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Environmental Sustainability Impact as Optimization Function of OSeMOSYS Energetic Modelling System

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Abstract: The energy transition is a convoluted process in which decision-makers are facing several challenges, including transitioning to sustainability. In building a sustainable energy transition, the identification of adequate strategies is compulsory. Moreover, this can be achieved through an appropriate energetic mix design to the user's needs at the local, regional, or global level. Suitable energy design aims to identify, among different scenarios, the optimal time frame strategy that maximizes both socio-economic benefits and sustainability. These scenarios are assessed before possible implementation via different energetic modeling tools that are widely available nowadays, designed for economic optimization. The Open-Source Energy Modeling System (OSeMOSYS) is also intended for long-term economic optimization. OSeMOSYS flexibility enables the development of methodologies that adhere to the user's optimization constraints. Hence, this paper bounces an optimization methodology in line with sustainability, where the Impact Mitigation Potential in terms of Climate Change (IMPcc), the environmental sustainability indicator, is evaluated through the selection of energetic transition scenarios. To ensure the study's reproducibility, scenarios are provided as an exercise using data from Atlantis, a hypothetical country having features of both a developing and developed country. Besides the strictly economical optimization, IMPcc scenarios are established with emission penalty sub-scenarios of $100, $50, and $30/ton $CO_{2\,e}$q. As a result, Scenarios comparison highlights a significance decrease in emission by at least 70% that increase of the global cost by at least 2% comparing to the standard optimization.
Keywords: Sustainable Energy Transition, Impact Mitigation Potential, Emission Penalty, CLEWs, OSeMOSYS.

I. INTRODUCTION

At the very least, the historic 2015 climate agreement aims to keep the average global temperature rise in the current century "far below 2°C" over pre-industrial levels [1]. All forms of energy production account for 72 % of total emissions, with 31% being attributed to fossil fuels' electrical generation [2]. That is, the transition to Renewable Energy (RE) in conjunction with Energy Efficiency (EE), became the path toward the global energy sector's transformation from fossil-based to zero-carbon. This energizing mix is the foundation of a viable climate and stands out as the key pillar of the Sustainable Development Goals (SDGs).

Alike, climate resilience necessitates effective management of key resources: Energy, Water, and Food or Land use (EWF). They constitute the four resource pillars that support global security, prosperity, and equity [3]. The EWF management is dependent on several elements, including technological and fuel choices, resource availability, and market conditions, all of which can be influenced by national resource policy. These resources are intricately integrated and form a coherent system (also known as a "Nexus"). For example, fossil fuel energy directly impacts GHG emissions, and prolonged droughts caused by climate change can exacerbate water supply stress, posing serious food and energy security concerns [4].

Several strategies for optimizing resource management are now often employed to handle nexus concept challenges [5]. This is the case with one of the most widely acknowledged frameworks namely Climate, Land, Energy, and Water Systems (CLEWs), an EWF-resolved open-source linear prediction model [6]. Originally used by the International Atomic Energy Agency to perform an integrated systems analysis of a biofuel chain [7], CLEWs evolved to clarify the links between various actions and their potential long- and medium-term implications through quantitative means.

It is technically possible to limit global warming as required to less than 2°C, but this would necessitate determining the best current and future energy strategic plan. It would be more economically, socially, and environmentally convenient than the current course of action policy plans [1]. Consequently, various projects are being undertaken at the global level towards transition on renewable energy and enhance energy-efficiency.

Almost 257 Gigawatts (GW) of additional renewable energy capacity was added globally in 2021, according to the International Renewable Energy Agency (IRENA) [8], boosting renewable energy supply by 9.1% and contributing an astounding 81% of global power additions. With a record 133 GW of solar power added alone, it made up more than half of the total renewable energy additions. Wind energy came in second with a total capacity of 93 GW and a record 21 GW of capacity from offshore sources.

The transition to renewable energy poses economic and reliability challenges [9]. As a result, economic optimization alone is insufficient for an adequate energy planning system. Other sustainability-related optimization criteria need to be introduced when analyzing different scenarios during the modeling of energy systems [6]. These tasks are complex, which means that flexible and open tools that will become increasingly serviceable for testing new hypotheses and approaches [10]. Effectively, the Open-Source Energy Modeling System (OSeMOSYS), a CLEWs tool, is ideally suited for this purpose [5]. OSeMOSYS is a designed open-source systems optimization model covering a medium to long-term time frame [11]. OSeMOSYS flexibility enables the development of methodologies that adhere to the user's optimization restrictions, merging different blocks into a common model; model stages generation is thoroughly documented in [12].

OSeMOSYS core for economical optimization has been used in numerous studies, and so far, analysis of literature found that authors such as [13]-[19] established approaches based on constraints, including cost assessments, CO_2 emissions activity, energy efficiency, energy security, and to name a few. Using the Tunisian power system as a study case, A. Dhakouani et al [13] incorporated power reliability as an optimization component into OSeMOSYS and proved that a high rate of renewable energy source penetration is associated with a reduction in power system reliability based on energy efficiency initiatives and peak clipping. Through OSeMOSYS, G. Godinez-Zamora et al [14] outlined the path to net-zero emissions in Costa Rica's National Decarbonization Plan, thus in comparison to the baseline scenario, this necessitates the installation of 4.4 GW of additional renewable power plants by 2050 resulting in a reduction in operating costs that offsets additional investments for deep decarbonization. To shocks based on OSeMOSYS flexibility, J. Augutis et al. [15] developed an optimization approach of energy generation technologies optimization from an energy security perspective in terms of energy system resistance to disturbances and concluded that gas technology dominates, reaching almost 80% of the total energy mix, while nuclear technology is the most unstable, losing half of its share in profits of REs that do not surpass 60%. Based on its flexibility as well, T. Niet et al. [19] included a stochastic risk structure to the OSeMOSYS optimization model to account for uncertainty around the emissions of technologies used to generate energy. Moreover, P. de Moura et al. [16] also used OSeMOSYS to emphasize the role of renewable energy generation and to throw light on cross-border trade prospects of power system interconnection operations between Brazil and its South American neighbors where the bargaining power of each country (player) was assessed using the Shapley value concept.

