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An approach to prospective consequential life cycle assessment and net energy analysis of distributed electricity generation

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HIGHLIGHTS

- A common LCA and NEA framework for prospective, consequential analysis is discussed.
- Approach to combined LCA and NEA of distributed generation scenarios is proposed.
- Static and dynamic temporal allocation needed to assess distributed generation uptake.

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ABSTRACT

Increasing distributed renewable electricity generation is one of a number of technology pathways available to policy makers to meet environmental and other sustainability goals. Determining the efficacy of such a pathway for a national electricity system implies evaluating whole system change in future scenarios. Life cycle assessment (LCA) and net energy analysis (NEA) are two methodologies suitable for prospective and consequential analysis of energy performance and associated impacts. This paper discusses the benefits and limitations of prospective and consequential LCA and NEA analysis of distributed generation. It concludes that a combined LCA and NEA approach is a valuable tool for decision makers if a number of recommendations are addressed. Static and dynamic temporal allocation are both needed for a fair comparison of distributed renewables with thermal power stations to account for their different impact profiles over time. The trade-offs between comprehensiveness and uncertainty in consequential analysis should be acknowledged, with system boundary expansion and system simulation models limited to those clearly justified by the research goal. The results of this approach are explorative, rather than for accounting purposes; this interpretive remit, and the assumptions in scenarios and system models on which results are contingent, must be clear to end users.

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1. Introduction

The challenges posed by pressing environmental concerns, such as climate change, often prompt long term goals and targets for stakeholders in large systems such as a national energy infrastructure. As the ultimate concern in these circumstances is an overall change in the performance of a system, commensurate with regional, national or supranational targets, understanding future, system-wide impacts of an intervention is a priority for decision makers.

A shift to distributed renewable electricity generation is considered to be one pathway to meeting environmental objectives and social goals, including resilience to supply disruption (Barnham et al., 2013; Ruiz-Romero et al., 2013). The principle distributed generation technologies considered for the decarbonisation of electricity generation in developed countries are grid-connected solar photovoltaics (PV) and small scale or micro wind generators (Nugent and Sovacool, 2014). Distributed generation may be integrated with a building (i.e. installed on a rooftop or mounted nearby and connected to a building's electricity supply), or deployed in relatively small arrays (typically < 50 MW) connected to the electricity distribution network. While these technologies cause negligible environmental impact in their use phase, other phases of their life cycles, particularly manufacturing, do entail environmental burdens. Furthermore, increasing distributed generation leads to a change in the utilisation of electricity

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networks, and additional power flows on local networks may require modifications to this infrastructure. Increasing intermittent renewable electricity generation, has consequential impacts on the use of centralised thermal generation and back up capacity which may offset some environmental benefits from a grid level perspective (Pehnt et al., 2008; Turconi et al., 2014). A switch to distributed renewables therefore implies a shifting of resource use and environmental impacts both spatially and temporally (e.g. GHG emissions arising 'upfront' in the country of product manufacture, rather than during the operational life in the country of deployment), and potential reconfiguration throughout the electricity system. These dynamics pose a challenge for the accounting of change in the system in relation to environmental goals when distributed renewables replace incumbent generation.

This paper considers two methodological traditions that can be used for prospective whole system analysis and can therefore be applied to exploring the implications of increased distributed generation uptake: life cycle assessment (LCA) and net energy analysis (NEA). Both approaches share similar procedural features, but have important conceptual differences that provide distinct and complementary results (Arvesen and Hertwich, 2015; Raugei et al., 2015). Integration of the NEA and LCA has been argued for in the recent literature (Leccisi et al., 2016; Raugei and Leccisi, 2016), and, specifically, the International Energy Agency has made an effort to standardise and homogenise the parallel application of the two methods when applied to photovoltaics (Frischknecht et al., 2016; Raugei et al., 2016). However, applying NEA and LCA jointly in a prospective whole system level study has not been fully realised so far, and therefore this paper provides a detailed conceptual approach to doing so.

The overarching aim of an LCA is to provide information on the environmental impacts of a product or system for a number of impact categories (Klöpffer, 2014) and, in the case of a comparative analysis, to inform on the relative environmental benefits and detriments of the analysed alternatives. LCA may therefore be used to provide a long-term perspective on whether scenarios of distributed renewable electricity generation deployment *or* alternative grid development pathways minimise: (a) the overall depletion of non-renewable primary energy reserves, as measured by the non-renewable cumulative energy demand (nr-CED) indicator (Frischknecht et al., 1998, 2015); and (b) the cumulative emission of climate-altering greenhouse gases, as measured by the global warming potential (GWP_{100}) indicator (IPCC, 2013; Soimakallio et al., 2011).

