



A comparative analysis of renewable energy simulation tools: Performance simulation model vs. system optimization



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ABSTRACT

Whether you are beginning to learn about renewable energy or are an expert, there are a number of software-tools that can be used to help simulate and optimize your system. Performance models simulate energy outputs with system configurations specified by the user, while optimization models can help plan appropriate system sizes to meet energy goals such as minimizing life-cycle system costs or maximizing carbon reduction.

The models reviewed in this paper have been categorized into different project level subgroups: 'Multi-scale Renewable Energy (RE) Tools', 'District Level Tools', and 'Regional Level Tools'. The tools in each category will be compared to one another to show similarities and differences. Concluding this research, a summary of which tools are more suitable for each scale will be suggested.

1. Introduction

1.1. Overview

With the growing demand for energy in the world today, expanding 2.4% annually, interest in renewables technologies are growing fast [1]. When installing renewables, there is great potential to have significant reductions in emissions, as well as cost savings [2].

Models and tools that are developed for renewable energy are used to assess, analyze, and optimize the potential energy and cost impact of renewable energy and energy efficiency technologies [3].

These tools can be applied on many different levels, such as local, district, and regional. These models differ in scale and complexity, as well as the inputs that the software requires to generate the intended outputs [4].

Models need to balance simplicity and ease of use; accuracy, precision, and representativeness; and data granularity [5]. Many models make performance estimates based on installation and operating costs and system design parameters that you specify as inputs into the model. General technical inputs include site location and resource data (weather information) [6], system components [7], electricity rates, and electric load (energy usage per month) [7]. Financial inputs can be, but are not limited to, system costs (i.e. cost of module and inverter, construction, land acquisition, tax) [8], system degradation rate [9], financial parameters (debt ratio, depreciation rate, inflation rate, energy escalation rate, analysis Period, and insurance Rates) [10], and incentives (tax credits, investment based incentives, production

based incentives, capacity based incentives, and the Modified Accelerated Cost Recovery System (MACRS)) [11]. Incentives can lead to a great cost advantage when wanting to pursue a renewable energy system in your area. Some advanced modeling tools require more input data such as fuel types, investment options, operation costs, and precise site load data, such as fifteen-minute interval data for gas and electricity consumption [12,13].

The most appropriate model to assess a renewable energy opportunity will depend on the type of renewable technology being considered, complexity of the project, sophistication of the user, and data that you have available. This paper describes the different renewable energy tools available today, including technologies they evaluate, the scale and level of analysis, their modeling approach and limitations, data inputs required, and typical outputs. It also provides case studies of each tool.

The tools are divided into three sections: Multi-scale RE Tools (including basic renewable energy modeling tools that are easier to use), District Level Tools (including more detailed level result models taking more inputs into account), and Regional Level Tools (including higher scale project tools that can be applied at a national level).

1.2. Previous reviews

A number of previous modeling reviews have examined different aspects and approaches to RE modeling. The tools investigated are not all specifically ones reviewed in this paper, but similar in their focus on performance and financial modeling.

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Allegrini, Orehounig, Mavromatidis, Ruesch, Dorer, and Evins [14] published a review of models and tools for energy systems on the district-scale level. The research discussed modeling approaches that are relevant to urban and district-level energy systems. They discussed details about the tools and software packages available that implement these models. The discussion section of the review covered key topics emerging in urban energy systems modeling, particularly cross-disciplinary and integration issues.

Li and Wen [15] discussed renewable energy building modeling for control and operation. The research focused on building energy modeling and forecasting, with studies included focusing on building energy forecasting, modeling for major components such as power generation, energy storage, and short-term weather forecasting. The conclusion of the review suggested choosing the modeling tool depending on the system type.

Vreenegeer, Hensen, and de Vries [16] researched the advantages and disadvantages of eleven simulation tools (not all being renewable energy related), which are all different than the tools reviewed in this paper. The tools discussed in their research primarily relate to district-level modeling and how energy is calculated. The objective of this work was to develop a district evaluation model based on energy performance to support housing associations in choosing the optimal renovation solution.

Crawley, Hand, Kummert, and Griffith [17] summarized existing building-level energy simulation tools. They surveyed more than 230 tools and listed the best ones, in their opinion. The main tools in the building energy field are the whole-building energy simulation programs, which provide users with building performance indicators such

as energy use and demand, temperature, humidity, and costs.

