REopt: A Platform for Energy System Integration and Optimization

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REOPT: A PLATFORM FOR ENERGY SYSTEM INTEGRATION AND OPTIMIZATION

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ABSTRACT

REopt is an energy planning platform offering concurrent, multiple technology integration and optimization capabilities to help clients meet their cost savings and energy performance goals. The REopt platform provides techno-economic decision support analysis throughout the energy planning process, from agency-level screening and macro planning to project development to energy asset operation. REopt employs an integrated approach to optimizing the energy costs of a site by considering electricity and thermal consumption, resource availability, complex tariff structures including time-of-use, demand and export rates, incentives, net metering, and interconnection limits. Formulated as a mixed integer linear program, REopt recommends an optimally sized mix of conventional and renewable energy, and energy storage technologies; estimates the net present value associated with implementing those technologies; and provides the cost-optimal dispatch strategy for operating them at maximum economic efficiency. The REopt platform can be customized to address a variety of energy optimization scenarios including policy, microgrid, and operational energy applications. This paper presents the REopt techno-economic model along with two examples of recently completed analysis projects.

INTRODUCTION

Energy asset modeling tools are a class of decision support tools that provide analysis of energy generation and consumption at all stages of the project development cycle, from master planning and project screening to detailed feasibility analysis to real-time control of energy assets. During the screening phase, these tools often leverage geospatial renewable energy resource datasets in conjunction with standardized technology models to provide estimates of the energy production capabilities of a given technology. After a potential project has been identified during the screening phase, more detailed techno-economic analysis is performed during the development phase. After commissioning is completed, real-time energy modeling tools may be used to help operate the asset. A few examples of such energy modeling tools that provide analysis and decision support at one or more stages of the development cycle include RETScreen [1], PVWatts [2], SAM [3], DER-CAM [4-7], and HOMER [8,9].

A common limitation of many energy asset modeling tools is that they require the user to specify the size of the system to be considered, a detail which—by definition—is not known at the screening stage. Although the user can make an estimate of the system size, the economic feasibility may be significantly worse if the analysis is performed at a size other than the optimal, possibly leading the user to incorrectly conclude that a particular technology is not economically viable. The more detailed energy modeling tools improve the fidelity of the analysis during the feasibility stage, but they typically only consider one technology at a time and therefore fail to account for the interactions that occur when multiple technologies are operating concurrently. Finally, many tools do not accurately model the interaction between the load and the onsite generation, particularly the periods when an asset is out-producing the load. If this electricity cannot be sold back to the utility, the energy may be of no economic value.

In 2007, NREL began developing a platform for energy system integration and optimization that could be used throughout the project development cycle. This tool was called REO and was specifically developed to provide early estimates of sizing, even during the screening phase of the project when only basic data is available [10,11]. Later in the project, the default estimates could easily be replaced with more detailed data, and the analysis rerun. It was also designed to support batch mode automation such that a large portfolio of sites could be analyzed programmatically to help clients meet macro-level energy goals.

The REO tool was recently converted to a Mixed Integer Linear Program (MILP) to improve the speed and accuracy of the solver. Time series integration was also implemented for considering the effects of multiple technologies operating concurrently. The resulting platform for energy system integration and optimization was rebranded as REopt.

REopt, along with its predecessor REO, has been used to screen energy opportunities at over 1,000 sites for multiple government and private clients. The REopt platform has also been used for more detailed analysis of cost-optimal operating strategies for dispatchable technologies, energy security analysis using a combination of renewable generation and energy storage, and long range master planning to help a campus achieve its carbon neutral goals. The remainder of this paper describes the REopt techno-economic model as well as two analysis projects completed using the REopt platform.

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THE REOPT MODEL

The REopt model is a deterministic optimization model of the thermal and electrical energy use at one or more sites. The model achieves an energy balance between consumption and generation during every time period by building and dispatching a cost-optimal combination of renewable generation, conventional generation, and energy storage. The renewable energy technologies that REopt considers include photovoltaics (PV), wind, solar ventilation air preheating (SVP), solar water heating (SWH), biomass, waste-to-energy (WTE), and landfill gas (LFG).

The major outputs of REopt include the optimal system size, dispatch strategy, and installation cost for each technology in the solution set as well as the present value of all future energy costs associated with implementing it. Additional metrics such as the Levelized Cost of Energy (LCOE) are also computed for each technology.

