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Carbon accounting in the context of multi-criteria assessment for SLES: challenges and opportunities

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Abstract: In the UK, national carbon emission reduction targets aim to reach Net Zero by 2050, with a fully decarbonised electricity system by 2035. Smart Local Energy Systems (SLES) are being deployed to combine and intelligently control complementary low and zero carbon technologies within micro-grids to amplify their impacts and accelerate this ambitious transition towards a decarbonized energy system and low-carbon society.

Today, national and local governments monitor the potential carbon reduction of energy system retrofitting and policy implementation through simplified carbon accounting methods, which allow for calculation of the accumulated carbon emissions. This focus on carbon may, however, neglect broader socioeconomic impacts and benefits of these actions.

This paper describes the how the application of a multi-criteria assessment tool focusing on SLES can be used to evaluate (i) the carbon emissions from an energy system and (ii) the carbon reduction potential of renewable and smart energy technology implementation. Alongside the carbon accounting this MCA-SLES tool provides assessment and insights into the local socioeconomic and environmental benefits and impacts of the SLES development. The application of such a complex assessment tool has challenges in application, such as data collection, the intensity of the stakeholder approach, and the large volume of information for user dissemination. This paper illustrates how the developed assessment tool mitigates for these challenges and highlights the opportunity for small-scale energy development projects to employ it to assess project feasibility and progress towards economic, social, and environmental co-benefits.

Keywords: Carbon Accounting, Life Cycle Assessment, Multi-Criteria, Energy System Assessment

1. Introduction

Transitioning the global energy systems away from burning of fossil fuel for energy generation towards greener and low-carbon energy systems is a critical element in global efforts to combat the climate crisis and mitigating the overall negative future impact caused by climate change (Blanco et al. 2020; Morrissey et al. 2020; Ford et al. 2021). Carbon reduction is thus one of the core objectives of the energy transition strategy centred around the phase-out of fossil-fuel-driven energy technologies with renewable and low-carbon energy technologies (Clarke et al. 2017; Bottero et al. 2021; Ahmed et al. 2023).

This energy system transition on a national scale can be achieved through various approaches and strategies. In the United Kingdom, the energy system decarbonization strategy includes full-scale development and deployment of new energy system solutions, i.e., the development and deployment of Smart Local Energy System (SLES) projects like Reflex in the Orkney Islands (Reflex Orkney 2020; Couraud et al. 2023). Alongside this, the UK strategy includes more focused investment and development of offshore wind farm projects, greener buildings, and technology for energy generation from emerging low-carbon energy sources, such as hydrogen (Foxon 2013; Nerini, Keppo & Strachan 2017; BEIS 2020; HM Government 2020, Lovell & Foxon 2021).

Modelling and energy system analysis are critical to assess the dynamic interaction between all dimensions associated with an energy system (energy, technology, social, economic, and environment) (de Blas et al., 2020; Gudlaugsson et al., 2022). Models are widely used to understand the potential impacts of energy system changes, and implementation of energy policy and strategy (Antenucci et al., 2019; Bottero et al., 2021; de Blas et al., 2020; Blanco et al. 2020).The ability to monitor the potential of energy projects alongside overall emission reduction capabilities is, therefore, important for project developers and policymakers to ensure that the project contributes to the overall objectives of the energy transition (Antenucci et al., 2019; Bottero et al., 2021; de Blas et al., 2020; Blanco et al. 2020**).**

The framework for such models is based on a number of standardised methods. In recent years LCA methodology has been widely recognised as a powerful modelling tool to assess the environmental impacts of energy systems (such as GHG emissions, impact of human health, ecosystem and biodiversity) throughout the whole life cycle of components and processes (Blanco et al., 2020; Ahmed et al. 2023). Ahmed et al. (2023) also points out that various economic analysis tools like Cost-Benefit Analysis (CBA) have been developed and applied to understand the impacts and benefits of energy system retrofitting. Integrated Assessment Models (IAMs) are often used to connect together core elements of society and the economy dimensions with environmental and climate dimensions when assessing energy system transition (De Blas et al., 2020). Carbon accounting assessment and modelling is another approach that has been used in relation to sustainability management (Schaltegger & Csutore 2012, de Souza Leao et al. 2019).

