A literature review of the integration of optimization algorithms and LCA for microgrid design: a replicable model for off-grid systems in developing countries

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Abstract

As of today, about 1 billion people, mostly living in rural areas of developing countries, still lack access to electricity. A lot of research has been done on the optimal design process for rural electrification, in particular for the microgrid approach, but the evaluations performed so far still have the shortcoming of including only a small part of the environmental impacts and, in most of the cases, none of the social impacts. A suitable approach to fill this gap is the adoption of LCA and Social LCA outputs as objective functions in a multi-objective optimization model. This work aims at investigating the progress in literature on this specific methodology and at analysing the advantages and the drawbacks of the strategy presented in the different scientific publications.

1. Introduction

The United Nations have set universal access to energy as one of the Sustainable Development Goals to be reached within 2030, but nowadays there are still about 1 billion people living without electricity and much more suffering of an unreliable and intermittent service; moreover, most of them live in rural areas of developing countries (IEA, 2017). This lack brings about disadvantages in terms of education, job opportunities, healthcare, food security, gender equality and many other aspects. Investments in extension of national grids are not enough yet to reach the global objective within the set time. Furthermore, many factors make these expenditures not that economically viable: among them there are high costs, high dispersion of population, difficult terrains, lack of skilled labour, low level of domestic demand and scarce industrialization, long payback periods for investments. Thus, isolated systems (to be eventually integrated into the national network) are considered to be the solution which could address the energy poverty issue in the most effective way. Hybrid microgrids, integrating conventional units and renewable generators, are the most suitable option in many cases because they exploit resources which are locally available, clean, free and usually abundant in the area in which their installation is needed.

2. Problem statement

Many researchers have focused on the investigation of the most suitable solutions for rural microgrids and optimization algorithms have been widely employed in order to determine the best configuration and the optimal operation of such systems. This is now a well consolidated topic, but still lacking several core elements. One of them is certainly the ability to evaluate and maximize the benefits not only in terms of costs, but also in terms of environmental and social impacts. Classic algorithms just aim at minimizing the investment and operation costs (Moshi et al., 2016), but this could come at the expense of the wellbeing of the community and of the surrounding ecosystem. This is why a growing interest in multi-objective optimization has been registered (Dufo-López et al., 2016). The methodology allows to evaluate multiple aspects, which are often conflictive, and to provide the decision-maker with a set of optimal solutions among which he/she can choose the most suitable option.

This field is still developing, in particular in finding effective ways to quantify holistically the impacts of the system along its lifecycle. An interesting tool for this application is surely the Life Cycle Assessment (LCA), which allows a cradle-to-grave evaluation of the environmental impacts caused by a plant. It is then possible to insert its outputs into a multi-objective function in order to minimize the impacts and consequently design the microgrid. Moreover, a completely open field is the Social LCA (SLCA), which could suitably provide the indicators of an additional objective function for the assessment of social effects.

The purpose of this work is to investigate the progress in literature in the integration of optimization algorithms with environmental and, possibly, social LCA in the field of microgrids. This analysis will serve the aim of supporting future developments in the specific application of optimizing not only the design of the plant according to the associated costs, but of the whole process of rural electrification for isolated communities in developing countries.

3. Optimization of rural microgrids

The issue of rural electrification through microgrids has been investigated deeply in the last years, but so far no study has been able to comprehensively describe the system and find the best solution for the specific application. The most common approach is to develop an algorithm aimed at minimizing the total operating and, in some cases, investment cost of the plant, according to the technical capabilities of the components and to the power balance in the system (Kusakana, 2015; Luna et al., 2016). A generic deterministic optimization problem can be represented as follows:

$$\begin{aligned} &\text{minimize} && f(x) && \\ &\text{subject to} && c_i(x) = 0 && i \in E \\ & && c_i(x) \geq 0 && i \in I \end{aligned} \tag{1}$$

with $f(x)$ objective function, $c_i(x)$ constraint functions, E set of equality constraints, I set of inequality constraints.

A step forward towards a holistic evaluation is made with the adoption of multi-objective optimization, which allows to simultaneously aim at different goals, by formulating the problem as:

$$\begin{aligned} &\text{minimize} && f(x) = [f_1(x), f_2(x), \dots f_k(x)] && (2)\\ &\text{subject to} && c_i(x) = 0 && i \in E\\ & && c_i(x) \geq 0 && i \in I \end{aligned}$$

with k number of goals to be pursued. This algorithm does not produce a unique solution, but a set of non-dominated solutions (no solution performs better than the others in every objective) that compose the Pareto front (Dufo-López et al., 2016; Soroudi, 2017).

