





# CLOVER: A modelling framework for sustainable community-scale energy systems

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## Software

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## Summary

Sustainable Development Goal 7 aims to provide sustainable, affordable, reliable and modern energy access to all by 2030 ([United Nations, 2015](#)). In order for this goal to be achieved, sustainable energy interventions in developing countries must be supported with design tools which can evaluate the technical performance of energy systems as well as their economic and climate impacts.

CLOVER (Continuous Lifetime Optimisation of Variable Electricity Resources) is a software tool for simulating and optimising community-scale energy systems, typically minigrids, to support energy access in developing countries ([Winchester et al., 2022](#)). CLOVER can be used to model electricity demand and supply at an hourly resolution, for example allowing users to investigate how an electricity system might perform at a given location. CLOVER can also identify an optimally-sized energy system to meet the needs of the community under specified constraints. For example, a user could define an optimum system as one which provides a desired level of reliability at the lowest cost of electricity. CLOVER can provide an insight into the technical performance, costs, and climate change impact of a system, and allow the user to evaluate many different scenarios to decide on the best way to provide sustainable, affordable and reliable electricity to a community.

CLOVER can be used on both personal computers and high-performance computing facilities. Its design separates its general framework (code, contained in a source `src` directory) from user inputs (data, contained in a directory entitled `locations`) which are specific to their investigations. The user inputs these data via a combination of `.csv` and `.yaml` files. CLOVER's straightforward command-line interface provides simple operation for both experienced Python users and those with little prior exposure to coding. An installable package, [clover-energy](#), is available for users to download without needing to become familiar with GitHub's interface. Information about CLOVER and how to use it is available on the [CLOVER wiki pages](#).

## Statement of need

CLOVER was developed to provide a robust techno-economic and climate impact analysis tool to support users in evaluating sustainable energy interventions in developing countries. By providing an open-source alternative to proprietary minigrid design tools such as HOMER ([HOMER Energy, 2022](#)), CLOVER offers a more comprehensive analysis tool than common spreadsheet-based alternatives. CLOVER was designed to provide a fast, flexible and user-friendly software to assess energy systems at both short-term (hourly) and multi-year timescales under a wide variety of user-defined scenarios, constraints and optimisation conditions.

CLOVER can provide an insight into the technical performance, costs, and greenhouse gas emissions of a system, and allow the user to evaluate many different options to decide on the best way to provide sustainable, affordable and reliable electricity to the community. Its simulation functionality offers the user an insight into the hourly, daily, seasonal and multi-year technical performance of a system in response to changing electricity demands and varying renewable resources. Its optimisation process replicates the design process common in sustainable development settings by identifying optimum system design over short-term time horizons, but allowing the system to increase in capacity over its lifetime as the demand of the community grows in response to its economic development ([Sandwell, 2017](#)).

Other Python libraries exist which can be used to investigate solar and/or off-grid electricity systems, however CLOVER offers alternative or additional functionalities relevant and beneficial to the design and assess community-scale electricity systems. These alternatives include:

- `pvl` is an established open-source package for estimating the generation output of solar technologies ([Holmgren et al., 2018](#)). It focuses on the technical performance of the PV system (modules, inverters, trackers etc.) in detail, whereas CLOVER also models and optimises other parts of the electricity system (battery storage, distribution, demand, other generation technologies) and the economic/environmental impacts.
- `Offgridders` is an open-source Python tool for simulating and optimising minigrids ([Hoffmann et al., 2020](#)). It has many of the same functions as CLOVER, however CLOVER can simulate and optimise over multiple years and resize system capacities and re-evaluate impacts as load demand grows over time, as is the aspiration in many development settings. Furthermore CLOVER can automatically generate or acquire user inputs for energy generation and demand, rather than requiring these inputs as `.csv` files.
- `0SeMOSYS` ([Howells et al., 2011](#)) and `pypsa-earth` (developed from the established `PyPSA` framework ([Brown et al., 2018](#))) are both energy system models for long-term energy planning. Both have focused on applications in developing countries, similarly to CLOVER, but do so at the national or international scale for large-scale electricity networks, rather than the relatively small community-scale applications for which CLOVER is designed.

The primary target user group of CLOVER is academic researchers who investigate electricity access in developing countries and the design of community-scale electricity systems, with examples of research outputs given in [Research and future development](#). Secondary target groups include development practitioners and energy service providers, such as non-governmental organisations or businesses, which could use CLOVER to inform their strategies and operations. These two main target groups have collaborated to deliver academic research with a focus on the practical implementation of sustainable electricity systems in developing countries ([Beath et al., 2021](#); [Few et al., 2022](#); [Matthey-Junod et al., 2022](#)).

