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Comparison of environmental assessment methodology in hybrid energy system simulation software

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Abstract

The advent of renewable energy systems has led to an increase in decentralised energy systems. Consequently, the last 10 years have seen development of specialised software such as HOMER, iHOGA, EnergyPro, RETScreen and TRNSYS to analyse these systems. This study compares these software in detail especially in terms of the environmental assessment. It is concluded that these software do not adequately include environmental analysis since only 1 out of 5 software considers more than one life cycle stage, neglecting other upstream/downstream emissions. Furthermore, the emphasis is on emissions such as NO_x and SO₂ that are usually associated with fossil fuel utilization. As the energy systems are becoming increasingly complex, especially with storage technologies such as hydrogen and batteries, emissions ‘shift’ away from the operating stage. Moreover, it becomes essential to look further than global warming potential and take into account other impacts such as depletion of critical materials, acidification, eco-toxicity, etc. Hence, it becomes essential to take into account entire life cycle stages and provide comprehensive environmental impacts along with the already available techno-economic capabilities to the designers and decision-makers. Finally, this study provides recommendations on the methodology to include environmental analysis in the investigated software.

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Keywords: hybrid energy system; environmental assessment; life cycle assessment (LCA).

1. Introduction

Conventional energy systems are largely centralized. For example, if an energy supply was required, a large coal or gas plant was built and the subsequent connections were made accordingly. The advent of renewable energy with its decentralized nature has provided us with more design choices. To assist designers in making these choices, various software have also emerged in the market. These software cater to different needs of various stakeholders such as policy making, financial planning, technical design, optimization and so on in the energy market. They are also available at different levels of geography from analyzing a single house to the

global energy system [1]. In this paper, software selected are restricted to technical or economic simulation applicable to community-level energy systems.

Environmental impacts of energy generation have been receiving a lot of attention recently and consequently been widely documented. Especially with the increasing awareness about climate change [2]. Simulation is an important step in promoting clean energy technologies as it provides system designers and decision-makers with alternatives. Environmental impact of energy systems might not be the main driver behind decision-making but it certainly is an important factor. It especially helps in determining environmental hotspots for research and initial design stages.

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There have been ample studies reviewing energy software in the literature. Arribas et al [3] conducted a survey of design and simulation tools for hybrid PV systems. The aim of this study is to assist designers to get an overview of the available tools and their uses. They also provide guidelines on the selection of tools according to their needs. Zhou et al [4] conducted research on the latest trends in optimization of hybrid solar-wind energy generation systems. As a part of this investigation, general methodology and merits-demerits of the software, HOMER, HYBRID 2, HOGA and HYBRIDS were also reviewed. Connolly et al [1] carried out a comprehensive review of software tools for integrating renewable energy systems. They also classified tools according to geographical area, number of users, level of detail, and energy sectors modelled. Along with this, a detailed overview of the selected software was also completed. Bernal-Agustin and Dufo-Lopez [5] studied simulation and optimization models in the published scientific literature. Furthermore, a brief description of software for designing hybrid energy systems and their classification in terms of features is also presented. Turcotte et al [6] surveyed and classified various software for simulation and sizing of PV hybrid systems. The aim of this study is twofold. First, to assist designers in identifying tools corresponding to their needs. Secondly, to assess future development opportunities for such software. However, they do not touch upon possible improvements in environmental criteria. Urban et al [7] investigated energy systems modelling software for developing countries. The aim of this study was to assess if characteristics of developing are appropriately represented in these tools. In total, 12 tools included in this review, not limited to techno-economic modelling. These tools were classified according to the type of simulation, energy sectors modelled and computation methodology. Jebaraj and Iniyar [8] reviewed energy modelling approaches related to planning, supply-demand, forecasting, optimization, neural networks and emission reduction. Since this article has a broad scope, information presented about individual models was limited. Erdinc and Uzunoglu [9] reviewed commercially available software and optimization techniques in scientific literature for optimum sizing of hybrid energy systems. Finally, Sinha and Chandel [10], is the most recent publication that reviews software for designing hybrid renewable energy systems with a goal of helping researchers identify the ideal tool according to the requirements. Apart from discussing software, they also use a case study to identify differences between HOMER and RETScreen.