The application of a broad multi-criteria assessment (MCA) to complex SLESs is, however, a challenge. This paper provides insights into the development of such an MCA-SLES tool, describing how it embraces and integrates carbon accounting and LCA fundamentals to track climate change impacts alongside multiple other criteria in a simplified and user-friendly modelling framework. The rest of the paper is organised as follows: **Section 2** provides a brief background on the carbon accounting and LCA methods, and the MCA-SLES Tool. **Section 3** addresses the discussion on how the MCA-SLES tool delivers a simple assessment framework for a wide range of users, adapting for the complex nature of LCA and carbon accounting, and the limitations and challenges. **Section 4** provides the concluding remarks.

2. Background

2.1. Carbon Accounting

According to Stechemesser and Guenther, (2012) carbon accounting comprises the recognition, evaluation and monitoring of greenhouse gas (GHG) emissions on all levels of the value chain and the corresponding effects of these emissions on the carbon cycle of ecosystems. Therefore, carbon accounting has become the favoured tool to assess GHG emissions for, for example, national emission numbers (Department for Energy Security and Net-Zero, 2023), corporation emissions numbers (Schaltegger & Csutore 2012) and urban emissions (de Souza Leao et al. 2020). Nevertheless, de Souza Leao et al. (2020) points that the carbon accounting method has its limitation when assessing GHG emissions at different levels, which can result in some GHG emissions sources being underestimated or neglected. This limitation is associated with the scope and carbon accounting approaches selected, data availability, and higher degrees of uncertainty.

2.2. Life-Cycle Analysis

LCA has become one of more prominent assessment methods used to assess and understand the environmental impacts of the energy system transition (Blanco et al. 2020) and national emissions (Clarke et al. 2017). There are several LCA methods including: input-output (IO) analysis (a top-down technique); process-based (PB) LCA, which is a bottom-up approach; hybrid LCA that combines both IO and PB systems (Kennelly *et al.*, 2019). IO analysis is a form of consumption-based accounting. For all methods the system boundary should identify how allocation is managed when there are multiple co-products: whether it is based on physical or economic allocation or system expansion.

The LCA method, however, has limitations when it comes to assessment of the environmental impacts of an energy system (Blanco et al., 2020; Clarke et al., 2017). These include: (i) double-counting of related values when expending the LCA assessment model, leading to double counting of emissions or factors attached to inputs and outputs in the system; (ii) uncertainties introduced by assumptions on the performance of future technologies with regards to factors such as fuel consumption, energy production, and efficiencies, which can vary between models and studies; (iii) spatial differences in source data depending on data variability (i.e. geographically local or global information), which can impact the overall results when looking at the local level impacts (Blanco et al., 2020; Clarke et al., 2017).

2.3. MCA-SLES Tool

The MCA-SLES tool that was developed by the Energy Revolutions Research Consortium (EnergyREV) focusses on delivering a simplified energy system assessment framework for local policymakers, project teams and planners for smart local energy systems developed and deployed in local communities (Francis et al. 2020; Francis et al. 2022; Gudlaugsson et al. 2023a; 2023b). The MCA-SLES tool enables identification of the benefits, potential risks and underlying consequences associated with the energy project. The MCA-SLES tool assesses two main sections (see Figure 1).

