Energetic Sustainable Transition Process Optimization in Terms of LCA Using CLEWs Tools

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Abstract. Ensuring a sustainable transition process, whether at a global or local level, involves designing an energy mix appropriate to the user's needs. The aim is to identify the optimal future strategy that maximizes both socio-economic benefits and sustainability. To address these challenges, multiple modeling tools are now available to assess different scenarios before implementation. However, modeling tools are generally designed for economic optimization. This is the case with the Open-Source Energy Modeling System (OSeMOSYS) a CLEWs tool. This paper proposes an optimization methodology in terms of sustainability, introducing Life Cycle Assessment (LCA) as a global estimator. In particular, the effects of energy payback times (EPBT) on the selection of transition scenarios will be evaluated. To ensure the reproducibility of the study, we present an exercise that uses data for a fictitious country that shares features of both a developing and a developed country (Atlantis).

Keywords: Sustainable energetic transition · CLEWs · OSeMOSYS · Life cycle analysis · Energy payback time

1 Introduction

Climate resilience requires optimal management of vital resources: Energy, Water, and Food or land use (EWF). The management of these resources relies on several factors like technology and fuel choices, resource availability, and market factors, which can all be affected by national resource policies [1]. These resources are strongly interlinked and comprise a coherent system (also called "Nexus"). For example, energy from fossil fuels has a direct effect on GHG emissions and then extreme droughts caused by climate changes can lead to significant food and energy security problems due to intensified water supply stress [2].

Nowadays, several models for optimizing resource management are widely used [3]. In particular, one of the most accepted namely Climate, Land, Energy, and Water systems (CLEWs), arose to clarify the connections between different actions and their possible

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consequences [4] both in the medium and long term. Indeed, CLEWs is an open-source linear predictive model, sequentially EWF resolved.

Energy transition toward Renewable Energy (RE) as recommended by the Sustainable Development Goals (SDG 7), raises questions about economical and reliability issues. Nevertheless, some RE technical solutions are not economically competitive within the long-term time frame. However, for an adequate energy planning system, economic optimization is not enough. Other optimization criterions linked to sustainability need to be added.

Modeling an energy system and its relevant scenarios is complex, likewise flexible and open tools will be increasingly useful to test out new hypotheses and approaches [5, 6]. Indeed, the Open Source Modeling System (OSeMOSYS) a CLEWs tool, a newly developed open-source systems optimization model covering a medium- to long-term time frame [7], is well suited for this purpose. OSeMOSYS can be freely applied following the user's needs, thus in the present case, through its interface known as Model Management Infrastructure (MoManI), a set of scenarios are modeled. Employing OSeMOSYS and MoManI, users can create and add individual blocks into a common model, model step creation is fully described in [8].

The review of the literature revealed that authors including [9–12], developed within the OSeMOSYS core for economical optimization, methodologies relying on constraints including costs evaluations, CO_2 emissions activity, energy efficiency, energy security, etc. None of these constraints address the sustainability context. Therefore, this paper aims to develop a methodology aiming to model and provide an optimal evaluation of sustainable transition scenarios across an adequate mix of energy generations technologies not by considering a single criterion (technical or economical) but from a sustainability perspective as a multicriteria approach by introducing the Life Cycle Assessment (LCA) concept, as a sustainability estimator [13, 14]. For that, the LCA indicators will be involved in OSeMOSYS as an optimization procedure. The algebraic formulation of the modified and remaining code and the code itself [15], are provided as an online supplement to this paper. For this early stage of work, the corresponding energetic sustainability indicator, the Energy Payback Time (EPBT) has been included and evaluated.

To simplify the identification of the optimization effects in terms of the energetic sustainability, a well-known nexus framework, named Atlantis is considered [8]. Even if Atlantis nexus defaults data and its build methodology might not be realistic but is interesting because of the implication of several technologies used in its modeling including renewable and non-renewable energies. A set of scenarios are defined, and the obtained results are compared considering the optimization estimators both only economic factors and including additional energetic sustainability constraints.