Nonetheless, few studies rely on constraints that address the context of sustainability. In this paper, is developed a new methodology that include the environmental sustainability indicator in the OSeMOSYS energy optimization tool. This methodology leverages the multicriteria approach by incorporating the Impact Mitigation Potential in terms of Climate Change (IMPcc) that is a well-known and the widely used to assess the environmental sustainability. The IMPcc is used as a means of determining the degree of environmental sustainability to which the modeled scenarios are sustainable. Thus, IMPcc, is included into OSeMOSYS as an entirely novel optimisation function in the current study as part of the optimization method.

To confirm the feasibility and the replicability, the influence of the suggested methodology is identified in the context of a well-known framework called Atlantis developed by M. Howells et al [12]. Even though Atlantis is not a nexus framework, its default data and build methods are unlikely to be realistic, it is intriguing due to the implications of various energy generation technologies used in its modeling, including renewable and non-renewable. A set of scenarios is developed, and the resulting results are compared while accounting for the optimization estimators on economic parameters and introducing an additional environmental sustainability constraint. Although the current analysis is based on hypothetical country data, it has allowed us to confirm the feasibility of incorporating the environmental sustainability indicator into OSeMOSYS energy mix planning for cost-effectiveness assessment.

II. METHODOLOGY AND DATA

This section discusses the key features of OSeMOSYS and introduces the environmental sustainability paradigm within this modeling tool as an extra-cost. Besides, it contains the Atlantis power system as a case analysis to ensure the feasibility of incorporating the environmental sustainability into OSeMOSYS as well as evaluating the outcomes of its inclusion. The goal of reaching the specified objectives, specific values of emission penalty, are emphasized in OSeMOSYS through scenario comparison, where scenarios reflect the shares of conventional and renewable energies.

A. *Open-Source energy Modeling System (OSeMOSYS)*

Following the oil crisis of the 1970s, analyses of demand-side energy systems emerged and continued to evolve, resulting in forecasting approaches, which were later translated into top-down models [13]. In the meantime, the supply-driven strategy has progressed, resulting in integrated bottom-up models that are technologically focused on identifying needed investments or operating short-term solutions [20], [21]. Finally, combining bottom-up and top-down models yielded improved insights for decision-makers [13], [22], [23]. Therefore, several various models including OSeMOSYS were developed that seek to improve the design of energy supply systems, by enhancing knowledge of current and future interactions between demand and supply, the environment, and the economy.

OSeMOSYS is a dynamic, bottom-up, linear optimization model used for integrated assessment and energy planning with a medium-to-long time horizon [12], [16], [24]. This modeling tool calculates the energy supply mix in terms of generation capacity and delivery, as well as meeting the demand for energy services every year and at every stage of the case under investigation by minimizing the total costs across the board [25]. The system total cost, which includes the Capital Cost ($/KW), Fixed Cost ($/KW), Variable Cost ($/KWh), and Emission Costs ($/Year) are the merit variable to be optimized [26]. The capital cost is the price for a new capacity expansion, while the fixed cost goes to maintaining the existing capacity. The variable cost is tied to each available capacity per technological unit.

Linear optimization is linked to diverse input variables that are related to technological constraints, economic realities, or environmental aims; as a result, it relies on a single decision-maker, flawless foresee, and competitive markets. The objective function constraint of demand coverage in OSeMOSYS is expressed by Equation (1).

$$\text{TotCost} - \sum_{y,t}(\text{CapCost}_{y,t} + \text{FixCost}_{y,t} + \text{VarCost}_{y,t}) + \text{EmissCost}_{y} \qquad (1)$$

Where:
y: Indicates the year in the time frame
t: Indicates the technology
TotCost: Is the total objective function cost merit to be optimized.
$\text{CapCost}_{y,t}$ [$/KW]: Capital investment cost of a technology, per unit of capacity.
$\text{FixCost}_{y,t}$ [$/KW]: Fixed O&M cost of a technology, per unit of capacity.
$\text{VarCost}_{y,t}$ [$/KWh]: Cost of a technology for a given mode of operation (Variable O&M cost), per unit of activity.
EmissCost_{y} [$/year]: Stand for the Annual emission Cost.

Since its inception in 2011, various versions of OSeMOSYS have been developed to enhance the simulation condition such as timing and relaxing optimization; as well as energy-related coding blocks like storage, short-term flexibility, interconnections, and improved reality modeling to name a few. Currently, several analysis interfaces are in use, with MoManI being chosen for this work.

B. *Environmental sustainability across IMPcc.*

Currently, three pillars of sustainability indicators exist to easily evaluate the long-term viability and environmental performance when evaluating the sustainability of an energy system [27]. Among these metrics is the Input Mitigation Potential in Terms of Climate Change (IMPcc) [29], which is nowadays one of the most prominent and commonly employed carbon footprint estimators. The particularity of the IMPcc is that it considers during analysis the system's full life in a cradle-to-cradle paradigm to estimate the performance of the examined technology [5] in the long run making. The IMPcc is referred to the GHG emission for multiple gases such as CO_2, SO_2, NOx, CH_4, and others. It is defined as the ton of CO_2 equivalent (ton CO_2eq) of the potential global warming during the system lifetime bases on following the cradle-to-cradle paradigm [28].

OSeMOSYS includes a range of energetic modeling methodologies that are currently and commonly employed in addressing environmental concerns and hence targeting a lower feasible emission in the tendency. Among these approaches is an alternative of controlling emission activity, which is to be set employing the emission limitation parameter. Furthermore, there is the possibility of instituting a carbon tax (emission penalty) on the emitted greenhouse gases, which is currently used by several legislation as policy to mitigate high levels of carbon emissions. As an instance, in Costa Rica's National Decarbonization Plan [14], the authors have used the carbon control option in OSeMOSYS to illustrate the path to net-zero emissions. In the same vein, M. Habib Bechir et all [29] has developed a strategic plan to decarbonize the Bembibre's industrial park that is located in the el-bierzo region in Spain. By employing emission penalty using OSeMOSYS code, Emodi. N et all [30] addresses the effective plan in order to identify potential energy reduction plans and climate change scenarios for the Australian power sector.

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Plus, 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, that could act as a further strategy for achieving this endeavor.

