Energy Policy 100 (2017) 350–358

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

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

Christopher Jones [a,*], Paul Gilbert [a], Marco Raugei [b], Sarah Mander [a], Enrica Leccisi [b,c]

[a] Tyndall Centre for Climate Change School of Mechanical, Aerospace and Civil Engineering, University of Manchester, M13 9PL United Kingdom
[b] Department of Mechanical Engineering and Mathematical Sciences, Oxford Brookes University, OX3 0BP United Kingdom
[c] Department of Science and Technology, Parthenope University of Naples, Italy

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.

ARTICLE INFO

Article history:
Received 30 November 2015
Received in revised form
29 July 2016
Accepted 25 August 2016
Available online 9 September 2016

Keywords:
Life cycle assessment
Net energy analysis
Distributed energy
Energy scenarios
Consequential assessment

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.

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

* Correspondence to: University of Manchester, H1, Pariser Building, Manchester M13 9PL United Kingdom.
E-mail addresses: c.w.jones@manchester.ac.uk (C. Jones), p.j.gilbert@manchester.ac.uk (P. Gilbert), marco.raugei@brookes.ac.uk (M. Raugei), s.mander@manchester.ac.uk (S. Mander), enrica.leccisi@brookes.ac.uk (E. Leccisi).

http://dx.doi.org/10.1016/j.enpol.2016.08.030

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).

changes within the boundary of the system resulting from the displacement and/or substitution of individual processes.
- The often complex relationships (including difficult to model social and economic dynamics) between a product and a wider system means that although a CLCA might be considered more comprehensive there is greater uncertainty in CLCA than in ALCA.

While all or most of these features may be common to past CLCA studies, there is no fixed methodology as in the case of ALCA, leading to differences in application (Zamagni, 2015). Specifically, the extent to which the system boundary is expanded, how future systems are defined and the use of modelling to simulate impacts varies across the multiple CLCAs reviewed by Zamagni et al. (2012).

There is also debate about the relative merits of ALCA and CLCA and whether the respective methodologies and assumptions of these approaches, in practice, aid or mislead end users (Dale and Kim, 2014; Plevin et al., 2014; Suh and Yang, 2014; Zamagni, 2015). In particular, while on the one hand many of the features of CLCA, such as expanding study boundaries to include more impacts and use of marginal data, offer the potential to increase understanding of change within a system, on the other hand the use of additional models and assumptions raises concerns about validation (Suh and Yang, 2014). As discussed in Thomassen et al. (2008), ALCA and CLCA approaches are also likely to produce different results and offer different messages to end users.

For these reasons it is important that studies, which choose to adopt the features of CLCA clarify and justify the appropriateness of the method to the intended research aim and questions, the system boundary applied, and the use of models to define causal relationships in the system (Zamagni et al., 2012).

2.2. Establishing research aims and questions

When setting the research aims and questions of a study it is important to be clear whether a precise quantification of impacts is sought for a specific product or process, comparable to similar results for alternative products or processes, or if the aim is a more comprehensive assessment of impacts across a wider system (Brander et al., 2009). As discussed in Pochat (2015), time and financial resource, as well as data availability, often prevent the practical achievement of both objectives.

Specifically, LCAs and NEAs of energy supply systems may be carried out for a range of different goals, which may be classified into three broad categories (Carbajales-Dale et al., 2015):

1. Short term analysis of one specific energy supply system;
2. Comparative assessment of a range of energy supply systems taken in isolation;
3. Calculation of the overall energy and environmental performance of alternative scenarios of development for an entire energy supply mix at the level of a country or region.

While established assessment methods such as ALCA are fit for addressing goals 1 and 2, goal 3 is better served by a consequential approach, which entails a shift in scope to include additional direct and indirect impacts which leads to further considerations about system boundary and the interactions within a system when there is change (Ekvall and Weidema, 2004).

Indeed, the extent to which renewable technologies may contribute to tackling environmental, human health and social development issues has been a key stimulus for a shift in focus in LCA and NEA from products and processes to system level changes (Zamagni, 2015). A prominent example of this has been the adaption of LCA methodology to include the consequential impacts of biofuel production on land use and other connected processes (Zamagni et al., 2012).

Furthermore, the research questions being asked under goal 3 are often heuristic and prospective: e.g., what if there is significant shift from centralised (mainly baseload) fossil fuel electricity generation to distributed intermittent renewable generation? An assessment approach that is prospective and accounts for consequential relationships within a system is thus required to inform decision making on future pathways with broad environmental goals (Fthenakis et al., 2011).

There is however no formalised and fully agreed methodology for a prospective and consequential approach (Pochat, 2015; Sandén and Karlström, 2007), nor are there existing consequential studies specifically addressing the aggregated environmental impacts of distributed generation uptake. The wider scope of the analysis also inevitably results in increased uncertainty in the calculated indicators.

This is considered acceptable for a whole system perspective of distributed generation, given the aim of comparing scenarios to provide decision makers with an informed understanding of the consequences of changing to more distributed electricity generation.

2.3. System boundary

A crucial stage in both consequential LCA and NEA is selecting which products and process are to be included in the boundary of the system being studied (Ekvall and Weidema, 2004; Pochat, 2015). There are a number of ways the scope of analysis can be expanded to include different cause and effect relationships (Sandén and Karlström, 2007).