The current analysis relies on a fictive country data example but allowed us to confirm the possibility to conduct a sustainability evaluation into OSeMOSYS energy mix planification for an economical optimization. So, Scenarios comparison will allow pointing out the importance of considering EPBT estimator actions alongside the objective of integrating RE in a target nexus.

2 Methodology

In this paper, the Atlantis nexus example of OSeMOSYS has been used to evaluate how the application of the energetic sustainability indicator affects the energetic mixing optimization. Atlantis is a fictional country that shares features of both a developing and a developed country. This energy model is developed by [16] as an exercise demonstrating the use of MoMani. The data (Technical and economical) used in Atlantis are not specific for any country but were extracted from the International Renewable Energy Agency reports and IEA-Energy Systems Analysis Program -Technology briefs (E01, E02, E03, E06, E10, and E11).

Different scenarios linked to nuclear and Solar technology are evaluated using strictly economic optimization by including EPBT as constraining.

In this section, the energy modeling and optimization tool OSeMOSYS is described. In addition, it discusses LCA and its indicators and introduces the energy system modeling.

2.1 Open-Source Energy Modeling System (OSeMOSYS)

OSeMOSYS tool is specifically designed to model and computes the energy supply mix in term of generation capacity and delivery. This energy modeling tool aims to meet the energy services demands every year and in every time step of the case under study, minimizing globally the total discounted costs [17].

The merit variable to be optimized is the system total cost including the capital cost, the fixed costs, the variable costs as well as the emission penalty costs. The variable cost is related to each available capacity per technology unit, while the fixed cost goes to the maintenance of the existing capacity and the capital cost is the cost for a new addition in the capacity [16].

OSeMOSYS uses a deterministic linear optimization associated with different input data related to technical constraints, economic realities, or environmental targets and therefore assumes a unique decision-maker, perfect foresight, and competitive markets [17].

Several analysis interfaces are currently used being MoManI selected for the present work.

2.2 Energetic Sustainability Across EPBT the Frame of the Lifetime Analysis

LCA of energy generation system implies the investigation of its three indicatives to easily evaluate their sustainability and environmental performance. These indicatives are the Internal Rate of Return (IRR), Energy Payback Time (EPBT), and the Input Mitigation Potential in Term of Climate Change (IMPcc) [18]. In reality, these indicatives are evaluated separately to estimate the studied technology performances such as the entire emission activity during its entire lifetime in a cradle-to-cradle paradigm.

EPBT is considered one of the most effective unbiased estimators to evaluate the energetic sustainability of a product/process/initiative. Expressed in years, EPBT is defined as the period required for an energy generation system to produce the same amount of energy which is the primary energy that was used to produce the entire system [19]. It is theoretically given by the cumulative energy demand; CED (MJ) over the annual energy generated by the system; Ep (MJ/year).

$$EPBT = \frac{CED}{E_p} \tag{1}$$

The CED expresses the energy input during the system's lifetime including the energy required starting from the extraction of raw materials, transportation, processing, manufacturing, and usage to the end-of-life of the activities. While Ep is the system electricity generation over a year.

2.3 EPBT Inclusion on the OSeMOSYS Tool

As explained before, the core of the presented work is to evaluate the effect of including the energetic sustainability estimator EPBT in the optimization process. For that, based on the flexibility of OSeMOSYS, EPBT can be integrated into MoManI through an accurately designed function being the main challenge convert an energetic variable into an economic cost weight.

As a first-order approximation, we will work under the hypothesis that, the energetic system must produce yearly an extra quantity of energy to recuperate the expended during the implementation process (cradle-cradle). Considering the extra production annually distributed evenly, we can define the ratio between the EPBT and the operational useful life of the energetic system as a correction factor.

The extra production will increase the corresponding yearly variable cost associated with the technology, avowing, at the same time the implementation of extra energetic capacity. Equation (2) shows the Yearly Total variable cost:

$$YTVc = \left[Pr \times \left(1 + \frac{EPBT}{OL} \right) \right] \times VC \tag{2}$$

where;

YTVc: Represents the Yearly Total Variable cost. It is the annual variable operating cost of each technology derived from the total annual by mode and the parameter variable cost;

Pr: Is the Yearly Energy Production per technology;

OL [year]: Is the Operation Life, it is the useful operational Lifetime per technology;

VC: Represents the Variable Cost and it is related to each available capacity per unit.