C. IMPcc integration on the OSeMOSYS tool

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 basically an optimization constraint.
As the fundamental base of OSeMOSYS is strictly economic optimization, hence in this case, we convert the effect of each adjustment as an extra cost by monetizing the estimators. The main challenge is to convert the emission variable into an economic cost weight using a precisely designed function the “EmissCost”. Whereby no tabulated values of IMPcc are immediately available, but the matching emissions per unit of energy produced also called emission rate per unit of activity (EmissRate) of energy produced and technology are. Indeed, the rationale beneath this approach hinges on the simple fact that “EmissCost” is the sole factor within the OSeMOSYS code as shown in Equation 2, with an immediate correlation across energetic production, output emissions, emission penalty and the objective function which is the root of optimization function.

$$\text{EmissCost}_y = \text{Emission Penalty} \sum_t \text{Emission}_{t,y} \qquad (2)$$

Where:
y: Indicates the year in the time frame.
t: Indicates the technology.
EmissCost_y [$/year]: Stand for the Annual emission Cost.
Emission Penalty ($/ton CO_2 eq): Is the corresponding carbon tax.
$\text{Emission}_{t,y}$ (ton /year): Is the total annual emissions emitted by each technology included in the energetic mix.
The Energy Reference System (ERS) is a network representation of all of the technical activities required to supply various forms of energy to end-use activities. Usually given as a schematic representation of the real energy system that is being modeled, and it depicts the flow of energy horizontally from resources on the far left, through various transformation technologies, to final energy use on the far right [31].
So, to evaluate the environmental sustainability within a specific ERS, a first order rude approach is adopted in order to normalize the actual purpose. To do so, we defined the “Mean ERS Emission Rate” (MeErsEmissRate) concept as an unweighted mean value of the emission rate of all the technology included in the ERS. Therefore, the main idea of this approach consists of gauging the emissions per unit of energy that is to be produced per technology the “EmissRate” (ton CO_2eq) with respect to the mean ERS value emission rate of all technologies included in the ERS (MeErsEmissRate).
This will lead to the improvement of the “EmissCost” and increase the level of its effectiveness in the development of non-captive technologies in the context of environmental sustainability. This newly integrated function will not consider only emission penalty as constraint but also serves as an emission-specific to evaluate how emissive is a technology compared to the technologies in the ERS. As a starting point for adopting the mean emission rate mean value of the ERS, this approach is reasonable; however, an iterative second-stage methods will be ideal since the contribution of each technology can be successfully taken into consideration as well.
More importantly, the prevailing approach appeals only emissions associated with energy production phase corresponding to emissions from the cradle to the entrance-door and the associated out-door to cradle. The enhanced EmissCost adjusted by the IMPcc estimator, dubbed sustainable emission cost (SusEmissCost), is represented as follows in equation (3).

$$\text{SusEmissCost}_y = \text{Emission Penalty} \sum_t \text{Emission}_{t,y} \times \frac{\text{RateEmiss}_t}{\text{MeErsEmissRate}} \qquad (3)$$

The SusEmissCost incurs an additional extra cost with deployment of the emission ratio, which, when paired with the emission penalty, gives a greater credit to technologies that generate lower emissions activity levels and are not susceptible to the emission penalty. As an outcome, technologies with lower emission levels than the mean emission of RES will have lower related costs, whereas those with higher pollution levels will incur extra costs. As a consequence of doing so, the relative contributions of the remaining ERS technologies (lower emissive technologies) to the mix increase while still having an appropriate effect.

The integrated approach in the OSeMOSYS framework is shown in Figure 1 employing environmental sustainability as an optimization function.

To recapitulate, OSeMOSYS is a bottom-up supply-oriented linear optimization model that suits demand. The intent of this work is to demonstrate how an energetic optimization in OSeMOSYS can take the sustainability approach into account by integrating the IMPcc relevant to environmental sustainability indicator. Given the flexibility of OSeMOSYS, a novel first order approach is developed in which the IMPcc is integrated as an extra cost in MoManI interface. In simple terms, this method is based on aggregating emission penalty and emission-specific evaluation, with an overall objective to allocate greater weight to technology that emits less GHG and is therefore not subject to the emission penalty. The proposed enhanced objective function is not yet accessible in the OSeMOSYS package; however, it can be considered once its feasibility and reproducibility are validated.

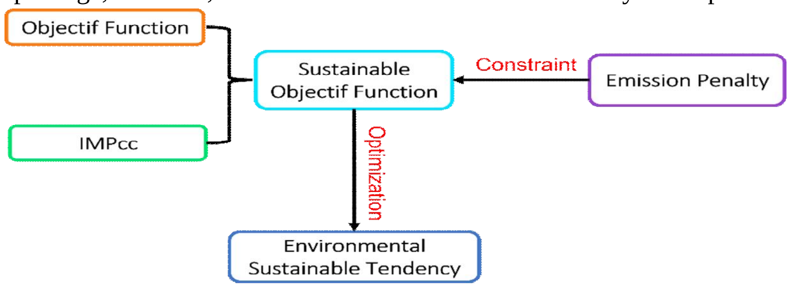

Figure 1. Developed environmental sustainability as function of OSeMOSYS framework optimization

D. Case study: Atlantis Power System

Since MoMani, one of the OSeMOSYS interfaces, has the capability of creating and implementing new energetic modeling targets, the main goal of this paper is to evaluate both the developed approach and the impact that results from adding sustainability criteria to it. This is one of the reasons for using the Atlantis energetic framework scenario from the MoManI interface, which was designed as a model for methodical validation and control [26]. Regardless of the fact that Atlantis is a fictitious country, it possesses the features typical of both a developing and a developed country. Furthermore, it is enthralling due to the implications of the multiple power generation technologies used in its modeling, a mix of renewable and non-renewable, allowing the validity and consistency of the developed approach to be adequately examined in a broad energetic framework.

Atlantis energy framework includes five power plants, each of which employs a specific imported fuel type. A large hydropower plant, a single cycle steam turbine that runs on natural gas, a single cycle steam turbine that runs on heavy fuel oil, a diesel-fed gas turbine, and a coal-based integrated gasification combine cycle facility are among the installations. This system is being expanded over the course of the modelling period, to examine the viability of including new technologies like wind turbines (25% load factor), mini hydro power plants (less than 1 MW), grid-connected PV systems (commercial), a nuclear power plant (light water reactor), and new combined cycle power plants powered by natural gas. In the instance of Atlantis, the ERS has five main energy levels: resources, primary, secondary, tertiary, and final demand, which is divided into various demand sectors. Figure 2 depicts the Atlantis ERS. Technologies are shown as blocks, whereas energy sources like coal, natural gas, electricity, etc. are shown as lines.