Kandt et al. [18] completed a comparative analysis of seven different solar mapping tools in 2010. This research showed how the modeling tools have changed over time, and described new commercially available tools. They felt it was important to assess each individual modeling tool based on its accuracy and portrayal of PV potential.

Although previous reviews have assessed different modeling tools and their advantages and disadvantages, none of these reviews have specifically targeted renewable energy modeling tools. This review will focus on renewable energy modeling tools, and the unique characteristics that distinguish them.

2. Review of renewable energy tools

In this section, we will discuss the different modeling tools that can be used for renewable energy assessment and what each one entails. This review paper classifies each tool by project scale. Multi-scale RE tools have the capability of modeling residential, commercial, and utility-scale projects. District level tools can model residential and commercial buildings, as well as higher scale projects like microgrids. Regional scale tools are mainly focused on large scale projects, such as regional and national.

Table 1 provides a detailed matrix in which the twelve tools evaluated in this paper are shown, along with thirteen attributes that classify and make each tool unique. Two classifications are indicated on the table: the model having the specific attribute (green box with an X), and the model not having the specific attribute (empty red box). This

Table 1
Synopsis of renewable energy modeling tools' complexity, capability, and general attributes.

	Simulation	Optimization	Photovoltaics	Wind Energy	Biomass Energy	Battery Storage	Residential Modeling	District Modeling	Regional Modeling	Consecutive Technology Modeling	Finance	Performance	Free?	Capability of modeling large plant	Beginner Tool	Advanced Tool
SAM	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
CREST	X		X	X	X	X	X		X		X		X			
PVWatts	X		X			X			X		X		X			
Pvsyst	X		X			X	X		X	X			X	X		
Windographer	X		X			X			X				X	X		
windPro	X		X			X			X		X		X			X
RETScreen	X		X	X	X	X			X	X	X		X	X		
Helioscope	X		X			X	X	X	X	X			X	X		
REopt	X	X	X	X	X	X		X	X	X			X			X
HOMER	X	X	X	X	X	X		X	X	X			X			X
Gatecycle	X			X		X				X			X			X
ReEDS	X		X	X	X		X	X	X	X	X	X	X			X
EnergyPLAN	X		X	X	X	X		X	X	X	X	X	X			X
KomMod	X		X	X	X	X		X	X	X	X	X	X			X

table is designed to be a quick reference for comparing each tool discussed in this review paper. Attributes of each tool are discussed in detail in the following sections.

2.1. Multi-scale RE tools

Multi-scale RE tools have the capability of modeling residential, as well as commercial buildings. These tools are well-rounded for many scales of modeling.

2.1.1. System Advisor Model (SAM)

Developed by the National Renewable Energy Laboratory (NREL), SAM is a free performance and financial model designed to facilitate decision making for people involved in the renewable energy industry, including project managers and engineers, policy analysts, technology developers, and researchers [19]. The software makes performance predictions and cost of energy estimates for grid-connected power projects based on installation and operating costs and system design parameters that the user specifies as inputs [14]. SAM models a variety of technologies including solar photovoltaic (PV) systems, battery storage, solar water heating, wind power, geothermal power, and biomass power. Each technology is modeled separately; SAM cannot model the integration of multiple technologies which can limit its use [20].

SAM is a simulation-based software [4], and users typically evaluate a number of scenarios with different inputs to model a system that meets your need.

SAM requires inputs describing the weather at the system's location, information about the project's cost and financial assumptions, and specifications of the system's performance characteristics [21]. As an analyst/researcher, it is your responsibility to review and modify the input data as appropriate for each analysis. Default inputs, which you can adjust, are financial and economic inputs, incentives, system performance, and costs.

Outputs of SAM are levelized cost of energy (LCOE), power purchase price, rate of return, and other financial metrics for utility-scale projects. It also provides payback period and net present value for residential and commercial projects. Hourly, monthly, and annual average predictions of the system's performance are given, including net electric output and component efficiencies [21]. The tool also outputs customizable graphs that show summaries of results from both the performance model and financial model.