The effect associated with the EPBT inclusion for technology will be inversely proportional to its operational useful life. Moreover, the EPBT effect is so much less the cheaper the technology is implemented.

3 Case Study: Atlantis Power System

The proposed methodology is evaluated in a set of energetic scenarios for the Atlantis nexus. Atlantis nexus is a fictitious country developed into the MoManI interface as an example for validation and software control. Atlantis energy modeling system parameter data is fully described in Table 1.

Table 1. Atlantis parameter data set.

Technology \ Parameter	Output to activity ratio (Year)	Life time (Year)	EPBT (Year)	Fixed cost (M$/PJ)	Capital cost (M$/GW) 2014		Variable cost (M$/PJ) 2025	2040	Capacity to activity Unit	Capacity Factor (Daily variation) D	N
PP1 NGSC ; Nat gas	1	30	8.17	44	2300	-	-	24.15	31.53	1	1
PP2 DSGC ; Diesel	1	30	12.68	36	900	-	-	109.50	31.53	1	1
PP3 IGCC ; Coal gasification	1	30	12.93	148	3700	-	-	11.57	31.53	1	1
PP4 HFSC ; Heavy oïl	1	35	29.33	50	2300	-	-	35.67	31.53	1	1
PP5 Large Hydro	1	35	7.20	60	4000	-	-	0.0001	31.53	0.34 - 0.5	0.34 - 0.5
Mini Hydro	1	25	3.63	65	4500	-	-	0.0001	31.53	0.34 - 0.56	0.34 - 0.56
Distributed Diesel	1	40	12.68	55	1070	-	-	50.95	31.53	1	1
CSP	1	25	3.10	0	4500	-	-	46	31.53	0.28	0
PV_UTL	1	25	1.30	0	1800	-	-	8.33	31.53	0.15	0
PV_ROF	0	20	0	0	3200	-	-	8.33	31.53	0.15	0
Wind	1	25	10.32	0	1362	-	-	4.16	31.53	0.25	0.25
NGCC; NEW: Combined Cycle GT	1	35	8.17	44	1100	-	-	22.13	31.53	1	1
NEW : Nuclear (Light Water)	1	50	N. A	0	3000	-	-	13.42	31.53	1	1

3.1 Modeling Scenarios

To model the scenarios, all the parameters including technical and economical are identified from the MoManI training manual where the Atlantis power system has been modeled using OSeMOSYS [8]. For each technology, the EPBT is computed following Eq. 1.

Business As Usual (BAU). BAU is defined as a frozen version of the energetic system. The long-term evaluation of BAU allows the evaluation of the non-insertion of new initiatives into the nexus energetic mix. Figure 1 shows the yearly energy generation of the optimized technologies. Thus, the most competitive technology over the time horizon in terms of economical optimization is the Hydro dam next to the nuclear and wind technologies. Wind technology needs ten years since its introduction into the mix to reach the maximum capacity of 2 PJ. With the time horizon, nuclear production capacity increases by 70% and reaches a total of 2,400 MW on capacity integrated over the full period.

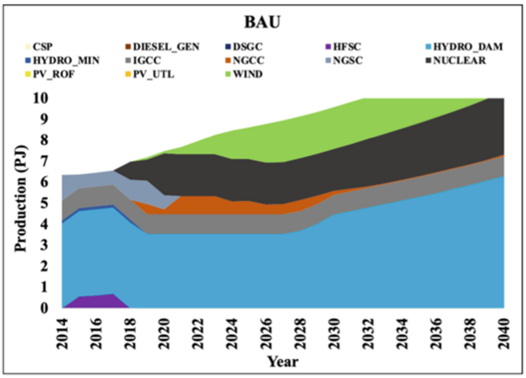

Fig. 1. BAU Annual energy production by technology

Effect of Applying Nuclear EPBT Values on the Energetic Mix. The first assumed scenarios are related to evaluating the effect of applying Nuclear EPBT values into the energy mix for economical optimization. Nuclear scenarios are compared with BAU to evaluate the effect of the EPBT.

