In comparison with their correlation degree within $SI_CorrMtx^{EC}$, the correlation is diminished by a 15% gap, primarily due to the divergence in emission trends between EPBT and IMPcc. Despite this variance, they still maintain a positive correlation, albeit weakened by the influence of emissions trends.

5.3.3. Decision Table design

Based on the results obtained, Figure 5.7 provides a visual representation of the Pearson coefficient values between sustainability indicators, categorized based on the variables utilized as constraints. This depiction allows for an insightful observation of the behavioral trends among the indicators. Notably, the strongest correlation emerges between EPBT and IMPcc, underscoring their closely aligned trajectories. Conversely, the association between ITR and EPBT reveals a weaker correlation, while the relationship between ITR and IMPcc demonstrates the strongest anticorrelation.

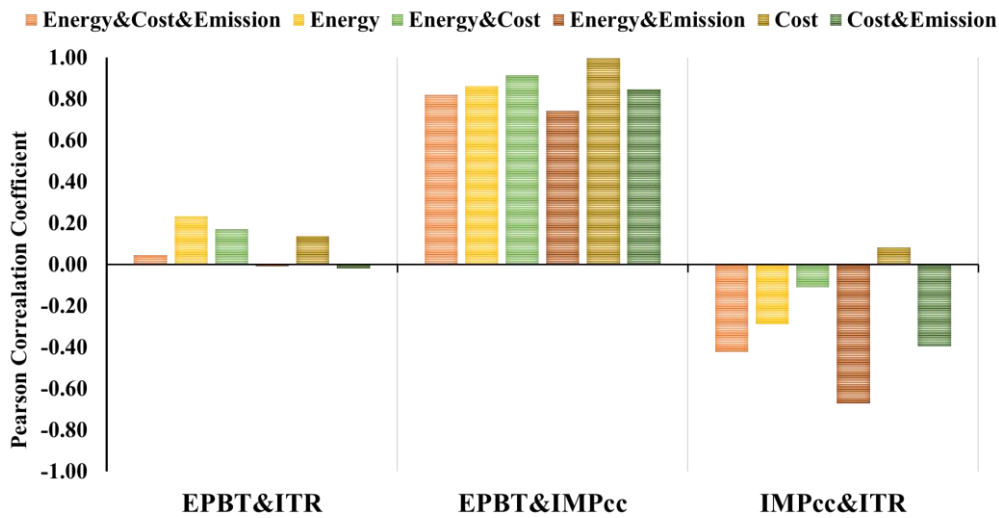


Figure 5.7 Comparison of the person correlation coefficient for each set of constraint between the sustainability indicators

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From the analysis presented in Figure 5.7, significant insights emerge regarding the prioritization of sustainability indicators based on specific decision-making objectives. For instance, when the correlation coefficient between two sustainability indicators attains an absolute value ($Cc = 1$) for a particular set of decision objectives, it implies redundancy when these indicators are used in conjunction. In such scenarios, it is prudent to avoid their combined usage to prevent redundancy. This suggests that a single indicator can be sufficient to meet the corresponding decision goals effectively.

The observed redundancy between certain sustainability indicators, such as environmental and energetic sustainability, particularly in the context of economic cost constraints, underscores this point. When the correlation coefficient reaches unity, selecting either the energetic or environmental sustainability criterion alone is adequate to achieve the desired objectives. This approach ensures that decision-making remains efficient and avoids the

unnecessary complexity and potential cost duplication associated with using multiple, redundant indicators.

Still in the context of both energetic and environmental sustainability criteria, it is evident from Figure 5.7 that their correlation is not absolute across decision-making constraints, such as “energy production-emissions” or “cost-emissions”. Additionally, when addressing multiple objectives (e.g., cost, emissions, and energy production), both energetic and environmental sustainability indicators must be considered in tandem convolution. This necessity arises because no single criterion achieves perfect correlation with the others.

Focusing on economic sustainability criteria maintains its distinctiveness and relevance across various decision-making scenarios therefore it is crucial to pair it with either energetic or environmental sustainability indicators, regardless of the specific decision-making constraints. This approach ensures a comprehensive evaluation, as economic sustainability does not fully correlate with the other two criteria. In fact, economic sustainability criteria slightly positively correlate with energetic sustainability and negatively correlate with environmental sustainability (Figure 5.7). This nuanced interplay highlights the importance of a consideration of the economic sustainability-based decision making in convolution with at least another sustainability criteria to achieve well-rounded and effective decision-making.

Table 5. 4 Decision table detailing the behaviour of each indicator across various sets of constraints. (The upward arrows indicate a high influence of the indicators on achieving the proposed goals, whereas the downward arrows suggest the opposite. In the case of *in the case of* slanted arrows, the influence is not definitive and should be analysed in each specific case)

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Optimization Function	Energy Production Sources			Economic Costs		Emissions
	Renewable	Fossil	Nuclear	Variable Cost	Capital Cost	
Op_EPBT	↑	↗	↓	↓	↑	↑
Op_IMPcc	↑	↓	↗	↓	↑	↑
Op_ITR	↓	↑	↓	↑	↓	↓
Op_EPBT_IMPcc	↑	↓	↓	↓	↑	↑
Op_EPBT_ITR	↗	↑	↗	↑	↓	↓
Op_ITR_IMPcc	↗	↑	↗	↑	↓	↓
Op_EPBT_ITR IMPcc	↗	↗	↓	↗	↗	↗

Building upon these observed trends, Table 5.4 presents a decision table outlining the behavior of each indicator concerning the considered output variables, which encompass energy production sources categorized according to economic costs (specifically, capital investment and variable costs) and emissions. These findings furnish valuable insights into the nuanced dynamics between sustainability indicators, thereby affording decision-makers the opportunity to tailor their prioritization based on specific objectives and requirements.

As a proposition for future considerations, this customization could potentially be achieved through the integration of modulation factors within the optimization function, denoted as W_j . Such modulation factors would allow for the fine-tuning of the importance assigned to each sustainability criterion, thereby enhancing the adaptability and effectiveness of decision-making processes.

5.4. Chapter Conclusions

In this chapter, we explore the impact of integrating two sustainability indicators to achieve comprehensive sustainable development. Our objective is clear: to assess the interdependence and individual necessity of each sustainability criterion, especially given that incorporating these criteria often leads to increased overall costs, sometimes significantly so. By examining these relationships based on the decision-maker's objectives, we aim to identify and eliminate unnecessary indicators. This approach seeks to strike a better balance between sustainability goals and associated costs.

Using Atlantis as a case study and applying the sustainability optimization functions introduced in previous chapters within the OSeMOSYS framework, we begin by analyzing the outcomes of integrating various sustainability indicators. Our findings demonstrate that the simultaneous application of energy and environmental sustainability criteria yields the most favorable results in terms of residual energy price (\$38.02/MWh), variable costs (\$1177 million), and pollutant emissions (0.276 t CO₂/MWh), making it the optimal set of indicators for achieving neutrality. Remarkably, these outcomes are achieved with only a marginal increase in overall costs. Conversely, economic sustainability exerts the most significant influence on the system's behavior when combined with any other indicator.

Comparing these results with those obtained using the standard function, which excludes sustainability criteria, provides less biased information. This comparison enables us to identify trends in the dominance of certain indicators and the enhancement effects observed between EPBT and IMP_{CC} when applied separately versus together.

Our observations reveal the mutual influence of each sustainability indicator, highlighting intricate interrelations among them. To quantify these findings, we constructed correlation matrices using the Pearson method for coefficient calculation. This approach offers a quantitative analysis of the dependencies under various boundary conditions. Merit variables such as energy production (categorized into renewable, fossil fuels, and nuclear), economic costs (including capital, fixed, and variable costs), and emissions serve as constraints for calculating correlation coefficients. These constraints can be applied individually or collectively, allowing us to refine multidimensional datasets to focus on specific conditions or criteria.

It is important to note that the effectiveness of correlating sustainability indicators cannot solely be attributed to the simultaneous application of a set of constraints. Trade-offs among various technical factors in the optimization process may lead to interdependencies between certain sets of output constraints. For instance, our study identified complex interrelations among the merit variables, including emissions, renewable energy, fossil fuels, capital, and variable costs, in alignment with sustainability optimization. Constructing a correlation matrix using these variables may result in a biased interpretation, potentially favoring an ambiguously positive absolute correlation between sustainability indicators.

Correlation matrices evaluated using simpler selection criteria demonstrate an inverse correlation between economic sustainability optimization criteria and environmental sustainability indicators. However, environmental indicators positively correlate with the energy sustainability indicator unless economic constraints are explicitly considered.

While economic sustainability indicators may offer rapid returns on investment and cost reduction, they may also lead to increased fossil fuel usage, higher variable costs, and elevated pollutant emissions. Consequently, economic sustainability indicators may not be suitable when primary objectives align with decarbonization efforts. This highlights a significant inherent dichotomy between economic and environmental sustainability goals, especially concerning carbon emissions reduction and climate change mitigation, alongside an increasing reliance on renewable attributes and associated investment costs.

Addressing the challenge of decarbonization requires considering both economic and environmental factors. This may entail integrating environmental sustainability criteria into economic decision-making processes using energy sustainability indicators. Although energy sustainability indicators exhibit a stronger correlation with environmental sustainability, their characteristic within the cradle-to-cradle paradigm presents a balanced approach between economic and environmental factors.

In conclusion, fostering stronger alignment among economic, energy, and environmental sustainability goals often entails reevaluating the weighting assigned to different indicators within optimization functions. Explicitly prioritizing optimization objectives that promote sustainability is essential. The insights gained from the results facilitate this prioritization, allowing it to be directly incorporated into the optimization function of modelling tools. This enables decision-making that aligns more closely with the objectives of decision-makers, providing a comprehensive understanding of each indicator's behavior concerning the considered output variables, such as energy production sources categorized by economic costs and emissions.

Chapter 6. Decision-making in Sensitive Energy Sectors through the Integration of Sustainability Indicators

This chapter partially reproduces content from the following publications, which was derived from research conducted by the doctoral candidate during the thesis development period:

Publications 1:

- Title: Energetic sustainable transition process optimization in terms of LCA using CLEW tools.
- Authors: Mahamat Habib Bechir, M. Darío Ferreira, A. López Agüera
- Publisher : Springer Nature
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Publications 2:

- Title: Environmental Sustainability Impact as Optimization Function of OSeMOSYS Energetic Modelling System
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Publications 3:

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6.1. Introduction

In the preceding chapters, we set out the methodology for integrating sustainability indicators into the OSeMOSYS framework and demonstrated its viability in both singular and integrated decision-making contexts. This sustainability-centric approach not only fosters informed decision-making but also addresses the complex challenges inherent to energy planning processes, particularly demonstrating effectiveness in navigating sensitive energy concerns.

These sensitivities, which frequently serve as the focal point of discourse across a range of media, social platforms, scientific arenas, and political forums, encompass a spectrum of pivotal issues. These include examining the sustainability of nuclear energy [173], debating the effectiveness of increased carbon taxation to achieve net-zero emissions and ensure environmental sustainability [174], and promoting the adoption of renewable energy technologies as the optimal sustainable solution [175].

Navigating sensitive concerns in decision-making poses perennial challenges for stakeholders, particularly when sustainability outcomes are paramount [176]. This chapter aims to underscore the utility of the developed sustainability approach in addressing such complexities. Specifically, it elucidates the application of this framework by scrutinizing sensitive energy sectors and evaluating their sustainability footprint through the application of the sustainability indicator optimization within the OSeMOSYS model.

The chapter investigates the sustainability discourse surrounding nuclear energy [173] by examining various aspects, such as energetic and economic sustainability metrics, as well as the complex landscape of nuclear waste management. Despite its low-emission status [80], nuclear energy is examined through these various lenses in order to gain a comprehensive understanding of its overall impact.

Similarly, the narrative progresses to investigate the implications of increased emissions penalties [174] in terms of environmental sustainability indicators. It weighs the potential environmental benefits of lower carbon emissions against the economic costs associated with carbon taxes. This analysis aims to illuminate the intricate trade-offs inherent in such policy deliberations.

Furthermore, this work to examine the case in favour of renewable energy technologies, with a particular focus on solar photovoltaic (PV) systems. It examines the intricacies of the climatic dependencies that characterise these technologies, demonstrating how geographical variables can be influenced by both energetic and economic sustainability indicators. Such a detailed examination emphasises the importance of considering local circumstances when planning and implementing renewable energy projects.

Each sensitive matter corresponds to a published paper, referenced as [147], [70] and [177].

6.2. Sustainability of nuclear energy

Nuclear energy is a complex sector characterized by its multifaceted stages throughout its useful lifetime. This complexity arises from the interconnected processes that span from raw material extraction to waste disposal, necessitating collaboration among various entities and regulatory bodies [178], [179]. Figure 6.1 illustrates these stages, highlighting their interconnections over the useful lifetime of nuclear energy.

Initially, raw material extraction marks the beginning of the nuclear fuel life debut, with mining companies. Uranium, the primary fuel for nuclear reactors, is typically obtained through mining operations. This process entails significant environmental impacts such as habitat disruption and water contamination, leading to conflicts between profit-driven mining companies and local communities because of health and environmental consequences [180].

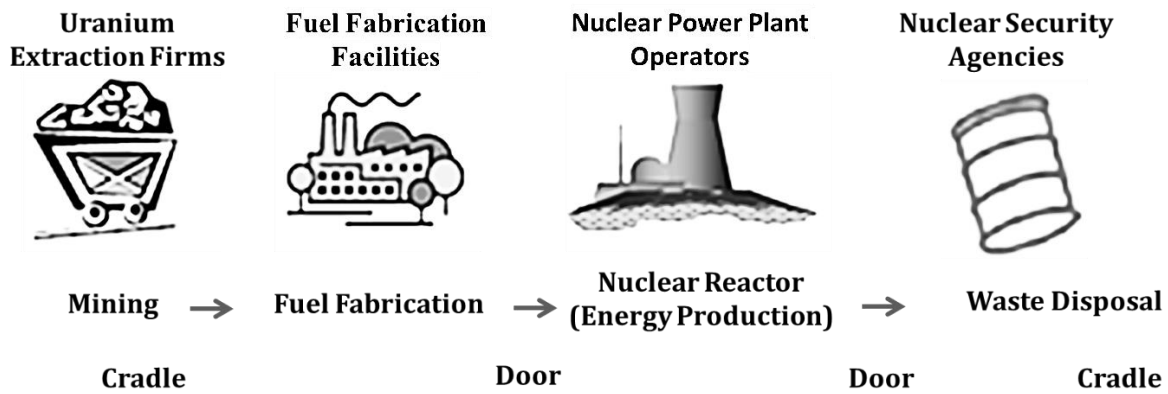


Figure 6.1 Schematic of the nuclear fuel lifetime stages
This figure is reproduced from the following reference [181]

Subsequently, fuel production entities are responsible for processing raw materials into usable nuclear fuel. This stage involves enrichment facilities, fuel fabrication plants, and regulatory bodies. Multinational corporations dominate this sector, driven by profit motives and efficiency goals. However, regulatory bodies strive to ensure safety and environmental protection, leading to tensions between industry interests and regulatory oversight [182].

Finally, waste management entities, often government-affiliated nuclear security agencies, handle and dispose of nuclear waste generated after power production [183]. The disposal of radioactive waste, particularly high-activity waste, poses significant technical, environmental, and societal challenges. Disparities arise in waste management strategies, with differing viewpoints on disposal methods, safety requirements, and long-term environmental impacts[182], [184].

The management of nuclear waste involves several key components, including storage and transportation, treatment and reprocessing, long-term disposal, regulatory compliance, research and development, and liability and insurance considerations. Each of these facets contributes to the overall energy consumption and economic burden associated with nuclear waste management, with costs varying significantly depending on regulatory frameworks, technological approaches, waste volumes, and management duration [185].

Nuclear energy is often lauded for its low-carbon footprint and minimal greenhouse gas emissions, making it environmentally sustainable in this regard [186]. However, its sustainability becomes questionable when considering economic and energetic criteria [187], [188], [189]. The involvement of diverse stakeholders throughout the nuclear lifetime interval often leads to disparities driven by divergent interests and priorities [190]. Assessing the sustainability of nuclear technology remains a central topic of debate within the energy sector and among decision-makers.

Literature reviews frequently evaluate the economic and energetic return times of nuclear technology by utilizing data pertains to stages ranging from raw material extraction to energy generation in power plants, a framework known as the cradle-to-door paradigm (See figure 6.1). In some cases, evaluations focus solely on the energy production phase, referred to as the door-to-door paradigm (See figure 6.1).

The cradle-to-door and door-to-door sustainability measurement are more straightforward and accessible because they concentrate on the immediate phases of nuclear energy production, where data is more readily available and less sensitive. For example, the high efficiency of nuclear power plants in converting fuel into electricity yields favorable economic and energetic return times, reinforcing the perception of nuclear energy as a sustainable option [191].

While for a comprehensive sustainability assessment, it is crucial that the indicators consider the entire lifetime of the technology from raw material extraction to waste disposal (cradle-to-

cradle paradigm) [192]. Nevertheless, in the case of nuclear technology energetic economic indicators are characterized by the lack of comprehensive data corresponding to the waste management stage. This gap arises primarily from the opacity of nuclear security agencies.

Obtaining detailed data on nuclear waste management is challenging due to the sensitive nature of the information. Nuclear security agencies, tasked with the safe disposal of radioactive materials, commonly restrict access to such data due to national security issues concerns[184]. As a result, the cradle-to-cradle consideration, is frequently neglected.

The lack of transparency hampers researchers' ability to include accurate and complete information in their sustainability assessments [193]. Consequently, the cradle-to-cradle assessment, which includes the disposal of nuclear waste, presents a more complex and less optimistic scenario. According to [194] managing nuclear waste involves handling and storing radioactive materials, a process that can extend over 100 years or more).

In Chapter 4, our examination provided insights into nuclear energy sustainability. When assessed based on environmental sustainability (Chapter 4, Section 4.6.3), nuclear energy appears sustainable. However, it is not sustainable when evaluated based on economic cost return time or energetic return time within the cradle-to-cradle paradigm, which is the adequate approach for sustainable decision-making.

Our aim is to integrate corresponding sustainability indicators into both economic and energetic sustainability decision-making to illuminate the sustainability of nuclear energy and to clarify the conditions under which it can be considered sustainable. This evaluation involves utilizing sustainability indicators to evaluate the nuclear energy across each stage of its lifetime, as illustrated in Figure 6.1. These evaluations encompass:

- ✚ *Cradle-to-cradle evaluation: This approach provides a comprehensive assessment of nuclear energy sustainability by evaluating its entire lifetime, from raw material extraction to waste management.*
- ✚ *Cradle-to-door evaluation: This approach assesses sustainability from raw material extraction to the energy generation phase, excluding waste management.*
- ✚ *Door-to-door evaluation: This approach focuses solely on the energy generation phase and excludes waste management processes.*

To maintain consistency and enable accurate comparisons with previous optimization results, particularly those derived from the standard OSeMOSYS optimization (Op_Standard) and subsequent outcomes from Op_EPBT and Op_ITR within the cradle-to-cradle framework, we have utilized the same input parameters for each technology throughout this thesis. Details about the input parameters are provided in Chapter 1, Section 1.6.4, with the input values for EPBT and ITR detailed in Chapter 2, Section 2.4.1.1 and Section 2.4.2.1 respectively.

The only exception pertains to the input values for EPBT and ITR associated with nuclear energy, which have been individually estimated for each lifecycle stage. Through a literature review, we have compiled mean values as initial estimates for assessing nuclear EPBT and ITR in both cradle-to-door and door-to-door stages.

Table 6.1 outlines the input data parameters for EPBT and ITR, with relevant sources provided in brackets. Additionally, the table displays Correction Factors (F_{EPBT} and F_{ITR}) for each lifecycle stage, calculated using the same Useful Lifetime (ULT) data as obtained from default Atlantis settings, as outlined in Table 1.2, ensuring consistency across assessments.

The merit variables outlined in Chapter 1, section 1.6.5, will be employed to present the optimization outcomes.

Table 6.1 EPBT, FEPBT ITR, and FITR values associated with the nuclear lifetime Stage.
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Nuclear Life cycle stages	Sustainability Indicator		Extra Cost Correction Factor	
	EPBT (Year)	ITR (Year)	F _{EPBT}	F _{ITR}
cradle-to-cradle	80 [140], [147]	75 [151], [152], [161]	1.6	1.5
door-to-door	3 [140], [147]	4 [151], [152], [161]	0.06	0.08
cradle-to-door	18 [140], [147]	30 [151], [152], [161]	0.36	0.60

6.2.1. Sustainability optimization scanning on Nuclear useful lifetime.

The results that are going to be presented in the next sub-section delve into presenting the sustainability of nuclear energy on how it's the corresponding sustainability indicators are computed with focus both energetic and economic sustainability indicators, each optimized individually.

The modulation weight attributes outlined in Table 6.2 are instrumental in fine-tuning the prioritization of each sustainable development aspect and gauging the impact of individual sustainability indicators.

Table 6.2 Modulation Weight setting associated with the different optimization functions under each optimization.

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Op_EPBT	Sus_Op_index with $\begin{cases} W_{EPBT} = 1 \\ W_{ITR} = 0 \\ W_{IMPcc} = 0 \end{cases}$
Op_ITR	$\forall$ Sus_Op_index with $\begin{cases} W_{EPBT} = 0 \\ W_{ITR} = 1 \\ W_{IMPcc} = 0 \end{cases}$

6.2.2. Energetic optimization results (Op_EPBT)

Table 6.3 presents the merit variables derived from the post-optimization of energetic sustainability criteria, focusing on the nuclear lifetime stages encompassing the cradle-to-door, door-to-door, and cradle-to-cradle phases.