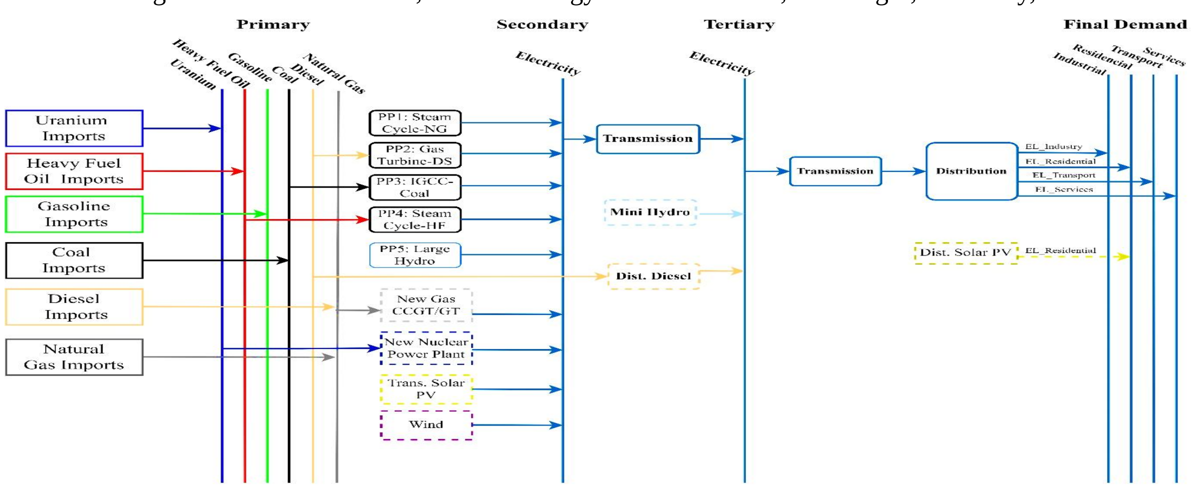

Figure 2. Atlantis Energy Reference System

E. Atlantis Input parameters Data

The Atlantis default data as detailed in the Momani Training Manual [26] are considered. The data (both technical and economic) used in Atlantis are not country-specific, however, they were derived from IRENA reports and IEA-Energy Systems Analysis Program-Technology briefs (E01, E02, E03, E06, E10, and E11). But some of the initial parameters had a less-than-ideal configuration and were reviewed to give a more realistic appearance. The current Atlantis parameters were established using technical and economic inputs from the last decade, but in view of recent developments and the rapid deployment of renewable and even non-renewable technologies in recent years, some key parameters such as the variables cost and emissions per unit of energy are revised. Hence, basic data was acquired from the most recent bibliographic reports. That is, the variable costs of technologies were approximated using IRENA reports [32]–[34] and the World Bank [35]. In regard to emissions, a specific technology's emissions have two components. The first pertains to installed capacity power (KW) while the other associated with the energetic production (KWh). In this work only CO_2-related emissions during the energetic production phase are assumed. The CO_2 emission activity ratio is derived from a review of published publications [36], [37].

Among the modified parameters was the limitation of the large hydroelectric plant's maximum annual production to 2 PJ rather than the default unlimited production. Furthermore, during the initial Atlantis modelling, technologies like as CSP and PV roof were turned off, thus these technologies are not addressed in this analysis.

In OSeMOSYS, a technology's capacity factor (CF) essentially measures the frequency at which it runs at peak efficiency. Therefore, a technology is continuously supplying energy if it has a (CF = 1) for that time slice. Most technologies in Atlantis have a default CF of 1. In contrast to renewables, CF is lower for renewable plants due to the intermittent nature of the energetic resources. Even though Atlantis is a fictitious country, solar technologies were given a capacity factor of 0.15, which is unattainable without knowledge of the region's irradiation level. To provide more transparency on the effect of the IMPcc, a hypothesis has been defined for solar technologies. Since this system lacks an accumulation system, the hypothesis assumes that Atlantis receives constant illumination throughout all four seasons, leading to a CF of 0.35 during the day and zero at night.

The updated parameters can be employed to assess the implications of the IMPcc, although they are not perfect unless the instance being analysed is unique to a genuine country. The integrated revised parameter data for the Atlantis energy Modeling system, are all described in detail in Table 1.

Table 1. Main power generation technologies characteristics parameters

Parameter Technologies	Fixed Cost (M$/PJ)	Capital Cost (M$/GW)	Variable Cost (M$/PJ)	EmissRate (Mton CO_2 eq/PJ)	Useful Lifetime (Year)
Natural Gas (NGSC)	*44*	*2300*	*24.05*	*0.132*	*30*
Diesel Generator (DSGC)	*36*	*900*	*22.49*	*0.193*	*30*
Integrated Gasification Coal (IGCC)	*148*	*3700*	*11.58*	*0.268*	*30*
Heavy oïl (HFSC)	*50*	*2300*	*30.23*	*0.203*	*35*
Large Hydro (Hydro_Dam)	*60*	*4000*	*1.39*	*0*	*35*
Mini Hydro (Hydro_Min)	*65*	*4500*	*1.39*	*0*	*25*
Distributed Diesel (Diesel_Gen)	*55*	*1070*	*22.48*	*0.193*	*40*
Photovoltaic Utility Grid (PV_UTL)	*0*	*2000*	*1.39*	*0*	*25*
Wind	*0*	*1845*	*2.69*	*0*	*25*
NEW Combined Cycle Gas Turbine (NGCC)	*44*	*1100*	*16.17*	*0.101*	*35*
Nuclear	*0*	*3000*	*6.12*	*0.004*	*50*

III. MODELING SCENARIOS

Emission penalties are frequently fully reliant on country regulation and communities and fluctuate through a period to another. That is, penalties are currently being enforced in numerous countries, most notably in Europe [38] , and with a very hefty emission charge for exceeding yearly emission quotas in order to meet the green deal initiative [39], which aimed at lowering the risk of carbon leakage. Indeed, the penalty underneath the European Union (EU) ranges from \$30 to \$50/ tCO_2eq and has risen to \$100/tCO_2eq in 2022, much over the permitted ceiling [40].