Nuclear energy has been always at the center of social discussions. Probably, for this reason, EPBT cannot be precisely estimated. Because the nuclear fuel efficiency is high, only in production terms the EPBT is around 3 years. But, considering the power plant implementation as well as the waste management, the last estimations reflect a realistic EPBT between 80 and 300 years. Therefore, a set of three sub-scenarios are defined: a) Scenario with Nuclear EPBT = 20 years; b) Scenario with Nuclear EPBT = 80 years; c) Scenario with Nuclear EPBT = 300 years.

The effect of energetic sustainability on the optimization procedure for each of the defined sub-scenario is discussed following the annual energy production per technology as illustrated in Fig. 2. Indeed, Fig. 2 (b) and (c) show clearly that nuclear technology is not energetically sustainable and is not included in the energetics mix. The energy needed to be produced using the nuclear plant in BAU is now generated by the hydro dam. Even considering a short EPBT, the effect on the nuclear contribution to the energetic mixing decreases by 13% in terms of annual production capacity while additional new capacity integration is practically unnecessary (see Table 2 for details).

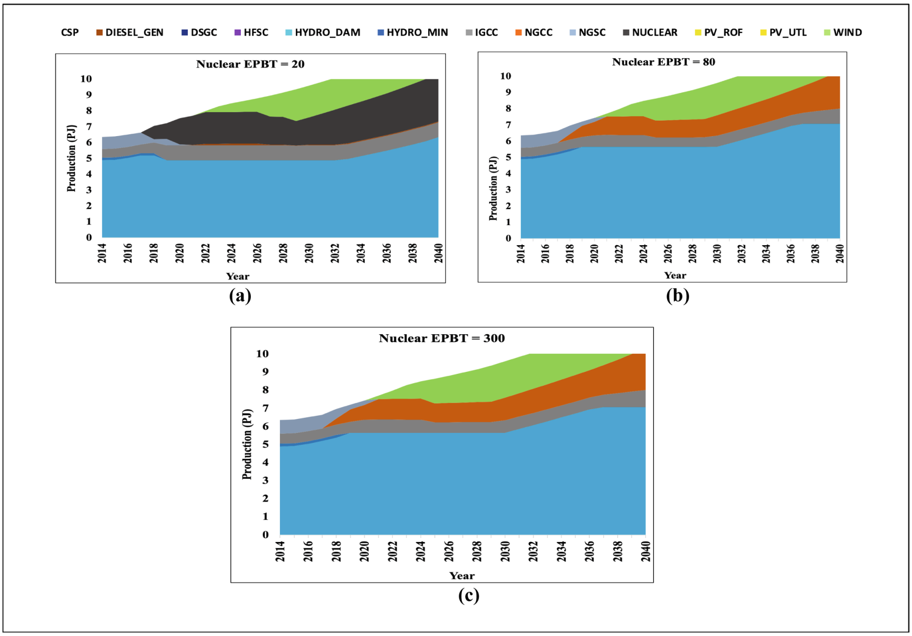

Fig. 2. Nuclear Scenarios; EPBT effect on the annual energy production by technology

Taking into account the current tendencies policymakers and experts argue toward nuclear energy that favoring the transition toward clean and safe energy without nuclear technologies. In addition, nuclear EPBT of 50 years of a lifetime can easily reach 100 or more years due to its dismantlement operation and its waste management which cost more in terms of financial cost, energy, and environmental hazard.

However, in all scenarios, Solar Photovoltaic (PV) technology looks still not competitive being its contribution null.

Table 2. Nuclear Total annual new capacity to be installed (MW) nuclear power

Year	**2014**	**2016**	**2018**	**2020**	**2022**	**2024**	**2026**	**2028**	**2030**	**2032**	**2034**	**2036**	**2038**	**2040**
BAU	0	0	33	70	70	80	85	86	100	130	140	145	155	162
Nuclear EPBT =20 year	0	0	57	100	110	110	110	110	110	125	136	145	151	160
Nuclear EPBT =80 year	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nuclear EPBT =300 year	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Effect of Applying PV Solar EPBT Values on the Energy Mix as a Function of the Climatic Condition. Technologies cannot only be optimized depending only on their financial cost but also depend on the resource availability, especially for RE that are climatically dependent as the solar PV. Solar PV technology efficiency hardly depends on both temperature and irradiation level, increasing the corresponding capacity factor (CF) which is the percentage of the daily effective working time. Solar PV in Atlantis is modeled with a CF of 15% which cannot be considered realistic. To adequate the CF values and based on the Köppen-Geiger climate classification as used by [20], three scenarios have been defined attending to their local solar resource as shown in Table 3.