Table 6.3 Details of the merit's variables of the Op_EPBT (cradle-to-door) and Op_EPBT (door-to-door)

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Merit variable			Op_Standard	Op_EPBT		
				Nuclear in the cradle-to-door	Nuclear in the door-to-door	Nuclear in the cradle-to-cradle
Energetic trend	Global Energy Production (MWh)	Renewable	38594×10^3	45980×10^3	45980×10^3	53221×10^3
		Fossil Fuels	14238×10^3	8003×10^3	8003×10^3	15774×10^3
		Nuclear	15012×10^3	15012×10^3	15012×10^3	0
	ROP (%)	Renewable	57	67	67	77
		Fossil Fuels	21	11	11	23
		Nuclear	22	22	22	0
Economic trend	Economic Cost features (M\$)	Capital Cost	1867×10^6	3529	3529	3530
		Variable Cost	2882×10^6	1495	1495	1607
		Fixed Cost	773×10^6	1289	1289	1465
	Economic Cost (\$/MWh)	Global Cost	80.09	91.57	91.57	95.76
		Residual Price	53.01	40.38	40.38	44.56
Emissions trend	Global Emissions (t CO ₂)		11.05×10^6	6.54×10^6	6.54×10^6	9.20×10^6
	Global Emissions (t CO ₂ /MWh)		0.160	0.095	0.095	0.133

Additionally, the table includes results from Op_Standard. While the results of leading to an energetic sustainable outcome with nuclear in the cradle-to-cradle stage and the strictly economic optimization are presented in Chapters 4 and 1 respectively, they are included in this section to facilitate a comparative analysis of the impact of nuclear sustainability.

The cradle-to-cradle analysis of nuclear technology reveals challenges associated with waste management, hindering its deployment as a sustainable solution. However, when nuclear technology is assessed without factoring in waste management considerations, it emerges as a competitive and sustainable option. This assertion is supported by the comparable trends observed in energetic, economic, and emission aspects in both energetic leading sustainability decision results, specifically for nuclear in the cradle-to-door and nuclear in the door-to-door scenarios, as outlined in Table 4.3. The similarity in outcomes can be attributed to the 22% deployment saturation of nuclear energy in both scenarios, aligning closely with the deployment rate observed for nuclear technology in economic optimization (Op_Standard).

In addition to the insights presented in Table 6.3, Figure 6.2 serves as a visual representation of the annual energy production for competitive technologies, specifically delineating the influence of energetic time of return on the energetic mix. This visualisation elucidates the impact on energetic sustainability when considering nuclear technology with and without waste management considerations. As can be seen, nuclear is inhibited in the cradle-to-cradle scenario as the effect of the energetic sustainability indicator inclusion while it is represented in the door-to-door implication.

Whether nuclear energy is deployed or not, the effect of the sustainable decision making requiring a fast energetic time of return leads to an increase in global costs compared to the Op_Standard. Specifically, the deployment of nuclear energy under the influence of energy payback time increases global costs by 10%, with electricity prices showing a significant rise, at least \$10/MWh higher than the current trend. Furthermore, the integration of nuclear energy impacts emission trends, resulting in a notable 30% decrease in emissions in the cradle-to-cradle scenario compared to the optimization using energetic sustainability indicator, culminating in a total emission reduction of 40% compared to the economic optimization.

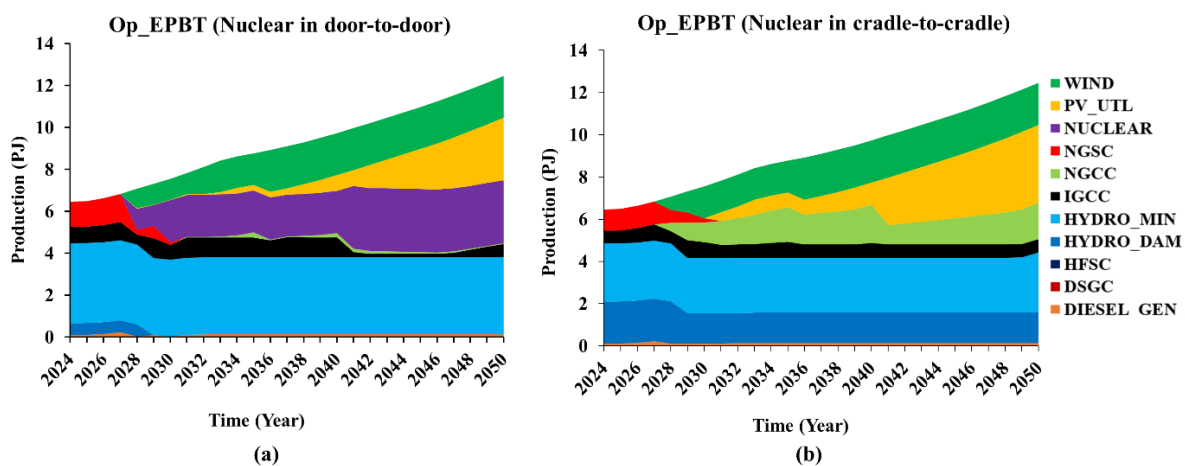


Figure 6.2 Annual energy production per technology, (a): Op_EPBT (nuclear in door-to-door); (b): Op_EPBT (nuclear in cradle-to-door)

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The published paper [147] provides an in-depth analysis of the impact of energetic sustainability criteria, specifically considering nuclear energy from various lifecycle perspectives. The study concludes that nuclear energy generation is a viable sustainable solution

when evaluated based on energetic sustainability criteria in both cradle-to-door and door-to-door analyses. However, it is not considered a sustainable solution when the energetic expenses associated with waste management are taken into account.

6.2.3. Economic optimization results (Op_ITR)

Table 6.4 presents the merit variables derived from the post-optimization of economic sustainability criteria, focusing on the nuclear lifetime stages encompassing the cradle-to-door, door-to-door, and cradle-to-cradle phases. For comparative purposes, Table 6.4 also includes results from the economic optimization to facilitate an analysis of the impact of nuclear sustainability.

Table 6.4 Details of the merit's variables of the Op_ITR (cradle-to-door) and Op_ITR (door-to-door)
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Merit variable			Op_Standard	Op_ITR		
				Nuclear in the cradle-to-door	Nuclear in the door-to-door	Nuclear in the cradle-to-cradle
Energetic trend	Global Energy Production (MWh)	Renewable	38594×10^3	22638×10^3	22638×10^3	21372×10^3
		Fossil Fuels	14238×10^3	31337×10^3	31337×10^3	47571×10^3
		Nuclear	15012×10^3	15012×10^3	15012×10^3	0
	ROP (%)	Renewable	57	33	33	77
		Fossil Fuels	21	45	45	31
		Nuclear	22	22	22	0
Economic trend	Economic Cost features (M\$)	Capital Cost	1867×10^6	2126	2126	2859
		Variable Cost	2882×10^6	3286	3286	4201
		Fixed Cost	773×10^6	889	889	1108
	Economic Cost (\$/MWh)	Global Cost	80.09	91.83	91.83	118.48
		Residual Price	53.01	60.70	60.70	77
Emissions trend	Global Emissions (t CO ₂)		11.05×10^6	17.34×10^6	17.34×10^6	22.27×10^6
	Global Emissions (t CO ₂ /MWh)		0.160	0.252	0.252	0.323

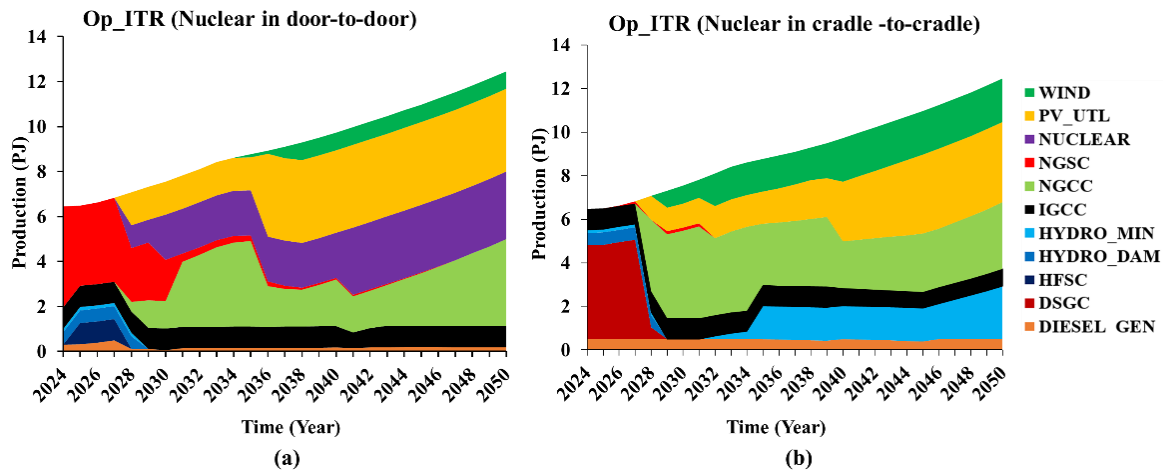


Figure 6.3 Annual energy production per technology, (a): Op_ITR (nuclear in door-to-door); (b): Op_ITR (nuclear in cradle-to-door)

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Similar to previous observations under the energetic sustainability criteria, nuclear energy is inhibited when waste management is considered in economic leading sustainability decision, rendering it an unsustainable solution in terms of economic return. Its sustainability is justified

only if the waste management cycle is not accounted for, achieving saturation in both the cradle-to-door and door-to-door scenarios, where consistent trends are observed.

Complementing the results in Table 6.4, Figure 6.3 visually represents the annual energy production for competitive technologies, showing the impact of economic sustainability consideration and emphasizing the outcomes of nuclear life cycle consideration in both door-door and cradle-to-cradle scenarios.

Regarding the impact of economic sustainability indicator, outcomes remain more costly compared to strictly economic optimization. However, the deployment of nuclear technology (both cradle-to-door and door-to-door) significantly impacts the cost analysis, revealing a decrease in both global costs and electricity prices by substantial margins of at least \$25/MWh and \$15/MWh, respectively, compared to economic based sustainability outcome when nuclear is analyzed under the cradle-to-cradle paradigm.

Although the economic sustainability optimization (Op_ITR) effect leads to an increase in emission rates compared to OSeMOSYS standard optimization, the emissions within the cradle-to-cradle scenario are higher, reaffirming the non-emissive nature of nuclear technology when deployed.

In summary, the developed methodology has provided significant insights into the sustainability of nuclear technology. Although nuclear energy is often regarded as a green technology due to its non-emitting nature, as demonstrated in the analysis of environmental sustainability (see Chapter 4), its sustainability in energetic and economic terms remains contentious among decision-makers.

Our analysis using the developed methodology clarifies this issue, revealing that nuclear power can be deemed sustainable only if the costs and energy associated with nuclear waste treatment are excluded from consideration. This exclusion, however, represents an idealized scenario that allows energy producers to generate nuclear power without accounting for the full lifetime of nuclear energy, specifically from the cradle-to-door or door-to-door phases, while excluding the waste management phase.

In reality, the Useful lifetime of nuclear technology includes waste management, which is commonly referred to as "negative heritage [191]. This term highlights the long-term energetic and economic burdens associated with the management of nuclear waste and underscores the intergenerational implications of nuclear waste management, which can last for thousands of years. These challenges include safe storage, containment, and environmental protection.

Overall, while nuclear technology consistently meets environmental sustainability criteria, its sustainability is more complex when considering energetic and economic criteria. It may appear sustainable when only partial lifetime stages are considered. However, it cannot be deemed sustainable over its complete cradle-to-cradle lifecycle, particularly when accounting for the waste management phase except in term emission (greenhouse gas based environmental sustainability). This comprehensive perspective is essential for a realistic assessment of the sustainability of nuclear technology.

6.3. Carbon Pricing Mechanisms: Catalysts for Advancing Sustainable Energy Transition

The imperative to mitigate climate change and transition towards sustainable energy sources has prompted policymakers to consider various strategies, including the imposition of emission penalties [195], [196]. Emission penalties, which levy charges on carbon dioxide emissions, aim to incentivize emission reductions and promote the adoption of cleaner energy technologies [197]. They are considered an essential component of environmental regulation, serving as a deterrent against excessive pollution and a mechanism to internalize the costs of environmental degradation [198]. The stringency of emission penalties can vary widely across countries and

communities, reflecting differences in regulatory approaches, political priorities, and economic circumstances [199].

Understanding the variability and dynamics of emission penalties is crucial for designing effective environmental policies and promoting sustainable development [200]. The mechanism for fixing penalties for exceeding emission quotas varies depending on the regulatory framework established by each jurisdiction. Typically, governments set emission quotas which may include their Nationally Determined Contributions (NDCs). NDCs represent the commitments made by individual countries under the Paris Agreement, outlining their specific goals for mitigating greenhouse gas emissions and adapting to climate change impacts [201]. Once the quotas are established, penalties for exceeding them are imposed to incentivize compliance and deter excessive emissions.

The level of penalties is influenced by factors such as the severity of the violation, the economic impact on affected parties, and the desired level of emission reductions [202]. For example, in the European Union (EU), the mechanism for fixing penalties for exceeding emission quotas is outlined in the EU Emissions Trading System (EU ETS) [203], that is a regional cap-and-trade scheme aimed at reducing carbon emissions across member states including the goal of reaching net-zero emissions by 2050. Under this system, industries including Electric Power Industry are allocated a certain number of emission allowances, with each allowance representing the right to emit a certain amount tonne of carbon dioxide equivalent (t CO₂ eq). If a company exceeds its allocated allowances, it must purchase additional allowances on the carbon market or face financial penalties [204], [205].

Similarly, in other countries, penalties for exceeding emission quotas may be determined through legislative processes or regulatory mechanisms specific to each country or region. These penalties may take the form of fines, fees, or other punitive measures designed to encourage compliance with emission reduction targets. By assigning a price to carbon emissions, these mechanisms aim to incentivize emission reductions and drive investment in renewable energy and energy efficiency initiatives [206].

Proponents argue that higher penalties can provide stronger economic incentives for emission reductions, thereby accelerating the transition to a low-carbon economy. Recent debates within the countries including the EU have centered on the efficacy of emission penalties in driving sustainable energy transition. Some argue that increasing carbon tax prices could accelerate the transition towards low-carbon solutions by providing stronger economic incentives for emission reductions. In some cases, ambitious targets for emission reductions and renewable energy deployment are accompanied by proposals to increase carbon prices or tighten emission caps [70], [174].

A growing body of literature has explored the relationship between emission reduction and penalties, with particular attention to the effectiveness of regional carbon markets [207], [208]. Indeed, the penalty underneath the European Union (EU) ranges from \$30 to \$50/t CO₂ eq and has risen to \$100/t CO₂ eq in 2022, much over the permitted ceiling [209], [210]. Even more, the findings of Dellink et al.[211] suggest that increasing carbon taxes to \$200/t CO₂ eq or higher could play a pivotal role in achieving net zero decarbonization objectives. This underscores the potential effectiveness of ambitious carbon pricing policies in driving emission reductions and accelerating the transition to a low-carbon economy.

Despite the potential benefits of imposing emission penalties, challenges remain, particularly regarding equity and social justice [212], [213]. Critics often highlight the regressive nature of carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems, which could disproportionately affect low-income households and vulnerable communities [174], [214].

For example, Carleton and Greenstone [215] found that carbon pricing policies could lead to higher energy costs for low-income households, potentially exacerbating income inequality.

Similarly, The IMF report presented by Baoping Shang [216] suggests that carbon pricing may have adverse distributional impacts on certain demographic groups, particularly those living in regions heavily reliant on fossil fuels. These concerns underscore the importance of designing emission pricing policies in a manner that addresses equity considerations and mitigates potential adverse effects on disadvantaged populations. Policymakers must carefully consider measures such as targeted subsidies, income transfers, and investments in renewable energy and energy efficiency programs to ensure that emission penalties contribute to environmental objectives without exacerbating social inequalities [217].

In addition, the effectiveness of emission penalties hinges on several factors, including the availability of viable alternatives to fossil fuels and the potential for carbon leakage. Emission pricing mechanisms must be carefully crafted to incentivize emission reductions while fostering innovation and investment in low-carbon technologies [218]. For instance, revenue generated from penalties of emission can be reinvested in renewable energy projects or used to support research and development of clean energy technologies [219].

However, the success of such initiatives relies on the existence of accessible and affordable alternatives to fossil fuels, such as wind, solar, and hydroelectric power. Moreover, the unilateral implementation of emission penalties by individual regulations may result in carbon leakage, wherein industries relocate to areas with laxer regulations, leading to competitive disadvantages for firms operating in regions with stricter carbon pricing policies [220]. This underscores the importance of international cooperation and coordination in addressing climate change through carbon pricing, as highlighted in the Paris Agreement.

The challenges outlined above have prompted us to assess the relevance of implementing higher carbon taxes as a definitive solution toward achieving environmentally sustainable energy transition. In our study, detailed in the published paper [70], we utilized the Atlantis energetic mix to investigate the efficacy of different carbon tax levels set by the EU, ranging from \$30, \$50, and \$100 per tons CO₂ eq. We employed the environmental sustainability leading criteria (IMPcc) optimization approach, utilizing the Op_IMPcc following the modulation weight: Sus_Op_index with $W_{IMPcc} = 1$ and W_{EPBT} and $W_{ITR} = 0$.

The objective of this work is to evaluate to what extent the increase in penalties moves towards achieving decarbonization. To do this, a sweep has been carried out between \$30 and \$200 \$/t CO₂ eq, including the environmental sustainability indicator optimization function developed in OSeMOSYS (Op_IMPcc).

The findings presented in Table 6.5 provide insights into the implementation of high carbon pricing mechanisms to drive emission reductions and promote the adoption of cleaner energy technologies. The analysis of these results reveals consistent trends across all scenarios, emphasizing a significant focus on renewable energy expansion, with a contribution rate of at least 70%, and a consistent pattern of emission reductions, even at lower levels of emission penalties.

Figure 6.4 provides a graphical comparison of each sustainable environmental optimization scenario applied for emissions penalties levels, against the standard economic optimization, contrasting output global costs and corresponding global emissions. Notably, the analysis reveals that imposing higher emission penalties does not necessarily align with achieving carbon neutrality. More importantly, it demonstrates that even a penalty of \$30/t CO₂ eq equivalent is sufficient to meet the EU emission mitigation requirements [221].

Plus, the findings (Figure 6.4) reveal a clear trend in global costs, demonstrating that the costs associated with the environmental sustainability decision making when emission penalties are

set at \$30/t CO₂ and \$50/t CO₂ are consistently 10% lower than those observed with higher carbon taxes exceeding \$100/t CO₂.

Interestingly, despite the higher carbon taxes, the resulting emission reductions only exhibit a marginal increase compared to scenarios with lower carbon taxes set at \$30/t CO₂ and \$50/t CO₂. This underscores the limited effectiveness of excessively high carbon taxes in achieving significant emission reductions beyond what is achieved with moderately priced carbon taxes.

Table 6.5 Details of the merit's variables of the Op_IMPcc with emission penalty of \$30, \$50, \$100, and \$200/t CO₂ eq
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Merits variables			Op_IMPcc			
			Carbon Tax fixed at \$30/t CO ₂ eq	Carbon Tax fixed at \$50/t CO ₂ eq	Carbon tax fixed at \$100/t CO ₂ eq	Carbon tax fixed at \$200/t CO ₂ eq
Energetic trend	Global Energy Production (MWh)	Renewable	48650×10 ³	49762×10 ³	51041×10 ³	51041×10 ³
		Fossil Fuels	5560×10 ³	4381×10 ³	3087×10 ³	3087×10 ³
		Nuclear	15012×10 ³	14826	14871×10 ³	14871×10 ³
	ROP (%)	Renewable	70	72	74	74
		Fossil Fuels	8	6	4	4
		Nuclear	22	22	22	22
Economic trend	Economic Cost features (M\$)	Capital Cost	3402	3456	3662	3662
		Variable Cost	1477	1379	1261	1261
		Fixed Cost	1358	1362	1393	1393
	Economic Cost (\$/MWh)	Global Cost	89.21	89.90	91.61	91.61
		Residual Price	39.87	39.76	41.47	41.47
Emissions trend	Global Emissions (t CO ₂)		2.78×10 ⁶	2.33×10 ⁶	1.77×10 ⁶	1.77×10 ⁶
	Global Emissions (t CO ₂ /MWh)		0.040	0.034	0.026	0.026

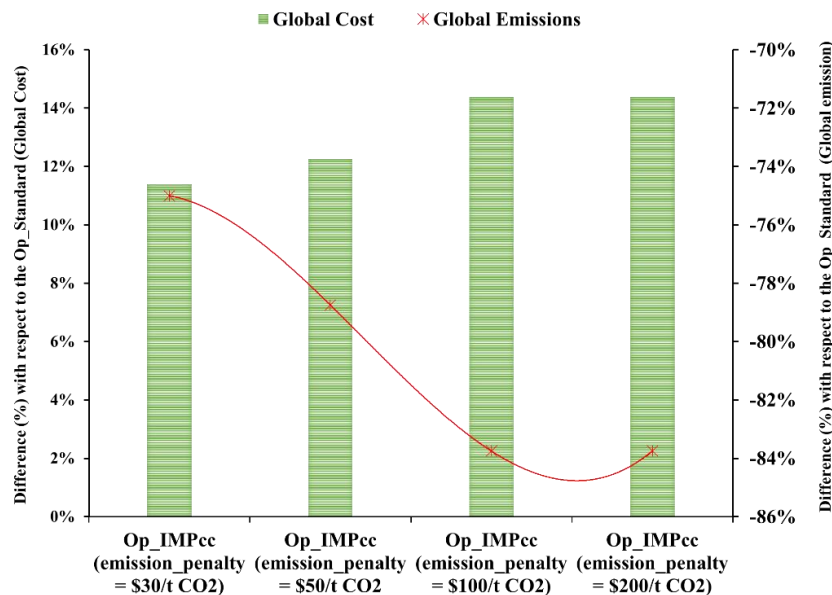


Figure 6.4 Comparative Analysis of Global Costs and Emissions Relative to Op_Standard: The Impact of Carbon Tax Levels (\$30/t CO₂, \$50/t CO₂, \$100/t CO₂, and \$200/t CO₂) in Op_IMPcc Optimization.
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Overall, these results underscore the main conclusion highlighted in the published paper [70], which suggests that despite advocating for comprehensive carbon taxes through the implication

of the environmental sustainability criteria optimization approach, achieving climate change mitigation can be more cost-effective than imposing excessive emission penalties.