Concerning developing countries in general, the global expansion of carbon taxes generates various debates and proposals for a broader concept of emissions trading that may be better adapted to emerging economies. Nonetheless, most developing countries' carbon prices are out of date. The dilemma is that the quotation appears to be somewhat contrived, as illustrated in Figure 3, which plots the projections of the region's linking carbon taxes in 2020 and 2050 published by Dellink, Rob, et al [41], towards the goal of global carbon pricing and its influence.

In light of this, two Atlantis energy mix scenarios are proposed and contrasted. The postulated scenarios are linked to assessing the impact of incorporating the above-mentioned approach in conformity with environmental sustainability into the energy mix for economic optimization. The emission penalty is thus presented as an optimization constraint, leading to the definition of sub-scenarios.

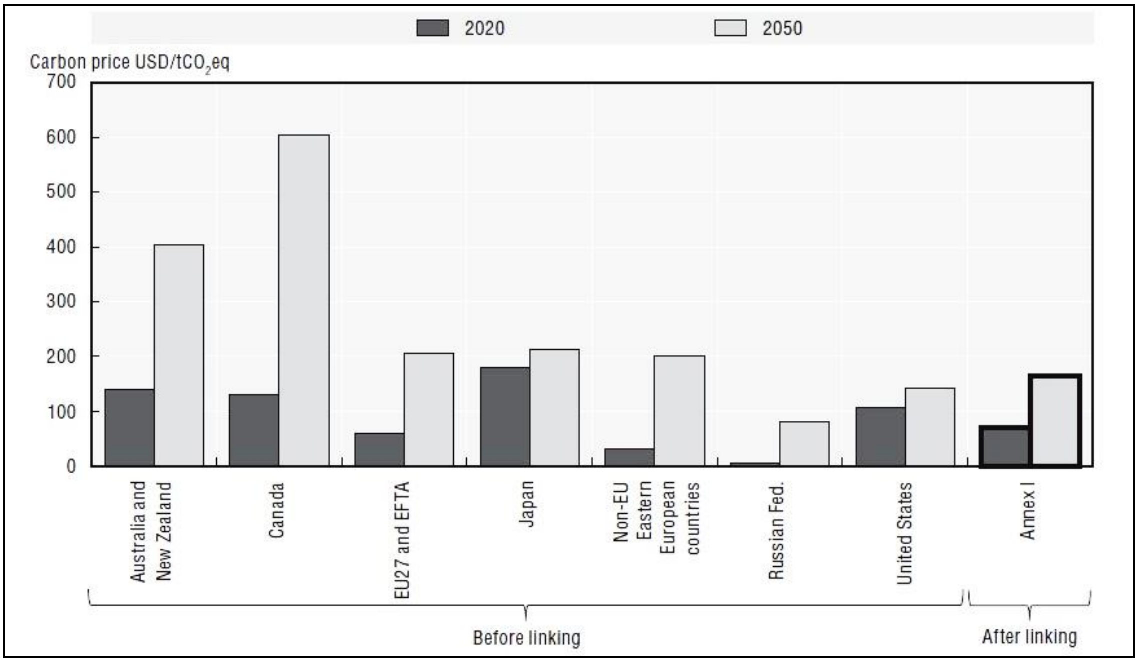

Figure 3. Regional linking on carbon taxes prices [41]

Thus, the first scenario the Standard optimization, restrictedly economic optimization relates to a frozen form of the energetic system without the implication any initiative resulting in a no-emission-penalty situation that matches emerging nations.

For this study, the carbon tax values examined consider the most recent 2022 regulatory range of EU emission costs during the "permitted" emissions level. Aside from simply testing the feasibility of the developed methodology, the justification for this thought process is that the EU predicts that increasing carbon taxes to \$200/ tCO_2eq by 2050 will significantly improve carbon soberness (See Figure 3 for detail). The premise therefore can be evaluated more thoroughly by means of the current research using OSeMOSYS and the novel IMPcc approach.

Along with the analysis related to the standard scenario, three other scenarios with environmental sustainability inclusion with set emission penalties of \$30, \$50, and \$100/tCO_2eq adhering to exclusively the latest 2022 regulatory range of the EU will be analyzed. Thereby, the selected context will be a great asset showing whether or not future hikes in carbon taxes will be required to attain net zero in the long run while employing the IMPcc sustainability indicator.

Among the several output variables, the following were chosen as the most representative: global-costs, global-emissions, and energy production, that is, integrated into the time period that is, between 2024 and 2050. In terms of global energy production, the ones coming from renewable sources, fossil sources and nuclear energy have been analyses into three categories.

IV. RESULTS AND DISCUSSIONS

The following section breaks out the tendencies, shares, global-emissions, and costs across the stated scenarios, encompassing the standard scenario and those linked with sustainable environmental scenarios.

1) *Standard economic optimisation:* In the standard scenario, the energetic mix is optimized merely in economic terms, whereas being long-term evaluated in the absence of any extra initiatives or constraints. The annual energy production per technology over the long term that encompass the demand covered in the time frame is illustrated in Figure 4.

In the long run, the most viable technologies are Hydro_Min, Nuclear, Wind, Solar, and IGCC, in that sequence. Diesel_Gen, despite its continuous presence throughout the entire interval time, only produces residually. DSGC appears to be an inadequate technology in terms of economic optimization; Hydro_Dam, NGSC, and HFSC production are not economically competent over the long run and the massive deployment of the more cos effective technologies.

The image processing shows a tendency toward an energetic mix heavily dominated by renewable generation, which accounts for half of total of the global production. While the remaining production goes to nuclear and fossil reaching respectively the half of the remaining production as seen in Figure 5. wherein is illustrated the relative contributions of the different energy source categories on the global energetic production.