Table 3. Solar PV capacity factor under the Köppen-Geiger climate classification

	Köppen-Geiger Climate type	Calculated Capacity factor
1	Polar	35%
2	Temperate and Continental	55%
3	Tropical, Arid	95%

For each climate type, two sets of scenarios are gathered and then optimized. The first set corresponds to the standard OSeMOSYS economic optimization, while in the second set of scenarios EPBT is included in the optimization procedure. In all the cases, EPBT for nuclear technology is higher than 80 years and has not been considered.

The corresponding energetic mixing optimization via the annual production by technology is plotted in Fig. 3 (a), (c), and (e). The first notice concern eventually the PV technology which doesn't weigh in the energetic mix when considering Atlantis as a polar region, where wind, hydro, and the non-conventional technologies are more competitive.

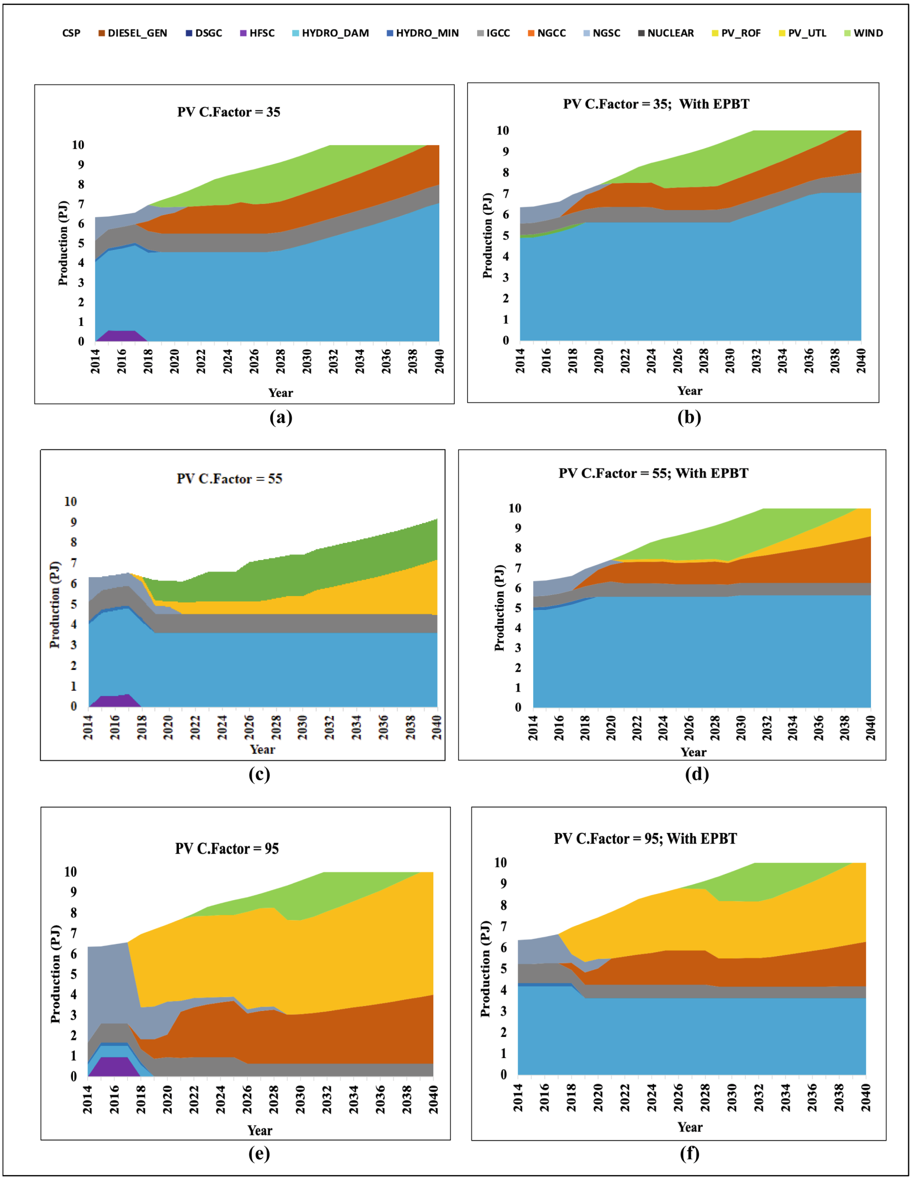

Fig. 3. Energetic mixing optimization via the annual production for different climatic condition. (a, c, e) economic optimization. In Fig (b, d, f) the corresponding EPBT is applied

Comparing the annual energy production for tropical and arid scenarios increases up to 57% more than the temperate and continental climate types.

Figure 3 (b), (d), and (f) show the same annual energetic production for the second set of scenarios when the EPBT estimator has been introduced into the optimization procedure. The EPBT value associated with the PV technology has been rudely calculated for each climatic condition. In all the cases, the EPBT inclusion effect is a decrease of the PV contribution to the energetic mixing being, by the time horizon ending, the 40% smaller for temperate continental climate, or 34% smaller for arid conditions.

Finally, Fig. 4 shows the contributions of PV technology to a wide spectrum of climatic zones. As can be seen, the effect of forcing energy sustainability is a slower installation of new capacity. Moreover, only for strongly irradiated climatic locations, the contribution of PV technology is greater than 10% of the demand when energetic sustainability constraints are applied.