Excessive emission penalties may elevate electricity prices, thereby disproportionately impacting low-income households and potentially worsening income inequality, as reported by Carleton and Greenstone.

6.4. Solar PV sustainability as a function of the climate conditions

Solar photovoltaic (PV) technology has undergone significant advancements in recent years, including improvements in panel efficiency and energy storage capabilities resulting in reduced costs and increased scalability. This progress has positioned solar PV as a competitive alternative to conventional energy sources worldwide, contributing to the global transition towards cleaner and more sustainable energy solutions [222].

In alignment with the findings of the International Renewable Energy Agency (IRENA) as outlined in their REmap analysis, projections indicate a remarkable surge in solar PV power installations within the upcoming decade. As shown in Figure 6.5 plotting the projection of the cumulative PV installed capacity, by 2030, it is forecasted that global solar PV capacity could escalate nearly sixfold, reaching an impressive cumulative capacity of 2,840 gigawatts (GW). Looking further ahead, by 2050, this capacity is expected to soar to a staggering 8,519 GW [223].

These projections highlight the pivotal role that solar PV technology is poised to play in meeting global energy demands and transitioning towards sustainable and renewable energy sources. Such insights are invaluable for policymakers, industry stakeholders, and researchers alike, as they navigate the complexities of energy planning, investment decisions, and climate change mitigation strategies on a global scale.

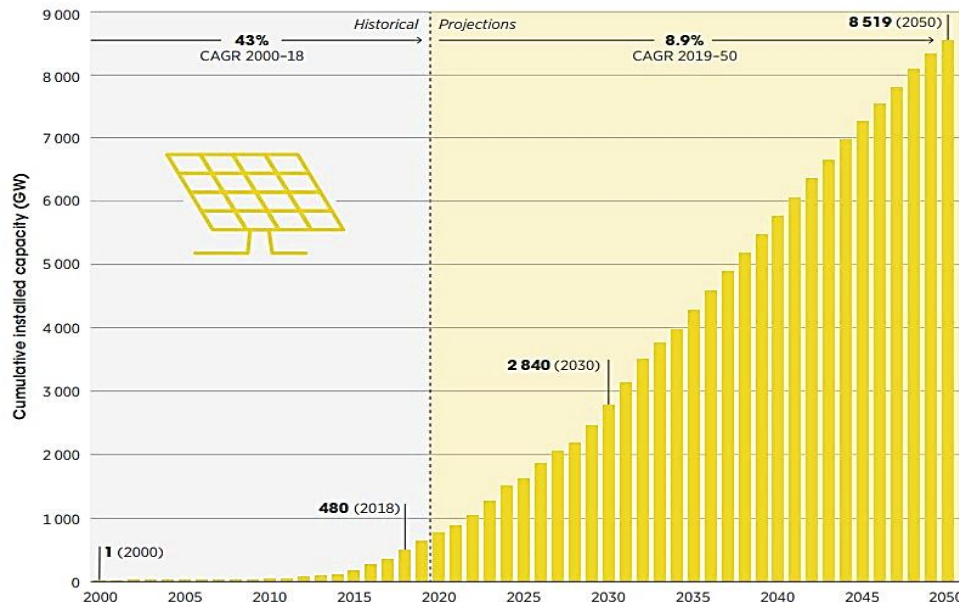


Figure 6.5 Projection of the cumulative PV installed Capacity; in the Graph, CAGR represents the compound annual growth rate

This figure is reproduced from the following reference [223].

Despite remarkable progress in solar PV technology, geographical variability remains a crucial consideration when evaluating the feasibility and competitiveness of solar PV projects within an energy mix. Indeed, the effectiveness of solar PV within an energy mix is heavily influenced by the availability of solar irradiation resources, which vary based on geographical location [224].

Local solar resource potential varies depending on factors such as latitude, climate patterns, and topography, all of which influence solar irradiation levels and, consequently, the performance of solar PV systems. Regions closer to the equator typically receive higher levels of solar irradiation throughout the year, making them more conducive to solar energy generation. Conversely, areas at higher latitudes or with frequent cloud cover may experience lower solar irradiation levels, presenting challenges for efficient solar energy harnessing [225], [226].

Therefore, understanding and accounting for these geographical factors are essential when planning and implementing solar PV projects to maximize their effectiveness and ensure optimal energy generation.

An important aspect to consider in the context of solar PV technology is its dependency on natural resources, particularly solar irradiation. Long-term energy planning and modelling pose challenges in accurately assessing the competitiveness and sustainability of solar PV solutions, as their efficacy relies heavily on the amount of irradiation received in a given area [226].

While various energy modelling tools such as OSeMOSYS focus on parameters like Capacity Factor (CF) to estimate technology efficiency [10], calculating CF for solar PV presents unique challenges. Unlike fossil fuels or nuclear technologies, where CF calculation is straightforward (via Equation 1.1) based on fuel input and operational duration, solar PV efficiency is closely linked to the duration of solar irradiation received.

Traditionally, solar PV capacity factors are estimated using historical data collected from existing installations. This approach involves analyzing the actual energy output of installations over a specified period, typically a year, to calculate the average capacity factor. While this method offers valuable insights, it has limitations [226], [227]. Historical data may not capture long-term trends or future technological advancements, leading to potential inaccuracies in capacity factor estimates. Additionally, the variability of daily solar irradiance, influenced by factors like weather patterns and geographical location, introduces uncertainties in capacity factor calculations [225].

To address the limitations of traditional methods for estimating solar PV CF researchers are exploring alternative approaches. One such approach, which we have proposed and detailed in a research paper [177], focuses on regional irradiation levels to calculate the CF of solar PV systems. This method aligns with best practices in energy modelling by emphasizing the importance of considering regional differences in solar radiation levels and climate conditions.

Our proposed approach led to considers for the area under study factors including the peak sun hours (PSH), which represent the hours in a day when the intensity of solar irradiance reaches an average of 1000 W/m² [177], [228]. By analyzing the duration of peak solar hours within a specific time frame and the available solar irradiance, we can derive insights into the efficiency of solar PV systems in harnessing solar energy.

The calculation of the Solar CF for a given region involves determining the ratio of Peak Solar Hours (PSH) to the solar irradiance at standard test conditions (STC) within the corresponding time frame [177]. This equation, outlined as Equation 6.1, provides a structured method for estimating the CF of a solar system based on regional solar irradiation levels and PSH.

$$\text{Solar_CF}_{r,l} (\%) = \frac{\text{SPH}_{r,t}}{\text{Irr}_r \times t_{r,l}} \quad (\text{Eq. 6.1})$$

Where:

SPH [Wh/m²]: is the number of equivalent hours in the time slice during which the solar irradiance reaches an average of 1,000 watts under Standard Test Conditions (STC), typically occurring at 25°C.

Irr [W/m²]: Solar irradiance levels of the standard test conditions; Irr = 1000 W/m².

t [h]: is the total number of hours in the corresponding time slice.

By employing this approach, we can better understand solar PV system performance and its suitability for specific geographic areas. This approach is invaluable for informing energy planning and investment decisions, ensuring that modelling results are more precise and contributing to the development of sustainable long-term energy strategies specifically when Solar PV is involved.

By leveraging Equation 6.1 within the framework of the Atlantis temporal time parameter, we conducted estimations to ascertain the CF of solar technologies across a spectrum of irradiation levels. As illustrated in Figure 6.6, our analysis reveals a direct correlation between peak sun hours (PSH) and the resulting CF, demonstrating that higher PSH values correspond to elevated CF levels. This observation provides valuable insights into the dynamic nature of solar energy production, elucidating how variations in solar irradiance impact the efficiency of solar energy systems.

It's important to note that the capacity factor primarily captures diurnal variations, reflecting the solar energy production during daylight hours. Consequently, during the energy modelling process, it's imperative to account for the nocturnal phase by automatically setting the corresponding solar PV output to zero.

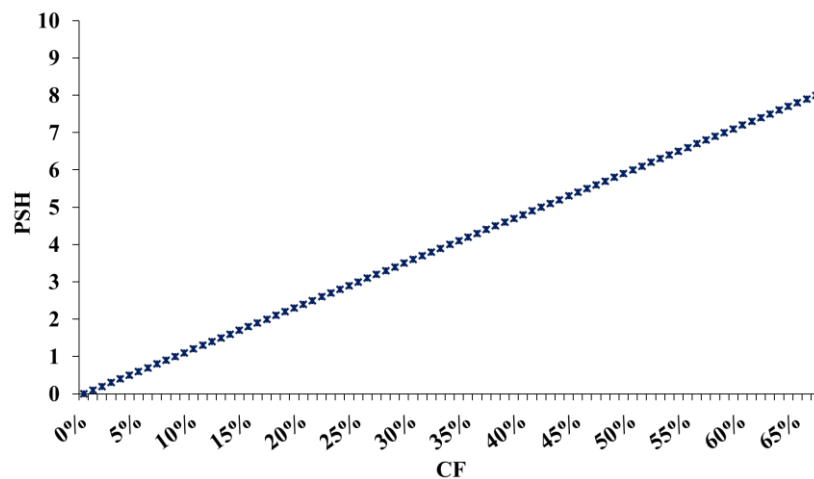


Figure 6.6 Solar technologies capacity factor for different irradiation levels
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In the pursuit of comprehensively understanding the solar energy potential across diverse climate conditions globally, the Köppen-Geiger climate classification system emerges as a valuable tool [130], [229]. This system provides a structured framework for categorizing climates based on average monthly temperatures and precipitation patterns, offering foundational insights into the climatic characteristics of specific regions.

Incorporating the Köppen classification system into the study of solar energy deployment enables a deeper understanding of the interplay between climate factors and solar irradiation levels [130], [230]. While the Köppen system does not directly quantify irradiation, its classification of climates based on temperature and precipitation serves as a proxy for assessing solar energy potential in different geographical areas.

Despite its merits, one of the primary challenges lies in extrapolating PSH values from Köppen classifications to estimate solar CF accurately. However, leveraging the linear relationship elucidated in Figure 6.6, CF values enable an approximation of PSH for each Köppen climate type. This methodology provides a means to assess solar energy potential across various climate classifications, as depicted in Figure 6.7, where CF values vary across different Köppen climate types [177].

By integrating insights from the Köppen classification system with CF estimations, researchers and policymakers gain a comprehensive understanding of solar energy prospects in diverse climatic regions. This informed approach informs strategic decision-making processes, facilitating the optimization of solar energy systems tailored to specific environmental contexts.

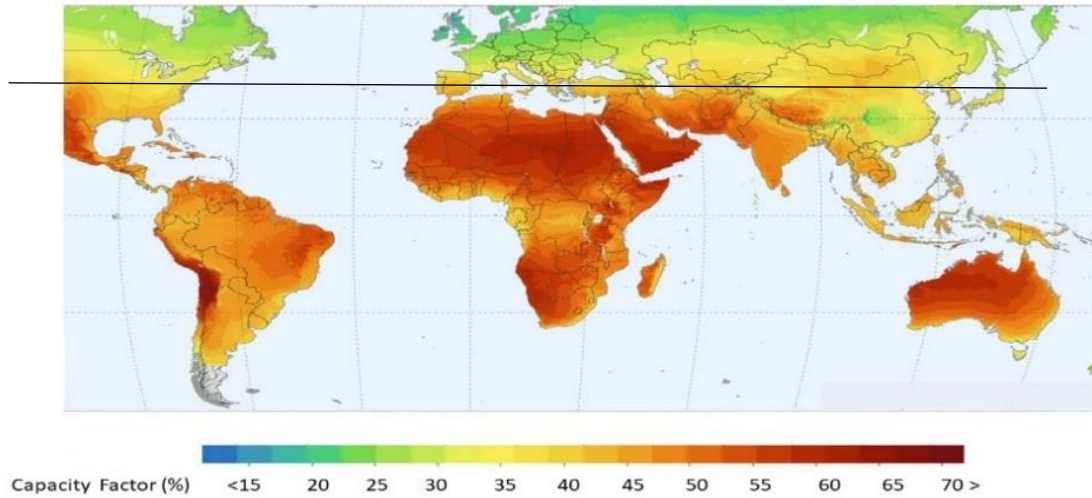


Figure 6.7 Global Solar CF in line with the Köppen-Geiger climate classification
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6.4.1. Sustainability of Solar PV as a function of the climate conditions

Utilizing the Atlantis energetic framework and consistent input parameters, we embarked on a study to investigate the influence of varying Solar CF on optimization outcomes and its sustainability. This investigation, detailed in a research paper [177], explored a range of PV CFs (10%, 20%, 30%, 40%, 50%, and 60%) to assess their impact on energy system optimization.

Notably, nuclear technology was excluded from the analysis to allow for a focused evaluation of Solar PV alongside other renewable energy sources and fossil fuels, aiming to meet energy demands efficiently.

Our approach encompassed both standard economic optimization (Op_Standard) and a sustainability-oriented perspective incorporating energetic sustainability criteria (Op_EPBT). The study's key findings revealed that Solar PV begins to exhibit competitiveness when its CF exceeds a threshold of 30%. As the CF surpasses this threshold, Solar PV's contribution to the total energy mix demonstrates linear growth. However, a saturation effect is observed beyond a CF of 50%, indicating diminishing returns in terms of the contribution of solar energy to the energy mix.

Figure 6.8 provides a visual representation of the effects of energetic sustainability optimization within each PV CF scenario, comparing the energetic sustainability optimization outcome to the standard decision-making optimization. Notably, the deployment of solar PV faces constraints in regions with lower Solar CF below 30%. However, once the CF exceeds this threshold, PV deployment becomes sustainable. Nevertheless, the imposition of sustainability exerts a limiting effect on solar deployment, ensuring reliability and affordability.

Figure 6.8 illustrates a slight decrease in PV deployment under the sustainability optimization outcome, which remains under 10% across all trends. This decrease is attributed to factors associated with intermittency and the capacity factor being zero during nighttime. However, this limitation can be mitigated if energy storage technologies are incorporated into the RES.

More details of the impact of solar PV CF and EPBT optimization are provided in [177].

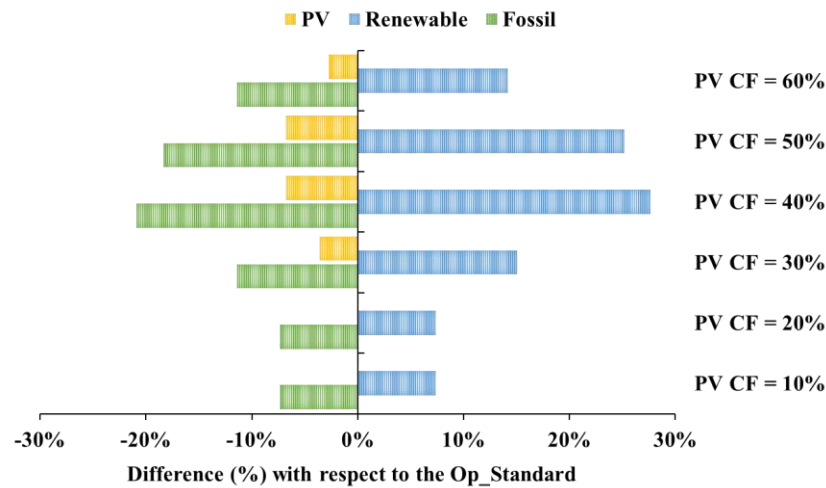


Figure 6.8 Percentage of differences of the Op_EPBT against the Op_Standard
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As our research progresses, we uncover the intricate interplay between EPBT and ITR within the context of renewable energy, specifically focusing on solar photovoltaic (PV) systems. Notably, lower CF can pose challenges for energy production, potentially prolonging EPBT and affecting revenue streams, thus impacting the overall ITR. Conversely, PV systems with higher CFs boast greater electricity output and may experience accelerated revenue generation rates over a shorter timeframe. This results in faster energy offsets and reductions in EPBT, thereby facilitating quicker returns on investment within the ITR framework [99].

Because both EPBT and ITR are influenced by irradiation levels [231], highlights the crucial importance of considering the climate conditions associated with PV CF before any potential deployment. Understanding these dynamics is essential to maximize energy production potential and ensure long-term sustainability. In our previous chapter (Chapter 5, section 5.4.2.1), we established a positive correlation between EPBT and ITR, particularly when energetic production constraints are considered. This reaffirms the critical role of optimal PV CF in shaping energy production outcomes.

While emphasizing the sustainability of PV technology is crucial for any given region, solely focusing on energetic sustainability criteria, as detailed in our research paper [177] may not provide a comprehensive picture.

Hence, we have delved deeper into this issue by evaluating the combined impact of energetic and economic sustainability criteria (Op_EPBT_ITR) using the Atlantis energetic framework. By assigning equal weights to EPBT and ITR ($W_{EPBT} = W_{ITR} = 1$) and excluding IMP_{cc} considerations ($W_{IMPcc} = 0$), we aim to provide a comprehensive assessment of PV competitiveness and sustainability across varying CF scenarios.

The input parameters remain consistent with the working hypothesis outlined in [177] ensuring uniformity and facilitating straightforward result reproduction. This approach is essential for maintaining methodological integrity and enabling seamless comparisons across different analyses and scenarios. In this context, the key variables under scrutiny for analyzing the optimization outcomes are the energetic production levels coupled with the corresponding production rates associated with each technology within their respective categories (Solar PV, Renewable, and Fossil Fuels).

Moreover, the observations drawn from the obtained output results under the optimization combining both energetic and economic leading sustainability criteria for each PV CF scenario are juxtaposed with those derived from the standard optimization function (Op_Standard) delineated in [177]. This comparative analysis sheds light on the nuanced impacts of energetic

and economic sustainability considerations on the optimization process, thus enriching our understanding of the intricate dynamics of climatic conditions governing Solar PV in energy planning.

Table 6.6 Detail of the energetic production of the Op_EPBT_ITR for each of the studied PV CF
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Op_EPBT_ITR	Energy Sources Category					
	Solar PV		Renewable Energy		Fossil Fuels	
	Global Energy Production (MWh)	ROP (%)	Global Energy Production (MWh)	ROP (%)	Global Energy Production (MWh)	ROP (%)
PV CF = 10%	0	0	33325×10^3	48	35061×10^3	51
PV CF = 20%	0	0	33325×10^3	48	35061×10^3	51
PV CF = 30%	13339×10^3	19	20969×10^3	30	34655×10^3	50
PV CF = 40%	19594×10^3	28	16403×10^3	24	32968×10^3	48
PV CF = 50%	23611×10^3	34	12655×10^3	18	32717×10^3	47
PV CF = 60%	27304×10^3	40	9596×10^3	14	32167×10^3	47

Table 6.6 serves as a comprehensive synthesis, encapsulating the dynamic energetic trends observed under the convolution of both economic and energetic sustainability framework. This table delineates the global energy production levels, offering a nuanced portrayal of the sustainability outcomes across various Solar PV CF scenarios. Additionally, it provides a detailed breakdown of the percentage contribution of each energy category to the overall energetic mix, thereby offering insights into the evolving landscape of energy production.

The data in (Table 6.6) analysis reveals how the sustainability of Solar PV technology vary across various CF scenarios. Notably, PV technology begins to exhibit a sustainable behaviour when the Solar CF exceeds 30%. Beyond this threshold, the contribution of PV technology to the overall energy mix escalates steadily, albeit at a diminishing rate for CFs surpassing 50%, suggesting a saturation point where further increases in CF have no impact on energy production. This trend is vividly depicted in Figure 6.9, which illustrates the annual energy output for each PV CF studied optimization.

As shown in Figure 6.9 (a and b), lower CFs constrain PV deployment, leading to a notable uptick in the utilization of both renewable energy and fossil fuels, with their shares nearly equivalent. However, once the PV CF surpasses 30% (Figure 6.9, c, d, e, and f), the competitiveness of PV technology triggers a decline in the renewable energy share, particularly in daily production, as evidenced in Figure 6.10, which elucidates the Rate of Production dynamics across different time periods.

The integration of sustainability criteria, encompassing both energetic requirement and initial investment requirement, significantly influences technology sustainability. Hydroelectric technologies, for instance, experience a decline in their energy mix share, supplanted by the ascendance of PV technology. These trends underscore the multifaceted challenges associated with renewable energy integration and underscore the pivotal role of storage systems in enhancing reliability and sustainability.

The juxtaposition of PV technology with other renewables underscores the necessity of complementary measures to mitigate intermittency challenges inherent in renewable energy generation. In scenarios devoid of storage systems, fossil fuels emerge as the optimal solution, particularly during nighttime when solar generation is dormant, doubling its contribution rate at the PV CF saturation point of 60%.

Furthermore, the analysis underscores the contextual dependence of PV technology sustainability, contingent upon the abundance of solar resources in each region. In areas with limited solar energy potential, PV technology may not be deemed sustainable from energetic

sustainability requirement and investment recovery perspectives, rendering long-term investments in fossil fuels and alternative renewables more favorable. Nevertheless, the intermittent nature of PV technology necessitates backup systems, such as storage systems or fossil fuels, to ensure reliability.

Conversely, regions with abundant solar resources (CF of 35% or higher) experience significantly shorter energy and economic payback periods for PV, making it an attractive and sustainable investment. Referring to Figure 6.7, PV systems can be deemed a sustainable solution for regions situated below the depicted line on the map.