As we can see, the review of available software for energy systems, their classification, guidelines for use according to user needs and other techniques has been already well documented in the scientific literature. However, discussion on whether these software adequately include the environmental dimension is missing. The aim of this study was to understand the methodology behind community-level energy simulation software to quantify environmental performance of systems. These software cannot be expected to make a detailed environmental study, but with the changing energy scenario, as we will see, it becomes crucial to reassess our methodology. Hence, by using elements of environmental

analysis, opportunities for improvement are highlighted. Additionally, it is important to understand the software goals, inputs & outputs and computation procedure. This will enable us to have a clear idea on its further development. Therefore, this study can be useful for developers and for the users to be aware of the limitations of these software.

In the next section, the software selection criteria is presented followed by a short review of each software and their approach to estimate environmental impacts. Finally, conclusions and discussions from this review are presented.

2. Software Selection

There are numerous energy simulation software available on the market depending on the geographical area, level of detail and the objective. A comprehensive list of energy software incorporating renewable energy is present at energyplan.eu [11] and in studies conducted by Sinha et al [10] and Connolly et al [1]. This list resulted in more than 50 software, which were then screened according to the following criteria:

- Software catering to a geographical area greater than a region were excluded.
- Only the software dealing with technical or economic simulation were selected. Hence, the ones dealing with objectives such as policy, markets, networks, etc. were neglected.
- Finally, software unavailable on the market because of being obsolete or internally used, were not investigated in this paper.

The five software passing the screening are HOMER, iHOGA, EnergyPro, RETScreen and TRNSYS. For the selected software, the simulation procedure and their methodology for estimating environmental impact is reviewed in the following section.

3. Review

Results from reviewing the software are presented in tables 1-3. Table 1 shows general information about the software such as developer and sectors modelled. Information about software features and type of computation is displayed in Table 2. Finally, information about environmental assessment conducted by the software can be seen in Table 3. Apart from the tabular results, an overview of the software with their computation methodology of environmental emissions is presented in this section

3.1. HOMER

The main inputs required by the software consist of technical and economic information about load characteristics, specifications of energy component and resource data. The latter includes both renewable and non-renewable resource such as solar data, wind data, fuel composition, etc.

Table 1: General information about the reviewed software.

Software	Developer	Description	Time step	Sectors Modelled		
				Electricity	Thermal	Hydrogen
HOMER	National renewable energy laboratory, USA	Techno-economic optimization	1 min – 1 hour	✓	✓	✓
iHOGA	University of Zaragoza, Spain	Techno-economic, multi-criteria optimization	1 min – 1 hour	✓	-	✓
EnergyPRO	EMD International, Denmark	Operation strategy optimization for a single project	1 min – 1 hour	✓	✓	-
RETScreen Expert	Ministry of Natural Resources, Canada	Economic feasibility and energy performance analysis	Monthly	✓	✓	-
TRNSYS	University of Wisconsin & University of Colorado	Detailed technical analysis for energy systems	0.01 s – 1 hour	✓	✓	✓

Once all the information is fed in the software, HOMER performs calculations in the following steps:

- An energy balance between available production options and load to be satisfied is performed at each time step throughout the year. Time step can vary from 1 minute to 1 hour.
- Out of the possible options, one with the lowest operating cost is selected at each time step. This calculation is repeated for all possible system configurations and after taking into account other factors such as capital cost, interest rates, project lifetime, etc., NPC (Net Present Cost) of all systems is calculated.
- A second algorithm sorts the feasible systems according to the increasing NPC or other available variables.

In the standard version, HOMER does not consider annual variations hence NPC is calculated for the project life based on the same data but taking into account the interest rate.