Formulation of the Mixed Integer Linear Program

The objective function of the MILP is to minimize the present value of all future energy costs over the analysis period, including:

- The capital cost of building new energy generation and storage capacity.
- The present value of any incentives and depreciation.
- The present value of all operating expenses and revenues, such as operations and maintenance (O&M) costs, biomass feedstock costs, WTE tipping fees, fuel costs, or utility purchases.

The constraints governing how REopt builds and dispatches technologies fall into several categories, including:

- Load constraints: The electrical and thermal loads must be fully met by some combination of renewable and conventional generation during every time step. Additional load constraints restrict the amount of energy that a particular technology can replace; for example, solar water heating can only replace the energy that is used to heat domestic hot water.

- Resource constraints: The amount of energy that a technology can produce is limited by the amount of resource within the region. Biomass and WTE, for example, may only consume the material within close proximity of the plant. The energy production of variable technologies is limited by the renewable resource at the location. The utility grid is assumed to be able to produce unlimited amounts of energy.

- Operating constraints: Dispatchable technologies such as biomass, WTE, and LFG may have minimum turndown limits that prevent them from operating at partial loads less than a specified level. Other operating constraints may limit the number of times a dispatchable technology can cycle on and off each day.

- Sizing constraints: Most sites have limited land and roof area which may restrict the size of technologies such as PV, wind, SWH, and SVP. LFG is limited by the gas generation of the nearest candidate landfill.

- Policy constraints: Utilities often impose limits on the cumulative amount of renewable generation that a site can install and still qualify for a net metering agreement. Similarly, interconnection limits may restrict the total amount of renewable energy systems that may be connected to the grid. Other policy constraints may restrict the size of variable technologies or the size of a system that may be eligible for a production incentive.

- Emissions constraints: CO_2 and other greenhouse gases are tracked in the model and constraints may be included such that the solution meets specified emissions objectives.

- Scenario constraints (optional): Net zero electricity constraints require that a site produce as much electricity from renewable generation over the course of a year as it consumes. Similar constraints may require a site to obtain a specified percentage of its total energy from renewable generation or that it achieves some measure of energy security by always meeting the critical load with onsite renewable generation.

Financial Calculations: The REopt economic model considers an N-year analysis period. Energy consumption and production, however, are assumed to be constant in all years such that the optimal energy balance achieved in year 1 holds for subsequent years in the analysis period. By making this assumption, the present value of the total energy costs over the next N years can be determined by escalating the current energy cost (using an electricity or fuel escalation rate) and then discounting those costs back to the present using an appropriate discount rate. In this way, REopt models the economics of the entire N-year analysis period while only optimizing the energy balance in the first year. All projects are assumed to be built immediately and then start operating in year 1.

Temporal Resolution: REopt uses time series integration to combine the energy production from concurrently operating technologies. The typical time step is one hour. Since the optimization model assumes that production and consumption are constant across all years, only the energy balance of year 1 need be considered, and thus there are 8760 time steps in a typical N-year optimization. To simplify the complexity for lower fidelity screenings of multiple sites, 288 time steps are used such that a typical day of 24 hours is included for each month. Detailed analysis using 35,040 time steps (or more) can be performed when 15-minute load and resource data is available.

Thermal and Electrical Loads: REopt is designed to consider the entire energy consumption for a site, including electricity and up to five fuels such as natural gas, propane, #2 oil, #6 oil, or coal. The actual hourly or 15-minute load data is used, where available. Since many sites do not have detailed load profile information, REopt queries a database of EnergyPlus simulations based on building type (or mix of building types in the case of a campus or installation) and climate zone to obtain a simulated hourly load profile. The commercial reference buildings are used for this purpose [12]. These load profiles are then scaled in proportion to the annual or monthly consumption data.

Cost Models: NREL maintains a cost dataset containing capital, O&M, and variable operating costs for each technology. It is regularly updated and is based on market data, NREL cost research, and actual costs of recently constructed projects. The capital cost curve for each technology incorporates economies of scale for larger system sizes, and is approximated as piecewise linear in the MILP. The capital cost models may also be adapted to a specific location using a local cost adjustment factor.