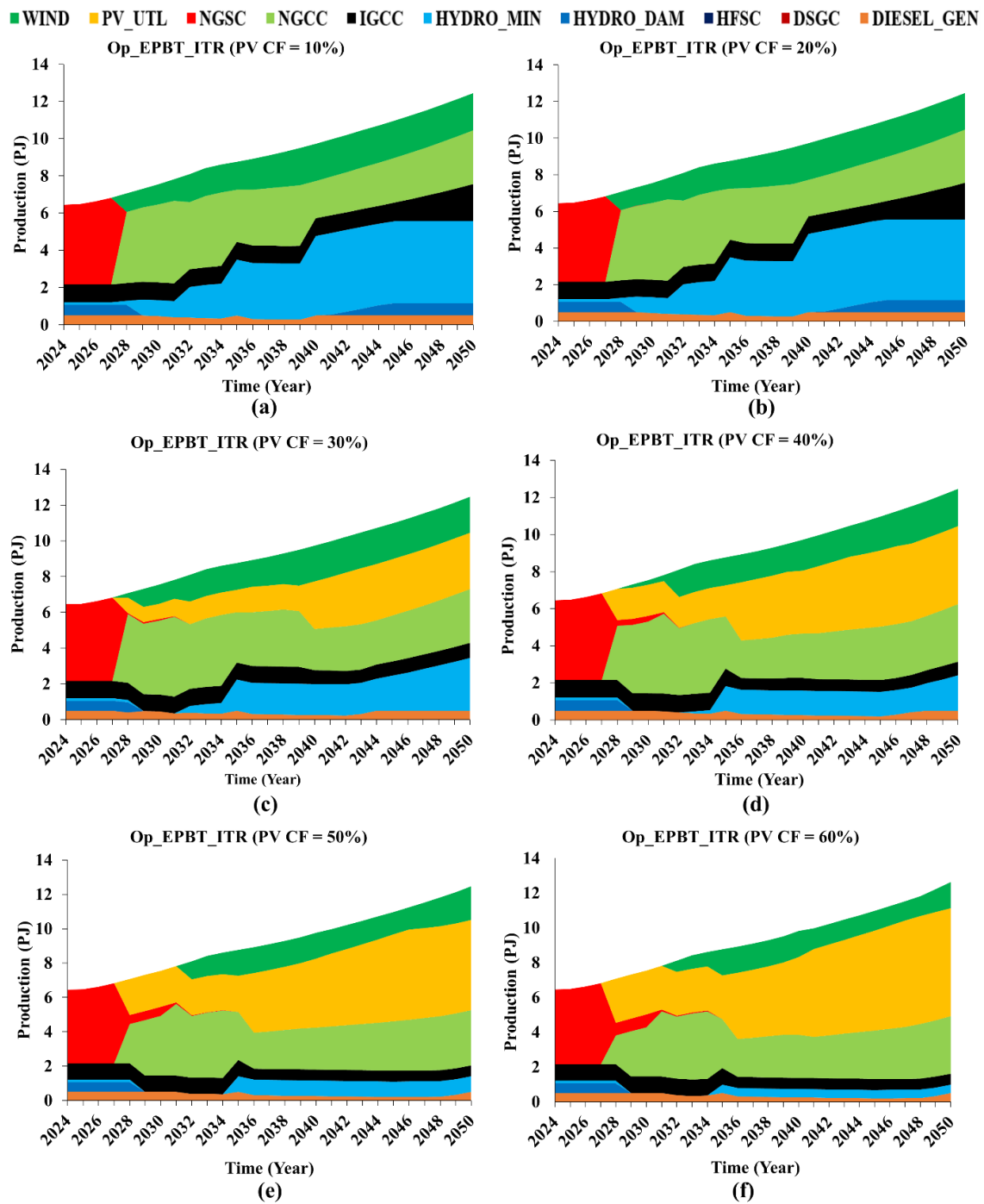


Figure 6. 9 Op_EPBT_IMPcc. Yearly distribution of the energetic production differentiated by technologies.
(a) PV CF=10%; (b) PV CF=20%; (c) PV CF=30%; (d) CF=40%; (e) CF=50%; (f) CF=60%

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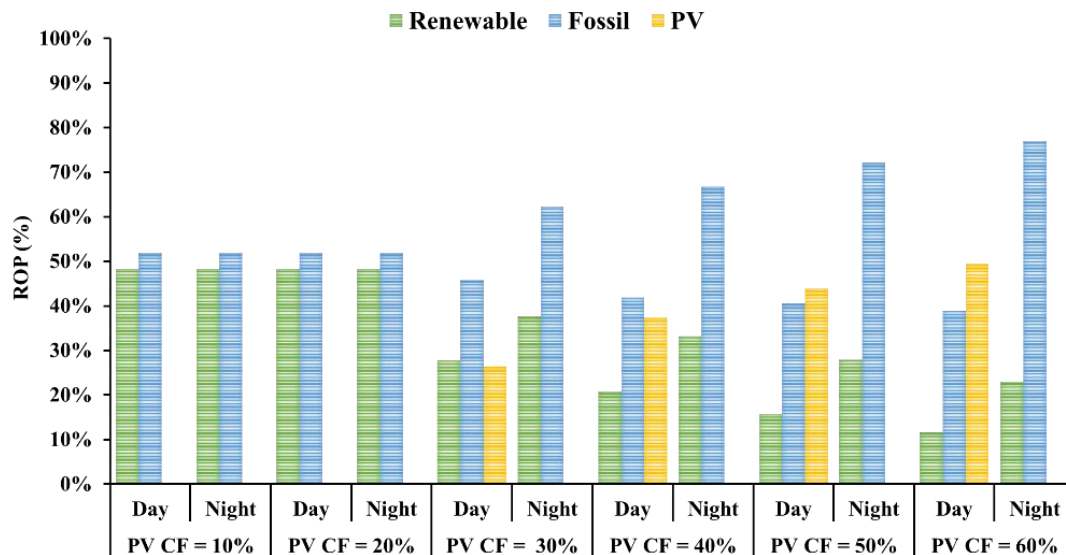


Figure 6. 10 Contribution rate per Daily type of each energy category for each PV CF at the Op_EPBT_ITR
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6.5. Chapter Conclusions

This chapter underscores the significance of the methodology developed for the sustainability indicator integration into OSeMOSYS, offering valuable support to decision-makers, particularly in navigating critical energy challenges.

Specifically, we have looked at three main concerns that make decision-making tricky. These concerns are whether nuclear power generation is sustainable, the impact of high carbon taxes meant to ensure environmental sustainability pathway, and how the sustainability of renewable energy, like solar panels, is affected by different climates.

Using Atlantis RES, we have examined the sustainability of nuclear energy, recognizing its environmental friendliness due to its lack of emissions. However, we have focused on optimizing its sustainability in terms of both energy and economic factors. Our primary objective was to address stakeholder arguments regarding the sustainability of nuclear technology throughout its life cycle. Stakeholders often advocate for assessing nuclear sustainability only within stages that are involved in, such as from raw material extraction to fuel fabrication (cradle-to-door) or electricity production (door-to-door), rather than considering the entire life cycle, including waste management (cradle-to-cradle). Our analysis has shed light on the sustainability of nuclear technology.

Our analysis reveals that nuclear power can be considered sustainable only if the costs and energy associated with nuclear waste treatment are disregarded. However, this approach presents an idealized scenario that overlooks the full life cycle of nuclear energy, specifically the waste management phase, which is often referred to as "negative heritage." In reality, considering the complete life cycle, including waste management, is crucial for a realistic assessment of nuclear technology's sustainability.

Subsequent the study examined the efficacy of carbon taxation policies, employing the IMPcc approach to evaluate their effectiveness in reducing emissions. The Atlantis energy mix was employed to assess the impact of various carbon tax levels, ranging from \$30 to \$200/t CO₂ eq.

The analysis indicates that higher emission penalties do not necessarily result in carbon neutrality. It is noteworthy that even a penalty of \$30/ t CO₂ eq is sufficient to meet EU emission reduction targets. The costs associated with Op IMPcc are consistently 10% lower when carbon taxes are set at \$30 or \$50/ t CO₂ eq, compared to higher carbon taxes tariff. In addition higher carbon taxes results by emission reductions exhibit only a marginal increase when compared to scenarios with lower taxes of \$30 or \$50/t CO₂ eq.

Excessive carbon taxes result in increased electricity prices, which would have a disproportionate impact on low-income households and potentially exacerbate income inequality. This demonstrates the limited efficacy of exceedingly high carbon taxes in achieving substantial emission reductions beyond those achieved with more moderate taxes.

Finally, we assess the sustainability of solar PV technology, considering both energetic and economic sustainability indices through paired convolution optimization using the Atlantis energetic framework. Our analysis reveals that solar PV emerges as a sustainable solution for regions blessed with high Peak Sun Hours (PSH) and corresponding high-capacity factors (CF). Regions with a CF of more than 30% demonstrate the potential for solar PV sustainability, with marginal reductions in solar production rates of no more than 5% compared to standard scenarios. However, a saturation point is observed at a CF of 50%, highlighting the importance of integrating storage systems to mitigate intermittency issues.

Chapter 7. Conclusions

Since the adoption of the sustainable development paradigm, decision-making processes have increasingly been guided by the necessity to ensure sustainable and sound actions. This imperative has become even more pronounced in light of global challenges, particularly those associated with climate change. The energy sector, as one of the largest contributors to global climate change, compels countries to adopt policies that facilitate the transition to more sustainable energy solutions.

The complexity of the energy system presents a formidable challenge further complicating the energy transition process and presenting decision-makers with myriad challenges, particularly in the pursuit of sustainability objectives specifically during energy planning process. To navigate these complexities, decision makers increasingly rely on energy modelling tools designed to achieve planning processes, provide short-, medium and long-term projections that enhance decision-making capabilities, streamline the identification of optimal pathways, and bolster the development of resilient energy systems. A wide array of modelling tools exists offering structured and quantitative insights into diverse energy scenarios using advanced computing capabilities. These tools can accommodate multi-objective optimization constraints and incorporate multiple parameters, thereby expediting the transition to sustainable energy.

Despite their utility, these tools often lack the capacity for sustainability-based decision-making optimization. Instead, they frequently employ economic optimization, leading decision-making processes to prioritize economic outcomes. Consequently, the use of such tools is often sponsored by economic entities, which can skew the focus towards economic interests rather than holistic sustainability goals. This limitation underscores the need for integrating sustainability metrics into energy modelling tools to ensure that decision-making processes align with broader sustainability objectives.

The added value of this work lies in integrating widely used sustainability indicators into the objective function of OSeMOSYS (Open Source Energy Modelling System), a powerful and flexible open-source tool for multi-objective, medium- to long-term linear energy planning. OSeMOSYS is designed for comprehensive energy system analysis and planning, enabling detailed scenario assessments and optimization. While it is currently highly effective, it lacks inherent sustainability-based decision-making frameworks.

This study aims to address a significant limitation in current energy transition modelling tools: the absence of integrated sustainability criteria. Specifically, it seeks to enhance OSeMOSYS by incorporating key sustainability indicators into its optimization function. By doing so, the study aims to improve the model's capacity to support sustainable energy planning, reflecting a broader commitment to responsible resource management and the well-being of both current and future generations.

The sustainability indicators integrated into the model include energetic sustainability, quantified by the Energy Payback Time (EPBT); economic sustainability, measured by the Internal Rate of Return (ITR); and environmental sustainability, evaluated through Impact Mitigation in terms of Climate Change (IMPcc). By incorporating these indicators and their convolution, the model provides a more comprehensive framework for assessing the sustainability of various energy scenarios, thereby guiding decision-making towards more sustainable outcomes. The main milestones developed in this work are:

- ✚ **Methodology Development:** A methodology has been developed that allows the incorporation of sustainability indicators into the OSeMOSYS objective function. This function optimizes the overall costs of the integrated energy matrix over the study period, including investment, maintenance, variable costs, and emissions. The proposed approach converts each sustainability indicator into economic terms and incorporates them as extra cost factors within the objective function. Although this functionality is not inherent to OSeMOSYS, it has been integrated into the core code to enhance the software's capabilities. This enhancement, while potentially increasing computational demands, aims to provide decision-makers with valuable information to achieve sustainable energy outcomes.
- ✚ **Feasibility Evaluation:** To evaluate its feasibility, the proposed methodology was implemented within the pre-built energy framework of Atlantis. This framework is specifically designed to validate methodologies and facilitate controlled assessments of their reproducibility. Atlantis, characterized by a diverse range of technologies including renewable, non-renewable, and nuclear energies, serves as a robust platform to test new methodologies and ensure result reproducibility among OSeMOSYS users.
- ✚ **Results Analysis:** The analysis focuses on merit variables encompassing energy production, economic aspects, and emission activities. These results are compared with those of the standard OSeMOSYS optimization function, which serves as the reference scenario.
- ✚ **Indicator Impact:** The analysis reveals how EPBT prioritizes renewable energy over fossil fuels, leading to a reduction in pollutant emissions. Regarding ITR, this economic sustainability indicator favors fossil fuels to accelerate investment returns, albeit at the cost of increased emissions. Both indicators discourage nuclear deployment. Finally, IMPcc predominantly supports non-emissive solutions, notably renewable and nuclear energy. In terms of economic costs, IMPcc and EPBT, due to their prioritization of renewable sources, increase investment costs while reducing fuel-associated costs. Conversely, ITR shows an opposite trend. Thus, in terms of overall costs and electricity prices, both EPBT and IMPcc trends are comparable, while ITR trends are significantly higher.
- ✚ **Integration Effects:** The effects of integrating the three sustainability indicators within an integrated approach have been evaluated. An initial analysis of the combination of the three indicators reveals a lesser effect on merit variables than each indicator applied separately, although it induces variations in the energy matrix and a slight cost reduction.
- ✚ **Interdependence of Indicators:** Given that each sustainability criterion often implies an increase in overall costs, sometimes significantly, the interdependence of sustainability indicators has been studied. This approach allows identifying and eliminating unnecessary indicators, achieving a better balance between sustainability objectives and costs. To this end, an evaluation of the effects of applying paired indicators has been conducted.
- ✚ **Comparative Analysis:** Comparing these results with the response of the standard function, excluding sustainability criteria, provides less biased information. As a result, trends in the dominance of certain indicators over others, as well as specific improvement effects between EPBT and IMPcc when applied separately versus together, have been identified. It has been observed that simultaneously applying energy and environmental sustainability criteria constitutes the optimal set of indicators to pursue the goal of climate neutrality. Meanwhile, economic sustainability prevails in influencing system behavior when combined with any other indicator.
- ✚ **Quantifying Interactions:** To quantify the observed interactions, correlation matrices have been constructed using the Pearson method for calculating coefficients. This

method offers a quantitative analysis of these dependencies under various boundary conditions. The results obtained allow for modulating the weight of each sustainability indicator based on the goals pursued by the decision-maker.

-  **Decision-Making Support:** To assess how the developed methodology can help decision-makers, especially when facing sensitive energy issues, three sensitive topics in the current energy landscape have been analyzed: the sustainability of nuclear technology within the energy matrix, the impact of high carbon taxes aimed at ensuring an environmental sustainability pathway, and how the sustainability of renewable energy such as solar panels is affected by different climates. Key conclusions include:
- **Nuclear Energy:** Nuclear energy can be considered economically and energetically sustainable only if the costs and energy associated with nuclear waste treatment are disregarded. However, this approach presents an unrealistic scenario, particularly in the waste management phase, often referred to as a "negative legacy." Thus, in a cradle-to-grave philosophy, nuclear energy can only be considered environmentally sustainable.
 - **Carbon Taxes:** The effectiveness of carbon tax policies using the IMPcc approach to assess their effectiveness in reducing emissions shows that penalties above \$50/t CO₂ eq do not necessarily result in carbon neutrality. In fact, even a penalty of \$30/t CO₂ eq is sufficient to meet the EU's emission reduction targets.
 - **Solar PV:** The assessment of the sustainability of photovoltaic (PV) solar technology based on solar resource availability shows that PV solar energy emerges as a sustainable solution for regions blessed with high Peak Sun Hours (PSH) and capacity factors (CF) above 30%. This leads to the conclusion that for a third of the planet, this type of energy, while environmentally sustainable, is unsustainable in terms of energy and economic factors.

In summary, the proposed methodology proves to be both viable and easily implementable within the OSeMOSYS modelling tool, significantly enhancing its performance. By integrating key sustainability indicators EPBT, ITR and IMPcc, and into the objective function, the methodology allows for a more comprehensive and nuanced analysis of energy scenarios. This integration not only broadens the scope of the model but also provides decision-makers with more robust tools to evaluate the sustainability of different energy pathways.

Furthermore, the detailed evaluation of the interrelations between these indicators enables a more precise modulation of their importance based on the specific goals and priorities of the decision-makers. This adaptability is crucial for tailoring energy strategies to meet varied sustainability objectives, whether they are focused on economic efficiency, environmental impact, or energy return on investment.

Finally, the enhanced OSeMOSYS tool shows significant promise in addressing complex and sensitive problems in the field of energy transition. By providing a more detailed and integrated assessment framework, it helps identify optimal pathways for achieving sustainable energy systems. This methodological advancement supports more informed and balanced decision-making processes, ensuring that long-term sustainability goals are met without compromising economic and energy security. The implementation of this approach marks a substantial step forward in the ability to plan and execute effective energy transitions, aligning technological development with environmental and societal well-being.

To be done

- + Enhance the understanding and application of sustainability-based decision-making criteria within energy modelling endeavors.
- + Expand Methodological Approaches to integrate a broad spectrum of sustainability indicators
- + Investigate the inclusion of social indicators in sustainability criteria to provide a more holistic evaluation of sustainability.
- + Conduct studies to elucidate the interrelationships among existing sustainability indicators.
- + Develop weighting schemes that effectively align with specific sustainability goals, providing a panoramic understanding for informed decision-making.

Appendix A: OSeMOSYS features (Set, Parameters and Variables).

The sets form the foundational framework of a model and are generally independent of the specific scenarios to be executed. They establish the parameters for time, spatial coverage, energy vectors, and technologies to be considered. For instance, if a variable is defined as a function of the "YEAR" set, it will be represented as `variablename [y]` and calculated for each year listed in the set. Table A.1 displays the primary sets used in this work along with their corresponding indices.

Table A. 1 Sets in OSeMOSYS
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Name	Description	Index
YEAR	It represents the time frame of the model; it contains all the years to be considered in the study.	y
TECHNOLOGY	It includes any element of the energy system that changes a commodity from one form to another, uses it or supplies it. All system components are set up as a 'technology' in OSeMOSYS. As the model is an abstraction, the modeller is free to interpret the role of a technology at will, where relevant. It may for example represent a single real technology (such as a power plant) or can represent a heavily aggregated collection of technologies (such as the stock of several million light bulbs) or may even simply be a 'dummy technology', perhaps used for accounting purposes.	t
TIMESLICE	It represents the time split of each modelled year, therefore the time resolution of the model. Common to several energy systems modelling tools (incl. MESSAGE / MARKAL / TIMES), the annual demand is 'sliced' into representative fractions of the year. It is necessary to assess times of the year when demand is high separately from times when demand is low, for fuels that are expensive to store. In order to reduce the computation time, these 'slices' are often grouped. Thus, the annual demand may be split into aggregate seasons where demand levels are similar (such as 'summer, winter and intermediate'). Those seasons may be subdivided into aggregate 'day types' (such as workdays and weekends), and the day further sub divided (such as into day and night) depending on the level of demand.	l
FUEL	It includes any energy vector, energy service or proxies entering or exiting technologies. These can be aggregate groups, individual flows or artificially separated, depending on the requirements of the analysis.	f
EMISSION	It includes any kind of emission potentially deriving from the operation of the defined technologies. Typical examples would include atmospheric emissions of greenhouse gasses, such as CO ₂ .	e
MODE_OF_OPERATION	It defines the number of modes of operation that the technologies can have. If a technology can have various input or output fuels and it can choose the mix (i.e. any linear combination) of these input or output fuels, each mix can be accounted as a separate mode of operation. For example, a CHP plant may produce heat in one mode of operation and electricity in another.	m
REGION	It sets the regions to be modelled, e.g. different countries. For each of them, the supply-demand balances for all the energy vectors are ensured, including trades with other regions. In some occasions it might be computationally more convenient to model different countries within the same region and differentiate them simply by creating ad hoc fuels and technologies for each of them.	r
SEASON	It gives indication (by successive numerical values) of how many seasons (e.g. winter, intermediate, summer) are accounted for and in which order. This set is needed if storage facilities are included in the model.	ls
DAYTYPE	It gives indication (by successive numerical values) of how many day types (e.g. workday, weekend) are accounted for and in which order. This set is needed if storage facilities are included in the model.	ld
DAILYTIMEBRACKET	It gives indication (by successive numerical values) of how many parts the day is split into (e.g. night, morning, afternoon, evening) and in which order these parts are sorted. This set is needed if storage facilities are included in the model.	lh
STORAGE	It includes storage facilities in the model.	s

Typically, sets remain static across various scenarios. However, parameters are user-defined numerical inputs to the model. For instance, $\text{Capitalcost}[r,t,y]$ indicates that the capital cost depends on the region (r), the technology (t), and the year (y).