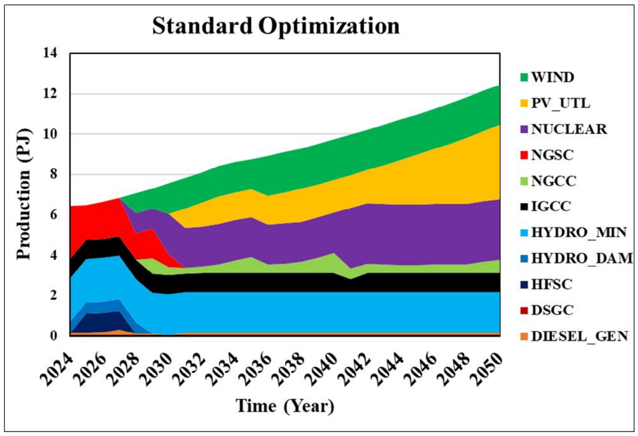

Figure 4. Standard optimization: Yearly distribution of the energetic production differentiated by technologies

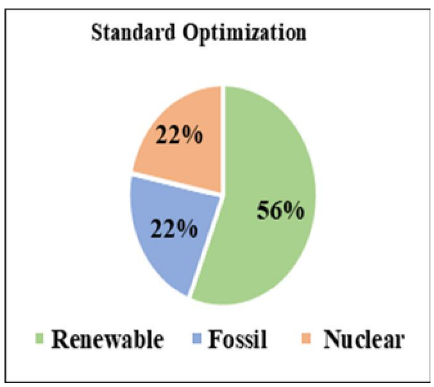

Figure 5. Standard optimization: Percentage of the energetic production of each defined category

2) *Environmental sustainability optimization impact; Effect on the energetic production:* The environmental sustainability application enhances renewable energetic production, whereas the reverse behaviour is being noticed with fossil energetic production, as displayed in Figure 6, which portrays the annual contribution of each technology within each sub-scenario tendency. Hence across each sub-scenario, the PV_UTL output is 39 PJ, and the wind contribution is nearly 22 PJ. In the sub-scenario in which the penalty is \$30/tCO_2eq, Hydro_Min energetic output is 30% greater than what is produced in the two other sub-scenarios. This is mainly attributable to the significant deployment of Hydro_Dam in sub scenarios in which the emission penalty is set at both \$50 and \$100/tCO_2eq. With the end result being that the emission penalty gets bigger, forces the energetic generation of both NGCC and NGSC to drop by 36% and 10%, respectively. Table 2 summarized comprehensively the global energy output per technology for each of the assessed scenarios, highlighting the impact of the IMPcc in each technology, such as the impeding effect of the Heavy oil when the environmental sustainability criteria is applied.

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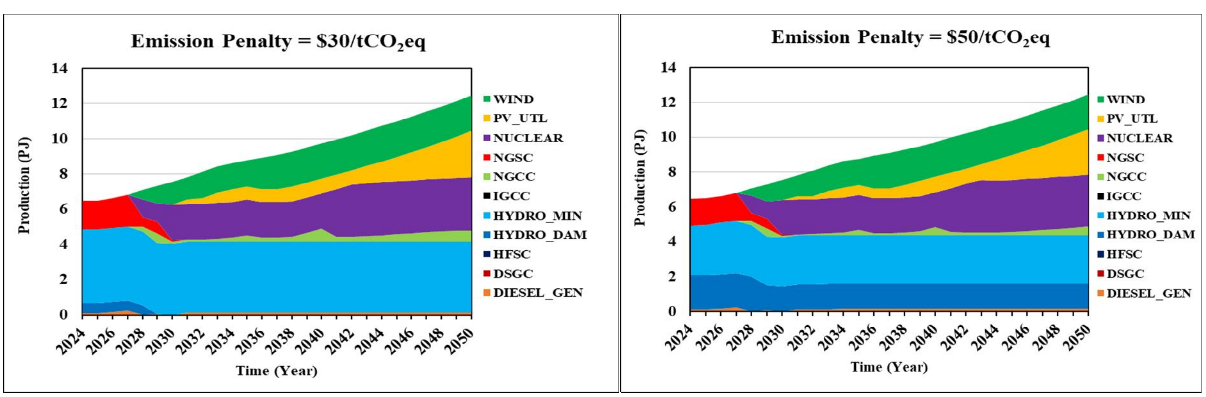
Table 2. Global energy production per technology

Sub scenario Technologies	*Standard*	Emission Penalty = $30/tCO$_2$eq	Emission Penalty = $50/tCO$_2$eq	Emission Penalty = $100/tCO$_2$eq
Natural Gas (NGSC)	*11.50*	*8.08*	*7.31*	*6.00*
Diesel Generator (DSGC)	*0*	*0*	*0*	*0*
Integrated Gasification Coal (IGCC)	*25.26*	*7.45*	*0*	*0*
Heavy oïl (HFSC)	*2.84*	*0*	*0*	*0*
Large Hydro (Hydro Dam)	*2.82*	*2.82*	*41.58*	*41.07*
Mini Hydro (Hydro_Min)	*55*	*109.77*	*76.41*	*83.10*
Distributed Diesel (Diesel_Gen)	*0.193*	*3.55*	*3.30*	*2.71*
Photovoltaic Utility Grid (PV_UTL)	*40*	*22.34*	*21.50*	*18.10*
Wind	*41*	*39.86*	*39.60*	*39.33*
NEW Combined Cycle Gas Turbine (NGCC)	*0.101*	*8.09*	*5.16*	*2.39*
Nuclear	*54*	*53.64*	*53.34*	*53.49*

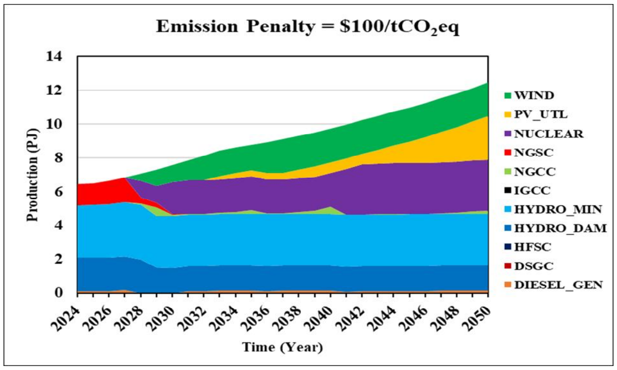
The relevant point lies in the fact that even with a heavier penalty of $100/tCO$_2$eq, the share of renewable energy stays approximately the same as in the other two sub-scenarios. This view is reinforced by Figure 7, which features the proportionate shares of the different energy source categories in terms of global energetic production relevant with each sub-scenario. The primary conclusion is that, even with a low-level carbon tax, the sustainable environmental estimators' applications promote the spread of renewable sources, thereby lowering the production of fossil fuels. In comparison to the standard scenario, the effect on production is more than a 15% decline in the production of fossil technologies across all the three sub-scenarios associated with the adoption of environmental sustainability.