Utility Policy and Tariff Structures: Net metering refers to a policy agreement whereby electricity generated onsite and delivered to the grid by an electric utility customer can be used to offset electricity provided by the utility to the customer. Specifically, a site can overproduce electricity in one time period, export it to the grid, and then consume it in a later time period without incurring any transactional cost.

Utilities that offer net metering programs may impose limits on the size of the system that can engage in net metering. For sites which lack a net metering program, the export of electricity may still be allowed, but it may have no economic value. Similarly, some utilities also restrict the size of renewable energy systems that can be interconnected to the grid. REopt obtains both the default net metering limit and the interconnection limit from the Database for State Incentives in Renewable Energy (DSIRE[1]) and models the resulting value of the energy produced and consumed accordingly.

REopt supports complex tariff structures that include both peak demand charges and time-of-use (TOU) consumption rates. Demand rates may be specified for on- and off-peak hours, which can vary by season. TOU consumption rates may vary by the time of day, the season, or both.

Economic Parameters and Incentives: REopt considers any available federal, state, and local incentives for each technology, including capital cost incentives and production incentives. Incentive information is queried from DSIRE. A matrix of energy escalation rates based on fuel type and region is obtained from the National Institute of Standards and Technology, or through consultation with the local utility. The appropriate discount rate is selected in consultation with the client.

REopt is capable of considering both owner financed projects as well as third-party financed projects, where the owner and financier may each have different costs of capital and corporate tax rates. Depreciation schedules such as the 5- or 7-year Modified Accelerated Cost Recovery System are also applied based on the relevant tax code.

Scenarios: Typical REopt scenarios include:

- Base Case / Business as Usual. In this scenario, the site is constrained to continue purchasing energy from the grid or using their existing energy assets; no new technologies are considered. The solution is the present value of all future energy costs over the analysis period. The net present value (NPV) of other scenarios is the difference between the energy cost associated with their optimal solutions and the base case energy cost, and may be positive or negative.
- Minimize energy costs. The objective of this scenario is to reduce energy costs by building new technologies. If one or more technologies are cost effective, the present value of energy costs in this case will be lower than that of the base case and the resulting NPV will be positive. If no technologies are cost effective, the solution set for this scenario will contain only the utility grid and the present value will be the same as the base case.
- Net zero electricity. In the net zero scenario, the site must produce at least as much electricity from onsite renewable energy technologies as it consumes over the course of the year. The solution consists of a set of technologies that achieve this goal at the minimum present value of future energy costs. Depending on the resources and land available for building projects, this scenario may be infeasible. The NPV of this scenario may be negative, indicating that there is a cost to achieving net zero.
- Energy security. The energy security scenarios typically require the site to meet some fraction of the load for a defined period of time using onsite energy assets.

Description of the Technologies

A common set of characteristics define each of the technologies. These characteristics include the capital, O&M, and operating costs as well as the temporal production factors. The production factor for a given time step is the percent of the rated output that can be obtained for that time step. For example, if a system has a rated capacity of 10 MW but the production factor for a given time step is only 10%, it would be expected to produce 1 MW of power during that time step.

Dispatchable technologies are those that can adjust their power output on demand or be switched on or off by a controller. Examples include biomass, WTE, LFG, conventional generators, and the utility grid. These

[1] http://www.dsireusa.org/

technologies are both sized and dispatched by the solver for maximum economic benefit. The production factors for these technologies are based on the availability of the system, including both planned and unplanned maintenance. These technologies can be dispatched at partial loads so long as the minimum turndown ratio is upheld. Further, the dispatch can vary temporally, subject to ramp rate restrictions of the technology.

Variable technologies are those that cannot be dispatched. Examples include PV, wind, SWH, and SVP. The production factors for these technologies are a function of the typical meteorological year (TMY) time series resource data. The solver optimally sizes these technologies. In general, they are assumed to generate energy at a rate proportional to their production factor at all times and therefore do not curtail.

Energy storage is similar to the dispatchable technologies in that the solver both sizes and dispatches the charging and discharging of these devices. A detailed description of the variable and dispatchable technologies is provided in the following sections.

Photovoltaics: The PV model assumes a fixed panel tilted towards the equator at an angle equal to the latitude of the installation. Since REopt assumes that the energy output from a given technology stays constant in all years, but PV production is known to degrade over time, REopt uses an annualized PV energy output over the analysis period to properly account for the economic impact of degradation [13].