However, The variables are the outputs generated by OSeMOSYS as optimizations results. Similar to the parameters, the variables are functions of the elements within one or more sets. Table A.2 lists the parameters and the variables declared in the master version of OSeMOSYS

Table A. 2 Main parameters and variables

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Category	Parameter/Variable	Description
Input Parameters		
General	StartYear	The first year of the modelling period.
	EndYear	The last year of the modelling period.
	DiscountRate	The discount rate used for the net present value calculation.
	Region	The geographic region for the analysis.
Technologies	TechCapitalCost	Capital cost of each technology (\$/unit capacity).
	TechFixedOMCost	Fixed operation and maintenance cost (\$/unit capacity/year).
	TechVariableOMCost	Variable operation and maintenance cost (\$/unit output).
	TechLifetime	Expected lifetime of the technology (years).
	TechEfficiency	Efficiency of the technology (%).
	TechCapacity	Existing and new installed capacity of the technology (MW).
	TechOperationalLife	Operational life of the technology (years).
Fuels	FuelPrice	Price of each fuel type (\$/unit energy).
	FuelEmissionFactor	Emission factor of each fuel type (ton CO ₂ /unit energy).
	FuelAvailability	Availability constraints for each fuel type (unit energy).
Demand	EnergyDemand	Annual energy demand for each sector (MWh/year).
	DemandGrowthRate	Growth rate of energy demand per sector (%/year).
Resources	ResourceAvailability	Availability of primary energy resources (unit energy/year).
	ResourceCost	Cost associated with resource extraction or import (\$/unit energy).
Emissions	EmissionLimit	Maximum allowable emissions (ton CO ₂ /year).
Policy Constraints	RenewableTarget	Renewable energy target (percentage of total energy).
	EmissionPenalty	Penalty cost for exceeding emission limits (\$/ton CO ₂).
Transmission	TransmissionCapacity	Capacity of transmission lines (MW).
	TransmissionCost	Cost of electricity transmission (\$/unit energy).
Output Variables		
General	TotalSystemCost	Total cost of the energy system over the modelling period (\$).
	AnnualSystemCost	Annual cost of the energy system (\$/year).
	DiscountedSystemCost	Net present value of the system cost (\$).
Technologies	NewCapacity	Amount of new capacity installed for each technology (MW).
	OperatingCapacity	Annual operating capacity of each technology (MW).
	ElectricityGeneration	Annual electricity generation by each technology (MWh/year).
Fuels	FuelConsumption	Annual consumption of each fuel type (unit energy/year).
	FuelCost	Annual cost associated with fuel consumption (\$/year).
Demand	MetDemand	Annual energy demand met by the system (MWh/year).
Emissions	TotalEmissions	Total emissions produced by the energy system (ton CO ₂ /year).
	EmissionCost	Total cost associated with emissions (\$/year).
Resources	ResourceUse	Annual use of primary energy resources (unit energy/year).
	ResourceCost	Annual cost associated with resource use (\$/year).
Policy Outcomes	RenewableShare	Share of renewable energy in total energy generation (%).
	EmissionReduction	Reduction in emissions compared to a baseline scenario (ton CO ₂ /year).

Appendix B: Merits Variables

B.1 Global Energy production

The global energy production for an energy category is estimated by considering the integral sum of the energy production for each technology within each defined category over the whole time under consideration (Equation B.1).

$$\text{GlobalEnergyProduction (MWh)} = \sum \text{ProductionByTechnologyAnnual}_{r,t,f,y} \quad (\text{Eq B.1})$$

B.2 Rate of energy production per energy category (RoP)

This variable expressed as a percentage (Equation B.2) represents the proportion of total energy produced by each of the defined energy category.

$$\text{RoP (\%)} = \frac{\text{GlobalEnergyProduction}_t}{\text{TotalEnergyProduction}_{\text{System}}} \times 100 \quad (\text{Eq B.2})$$

Where:

GlobalEnergyProduction_t (MWh): is the global energy production for a specific category of technology.

TotalEnergyProduction: is the total energy production across all energy source categories. It corresponds to the total energy demand for the entire period. In this work, the Atlantis TotalEnergyProduction = 6.89×10^7 MWh.

B.2 Output Costs Components

The cost component is calculated by integrating the annual costs of each technology in the energy mix over the entire period. This includes the Capital Cost (\$), Variable Cost (\$), and Fixed Cost (\$), which are represented by Equations 3.5, 3.6, and 3.7 respectively.

$$\text{Capital Cost (M\$)} = \sum \text{CapitalInvestment}_{r,t,y} \quad (\text{Eq B.3})$$

$$\text{Variable Cost (M\$)} = \sum \text{AnnualVariableOperatingCost}_{r,t,y} \quad (\text{Eq B4})$$

$$\text{Fixed Cost (M\$)} = \sum \text{AnnualFixedOperatingCost}_{r,t,y} \quad (\text{Eq B5})$$

B.3 Output Global Costs and electricity price

The global cost per unit of energy, Global Cost, (\$/MWh) measures the net present cost of electricity generation for the entire energy mix over the entire period. As shown in (Equation B.6), is the ratio of the sum of the cost components of the corresponding trend, and the total energy production within the integral period.

$$\text{Global Cost (M\$/MWh)} = \frac{\text{Capital Cost} + \text{Variable Cost} + \text{Fixed Cost}}{\text{TotalEnergyProduction}} \quad (\text{Eq B.6})$$

The residual price, R_{price} , which is the electricity tariff and as shown in (Equation B.7), is defined as the ratio of the gap between the global cost and the global investment cost of the total energy production, all within the integral time.

$$R_{\text{price}} \text{ (M\$/MWh)} = \text{Global Cost} - \frac{\text{Capital Cost}}{\text{TotalEnergyProduction}} \quad (\text{Eq B.7})$$

B.3 Output Emissions Component

The estimation of global emissions (Mt CO₂) involves the summation of the corresponding annual emissions E_{emission} within the energy mix over the entire period considered, as shown in Equations B.8.

$$\text{Global Emission (t CO}_2\text{)} = \sum \text{Annual Emissions}_{r,e,y} \quad (\text{Eq B.7})$$

Equation 3.11 gives the global emissions per unit of energy produced which takes into account the global emissions of the energy mix per unit of energy produced during the integral time.

$$\text{Global Emissions (t CO}_2\text{/MWh)} = \frac{\text{Global Emission}}{\text{TotalEnergyProduction}} \quad (\text{Eq B.8})$$