There are a number of publications that go into depth about projects that have been completed using SAM [22]. Rudié, Thornton, Rajendra, and Kerrigan [23] used SAM to analyze different scenarios to compare attributes such as total data on solar irradiance, and trends that occur each season. The analysis was conducted over the course of a year, and error metrics were calculated on time increments of hourly, daily, monthly, and annually.

2.1.2. The Cost of Renewable Energy Spreadsheet Tool (CREST)

CREST is a free economic cash flow model designed to allow policymakers, regulators, and the renewable energy community to assess project economics, system design, cost-based incentives (e.g., feed-in-tariffs), and evaluate the impact of various state and federal support structures [24]. CREST is composed of four analytic tools, including solar (PV and thermal), wind, geothermal, and anaerobic digestion technologies. These four Excel-based tools are directly downloadable on NREL's website [24].

For users seeking a quick analysis of incentives and other economic drivers of a renewable energy project's cost of energy (COE) and LCOE, CREST can serve as a simple and focused financial tool. Although this tool does not provide as detailed results as SAM and other modeling tools, it is a quick, user-friendly financial spreadsheet [25].

Inputs for CREST vary by the type of technology the user wants to simulate. There are fourteen separate input categories, and each

category, using one or more inputs, provides the flexibility for policy makers and stakeholders to analyze numerous combinations of sample projects and scenarios [25]. The inputs are as follows:

1. Project Size & Performance
2. Capital Costs (the geothermal model separates capital costs into three sub-groups)
3. Operations & Maintenance
4. Construction Financing
5. Permanent Financing
6. Tax
7. Supplemental Revenue Streams: Tipping Fees
8. Cost-Based Tariff Rate Structure
9. Forecasted Market Value of Production
10. Incentives
11. Capital Expenditures during Operations
12. Reserves Funded from Operations
13. Initial Funding of Reserve Accounts
14. Depreciation Allocation

The outputs of the CREST model represents the all-in-price necessary to make the modeled renewable energy project financially feasible by meeting its equity investors' required minimum after-tax return. Analysis using the model also provides valuable information to inform rate-setting decisions [25]. Corbus et al. [26] used CREST to examine the economics of new transmission to deliver wind power from Wyoming to electricity customers in California. For the analysis that they completed, CREST served as a tool for comparing different technologies with significantly different resource cost profiles. The tool also showed an analysis of changes in global factors, such as the Production Tax Credit (PTC) and Investment Tax Credit (ITC).

2.1.3. PVWatts

PVWatt's is a free tool, developed by NREL, that estimates the energy production and energy value of grid-connected PV energy systems throughout the world. It allows homeowners, building owners, installers and manufacturers to easily develop estimates of the performance of potential PV installations [27]. The tool is very simple to use and can provide a quick energy production estimate.

PVWatts is suitable for very preliminary studies of a PV system. However, the production estimates calculated by PVWatts do not account for some factors that are important to the detailed design of a PV system [27].

The first step is to enter the address, zip code, or geographic coordinates of the system's location, and PVWatts will automatically identify nearby solar resource data for you to choose from.

After inputting your location, the tool will require five inputs: the system's DC size, array type, a DC-to-AC derate factor, tilt angle, and azimuth angle [28]. PVWatts makes cost of electricity estimates based on whether the system is on a residential or commercial property, its installation cost, and the retail cost of electricity.

PVWatts is also embedded within two other tools: SAM and REopt. Within SAM, PVWatts is one of four PV performance models available. SAM will generate results based on the PVWatts performance model, but using SAM's cost and financial model and assumptions. REopt uses PVWatts similarly to generate PV energy production estimates. The PVWatts Manual [29] describes the software and example output scenarios.

Liu, Hoekman, Robbins, and Ross [30] conducted a lifecycle climate impact and economic performance case study of solar PV systems on a commercial-scale level. They used PVWatts for their research because the software incorporates complex climate data (covering a 30-year period) to calculate average monthly solar insolation at large cities around the world.

2.1.4. PVsyst

PVsyst is a paid modeling tool [31] widely used by architects, engineers, and researchers in the renewable energy industry. It includes a detailed contextual help menu that explains the modeling process and offers a user-friendly guide to developing a project [24]. This tool presents results in the form of a full report, specific graphs and tables, and data that can be exported for use in other software tools [32].