The O&M cost for PV includes annual maintenance costs plus an amortized inverter replacement. The solar resource is comprised of the direct, diffuse, and global irradiance obtained from the TMY geospatial dataset[2]. The PV system size is limited by the amount of land or roof area available.

Wind: The model includes three categories of wind power turbines: 10 kW, 100 kW, and utility scale (> 1 MW). Further, the utility scale wind turbine is based on the wind class of the wind resource.

REopt utilizes time series TMY wind resource data (at heights of 50 m, 80 m, and 110 m) which is obtained from AWS Truepower[3] for locations within the continental US. REopt then calculates and adjusts for wind shear between the different heights in the TMY file to determine the time series production factor at the hub height of the selected turbine. The wind size is limited by the land area available.

Solar Water Heating: The solar water heating model assumes an indirect closed-loop system comprised of a glazed flat-plate collector, storage tank, and heat transfer fluid circulating pump. SWH uses the solar resource including direct normal and diffuse irradiance obtained from the TMY geospatial dataset. The production of hot water need not be temporally aligned with consumption (due to the existence of a storage tank), but must occur within the same day – i.e. water heated on a given day must be consumed the same day. This allows for SWH thermal energy to be used at a different time period within a day without explicitly modeling the storage system. SWH can replace either a conventional gas or electric system and the energy that such a system can provide is limited by the domestic hot water load.

The efficiency of the SWH system is inversely proportional to the solar fraction that the system achieves. For a given SWH size-to-load ratio, a constant collector efficiency is used (based on simulations performed in higher fidelity SWH models.) This efficiency is assumed to apply during each time step of the analysis.

Solar Ventilation Air Preheating: The SVP model consists of a transpired solar collector on the south-facing wall of a building coupled with a circulating fan which draws air into the outside air intake of the HVAC system. The preheated air produced by such a system can reduce the heating costs associated with either electrical or thermal space heating. The quantity of preheated air produced, and therefore the fuel saved, is limited by the outside air heating load. The system size is limited by the area available on the south-facing wall of the building.

The heat production of the modeled SVP system is based on a preprocessed geospatial dataset that considers ambient temperature and solar insolation [14-15]. The efficiency of the modeled system is inversely proportional to penetration, i.e. as the fraction of ventilation air preheated increases for a given space heating load, the efficiency decreases.

Biomass and Waste-to-Energy: The model includes four configurations of biomass systems each of which is modeled as a mass-burn combustion system. The four configurations include an electric-only system using a condensing steam turbine, a combined heat and power (CHP) system using a condensing turbine and main steam extraction, a CHP system with a backpressure turbine, and a thermal-only option. The primary difference between the two CHP systems is that the backpressure system provides a fixed ratio of electricity to thermal output, while the condensing turbine is able to vary this ratio, though at a higher capital cost.

Each system is assumed to have a minimum turndown ratio, meaning that it can operate at partial loading down to a given fraction of its nameplate capacity, but then it must shut off. Four types of biomass resource are included and are programmatically queried from the geospatial database: crop residues, forest residues, primary mill residues, and secondary mill residues [16]. A cost to acquire and transport the material is assumed, unless a biomass resource exists onsite, in which case it is assumed to be free. An additional fee is included for material being transported an extended distance.

The WTE module contains the same four configurations as the biomass module and has similar turndown requirements. The primary difference between these models is the boiler and

[2] http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/
[3] www.awstruepower.com (subscription only)

turbine efficiencies as well as the capital costs to build the systems. The system efficiencies are different due to the lower operating pressures of the WTE systems resulting from the chlorides released from the combustion of municipal solid waste (MSW).

The MSW within a given area is calculated by multiplying the population within that area by the waste generation per capita. Although the procurement of a contract diverting MSW to a WTE plant can be difficult to obtain, the client is assumed to be able to obtain sufficient quantities of this waste during the prescreening process. WTE facilities are paid to accept MSW, and this significant source of revenue is referred to as a tipping fee. The tipping fee is estimated based on published data [17].

Landfill Gas: The LFG model includes three configurations: an electric-only generator coupled to an internal combustion engine, a CHP internal combustion engine generator with heat recovery system, and a thermal-only gas collection system. A minimum turndown ratio is assumed for each of the system types.

