



5. Designing and Modeling Off-Grid Solar Systems

Foundations of Off-Grid Solar in Haiti





Foundations of Off-Grid Solar in Haiti



1. Basics of Electricity, Energy Access, and Off-grid Solar



2. Key Products and Quality Assurance for Off-grid Solar



3. Market Potential for Off-grid Solar in Haiti



4. Understanding Off-Grid Solar Customers



5. Designing and Modeling Off-Grid Solar Systems



6. Installation, Operations, and Maintenance of Off-Grid Solar Systems



7. Elements of Business Models for Off-Grid Solar



8. Financial Modeling for Off-grid Solar



9. Gender and Off-Grid Solar



10. Productive Use of Energy



11. Climate Adaptation and Resilience

Overview



The objectives of this module are to provide an overview and key resources/tools for understanding:

- What is the Renewable Energy Optimization Tool (REopt®) and how is it used for designing and modeling distributed renewables? ([Go to Section](#))
- What kinds of off-grid solar projects has REopt been used for? ([Go to Section](#))
- What information/data is needed to run a REopt analysis? ([Go to Section](#))
- How can REopt be used in Haiti? (Case study for a rural health clinic) ([Go to Section](#))

Who is this REopt Training For?



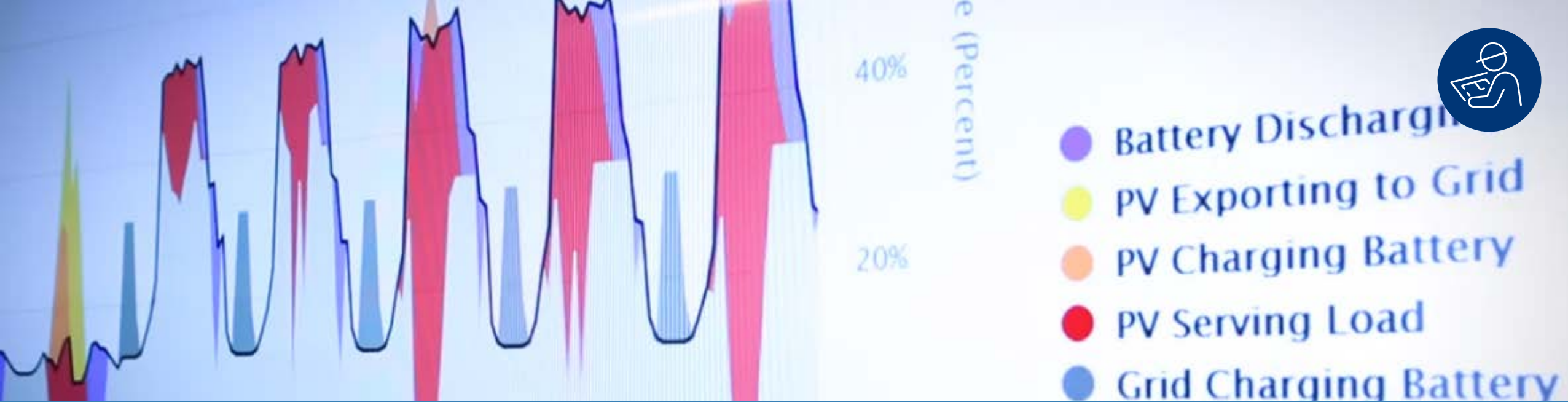
Anyone wanting to understand:

- Key considerations for designing an off-grid solar system
- How an optimization tool (like REopt) can help evaluate different system designs