The software is limited to just solar PV modeling, which can limit its overall use compared to other renewable energy modeling tools. The tool is a simulation-based model [4], which allows the user to model different system sizes and inputs. As described in the following paragraph, the tool only needs a couple inputs, so results may not be as accurate as tools that require more user input data [33].

For a given project, the user is able to construct several variations for the system. Inputs for the software include specifying the desired power or available area, and choosing the PV module and inverter [33]. From those inputs, PVsyst will propose an array/system configuration, that allows you to conduct a preliminary simulation.

The simulation calculates distribution of energy throughout the year, and will provide results including the total energy production (MWh/year), the performance ratio, and the specific energy (kWh/kWp) based on the available irradiation, as well as location and orientation of the panels. The results will also include a loss diagram, showing the main energy outputs and the gains/losses involved in the simulation [33].

Overall, PVsyst is a powerful tool that can provide a quick analysis for the system you are researching, and show you potential improvements that can be made in the system design [34,35]. Annegren, Hällqvist, and Salander [36] performed a case study in Sweden, using PVsyst as their main modeling tool. The purpose of their research was to evaluate the benefits of optimizing an existing PV system, and evaluate the costs of the optimization. They chose to use PVsyst because it can accurately analyze different configurations and evaluate the results to suggest the best solution.

2.1.5. Windographer

Windographer is a paid performance tool [37] that is the industry leading software for analyzing wind resource data measured by met tower, Sonic Detection and Ranging (SODAR), or Light Detection and Ranging (LIDAR). The tool can import virtually every data format encountered in the wind industry, allows rapid quality control and statistical analyses including Measure-Correlate-Predict (MCP), and can export to all wind flow models common in the wind power industry [38].

This renewable energy modeling tool is specifically developed for wind data simulation. Other renewable energy resources are not included in this model. For simulations in Windographer, you must have your own wind data set to import into the software, and it can only model individual turbines (not large wind farms). This tool is mainly used by wind engineers that are looking to dig into the details of their wind resource data.

In Windographer, a data set is comprised of many different inputs [39], including:

1. Data columns (actual wind speed data)
2. Data column properties (type, name, units, measurement height, and color of each data column)
3. A list of the properties of the flags used in the data set (name and color of each)
4. A list of flagged segments
5. The data set history (a list of all modifications made to the data set)

When these inputs are imported into the software, you can simulate a detailed analysis of your wind data. These results include, but are not limited to, wind shear, turbulence, tower distortion, temperature

gradient, inflow angle, extreme winds, and wind turbine performance [40]. The results that are generated from the simulation can then be exported into different formats. More detailed examples of inputs can be found in [41–43]. Aldeman et al. [44] used Windographer to help determine the technical potential for wind energy in the state of Illinois. Twelve different wind turbine models that are in Illinois were modeled by using the Windographer software. The tool was mainly used for their research to compute the power production, as time varies, of the wind turbines throughout the course of a year.

2.1.6. windPro

windPro is a paid [45], module-based software suited for project design and planning of both single Wind Turbine Generation (WTG) and large wind farms. Windographer only has the capability of modeling one turbine at a time, while windPro can model an entire wind farm in one simulation. This tool is used to get a wind turbine's generated energy outputs, financial results for your wind project, air density, turbulence intensity, as well as many different wind speed measurements (wind speed shear, wind direction shear) [46].

Much like Windographer, windPro is just focused on wind energy. In order to create wind and energy models of an area using the tool, the user must import wind resource data [42].

The inputs in windPro are similar to the Windographer tool. Imported data includes coordinates, wind data, and maps from the wind site [47]. Once wind data from all meteorological towers are imported to windPro, wind statistics are created for each site [48]. Companies that use the windPro tool can be seen in [49]. Ozerdem and Turkeli [50] used windPro for their research predicting the wind energy content over the campus area of the Izmir Institute of Technology. They collected data from different wind turbines of varying heights, and used the software to analyze the data.

2.1.7. RETScreen

RETScreen is a free energy modeling software that simulates a comparison between a “base case”, typically the conventional technology or measure, and the “proposed case”, which is the clean energy technology [51]. The software can be used to evaluate benefits from both clean energy production from power generation projects and savings through energy efficiency projects, accounting for project costs, emission, reductions, and financial risk [52].

