Life Cycle Assessment and Net Energy Analysis: analysing scenarios of large-scale deployment of PVs in urban systems.

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Abstract

Distributed electricity generation by rooftop photovoltaic (PV) panels and, where appropriate, integrated battery storage systems, offers new possibilities for the built environment to be more self-sufficient in energy, and to reduce the environmental impact of the electricity grid. However, in order to correctly assess the full consequences of the deployment of up to 50 GWp of distributed rooftop PV systems, the scope of the analysis needs to be expanded to three system levels: (1) the impacts of material and energy flows to provide the PV modules, the inverter, and the batteries; (2) any new infrastructure that may be required to adapt the distribution network and transmission grid to variable and dispersed PV electricity production; (3) the co-evolution of the rest of the grid, since the impact on electricity grid emissions from distributed PV generation ultimately depend on what electricity generation technologies are displaced by PV output.

This paper presents a novel approach to integrate two independently developed but arguably complementary methodological approaches, namely Life Cycle Assessment (LCA) and Net Energy Analysis (NEA), and apply them to the common goal of a prospective consequential life cycle analysis of large-scale PV deployment in the UK (this work is part of the UK EPSRC funded ‘WISE PV’ project). Specifically, two stakeholder-informed deployment scenarios are considered, both leading to a cumulative installed capacity of 50 GWp of PV in 2035: a ‘network-focused’ scenario with a high proportion of ground mounted PV and without building-scale battery storage; and a ‘user-led’ scenario, in which PV is predominantly deployment on rooftops, and battery systems are used to enable high levels of self-consumption. We focus here on the latter scenario, and present the method for a unified life cycle inventory underpinning both the LCA and NEA, thereby ensuring internal consistency.

1. Introduction and background

Electricity generation accounts for around 28% of UK GHG emissions (DECC, 2013). The recent growth in the UK PV sector has stimulated interest in the involvement of a high level of installed capacity on the UK electricity system. The UK grid has potential for large-scale deployment of PVs in urban systems. The EPSRC funded Whole System Impacts and Socio-Economics of Wide Scale PV Integration (WISE PV) project is an investigation of ambitious levels of PV in the UK using a range of technical, environmental, economic and social assessment methods – one goal of the WISE PV project is to assess the environmental effects (focusing on GHG emissions) of electricity systems and the energy return on energy invested (EROI). A combined prospective consequential life cycle assessment (CLCA) and Net Energy Analysis (NEA) approach is proposed here to investigate the whole-system impacts of a set of future national electricity generation scenarios in which high levels of PV are achieved by 2035. The subject of the analysis is the entire electricity system in a particular state rather than a product, such as a unit consisting of PV modules, inverter and batteries. Scenarios with high levels of PV are necessarily based on assumed future UK energy systems whereby high levels of deployment can be reasonably achieved. The system-level view increases how comprehensive the analysis is in terms of the emissions covered and primary energy harvested, but this
and the prospective outlook into the future also increases the number of assumptions needed to define key elements. The increase in uncertainty regarding output values that arises from this is acceptable because the purpose is to compare between scenarios in order to assess the implications of a particular pathways regarding PV. Ultimately the goal of the methodology is to provide decision makers with a more informed understanding of the consequences of changing to more distributed generation with the urban environment, from a whole system perspective.

2. Methodology

2.1 Consequential LCA (CLCA)

The research approach used for this study is that offered by consequential life cycle assessment (CLCA), which broadens the scope and boundary of ALCA to consider the direct and indirect effects on processes and products (T. Ekvall, B. Weidema, 2004). Attributional analyses is focused on direct environmental impacts of a product through its life cycle (cradle to grave), while CLCA defines a life cycle assessment that incorporates the impact of changes to products and processes that are directly or indirectly related to the unit of study (Brander, Tipper et al., 2008). CLCA is therefore a more appropriate approach to studying change within a system.