System boundary expansion can allow for more impacts to be considered within a study; however, increasing co-dependent products and processes will increase the number of assumptions in the study and the need for modelling, which lead to more uncertainty in the results (Suh and Yang, 2014). Ultimately, the practitioner needs to use their judgement about what they consider to be the most relevant processes, and communicate these clearly to the end user with the appropriate rationale (Ekvall and Weidema, 2004; Pochat, 2015).

For the analysis considered in this paper, it is therefore valuable to limit the expansion of system boundary to the most relevant processes within the system that are affected by changes in the key variable (i.e. distributed generation uptake). A detailed discussion of the specific processes and system components that are included in the system boundary is provided in Section 3.1.

2.4. System modelling

Modelling the cause and effect relationships within the system of study is an important feature of both CLCA and NEA. Yet the role and choice of system model(s) and their application is debated in the literature (Dale and Kim, 2014; Pochat, 2015; Suh and Yang, 2014).

Models that define and quantify marginal changes in data dynamically over a timeframe distinguish CLCA from the averaged data and static assumptions of ALCA. In ALCA all the inputs and outputs to/from the system are integrated over the full life cycle of the system, which removes any dynamic information and essentially corresponds to modelling them as though they occurred simultaneously, or averaged as a steady rate (Brander et al., 2009; Earles and Halog, 2011; Sandén and Karlström, 2007). The use of modelling for cause and effect within a system offers the potential to better characterise and quantify impacts on related components in the system resulting from the change being investigated than is possible with an ALCA approach (Earles and Halog, 2011; Plevin et al., 2014). It has also been suggested that with partial equilibrium economic modelling approaches, global changes in supply chains and markets resulting from decision making could be accounted for in CLCA (Igos et al., 2015; Plevin et al., 2014). This increase in comprehensiveness, and likely resulting complexity, has a potential transactional cost in terms of the transparency of the assumptions which are integral to model outcomes and the means to validate results (Dale and Kim, 2014; Suh and Yang, 2014). These apparent trade-offs in the use of modelling in LCA reinforce the role of research aims and system boundary definition in framing the research method and communicating the results to end users.

From the points of view of both CLCA and NEA, a static assumption alone becomes problematic for distributed generation technologies like PV and small-scale wind generators. In this case, most of the associated energy 'investment' is required at the beginning of the technology's life cycle, while the electricity output is spread over the much longer use phase. A suitably framed 'dynamic' NEA can show that, during periods of heavy investment and rapid deployment of new distributed generation capacity, the actual overall EROI of the electricity output would be temporarily reduced with respect to the time-averaged value that might otherwise have been calculated under the theoretical (and in fact abstract) 'steady state' assumption. Carbajales-Dale et al (2014) have shown that, if analysed in isolation from the rest of the grid, and pushed beyond a given rate of deployment, the resulting net energy gain of PV and wind may be reduced to the point of running into a temporary energy 'deficit'. This is then followed by a time of higher EROI, once the up-front 'investment' has been 'repaid' and the energy 'returns' can be freely reaped. These dynamic considerations are thus relevant to the prospective and consequential assessment of distributed generation uptake in the UK electricity system presented here.

3. A combined CLCA and NEA approach to distributed generation impacts on electricity systems

Drawing on considerations in the literature (Section 2), three key processes which overlay both LCA and NEA and which have a fundamental bearing on the results and interpretation of both methods are considered. Firstly, the research goal and system boundaries are set, against which the appropriateness of subsequent data assumptions, methodological choices (such as allocation) and additional models are gauged. Secondly, an approach to building prospective representations of the system being assessed through scenario development is discussed. Thirdly the common application of models to represent interactions within the system of study, and how impacts and benefits are allocated in LCA and NEA is set out.

3.1. Goal and system boundaries

A common goal and system scope aligns CLCA and NEA to enable complementary analysis of long-term environmental impacts (as measured by nr-CED and GWP) and short-term net energy performance (as measured by EROI) in the study.

The research goal in this case is to understand the implications for the wider electricity system of increasing distributed generation uptake in the future. This is, necessarily, the analysis of a prospective system that does not yet exist, and therefore the goal is to enable fair and robust comparison between alternative system states (i.e. with and without increased distributed generation, discussed in Section 3.2). The functional unit is 1 kW h of electricity delivered to consumers by the system as a whole. This is slightly different to consequential studies of renewables which focus on the grid level rather than distributed generation such as Pehnt et al (2008) and Turconi et al (2014) where the functional unit is 1 kW h of power produced by the system. The difference here is so that loses in electricity transmission and distribution from onsite generation and self-consumption of power are considered.

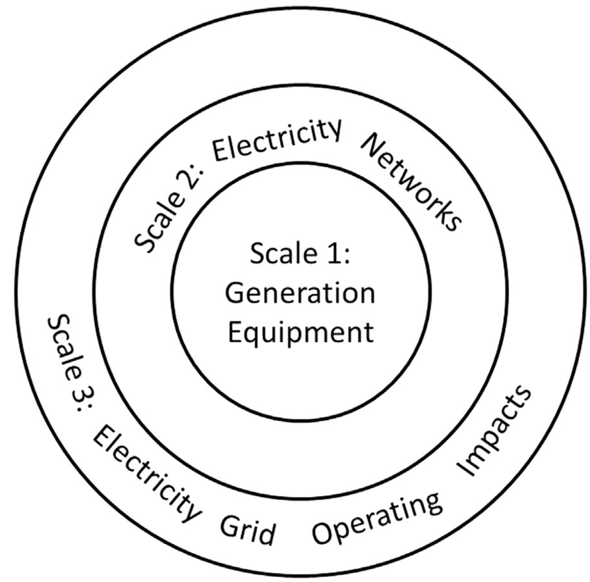

Fig. 1. System scales for consequential analysis of distributed generation deployment.