Environmental impact is only calculated for direct emissions of CO₂, CO, NO_x, SO₂, particulate matter and unburnt hydrocarbons from fuel combustion technologies. Emissions are calculated in HOMER as the product of emission factor and annual consumption of fuel. Emission factor is grams of pollutant emitted per unit fuel consumed. Emission factor for carbon dioxide is not required, as it is calculated using fuel consumption and simple mass balance assumptions. Lastly, emission factors for electricity grid can also be entered with values for United States available on the HOMER website.

3.2. iHOGA

Improved Hybrid Optimization by Genetic Algorithm also known as iHOGA is also a techno-economic simulation and optimization tool developed by the University of Zaragoza [13]. The primary objective of iHOGA, which is simulation and optimization of hybrid energy systems, is similar to HOMER. Hence, it is used in same design phase of sizing and feasibility analysis of energy systems.

The major difference between the two software lies in the optimization algorithm. Along with simulating all possible solutions, iHOGA also provides the option of utilizing genetic algorithm to find the optimum solution. The calculation methodology of the latter can be described as follows:

- Selection of a limited, random set of possible solutions called ‘Population’. In this context, an example of population could be solar panels (0-10kW), battery bank (0-100Ah) and wind turbine (0-10kW) in certain combinations. For each member of the population, an energy balance at each time step throughout the year is performed to select the technology with the lowest operating cost. Again, after considering other factors, NPC for each configuration is calculated.
- Solutions with highest NPC are discarded. While a crossover is performed between the remaining configurations to form a new ‘Population’. Crossover essentially means mixing the variables between the possible solutions. Let’s say for example, if the remaining population is solar panels (5-10kW), battery bank (50-100Ah) and wind turbine (7-10kW), configuration changes only within this range will be considered.
- Then, previous two steps are repeated until the stopping criterion is satisfied. This criterion is either when a maximum number of iterations are reached or NPC does not improve after a few consecutive iterations.

Main advantage of this algorithm is that, it takes considerably less time for convergence. Furthermore, iHOGA can also perform multi-criteria optimization taking into account other factors such as lifecycle CO₂ emissions, % unmet load, human development index and job creation. A maximum of three variables can be simultaneously optimized.

iHOGA is the only software in this review where the user can enter lifecycle emissions. However, only CO₂ equivalent emissions can be calculated. There is no possibility to add other emissions. Total CO₂ equivalents is the sum of emissions in operating stage plus total emissions in other lifecycle stages (Manufacturing, recycling, transport, etc).

Table 2: Type of analysis done by the reviewed software.

Software	Simulation		Sizing	Operation strategy optimization	Computation type
	Economic	Technical			
HOMER	✓	✓	✓	✓	Simulation & ranking
iHOGA	✓	✓	✓	✓	Multi-objective genetic algorithm
EnergyPRO	✓	✓	-	✓	Simulation
RETScreen Expert	✓	✓	-	-	Simulation
TRNSYS	-	✓	-	-	Simulation

Both these values are entered as emission factors that scale according to per unit fuel consumed or size of the equipment. Grid emission factors can also be entered as per unit of electricity consumed.

3.3. EnergyPro

EnergyPro is developed and maintained since the last 20 years by a Danish Company called EMD International [14]. EnergyPro is slightly different to the previous two software because of its diverging goal of optimizing ‘daily operation’ of energy systems rather than its configuration. EnergyPro is thus well suited to simulate performance of an energy system and to minimize its operating cost. Even though there will be discrepancies between load, demand, weather conditions, electricity market, etc. with real time values, the software can provide insight into the system operation.