The method is generally used to minimize, beside the total cost of the system, also the emissions of CO_2 and other polluting gases produced by the system during its operation (G. Li et al., 2016). Other works include different environmental and social impact evaluation, such as land use (Silva & Nakata, 2009), job creation (Dufo-López et al., 2016; Hiremath et al., 2010; Silva & Nakata, 2009) and Human Development Index (Dufo-López et al., 2016). Capturing all the benefits/disadvantages that the microgrid may cause is a difficult challenge and the research performed so far shows two main shortcomings: the partial evaluation of environmental impacts (usually limited to CO_2 emissions and only during the operational phase of the plant) and the absence of consolidated methods to account for social effects. Especially when dealing with electrification projects in developing countries, taking into account the impacts in the most complete way possible is of pivotal importance, since the availability of electricity would dramatically change the lifestyle of the community.

In order to tackle this issue, a growing interest in the Life Cycle Assessment (LCA) methodology has been registered, because it aims at assessing environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal of the whole product, namely from cradle to grave, or even from cradle to cradle when recycling and reuse are considered (ISO 14040, 2006). A very good quality of the method is that it avoids "burden shifting" among phases of the life cycle, regions or impact categories, since each possible aspect is evaluated and adds up to the total assessment. On the other hand, LCA alone is not immediately significant for engineers because its raw outputs are of difficult comprehension if treated by a non LCA expert and they do not provide alternatives for environmental improvements (Murgante et al., 2014; Tao et al., 2018). For this reason, the applicability and effectiveness of LCA would benefit from its integration into optimization algorithms, too. Moreover, a methodology for Social LCA is under development, starting from the guidelines provided in (UNEP/SETAC, 2009) and the quality of the analysis of microgrids' impacts would truly benefit from its integration in the model.

4. LCA for microgrid optimization: literature review

Even if the potential of LCA for these applications has been widely recognized, just few works have included it in multi-objective optimization algorithms, and, to the author's knowledge, only (Abo-Elyousr & Elnozahy, 2018) dealt with this coexistence in the scope of rural electrification. For this reason, the literature review had to be diverted to a more general application, namely microgrids, including also industrial, grid connected plants and in the context of industrialized countries. The scientific publications analysed have been selected from the ScienceDirect database, by searching the keywords "optimization", "LCA" and "microgrid"/"micro-grid" and by analysing the works produced in the period 2012-2019. In total, 7 papers have been examined.

Basically, two methodologies emerge from the analysis for the LCA-optimization integration:

- Environmental impact assessment using LCA approach on the output results of a traditional optimization algorithm, i.e. aimed at maximizing economic and/or technical efficiency (Apurva, 2015; Nagapurkar & Smith, 2019; Quiggin et al., 2012);
- Adoption of the selected environmental impact as objective function in the scope of a multi-objective optimization (Abo-Elyousr & Elnozahy, 2018; M. Li et al., 2016; Shi et al., 2017; Zhang et al., 2015).

There is a deep distance between the goals of the two different strategies: in the first case, the design of the system is only influenced by technical and/or economic considerations and the LCA is used just for ex-post evaluations; in the second case, environmental impacts tangibly influence the microgrid planning and operation strategy and decision makers can freely establish the relative importance of the different goals. This last method allows a larger number of operative applications and a more accurate evaluation because, in order for a project to be successful, it is always important to assess the impacts of the microgrid as widely as possible but, depending on who the decision maker is (private company, government, NGOs), the priorities surely change and the multi-objective function can be tailored on the specific needs.

A general shortcoming of the scientific publications under analysis is that in most of the cases greenhouse gas (GHG) emissions are the only impacts assessed. It means that many other categories are neglected and this could lead to a partial and lacking analysis, since other impacts may have even more immediate and serious repercussions, as it may happen for land use in the case of microgrids for rural electrification in developing countries. There are a couple of exceptions to this trend: (Zhang et al., 2015) also included acidification potential (AP) in its evaluation, while (Apurva, 2015) adopted the ReCiPe method and quantified the impacts of the system through all the 18 sub-categories, then aggregated into 3 macro-areas.

For what concerns the source of data for LCA, only (M. Li et al., 2016) resorted to internal reports, therefore on primary information coming from the actual field;

(Zhang et al., 2015) and (Apurva, 2015) used the data available in Ecoinvent database as inputs in LCA softwares in order to compute the required figures. The rest of the works analysed resorted to a literature review, directly deriving the value of the impact.