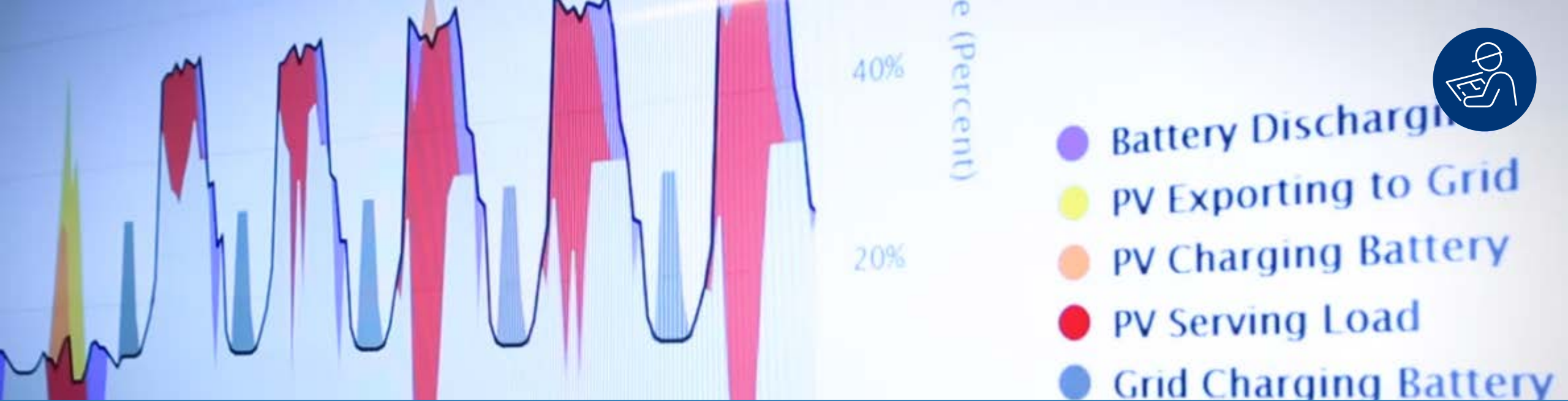
Photo by Dennis Schroeder / NREL

What is the REopt tool and how is it used for designing and modeling distributed renewables?



What is REopt?

- REopt is an energy decision-making tool developed and maintained by the National Renewable Energy Laboratory (NREL).
- REopt determines the **cost-optimal sizing and dispatch** of generation and storage technologies for **grid-connected** sites or **off-grid microgrids**.
- REopt can be used to meet **economic**, **resilience**, and **decarbonization** goals.
- The tool is available as a **free, easy-to-use webtool**, application programming interface (API), or open-source codebase.



What is REopt?

This series will focus on REopt's **off-grid** modeling capabilities.

For more information regarding using REopt to model grid-connected systems, see resources at

<https://reopt.nrel.gov>.



REopt can help answer key questions for a given off-grid site.



What is the **least-cost mix and size of technologies** to meet the energy needs of this community?



What is the expected **levelized cost of energy** of this project?



How do expected sizes and costs **vary based on community size, service levels, fuel costs, etc.?**

What is REopt?



- At its core, REopt is an **optimization model**
- The **goal** of the model is to **minimize the lifecycle cost (LCC) of energy** while meeting operational and **user-defined constraints** (e.g., reliability requirements)



- REopt minimizes energy costs by recommending the optimal **sizing and dispatch of microgrid technologies**, given a site's specifications

REopt Assumes PV and Battery Are Separately **AC-Coupled**



- **AC-coupled** systems convert DC power from the PV array to AC power, then convert this AC power back to DC power to charge the batteries.
- The PV and battery systems are assumed to each have their own DC to AC inverter(s)