Landfills that are candidates for energy generation are identified by the Landfill Methane Outreach Program[4] of the Environmental Protection Agency (EPA). This program uses a first-order decay model to estimate the gas production of a landfill based on the dates of operation, quantity of waste in place, and the fill rate. For a site to access the gas at a candidate landfill, a pipeline must be constructed and the cost of this is included in the model. The size of an LFG system is limited by the maximum size that the EPA has designated for the associated landfill.

Conventional Generators: The conventional generator model includes both diesel and natural gas engine generators. The fuel consumption of these generators is modeled using a linear fuel curve with nonzero y-intercept (which allows for nonlinear generator efficiency) based on data provided by the manufacturer. These technologies incur capital, O&M, and fuel costs and may be subject to turndown and cycle limits.

Utility Grid: The utility grid is assumed to be able to supply an unlimited amount of electricity and thermal fuel. Energy from the grid incurs only the costs specified by the tariff structure; there are no capital or O&M costs. For microgrid analyses, the utility grid can be disabled.

Energy storage: REopt models energy storage as a device that allows energy to be shifted from one time period to another. A round-trip efficiency is assumed and limits are imposed on the minimum state of charge, the charging and discharging rates, and the number of cycles per day. Energy storage devices incur capital and O&M costs. By default, any technology can charge the energy storage device, but charging can also be limited to specific technologies.

RENEWABLE ENERGY SCREENING FOR THE NAVY

In 2012, the Secretary of the Navy announced five energy goals, two of which were as follows:

1. Produce at least 50% of shore-based energy requirements from alternative energy sources, and
2. Achieve net zero status at 50% of Department of Navy installations, meaning that those installations would produce at least as much electrical energy onsite as they consume over the course of a year.

The Navy requested assistance with identifying and prioritizing cost effective renewable energy project opportunities across 69 domestic and international installations to help meet these goals. REopt was used to analyze two scenarios of particular interest to the Navy:

1. The optimal mix of renewable generation to achieve net zero electricity status at the minimum present value of energy costs for a given installation, and
2. The optimal mix of renewable and conventional technologies to meet electrical and thermal loads at a given installation for the lowest present value of energy costs.

The process began by collecting and collating data for the installations. At the beginning of the process, only the most basic data was needed, such as the geographic coordinates of the installations and their annual utility costs and consumptions for all fuels and electricity. REopt was then run to determine the most cost effective technologies that meet the energy goals.

A list of the most technically and economically viable renewable energy technologies at each of the installations was produced. For each installation, the capital cost, estimated annual cost under third-party financing, and the NPV of the recommended technologies was provided. The LCOE for each technology at each installation was also calculated.

The results for a representative installation are shown in Table 1. The recommended portfolio of technologies to minimize the present value of energy costs at the installation includes wind, PV and SWH, and saves $2.5M over the 25-year analysis period compared to the base case. Net zero electricity can be achieved by implementing a PV and wind solution at a savings of $0.5M over the analysis period.

The NPV of the recommended technologies at each installation was compared to other installations in the region. A sample comparison of ten installations is shown in Fig. 1.

Table 1. REopt screening results for Installation 6

Goal	Maximize NPV	Net Zero
Solution	4 MW Wind 3 MW PV 5000 ft^2 SWH	5 MW Wind 7 MW PV
NPV	$2.5M	$0.5M
Capital Cost	$19M	$32M

[4]http://www.epa.gov/lmop/

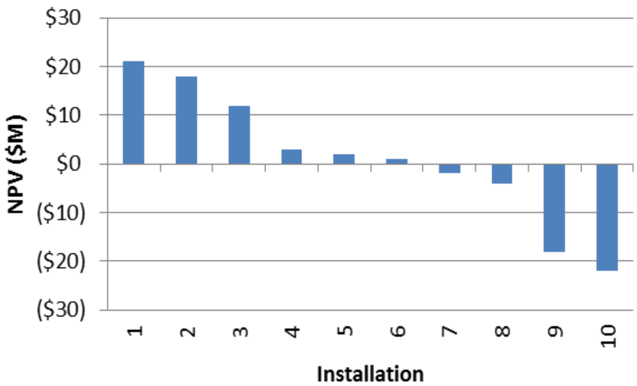

Figure 1. NPV of the net zero solutions for ten installations

At the conclusion of the screening analysis, the Navy selected candidate projects at specific installations for more detailed analysis. During this phase, in-depth installation assessments were conducted and meetings with onsite energy managers, master planners, command leadership, and utility representatives were held. During these visits some technologies originally in the optimal mix were deemed infeasible and were excluded. At Installation 6, for example, wind was eliminated as a candidate due to the proximity of an airfield. In addition, discussions with utility representatives revealed that the local utility has a policy whereby only 10 MW of RE systems can be connected to the grid. This further limited the capacity of renewable generation at this installation.