Appendix C: OSeMOSYS Code in GNU MathProg

Modifications to include sustainability indicators are highlighted in red.

```
# Sets #
set EMISSION;
set FUEL;
set MODE_OF_OPERATION;
set REGION;
set STORAGE;
set TECHNOLOGY;
set TIMESLICE;
set YEAR;

# Parameters #
param AccumulatedAnnualDemand{r in REGION, f in FUEL, y in YEAR};
param AnnualEmissionLimit{r in REGION, e in EMISSION, y in YEAR};
param AnnualExogenousEmission{r in REGION, e in EMISSION, y in YEAR};
param AvailabilityFactor{r in REGION, t in TECHNOLOGY, y in YEAR};
param CapacityFactor{r in REGION, t in TECHNOLOGY, l in TIMESLICE, y in YEAR};
param CapacityOfOneTechnologyUnit{r in REGION, t in TECHNOLOGY, y in YEAR};
param CapacityToActivityUnit{r in REGION, t in TECHNOLOGY};
param CapitalCost{r in REGION, t in TECHNOLOGY, y in YEAR};
param CapitalCostStorage{r in REGION, s in STORAGE, y in YEAR};
param DepreciationMethod{r in REGION};
param DiscountRate{r in REGION};
param EmissionActivityRatio{r in REGION, t in TECHNOLOGY, e in EMISSION, m in MODE_OF_OPERATION, y in YEAR};
param EmissionsPenalty{r in REGION, e in EMISSION, y in YEAR};
param FixedCost{r in REGION, t in TECHNOLOGY, y in YEAR};
param InputActivityRatio{r in REGION, t in TECHNOLOGY, f in FUEL, m in MODE_OF_OPERATION, y in YEAR};
param ModelPeriodEmissionLimit{r in REGION, e in EMISSION};
param ModelPeriodExogenousEmission{r in REGION, e in EMISSION};
param OperationalLife{r in REGION, t in TECHNOLOGY};
param OperationalLifeStorage{r in REGION, s in STORAGE};
param OutputActivityRatio{r in REGION, t in TECHNOLOGY, f in FUEL, m in MODE_OF_OPERATION, y in YEAR};
param REMinProductionTarget{r in REGION, y in YEAR};
param RETagFuel{r in REGION, f in FUEL, y in YEAR};
param RETagTechnology{r in REGION, t in TECHNOLOGY, y in YEAR};
param ReserveMargin{r in REGION, y in YEAR};
param ReserveMarginTagFuel{r in REGION, f in FUEL, y in YEAR};
param ReserveMarginTagTechnology{r in REGION, t in TECHNOLOGY, y in YEAR};
param ResidualCapacity{r in REGION, t in TECHNOLOGY, y in YEAR};
param SpecifiedAnnualDemand{r in REGION, f in FUEL, y in YEAR};
param SpecifiedDemandProfile{r in REGION, f in FUEL, l in TIMESLICE, y in YEAR};
param TotalAnnualMaxCapacity{r in REGION, t in TECHNOLOGY, y in YEAR};
param TotalAnnualMaxCapacityInvestment{r in REGION, t in TECHNOLOGY, y in YEAR};
param TotalAnnualMinCapacity{r in REGION, t in TECHNOLOGY, y in YEAR};
param TotalAnnualMinCapacityInvestment{r in REGION, t in TECHNOLOGY, y in YEAR};
param TotalTechnologyAnnualActivityLowerLimit{r in REGION, t in TECHNOLOGY, y in YEAR};
param TotalTechnologyAnnualActivityUpperLimit{r in REGION, t in TECHNOLOGY, y in YEAR};
param TotalTechnologyModelPeriodActivityLowerLimit{r in REGION, t in TECHNOLOGY};
param TotalTechnologyModelPeriodActivityUpperLimit{r in REGION, t in TECHNOLOGY};
param TradeRoute{r in REGION, rr in REGION, f in FUEL, y in YEAR};
param VariableCost{r in REGION, t in TECHNOLOGY, m in MODE_OF_OPERATION, y in YEAR};
param YearSplit{l in TIMESLICE, y in YEAR};
param ZActivateIMPccequation;
param ZEPBT{r in REGION, t in TECHNOLOGY};
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param ZITR{r in REGION, t in TECHNOLOGY};
 param ZMeanEmissionValue{e in EMISSION};

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# Model Variables #
var AccumulatedNewCapacity{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0;
var AnnualEmissions{r in REGION, e in EMISSION, y in YEAR} >= 0;
var AnnualFixedOperatingCost{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0;
var AnnualTechnologyEmission{r in REGION, t in TECHNOLOGY, e in EMISSION, y in YEAR} >= 0;
var AnnualTechnologyEmissionByMode{r in REGION, t in TECHNOLOGY, e in EMISSION, m in
MODE_OF_OPERATION, y in YEAR} >= 0;
var AnnualVariableOperatingCost{r in REGION, t in TECHNOLOGY, y in YEAR};
var CapitalInvestment{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0;
var Demand{r in REGION, l in TIMESLICE, f in FUEL, y in YEAR} >= 0;
var DiscountedSalvageValue{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0;
var DiscountedTechnologyEmissionsPenalty{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0;
var NewCapacity{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0;
var NewStorageCapacity{r in REGION, s in STORAGE, y in YEAR} >= 0;
var NumberOfNewTechnologyUnits{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0, integer;
var ProductionByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR} >= 0;
var ProductionByTechnologyAnnual{r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR} >= 0;
var RateOfActivity{r in REGION, l in TIMESLICE, t in TECHNOLOGY, m in MODE_OF_OPERATION, y in YEAR} >= 0;
var RateOfProductionByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR} >= 0;
var RateOfProductionByTechnologyByMode{r in REGION, l in TIMESLICE, t in TECHNOLOGY, m in
MODE_OF_OPERATION, f in FUEL, y in YEAR} >= 0;
var RateOfUseByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR} >= 0;
var RateOfUseByTechnologyByMode{r in REGION, l in TIMESLICE, t in TECHNOLOGY, m in MODE_OF_OPERATION,
f in FUEL, y in YEAR} >= 0;
var SalvageValue{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0;
var SalvageValueStorage{r in REGION, s in STORAGE, y in YEAR} >= 0;
var TotalAnnualTechnologyActivityByMode{r in REGION, t in TECHNOLOGY, m in MODE_OF_OPERATION, y in
YEAR} >= 0;
var TotalCapacityAnnual{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0;
var TotalTechnologyAnnualActivity{r in REGION, t in TECHNOLOGY, y in YEAR} >= 0;
var TotalTechnologyModelPeriodActivity{r in REGION, t in TECHNOLOGY};
var Trade{r in REGION, rr in REGION, l in TIMESLICE, f in FUEL, y in YEAR};
var UseByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR} >= 0;

# Objective Function #
minimize OFS_Cost: sum{y in YEAR, r in REGION, t in TECHNOLOGY} (((sum{yy in YEAR: y - yy < OperationalLife
[r, t] && y - yy >= 0} NewCapacity [r, t, yy]) + ResidualCapacity [r, t, y]) * FixedCost [r, t, y] + sum{l in TIMESLICE, m in
MODE_OF_OPERATION} RateOfActivity [r, l, t, m, y] * YearSplit [l, y] * VariableCost [r, t, m, y] * (1 + ZEPBT [r, t] /
OperationalLife [r, t])) / ((1 + DiscountRate [r]) ^ (y - min{yy in YEAR} min(yy) + 0.5)) + CapitalCost [r, t, y] * (1 +
ZITR [r, t] / OperationalLife [r, t]) * NewCapacity [r, t, y] / ((1 + DiscountRate [r]) ^ (y - min{yy in YEAR} min(yy))) +
DiscountedTechnologyEmissionsPenalty [r, t, y] - DiscountedSalvageValue [r, t, y]) + sum{s in STORAGE} (CapitalCostStorage [r, s, y] * NewStorageCapacity [r, s, y] / ((1 + DiscountRate [r]) ^ (y - min{yy in YEAR} min(yy)))) -
SalvageValueStorage [r, s, y] / ((1 + DiscountRate [r]) ^ (max{yy in YEAR} max(yy) - min{yy in YEAR} min(yy) + 1))));

# Constraints #
# Common Equations
s.t. Acc1_FuelProductionByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR}:
RateOfProductionByTechnology [r, l, t, f, y] * YearSplit [l, y] = ProductionByTechnology [r, l, t, f, y];
s.t. Acc2_FuelUseByTechnology{r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR}:
RateOfUseByTechnology [r, l, t, f, y] * YearSplit [l, y] = UseByTechnology [r, l, t, f, y];
s.t. Acc3_AverageAnnualRateOfActivity{r in REGION, t in TECHNOLOGY, m in MODE_OF_OPERATION, y in YEAR}:
sum{l in TIMESLICE} RateOfActivity [r, l, t, m, y] * YearSplit [l, y] = TotalAnnualTechnologyActivityByMode [r, t, m, y];
s.t. CAa1_TotalNewCapacity{r in REGION, t in TECHNOLOGY, y in YEAR}: AccumulatedNewCapacity [r, t, y] = sum{yy
in YEAR: y - yy < OperationalLife [r, t] && y - yy >= 0} NewCapacity [r, t, yy];
s.t. CAa2_TotalAnnualCapacity{r in REGION, t in TECHNOLOGY, y in YEAR}: AccumulatedNewCapacity [r, t, y] +
ResidualCapacity [r, t, y] = TotalCapacityAnnual [r, t, y];
s.t. CAa5_TotalNewCapacity{r in REGION, t in TECHNOLOGY, y in YEAR: CapacityOfOneTechnologyUnit [r, t, y] < 0}:
CapacityOfOneTechnologyUnit [r, t, y] * NumberOfNewTechnologyUnits [r, t, y] = NewCapacity [r, t, y];
s.t. CC1_UndiscountedCapitalInvestment{r in REGION, t in TECHNOLOGY, y in YEAR}: CapitalCost [r, t, y] *
NewCapacity [r, t, y] = CapitalInvestment [r, t, y];
s.t. E2_AnnualEmissionProduction{r in REGION, t in TECHNOLOGY, e in EMISSION, y in YEAR}: sum{m in
MODE_OF_OPERATION} AnnualTechnologyEmissionByMode [r, t, e, m, y] = AnnualTechnologyEmission [r, t, e, y];
s.t. EBa10_EnergyBalanceEachTS4{r in REGION, rr in REGION, l in TIMESLICE, f in FUEL, y in YEAR}: Trade [r, rr, l, f,
y] = -1 * Trade [rr, l, f, y];
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s.t. Eba1_RateOfFuelProduction1 {r in REGION, l in TIMESLICE, t in TECHNOLOGY, m in MODE_OF_OPERATION, y
in YEAR, f in FUEL: OutputActivityRatio [r, t, f, m, y] < 0}: RateOfActivity [r, l, t, m, y] * OutputActivityRatio [r, t, f, m,
y] = RateOfProductionByTechnologyByMode [r, l, t, m, f, y];
s.t. Eba2_RateOfFuelProduction2 {r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR, l in TIMESLICE}: sum{m in
MODE_OF_OPERATION: OutputActivityRatio [r, t, f, m, y] < 0} RateOfProductionByTechnologyByMode [r, l, t, m, f, y]
= RateOfProductionByTechnology [r, l, t, f, y];
s.t. Eba4_RateOfFuelUse1 {r in REGION, l in TIMESLICE, t in TECHNOLOGY, m in MODE_OF_OPERATION, y in YEAR,
f in FUEL: InputActivityRatio [r, t, f, m, y] < 0}: RateOfActivity [r, l, t, m, y] * InputActivityRatio [r, t, f, m, y] =
RateOfUseByTechnologyByMode [r, l, t, m, f, y];
s.t. Eba5_RateOfFuelUse2 {r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR, l in TIMESLICE}: sum{m in
MODE_OF_OPERATION: InputActivityRatio [r, t, f, m, y] < 0} RateOfUseByTechnologyByMode [r, l, t, m, f, y] =
RateOfUseByTechnology [r, l, t, f, y];
s.t. NCC1_TotalAnnualMaxNewCapacityConstraint {r in REGION, t in TECHNOLOGY, y in YEAR}: NewCapacity [r, t, y]
<= TotalAnnualMaxCapacityInvestment [r, t, y];
s.t. NCC2_TotalAnnualMinNewCapacityConstraint {r in REGION, t in TECHNOLOGY, y in YEAR:
TotalAnnualMinCapacityInvestment [r, t, y] > 0}: NewCapacity [r, t, y] >= TotalAnnualMinCapacityInvestment [r, t, y];
s.t. OC1_OperatingCostsVariable {r in REGION, t in TECHNOLOGY, y in YEAR}: sum{m in MODE_OF_OPERATION}
TotalAnnualTechnologyActivityByMode [r, t, m, y] * VariableCost [r, t, m, y] = AnnualVariableOperatingCost [r, t, y];
s.t. OC2_OperatingCostsFixedAnnual {r in REGION, t in TECHNOLOGY, y in YEAR}: TotalCapacityAnnual [r, t, y] *
FixedCost [r, t, y] = AnnualFixedOperatingCost [r, t, y];
s.t. SI6_SalvageValueStorageAtEndOfPeriod1 {r in REGION, s in STORAGE, y in YEAR: (y + OperationalLifeStorage [r, s]
- 1) <= (max{yy in YEAR} max(yy))}: 0 = SalvageValueStorage [r, s, y];
s.t. SV3_SalvageValueAtEndOfPeriod3 {r in REGION, t in TECHNOLOGY, y in YEAR: (y + OperationalLife [r, t] - 1) <=
(max{yy in YEAR} max(yy))}: SalvageValue [r, t, y] = 0;
s.t. SV4_SalvageValueDiscountedToStartYear {r in REGION, t in TECHNOLOGY, y in YEAR}: DiscountedSalvageValue [r,
t, y] = SalvageValue [r, t, y] / ((1 + DiscountRate [r]) ^ (1 + max{yy in YEAR} max(yy) - min{yy in YEAR} min(yy)));
s.t. TAC1_TotalModelHorizonTechnologyActivity {r in REGION, t in TECHNOLOGY}: sum{y in YEAR}
TotalTechnologyAnnualActivity [r, t, y] = TotalTechnologyModelPeriodActivity [r, t];

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Short Code Equations

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s.t. AAC2_TotalAnnualTechnologyActivityUpperLimit {r in REGION, t in TECHNOLOGY, y in YEAR}: sum{l in
TIMESLICE, m in MODE_OF_OPERATION} RateOfActivity [r, l, t, m, y] * YearSplit [l, y] <=
TotalTechnologyAnnualActivityUpperLimit [r, t, y];
s.t. AAC3_TotalAnnualTechnologyActivityLowerLimit {r in REGION, t in TECHNOLOGY, y in YEAR:
TotalTechnologyAnnualActivityLowerLimit [r, t, y] > 0}: sum{l in TIMESLICE, m in MODE_OF_OPERATION}
RateOfActivity [r, l, t, m, y] * YearSplit [l, y] >= TotalTechnologyAnnualActivityLowerLimit [r, t, y];
s.t. CAa4_Constraint_Capacity {r in REGION, l in TIMESLICE, t in TECHNOLOGY, y in YEAR}: sum{m in
MODE_OF_OPERATION} RateOfActivity [r, l, t, m, y] <= ((sum{yy in YEAR: y - yy < OperationalLife [r, t] && y - yy >=
0} NewCapacity [r, t, yy]) + ResidualCapacity [r, t, y]) * CapacityFactor [r, t, l, y] * CapacityToActivityUnit [r, t];
s.t. CAB1_PlannedMaintenance {r in REGION, t in TECHNOLOGY, y in YEAR}: sum{l in TIMESLICE} sum{m in
MODE_OF_OPERATION} RateOfActivity [r, l, t, m, y] * YearSplit [l, y] <= sum{l in TIMESLICE} (((sum{yy in YEAR: y -
yy < OperationalLife [r, t] && y - yy >= 0} NewCapacity [r, t, yy]) + ResidualCapacity [r, t, y]) * CapacityFactor [r, t, l, y] *
YearSplit [l, y]) * AvailabilityFactor [r, t, y] * CapacityToActivityUnit [r, t];
s.t. E5_DiscountedEmissionsPenaltyByTechnology {r in REGION, t in TECHNOLOGY, y in YEAR: ZActivateIMPccequation
= 0}: sum{e in EMISSION, m in MODE_OF_OPERATION, l in TIMESLICE} EmissionActivityRatio [r, t, e, m, y] *
RateOfActivity [r, l, t, m, y] * YearSplit [l, y] * EmissionsPenalty [r, e, y] / ((1 + DiscountRate [r]) ^ (y - min{yy in YEAR}
min(yy) + 0.5)) = DiscountedTechnologyEmissionsPenalty [r, t, y];
s.t. E6_EmissionsAccounting1 {r in REGION, e in EMISSION, y in YEAR}: sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION, l in TIMESLICE: EmissionActivityRatio [r, t, e, m, y] < 0} EmissionActivityRatio [r, t, e, m, y]
* RateOfActivity [r, l, t, m, y] * YearSplit [l, y] = AnnualEmissions [r, e, y];
s.t. E8_AnnualEmissionsLimit {r in REGION, e in EMISSION, y in YEAR}: sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION, l in TIMESLICE} EmissionActivityRatio [r, t, e, m, y] * RateOfActivity [r, l, t, m, y] * YearSplit
[l, y] + AnnualExogenousEmission [r, e, y] <= AnnualEmissionLimit [r, e, y];
s.t. E9_ModelPeriodEmissionsLimit {r in REGION, e in EMISSION}: sum{t in TECHNOLOGY, m in
MODE_OF_OPERATION, y in YEAR, l in TIMESLICE} EmissionActivityRatio [r, t, e, m, y] * RateOfActivity [r, l, t, m, y]
* YearSplit [l, y] + ModelPeriodExogenousEmission [r, e] <= ModelPeriodEmissionLimit [r, e];
s.t. Eba11_EnergyBalanceEachTS5 {r in REGION, f in FUEL, y in YEAR, l in TIMESLICE}: sum{t in TECHNOLOGY, m
in MODE_OF_OPERATION: OutputActivityRatio [r, t, f, m, y] < 0} RateOfActivity [r, l, t, m, y] * OutputActivityRatio [r,
t, f, m, y] * YearSplit [l, y] >= SpecifiedAnnualDemand [r, f, y] * SpecifiedDemandProfile [r, f, l, y] + sum{t in
TECHNOLOGY, m in MODE_OF_OPERATION: InputActivityRatio [r, t, f, m, y] < 0} RateOfActivity [r, l, t, m, y] *
InputActivityRatio [r, t, f, m, y] * YearSplit [l, y] + sum{rr in REGION} Trade [r, rr, l, f, y] * TradeRoute [r, rr, f, y];
s.t. Eba9_EnergyBalanceEachTS3 {r in REGION, f in FUEL, y in YEAR, l in TIMESLICE}: SpecifiedAnnualDemand [r, f, y]
* SpecifiedDemandProfile [r, f, l, y] = Demand [r, l, f, y];
s.t. Ebb4_EnergyBalanceEachYear4 {r in REGION, f in FUEL, y in YEAR}: sum{l in TIMESLICE, t in TECHNOLOGY, m
in MODE_OF_OPERATION: OutputActivityRatio [r, t, f, m, y] < 0} RateOfActivity [r, l, t, m, y] * OutputActivityRatio [r,
t, f, m, y] * YearSplit [l, y] >= sum{l in TIMESLICE, t in TECHNOLOGY, m in MODE_OF_OPERATION: InputActivityRatio

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[r, t, f, m, y] < 0} RateOfActivity [r, l, t, m, y] * InputActivityRatio [r, t, f, m, y] * YearSplit [l, y] + sum{rr in REGION, l in TIMESLICE} Trade [r, rr, l, f, y] * TradeRoute [r, rr, f, y] + AccumulatedAnnualDemand [r, f, y];
s.t. RE1_FuelProductionByTechnologyAnnual{r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR}: sum{l in TIMESLICE, m in MODE_OF_OPERATION: OutputActivityRatio [r, t, f, m, y] < 0} RateOfActivity [r, l, t, m, y] * OutputActivityRatio [r, t, f, m, y] * YearSplit [l, y] = ProductionByTechnologyAnnual [r, t, f, y];
s.t. RE4_EnergyConstraint{r in REGION, y in YEAR}: REMinProductionTarget [r, y] * sum{f in FUEL, l in TIMESLICE} sum{t in TECHNOLOGY, m in MODE_OF_OPERATION: OutputActivityRatio [r, t, f, m, y] < 0} RateOfActivity [r, l, t, m, y] * OutputActivityRatio [r, t, f, m, y] * YearSplit [l, y] * RETagFuel [r, f, y] <= sum{l in TIMESLICE, t in TECHNOLOGY, m in MODE_OF_OPERATION, f in FUEL: OutputActivityRatio [r, t, f, m, y] < 0} RateOfActivity [r, l, t, m, y] * OutputActivityRatio [r, t, f, m, y] * YearSplit [l, y] * RETagTechnology [r, t, y];
s.t. RM3_ReserveMargin_Constraint{r in REGION, y in YEAR, l in TIMESLICE}: sum{t in TECHNOLOGY, m in MODE_OF_OPERATION, f in FUEL: OutputActivityRatio [r, t, f, m, y] < 0} RateOfActivity [r, l, t, m, y] * OutputActivityRatio [r, t, f, m, y] * ReserveMarginTagFuel [r, f, y] * ReserveMargin [r, y] <= sum{t in TECHNOLOGY} ((sum{yy in YEAR: y - yy < OperationalLife [r, t] && y - yy >= 0} NewCapacity [r, t, yy]) + ResidualCapacity [r, t, y]) * ReserveMarginTagTechnology [r, t, y] * CapacityToActivityUnit [r, t];
s.t. SV1_SalvageValueAtEndOfPeriod1{r in REGION, t in TECHNOLOGY, y in YEAR: DepreciationMethod [r] = 1 && (y + OperationalLife [r, t] - 1) > (max{yy in YEAR} max(yy)) && DiscountRate [r] > 0}: SalvageValue [r, t, y] = CapitalCost [r, t, y] * NewCapacity [r, t, y] * (1 - (((1 + DiscountRate [r]) ^ (max{yy in YEAR} max(yy) - y + 1) - 1) / ((1 + DiscountRate [r]) ^ OperationalLife [r, t] - 1)));
s.t. SV2_SalvageValueAtEndOfPeriod2{r in REGION, t in TECHNOLOGY, y in YEAR: DepreciationMethod [r] = 1 && (y + OperationalLife [r, t] - 1) > (max{yy in YEAR} max(yy)) && DiscountRate [r] = 0 || (DepreciationMethod [r] = 2 && (y + OperationalLife [r, t] - 1) > (max{yy in YEAR} max(yy))): SalvageValue [r, t, y] = CapitalCost [r, t, y] * NewCapacity [r, t, y] * (1 - (max{yy in YEAR} max(yy) - y + 1) / OperationalLife [r, t]);
s.t. TAC2_TotalModelHorizonTechnologyActivityUpperLimit{r in REGION, t in TECHNOLOGY: TotalTechnologyModelPeriodActivityUpperLimit [r, t] > 0}: sum{l in TIMESLICE, m in MODE_OF_OPERATION, y in YEAR} RateOfActivity [r, l, t, m, y] * YearSplit [l, y] <= TotalTechnologyModelPeriodActivityUpperLimit [r, t];
s.t. TAC3_TotalModelHorizonTechnologyActivityLowerLimit{r in REGION, t in TECHNOLOGY: TotalTechnologyModelPeriodActivityLowerLimit [r, t] > 0}: sum{l in TIMESLICE, m in MODE_OF_OPERATION, y in YEAR} RateOfActivity [r, l, t, m, y] * YearSplit [l, y] >= TotalTechnologyModelPeriodActivityLowerLimit [r, t];
s.t. TCC1_TotalAnnualMaxCapacityConstraint{y in YEAR, r in REGION, t in TECHNOLOGY}: ((sum{yy in YEAR: y - yy < OperationalLife [r, t] && y - yy >= 0} NewCapacity [r, t, yy]) + ResidualCapacity [r, t, y]) <= TotalAnnualMaxCapacity [r, t, y];
s.t. TCC2_TotalAnnualMinCapacityConstraint{y in YEAR, r in REGION, t in TECHNOLOGY: TotalAnnualMinCapacity [r, t, y] > 0}: ((sum{yy in YEAR: y - yy < OperationalLife [r, t] && y - yy >= 0} NewCapacity [r, t, yy]) + ResidualCapacity [r, t, y]) >= TotalAnnualMinCapacity [r, t, y];

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s.t. ZE5_DiscountedEmissionsPenaltyByTechnology{r in REGION, t in TECHNOLOGY, y in YEAR: ZActivateIMPecequation = 1}: sum{e in EMISSION, m in MODE_OF_OPERATION, l in TIMESLICE} EmissionActivityRatio [r, t, e, m, y] * RateOfActivity [r, l, t, m, y] * YearSplit [l, y] * EmissionsPenalty [r, e, y] * EmissionActivityRatio [r, t, e, m, y] / ZMeanEmissionValue [e] / ((1 + DiscountRate [r]) ^ (y - min{yy in YEAR} min(yy) + 0.5)) = DiscountedTechnologyEmissionsPenalty [r, t, y];

Output

table tout {r in REGION, t in TECHNOLOGY, y in YEAR} OUT "CSV" "res/csv/AccumulatedNewCapacity.csv" : r, t, y, AccumulatedNewCapacity[r, t, y];
table tout {r in REGION, e in EMISSION, y in YEAR} OUT "CSV" "res/csv/AnnualEmissions.csv" : r, e, y, AnnualEmissions[r, e, y];
table tout {r in REGION, t in TECHNOLOGY, y in YEAR} OUT "CSV" "res/csv/AnnualFixedOperatingCost.csv" : r, t, y, AnnualFixedOperatingCost[r, t, y];
table tout {r in REGION, t in TECHNOLOGY, e in EMISSION, y in YEAR} OUT "CSV" "res/csv/AnnualTechnologyEmission.csv" : r, t, e, y, AnnualTechnologyEmission[r, t, e, y];
table tout {r in REGION, t in TECHNOLOGY, e in EMISSION, m in MODE_OF_OPERATION, y in YEAR} OUT "CSV" "res/csv/AnnualTechnologyEmissionByMode.csv" : r, t, e, m, y, AnnualTechnologyEmissionByMode[r, t, e, m, y];
table tout {r in REGION, t in TECHNOLOGY, y in YEAR} OUT "CSV" "res/csv/AnnualVariableOperatingCost.csv" : r, t, y, AnnualVariableOperatingCost[r, t, y];
table tout {r in REGION, t in TECHNOLOGY, y in YEAR} OUT "CSV" "res/csv/CapitalInvestment.csv" : r, t, y, CapitalInvestment[r, t, y];
table tout {r in REGION, l in TIMESLICE, f in FUEL, y in YEAR} OUT "CSV" "res/csv/Demand.csv" : r, l, f, y, Demand[r, l, f, y];
table tout {r in REGION, t in TECHNOLOGY, y in YEAR} OUT "CSV" "res/csv/DiscountedSalvageValue.csv" : r, t, y, DiscountedSalvageValue[r, t, y];
table tout {r in REGION, t in TECHNOLOGY, y in YEAR} OUT "CSV" "res/csv/DiscountedTechnologyEmissionsPenalty.csv" : r, t, y, DiscountedTechnologyEmissionsPenalty[r, t, y];
table tout {r in REGION, t in TECHNOLOGY, y in YEAR} OUT "CSV" "res/csv/NewCapacity.csv" : r, t, y, NewCapacity[r, t, y];

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table tout {r in REGION, s in STORAGE, y in YEAR} OUT "CSV" "res/csv/NewStorageCapacity.csv" : r, s, y,
NewStorageCapacity[r, s, y];
table tout {r in REGION, t in TECHNOLOGY, y in YEAR} OUT "CSV" "res/csv/NumberOfNewTechnologyUnits.csv" : r, t,
y, NumberOfNewTechnologyUnits[r, t, y];
table tout {r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR} OUT "CSV"
"res/csv/ProductionByTechnology.csv" : r, l, t, f, y, ProductionByTechnology[r, l, t, f, y];
table tout {r in REGION, t in TECHNOLOGY, f in FUEL, y in YEAR} OUT "CSV"
"res/csv/ProductionByTechnologyAnnual.csv" : r, t, f, y, ProductionByTechnologyAnnual[r, t, f, y];
table tout {r in REGION, l in TIMESLICE, t in TECHNOLOGY, m in MODE_OF_OPERATION, y in YEAR} OUT "CSV"
"res/csv/RateOfActivity.csv" : r, l, t, m, y, RateOfActivity[r, l, t, m, y];
table tout {r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR} OUT "CSV"
"res/csv/RateOfProductionByTechnology.csv" : r, l, t, f, y, RateOfProductionByTechnology[r, l, t, f, y];
table tout {r in REGION, l in TIMESLICE, t in TECHNOLOGY, m in MODE_OF_OPERATION, f in FUEL, y in YEAR}
OUT "CSV" "res/csv/RateOfProductionByTechnologyByMode.csv" : r, l, t, m, f, y,
RateOfProductionByTechnologyByMode[r, l, t, m, f, y];
table tout {r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR} OUT "CSV"
"res/csv/RateOfUseByTechnology.csv" : r, l, t, f, y, RateOfUseByTechnology[r, l, t, f, y];
table tout {r in REGION, l in TIMESLICE, t in TECHNOLOGY, m in MODE_OF_OPERATION, f in FUEL, y in YEAR}
OUT "CSV" "res/csv/RateOfUseByTechnologyByMode.csv" : r, l, t, m, f, y, RateOfUseByTechnologyByMode[r, l, t, m, f, y];
table tout {r in REGION, t in TECHNOLOGY, y in YEAR} OUT "CSV" "res/csv/SalvageValue.csv" : r, t, y, SalvageValue[r,
t, y];
table tout {r in REGION, s in STORAGE, y in YEAR} OUT "CSV" "res/csv/SalvageValueStorage.csv" : r, s, y,
SalvageValueStorage[r, s, y];
table tout {r in REGION, t in TECHNOLOGY, m in MODE_OF_OPERATION, y in YEAR} OUT "CSV"
"res/csv/TotalAnnualTechnologyActivityByMode.csv" : r, t, m, y, TotalAnnualTechnologyActivityByMode[r, t, m, y];