Imposing emissions-related penalties does not imply a mix comprised entirely of renewable components. In this case, despite the application of penalties, fossil technologies still make up a little portion of the final mix in the IMPcc scenarios, despite the application of penalties and their significant decline (< 15%) compared to the standard scenarios (see Figure 5 and Figure 7 for details). Indeed, the attendance of fossil technologies in this specific case can be accounted for on the one hand by the purely economic optimization and on the other hand by the low reliability of renewable resources, which is due to their inherent intermittency that is linked to each associated technology CF. In our case study, no renewable technology achieves a CF of 40%. Accordingly, it is heavily dependent on the study area, where each renewable technology can have a low intermittency and thus a strong CF. Therefore, when environmental sustainability is applied, the greater the CF of renewable technologies and the lower is the presence of fossil technologies in the energetic mix.

Furthermore, nuclear technology has a consistent tendency across all scenarios, which can be justified by the lack of emission activity during the production phase, and therefore no significant influence arises toward this technology within the IMPcc incorporation.

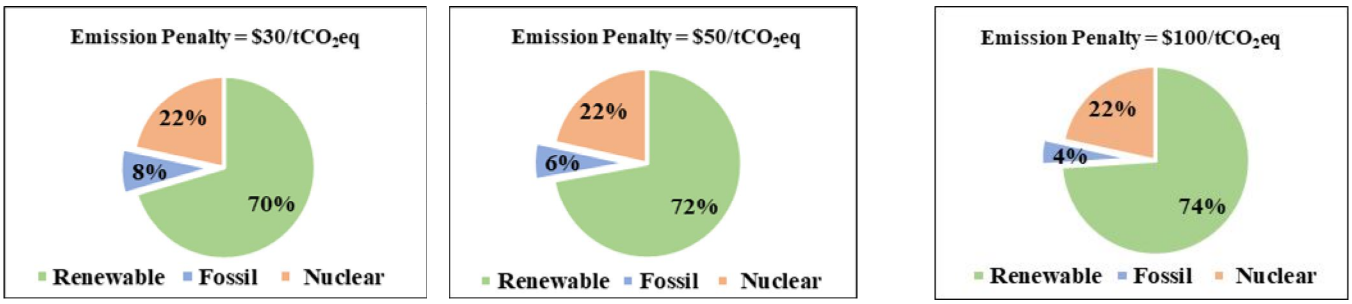


(a) (b)



(c)

Figure 6. IMPcc Scenarios: Yearly distribution of the energetic production differentiated by technologies; (a) Emission Penalty of $30/ tCO2eq; (c) Emission Penalty of $50/ tCO2eq; (d) Emission Penalty of $100/tCO2eq



(a) (b) (c)

Figure 7: IMPcc Scenarios: Percentage of the energetic production of each defined category; (a) IMPcc Penalty of $30; (b) IMPcc Penalty of $50; (c) IMPcc Penalty of $100

3) *Environmental sustainability optimization impact; Effect on the global-emission and cost:* In terms of the associated cost and emissions adhering in each of the optimized sub-scenario , Figure 8 illustrates in contrast to the standard scenario how the incorporation of environmental sustainability impacts the evolution of the global price and the global emissions. Indeed, it is feasible to evaluate these parameters in the annual bases, however in our case, these two output parameters are considered on their global value to easy evaluate the direct impact the IMPcc estimator's scenarios in the long run. The global cost here refers to a combination of the fixed, variable, and investment costs for each tendency scenario throughout the entire study period. As well the global emission refers to the aggregated value of the annual emission over the full period of each of the studied scenario's tendency.

As a simple evaluation, the IMPcc and carbon tax growth increase system global costs, but the reverse trend occurs with global-emission outputs via the IMPcc and carbon tax growth. The associated carbon mitigation increases in the global cost just under 20% while the global emission drops sharply by at least 70%.

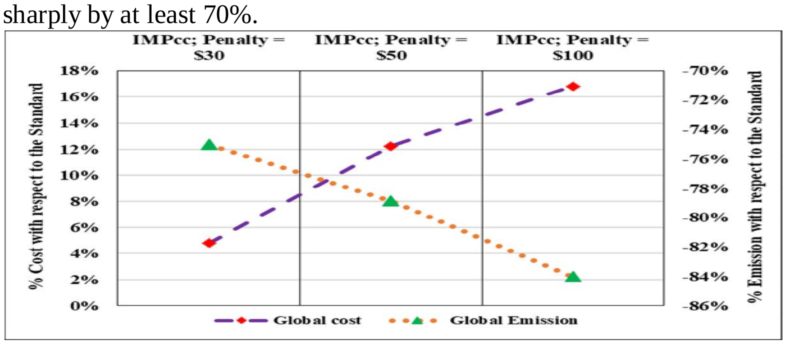


Figure 8: Effect on both global costs and global emissions of the different scenarios in comparison with respect to the standard scenario.

The implementation of IMPcc has culminated in an identical boost to the production rate of non-polluting technology in all three sub-scenarios (see Figure 7 for details), leading to in a tremendous decarbonization rate as opposed to the standard scenario. However, the subsequent rise in emission penalties resulted in only a 2% decrease in fossil technologies across sub-scenarios. The proportion of variance in global emissions amongst sub-scenarios does not exceed than 10%; more precisely, when comparing emission penalties sub-scenarios of \$30/tCO_2eq to sub-scenarios of \$50 and \$100/tCO_2eq, respectively, the emission diminishes only by 4% and 9%. This constituted confirmation that a more affordable emission penalty (\$30/tCO_2eq) may successfully accomplish the same emission target as penalties of \$50 and \$100/tCO_2eq, and at a lower global cost with a roughly 5% cost savings, as shown in Figure 8. This is mainly due to combined economic optimization and the necessity for compensation up the reliability of renewable technology in the energy mix; even a greater penalty will not result in a significant reduction in emission. This demonstrates the worth of integrating the IMPcc alongside the developed approach in which technologies are crudely balanced with the mean value of the EmissRate of all technologies included in the ERS before possible deployment.