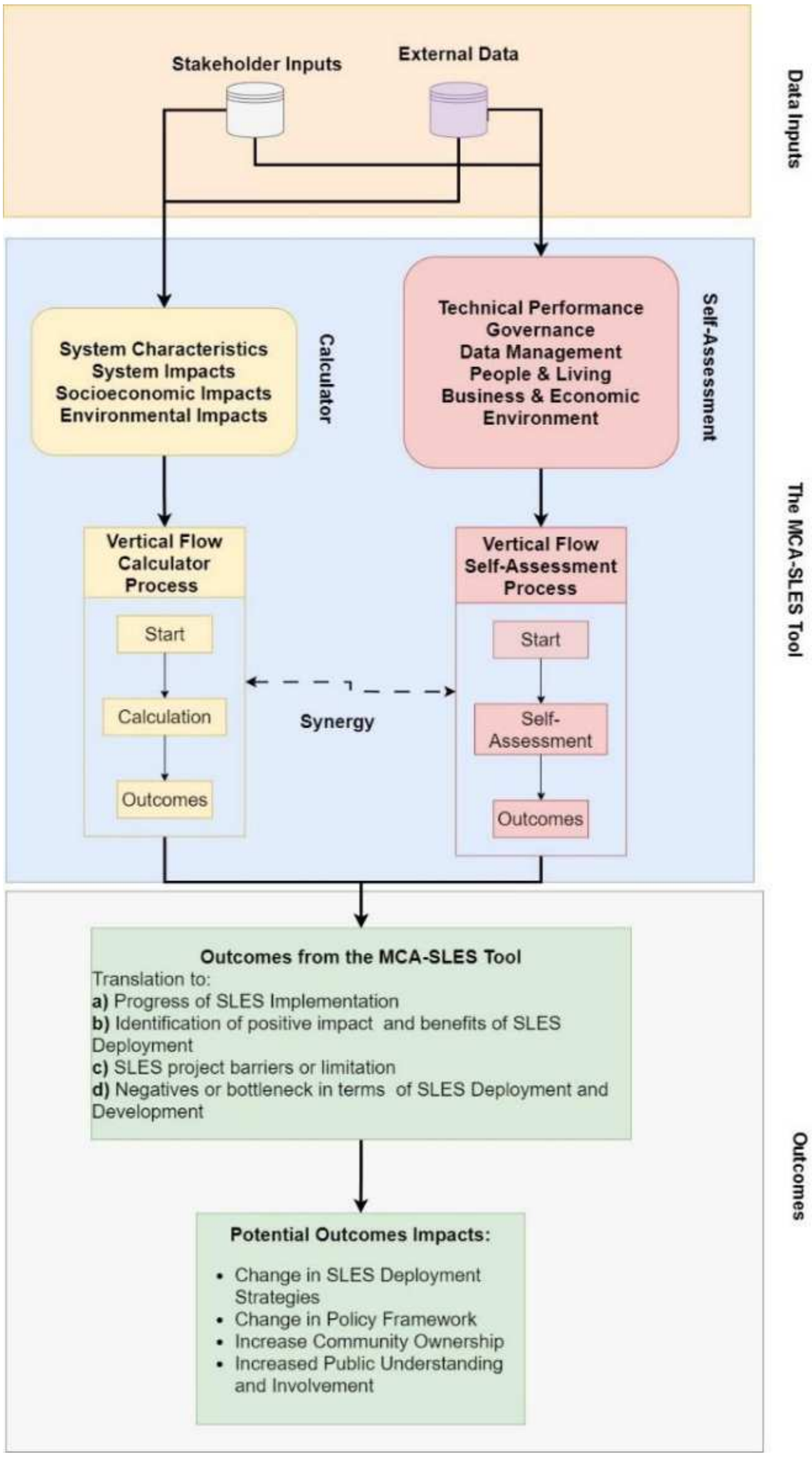

Figure 1: MCA-SLES Tool – Flowchart illustration of the tool processes and outcomes

The first section is a general calculation of a range of variables to be measured (system characteristics and impacts; socioeconomic and environmental impacts). The second section is a qualitative self-assessment (across six high-level themes: technical performance, governance, data management, people and living, business economic and environment) by the project team focused on setting targets of their goals for each of the variables, which allows for progress analysis to carried out in the second sections, and results present as shown in figure 2 below. Consequently, the input-data provided to assess the multiple criteria for the SLES monitors the progress made towards the objectives set by the project team and primary stakeholders.