Following the installation visit, the inputs to the model were updated and the two scenarios were rerun using batch mode processing. The revised optimal mix of technologies is shown in Table 2 and reflects the new constraints that exclude wind and limit the cumulative system sizes of all renewable energy technologies to less than 10 MW.

To offset the lack of wind in the net zero case, the solver built the maximum amount of PV but was only able to achieve 87% of the net zero goal. (The net zero goal became infeasible at this installation due to the interconnection limit imposed by the utility.) The NPV of this scenario was now -$0.8M, compared to a savings of $0.5M in the initial results.

Table 2. Revised optimal mix of RE at Installation 6

Goal	Maximize NPV	Net Zero[5]
Solution	5 MW PV 5000 ft^2 SWH	10 MW PV
NPV	$2.0M	-$0.8M
Capital Cost	$16M	$31M

DISPATCH STRATEGY ANALYSIS FOR THE ARMY

Fort Hunter Liggett is a US Army installation near King City, CA. The installation currently has 2 MW of PV installed and is in the process of adding additional PV and a 1 MWh/1.25 MW lithium-ion energy storage system as part of their net zero initiative. The US Army was interested in using REopt to analyze cost-optimal economic dispatch strategies for operating the storage system while it was connected to the grid.

Figure 2 illustrates the optimal economic dispatch of a combined battery and PV system considering on- and off-peak demand periods, TOU rates and the electrical load for a representative week in July. During the afternoons of the first three days, the PV generation out-produces the load and the excess energy is stored in the battery for use during evening hours. During the next four days, the peak demand is reduced by strategically discharging the battery during the late afternoon hours. The truncated peak of the utility purchases (~1950 kW) is determined by the solver to be cost-optimal and reflects the peak-shaving operation. During the first three days

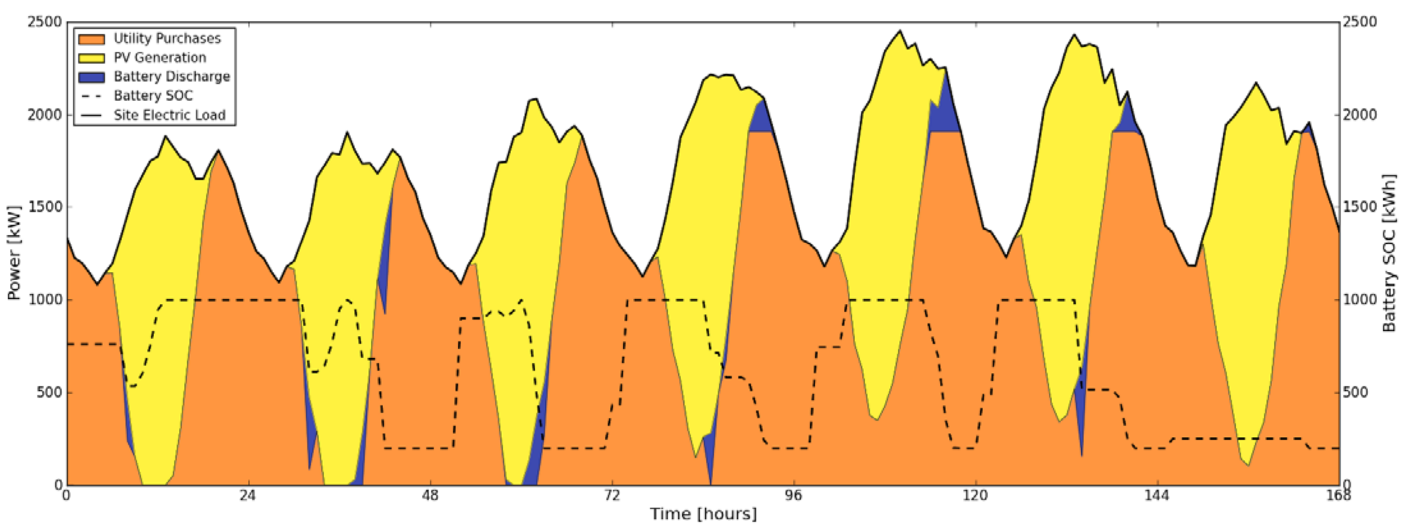

Figure 2. Cost-optimal economic dispatch strategy for a combined battery and PV system at Fort Hunter Liggett