## Main features

### Electricity supply

CLOVER can simulate a variety of electricity supply technologies:

- Solar generation is sourced from the `Renewables.ninja` API ([Pfenninger & Staffell, 2016b](#)) with the synthesis of the data described in [Pfenninger & Staffell \(2016a\)](#);
- Battery storage, charged from solar, with user-defined characteristics for battery performance and lifetime to emulate many kinds of technologies;
- Diesel generation can be included as a source of power when no other source is available;
- Grid power can be treated as a primary or backup source of electricity with a user-defined availability profile. These electricity sources can be included as the single source of electricity or in any combination as part of a hybrid system.

## Electricity demand

Users can generate electricity load profiles based on appliance ownership, usage patterns, power demands, and other device-specific information. Load profiles are based on the probability that individual user-specified appliances are in use, which can vary throughout the day and year, using processes described in Sandwell et al. (2016) and applied in Chambon et al. (2020). Any kind of electrical appliance and usage pattern can be defined by the user and ownership of appliances can be set to increase over time. Demands can be segregated into domestic, commercial, public, or other demand categories and included independently within the system. Alternatively users can provide their own hourly load profile, for example taken from monitored data.

## Simulation

CLOVER assesses the balance of energy sources and demands at an hourly resolution over a user-specified lifetime period. During this process data, including energy flows, battery state of charge, demand satisfaction, and times at which electricity is (un)available, are recorded.

The simulation functionality of CLOVER can be used to explore the technical performance of existing or theoretical case study systems. Data from the simulation process can be processed to give insight into how a system might perform over an average day, year, or over its lifetime. These could be used to explore opportunities to maximise electricity utilisation by integrating additional user loads or investigating the impact of incremental increases in storage capacity for more efficient system design (Sandwell, Ekins-Daukes, et al., 2017).

## Optimisation

CLOVER can identify the optimum energy system, defined by a selected optimisation criterion, subject to any number of user-specified constraints (threshold criteria). Potential optimisation criteria include lowest cost, lowest greenhouse gas emissions, or others depending on the goals of the system; potential threshold criteria could set minimum allowable levels for the reliability of electricity supply, energy demand satisfaction, renewable energy penetration, or many more.

Users can specify the types of technologies available to include in the system and CLOVER uses an iterative heuristic search algorithm to identify the optimum combination and capacities to meet the needs of the community over its lifetime. A diagrammatic overview of this process is shown in Beath et al. (2021).

## Research and future development

CLOVER has been used to evaluate the design and techno-economic impacts of sustainable electricity systems across a wide range of development contexts. These include the costs and greenhouse gas emissions of solar minigrids in India (Sandwell, 2017; Sandwell, Ekins-Daukes, et al., 2017), including for healthcare applications (Beath et al., 2021) and as electricity demand grows over time (Sayani et al., 2022). CLOVER has been applied to community-scale electricity access in displacement settings, such as refugee camps in Rwanda (Baranda Alonso et al., 2021; Baranda Alonso & Sandwell, 2020) and Djibouti (Matthey-Junod et al., 2022), and for comparisons of the impacts of rurality and climate (Few et al., 2022) and existing energy infrastructure (Sandwell, Wheeler, et al., 2017) on minigrid design in different countries. To date, CLOVER has been used as part of six PhD projects and by more than 10 MSc students.

CLOVER is being used as part of several ongoing research projects. These include:

- An assessment of the cost and climate impacts of optimally-sized grid-connected solar-battery systems in India under different levels of grid availability;

- The opportunities for solar minigrid systems to support social development in rural Pakistan;
- An evaluation of the costs and climate impacts of achieving energy access at the global scale.

CLOVER remains under continuous development to increase its functionality and to address new and emerging research questions. Future releases are planned to include the ability to model thermal energy for heating and cooling, variable grid pricing, advanced diesel generator modelling, and more.