table tout {r in REGION, t in TECHNOLOGY, y in YEAR} OUT "CSV" "res/csv/TotalCapacityAnnual.csv" : r, t, y,
TotalCapacityAnnual[r, t, y];
table tout {r in REGION, t in TECHNOLOGY, y in YEAR} OUT "CSV" "res/csv/TotalTechnologyAnnualActivity.csv" : r, t,
y, TotalTechnologyAnnualActivity[r, t, y];
table tout {r in REGION, t in TECHNOLOGY} OUT "CSV" "res/csv/TotalTechnologyModelPeriodActivity.csv" : r, t,
TotalTechnologyModelPeriodActivity[r, t];
table tout {r in REGION, rr in REGION, l in TIMESLICE, f in FUEL, y in YEAR} OUT "CSV" "res/csv/Trade.csv" : r, rr, l,
f, y, Trade[r, rr, l, f, y];
table tout {r in REGION, l in TIMESLICE, t in TECHNOLOGY, f in FUEL, y in YEAR} OUT "CSV"
"res/csv/UseByTechnology.csv" : r, l, t, f, y, UseByTechnology[r, l, t, f, y];
end;

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References

- [1] “Background paper for the Bonn 2011 Nexus Conference: THE WATER, ENERGY AND FOOD SECURITY NEXUS.”
- [2] World Economic Forum, “Report from the World Economic Forum on Water Security; The WTAER-FOOD-ENERGY-CLIMATE NEXUS Initiative,” Davos, 2011.
- [3] E. M. Biggs *et al.*, “Sustainable development and the water-energy-food nexus: A perspective on livelihoods,” *Environ Sci Policy*, vol. 54, pp. 389–397, Dec. 2015, doi: 10.1016/j.envsci.2015.08.002.
- [4] “The Water-Energy-Food Nexus A new approach in support of food security and sustainable agriculture.”
- [5] M. Al-Saidi and N. A. Elagib, “Towards understanding the integrative approach of the water, energy and food nexus,” Jan. 01, 2017, *Elsevier B.V.* doi: 10.1016/j.scitotenv.2016.09.046.
- [6] M. Kurian, “The water-energy-food nexus: Trade-offs, thresholds and transdisciplinary approaches to sustainable development,” *Environ Sci Policy*, vol. 68, pp. 97–106, Feb. 2017, doi: 10.1016/j.envsci.2016.11.006.
- [7] “World Water Development Report 2018 | UN-Water.” Accessed: May 22, 2024. [Online]. Available: <https://www.unwater.org/publications/world-water-development-report-2018>
- [8] M. Howells *et al.*, “Integrated analysis of climate change, land-use, energy and water strategies,” Jun. 2013. doi: 10.1038/nclimate1789.
- [9] M. Bazilian *et al.*, “Considering the energy, water and food nexus: Towards an integrated modelling approach,” *Energy Policy*, vol. 39, no. 12, pp. 7896–7906, Dec. 2011, doi: 10.1016/j.enpol.2011.09.039.
- [10] M. Howells *et al.*, “OSeMOSYS: The Open Source Energy Modeling System. An introduction to its ethos, structure and development.,” *Energy Policy*, vol. 39, no. 10, pp. 5850–5870, Oct. 2011, doi: 10.1016/j.enpol.2011.06.033.
- [11] M. Howells *et al.*, “OSeMOSYS: The Open Source Energy Modeling System. An introduction to its ethos, structure and development.,” *Energy Policy*, vol. 39, no. 10, pp. 5850–5870, Oct. 2011, doi: 10.1016/j.enpol.2011.06.033.
- [12] M. Welsch, M. Howells, M. Bazilian, J. F. DeCarolus, S. Hermann, and H. H. Rogner, “Modelling elements of Smart Grids - Enhancing the OSeMOSYS (Open Source Energy Modelling System) code,” *Energy*, vol. 46, no. 1, pp. 337–350, 2012, doi: 10.1016/j.energy.2012.08.017.
- [13] F. Gardumi *et al.*, “From the development of an open-source energy modelling tool to its application and the creation of communities of practice: The example of OSeMOSYS,” *Energy Strategy Reviews*, vol. 20, pp. 209–228, Apr. 2018, doi: 10.1016/j.esr.2018.03.005.
- [14] United Nations, “Report of the World Commission on Environment and Development: Our Common Future,” 1987.
- [15] J. Sachs and K. Pan, *The age of sustainable development*. New York: Columbia University Press , 2015.
- [16] J. A. Du Pisani, “Sustainable development – historical roots of the concept,” *Environ Sci (Ruse)*, vol. 3, no. 2, pp. 83–96, Jun. 2006, doi: 10.1080/15693430600688831.
- [17] W. M. Adams, “Green Development 3rd edition: Environment and sustainability in a developing world.”
- [18] RACHEL CARSON, *Silent Spring*, Crest Book. 1962.
- [19] United Nations, “Report of the United Nations conference on the Human Environment,” 1972.
- [20] “Report of the United Nations Conference on Environment and Development CONTENTS ’.”
- [21] “United Nations Millennium Declaration | OHCHR.” Accessed: May 22, 2024. [Online]. Available: <https://www.ohchr.org/en/instruments-mechanisms/instruments/united-nations-millennium-declaration>
- [22] S. U. Org, “TRANSFORMING OUR WORLD: THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT UNITED NATIONS UNITED NATIONS TRANSFORMING OUR WORLD: THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT.”
- [23] John Elkington, *cannibalswithforks; The tripple bottom line of 21st cetury business*, Capstone. 1997. Accessed: May 26, 2024. [Online]. Available: <http://www.elecbook.com/>
- [24] E. B. Barbier, “The Concept of Sustainable Economic Development,” *Environ Conserv*, vol. 14, no. 2, pp. 101–110, 1987, doi: 10.1017/S0376892900011449.
- [25] T. F. Slaper, “The Triple Bottom Line: What Is It and How Does It Work?”
- [26] B. Hopwood, M. Mellor, and G. O’Brien, “Sustainable development: Mapping different approaches,” *Sustainable Development*, vol. 13, no. 1, pp. 38–52, Feb. 2005, doi: 10.1002/sd.244.

- [27] R. B. Gibson, "Sustainability assessment: Basic components of a practical approach," *Impact Assessment and Project Appraisal*, vol. 24, no. 3, pp. 170–182, Sep. 2006, doi: 10.3152/147154606781765147.
- [28] J. Pope, D. Annandale, and A. Morrison-Saunders, "Conceptualising sustainability assessment," *Environ Impact Assess Rev*, vol. 24, no. 6, pp. 595–616, 2004, doi: 10.1016/j.eiar.2004.03.001.
- [29] B. Ness, E. Urbel-Piirsalu, S. Anderberg, and L. Olsson, "Categorising tools for sustainability assessment," Jan. 15, 2007. doi: 10.1016/j.ecolecon.2006.07.023.
- [30] M. S. Reed, E. D. G. Fraser, and A. J. Dougill, "An adaptive learning process for developing and applying sustainability indicators with local communities," *Ecological Economics*, vol. 59, no. 4, pp. 406–418, Oct. 2006, doi: 10.1016/j.ecolecon.2005.11.008.
- [31] J. B. Guinée *et al.*, "Life cycle assessment: Past, present, and future," *Environ Sci Technol*, vol. 45, no. 1, pp. 90–96, Jan. 2011, doi: 10.1021/es101316v.
- [32] Anthony E. Boradman, David H. Greenberg, Aidan R. Vining, and David L. Weimer, *Cost-Benefit Analysis Concepts and Practice*, 5th ed. CAMBRIDGE UNIVERSITY PRESS, 2018. doi: 10.1017/9781108235594.
- [33] F. Vanclay, "International principles for social impact assessment," *Impact Assessment and Project Appraisal*, vol. 21, no. 1, pp. 5–12, 2003, doi: 10.3152/147154603781766491.
- [34] R. K. Singh, H. R. Murty, S. K. Gupta, and A. K. Dikshit, "An overview of sustainability assessment methodologies," Mar. 2009. doi: 10.1016/j.ecolind.2008.05.011.
- [35] R. W. Kates, T. M. Parris, and A. A. Leiserowitz, "What Is Sustainable Development? Goals, Indicators, Values, and Practice by Robert W. Kates, Thomas M. Parris, and Anthony A. Leiserowitz (Article in April 2005 issue of Environment: Science and Policy for Sustainable Development)," 2005. [Online]. Available: <http://www.heldref.org/env.php>
- [36] W. Klöpffer, "Life-cycle based methods for sustainable product development," 2003, *Springer Verlag*. doi: 10.1007/BF02978462.
- [37] "Bonn2011 Conference: The Water, Energy and Food Security Nexus-Solutions for a Green Economy Policy Recommendations." [Online]. Available: <http://www.water-energy-food.org/en/conference.html>http://www.unep.org/pdf/water/WAT-Water_KB_17.08_PRINT_EDITION.2011.pdf
- [38] "Sustainable development goals for people and planet," 2013. [Online]. Available: www.cbd.int/sp/
- [39] "How Food Connects all the Sustainable Development Goals — Garn Press." Accessed: May 23, 2024. [Online]. Available: <https://www.garnpress.com/news/how-food-connects-all-the-sustainable-development-goals>
- [40] N. Weitz, M. Nilsson, and M. Davis, "37 A Nexus Approach to the post-2015 Agenda: Formulating Integrated Water, Energy, and Food SDGs," 2014.
- [41] "The SDGs wedding cake - Stockholm Resilience Centre." Accessed: May 23, 2024. [Online]. Available: <https://www.stockholmresilience.org/research/research-news/2016-06-14-the-sdgs-wedding-cake.html>
- [42] H. Leck, D. Conway, M. Bradshaw, and J. Rees, "Tracing the Water-Energy-Food Nexus: Description, Theory and Practice," *Geogr Compass*, vol. 9, no. 8, pp. 445–460, Aug. 2015, doi: 10.1111/gec3.12222.
- [43] "Background paper for the Bonn 2011 Nexus Conference: THE WATER, ENERGY AND FOOD SECURITY NEXUS."
- [44] K. Kuling, T. Barnes, A. Shivakumar, M. Brinkerink, and T. Niet, "Applying the open-source climate, land, energy, and water systems (CLEWs) model to Canada," Nov. 01, 2022, *Elsevier Ltd*. doi: 10.1016/j.esr.2022.100929.
- [45] B. Hamilton and M. Nada, "YFEW Workshop: Food, Energy, and Water Nexus in Sustainable Cities, NEW YORK INSTITUTE OF TECHNOLOGY In Collaboration with PEKING UNIVERSITY,," Beijing, 2015.
- [46] "Interlinkage of Climate, Land, Energy and Water Use (CLEW) | IAEA." Accessed: May 23, 2024. [Online]. Available: <https://www.iaea.org/topics/economics/energy-economic-and-environmental-analysis/climate-land-energy-water-strategies>
- [47] M. Bazilian *et al.*, "Considering the energy, water and food nexus: Towards an integrated modelling approach," *Energy Policy*, vol. 39, no. 12, pp. 7896–7906, Dec. 2011, doi: 10.1016/j.enpol.2011.09.039.
- [48] E. Ramos, V. Sridharan, and R. Engström, "Climate, Land, Energy and Water systems (CLEWs)," 2019.
- [49] "GCAM: Global Change Analysis Model | Global Change Intersectoral Modeling System." Accessed: May 23, 2024. [Online]. Available: <https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model>
- [50] A. Popp *et al.*, "Land-use futures in the shared socio-economic pathways," *Global Environmental Change*, vol. 42, pp. 331–345, Jan. 2017, doi: 10.1016/j.gloenvcha.2016.10.002.
- [51] I. Energy and E. Program, "MESSAGEix-GLOBIOM Release 2020 IIASA Energy, Climate, and Environment (ECE) Program," 2021.

- [52] Elke Stehfest, Detlef van Vuuren, Tom Kram, and Lex Bouwman, *Integrated Assessment of Global Environmental Change with Image 3.0 Model description and policy applications*. PBL Netherlands Environmental Assessment Agency, 2014.
- [53] D. Yates and D. Purkey, “International Water Resources Association WEAP21-A Demand-, Priority-, and Preference-Driven Water Planning Model Part 1: Model Characteristics,” 2005.
- [54] A. W. Harbaugh, “MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model-the Ground-Water Flow Process.” [Online]. Available: http://water.usgs.gov/software/ground_water.html/.
- [55] “THE MOLAND MODELLING FRAMEWORK FOR URBAN AND REGIONAL LAND-USE DYNAMICS,” 2007. [Online]. Available: <http://moland.jrc.it/>
- [56] B. Deal and V. G. Pallathucheril, “The Land-use Evolution and Impact Assessment Model: A Comprehensive Urban Planning Support System.” [Online]. Available: <https://www.researchgate.net/publication/261870551>
- [57] “LEAP: Low Emissions Analysis Platform.” Accessed: May 23, 2024. [Online]. Available: <https://www.sei.org/tools/leap-long-range-energy-alternatives-planning-system/>
- [58] “Introduction to OSeMOSYS — OSeMOSYS 0.0.1 documentation.” Accessed: Mar. 14, 2022. [Online]. Available: <https://osemosys.readthedocs.io/en/latest/manual/Introduction.html>
- [59] G. N. P. de Moura, L. F. L. Legey, and M. Howells, “A Brazilian perspective of power systems integration using OSeMOSYS SAMBA – South America Model Base – and the bargaining power of neighbouring countries: A cooperative games approach,” *Energy Policy*, vol. 115, no. March 2016, pp. 470–485, 2018, doi: 10.1016/j.enpol.2018.01.045.
- [60] F. Gardumi, “A multi-dimensional approach to the modelling of power plant flexibility,” DOCTORAL PROGRAMME IN ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY, POLITECNICO DI MILANO, 2016.
- [61] H. T. J. Henke, F. Gardumi, and M. Howells, “The open source electricity Model Base for Europe - An engagement framework for open and transparent European energy modelling,” *Energy*, vol. 239, p. 121973, 2022, doi: 10.1016/j.energy.2021.121973.
- [62] Mandy van den Ende, Arjan Wardekker, Heleen Mees, Dries Hegger, and Joost Vervoort, *Towards a climate-resilient future together A toolbox with participatory foresight methods, tools and examples from climate and food governance*. Utrecht University, 2021.
- [63] K. Amirnekoeei, M. M. Ardehali, and A. Sadri, “Integrated resource planning for Iran: Development of reference energy system, forecast, and long-term energy-environment plan,” *Energy*, vol. 46, no. 1, pp. 374–385, 2012, doi: 10.1016/j.energy.2012.08.013.
- [64] Y. Almulla, O. Broad, A. F. Shivakumar, E. Ramos, G. Avgerinopoulos, and M. Howells, “Model Management Infrastructure (MoManI) Training Manual,” *KTH-dESA*, pp. 1–61, 2017.
- [65] N. Bolson, P. Prieto, and T. Patzek, “Capacity factors for electrical power generation from renewable and nonrenewable sources,” 2022, doi: 10.1073/pnas.
- [66] KTH Royal Institute of Technology Division of Energy Systems Analysis, “Time representation in OSeMOSYS,” *OpTIMUS.community*.
- [67] M. H. Bechir, R. R. Alor-Rodriguez, and A. Lopez-Agüera, “Modelling a Decarbonization Agenda for Bembibre’s Industrial Park,” *Renewable Energy and Power Quality Journal*, vol. 21, pp. 471–476, Jul. 2023, doi: 10.24084/repqj21.362.
- [68] A. Dhakouani, E. Znouda, and C. Bouden, “Impacts of energy efficiency policies on the integration of renewable energy,” *Energy Policy*, vol. 133, no. June, p. 110922, 2019, doi: 10.1016/j.enpol.2019.110922.
- [69] J. Augutis, L. Martišauskas, and R. Krikštolaitis, “Energy mix optimization from an energy security perspective,” *Energy Convers Manag*, vol. 90, pp. 300–314, 2015, doi: 10.1016/j.enconman.2014.11.033.
- [70] M. H. Bechir and A. L. Agüera, “Environmental Sustainability Impact as Optimization Function of OSeMOSYS Energetic Modelling System,” *Int J Res Appl Sci Eng Technol*, vol. 11, no. 9, pp. 364–376, Sep. 2023, doi: 10.22214/ijraset.2023.55662.
- [71] “GLPK - GNU Project - Free Software Foundation (FSF).” Accessed: May 23, 2024. [Online]. Available: <https://www.gnu.org/software/glpk/>
- [72] G. Godínez-Zamora *et al.*, “Decarbonising the transport and energy sectors: Technical feasibility and socioeconomic impacts in Costa Rica,” *Energy Strategy Reviews*, vol. 32, 2020, doi: 10.1016/j.esr.2020.100573.
- [73] T. Niet *et al.*, “Hedging the risk of increased emissions in long term energy planning,” *Energy Strategy Reviews*, vol. 16, pp. 1–12, 2017, doi: 10.1016/j.esr.2017.02.001.
- [74] “Interfaces - OSeMOSYS.” Accessed: May 23, 2024. [Online]. Available: <http://www.osemosys.org/interfaces.html>

- [75] K. Poncelet, E. Delarue, D. Six, J. Duerinck, and W. D'haeseleer, "Impact of the level of temporal and operational detail in energy-system planning models," *Appl Energy*, vol. 162, pp. 631–643, Jan. 2016, doi: 10.1016/j.apenergy.2015.10.100.
- [76] European Academies Science Advisory Council., *Transforming Europe's electricity supply : an infrastructure strategy for a reliable, renewable and secure power system*. EASAC, 2009.
- [77] I. Renewable Energy Agency, *Renewable Power Generation Costs in 2017 ACKNOWLEDGEMENTS*. 2018. [Online]. Available: www.irena.org
- [78] Irena, *Renewable Power Generation Costs 2020*. 2021. [Online]. Available: www.irena.org
- [79] G. R. Timilsina, "Demystifying the Costs of Electricity Generation Technologies," 2020. [Online]. Available: <http://www.worldbank.org/prwp>.
- [80] "Carbon Dioxide Emissions From Electricity - World Nuclear Association." Accessed: Jan. 23, 2023. [Online]. Available: <https://www.world-nuclear.org/information-library/energy-and-the-environment/carbon-dioxide-emissions-from-electricity.aspx>
- [81] N. D. Strachan and A. E. Farrell, "Emissions from distributed generation - CEIC Working Paper," pp. 1–14, 2004.
- [82] R. Wiser, A. Mills, J. Seel, T. Levin, and A. Botterud, "Impacts of Variable Renewable Energy on Bulk Power System Assets, Pricing, and Costs," 2017.
- [83] INTERNATIONAL ATOMIC ENERGY AGENCY, "CLIMATE CHANGE AND NUCLEAR POWER 2018," 2018.
- [84] E. Information Administration, "Capital Cost Estimates for Utility Scale Electricity Generating Plants," 2016. [Online]. Available: www.eia.gov
- [85] "Replacement Energy Cost Estimates for Nuclear Power Plants: 2020-2030 Final Report Office of Nuclear Material Safety and Safeguards." [Online]. Available: www.nrc.gov/reading-rm.html.
- [86] I. Renewable Energy Agency, "RENEWABLE ENERGY TECHNOLOGIES: COST ANALYSIS SERIES," 2012. [Online]. Available: www.irena.org/Publications
- [87] G. Munda, "MULTIPLE CRITERIA DECISION ANALYSIS AND SUSTAINABLE DEVELOPMENT," in *Multiple Criteria Decision Analysis and Sustainable Development*, vol. 233, Springer New York, NY. , 2016, ch. 23, pp. 953–986. doi: https://doi.org/10.1007/978-1-4939-3094-4_27.
- [88] European Commission. Joint Research Centre. and Organisation for Economic Co-operation and Development., *Handbook on constructing composite indicators : methodology and user guide*. OECD, 2008.
- [89] S. Bell and S. Morse, *Sustainability Indicators : Measuring the Immeasurable?*, 2nd ed. Gateshead, UK: earthscan Publishing for a sustainable future, 2008.
- [90] Donella Meadows, *Indicators and Information Systems for Sustainable Development by Donella Meadows A Report to the Balaton Group*. 3 Linded Road, Hartland: Sustainability Institute , 1998.
- [91] M. G. Patterson, "What is energy efficiency? Concepts, indicators and methodological issues," *Energy Policy*, vol. 24, no. 5, pp. 377–390, 1996.
- [92] Calvo Buendia Eduardo *et al.*, "2019 REFINEMENT TO THE 2006 IPCC GUIDELINES FOR NATIONAL GREENHOUSE GAS INVENTORIES," 2019.
- [93] A. Y. Hoekstra and T. O. Wiedmann, "Humanity's unsustainable environmental footprint." [Online]. Available: <https://www.science.org>
- [94] "Air Quality Index (AQI) | AirNow.gov." Accessed: May 23, 2024. [Online]. Available: <https://www.airnow.gov/aqi/>
- [95] J. Gowdy, R. B. Howarth, and C. Tisdell, "DISCOUNTING, ETHICS, AND OPTIONS FOR MAINTAINING BIODIVERSITY AND ECOSYSTEM INTEGRITY i," 2010. [Online]. Available: <http://www.rpi.edu/dept/economics/E->
- [96] D. C. (David C. Wilson, United Nations Environment Programme, and International Solid Waste Association, *Global waste management outlook*.
- [97] A. Cherp and J. Jewell, "The concept of energy security: Beyond the four as," *Energy Policy*, vol. 75, pp. 415–421, Dec. 2014, doi: 10.1016/j.enpol.2014.09.005.
- [98] K. P. Bhandari, J. M. Collier, R. J. Ellingson, and D. S. Apul, "Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis," 2015, *Elsevier Ltd*. doi: 10.1016/j.rser.2015.02.057.
- [99] H. Lund, A. N. Andersen, P. A. Østergaard, B. V. Mathiesen, and D. Connolly, "From electricity smart grids to smart energy systems - A market operation based approach and understanding," 2012, *Elsevier Ltd*. doi: 10.1016/j.energy.2012.04.003.
- [100] United Nations. Department of Economic and Social Affairs., *Indicators of sustainable development : guidelines and methodologies*. United Nations, 2007.
- [101] United Nations, "The Sustainable Development Goals Report 2018," 2018.

- [102] M. S. Reed, “Stakeholder participation for environmental management: A literature review,” Oct. 2008. doi: 10.1016/j.biocon.2008.07.014.
- [103] *OECD Skills Outlook 2013*. in OECD Skills Outlook. OECD, 2013. doi: 10.1787/9789264204256-en.
- [104] 2020 World Economic Forum., “The Future of Jobs Report,” 2020.
- [105] “Sixth session of the Intergovernmental Committee for the Safeguarding of the Intangible Cultural Heritage.” [Online]. Available: <http://www.unesco.org/culture/ich/en/6COM/>
- [106] I. Renewable Energy Agency, *Renewable power generation costs in 2019*. 2020. [Online]. Available: www.irena.org
- [107] REN21 Rewable Now, “RENEWABLES 2019 GLOBAL STATUS REPORT: GSR 2019”.
- [108] I. Renewable Energy Agency, “Renewable Energy and Jobs: Annual Review 2018.”
- [109] I. Energy Agency, “Energy Technology Perspectives 2015 Mobilising Innovation to Accelerate Climate Action.” [Online]. Available: <http://www.iea.org/t&c/>
- [110] A. Reichel and L. Mortensen, *Environmental indicator report 2014 Environmental impacts of production-consumption systems in Europe*. European Environment Agency, 2014. doi: 10.2800/22394.
- [111] “The Changing of the Guard: Shifts in Commodity Demand Commodity Markets Outlook Oct Apr,” 2018. [Online]. Available: www.worldbank.org/commodities
- [112] “ACER/CEER Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2020 Snapshot of the 10 th Market Monitoring Report,” 2021.
- [113] G. Parolin, T. C. McAloone, and D. C. A. Pigosso, “How can technology assessment tools support sustainable innovation? A systematic literature review and synthesis,” *Technovation*, vol. 129, Jan. 2024, doi: 10.1016/j.technovation.2023.102881.
- [114] J. R. Meldrum, J. E. Macknick, G. A. Heath, and S. L. Nettles-Anderson, “Life cycle water use for electricity generation: Implications of the distribution of collected estimates,” in *American Society of Mechanical Engineers, Power Division (Publication) POWER*, American Society of Mechanical Engineers, 2013. doi: 10.1115/POWER2013-98229.
- [115] “Life Cycle Assessment (LCA) explained - PRé Sustainability.” Accessed: May 23, 2024. [Online]. Available: <https://pre-sustainability.com/articles/life-cycle-assessment-lca-basics/>
- [116] “Cradle to Cradle - William McDonough.” Accessed: May 23, 2024. [Online]. Available: <https://mcdonough.com/cradle-to-cradle/>
- [117] B. Corona, L. Shen, D. Reike, J. Rosales Carreón, and E. Worrell, “Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics,” Dec. 01, 2019, *Elsevier B.V.* doi: 10.1016/j.resconrec.2019.104498.
- [118] “Pathways to Sustainable Development and Poverty Eradication A Synthesis for Policy Makers Towards a.” [Online]. Available: www.unep.org/greenconomy
- [119] INTERNATIONALATOMIC ENERGYAGENCY, *Energy Indicators for Sustainable Development guidelines and Methodologies*. Vienna, 2005. [Online]. Available: <http://www.iaea.org/Publications/index.html>
- [120] M. J. Barasa Kabeyi and O. A. Olanrewaju, “Indicators of Sustainable Energy and Electricity,” IEOM Society International, Mar. 2024. doi: 10.46254/in03.20230174.
- [121] Varun, R. Prakash, and I. K. Bhat, “Energy, economics and environmental impacts of renewable energy systems,” Dec. 2009. doi: 10.1016/j.rser.2009.05.007.
- [122] A. Paiano, G. Lagioia, and C. Ingrao, “A combined assessment of the energy, economic and environmental performance of a photovoltaic system in the Italian context,” *Science of the Total Environment*, vol. 866, Mar. 2023, doi: 10.1016/j.scitotenv.2022.161329.
- [123] Intergovernmental Panel on Climate Change. Working Group III and O. Edenhofer, *Climate change 2014 : mitigation of climate change : Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.