As discussed in Section 2.3, a change to part of a system can affect various other processes and products within the system, which collectively determine the net change in the system. The products and processes which are included, and those that are not, must be specified and justified in the method (Ekvall and Weidema, 2004). Building on Ekvall and Weidman's (2004) concept of impact 'ripples' through a system, the electricity system in this approach is considered on three connected scales, as illustrated in Fig. 1. Products and processes most integral to understanding changes in electricity system environmental performance resulting from distributed generation uptake are selected:

3.1.1. Scale 1: Electricity Generation Technologies

The environmental impacts of all electricity generators in the electricity systems being compared in the assessment are included at this scale. The associated environmental burdens of resource extraction, manufacture, transport, installation and decommissioning of the additional distributed generation and centralised generation in the rest of the electricity system are also included at this scale. An attributional approach is used so that multiple technologies can be compared for a given functional unit.

Harmonisation studies which review and characterise existing attributional LCAs such as Dolan and Heath (2012), O'Donoughue et al. (2014) and Warner and Heath (2012) are suitable for providing a similar basis for comparison. They indicate which impacts are attributed to each use phase so that operational emissions (considered in Scale 3) can be omitted for this scale. As often discussed in meta-analysis of attributional LCA, the range in reported findings for the same technology is a potential issue (Price and Kendall, 2012). However as the goal is to compare between potential outcomes from different levels of distributed generation, it is more significant that consistent values are used.

3.1.2. Scale 2: Distribution Network Changes

Scale 2 system changes account for the aggregated impact of distributed renewable electricity generation on electricity distribution networks. Change in network utilisation when distributed generation technology is deployed may require interventions in the distribution network to maintain function within regulatory and technical thresholds for voltage, frequency and thermal load.

Interventions in the network include reinforcing electricity lines, up-rating transformers, installing on-load tap changer and monitoring equipment, as well as curtailing distributed generation on the network. These interventions have different associated environmental impacts and energy investments, resulting in either additional burdens for the system in terms of new infrastructure, or a decrease in electricity delivered per installed capacity of distributed generation.

3.1.3. Scale 3: Electricity Grid Operation

Understanding the impact of aggregated levels of distributed renewable energy on overall electricity grid emissions and impacts is a key component of a consequential approach to system level impacts. Renewable distributed generation uptake will change the requirement for electricity from the transmission grid, with more power generated and consumed onsite, and more overall intermittency in power generation. Intermittent renewables are matched to resource availability, not demand; therefore, it is necessary to account for changes in generation availability under different assumptions about the electricity systems being compared. Specifically, demand from the electricity grid is reduced when wind or solar resources are directly available, affecting the utilisation of other generators in the system. Changes to electricity emission intensities and the demand for energy investments can either be quantified as annual average impacts or as marginal differences resulting from changes in generation of demand over time (Hawkes, 2010; Pehnt et al., 2008; Rinne and Syri, 2013). Although potentially minor, the reduced utilisation of some thermal power stations will affect the EROI and environmental burden per unit of electricity supplied by the system (Pehnt et al., 2008; Turconi et al., 2014).

3.1.4. System boundary expansion

Further expansion of the system boundary was considered in developing this approach. For example, production, deployment and use of distributed generation, such as solar PV, may have multiple potential consequences throughout the supply chain. In the manufacturing phase, an increase in the number of PV panels or wind turbines and their balance of system (BOS) components will have marginal second-order impacts on mining, manufacturing and transport infrastructure that result from increased deployment of the technology. In the use phase, when distributed generation is integrated with buildings, there may be a resultant change in electricity consumption practices and the purchase of additional products such as electric vehicles and new electrical devices. However, it was decided that taking into account these second-order effects would have added additional complexity and uncertainty to the study without sufficiently contributing to the research goal. Therefore, they sit outside the system boundary.

3.2. Scenarios for prospective analysis

Long term prospective analysis of the uptake of distributed generation requires the characterisation and quantification of key features of the electricity system under contrasting future conditions. A prospective LCA and NEA analysis therefore entails the development of scenarios that describe how the electricity system might change with different assumptions about the constitution and performance of the system. There are multiple variants of scenario development, broadly ranging from near term extrapolation and modelling of trends or probability analysis (forecasting) to longer term normative explorations of a range of contrasting outcomes (backcasting) (Berkhout et al., 2002; Hughes and Strachan, 2010). A backcasting approach based on stakeholder engagement is proposed here to frame a combined LCA and NEA of distributed generation. The process of backcasting in relation to LCA and NEA is discussed and an example of scenarios for increased uptake of PV in the UK is provided.

Given that substantial changes in electricity systems often occur over decadal timescales (Hughes and Strachan, 2010), backcasting scenarios are an appropriate technique for framing LCA and NEA analysis of distributed generation uptake (Pesonen et al., 2000). In a backcasting scenario approach end points are set based on the aims of the research and then relevant variables in the system are modified and quantified. For LCA and NEA, scenarios developed to explore changes in environmental or sustainability performance should be accompanied by a reference scenario that enables comparison (Pesonen et al., 2000).