[5]This installation can only meet 87% of its net zero goal due to the interconnection limit.

when the utility purchases were not expected to exceed the peak demand, REopt determined that the battery was not needed for peak-shaving and instead dispatched it to discharge during the peak TOU rate period. These results assume perfect prediction of both solar irradiance and electrical load.

The REopt platform was also used to conduct a preliminary energy security analysis using the PV and battery system in microgrid mode. The objective of this analysis was to determine the length of outage for which the PV and battery system could sustain the critical load as well as to estimate the amount of additional PV and storage necessary to sustain the critical load for a range of outage durations.

FUTURE WORK: MODEL PREDICTIVE CONTROL

When REopt is used during the planning and investment phases of a project to develop cost-optimal operating strategies for dispatchable energy assets, TMY weather data and historical load profiles are used. Consequentially, REopt is an omniscient agent; for every time step it knows exactly what has happened in the past, and it knows exactly what will happen in the future. As a result, it can make expert decisions that are guaranteed to be optimal, subject to the characteristics and constraints of the model and the backward-looking data with which it has been presented. This is equivalent to saying that REopt assumes perfect prediction of all future events, in particular, the weather and the load.

One area of ongoing research is to adapt the REopt model to be a real-time, model predictive control (MPC) supervisory agent. The agent would receive weather predictions and load forecasts for the upcoming 24-72 hours which would be combined with the TMY weather data and historical load profiles to provide both short- and medium-term projections of upcoming conditions. This would allow REopt to use the same techno-economic models that are used during the planning and investment stage of the project to dispatch the installed energy assets thereby increasing the correlation between the predicted cost savings and those achieved in practice.

CONCLUSIONS

REopt has been developed as a platform for energy system integration and optimization. Formulated as a MILP, it is a deterministic optimization model with the objective of minimizing the energy costs of one or more sites over an N-year analysis period. REopt recommends the cost-optimal mix of RE technologies, including PV, wind, SVP, SWH, biomass, WTE, and LFG, conventional generation, including diesel, natural gas engine generators, and the utility grid, and energy storage to meet the energy goals of a site or portfolio of sites. REopt considers both the electrical and thermal loads simultaneously.

REopt can be used at various stages of the project development process. During the screening stage, REopt can quickly and inexpensively identify and optimally size economically viable renewable energy technologies. When additional input data is available such as electrical load profiles or detailed descriptions of the tariff structure, REopt can be used during the feasibility phase to refine system sizes and analyze cost-optimal dispatch strategies for the energy assets. Future work is underway to enhance the model by including forward-looking weather predictions and load forecasts such that REopt can be used in a real-time MPC environment.

NOMENCLATURE

CHP	Combined Heat and Power
CO_2	Carbon Dioxide
DSIRE	Database for State Incentives in Renewable Energy
EPA	Environmental Protection Agency
HVAC	Heating, Ventilation and Air Conditioning
LCOE	Levelized Cost Of Energy
LFG	Landfill Gas
MILP	Mixed Integer Linear Program
MPC	Model Predictive Control
MSW	Municipal Solid Waste
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
PV	Photovoltaics
RE	Renewable Energy
REO	Renewable Energy Optimization
SVP	Solar Ventilation air Preheating
SWH	Solar Water Heating
TMY	Typical Meteorological Year
TOU	Time-Of-Use
WTE	Waste-To-Energy

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REFERENCES

[1] RETScreen International, 2005, "Clean Energy Project Analysis: RETScreen Engineering & Cases Textbook," Minister of Natural Resources Canada

[2] Dobos, A. P., 2013, "PVWatts Version 1 Technical Reference," NREL Report No.TP-6A20-60272, National Renewable Energy Laboratory, Golden, CO.