2.2 Net Energy Analysis (NEA)

This study is based on a combined LCA methodology with Net Energy Analysis perspective – the purpose of NEA is to quantify the extent to which a given energy source is able to provide a net energy surplus to the end user – after accounting for all the losses occurring along the processes chain (extraction, delivery, etc.) as well as for all the additional energy investments that are required in order to carry out the same chain of processes (Slesser, 1974; Leach, 1975; Chambers, 1979; Herendeen, 1988; Cleveland, 1992; Herendeen, 2004).

3. The analysed system

This research is focused on two scenarios where 50 GW of PV is deployed, and a third scenario with low levels of PV deployment (20GW) is used as a comparison case. The low PV scenario is based on the National Grid’s ‘Gone Green’ Future Energy System scenario. The two high-PV scenarios are termed, respectively: ‘user-led’ – in which PV is predominantly deployment on rooftops, and battery systems are used to enable high levels of self-consumption – and ‘network-focused’ – a scenario with a high proportion of ground-mounted PV and without building-scale battery storage. Common assumptions about non-PV generation mix and electricity demand are applied to all three scenarios, including shifts to transport and heating services electrification.

3.1 User-led scenarios

This scenario focuses on high levels of self-consumption of rooftop PV generated power through small-scale battery storage. The scenario assumes that battery
storage costs continue to fall along the lines of optimistic industry and analyst expectations. Overall, average self-consumption of PV output increases from 44% to 75% for domestic rooftop installations and to 90% for non-domestic rooftop installations. As a result, growth in installations is mainly in the rooftop sector, with a more moderate rate of growth assumed for ground-mounted arrays.

Table 1: User-led Scenario

<table>
<thead>
<tr>
<th>PV Installed Capacity</th>
<th>[GW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic rooftop and BIPV</td>
<td>22.5</td>
</tr>
<tr>
<td>Non-domestic rooftop and BIPV</td>
<td>12.5</td>
</tr>
<tr>
<td>Ground-mounted</td>
<td>15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy Storage Capacity</th>
<th>[GWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic battery</td>
<td>16</td>
</tr>
<tr>
<td>Grid storage pumped hydro</td>
<td>4.8</td>
</tr>
</tbody>
</table>

4. Structure of the analysis

Inspired by Ekvall and Weidema’s (2004) concept of consequential impacts radiating out within a system, like a ripple in a lake, the scope of this project is structured around three ‘scales’ of analysis (fig. 1):

(1) the impacts attributed to the material and energy flows to provide the PV modules, the inverter, and the batteries;

(2) the aggregated impacts of multiple PV systems at the local electricity distribution network level, such as any new infrastructure that may be required to adapt the network and transmission grid to variable and dispersed PV electricity production;

(3) Changes to the operation of the electricity grid due to PV output, specifically changes in grid emission intensity.

Fig. 1: Levels of the analysis (Jones and Raugei et al, 2014)
The overarching research question is thus: “What would be the whole-system environmental consequences of opting for different pathways of large-scale deployment of PV in the UK urban system grid when compared to previously developed future grid scenarios without PV?”

The chosen functional unit of the study is 1 kWh of electricity produced by the whole grid. Furthermore, the CLCAs compare and contrast three scenarios for the UK energy system from 2015 to 2035 – the analysis is based on medium- to long-term scenarios and the ‘prospective’ LCA is a novel aspect, as it is less common in the literature.

4.1 Level 1: PV systems

PV systems include three components: a PV cell, a module frame/mounting, and a power inverter.

PV cell and module frame

A wide range of cell options are available, with differing implications for the module frame/assembly. The research will focus on mono- and poly-silicon PV which is currently still dominant in the UK market because of combined cost, efficiency and stability attributes (IEA PVPS, 2013). CdTe PV will be considered as a proportion of ground mounted capacity within the scenarios. Future PV module characteristics and production methods are expected to keep improving based on the reasoned extrapolation of past trends (Frischknecht et al., in press). Time ‘steps’ of five year intervals are used to incorporate these changes into the LCA, so that PV systems deployed in the future reflect expected changes in production and efficiency. A module lifetime of 30 years is assumed in much of the LCA literature for PV (Hsu, O'Donoughue et al., 2012). Over time module efficiency is predicted to decline by a rate of 0.5% per year.