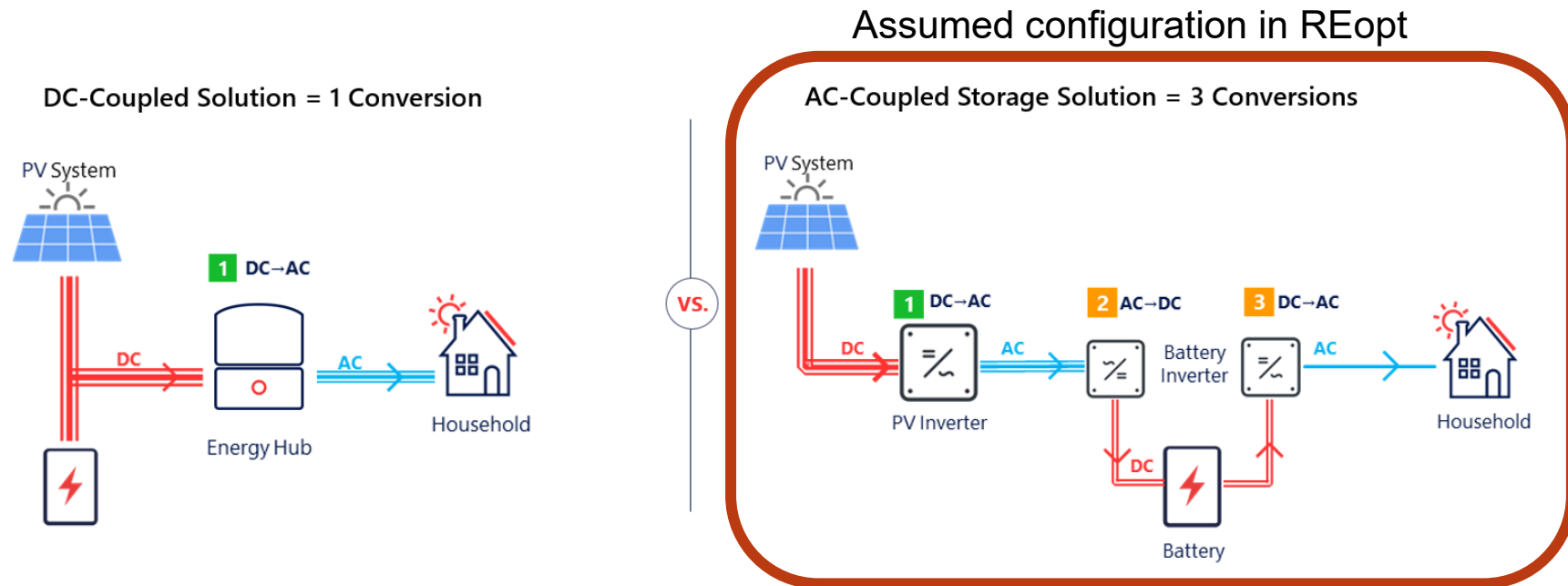
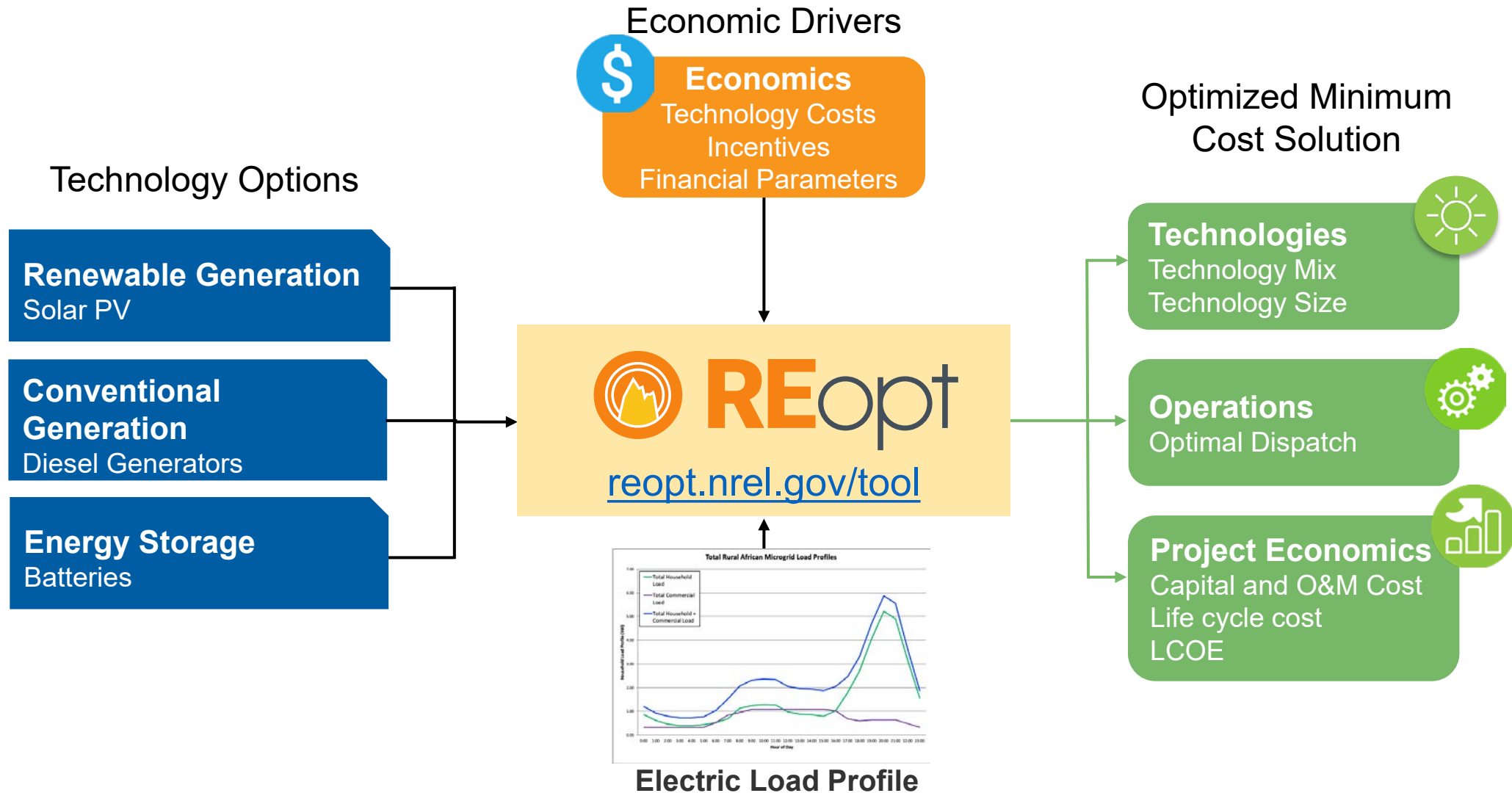