The inputs for the software remain the same again, although, there is more flexibility since values can be entered as formulae based on other variables in the software. The calculation methodology can be described as:

- The priority of energy component dispatch to satisfy a load is calculated based on the operating cost. Although custom priority can be defined.
- Energy balance is calculated at each time step and energy supply components are dispatched according to the priority list. However, energy balance is not calculated chronologically.
- Most economical time steps in the entire year are calculated in the increasing order. Calculations are performed in such a way that emphasis is on reducing the number of ‘stop-start’ of components, which gives a more practical solution. The result is minimized net operating cost of the energy system.

In other words, EnergyPro provides recommendations on when to operate which component of the energy system based on operating cost, electricity market price, variable load and so on. In addition, comparatively detailed techno-economic reports are provided.

For calculating the emissions, only the operating life cycle stage is taken into account. The approach relies on emission

factors, which scale according to the fuel consumption and/or technology type. EnergyPro does offer addition of custom emissions other than the standard CO₂, NO_x and SO₂.

3.4. RETScreen Expert

RETScreen has been developed by Ministry of Natural Resources, Government of Canada [15]. The unique selling point of this software is rapid feasibility analysis of energy systems and its comparison with industrial benchmarks. RETScreen makes it possible by providing large amount of background information in the databases. Even if scarce information is available about the project, it can still be analyzed using weather database, hydrology data and typical energy component specifications along with their prices. Optimization is not available; hence, it can only be used for single project simulations. The calculation methodology operates in the following steps:

- First step is selection of location. This enables automatic addition of comprehensive climate data to the specific location.
- Technical and economic data for the project are entered. Interesting thing here is, depending on the data available, project specifications can be entered at different levels of detail or even with default values in the software.
- Finally, detailed financial, technical and risk analysis reports are generated. A comparison between the current system and planned facility can also be made in the software based on these reports.

Furthermore, average energy cost and efficiencies of different energy technologies with respect to various locations are shown to calculate savings. Energy efficiency and demand management can also be analyzed in this software.

Emissions in RETScreen are also estimated using emission factors per unit energy generated. For example, kg CO₂/GJ energy produced. In the highest level of granularity, emissions available are CO₂, CH₄ and N₂O. These emissions are limited to the operating phase of lifecycle.

Table 3: Environmental analysis in the reviewed software

Software	Life cycle stages considered		Emission factor units	Emissions						Possibility to add more emissions	Emission limits or penalties
	Operation	Other		CO ₂	NO _x	SO ₂	CO	Unburnt fuel	Particulate matter		
HOMER	✓	-	kg pollutant/unit fuel consumed	✓	✓	✓	✓	✓	✓	-	✓
iHOGA	✓	✓	kg pollutant/unit fuel consumed & kg pollutant/size of equipment	✓	-	-	-	-	-	-	-
EnergyPRO	✓	-	kg pollutant/unit fuel consumed	✓	✓	✓	-	-	-	✓	✓
RETScreen Expert	✓	-	kg pollutant/unit energy produced	✓	✓	-	-	✓	-	-	-
TRNSYS	-	-	-	-	-	-	-	-	-	✓	-

3.5. TRNSYS

TRNSYS is a transient system simulation software developed by University of Wisconsin and University of Colorado [16]. It was first developed for thermal systems 35 years ago but the utility has been expanded to various sectors since. TRNSYS enables detailed technical simulation of energy systems and the built environment. With a possible time step of 0.01s and detailed models of components, it enables users to find any issues, particularly about the transient state. Although TRNSYS is a paid software, it has open source code. Moreover, building custom models is possible and consequently it has a large component library. Hence, it is attractive to users when the standard models do not simulate the real world performances. This can be when the models are not detailed enough or when dealing with a novel technology. Additionally, TRNSYS allows the user to expand boundaries of the simulation. For example, modelling the energy demand of a building depending on various factors such as geography, architecture, weather conditions, etc.

The software is divided into two parts, kernel and model library. Kernel performs the calculations for the system whereas the model library consists of various component models that can be added to the system. Typical steps of simulating energy systems using TRNSYS are presented below:

- Import the required components of the energy system from the library
- Import the corresponding weather data from the database. Complete the interconnections between components and ensure their compatibility.
- Kernel computes the detailed simulation and the results can be seen in a variety of graphs and figures.