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## References

- Baranda Alonso, J., & Sandwell, P. (2020). *Sustainable mini-grid systems in refugee camps: A case study of Rwanda*. Grantham Institute, Imperial College London. <https://doi.org/10.25561/77296>
- Baranda Alonso, J., Sandwell, P., & Nelson, J. (2021). The potential for solar-diesel hybrid mini-grids in refugee camps: A case study of Nyabiheke camp, Rwanda. *Sustainable Energy Technologies and Assessments*, 44, 101095. <https://doi.org/10.1016/j.seta.2021.101095>
- Beath, H., Hauser, M., Sandwell, P., Gambhir, A., Few, S., Chambon, C. L., & Nelson, J. (2021). The cost and emissions advantages of incorporating anchor loads into solar mini-grids in India. *Renewable and Sustainable Energy Transition*, 1, 100003. <https://doi.org/10.1016/j.rset.2021.100003>
- Brown, T., Hörsch, J., & Schlachtberger, D. (2018). PyPSA: Python for Power System Analysis. *Journal of Open Research Software*, 6(4, 1). <https://doi.org/10.5334/jors.188>
- Chambon, C. L., Karia, T., Sandwell, P., & Hallett, J. P. (2020). Techno-economic assessment of biomass gasification-based mini-grids for productive energy applications: The case of rural India. *Renewable Energy*, 154, 432–444. <https://doi.org/10.1016/j.renene.2020.03.002>
- Few, S., Barton, J., Sandwell, P., Mori, R., Kulkarni, P., Thomson, M., Nelson, J., & Candelise, C. (2022). Electricity demand in populations gaining access: Impact of rurality and climatic conditions, and implications for microgrid design. *Energy for Sustainable Development*, 66, 151–164. <https://doi.org/10.1016/j.esd.2021.11.008>
- Hoffmann, M. M., Pelz, S., Monés-Pederzini, Ò., Andreottola, M., & Blechinger, P. (2020). Overcoming the Bottleneck of Unreliable Grids: Increasing Reliability of Household Supply with Decentralized Backup Systems. *J Sustain Res.*, 2, e200009. <https://doi.org/10.20900/jsr20200009>
- Holmgren, W. F., Hansen, C. W., & Mikofski, M. A. (2018). Pvlb python: A python package for modeling solar energy systems. *Journal of Open Source Software*, 3(29), 884. <https://doi.org/10.21105/joss.00884>
- HOMER Energy. (2022). <https://www.homerenergy.com/>.
- Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolis, J., & Bazillian, M. (2011). OSeMOSYS: the open source energy

- modeling system: an introduction to its ethos, structure and development. *Energy Policy*, 5850–5870. <https://doi.org/10.1016/j.enpol.2011.06.033>
- Matthey-Junod, A., Sandwell, P., Makohliso, S., & Schönenberger, K. (2022). Leaving no aspect of sustainability behind: A framework for designing sustainable energy interventions applied to refugee camps. *Energy Research & Social Science*, 90, 102636. <https://doi.org/10.1016/j.erss.2022.102636>
- Pfenninger, S., & Staffell, I. (2016a). Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. In *Energy* (Vol. 114, pp. 1251–1265). <https://doi.org/10.1016/j.energy.2016.08.060>
- Pfenninger, S., & Staffell, I. (2016b). *Renewables.ninja*. <https://www.renewables.ninja/>.
- Sandwell, P. (2017). *Assessing the potential for photovoltaic technology to mitigate greenhouse gas emissions: life cycle analysis and energy systems modelling for electricity access in rural India* [PhD thesis]. Imperial College London.
- Sandwell, P., Chambon, C., Saraogi, A., Chabenat, A., Mazur, M., Ekins-Daukes, N., & Nelson, J. (2016). Analysis of energy access and impact of modern energy sources in unelectrified villages in Uttar Pradesh. In *Energy for Sustainable Development* (Vol. 35, pp. 67–79). <https://doi.org/10.1016/j.esd.2016.09.002>
- Sandwell, P., Ekins-Daukes, N., & Nelson, J. (2017). What are the greatest opportunities for PV to contribute to rural development? *Energy Procedia*, 130, 139–146. <https://doi.org/10.1016/j.egypro.2017.09.416>
- Sandwell, P., Wheeler, S., & Nelson, J. (2017). *Supporting Rural Electrification in Developing Countries*. Grantham Institute, Imperial College London.
- Sayani, R., Ortega-Arriaga, P., Sandwell, P., Babacan, O., Gambhir, A., Robinson, D., & Nelson, J. (2022). Sizing solar-based mini-grids for growing electricity demand: Insights from rural India. *Journal of Physics: Energy*. <https://doi.org/10.1088/2515-7655/ac9dc0>
- United Nations. (2015). *Transforming our world: the 2030 Agenda for Sustainable Development*. Resolution adopted by the General Assembly on 25 September 2015, (A/RES/70/1). Available from <https://digitallibrary.un.org/record/809145>.
- Winchester, B., Beath, H., Nelson, J., & Sandwell, P. (2022). *CLOVER* (Version v5.0) [Computer software]. Zenodo. <https://doi.org/10.5281/zenodo.6925534>