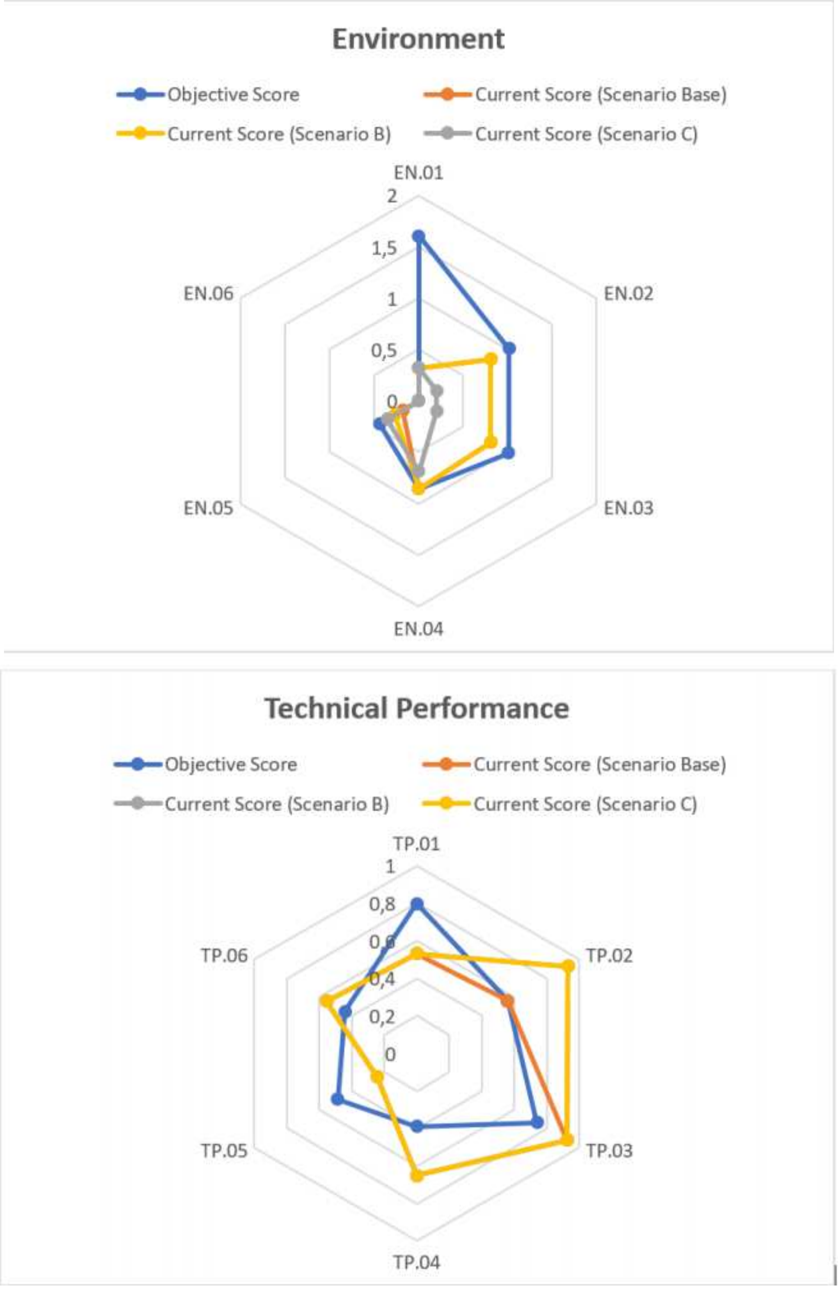

Figure 2: Visual illustration of the outcomes from Self-Assessment Section

The Calculator includes 93 parameters across four sections, some of which require inputs from the practitioners of the MCA-SLES tool to carry out the assessment calculations (Gudlaugsson et al. 2023b). The Self-Assessment includes 37 parameters that all need to be input by the practitioners in relation to project aspirations and objectives when setting up the MCA-SLES tool (Gudlaugsson et al. 2023b). These parameters and the relationships between the MCA-SLES tool sections are presented in Figure 3 below. This also gives some examples of required inputs; for example, Technology Readiness Level of the technologies in the current and proposed system, job creation in relation to system changes, and land requirements for each energy technology in the current and proposed systems.