Power inverter

Power inverters that convert the direct current from PV cells to alternating current suitable for most electronic equipment and for export to the electricity network are required. There is also a choice between inverters and micro inverters depending on the module type and other factors. Central ‘string’ inverters located away from the PV array have been common; however, micro-inverters that are affixed to each module in a PV installation are also now available, and are offered by a number of domestic PV installers. This study will also include battery storage that is integrated with the PV user’s system, which is an important component of the user-led scenario. New and more cost-effective manufacturing techniques and lifetime extensions are being developed with regard to battery storage, and in particular, lithium-ion technology, largely in response to the automotive sector (IEA, 2013). Inverters are expected to fail over the 30 year lifetime of PV systems. There are a range of uncertainties around failure rates, however it is assumed here that the inverter is replaced once in the first instance, while in the sensitivity analysis more frequent replacement is explored.

End of life

According Nugent and Sovacool (2014), only five of the 23 LCAs of PV they reviewed include a decommissioning stage, with recycling only assumed for CdTe. Hammond, Harajli et al. (2012), for example, state that there is insufficient data on PV system
decommissioning and recycling for it to be included in their study. Therefore, development of recycling processes will be included where appropriate. In the UK, PV modules are legally classified as waste electrical and electronic equipment (WEEE). This means that PV module sellers have an obligation to take back modules at end of life and ensure they are recycled. Most of the module weight is glass (85% for C-Si, 90% of Cd-Te modules), which can currently be used for fibreglass, and potentially for other purposes in the future. PV CYCLE – a group set up to develop PV recycling in Europe – has a recycling target of 85% by 2020; however, this is to be calculated by weight, much of which would be covered by glass and aluminium recycling.

Figure 2: Flow diagram of rooftop PV System

4.2 Level 2: Local distribution networks

Where the capacity of PV systems connected to the electricity distribution network exceeds certain thresholds there is a need to implement changes in the network to integrate the PV power flow. The key interventions in the electricity system to integrate high levels of PV are:

• PV curtailment – i.e. the peak output from PV power inverters is limited, for example to 70% as practiced in Germany (Wirth 2014).
• Additional power electronics – i.e. there are a range of ‘tap’ and capacitor power electronic products to regulate voltage and smooth frequency and harmonic distortions on power networks.
• Adding storage at the distribution level to smooth voltage, frequency and utilisation variations.
• Upgrading power transformers and power lines.

Project partners on the WISE PV project will provide a power system impact assessment model that will be used to determine and quantify distribution network changes corresponding to the scenarios. These results will be included in the LCA through attributional LCAs of the assets that are assumed by the impact assessment model.

4.3 Level 3: National transmission network

At the macro level the study is focused on the analysis of future changes to UK power flows due to higher levels of PV in the grid, in terms of both electricity generation and demand. The amount of PV deployed in each scenario is expected to have consequences for the high-voltage electricity transmission grid and ultimately the emissions associated with the grid electricity. Understanding the impact of aggregated levels of PV on overall electricity grid emissions is a key component of WISE PV. In common with previous CLCA approach such as Pehnt, M., M. Oeser, et al. (2008), a power dispatch model developed by WISE PV partners will be utilised to investigate changes in generation profile used to meet electricity demand as a result of PV generating capacity and self-consumption.

5. Conclusions

The assessment of the system environmental impacts of ambitious levels of PV in the UK from a whole system perspective requires a consequential approach so that wider impacts across the system are included. The CLCA to be carried out builds on different elements in the existing literature, and draws on power system models developed through WISE PV. This novel approach integrates CLCA and Net Energy Analysis, and requires that careful consideration be given to scope, both in terms of system boundary and the timeframe being considered. This research is in progress – the results will be presented in the full version of this article.

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References


Wirth, H. (2014). Recent Facts About PV in Germany Freiburg, Fraunhofer ISE.