For a combined LCA and NEA approach to distributed generation uptake, scenario end points need to at least contrast a high distributed generation end point with a low distributed generation reference (reflecting a continuation of centralised generation). Multiple end points characterising different forms or levels of distributed generation could also be developed, however it is recommended that the number of scenarios is constrained to account for difficulties end users may have interpreting multiple outputs (Pesonen et al., 2000).

The variables in a scenario refer to changes in the system compared to the present day baseline (existing data). These are the specific elements of the system that are assumed to be altered in order to reach the end points in the scenarios. For the combined LCA and NEA these variables should reflect the system features identified in the system boundary stage (Section 3.1). For this approach to distributed generation the key variables across the three system scales are:

- Type and number of distributed generation deployed and at what rate
- Electricity storage options
- The centralised electricity generation mix
- Electricity demand that includes the development of strategies to decarbonise transport and heating through electric vehicles and heat pumps, which may add to electricity demand over coming decades.

The assumptions about how these variables in the system change under the scenario conditions set by the end point used, determine the inputs into LCA and NEA models. For example, a scenario may state that domestic electricity and peak demand change respectively by 10% and 15% between the baseline year and the end point year of the study, and baseline data can modified accordingly.

The setting of scenario end points and system change variables are an important and influential step in LCA and NEA, as the assumptions applied shape what is being compared and therefore the results of the study. A criticism of scenario use in environmental assessment approaches is that embedded assumptions are not always clear to end users, particularly where economic models are used to determine changes (Pochat, 2015; Suh and Yang, 2014).

Scenario end points and variable assumptions can be set by a number of processes; practitioners themselves can decide upon them based on their own decisions or models, existing national targets or scenarios can be used, or stakeholders associated with the system being analysed can be engaged in the process. Producing assumptions that are justifiable and relevant to the research goal is a major challenge for scenario development. Alignment

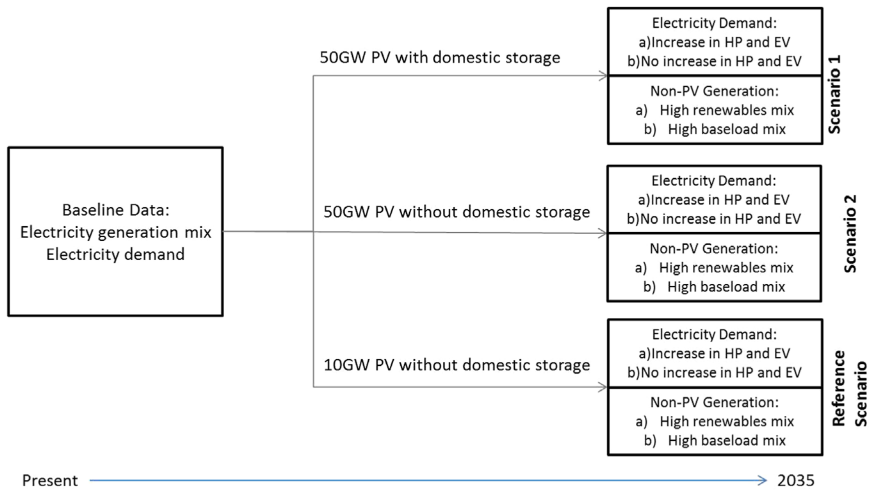

Fig. 2. Example backcast scenarios for PV uptake in the UK. "HP"=Heat Pump; "EV"=Electric Vehicle.

with existing national energy scenarios, where possible, reduces the need for the practitioner to develop their own bespoke assumptions. An additional means of improving confidence in scenario assumptions is to base them on the outcome of stakeholder consultation, particularly if such stakeholders are intended end users of the study (Jones et al., 2014). This involves consulting with stakeholders who represent distributed generation technology suppliers and installers, electricity network and grid operators and policy makers on scenario assumptions through deliberative processes, such as a workshop.

In Fig. 2 an example of backcast scenarios for PV uptake in the UK is shown. Two end points with high levels of PV deployment and a reference case with low PV uptake are illustrated. In this case the prevalence of domestic battery storage is selected as the key variable for comparison between high distributed generation scenarios. Variables within the scenarios, such as different centralised electricity mixes and changes to electricity demand explore the sensitivity of scenario outcomes to other system changes.

3.3. Modelling and allocation

As previously mentioned in Section 2.1, in the study of the impacts of distributed generation uptake, modelling of processes with a system is determined by the research question and system boundaries. Here, modelling is limited to characterising two key cause-and-effect relationships in the system: (i) changes in electricity network infrastructure and operation, and (ii) changes in energy investments for, and the greenhouse gas emissions intensity of, the electricity grid. Other potential variables are fixed as assumptions common to all scenarios in the study, to facilitate a clear comparison of the scenarios.

The chosen functional unit of 1 kW h of electricity supplied by the electricity system means that total change in the system as a whole over time is the focus of the study. Accordingly, and consistent with the fundamental features of CLCA (cf. Section 2.1), no inter-system allocation of the impacts due to Scale 2 system changes (e.g. network reinforcement) between PV, wind and other technologies is deemed appropriate.