[3] Blair, N., Dobos, A. P., Freeman, J., Neises, T., Wagner, M., Ferguson, T., Gilman, P., and Janzou, S., 2014, "System Advisor Model, SAM 2014.1.14: General Description," NREL Report No. TP-6A20-61019, National Renewable Energy Laboratory, Golden, CO.

[4] Stadler, M., Siddiqui, A., Marnay, C., Aki, H., and Lai, J., 2010, "Control of Greenhouse Gas Emissions by Optimal DER Technology Investment and Energy Management in Zero-Net-Energy Buildings," European Transactions on Electrical Power, **21**(2).

[5] Stadler, M., Marnay, C., Cardoso, G., Lipman, T., Mégel, O., Ganguly, S., Siddiqui, A., and Lai, J., 2009, "The CO_2 Abatement Potential of California's Mid-Sized Commercial Buildings," Report No. CEC-500-07-043, 500-99-013, LBNL-3024E, California Energy Commission, Public Interest Energy Research Program.

[6] Marnay, C., Venkataramanan, G., Stadler, M., Siddiqui, A., Firestone, R., and Chandran, B., 2008, "Optimal Technology Selection and Operation of Microgrids in Commercial Buildings," IEEE Transactions on Power Systems, **23**(3), pp. 975-982.

[7] Stadler, M., Marnay, C., Siddiqui, A., Lai J., Coffey, B., and Aki, H., 2008, "Effect of Heat and Electricity Storage and Reliability on Microgrid Viability: A Study of Commercial Buildings in California and New York States", Report No. LBNL - 1334E

[8] Lambert T., Gilman P., and Lilienthal P., 2005, "Micropower system modeling with HOMER" *Integration of Alternative Sources of Energy*, Farret F., Simões M. eds., John Wiley & Sons, Chap. 15.

[9] Lilienthal P., Lambert T., and Gilman P., 2004, "Computer Modeling of Renewable Power Systems", Cleveland C.J. eds., editor-in-chief, Encyclopedia of Energy, Elsevier Inc., **1**, pp. 633-647

[10] Walker, A., 2009, "Heuristic Approach to Renewable Energy Optimization," Paper No. ES2009-90456, *Proceedings of the ASME 3rd International Conference on Energy Sustainability* San Francisco, California, New York: American Society of Mechanical Engineers **1** pp. 419-426, NREL Report No. CP-7A2-45812.

[11] Walker, A., 2008, "Renewable Energy Planning: Multiparametric Cost Optimization; Preprint," NREL Report No. CP-670-42921, National Renewable Energy Laboratory, Golden, CO.

[12] Deru, M., Field, K., Studer, D., Benne, K., Griffith, B., Torcellini, P., Liu, B., Halverson, M., Winiarski, D., Rosenberg, M., Yazdanian, M., Huang, J., Crawley, D., 2011, "U.S. Department of Energy Commercial Reference Buildings Model of the National Building Stock," Report No. NREL/TP-5500-46861, National Renewable Energy Laboratory, Golden, CO.

[13] Jordan, D.C., and Kurtz, S.R., 2013, "Photovoltaic Degradation Rates – an Analytical Review," Progress in Photovoltaics, **21**(1), pp. 12-29.

[14] Federal Technology Alert, 1998 "Transpired Collectors (Solar Preheaters for Outdoor Ventilation Air)," DOE/GO-10098-528, U.S. Department of Energy, Washington, D.C. See also http://www1.eere.energy.gov/femp/pdfs/fta_trans_coll.pdf

[15] Christensen C., Hancock E., Barker G., and Kutscher C., 1990, "Cost and Performance Predictions for Advanced Active Solar Concepts," Proceedings of Solar 90 The National Solar Energy Conference, American Solar Energy Society, Inc., Austin, Texas, pp. 275–280

[16] Milbrandt, A., 2005, "A Geographic Perspective on the Current Biomass Resource Availability in the United States," NREL/TP-560-39181, National Renewable Energy Laboratory, Golden, CO. See also http://www.nrel.gov/docs/fy06osti/39181.pdf

[17] Van Haaren, R., Themelis, N., and Goldstein, N., 2008, "The State of Garbage in America," BioCycle, **51**(10), pp. 16-23. See also http://www.biocycle.net/images/art/1010/bc101016_s.pdf