The user inputs are general information about the project, such as project, facility, analysis type, and the location. Other inputs include fuel type, fuel rate, and schedule of utility electricity rates. There are a number of spreadsheets provided when downloading the tool [51], which are used to evaluate load and network design, the energy model, and emissions reduction [53].

The primary output of RETScreen is financial results [51]. A full cost and risk analysis contains information which can help you determine which parameters of a proposed case have the greatest risks and costs [53]. The logistics and resources for the software can be found at [54].

Lee et al. [55] conducted a preliminary case study to determine the optimal size for renewable energy technologies in buildings using RETScreen. They described the software as a ‘convenient and relatively accurate tool’ for evaluating the feasibility of renewable energy systems. RETScreen has been widely used for pre-feasibility of renewable systems, and this study provided a methodology to find the optimal design parameters for a renewable energy technology in the design of building energy systems.

2.1.8. Helioscope

Developed by Folsom Labs, Helioscope is a paid [56] tool used to design a solar array and quickly analyze design decisions. With Helioscope, you can generate a solar system layout and bankable energy production estimates quickly and efficiently [57]. The software can be used for pre-screening estimates or advanced analyses of sites.

Helioscope provides CAD-like tools, but it is specifically built for solar, so users are able to quickly design the system. The software includes an advanced energy simulation engine, which is used to compute every simulation component within the array [57].

This piece of software is valuable for solar PV design and performance modeling; however, it is limited to systems under 5 MW. The software focuses just on solar PV, and cannot model other types of renewable technology.

Ciriminna et al. [58] used Helioscope in their education case study that discussed curriculum for renewable energy technology in the classroom. Helioscope and HOMER were the two tools that they used to show renewable energy modeling, and their students used the software for their research projects. They chose these pieces of software due to their reliable high performance, and elegance of the building integration.

2.2. District level tools

District level tools require a more sophisticated user that can provide more detailed data sets for results. They can analyze systems with greater detail than Multi-scale RE Tools due to the inputs and complexity of results. District tools can also model higher scale projects, such as microgrids and larger gas turbines.

2.2.1. REopt

Developed by NREL, REopt is a modeling platform for energy systems integration and optimization that can help users to understand the optimal mix of renewable energy and fossil fuels required to meet cost savings, greenhouse gas reduction, and energy performance goals [59]. The software combines site, resource, cost, incentive, and financial data to identify the most cost-effective ways to meet energy goals at a single site or across a portfolio of sites. Formulated as a mixed integer linear program, the REopt model determines the optimal selection, sizing, and dispatching of technologies that typically include renewable and conventional distributed energy resources, the utility grid, energy storage technologies, and dispatchable loads. REopt leverages other tools and models for its performance data [59,60].

REopt can be used as an early screening tool to identify and prioritize renewable energy projects at a single site, or across a portfolio of sites in multiple cities, states, or countries. REopt can show you the optimal projects to install in your respective area, and when the optimal time would be [61,62].

The tool also has the capability of modeling microgrids, energy storage, resiliency, and detailed campus energy systems [63]. NREL is continuing to add new features to the REopt platform, which include energy efficiency, demand management, water planning, and an application program interface (API). NREL efforts to assist colleges and universities can be shown in [64].

Simpkins, Cutler, Hirsch, Olis, and Anderson [65] used REopt to analyze remote Alaskan Villages. With the tool, they were able to find an optimal path for the villages to achieve a 75% fuel reduction. In addition to the existing diesel generator and fuel oil heating technologies, the model was able to select from among wind, battery storage, and dispatchable electric heaters to meet the electrical and thermal loads of the system.

2.2.2. Hybrid Optimization of Multiple Energy Resources (HOMER)

HOMER is a paid tool [66] that is used for designing and deploying microgrids and distributed power systems that can include a combination of renewable power sources, storage, and fossil-based generation. The tool was designed by NREL and provides simulation and optimization capabilities [67]. The optimization process identifies least-cost options for microgrids and other distributed electrical power systems. HOMER makes it easy to compare thousands of possibilities in a single simulation. This allows you to see the impact of variables, such as fuel costs and wind speeds [67].