A question to be addressed, however, is the timeframe applied to the model outputs, and for the impacts and investments for Scale 1 products. The environmental burdens and energy investments for renewable electricity generation technologies are predominantly cradle to gate (upstream) whereas thermal fossil fuel power stations have a greater proportion of their impacts in the use phase (Nugent and Sovacool, 2014). This is also the case for carbon capture and storage technology (CCS) and nuclear, where inputs into the fuel cycle and decommissioning are greater per unit of electricity generated than for renewable technologies (Hammond and Spargo, 2014; Sovacool, 2008). Additionally, while many of the burdens, particularly for renewables, are upfront, the benefits of system assets with long useful lives will reach further into the future, over a time when the system itself may be considered to be changing further (Sandén and Karlström, 2007). This issue is particularly acute for the study of distributed generation where aggregated impacts over decades are being considered.

This is illustrated graphically for a simple idealised case study in Fig. 3. In this example, the timeframe of interest for the analysis is supposed to span from the present day (t=0) to 30 years into the future, and a single new renewable (e.g. PV) installation is assumed to be deployed on the 15th year of this time span, and have a useful lifetime of 30 years.

A conventional, static attributional approach to the analysis would simply take the portion of the cumulative impact over the full life cycle of the installation that takes place within the timeframe of analysis and 'spread it out' evenly over the 30 years of interest (shown in Fig. 3; the area under the dashed black line, from t=0 to t=30 is the same as the area under the continuous grey line from t=15 to t=30). The same logic would then also be applied to the accounting of the electricity produced by the installation (not depicted in Fig. 3).

When instead adopting a dynamic modelling approach, as discussed in Section 2.4, the impact attributed to the system in each year of the analysed time span accurately tracks the real-life impact as it takes place (i.e. the areas under the dotted black line and under the continuous grey line from t=0 to t=30 are the same). However, since the timeframe of interest for the analysis does not extend to the end of the useful life of the installation, the remaining portion of the impacts (i.e. those occurring from t=30 to t=45) remain unaccounted for in this approach, also. Again, the exact same logic is also applied to the electricity output of the system.

A common trait of the two modelling approaches is thus that a *temporal allocation* of the impacts and of the outputs is employed, whereby only the shares thereof that happen within the intended timeframe of analysis are taken into account. This is in fact a necessity in order not to fall into the trap of an infinite recursive search for the 'full' accounting of all impacts and outputs, since at any given point in time in the foreseeable future there will always be *some* new installations on the verge of being deployed, and *some* others which are instead in the middle of their useful life, and whose up-front production and installation impacts happened in the past, before the designated start of the timeframe of analysis.

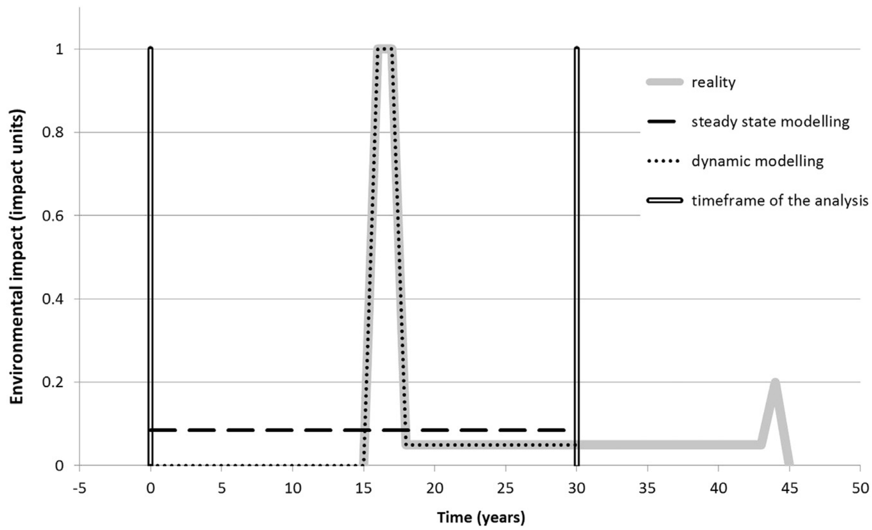

Fig. 3. 'Steady state' (static) and dynamic modelling approaches, and effect of temporal allocation of the environmental impacts.

These issues around temporal allocation have an implication for the results of consequential assessment of distributed electricity generation and how they are interpreted. It is recommended here that the results from both a static and a dynamic allocation approach should be presented and explained to end users of the analysis. Neither form of allocation can fairly represent the balance impacts and benefits (electricity generated) for technologies with impacts that are predominantly upstream (such as PV) and those with impacts that are mostly in the use phase (natural gas and coal power stations) alone, where aggregated deployment over time is being considered. To avoid misleading decision makers of the relative long and short term impacts of different scenarios relevant to the timeframe of study, the outcomes from both allocation methods can be presented and discussed.

4. Discussion

In this section the benefits and limitations of a prospective, consequential approach combining LCA and NEA are discussed and recommendations for implementing a combined framework to study distributed generation uptake are given.