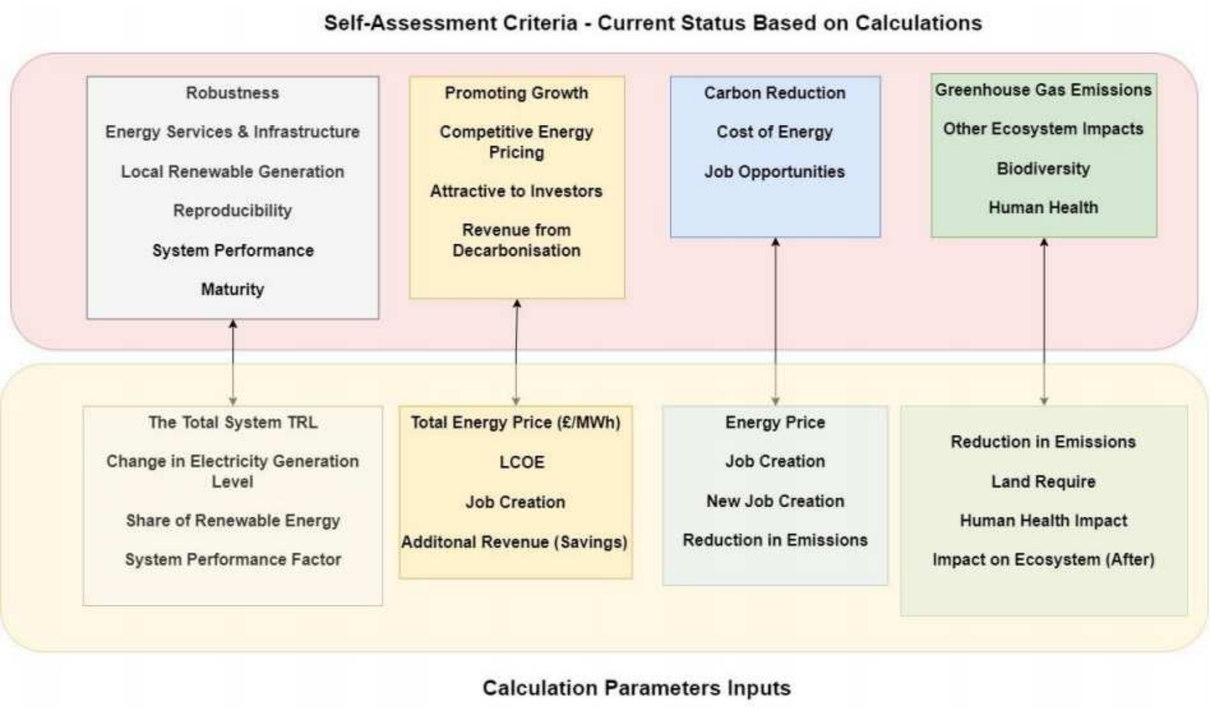

Figure 3: MCA-SLES tool parameters, and relationship between the Calculator and Self-Assessment Sections

The MCA-SLES tool estimates the carbon footprint of the whole SLES from climate change impacts per kWh for each type of energy generation. One of the limitations of this method is that the environmental impacts of renewable energy are assumed to be constant per unit of energy produced, as with fossil generation. For the latter, however, most of the environmental impacts are associated with fuel combustion for energy production, while for renewables they largely arise during manufacture and installation, and are thus independent of energy production. This can lead to an overestimate of environmental impact in areas with a higher availability of renewable resource. Future development of the MCA-SLES tool should estimate the impacts of non-thermal renewable generation based on installed capacity, rather than energy production. This will properly allow for the benefits or penalties of higher/lower availability of the renewable resource.

In order to test this, we estimated the LCA of different renewable energy technologies and fossil fuel-based technologies from a leading Life Cycle inventory dataset and the ReCiPe impact assessment method (Goedkoop et al., 2009).

Table 1. Case Study Information – Energy Technology and Generation Capacities (AquaTerra Ltd & Community Energy Scotland, 2022)

	Energy Technologies (Local)	**Generation Values**	**Unit**
	Large Scale Offshore wind power	44.7	MW
	Hydropower	30	MW
	Photovoltaic	1.3	MW
Case A	**Total Energy Generation**	**76**	**MW**
	Large scale Offshore wind power (accepted/planning)	47.3	MW
Case B	**Total Energy Generation**	**123.3**	**MW**
	Large Scale Offshore Wind power (in development)	183.5	MW
Case C	**Total Energy Generation**	**306.8**	**MW**

Then we mapped out the energy system and energy technology portfolio of a small local energy system (in this case the Orkney Islands), and generated three development scenarios based on published reports (Matthews & Scheer, 2020; Orkney Islands Council, 2022; AquaTerra Ltd & Community Energy Scotland, 2022). The LCA data was used to calculate the carbon emission and footprint of the current technologies in the system and added installed capacities. Figure 4 illustrate the system boundaries of the energy system that used as case study in the analysis, and table 1 provide information on generation capacity of the different energy technologies.