Numerous specialized software based on TRNSYS such as HYDROGEMS (stand-alone hydrogen), NREL SDHW (solar water heater), TRANSOL (solar thermal), etc. are also available. Some of them available free for TRNSYS users.

Estimation of emission does not exist in the basic version of TRNSYS. The specialized software based on TRNSYS were not investigated. However, since TRNSYS offers open source code and custom models, addition of basic emission factors at least should be straightforward.

4. Summary

As suggested by Turcotte et al [6], the five software can also be classified into the design stages for which they are relevant as done in Figure 1. RETScreen is used in the prefeasibility stage when scarce data is available to designers. The purpose at this stage is to check whether it is interesting to evaluate a project further given the local conditions. In the next stage, when more data is collected, HOMER and iHOGA provide the optimized component size and the ability to compare various system architecture. In the next step when the choice of a system is down to a few options, EnergyPRO gives us the operation strategy to minimize the net production cost with respect to the system and its corresponding constraints. Finally, TRNSYS can be used for detailed technical simulation or to improve the standard models. It allows the user to modify algorithms and specific component interactions. TRNSYS is also comparatively better equipped to model a novel technology and include external effects.

Hence, it can also be used at an early stage of technology modelling, which is not shown in Figure 1. It should be noted however, software are more flexible to be used in different stages than defined in this section. For example, HOMER and iHOGA can also be used for optimizing daily operations or single project simulations.

The environmental analysis included in the reviewed software is judged inadequate in its current form. There are three primary reasons identified for the same.

First, the energy scenario is changing rapidly. To analyze this, we look at greenhouse emissions according to lifecycle stages for wind turbines, solar PV, conventional natural gas and coal plants in Figure 2. For wind turbines and solar PV, we consult a paper investigating 153 LCA studies by Nugent

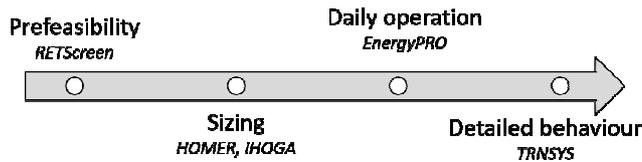


Figure 1: Stages of energy system design and the corresponding relevant software

and Sovacool [17]. Data for electricity production from natural gas and coal plants are taken from the LCA harmonization studies Donoughue et al [18] and Whitaker et al [19] respectively. Three life cycle stages: Upstream, Operation and Downstream are considered here. These emissions are further disaggregated in their primary studies, however for comparison, further breakdown was not possible. The upstream stage consist of all emissions resulting from construction of energy production facilities including material extraction, assembly and transport. Operation stage means the ongoing emissions during the electricity production phase of these plants. This includes emissions related to maintenance of facility, fuel cycle (e.g. extraction, transport, preparation) and direct combustion of natural gas and coal. Emissions due to decommissioning these systems followed by disposal or recycling the resulting waste is included in the downstream stage. Transportation where available is included in all stages above but not disaggregated. We can straight away see that for wind and solar PV, majority of the impact comes from upstream while for natural gas and coal, operation stage renders the rest of the life cycle stages insignificant. Operation stage of solar PV is generally expected to be low impact since it comprises of cleaning solar panels and if needed, replacement of certain electric components. As a result, 24 out of 26 samples in 9 studies excluded this stage from their analyses [17]. Hence, the contribution of solar PV operation stage is probably overestimated. While the number of samples for PV downstream was also low (5), this was due to lack of data. Finally, we can see that the emissions are an order of magnitude lower for PV and wind but the hotspot has 'shifted' to manufacturing stage. For conventional natural gas and coal plants, the primary studies [18,19] show that first order estimates are possible just by the knowledge of certain supply chain steps, since on average, 99% of greenhouse gas emissions result from fuel cycle and combustion phase. Since most of the software only offer emission calculation based on operation stage, their estimation for conventional technologies might be sufficient, their inability to evaluate renewable energy systems can lead to sub-optimal design.