4.1. Benefits and limitations of a prospective consequential approach combining LCA and NEA

Prospective, consequential analysis can be a very useful tool for helping decision makers to think through future implications of particular technology pathways at a whole system level (Pesonen et al., 2000). Where appropriately designed, scenarios and models that characterise dynamics within the system can provide important heuristic outputs that capture net changes in a system and facilitate a comparison of the efficacy of policies. The results from such an analytical approach are however intrinsically linked to the implicit and explicit assumptions in scenarios and system simulation models used. As presented in Section 2.1 there are very reasonable concerns about the application of these techniques for LCA and NEA that inform decision making, given the inherent unknown veracity of prospective analysis and the abstraction implicit in modelling consequential relationships. These issues can be addressed in the goal of a prospective, consequential study which should clearly acknowledge the explorative utility rather than predictive qualities or accuracy of the results. Having the required resources available to develop scenarios with stakeholder participation and integrate additional models, such as electricity network impact models, may also be a limiting factor. A combined LCA and NEA approach exploits the shared research framework of both methods to offer more comprehensive understanding of system change than a single set of indicators alone for the same resource commitment. Similarly, the representation of static and dynamic (Section 3.3) temporal allocation to decision makers may help to clarify misunderstanding between the relative long and short term impacts of different technologies.

4.2. Recommendations for applying prospective consequential analysis of distributed renewable generation uptake

Having considered the relative value and limitations for decision makers concerned with meeting long term targets for national or regional systems, the following recommendations for applying a prospective consequential approach to distributed generation uptake are made:

1. The intended explorative utility of the results from prospective, consequential LCA and NEA results should be clear from the goal and scope of the study. In the case presented here, the goal is to compare impacts of high distributed generation pathways and a low distributed generation reference on key elements of the electricity system. The results therefore can be used to examine the differences between scenario pathways, but not to quantify actual system impacts. While this may seem obvious, it is apparent from the literature that there has been room for misunderstanding about the conclusions that can be drawn from particular approaches.
2. A stakeholder-led backcasting approach (Section 3.2) is preferred for scenario development. Where the primary goal of the assessment is to inform the choice between options, it is more important to provide comparable representations of the required spectrum of outcomes rather than to try and attain accurate forecasting. Any future scenario entails multiple uncertainties; with backcasting the influential parameters can be agreed by system stakeholders so that the scenarios explore relevant alternatives and have buy in from end users. In comparison, endogenous assumptions by researchers may not achieve this. Where a stakeholder approach is not possible, preexisting national or regional energy scenarios could be drawn on for similar purposes.

3. Setting relevant system boundaries and prioritising key system dynamics can help balance comprehensiveness and uncertainty. In the case of assessing distributed generation uptake, two key dynamics are identified: interaction between installed distributed capacity and local distribution networks and; interaction between distributed generation and the operation of the national electricity grid. Modelling of electricity network impacts and electricity dispatch are necessary for characterising the consequential impacts within the electricity system. However, further expansion of the system boundary to include more cause and effect relationships (although ideal in pursuing a comprehensive consequential approach) is rejected after considering trade-offs with uncertainty and transparency of results.
4. The method of allocating burdens (in terms of emissions and energy invested) and benefits over time has a significant bearing on how LCA and NEA results are interpreted in the case of prospective analysis of distributed renewables. As discussed in Section 3.3 this is owing to the staggered deployment of aggregated distributed generation capacity that is anticipated, and the difference in environmental impact and energy investment profiles over time of wind and PV compared to fossil fuels. It is therefore recommended that both dynamic and static allocation is used when interpreting LCA and NEA outputs for end users.
5. Above all, as the outputs from such an approach are highly contingent upon the assumptions in scenarios and models, these facets must be clearly communicated to end-users. As discussed throughout the paper, several choices have to be made by practitioners in the consequential assessment process that will subtly or fundamentally alter the results. As the aim is for comparison rather than accuracy, the emphasis should be on justifying and communicating these choices to decision makers from the outset.

On balance a prospective consequential analysis has important value for informing policy makers about distributed generation scenarios. This is on condition that appropriate choices are made about the scope of study, scenario development, modelling and allocation, which are then clearly articulated. As shown here, the common procedural practices of LCA and NEA mean that although they retain their distinctiveness in approach and research goal, they can be applied in tandem for prospective consequential assessment. Furthermore, the outputs from a combined LCA and NEA approach would add significant additional insight to whole system analysis than can be achieved pursuing each approach in isolation.

5. Conclusion

The applications of environmental sustainability assessment methods continue to evolve as demand from end users such as policy makers changes. This is reflected in the literature through emerging CLCA variants and debates between practitioners about the appropriate use of ALCA, CLCA and NEA methods for informing decision making. Distributed renewable generation poses specific questions for sustainability assessments. The multi-level system impacts of aggregated distributed generation deployment, different impact profiles of thermal and renewable power generation, and short and long term life cycle impacts – in terms of EROI and life cycle carbon emissions – require an approach that is adapted to these considerations to ensure fair comparison of options. Applying the same framework of goal, system boundary, scenario assumption, system models and allocation to LCA and NEA enables these issues to be examined more thoroughly. The trade-offs between comprehensive coverage of system changes and increased uncertainty of multiple assumptions needs to be acknowledged in goal and scope stage so that boundaries and modelled cause and effect relationships are limited to essential needs of the analysis. The long term prospective outlook and aggregated impact of distributed generation over time makes the use of dynamic and static allocation important in the interpretation of results when comparing renewables and thermal generation. Above all the contingency of the results on implicit and explicit assumptions in models and scenarios needs to be clearly articulated to end users so that the results are used for heuristic rather than accounting purposes. The next stage is to implement this approach to test how the scenario, sub-system modelling and allocation methods will combine in practice to provide useable indicators for decision makers.