NEA by contrast was developed with the aim of evaluating the extent to which an energy supply system is able to provide a net energy gain to society by transforming and upgrading a 'raw' energy flow harvested from a primary energy source (PES) into a usable energy carrier (EC), after accounting for all the energy 'investments' that are required in order to carry out the required chain of processes (i.e. extraction, delivery, refining, etc.) (Chambers et al., 1979; Cleveland, 1992; Herendeen, 1988; Herendeen, 2004; Leach, 1975; Slesser, 1974). The principal indicator of NEA is the energy return on energy investment (EROI), defined as the ratio of the gross EC output (in this case, electricity) to the sum total of the aforementioned energy investments (expressed in terms of equivalent primary energy). Notably, the perspective of NEA is intrinsically short-term, since EROI measures the effectiveness of the energy exploitation chain without consideration for the ultimate sustainability of the PES that is being exploited.

LCA and NEA thus seek answers to different questions, and as a result often end up being unnecessarily siloed in the literature. However, their common methodological structure means that they can be implemented in tandem to provide a valuable broader perspective on system change. This is particularly significant for understanding the short- and long-term implications of a potentially rapid shift to distributed renewables, where there are concerns about resource management and overall efficacy in decarbonisation at a system level. Decision makers can gain a more nuanced understanding of the potential environmental and sustainability implications of change within a system by being presented with co-derived EROI and life cycle environmental impact metrics.

This paper proposes a combined LCA and NEA methodological approach to the consequential assessment of distributed generation uptake in an electricity system. The existing literature on LCA and NEA is reviewed to establish salient methodological and conceptual considerations for a consequential approach to change within a system. These considerations are then applied to provide a common framework for consequential assessment of high levels of distributed renewable generation. Recommendations are made about system boundary, scenario development, the modelling of relationships between system components and the allocation of environmental burdens. The paper concludes with a discussion of the challenges and benefits of a combined LCA and NEA approach and future research objectives.

2. Methodological considerations for the analysis of change within a system

2.1. Lessons from consequential life cycle assessment

A LCA consists of four main stages: goal and scope definition; life cycle inventory (LCI); life cycle impact assessment (LCIA); and interpretation (ISO, 2006a, 2006b). There are two types of LCA discussed widely in the literature, namely attributional LCA (ACLA) and consequential LCA (CLA). An ALCA attributes a defined allocation of environmental impacts to a product or process unit (Brander et al., 2009; Klöpffer, 2012). For example, for a solar panel the environmental impacts from the mining, refining, manufacturing, distribution, operation and disposal stages are attributed accordingly. Studies such as Searchinger et al. (2008) and Slade et al (2009) have however demonstrated the value of expanding LCA approaches beyond an ALCA, in order to consider wider system effects of change. Approaches to LCA that focus on changes within a system are most frequently referred to as CLCA (Earles and Halog, 2011; Ekvall, 2002; Zamagni, 2015; Zamagni et al., 2012). Brander et al. (2009) define CLCA as distinct from standard ALCA in four ways:

- CLCA expands the scope of LCA to the total change in a system (however that system is defined) arising from the product or process being investigated. This means the system boundary in a CLCA is potentially very broad, depending on what impacts are considered significant. It has been likened by Ekvall and Weidema (2004) to observing the ripples in a pool of water after throwing a stone, in that all the associated disruptions 'radiating' from the product or process should be of interest to the study.
- Unlike an ALCA, a CLCA will overlap with the boundaries of other LCA's, meaning there would be double counting if multiple CLCAs were added together.
- CLCA uses marginal data[1] rather than average data to quantify

[1] Marginal data are those pertaining to the technologies which are assumed to be directly (or indirectly) affected by the change(s) in the analysed system. For instance, one MWp of additional PV capacity may be assumed to replace the same nominal capacity of combined cycle gas turbines (CCGT); accordingly, the impact of each kWh of generated PV electricity may be algebraically added to the impact of the corresponding kWh of CCGT electricity that is displaced. Average data on the other hand is representative of the full mix of technologies currently deployed in the country or region of interest to produce the same output (i.e. the average grid mix).

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