The findings spark a new argument in the context of the present global trend toward carbon taxes, involving certain policymakers suggesting that increasing carbon taxes to \$200/tCO_2eq or higher will eventually result in net zero decarbonization. According to the modeling of emission prices performed by Dellink, Rob, et al [41], Figure 9 depicts the influence of predicted prices on emission reduction in percentage terms in the long run. Likewise worth noting that in the EU, the implementation of related carbon taxes in 2050 (\$200/tCO_2eq) will result in around a 50% reduction in emissions. Nonetheless, even though the adopted case study is related to a fictive country, the so far obtained results within this study show that the adoption of the sustainability indicators and particularly the IMPcc in OSeMOSYS, in conjunction with a comprehensive carbon tax price, can lead to an energetic mix with adequate technology that is both economically and environmentally friendly.

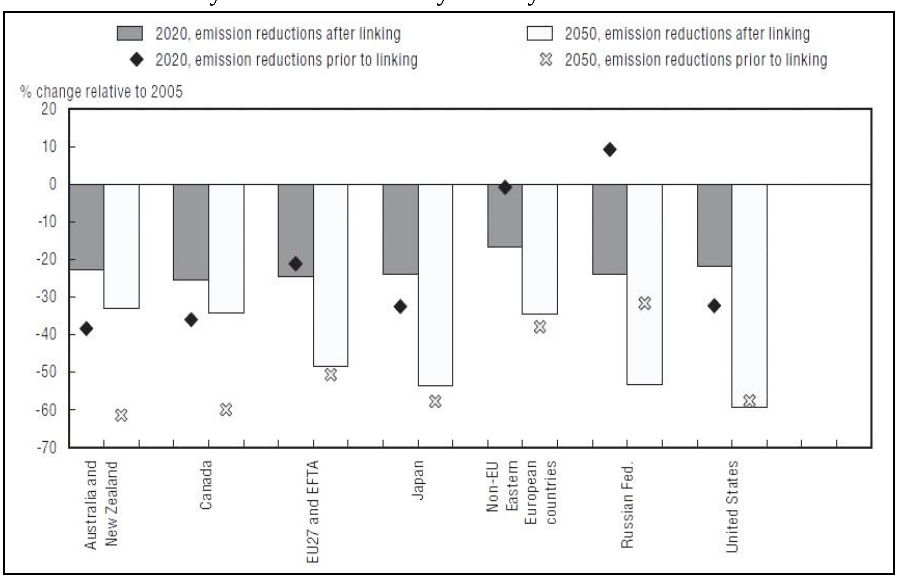


Figure 9. Prevision of Regional linking on carbon taxes prices effect on the emission reductions [41]

V. CONCLUSIONS

The IMPcc that stand as environmental sustainability indicator is incorporated as an extra cost into the optimization objective function of the flexible energy modeling tool that is OSeMOSYS initialy designed for pure econmic optimasation using exclusively its MoMani interface. The incorporation of the IMPcc adheres to a precise rude approach that entails taking into consideration the EmissRate per unit of activity of each technology involved in the ERS and gauging it by the free of weight mean value of the emission rate of all the technology included in the ERS. More specifically, the developed approach gathers the emission penalty and emission-specific evaluation, with the ultimate goal to assign greater importance to technology that produces less greenhouse gas emissions and thus is not subject to the emission penalty.

The developed initiatives will consist valuable assistance to decision-making settings in the development of an open and cost-effective energy modeling system in the framework of environmental sustainability.

The Atlantis energetic mix, developed in MoMani as a basis for approach and test control and featuring developed as well as developing countries, is used as a case study for the developed methodology's testing.

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The distinctiveness of Atlantis in gathering multiple energy generation technologies, including renewable and non-renewable has allowed us to reopen matters regarding the concept of increasing the carbon tax in the near future in order to mitigate emissions in the generation mix. Indeed, two scenarios are considered which are:

1) Standard scenario: Strictly economic optimization, no new initiative is included in the objective function.
2) IMPcc scenarios: Consider the developped approach and consists of three sub-scenarios differentiated by their emission penalty set to \$30, \$50, and \$100/tCO_2eq adhering to exclusively the latest 2022 regulatory range of the EU.

As an overall point, it is extremely important to include adequate estimators to ensure sustainability in a green energy transition. More particularly, the imposition of emission penalty and emission-specific evaluation forces the avoidance of high-emission technologies. In comparison to the standard scenario, IMPcc adoption lessens emissions activity by 75% when emission penalties are \$30/tCO_2eq, 79% when emission penalties are \$50/tCO_2eq, and 84% when emission penalties are \$100/tCO_2eq. While global costs are increasing slightly but is under 20%. Besides that, in terms of production, the imposition of the environmental sustainability increases the production of renewable energy, keeps the nuclear production constant and reduces the production of fossil technologies. Given the intermittent nature of renewable sources, resulting in a demand gap, fossil technology is included in the energy mix at a specific percentage in order to ensure that the demand gap is covered.

With application of the IMPcc in the energy modelling obtained, the optimization shows clearly applying an emission penalty of \$30/tCO_2eq can approximatively achieve the same decarbonization besides cost saving as an emission penalty of \$100//tCO_2eq. Moreover, in the long run comparison with prevision of the UE in decarbonization by 2050, 50% of the emission reduction are to be ensured only if carbon tax of \$200/tCO_2eq are imposed, while the IMPcc application will ensure at least 70% of emission reduction with the least cheaper carbon price.

The proposed enhanced objective function is not yet accessible in the OSeMOSYS package; however, it can be considered as its feasibility and reproducibility are validated. So far, this methodology stands for evaluating technologies only during production phase, however further analysis considering the cradle-to-cradle will be necessary in order to analysis the environmental performance for the full life of the technologies included in the ERS. Furthermore, while the actual approximation is acceptable, improving the normalization factor will make more sense; indeed, an iterative methodology will be ideal because of the contribution of each technology that ought to be properly weighed in the emission-specific evaluation phase.

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