Acknowledgement

This work was completed as part of the Whole System Impacts and Socio-Economics of Wide Scale PV Integration' (WISE PV) project (EP/K022229/1) funded by the UK Engineering and Physical Sciences Research Council (EPSRC) through the Supergen SuperSolar Hub. All the data used are referred to in the 'References' section of this publication.

References

Arvesen, A., Hertwich, E.G., 2015. More caution is needed when using life cycle assessment to determine energy return on investment (EROI). Energy Policy 76, 1–6.
Barnham, K., Knorr, K., Mazzer, M., 2013. Benefits of photovoltaic power in supplying national electricity demand. Energy Policy 54, 385–390.
Berkhout, F., Hertin, J., Jordan, A., 2002. Socio-economic futures in climate change impact assessment: using scenarios as [`]learning machines'. Glob. Environ. Change 12, 83–95.
Brander, M., Tipper, R., Hutchison, C., Davis, G., 2009. Consequential and attributional approaches to LCA: a guide to policy makers with specific reference to greenhouse gas LCA of biofuels. Technical Paper TP-090403-A. Ecometrica.
Carbajales-Dale, M., Barnhart, C.J., Benson, S.M., 2014. Can we afford storage? A dynamic net energy analysis of renewable electricity generation supported by energy storage. Energy Environ. Sci. 7, 1538–1544.
Carbajales-Dale, M., Raugei, M., Fthenakis, V., Barnhart, C., 2015. Energy return on investment (EROI) of solar PV: an attempt at reconciliation [Point of View]. Proc. IEEE 103, 995–999.
Chambers, R.S., Herendeen, R.A., Joyce, J.J., Penner, P.S., 1979. Gasohol: does it or doesn't it produce positive net energy? Science, 789–795.
Cleveland, C.J., 1992. Energy quality and energy surplus in the extraction of fossil fuels in the U.S. Ecol. Econ. 6, 139–162.
Dale, B.E., Kim, S., 2014. Can the predictions of consequential life cycle assessment be tested in the real world? comment on "using attributional life cycle assessment to estimate climate-change mitigation. J. Ind. Ecol. 18, 466–467.
Dolan, S.L., Heath, G.A., 2012. Life cycle greenhouse gas emissions of utility-scale wind power: systematic review and harmonization. J. Ind. Ecol. 16, S136–S154.
Earles, J.M., Halog, A., 2011. Consequential life cycle assessment: a review. Int. J. Life Cycle Assess. 16, 445–453.
Ekvall, T., 2002. Cleaner production tools: LCA and beyond. J. Clean. Prod. 10, 403–406.
Ekvall, T., Weidema, B., 2004. System boundaries and input data in consequential life cycle inventory analysis. Int. J. Life Cycle Assess. 9, 161–171.
Frischknecht, R., Heijungs, R., Hofstetter, P., 1998. Einstein's lessons for energy accounting in LCA. Int. J. Life Cycle Assess. 3, 266–272.
Frischknecht, R., Wyss, F., Büsser Knöpfel, S., Lützkendorf, T., Balouktsi, M., 2015. Cumulative energy demand in LCA: the energy harvested approach. Int. J. Life Cycle Assess. 20, 957–969.
Frischknecht, R., Heath, G., Raugei, M., Sinha, P., de Wild-Scholten, M., Fthenakis, V., Kim, H.C., Alsema, E., Held, M., 2016. Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, 3rd ed. IEA PVPS Task 12 Report IEA-PVPS T12-06:2016.
Fthenakis, V., Frischnecht, R., Raugei, M., Kim, H., C., Alsema, E., Held, M., de Wild-Scholten, M., 2011. Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity, 2nd ed. IEA PVPS Task 12.
Hammond, G.P., Spargo, J., 2014. The prospects for coal-fired power plants with carbon capture and storage: a UK perspective. Energy Convers. Manag. 86, 476–489.
Hawkes, A.D., 2010. Estimating marginal CO_2 emissions rates for national electricity systems. Energy Policy 38, 5977–5987.
Herendeen, R., 1988. Net energy considerations. In: West, R., Kreith, F. (Eds.),