At its core, HOMER is a simulation model, which makes it differ from REopt (which is mainly an optimization model) [68]. The tool is highly advanced at designing a system for microgrid or distributed connection, as well as stand-alone systems.

HOMER is a complex piece of software that has many different input options available to the user. For users inputting solar PV data, input options pertaining to the system size, cost, lifetime, and depreciation are available [69]. Economic values such as annual real interest rate, project lifetime, system fixed capital costs, and more are available to the user to input.

Outputs from the program include a whole cost summary, including capital costs, Operation and Maintenance (O & M) costs, fuel costs, and cash flow. If utility data is input, HOMER will output the monthly energy purchased (kWh), energy sold (kWh), peak demand (kW), as well as energy and demand charges (\$) [69].

Bahramara, Moghaddam, and Haghifam [70] described HOMER as ‘one of the most powerful tools’ to find the size most optimal for Hybrid Renewable Energy Systems (HRESs). HRES is a combination of renewable and traditional energy resources, as well as energy storage to meet the electrical load locally in grid connected and stand-alone modes. They conducted this research to access minimum investment and operation costs, and to also meet the technical and emission constraints in the electricity sector.

2.2.3. Gatecycle

Gatecycle is a paid simulation tool used for design and performance evaluation of thermal power plant systems for both new and completed projects [71]. The software combines an intuitive, graphical user interface with detailed analytical models for the thermodynamic, heat-transfer and fluid-mechanical processes within power plants. Gatecycle can accurately predict the performance of combined cycle plants, simple cycle plants, cogeneration systems, and many other energy systems, such as gas turbines that are used for biomass [72].

Gatecycle would generally not be used as a pre-screening tool, as it is a complex piece of software that requires experience to use; however, it can be used for pre-feasibility all the way to plant acceptance [72]. Since the tool is used to evaluate gas and heat generation, renewable energy resource simulation would be limited to biomass, landfill gas, and waste-to-energy. SAM can also model biomass energy performance; however, at a lower complexity compared to Gatecycle.

In the design mode of the software [72], the user specifies the performance attributes that are required, and the software identifies the equipment to match the performance criteria. The tool also works in the opposite way, where the user defines operational conditions, and the tool calculates the corresponding “as-built” performance [72].

Gatecycle provides both simple and in-depth analyses within the interface, allowing it to provide results for any situation needed. As described previously, the software has the capability to model equipment “as built”, meaning you can still be designing the plant. Gatecycle models are extremely flexible [72], allowing an indefinite number of calculation cases to cover variations in design parameters, as well as plant performance (if the plant is under “off-design” conditions).

Brusca et al. [73] presented a case study dealing with the performance of a gas turbine running on biofuels. For the research, they used Gatecycle to model the gas turbine using on-design parameters, while performance test results were compared with experimental running data.

2.3. Regional level tools

These tools are mainly focused on developments on a larger scale, such as regional or national. They require more advanced data sets in order to get more accurate results.

2.3.1. Regional Energy Deployment System (ReEDS)

Developed by NREL, ReEDS is a long-term capacity-expansion

model for the deployment of electric power generation technologies and transmission infrastructure throughout the contiguous United States [74]. This tool is designed to analyze critical issues in the energy sector, especially with respect to potential energy policies, such as clean energy and renewable energy standards or carbon restrictions.

ReEDS models electricity systems on statewide or nation-wide level, rather than individual projects. Multi-scale RE Tools or District Level Tools are more appropriate for an individual project.

The goal of ReEDS is to provide a detailed representation of electricity generation and transmission systems and specifically address a variety of issues related to renewable energy technologies, including accessibility and cost of transmission, regional quality of renewable resources, seasonal and diurnal load and generation profiles, variability of wind and solar power, and influence of utilities [74]. Inputs for the software include base overnight capital cost (\$/kW), variable O & M cost (\$/MWh), fixed O & M cost (\$/kW-Yr), and heat rate (Btu/kWh). A full list of inputs for ReEDS, as well as functionality, can be found at [75].

Major outputs of ReEDS include the amount of generator capacity and annual generation from each technology, storage capacity expansion, transmission capacity expansion, total electric sector costs, electricity price, fuel prices, and carbon dioxide (CO₂). Published work from ReEDS, including technical reports, journal articles, conference papers, and posters, can be found at [76].