Second, LCA results are highly case specific. Even more for renewable energy system. For example, a study by Padey et al [20] shows that greenhouse gas performance of wind turbines vary from 76.7 g CO₂-eq/kWh at average wind speed of 4 m/s at a lifetime of 10 years to 4.5 g CO₂-eq/kWh at average wind speed of 9 m/s with a lifetime of 30 years. That is a variation of almost 17 multiples. Hence, we can see that use of such simple emission factors may not offer sufficiently accurate results. Certainly not for non-conventional energy

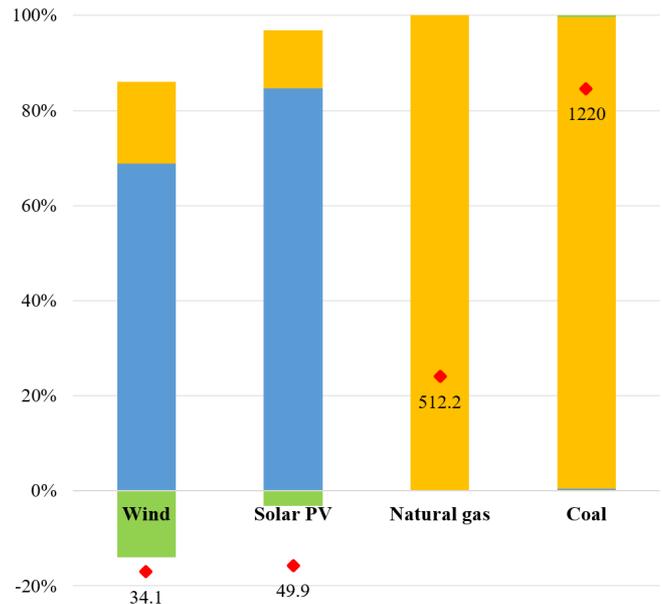


Figure 2: Disaggregated greenhouse gas emissions according to life cycle stages for electricity production from wind turbines [17], solar PV [17], conventional natural gas [18] and coal fired plants [19].

systems where results also vary with factors such as geography.

Third, we see that most of the software only take into account the greenhouse gases and emissions to air. Studies show that single impact categories, for example, global warming potential, are insufficient for representing the associated environmental problems [21,22]. Other emissions and the relevant impact categories are also crucial to make a reasonable estimation of the environmental performance. For example, a review conducted by Nordelöf et al [23] shows that impact categories of resource depletion and ecotoxicity should be included in lifecycle assessment studies of lithium-ion batteries. Mainly due to use of materials such as rare earth metal, lithium and emission intensive step of mining.

5. Discussion

Based on the limitations presented above, opportunities for future development of environmental analysis in the energy software can be identified as follows:

- The most important step is move towards inclusion of other lifecycle stages. It is accepted that streamlining of LCA's can be done and stages with negligible impact may be neglected. However, the current approach of measuring only operating phase emissions to air even for non-conventional technologies such as Solar PV, is in need of improvement.
- To estimate environmental assessment, the inherent variability present in these technologies must be addressed. It can be argued that LCA estimates of renewable energy are dependent on more factors than conventional systems. Apart from considering technology type and efficiency, factors such as climate conditions also become important. The ideal solution would be to link or integrate energy system analysis with LCA

specialised software. In case this is not possible, various regression based approaches available in the literature with varying levels of complexities and accuracy can be used. It is clear that such a methodology cannot replace the accuracy of a complete LCA study; it can provide respectable first order approximates. For example, simplified LCA models of Padey et al [20] can estimate GWP for wind turbines with an accuracy of 80-90%. Including studies mentioned earlier [18,19], other useful examples can be regression approaches used on nuclear energy by Lenzen [24] and on plastics by Bala et al [25]. However, such models might not be available for all energy technologies and may take considerable resources to develop.