Economic Analysis of Solar Thermal Energy Systems. MIT Press, United States, pp. 255–273.
Herendeen, R.A., 2004. Net energy analysis: concepts and methods A2. In: Cleveland, C.J. (Ed.), Encyclopedia of Energy. Elsevier, New York, pp. 283–289.
Hughes, N., Strachan, N., 2010. Methodological review of UK and international low carbon scenarios. Energy Policy 38, 6056–6065.
Igos, E., Rugani, B., Rege, S., Benetto, E., Drouet, L., Zachary, D.S., 2015. Combination of equilibrium models and hybrid life cycle-input-output analysis to predict the environmental impacts of energy policy scenarios. Appl. Energy 145, 234–245.
IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, in: Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, Midgley, P.M. (Eds.), Cambridge, United Kingdom and New York, NY, USA, p. 1535 pp.
ISO, 2006a. 14040 – Environmental management – Life cycle assessment – Principles and framework. International Organization for Standardization.
ISO, 2006b. 14044 – Environmental management – Life cycle assessment – Requirements and guidelines. International Organization for Standardization.
Jones, C., Raugei, M., Gilbert, P., J., Mander, S., 2014. Analysing stakeholder-informed scenarios of high PV deployment for a low-carbon electricity grid in the UK: a consequential LCA approach, in: Proceedings of the 29th European Photovoltaic Solar Energy Conference and Exhibition, Amsterdam, NL.
Klöpffer, W., 2012. The critical review of life cycle assessment studies according to ISO 14040 and 14044 - Origin, purpose and practical performance. Int. J. Life Cycle Assess., 1–7.
Klöpffer, W., 2014. Background and Future Prospects in Life Cycle Assessment Springer.
Leach, G., 1975. Net energy analysis – is it any use? Energy Policy 3, 332–344.
Leccisi, E., Raugei, M., Fthenakis, V., 2016. The energy and environmental performance of ground-mounted photovoltaic systems – a timely update. Energies 9, 622.
Nugent, D., Sovacool, B.K., 2014. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: a critical meta-survey. Energy Policy 65, 229–244.
O'Donoughue, P.R., Heath, G.A., Dolan, S.L., Vorum, M., 2014. Life cycle greenhouse gas emissions of electricity generated from conventionally produced natural gas: systematic review and harmonization. J. Ind. Ecol. 18, 125–144.
Pehnt, M., Oeser, M., Swider, D.J., 2008. Consequential environmental system analysis of expected offshore wind electricity production in Germany. Energy 33, 747–759.
Pesonen, H.-L., Ekvall, T., Fleischer, G., Huppes, G., Jahn, C., Klos, Z., Rebitzer, G., Sonnemann, G., Tintinelli, A., Weidema, B., Wenzel, H., 2000. Framework for scenario development in LCA. Int. J. LCA 5, 21–30.
Plevin, R.J., Delucchi, M.A., Creutzig, F., 2014. Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. J. Ind. Ecol. 18, 73–83.
Pochat, S., 2015. A review through significant examples. In: Blanc, I. (Ed.), EcoSD Annual Workshop Consequential LCA. Presses des MINES, Paris.
Price, L., Kendall, A., 2012. Wind power as a case study: improving life cycle assessment reporting to better enable meta-analyses. J. Ind. Ecol. 16, S22–S27.
Raugei, M., Leccisi, E., 2016. A comprehensive assessment of the energy performance of the full range of electricity generation technologies deployed in the United Kingdom. Energy Policy 90, 46–59.
Raugei, M., Carbajales-Dale, M., Barnhart, C.J., Fthenakis, V., 2015. Rebuttal: "Comments on 'Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants' – Making clear of quite some confusion". Energy 82, 1088–1091.
Raugei, M., Frischknecht, R., 2016. Olson, C., Sinha, P., Heath, G., 2016. Methodological guidelines on Net Energy Analysis of Photovoltaic Electricity. IEA-PVPS Task 12 Report T12-07.
Rinne, S., Syri, S., 2013. Heat pumps versus combined heat and power production as CO_2 reduction measures in Finland. Energy 57, 308–318.
Ruiz-Romero, S., Colmenar-Santos, A., Gil-Ortego, R., Molina-Bonilla, A., 2013. Distributed generation: the definitive boost for renewable energy in Spain. Renew. Energy 53, 354–364.
Sandén, B.A., Karlström, M., 2007. Positive and negative feedback in consequential life-cycle assessment. J. Clean. Prod. 15, 1469–1481.
Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.H., 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319, 1238–1240.
Slade, R., Bauen, A., Shah, N., 2009. The greenhouse gas emissions performance of cellulosic ethanol supply chains in Europe. Biotechnol. Biofuels, 2.
Slesser, M., 1974. Energy Analysis Workshop on Methodology and Conventions. IFIAS, Stockholm.
Soimakallio, S., Kiviluoma, J., Saikku, L., 2011. The complexity and challenges of determining GHG (greenhouse gas) emissions from grid electricity consumption and conservation in LCA (life cycle assessment) – a methodological review. Energy 36, 6705–6713.
Sovacool, B.K., 2008. Valuing the greenhouse gas emissions from nuclear power: A critical survey. Energy Policy 36, 2940–2953.
Suh, S., Yang, Y., 2014. On the uncanny capabilities of consequential LCA. Int. J. Life Cycle Assess. 19, 1179–1184.
Thomassen, M.A., Dalgaard, R., Heijungs, R., De Boer, I., 2008. Attributional and consequential LCA of milk production. Int. J. Life Cycle Assess. 13, 339–349.
Turconi, R., O'Dwyer, C., Flynn, D., Astrup, T., 2014. Emissions from cycling of thermal power plants in electricity systems with high penetration of wind power: life cycle assessment for Ireland. Appl. Energy 131, 1–8.
Warner, E.S., Heath, G.A., 2012. Life cycle greenhouse gas emissions of nuclear electricity generation: systematic review and harmonization. J. Ind. Ecol. 16, S73–S92.
Zamagni, A., 2015. An overview of current initiatives and approaches. In: Blanc, I. (Ed.), EcoSD Annual Workshop Consequential LCA. Presses des Mines, Paris.
Zamagni, A., Guinée, J., Heijungs, R., Masoni, P., Raggi, A., 2012. Lights and shadows in consequential LCA. Int. J. Life Cycle Assess. 17, 904–918.