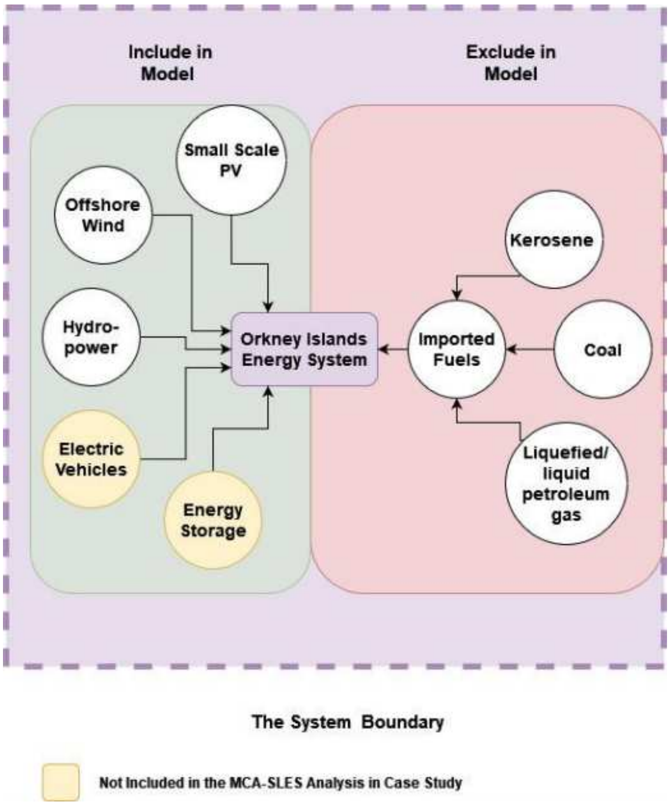

Figure 4: System Boundaries for the Testing Case for MCA-SLES Tool

The results obtained from the application of the MCA-SLES tool when looking at the carbon footprint in relation to the three scenarios, presents that the carbon footprint for the three scenarios were found to increase between the scenarios; being 0,012 kgCO2eq/kWh in scenario A, 0,013 kgCO2eq/kWh in scenario B, and 0,015 kgCO2eq/kWh in scenario C. Therefore, highlighting the overall impact of change in generation mix of the Orkney Islands, this increase is due to the higher share of the offshore wind added to the system, which has a higher carbon footprint then existing hydropower. The MCA-SLES tool is capable of evaluating the impacts of some demand and infrastructure technologies, such as electric vehicles and energy storage, but does not strictly consider the whole system as the impacts of the network infrastructure and any imported fuels are excluded, as illustrated in Figure 4.

This shows that the MCA-SLES Tool is has the ability to carry out environmental impact (carbon footprint), however the application is a result of the highly simplified nature of the analysis. This compromise was made to facilitate rapid use of the MCA-SLES tool for a holistic multi-criteria assessment. Furthermore, the results have a significant uncertainty due to the uncertainty of the source data. Further work is required to refine the carbon accounting process to improve the reliability and robustness of the results without creating an unacceptable burden for the end-user.

3. Discussion integration of Carbon Accounting and LCA Methods to MCA-SLES Tool

3.1. System Boundaries and Framing of Analysis

The first activities of an LCA or carbon accounting are to define the system boundaries and frame the analysis (Grafakos et al., 2017, Blanco et al. 2020). These provide the scope of the analysis and highlight what input data are required, identifying what components or factors of the system are included and excluded (Blanco et al. 2020).

The MCA-SLES tool integrates the LCA, carbon accounting and system thinking fundamentals into the tool's analytical process (Gudlaugsson et al. 2023a, 2023b). The MCA-SLES tool provides the practitioners with predefined system boundaries and framing of the analysis. The MCA-SLES tool's analytical framing is structured around energy system modelling and assessment, and the system boundary is structured around the energy system and key energy vectors (energy resources, generation technologies, energy demand and generation).

The MCA-SLES Tool users are given analytical framing and boundaries with creative freedom to adjust the energy system that being analysed i.e., a practitioner is asked in the System Characteristics section of the Calculator (see Figure 1) to define what energy technologies are in the system currently as well as those which are planned to be added to the system. In addition, the user is also asked to provide technical information on each technology, and current and planned generation capacity (following new technology integration), which allows the MCA-SLES tool to calculate any change in impacts associated with the change in generation capacity and energy technologies portfolio mix due to the SLES development.

