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Towards the Integration of Environmental and Bio-Economic Indicators in Energy Systems Modelling

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ABSTRACT

Current energy systems models do not generally provide a detailed analysis of environmental impacts. Even integrated assessment models (IAMs) that attempt to replicate the complex interactions between the economy, technosphere and biosphere at the global scale fail to consider impacts beyond the use of simplified relationships between parameters. This is troubling as energy technologies produce a range of environmental impacts within their life cycle beyond the carbon emissions that occur during the eventual energy production phase. Ignoring the nexus between energy systems, resource use and environmental impacts can also result in misleading information and misguided policy making. Life cycle assessment (LCA) methods provide far more detailed evaluations of processes within energy systems. Furthermore, combining LCA data with bio-economic metabolism approaches could enable the complex relationships between environmental impacts, material constraints and bio-economic functions to be assessed. Knowing that LCA outputs have previously been coupled with the well-established MuSIASEM approach to social metabolism, here we propose applying this synergy to the field of energy systems modelling. We introduce the ENBIOS module, a versatile methodology developed within the SENTINEL project that combines the bottom up, high resolution capabilities of LCA with the hierarchical multi-scale upscaling abilities of MuSIASEM for the analysis of energy systems at all scales. The module brings a more systemic methodology to the assessment of environmental impacts than previous approaches while offering a first attempt at quantifying the raw materials and circularity aspects that apply to energy systems. Recommended data inputs and possible indicators are also provided.

Keywords: renewable energy, energy transition, decarbonization, energy modeling, carbon emissions, critical raw materials

NONMENCLATURE

Abbreviations

CO_2	carbon dioxide
ESM	energy system model
EU	European Union
GHG	greenhouse gas
IAM	integrated assessment model
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
MJ	megajoule
MW	megawatt
PV	photovoltaic

1. INTRODUCTION

The European Union (EU) Energy Union Strategy [1] calls for a decarbonization of the energy system that allows member states to meet the commitments of the Paris Agreement. However, decarbonized energy systems with increased levels of renewable energy sources can have many "hidden" impacts over the environment [2]. Consequently, it has been suggested that the definition of sustainable energy transition pathways should consider the trade-offs between

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resources and other environmental impacts beyond direct greenhouse gas (GHG) emissions to air [3].

Administrations typically use energy system models (ESMs) for prospective energy scenario design. However, ESMs are generally weak at predicting the emergence of renewable energy technologies and do not adequately include sustainability dimensions [4]. While some efforts have been made to evaluate sustainability issues in energy systems using integrated assessment models (IAMs) and life cycle assessment (LCA) approaches, neither of these approaches is capable of providing thorough assessments in isolation. IAMs do not provide high-resolution environmental assessments while LCAs require support from integrated hierarchical frameworks when assessing technologies across a broader system [5].

Here, we introduce ENBIOS, an environmental assessment module that connects the bottom up, high resolution capabilities of LCA with the hierarchical upscaling abilities of the MuSIASEM approach [6]. We provide a brief introduction to LCA and MuSIASEM, explain the proposed integration of these two approaches using the ENBIOS package and provide a basic example of its implementation.

2. THEORETICAL ROOTS

2.1 Life cycle assessment (LCA)

LCA is a methodology for assessing environmental impacts across entire value chains and has been used to guide energy policy decisions by providing more detailed information relating to specific energy supply and demand processes. Individual input requirements are first determined as a life cycle inventory (LCI); these are then converted to impact indicators via a life cycle impacts assessment (LCA) process. LCA methodologies can be used to address the shortcomings of IAMs by providing more detailed estimates of the GHG emissions, environmental impacts, land and water use and raw material requirements associated with all individual energy sources within a system considering their full life cycle [5,7]. However, LCA can only report these indicators for individual processes and would require support from integrated hierarchical modelling frameworks to upscale and analyze the use of different energy technologies across entire energy systems within societies.

2.2 MuSIASEM

The foundational framework adopted in the ENBIOS module is taken from the MuSIASEM approach [8,9]. MuSIASEM is a well-established form of integrated assessment than uses the perspective of socio-ecosystem metabolism. Its power lies in its ability to analyze interactions that occur within and between levels in socio-ecosystems. By assuming that coherence is maintained across scales and dimensions, relationships between parameters and the locations of constraints within systems can be determined.