Ibanez and Zinaman [77] modeled the integrated expansion of the Canadian and U.S. power sectors by using the ReEDS model. Modeling future renewable energy scenarios needed tools that can accommodate the diversity of the different renewable energy technologies and applications, the location-dependent quality of many of these resources, as well as the variability and uncertainty of solar and wind generation. They chose to use ReEDS because it is 'unique' among nationwide and long-term capacity models for its highly complex regional structure.

2.3.2. EnergyPLAN

EnergyPLAN is a free tool developed by the Sustainable Energy Planning Research group at Aalborg University that simulates the operation of national energy systems on an hourly basis, including electricity, heating, cooling, industry, and transportation sectors [78]. The main purpose of the model is to analyze the energy, environmental, and economic impact of various energy strategies. The key objective is to model a variety of options so that they can be compared with one another, rather than model one 'optimum' solution based on defined pre-conditions [79].

The aim of this tool is to model the 'finishing point' of the energy system, rather than the starting point [79], which means this tool focuses on the future energy system that could be installed, rather than on today's energy system, making it unique compared to other modeling tools. This piece of software should not be used if you are doing pre-screening for a site and need preliminary results for research.

General inputs to the tool are energy demand, renewable energy sources, energy station capacities, costs, and a variety of regulation strategies emphasizing import/export and excess electricity production [79]. The tool focuses on the 'big picture' for resource installation and optimization. More detailed inputs and functionality of the tool can be found in [80].

Outputs for EnergyPLAN include energy balances and resulting annual productions, fuel consumption, import/export of electricity, and total costs including income from the exchange of electricity [79]. Furthermore, results include detailed hourly analyses of a complete energy system, access to the library of hourly data, and free online training to make the interface easier to navigate. Users can also expect access to a network of global users that can assist and share their simulations and expertise with you [79]. A number of case study scenarios are shown at [81], which provide studies done internationally.

Connolly, Lund, and Mathiesen [82] conducted a technical and economic case study to determine the impact of one potential 100% renewable energy implementation path for the European Union. They chose to use EnergyPLAN because it optimizes the technical operation of a given system, as opposed to tools that only identify an optimum within the regulations of an individual sector.

2.3.3. KomMod

KomMod is a simulation tool, developed by Fraunhofer ISE Germany, used to create sustainable energy scenarios [83]. The tool provides real-time estimates of demand side power requirements, as well as available sources producing power at optimal operation.

The interface of KomMod is similar to EnergyPlan, as well as the inputs that it requires. KomMod has three objectives: to analyze the requirements of a municipal energy system model, to compare the requirements with existing models, and to create an energy system model, based either on an existing solution or from the start [83].

Eggers and Stryi-Hipp [84] used the KomMod software as a tool to support municipalities, as they move along the path to becoming a Smart Energy City. KomMod was able to deliver recommendations depending upon the capacity of a city, the number of facilities to be installed, as well as the relevant time series for those operations.

2.4. Other tools

These tools do not specifically focus on renewable energy technologies as inputs. They are more suited for advanced modeling of systems that the other tools cannot model.

2.4.1. Energy Storage Valuation Tool (ESVT)

A piece of software that simulates finances of energy storage is the Energy Storage Valuation Tool (ESVT). ESVT is a paid [85] tool that is used to analyze the cost-effectiveness of energy storage. It does not fully incorporate renewable energy technology as an input, but can be very useful if you are also researching resiliency and storage of a solar PV system. Zakeri and Syri [86] used ESVT to evaluate different life cycle costs of electrical energy storage systems.

2.4.2. Long-Range Energy Alternatives Planning System (LEAP)

The Long-Range Energy Alternatives Planning System (LEAP) is a paid [87] tool that can simulate and optimize energy consumption, production and resource extraction in all sectors of an economy [88]. This tool goes as much in depth as REopt; however, it does not include renewable energy systems as technology options. The tool has the capacity to be used at a wide range of scales, from cities and states to national, regional, and even global applications [88]. Heaps [89] did a deep carbon reduction scenario analysis in China in 2009 using the LEAP software. The tool was able to optimize energy over the next four decades for the country to show how development and growth could be altered, as well as greenhouse gas (GHG) emissions. The ultimate goal of this research was to show the feasibility of massively reducing China's CO₂ emissions by the year 2050.