From the point of view of the design of the algorithms, most of the modellers chose Matlab as programming environment (Abo-Elyousr & Elnozahy, 2018; M. Li et al., 2016; Nagapurkar & Smith, 2019; Quiggin et al., 2012). An important feature to be highlighted is that only (Apurva, 2015) included uncertainty in its model, even if every work considered in the analysis, except for (Zhang et al., 2015), deals with renewable and intermittent sources of energy. This is a pivotal issue when microgrid modelling is studied. Moreover, when it comes to applications in rural areas, uncertainty cannot be overlooked because most of the plants are almost entirely based on renewables and because the load behaviour is much more difficult to predict.

All the information about the papers analysed is summarized in Table 1.

4.1. Social LCA in optimization

Despite the recognized influence that energy and, in particular, access to energy have on livelihood of the target community, the development of a methodology to account for social impacts is still at its early stages. Moreover, including it in the design phase of a microgrid is a quite unexplored field. In general, few scientific publications have adopted SLCA in the energy field (e.g. (Corona et al., 2017)). As mentioned before, there are few studies that include social indicators in multi-objective optimization algorithms (Dufo-López et al., 2016) but, to the author's knowledge, there is not any study which exploits SLCA for this purpose. Several challenges hinder the systematic adoption of the method, as explained in (Fortier et al., 2019):

- the troubles in getting primary data which are deeply site-specific; resorting to social hotspots databases can consequently strongly bias the results of the analysis;
- the reticence of the interviewed in providing some sensitive but essential pieces of information (e.g. income);
- the combination of quantitative, semi-quantitative and qualitative measures which are not immediately comparable.

Therefore, a lot of research and efforts are needed in order to get to a satisfactory result in this field, but it is of pivotal importance for the achievement of an efficient way to model off-grid systems in developing countries, where energy is a driver for numerous different social and economic mechanisms which are strictly interconnected.

Table 1: Highlights of the scientific publications considered

Reference	Role LCA in optimization	Impacts assessed	Sources of data	Tools adopted	Uncertainty treatment
(Quiggin et al., 2012)	Environmental evaluation after technical optimization	GHG emissions	Literature review	Optimization in MATLAB	No
(Zhang et al., 2015)	Objective function	GWP and AP	Ecoinvent database	LCA in GaBi 6.0, optimization in GAMS	No
(Apurva, 2015)	GHG emissions as objective function + Multi-criteria decision analysis (MCDA) after economic optimization	ReCiPe method: 18 midpoint categories and 3 endpoint categories	Ecoinvent database	LCA in OpenLCA	Yes, stochastic optimization
(M. Li et al., 2016)	Objective function	GHG emissions	Internal reports	Optimization in MATLAB	No
(Shi et al., 2017)	Objective function	GHG emissions	Literature review	X	No
(Abo-Elyousr & Elnozahy, 2018)	Objective function	GHG emissions	Literature review	Optimization in MATLAB	No
(Nagapurkar & Smith, 2019)	Environmental evaluation after economic optimization	GHG emissions	Literature review	Optimization in MATLAB	No

5. Conclusions

This work has analysed the scientific papers published after 2012 that have integrated optimization and LCA for microgrid design. It has been highlighted that just in few cases the two methods are used together for an organic and exhaustive evaluation of the system and, even when it is done, many times LCA does not influence the decision-making process. The procedure adopted in the different publications has been investigated in detail, in order to identify the advantages and drawbacks of each approach and provide a guide for replicability of the model in the specific context of isolated renewables-based microgrids in developing countries. In particular, the following features have been stressed: the role of LCA in the optimization process, which impacts have been assessed, the source of the data employed for the LCA computations, the tools adopted, whether uncertainty of the inputs has been taken into account. Moreover, the presence of social LCA studies for microgrids has been investigated. The main findings resulted from the analysis are that the evaluation of environmental impacts through LCA is still generally limited to GHG emissions, providing a partial view of the effects of a plant on the surrounding ecosystem, and that social LCA in optimization is a completely unexplored field and it is still strictly tied to the issue of quantifying and comparing indicators from different categories. Therefore, there is a great need for further research in this area in order to get to a good level of detail and completeness in the impact assessment of microgrids. This is crucial especially when designing a system to be placed in a rural area of a developing country, because the target community is deeply affected by the provision of electricity. A complete evaluation is essential in order to give higher chances of success to rural electrification projects, which often fail because too many aspects beyond mere technicalities are neglected and whose development is in line with the achievement of the Sustainable Development Goals (SDGs), set by the United Nations as target for the year 2030, and especially with the SDG7, aiming at clean and affordable energy for everyone. Improving the design procedure is therefore an essential step towards a faster, more efficient and more equitable process of electrification for universal access to energy.

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