In order to create a system framework within a MuSIASEM environment, once must create a "dendrogram", a multi-level structure that arranges the system hierarchically into "processor" nodes where the relationships between internal and external flows and funds are calculated. Processors can operate in one of two capacities within the "tree" of the dendrogram: (a) "structural processors" that represent the inputs and

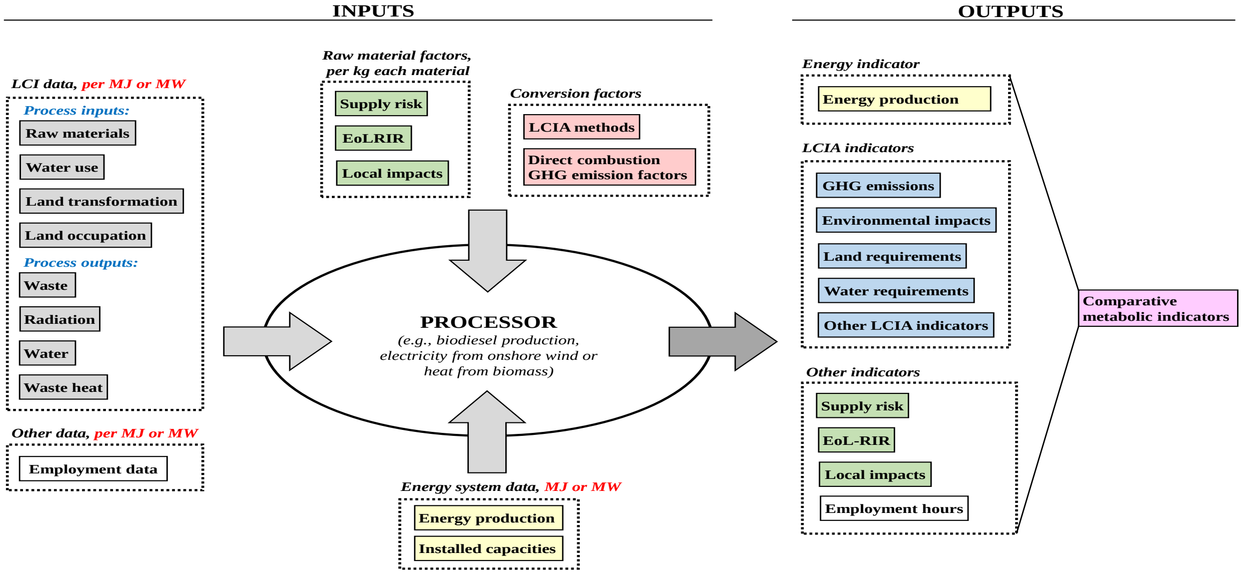

Fig. 1. Conceptual overview of ENBIOS module

outputs that occur at an individual structural element, e.g., energy produced via a specific electricity supply technology, and (b) "functional processors" occurring at higher levels that represent aggregations of lower-level attributes, e.g., all electricity generation.

3. ENBIOS EXPLAINED

To build upon previous efforts to integrate LCA functionality with IAM practices, and to include these connections within a framework also capable of considering raw material use and other socio-metabolic factors, a new module–known as ENBIOS–has been developed as part of the Horizon 2020 project SENTINEL.

The module uses defined energy system configurations–such as outputs from IAMs and other ESMs–which can then be analyzed in detail using the high-resolution environmental indicators from LCA alongside and a range of raw material, socio-metabolic and other factors. This is achieved using the well-established MuSIASEM approach that enables the upscaling of intensive properties within a system–in this case using energy system data including "energy mix" ratios and installed capacities–while also allowing the relationships between different functions within that system to be interrogated. A general conceptual overview of the module is given in Fig. 1.

While LCA outputs have previously been used as technical coefficients within MuSIASEM analyses for various systems, the new module is being developed as a universal tool specifically for analyzing energy systems. What's more, the required processes are to be operationalized into a Python software package that allows testing to be automated and permits system configurations, inputs and indicators to be easily customized to the needs of the user. As such, ENBIOS offers an innovative method for understanding the distribution of different environmental and socio-metabolic factors within energy systems which, in turn, allows for more rounded assessments of the interactions and constraints relating to different system configurations to be identified.