2.4.3. Distributed Energy Resources-Customer Adoption Model (DER-CAM)

Developed by the Microgrid Team at Berkeley Lab, DER-CAM is a free economic and environmental model of customer DER adoption [90]. This main purpose of this tool is to minimize the cost of operating on-site generation and combined heat and power (CHP) systems, either in residential or commercial sites (Multi-scale - District Level).

DER-CAM uses customer's load profiles, electricity policies and prices, capital, fuel costs, and other physical characteristics of the system to determine what the minimum cost of operating can be [91]. The model assumes that customer decisions are made based upon direct economic criteria, meaning that the only benefit is a reduction in the customer's electricity bill.

This tool was recently updated in March of 2016 [92] to further develop its features to expand beyond just residential modeling. Since then, it is a tool widely used in microgrid modeling. Stadler et al. [93] used DER-CAM to model strategic investment decisions for their distributed energy system. They used the software, as well, to show the trade-off between cost and CO₂ reduction.

2.4.4. GridLAB-D

Developed by the U.S. Department of Energy (DOE) the Pacific Northwest National Laboratory (PNNL), GridLAB-D is a power distribution simulation software tool that is used to provide users with information about the design and operation of their distributed energy system [94]. The tool incorporates advanced modeling techniques, along with high-performance algorithms to deliver real time modeling results. This is an open-source tool, much like PVWatts, where you can access and input information directly on their website simulation pages.

GridLAB-D incorporates voltage control, solar, energy storage, demand response, as well as a solar demonstration simulation. Thomas and Tesfatsion [95] used GridLAB-D to realistically model their distribution system. The software was able to accurately demonstrate the distributed energy system, highlighting how the price and load affect one another.

3. Discussion

In this section, I will discuss the differences of simulation and optimization modeling in software, and how each approach can provide different results. Each category of renewable energy modeling tools will be discussed, along with the best modeling tool for each scale of project, based on prior work done.

To begin, we must look back to our previous topic of a simulation versus an optimization [4]. The key difference between simulation and optimization are the specified system size. With simulation tools, you need to have a specific system size to model your inputs. If the user knows the specific system size they would like to model, then this type of modeling would work. Optimization does not need a specific system size, but rather the land available for a renewable energy technology installation. The optimization tool will find the best suitable system size based on your inputted land area, economics, and system constraints. This is better suited for a user that knows how much land is available to install a renewable technology, but not the specific size they should install.

The tools in this review were split into three different categories that we thought were fitting for each. Multi-scale RE Tools are the type of tools that are more straight-forward to comprehend than others, have fewer inputs, and are more publically known. District Level Tools have a higher capability of modeling more complex projects than Multi-scale RE Tools, and have more in-depth results; however, they cannot model to the scale of Regional Level Tools.

District Level Tools have the capability of working with larger projects, such as an educational institution or commercial building. These tools do not simulate and optimize on a regional level (consisting of an electric load on the regional scale). Common examples of using these tools are to do screenings at college institutions to show stakeholders a comprehensive, and cost-effective way to reduce energy costs.

Regional Level Tools give the user the ability to work with energy systems on the national level. These tools are not suitable for modeling individual projects. These tools have been used when comparing an institution's electrical load profile to the national level of energy load. The software is able to give very comprehensive results that show specifically which resource is influencing electricity and emissions.

4. Conclusion

This review paper has given an overview of many different modeling tools that are used for simulating and optimizing a renewable energy project. Each model has different qualities that make it unique such as user inputs and precision of results. Some tools have a goal of giving the user an easy to perform quick pre-screening. Some can give an optimized model that shows specifically what type of renewable resource should be installed, and to what scale. Nevertheless, all have a common goal of providing the user with useful information for their renewable energy work.

The intention is that users can use the information from this review to help them pick the right renewable energy modeling tool for their specific work. The review addresses some limitations that come with each model, and how researchers today use each tool.

Over the past years, there have been many advances in renewable energy systems, and the way they are modeled. Having a greater understanding of renewable energy modeling tools will help as you approach system design. Implementing a renewable energy system will have challenges along the way, and modeling your system can help to energy and cost impact of different design alternatives.

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