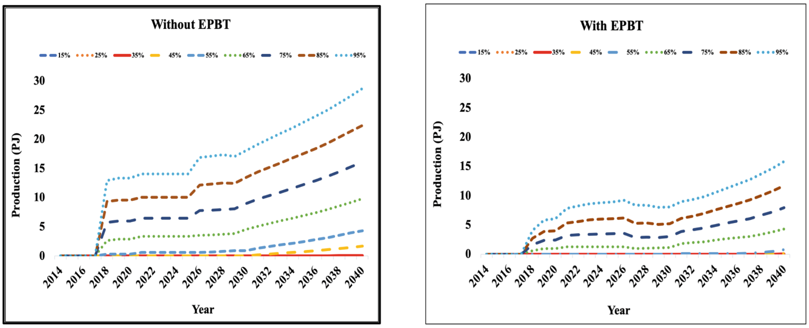

Fig. 4. Solar annual energy production scan over the capacity factor values

4 Conclusions

The effect of the implication of the energetic sustainability indicators on an optimal design of an energetic transition mix has been evaluated. The OSEMOSYS tool (CLEWs modeling tool for EWF optimization) has been used. As a case study, the Atlantis nexus has been considered. Because OSeMOSYS base the optimization procedures only on the economical index, a new equation, including energetic sustainability estimators (EPBT), has been designed and included in the standard tool.

Two particular cases have been studied: The effect of considering the EPBT on both nuclear and solar photovoltaic (PV) energy inclusion on the energetic mix on our target nexus Atlantis. In the case of PV, because the solar source depends on the climatic conditions, different scenarios, based on the Köppen-Geiger classification have been considered.

As a global conclusion, to ensure sustainability in the energetic transition, the inclusion of adequate estimators is crucial. More in detail, the inclusion of nuclear energy EPBT, force the not implementation of a new plant when nuclear waste management is included in the study.

Concerning the PV technology, as expected, the climatic condition is the parameter of merit to define the percentage of PV in the energetic mixing. Also, in this case, the EPBT plays an important role: because of the level of irradiation, high irradiation locations (smaller EPBT) are the best positioned. Moreover, the EPBT effect can inhibit the PV implantation in low irradiation locations, in terms of sustainability.

The developed initiatives will highly assist both developed and developing country decision-making settings toward an open and costless energy modeling system in the energetic sustainability context.

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