3.1 Defining the MuSIASEM dendrogram

When undertaking an assessment of an energy system in ENBIOS, a specific MuSIASEM dendrogram must be defined for the system of interest. Within the SENTINEL project, the dendrogram structure has been defined to be aligned with the most commonly available energy data for the EU–Eurostat–and with the outputs being supplied from two ESMs being used within the project–EnergyPLAN [10] and Calliope [11].

Here, the dendrogram contains a simplified version of the EU system that includes the most common forms of fuels used for direct consumption (mostly fuels for transport and non-centralized fuel and electricity production) and processes of electricity and heat generation at the centralized utility level. The framework is arranged such that structural processors representing the individual sub-technologies are shown as rounded blocks in the column at the center of the diagram. Meanwhile, the functional processors that aggregate these according to energy type and infrastructure type are shown as square blocks to the left and right of this

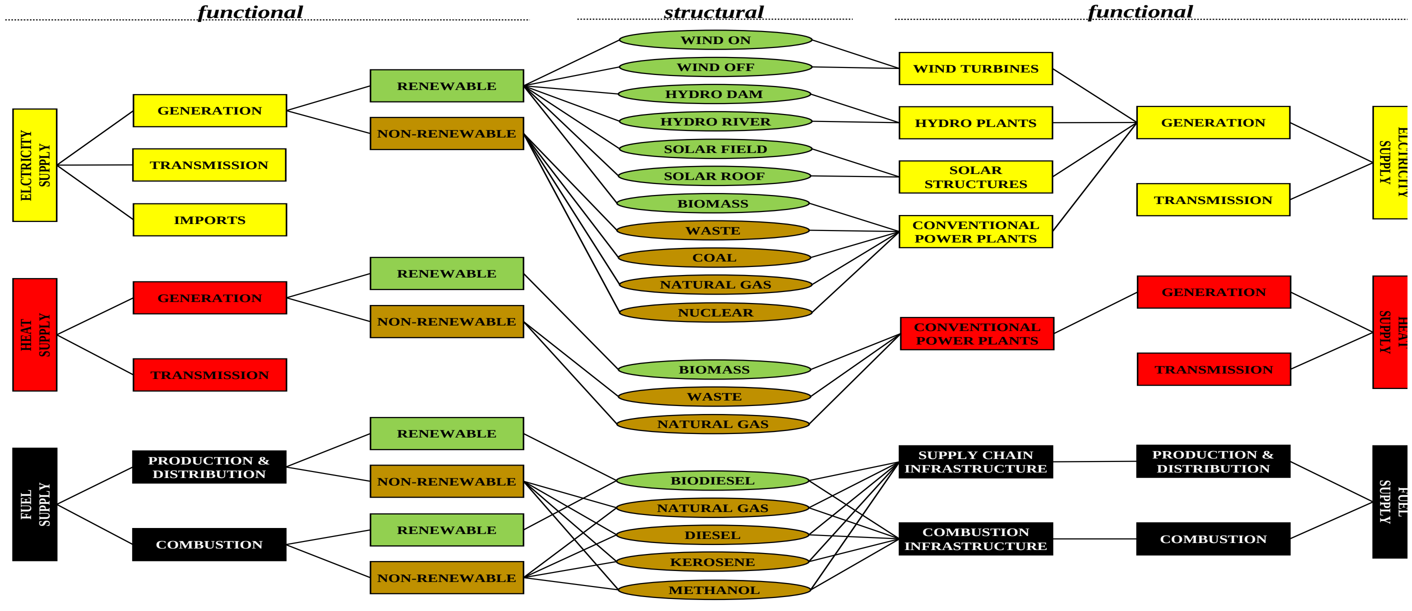

Fig. 2. ENBIOS dendrogram structure for EU energy system

column, respectively. A representation of the dendrogram for the EU is shown in Fig. 2.

Several types of data are required to enable calculations to be undertaken at each structural processor. Likewise, a number of result outputs in the form of LCIA and other indicators are produced at each processor (see Fig. 1). Firstly, LCI data must be assigned to the processor–one LCI process per processor–from the available databases. ENBIOS uses data in ecospold (.spold) format from the ecoinvent 3.8 database [12] that provides data for each megajoule (MJ) of energy produced via the given process. This includes data for the mass requirements–in kg–for 103 materials, water use–in m^3–for 10 classes of water, land transformation–in m^2–for 90 landcover types and land occupation–in m^2.yr–for 40 landcover types as inputs. Outputs to land, water and soil are given in relation to radiation–in kBq–for 71 radioactive chemicals, waste outputs in kg–for 664 materials, water outputs–in m^3–for nine classes of water and eight types of waste heat–in MJ. Other socio-metabolic data–e.g., raw material factors and employment data–can also be imported to the system for processing, as shown in Fig. 1.