- [124] W. Bank, I. Energy Agency, I. Renewable Energy Agency, U. Nations Statistics Division, and W. Health Organization, “A joint report of the custodian agencies THE ENERGY PROGRESS REPORT,” 2020. [Online]. Available: www.worldbank.org
- [125] Iso, “ISO (International Organization for Standardization). (2019),” 2018. [Online]. Available: www.isosystem.ir
- [126] “Handbook on Integrated Assessment of Trade-related Measures The Agriculture Sector Handbook on Integrated Assessment of Trade-related Measures The Agriculture Sector Handbook on Integrated Assessment of Trade-related Measures The Agriculture Sector,” 4298. [Online]. Available: www.unep.orgWeb:www.unep.ch/etu
- [127] UNDP, *Human Development Indices and Indicators: 2018 Statistical Update*. By the United Nations Development Programme 1 UN Plaza, New York, NY 10017 USA, 2018.
- [128] A. Dhakouani, F. Gardumi, E. Znouda, C. Bouden, and M. Howells, “Long-term optimisation model of the Tunisian power system,” *Energy*, vol. 141, pp. 550–562, 2017, doi: 10.1016/j.energy.2017.09.093.

- [129] M. H. Bechir, A. Mannelli, and A. L. Agüera, "Life Cycle Analysis and Sociocultural Impact for a Sustainable Nexus Design," in *Proceedings of the 1st International Conference on Water Energy Food and Sustainability (ICoWEFS 2021)*, Springer International Publishing, 2021, pp. 670–679. doi: 10.1007/978-3-030-75315-3_71.
- [130] C. Cabo Landeira, "PV systems design optimization as function of the climatic conditions," University of Santiago de Compostela, Santiago de Compostela, 2018. [Online]. Available: <http://hdl.handle.net/10347/17257>
- [131] M. Raugei, P. Fullana-i-Palmer, and V. Fthenakis, "The energy return on energy investment (EROI) of photovoltaics: Methodology and comparisons with fossil fuel life cycles," *Energy Policy*, vol. 45, pp. 576–582, Jun. 2012, doi: 10.1016/j.enpol.2012.03.008.
- [132] P. Razdan and P. Garrett, *Life Cycle Assessment of Electricity Production from an onshore V112-3.45 MW Wind Plant*. Vestas Wind Systems A/S, 2017.
- [133] "Life Cycle Assessment Harmonization | Energy Analysis | NREL." Accessed: May 23, 2024. [Online]. Available: <https://www.nrel.gov/analysis/life-cycle-assessment.html>
- [134] Richard A. Brealey, Stewart C. Myers, and Franklin Allen, *Principles of Corporate Finance*, 5th ed. McGraw-Hill Irwin, 2011.
- [135] D. G. Dhavale and J. Sarkis, "Stochastic internal rate of return on investments in sustainable assets generating carbon credits," *Comput Oper Res*, vol. 89, pp. 324–336, Jan. 2018, doi: 10.1016/j.cor.2017.02.014.
- [136] R. Turconi, A. Boldrin, and T. Astrup, "Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations," 2013, *Elsevier Ltd*. doi: 10.1016/j.rser.2013.08.013.
- [137] "Measuring Progress Towards achieving the environmental dimension of the SDGs." [Online]. Available: www.unenvironment.org
- [138] "Creating a Sustainable Food Future | World Resources Report." Accessed: May 23, 2024. [Online]. Available: https://research.wri.org/wrr-food?_gl=1*cgaoav*_up*MQ..&gclid=Cj0KCQjw0ruiBhDuARIsANSZ3wqBlrEhsgix8nrpztkv5QuuhvEvgHU3seLxH6W70VrNG0lk79an2fcaAkt6EALw_wcB
- [139] D. Ferreira-Martínez, M. H. Bechir, and A. López-Agüera, "Effect of the sustainability indicators within OSeMOSYS optimization transition scenarios," *Energy Strategy Reviews*, vol. 54, Jul. 2024, doi: 10.1016/j.esr.2024.101448.
- [140] D. Weißbach, G. Ruprecht, A. Huke, K. Czerski, S. Gottlieb, and A. Hussein, "Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants," *Energy*, vol. 52, pp. 210–221, Apr. 2013, doi: 10.1016/j.energy.2013.01.029.
- [141] D. J. Murphy, M. Raugei, M. Carbajales-Dale, and B. R. Estrada, "Energy Return on Investment of Major Energy Carriers: Review and Harmonization," Jun. 01, 2022, *MDPI*. doi: 10.3390/su14127098.
- [142] M. C. Guilford, C. A. S. Hall, P. O'Connor, and C. J. Cleveland, "A new long term assessment of energy return on investment (EROI) for U.S. oil and gas discovery and production," *Sustainability*, vol. 3, no. 10, pp. 1866–1887, 2011, doi: 10.3390/su3101866.
- [143] R. S. Atlason and R. Unnthorsson, "Energy Return on Investment of Hydroelectric Power Generation Calculated Using a Standardised Methodology." [Online]. Available: <https://www.researchgate.net/publication/>
- [144] N. Kittner, S. H. Gheewala, and D. M. Kammen, "Energy return on investment (EROI) of mini-hydro and solar PV systems designed for a mini-grid," *Renew Energy*, vol. 99, pp. 410–419, Dec. 2016, doi: 10.1016/j.renene.2016.07.023.
- [145] R. Frischknecht *et al.*, *Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems 2020*, no. June. INTERNATIONAL ENERGY AGENCY PHOTOVOLTAIC POWER SYSTEMS PROGRAMME: Report IEA-PVPS T12-04:2015, 2015.
- [146] V. Fthenakis, H. C. Kim, R. Frischknecht, M. Raugei, P. Sinha, and M. Stucki, "Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems," *International Energy Agency (IEA)*, p. 58, 2011, [Online]. Available: <http://iea-pvps.org/index.php?id=315>
- [147] M. H. Bechir, D. F. Martínez, and A. L. Agüera, "Energetic Sustainable Transition Process Optimization in Terms of LCA Using CLEWs Tools," in *Proceedings of the 2nd International Conference on Water Energy Food and Sustainability (ICoWEFS 2022)*, Springer International Publishing, 2023, pp. 147–157. doi: 10.1007/978-3-031-26849-6_16.
- [148] M. I. Blanco, "The economics of wind energy," Aug. 2009. doi: 10.1016/j.rser.2008.09.004.
- [149] R. Carvalho, E. Hittinger, and E. Williams, "Payback of natural gas turbines: A retrospective analysis with implications for decarbonizing grids," *Util Policy*, vol. 73, Dec. 2021, doi: 10.1016/j.jup.2021.101307.

- [150] D. Budiana and R. Dalimi, "The economics comparison of power plants fuelled by wellhead gas and liquefied natural gas in Aceh Province," *IOP Conf Ser Mater Sci Eng*, vol. 1041, no. 1, p. 012019, Jan. 2021, doi: 10.1088/1757-899x/1041/1/012019.
- [151] S. C. Bhattacharyya, *Energy Economics: Concepts, Issues, Markets and Governance*. Springer, 2011. doi: DOI 10.1007/978-0-85729-268-1.
- [152] OECD, *Projected Costs of Generating Electricity 2005 Update*. OECD PUBLICATIONS, 2 rue André-Pascal, 75775 Paris Cedex 16, 2005.
- [153] T. M. I. Riayatsyah, T. A. Geumpana, I. M. R. Fattah, and T. M. I. Mahlia, "Techno-Economic Analysis of Hybrid Diesel Generators and Renewable Energy for a Remote Island in the Indian Ocean Using HOMER Pro," *Sustainability (Switzerland)*, vol. 14, no. 16, Aug. 2022, doi: 10.3390/su14169846.
- [154] A. Jindal and G. Shrimali, "Cost-benefit analysis of coal plant repurposing in developing countries: A case study of India," *Energy Policy*, vol. 164, May 2022, doi: 10.1016/j.enpol.2022.112911.
- [155] Asian Development Bank (ADB), "Jamshoro Power Generation Project (RRP PAK 47094)," 2023.
- [156] Ottmar Edenhofer, R. Pichs Madruga, Youba. Sokona, United Nations Environment Programme., and World Meteorological Organization., *Special report on renewable energy sources and climate change mitigation : summary for policymakers : a report of working group III of the IPCC and technical summary*. The Intergovernmental Panel on climate change, 2012.
- [157] "Hydro return on investment - Renewables First." Accessed: May 24, 2024. [Online]. Available: <https://renewablesfirst.co.uk/renewable-energy-technologies/hydropower/hydropower-learning-centreold/what-would-the-return-on-investment-be/>
- [158] D. L. Talavera, G. Nofuentes, and J. Aguilera, "The internal rate of return of photovoltaic grid-connected systems: A comprehensive sensitivity analysis," *Renew Energy*, vol. 35, no. 1, pp. 101–111, Jan. 2010, doi: 10.1016/j.renene.2009.07.006.
- [159] J. Li, J. Shao, X. Yao, and J. Li, "Life cycle analysis of the economic costs and environmental benefits of photovoltaic module waste recycling in China," *Resour Conserv Recycl*, vol. 196, Sep. 2023, doi: 10.1016/j.resconrec.2023.107027.
- [160] R. Wiser and D. Millstein, "Evaluating the economic return to public wind energy research and development in the United States," *Appl Energy*, vol. 261, Mar. 2020, doi: 10.1016/j.apenergy.2019.114449.
- [161] "Energy Return on Investment - World Nuclear Association." Accessed: May 24, 2024. [Online]. Available: <https://world-nuclear.org/information-library/energy-and-the-environment/energy-return-on-investment>
- [162] "European Green Deal." Accessed: Jan. 23, 2023. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_7719
- [163] World Bank Group, *State and trends of carbon pricing 2020*. 2020 International Bank for Reconstruction and Development / The World Bank, 2020. doi: DOI: 10.1596/978-1-4648-1586-7.
- [164] "Nuclear Power in the World Today - World Nuclear Association." Accessed: May 24, 2024. [Online]. Available: <https://world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today>
- [165] "Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs." Accessed: May 24, 2024. [Online]. Available: <https://sdgs.un.org/2030agenda>
- [166] P. Sedgwick, "Pearson's correlation coefficient," Jul. 07, 2012. doi: 10.1136/bmj.e4483.
- [167] JOSEPH F. HAIR JR, WILLIAM C. BLACK, BARRY J BABIN, and ROLPH E. ANDERSON, *Multivariate Data Analysis*, 7th ed. Pearson, 2014.
- [168] "What is a Correlation Matrix? - Displayr." Accessed: May 24, 2024. [Online]. Available: <https://www.displayr.com/what-is-a-correlation-matrix/>
- [169] "The Correlation Coefficient: What It Is and What It Tells Investors." Accessed: May 24, 2024. [Online]. Available: <https://www.investopedia.com/terms/c/correlationcoefficient.asp>
- [170] M. M. Mukaka, "Statistics Corner: A guide to appropriate use of Correlation coefficient in medical research," 2012. [Online]. Available: www.mmj.medcol.mw
- [171] S. Kotsiantis, D. Kanellopoulos, and P. E. Pintelas, "Data Preprocessing for Supervised Learning," 2014. [Online]. Available: <https://www.researchgate.net/publication/228084519>
- [172] M. H. Bechir, D. F.- Martinez, and A. L.- Aguera, "Sustainability Indicators Correlation Matrix," *Int J Res Appl Sci Eng Technol*, vol. 12, no. 7, pp. 616–627, Jul. 2024, doi: 10.22214/ijraset.2024.63572.
- [173] A. Verbruggen and B. Wealer, "Nuclear Power and Sustainability," in *The Palgrave Handbook of Global Sustainability*, Springer International Publishing, 2023, pp. 87–111. doi: 10.1007/978-3-031-01949-4_15.
- [174] S. Carattini, M. Carvalho, and S. Fankhauser, "Overcoming public resistance to carbon taxes," Sep. 01, 2018, *Wiley-Blackwell*. doi: 10.1002/wcc.531.

- [175] S. Jacobsson and A. Bergek, "Transforming the energy sector: The evolution of technological systems in renewable energy technology," *Industrial and Corporate Change*, vol. 13, no. 5, pp. 815–849, 2004, doi: 10.1093/icc/dth032.
- [176] D. Parnell, "Ethics-The Importance of Stakeholder Engagements Course No: LE2-021 Credit: 2 PDH." [Online]. Available: www.cedengineering.com
- [177] M. H. Bechir and A. L.- Aguera, "Modelling of the Optimal Impact of Photovoltaic Technology on a Sustainable Energetic Mix as Function of the Climate Conditions," *Int J Res Appl Sci Eng Technol*, vol. 11, no. 10, pp. 1725–1735, Oct. 2023, doi: 10.22214/ijraset.2023.56000.
- [178] M. Alwaeli and V. Mannheim, "Investigation into the Current State of Nuclear Energy and Nuclear Waste Management—A State-of-the-Art Review," *Energies (Basel)*, vol. 15, no. 12, Jun. 2022, doi: 10.3390/en15124275.
- [179] OXFORD ENERGY FORUM, "NUCLEAR ENERGY IN THE GLOBAL ENERGY LANDSCAPE: ADVANCING SUSTAINABILITY AND ENSURING ENERGY SECURITY?," 2024.
- [180] "Environmental Aspects of Uranium Mining - World Nuclear Association." Accessed: May 24, 2024. [Online]. Available: <https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/environmental-aspects-of-uranium-mining>
- [181] S. Passerini and M. Kazimi, "Sustainability features of nuclear fuel cycle options," *Sustainability*, vol. 4, no. 10, pp. 2377–2398, 2012, doi: 10.3390/su4102377.
- [182] International Atomic Energy Agency (IAEA), "IAEA ANNUAL REPORT 2021," 2021.
- [183] "Used Nuclear Fuel." Accessed: May 24, 2024. [Online]. Available: <https://www.nei.org/advocacy/make-regulations-smarter/used-nuclear-fuel>
- [184] "Radioactive Waste | NRC.gov." Accessed: May 24, 2024. [Online]. Available: <https://www.nrc.gov/waste.html>
- [185] "Radioactive Waste Management - World Nuclear Association." Accessed: May 24, 2024. [Online]. Available: <https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-waste/radioactive-waste-management#storage-and-disposal>
- [186] IPCC, *Global Warming of 1.5°C*. Cambridge University Press, 2022. doi: 10.1017/9781009157940.
- [187] P. Abrecht *et al.*, "Public Acceptance of Nuclear Power-Some Ethical Issues," 1977.
- [188] "Nuclear Energy Agency (NEA) - Sustainable development and nuclear energy." Accessed: May 24, 2024. [Online]. Available: https://www.oecd-nea.org/jcms/pl_33568/sustainable-development-and-nuclear-energy
- [189] "Economics of Nuclear Power - World Nuclear Association." Accessed: May 24, 2024. [Online]. Available: <https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power>
- [190] International Atomic Energy Agency. and International Atomic Energy Agency., *Stakeholder involvement throughout the life cycle of nuclear facilities*. IAEA, 2011.
- [191] "Nuclear Energy and Sustainable Development - World Nuclear Association." Accessed: May 24, 2024. [Online]. Available: <https://world-nuclear.org/information-library/energy-and-the-environment/nuclear-energy-and-sustainable-development>
- [192] G. Finnveden *et al.*, "Recent developments in Life Cycle Assessment," 2009, *Academic Press*. doi: 10.1016/j.jenvman.2009.06.018.
- [193] International Atomic Energy Agency, *Communication and stakeholder involvement in environmental remediation projects — Vienna : International Atomic Energy Agency, 2014*. IAEA Publishing , 2014.
- [194] U.S. Nuclear Regulatory Commission, "NUREG/BR-0216, Revision 2, 'Radioactive Waste: Production, Storage, Disposal' .," 2002.
- [195] W. Nordhaus, "Climate change: The ultimate challenge for economics," 2019, *American Economic Association*. doi: 10.1257/aer.109.6.1991.
- [196] Nicholas Stern, *The Economics of Climate Change: The Stern Review*. Cambridge University Press, 2006.
- [197] KPMG, *KPMG Green Tax Index: An exploration of green tax incentives and penalties*. 2017.
- [198] F. A. Ackerman Elizabeth Stanton, W. Cline, S. DeCanio, R. Howarth, R. Litterman, and R. Warren, "Climate Economics: The State of the Art," 2011. [Online]. Available: www.sei-us.organdwww.sei-international.org
- [199] G. Karena, "Effective Carbon Rates 2018 PRiCing CaRbon Emissions ThRough TaxEs and Emissions TRading SUMMARY," 2018.
- [200] L. H. Goulder and A. R. Schein, "Carbon taxes versus cap and trade: A critical review," *Clim Chang Econ (Singap)*, vol. 4, no. 3, Aug. 2013, doi: 10.1142/S2010007813500103.
- [201] United Nations FCCC, "Conference of the Parties Twenty-first session Paris, 30 November to 11 December 2015: ADOPTION OF THE PARIS AGREEMENT Proposal by the President," 2015.
- [202] "Economic Aspects of Environmental Compliance Assurance Proceedings from the OECD Global Forum on Sustainable Development 2-3," 2004.

- [203] “EU Emissions Trading System (EU ETS) - European Commission.” Accessed: May 25, 2024. [Online]. Available: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en
- [204] “Emissions cap and allowances - European Commission.” Accessed: May 25, 2024. [Online]. Available: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/emissions-cap-and-allowances_en
- [205] J. W. Chang, K. Spees, and T. Lee, “CO 2 Allowance Allocation Options Considerations for State Policymakers when Developing Mass-Based Compliance Strategies Under the Clean Power Plan PREPARED FOR PREPARED BY,” 2016.
- [206] J. E. Aldy and R. N. Stavins, “The Promise and Problems of Pricing Carbon: Theory and Experience,” *Journal of Environment and Development*, vol. 21, no. 2, pp. 152–180, Jun. 2012, doi: 10.1177/1070496512442508.
- [207] D. Timmons, J. M. Harris, and B. Roach, “The Economics of Renewable Energy A GDAE Teaching Module on Social and Environmental Issues in Economics,” 2014. [Online]. Available: <http://ase.tufts.edu/gdae>
- [208] Easwaran Narassimhan, Kelly S Gallagher, Stefan Koester, and Julio Rivera Alejo, “Carbon Pricing in Practice: A Review of the Evidence. Medford, MA. Climate Policy Lab.,” 2017.
- [209] “2022 Carbon Tax Rates in Europe | European Countries with a Carbon Tax.” Accessed: Jan. 23, 2023. [Online]. Available: <https://taxfoundation.org/carbon-taxes-in-europe-2022/>
- [210] L. H. Goulder and M. A. C. Hafstead, “Tax Reform and Environmental Policy Options for Recycling Revenue from a Tax on Carbon Dioxide Considering a Carbon Tax: A Publication Series from RFF’s Center for Climate and Electricity Policy Tax Reform and Environmental Policy: Options for Recycling Revenue from a Tax on Carbon Dioxide,” 2013. [Online]. Available: www.rff.org
- [211] R. Dellink, S. Jamet, J. Chateau, and R. Duval, “Towards global carbon pricing Direct and indirect linking of carbon markets,” 2014, doi: 10.1787/19952856.
- [212] N. Atkinson, “Profiting from Pollution.” [Online]. Available: <https://perma.cc/P9NM-8BJT>.
- [213] “The challenging politics of climate change | Brookings.” Accessed: May 25, 2024. [Online]. Available: <https://www.brookings.edu/articles/the-challenging-politics-of-climate-change/>
- [214] B. Shang, “The Poverty and Distributional Impacts of Carbon Pricing: Channels and Policy Implications The Poverty and Distributional Impacts of Carbon Pricing: Channels and Policy Implications 1,” 2021.
- [215] T. Carleton and M. Greenstone, “Updating the United States Government’s Social Cost of Carbon,” 2021.
- [216] B. Shang, “The Poverty and Distributional Impacts of Carbon Pricing: Channels and Policy Implications The Poverty and Distributional Impacts of Carbon Pricing: Channels and Policy Implications 1,” 2021.
- [217] P. Martins Barata *et al.*, *NAVIGATING CARBON PRICING The G20 Experience and Global South Prospects*. bserver Research Foundation and Environmental Defense Fund, 2024.
- [218] Lawrence H. Goulder, “Carbon Taxes versus cap and trade: A critical review,” *Climate Change and Economics*, vol. 4, p. 28, 2013, doi: DOI:10.1141/S2010007813500103.
- [219] “Executive Briefing KEY MESSAGES,” 2016. [Online]. Available: www.carbonpricingleadership.org
- [220] B. R. Copeland and M. S. Taylor, “Trade, Growth, and the Environment 1,” *J Econ Lit*, vol. XLII, pp. 7–71, 2004.
- [221] “Climate change: what the EU is doing - Consilium.” Accessed: May 25, 2024. [Online]. Available: <https://www.consilium.europa.eu/en/policies/climate-change/>
- [222] I. Renewable Energy Agency, “A Renewable Energy Roadmap Report,” 2014. [Online]. Available: www.irena.org/remap
- [223] International Renewable Energy Agency (IRENA), *Future of Solar Photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper)*. International Renewable Energy Agency, Abu Dhabi., 2019.
- [224] M. Z. Jacobson and M. A. Delucchi, “Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials,” *Energy Policy*, vol. 39, no. 3, pp. 1154–1169, Mar. 2011, doi: 10.1016/j.enpol.2010.11.040.
- [225] T. Huld, R. Müller, and A. Gambardella, “A new solar radiation database for estimating PV performance in Europe and Africa,” *Solar Energy*, vol. 86, no. 6, pp. 1803–1815, Jun. 2012, doi: 10.1016/j.solener.2012.03.006.
- [226] A. Jäger-Waldau, “Snapshot of photovoltaics—February 2019,” *Energies (Basel)*, vol. 12, no. 5, Feb. 2019, doi: 10.3390/en12050769.
- [227] A. Blakers, B. Lu, and M. Stocks, “100% renewable electricity in Australia,” *Energy*, vol. 133, pp. 471–482, 2017, doi: 10.1016/j.energy.2017.05.168.
- [228] “Peak Sun Hours for Solar Panels by Region | 8M Solar.” Accessed: May 25, 2024. [Online]. Available: <https://8msolar.com/what-is-a-peak-sun-hour-psh/>

- [229] M. Kottek, J. Grieser, C. Beck, B. Rudolf, and F. Rubel, "World map of the Köppen-Geiger climate classification updated," *Meteorologische Zeitschrift*, vol. 15, no. 3, pp. 259–263, Jun. 2006, doi: 10.1127/0941-2948/2006/0130.
- [230] C. Cabo, A. Braña López, C. C. Landeira, Á. López-Agüera, and R. P. Leiro, "Optimal PV Technology Selection Depending On Climatic Conditions," *SJ Impact Factor:6*, vol. 887, 2017, [Online]. Available: www.ijraset.com2962
- [231] S. Sinha and S. S. Chandel, "Review of recent trends in optimization techniques for solar photovoltaic-wind based hybrid energy systems," Jun. 04, 2015, *Elsevier Ltd.* doi: 10.1016/j.rser.2015.05.040.

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PUBLICATION IN SCIENTIFIC JOURNALS

M. Darío Ferreira, Mahamat Habib Bechir, A. López Agüera. Effect of the sustainability indicators within OSeMOSYS optimization transition scenarios. *Energy Strategy Reviews* (2024). *Energy Strategy Reviews* Volume 54, July 2024, 101448 DOI: <https://doi.org/10.1016/j.esr.2024.101448> (See Chapter 4).

Mahamat Habib Bechir, M. Darío Ferreira, A. Lopez-Agüera. Sustainability Indicators Correlation Matrix. *International Journal for Research in Applied Science & Engineering Technology*, vol 12. ISSN: 2321-9653; 2024. <https://doi.org/10.22214/ijraset.2024.63572> (See Chapter 5).

Mahamat Habib Bechir and A. Lopez-Agüera. Environmental Sustainability Impact as Optimization Function of OSeMOSYS Energetic Modelling System. *International Journal for Research in Applied Science & Engineering Technology*, vol 11. ISSN: 2321-9653; 2023. DOI:10.22214/ijraset.2023.55662 (See Chapter 5 and Chapter 6).

Mahamat Habib Bechir and A. Lopez-Agüera, “Modelling of the Optimal Impact of Photovoltaic Technology on a Sustainable Energetic Mix as Function of the Climate Conditions. *International Journal for Research in Applied Science & Engineering Technology*, vol 11. ISSN: 2321-9653; 2023. DOI:10.22214/ijraset.2023.56000 (See Chapter 6).

PROCEEDINGS IN THE INTERNATIONAL CONFERENCES

Mahamat Habib Bechir, M. Darío Ferreira, A. López Agüera. Energetic sustainable transition process optimization in terms of LCA using CLEW tools. In book: *Proceedings of the 2nd International Conference on Water Energy Food and Sustainability* (2022), Pp.147-157. DOI:10.1007/978-3-031-26849-6_16 (See Chapter 6).

Effective energy planning is pivotal for guiding the shift towards sustainable energy. It requires analyzing and optimizing strategies considering energy demand, resource availability, technology, and socioeconomic factors. Advanced energy modeling tools are indispensable, providing insights into various scenarios to support resilient energy system development. OSeMOSYS (Open Source Energy Modelling System) is a widely used tool for evaluating energy dynamics and aiding transitions to sustainable energy systems. This study enhances OSeMOSYS by integrating key sustainability indicators—energetic, economic, and environmental—into its optimization function. These indicators are converted into economic terms and incorporated as additional cost factors, balancing sustainability and cost considerations.