Within the MCA-SLES tool the application of this process was intended to minimise the time required for extensive data collection and fully defining and framing an LCA modelling analysis. It also allows for consistency and comparison across assessments. The emphasis is to provide the users with an Excel-based tool that is ready to use, similar to the BEIS Whole Life Cost of Energy Calculator developed by the Department of Business, Energy, and Industrial Strategy (BEIS, 2020b).

The testing of the MCA-SLES tool by local government policy makers, academics, and industry stakeholders that attended an EnergyREV event in March 2023 provided insights into its usability. The policy makers found the tool extremely interesting for application in assessing energy system transition policies, with straightforward application, and easy understanding of the system framing and data input requirements, partially due to the MCA-SLES tool being implemented in Excel.

3.2. Accounting for System-Wide Impacts

Carbon accounting and LCA are commonly-used methods to assess overall system GHG emissions, alongside wider environmental impacts such as ecosystem degradation, biodiversity loss, and impact on human health (Blanco et al. 2020**)**. Moreover, in recent years both methods have been more commonly used in integration with others, such as Life-Cycle Costs (LCC), IO analysis, Multi-Criteria Decision Analysis (MCDA) and IMAs to enable the assessment and analysis of wider-system impacts of the system being analysed (Clarke et al 2017). This mitigates some limitations, such as neglecting or underestimating specific sources of GHG emissions within the system, or being too focused on the environmental impacts and not capturing the wider social and economic system impacts.

The MCA-SLES tool integrates carbon accounting and LCA fundamentals into a whole-system multi-criteria analysis, as illustrated in Figures 1 and 2. The MCA-SLES tool is designed to account for multi-dimensional aspects of an energy system in 4 separate sections. The calculation parameters (Figure 2) are divided as follows: *Section 1* – System Characteristics – focuses on the technical aspects of the energy system and gives insight into share of renewables, Technology Readiness Level, etc.; *Section 2* – System Impact – focuses on the economic impact such as cost of energy, level of renewable and fossil fuels in the system, and potential revenue; *Section 3* – Socioeconomic – focuses on the social impact such job creation and energy price; *Section 4* – Environmental Impact – focuses on understanding the environmental impact of the system change. The Tool incorporates data from LCA databases and analyses for values on land usage, emissions, human health impact and ecosystem impact for different energy generation technologies to enable the whole-system analysis to capture the holistic environmental impacts of the energy system transition and development.

The application process of the MCA-SLES tool allows for whole-system analysis of the current local energy system and comparison with the planned or intended local energy system. The MCA-SLES tool provides results and information on the wider system impact, enabling users to better understand the holistic impacts and benefits expected or attained from projects and strategies undertaken as part of the energy transition.

4. Conclusion and Further Work

The ability for local communities, policymakers, and energy strategy designers to carry out energy system analysis may be increasingly important to the success of local energy system transitioning towards greener and low carbon energy system. The described SLES MCA-SLES tool empowers local community policy making and design by providing visual illustrations and easily digestible information on the potential impacts, co-benefits and barriers concerning a specific energy policy strategy at a specific local level. The MCA-SLES tool incorporates LCA and carbon accounting methodological frameworks to conduct emissions and environmental impacts assessment while also incorporating multi-criteria and system thinking approaches to accounting for the dynamic and interconnective nature of an energy system to being able to carry out the wider system analysis of an SLES project. The MCA-SLES tool accounts for, and mitigates the potential limitations and challenges resulting from issues pertaining to the system boundary and double counting challenges of input and output values by providing practitioners with a structured analytical framework focused on the energy system with some predefined input parameters.

Regarding the collection of geographical location and local data availability the MCA-MCA-SLES tool requires local practitioners using the MCA-SLES tool to engage with the local stakeholders to acquire local data is possible. Where that is not possible the MCA-SLES tool provides a generic data input sheet providing information attained from literature, LCA databases and simulations. Overall, the MCA-SLES tool developed by the team at IES at the University of Edinburgh can provide practitioners with an excel based analytical tool that can be used carry out whole system assessment on current local energy systems while also providing a comparative scenario analysis tool to compare current local energy system performance before and after the proposed energy system changes in policy or strategy are implemented. Lastly, further work is required to test the MCA-SLES tool in real communities, real data and work with a range of possible practitioners to explore how the MCA-SLES tool might best be employed in future to cost-effectively accelerate the transition to a lower carbon future.

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