Meanwhile, many "methods" exist for defining the way that LCI data is converted to specific indicators during the LCIA stage [12,13]. The required methods must be specified prior to the module calculations and can be easily changed by the user to test the use of different methods. Lastly, as the LCI processes for fuel production do not consider the combustion of the fuels in final use stage (e.g., operation of internal combustion engines or home heating via natural gas) the additional GHG emissions for fuels must be added on to the GHG emissions total for the fuel production stages. Here, emission factors are taken from the IPCC database [14].

3.2 *Module application*

The outputs derived for each individual energy production process–i.e., at each structural processor–can then be further utilized in ENBIOS in two ways. Firstly, additional comparative metabolic indicators can be derived at the processor using combinations of other indicators. For example, one could create an additional indicator for the ratio of GHG emissions to employment job years or the land requirements to water requirements. Such metrics could be used as proxy performance indicators for comparing processors, for example. More fundamental to the MuSIASEM approach is the ability to scale-up indicators within and across levels of the dendrogram. This is typically done according to the "mix" of energy types provided by information from IAMs and other ESMs. Indicator values are "weighted" and aggregated at higher functional processors according to the relative amounts of energy contributed at each structural processor. This enables

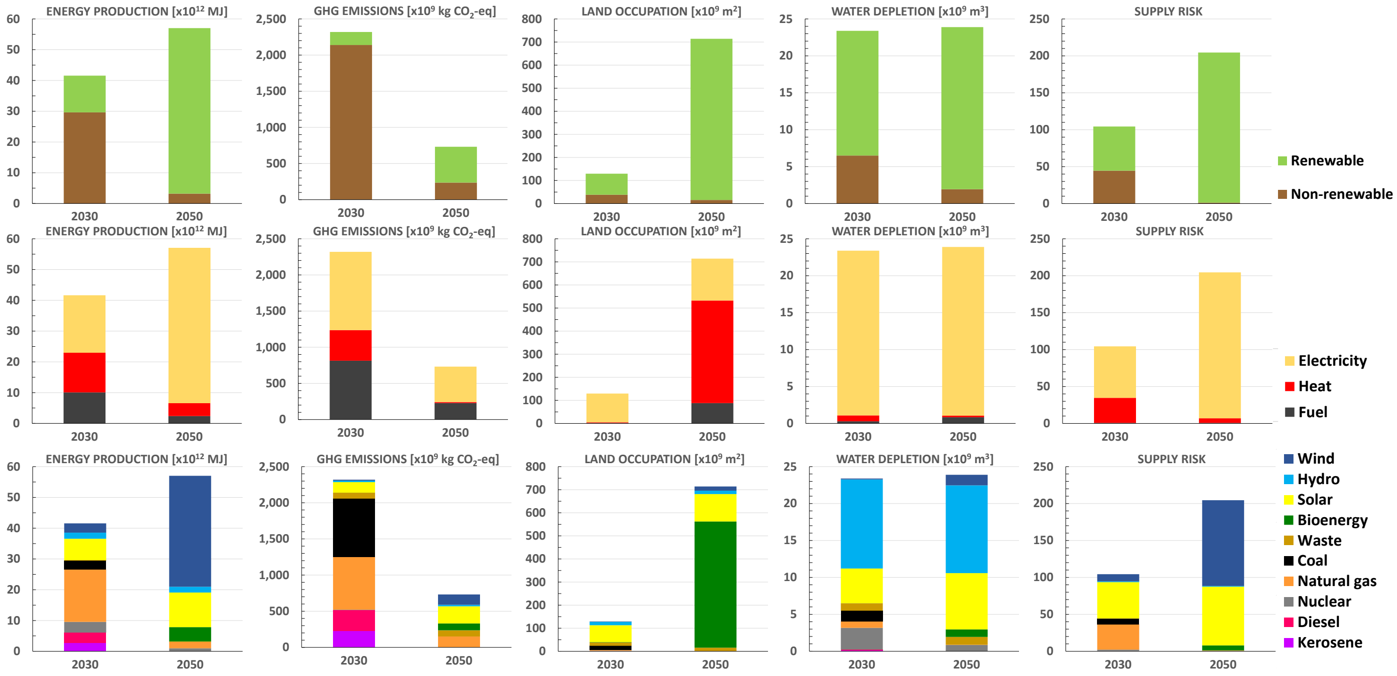

Fig. 3. Sample ENBIOS results showing outputs for five indicators across three categorizations for projected 2030 and 2050 energy mixes under the "climate neutrality" scenario for EU, according to preliminary Calliope model outputs

further analysis at functional processors and, eventually, entire systems.