- In terms of communication of results to the designers and decision makers, unlike presenting only emissions to air, comprehensive impact categories and the reasons behind selecting them must be presented. In recent years, some studies have shown how impact categories correlate [20,21] and a small number of impact categories may be sufficient to provide a holistic picture of environmental impact [28]. A promising approach building up on these studies, is objective reduction followed by multi-criteria optimisation. It allows the selection of limited number of impact categories explaining the maximum variance in the overall impact [29,30,31]. Since optimisation is frequently used for analysing energy systems, this approach can be especially be useful here not only for system designers but also for LCA experts.

References

- [1] D. Connolly, H. Lund, B. V. Mathiesen, and M. Leahy, "A review of computer tools for analysing the integration of renewable energy into various energy systems," *Applied Energy*, vol. 87, no. 4, pp. 1059–1082, Apr. 2010.
- [2] R. Pachauri and L. Meyer, *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. 2014.
- [3] L. Arribas, L. Cano, I. Cruz, M. Mata, and E. Llobet, "PV-wind hybrid system performance: A new approach and a case study," *Renewable Energy*, vol. 35, no. 1, pp. 128–137, Jan. 2010.
- [4] W. Zhou, C. Lou, Z. Li, L. Lu, and H. Yang, "Current status of research on optimum sizing of stand-alone hybrid solar-wind power generation systems," *Applied Energy*, vol. 87, no. 2, pp. 380–389, Feb. 2010.
- [5] J. L. Bernal-Agustín and R. Dufo-López, "Simulation and optimization of stand-alone hybrid renewable energy systems," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 2111–2118, Oct. 2009.
- [6] D. Turcotte, M. Ross, and F. Sheriff, "Photovoltaic Hybrid System Sizing and Simulation Tools: Status and Needs," presented at the PV Horizon: Workshop on PV Hybrid Systems, Montreal, 2001.
- [7] F. Urban, R. M. J. Benders, and H. C. Moll, "Modelling energy systems for developing countries," *Energy Policy*, vol. 35, no. 6, pp. 3473–3482, Jun. 2007.
- [8] S. Jebaraj and S. Iniyar, "A review of energy models," *Renewable and Sustainable Energy Reviews*, vol. 10, no. 4, pp. 281–311, Aug. 2006.
- [9] O. Erdinc and M. Uzunoglu, "Optimum design of hybrid renewable energy systems: Overview of different approaches," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 3, pp. 1412–1425, Apr. 2012.
- [10] S. Sinha and S. S. Chandel, "Review of software tools for hybrid renewable energy systems," *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 192–205, Apr. 2014.
- [11] "Other tools similar to energyPRO, <http://www.energyplan.eu/othertools/local/energypro/>."
- [12] "HOMER Energy - Support, <https://www.homerenergy.com/products/pro/docs/3.10/index.html>."
- [13] R. Dufo-López, "iHOGA version 2.4 User Manual, <https://ihoga.unizar.es/en/>." University of Zaragoza, Spain.
- [14] EMD International, "User's Guide energyPRO, <https://www.emd.dk/energypro/>."
- [15] Ministry of Natural Resources, Canada, *RETSscreen Expert - User Guide*, <http://www.nrcan.gc.ca/energy/software-tools/7465>.
- [16] University of Wisconsin Madison, *TRNSYS18 - User Guide*, <https://sel.me.wisc.edu/trnsys/>. Madison.
- [17] D. Nugent and B. K. Sovacool, "Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey," *Energy Policy*, vol. 65, pp. 229–244, Feb. 2014.