4. IMPLEMENTATION EXAMPLE

A graphical sample of typical results from an application of ENBIOS is shown in Fig. 3. Here, a preliminary set of projected results were obtained from the Calliope model that reflect the energy mix for the EU under the so-called “climate neutrality” scenario [15] for the years 2030 and 2050. The first column of graphs reflects total energy production, the middle three columns show results for three LCIA indicators using the ReCiPe Midpoint (H) V1.13 methods [16]–GHG emissions (GWP100) in kg CO2-eq, land occupation (ALOP and ULOP) in m^2 and water depletion (WDP) in m^3–while the final column reflects raw material supply risk, calculated using LCI data for 55 critical raw materials according to [17]. Aggregations are shown for the status of the energy source (renewable or otherwise), the energy carrier class (electricity, heat or fuel) and type of technology.

Results and implications of this and other scenarios are to be discussed in future publications. However, the representation shown in Fig. 1 demonstrates the manner in which ENBIOS can be used to aggregate and analyze outcomes for different scenarios from different perspectives. For example, in the example shown, analyses could be performed between categorizations (top to bottom) or indicators (left to right) to form different conclusions about different scenarios.

5. DISCUSSION

The module is thought to be innovative by improving on the functionality of existing methods in several key areas. Fundamentally, the module has been formulated to provide a streamlined method for assessing multiple future energy system scenarios that allows the benefits and limitations of different energy transition pathways to be compared with each other and with current benchmarks. To enable this, the module brings a new and more systemic approach to the assessment of environmental impacts using a methodology that combines the added resolution provided by LCA methodologies with the metabolic functionality of the MuSIASEM approach, all in a format that is easily linked to outputs from IAMs and other ESMs.

Furthermore, the module offers a first attempt to include supply risk, circularity, local impacts and other raw material indicators to the energy modelling area. This allows scenarios to be assessed from a raw materials perspective to see if certain pathways are significantly preferable or more viable than others in this regard. Ultimately, the module seeks to determine whether different scenarios proposed for implementing the renewable energy transition are technically feasible and if they are compatible with the broader aims of current climate policy in terms of GHG emissions and other environmental impacts.

Nevertheless, the module is subject to a number of limitations. A lack of LCA data for renewable energy sources, particularly for burgeoning technologies, remains an issue in the field. For example, no wind turbines have been defined with a capacity beyond 3 megawatts (MW), despite the fact that units with capacities above 5 MW are relatively commonplace. Newer solar photovoltaic (PV) and bioenergy technologies are also underrepresented. Energy storage technologies are also very poorly represented in the databases and have not been included in the current version of ENBIOS. Furthermore, many of the most common databases are restricted to paying clients. This could seriously restrict the penetration of ENBIOS and similar applications as the data that drives them could be “trapped” behind a paywall for many potential users.

Notwithstanding issues of data availability, the module in its current form is somewhat simplified by assigning one LCI process for each of the energy technologies for all of the EU. This is partly because the resolution of results coming from the Calliope and EnergyPLAN energy models do not allow for multiple sub-technologies. However, different combinations of sub-technologies could be simulated in ENBIOS if some assumptions about current or future “splits” were made. Furthermore, many energy models do offer higher levels of spatial resolution; many offer energy mix data at the national or regional level. To make better use of this data, the dendrogram in ENBIOS could be expanded to include different sub-systems, although this is unlikely to occur within the current project.

6. CONCLUSION

The ENBIOS module represents a first attempt at embedding high-definition LCA data into a social metabolism framework across a complete energy system. While the module does not yet attempt to use model outputs to alter LCI components directly like some applications, it joins a growing move towards the wider inclusion of LCA concepts in energy modelling processes applications [18,19]. This will result in models that include far better representations of environmental impacts and potential sources of constraint as we strive to achieve optimal solutions to the climate crisis while implementing cleaner and more sustainable energy systems as rapidly as possible.

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