- [18] P. R. O'Donoghue, G. A. Heath, S. L. Dolan, and M. Vorum, "Life Cycle Greenhouse Gas Emissions of Electricity Generated from Conventionally Produced Natural Gas: Systematic Review and Harmonization," *Journal of Industrial Ecology*, vol. 18, no. 1, pp. 125–144, Feb. 2014.
- [19] M. Whitaker, G. A. Heath, P. O'Donoghue, and M. Vorum, "Life Cycle Greenhouse Gas Emissions of Coal-Fired Electricity Generation," *Journal of Industrial Ecology*, vol. 16, no. s1, pp. S53–S72, Apr. 2012.
- [20] P. Padey, I. Blanc, D. L. Boulch, and Z. Xiusheng, "A Simplified Life Cycle Approach for Assessing Greenhouse Gas Emissions of Wind Electricity," *Journal of Industrial Ecology*, vol. 16, no. s1, pp. S28–S38, Apr. 2012.
- [21] A. Laurent, S. I. Olsen, and M. Z. Hauschild, "Limitations of Carbon Footprint as Indicator of Environmental Sustainability," *Environmental Science & Technology*, vol. 46, no. 7, pp. 4100–4108, Apr. 2012.
- [22] P. P. Kalbar, M. Birkved, S. Karmakar, S. E. Nygaard, and M. Hauschild, "Can carbon footprint serve as proxy of the environmental burden from urban consumption patterns?," *Ecological Indicators*, vol. 74, pp. 109–118, Mar. 2017.
- [23] A. Nordelöf, M. Messagie, A.-M. Tillman, M. L. Söderman, and J. V. Mierlo, "Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment?," *Int J Life Cycle Assess*, vol. 19, no. 11, pp. 1866–1890, Nov. 2014.
- [24] M. Lenzen, "Life cycle energy and greenhouse gas emissions of nuclear energy: A review," *Energy Conversion and Management*, vol. 49, no. 8, pp. 2178–2199, Aug. 2008.
- [25] A. Bala, M. Raugei, G. Benveniste, C. Gazulla, and P. Fullana-i-Palmer, "Simplified tools for global warming potential evaluation: when 'good enough' is best," *The International Journal of Life Cycle Assessment*, vol. 15, no. 5, pp. 489–498, Jun. 2010.
- [26] J. Pascual-González, C. Pozo, G. Guillén-Gosálbez, and L. Jiménez-Esteller, "Combined use of MILP and multi-linear regression to simplify LCA studies," *Computers & Chemical Engineering*, vol. 82, pp. 34–43, Nov. 2015.
- [27] M. A. J. Huijbregts, S. Hellweg, R. Frischknecht, H. W. M. Hendriks, K. Hungerbühler, and A. J. Hendriks, "Cumulative Energy Demand As Predictor for the Environmental Burden of Commodity Production," *Environ. Sci. Technol.*, vol. 44, no. 6, pp. 2189–2196, Mar. 2010.
- [28] Z. J. N. Steinmann, A. M. Schipper, M. Hauck, and M. A. J. Huijbregts, "How Many Environmental Impact Indicators Are Needed in the Evaluation of Product Life Cycles?," *Environmental Science & Technology*, vol. 50, no. 7, pp. 3913–3919, Apr. 2016.
- [29] E. Antipova, D. Boer, L. F. Cabeza, G. Guillén-Gosálbez, and L. Jiménez, "Uncovering relationships between environmental metrics in the multi-objective optimization of energy systems: A case study of a thermal solar Rankine reverse osmosis desalination plant," *Energy*, vol. 51, pp. 50–60, Mar. 2013.
- [30] C. Vadenbo, D. Tonini, and T. F. Astrup, "Environmental Multiobjective Optimization of the Use of Biomass Resources for Energy," *Environmental Science & Technology*, vol. 51, no. 6, pp. 3575–3583, Mar. 2017.
- [31] A. Gonzalez-Garay and G. Guillen-Gosalbez, "SUSCAPE: A framework for the optimal design of SUSTainable Chemical ProcEsses incorporating data envelopment analysis," *Chemical Engineering Research and Design*, vol. 137, pp. 246–264, Sep. 2018.