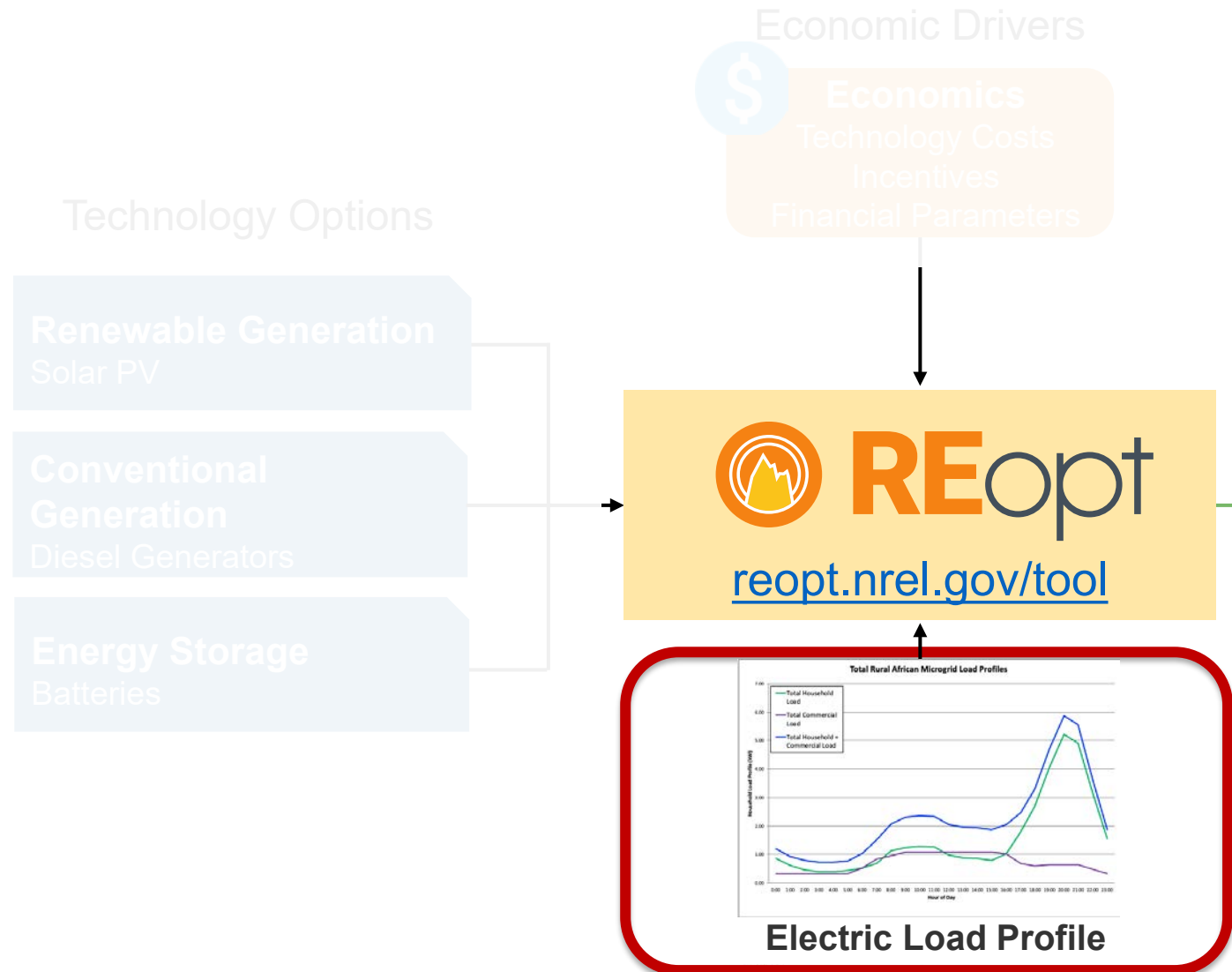
Image Source:

<https://www.solaredge.com/uk/solaredge-blog/dc-coupled-vs-ac-coupled-pv-systems>

REopt Overview for Off-Grid Applications



REopt Overview for Off-Grid Applications



Input: Expected total hourly electricity demand (for one year).

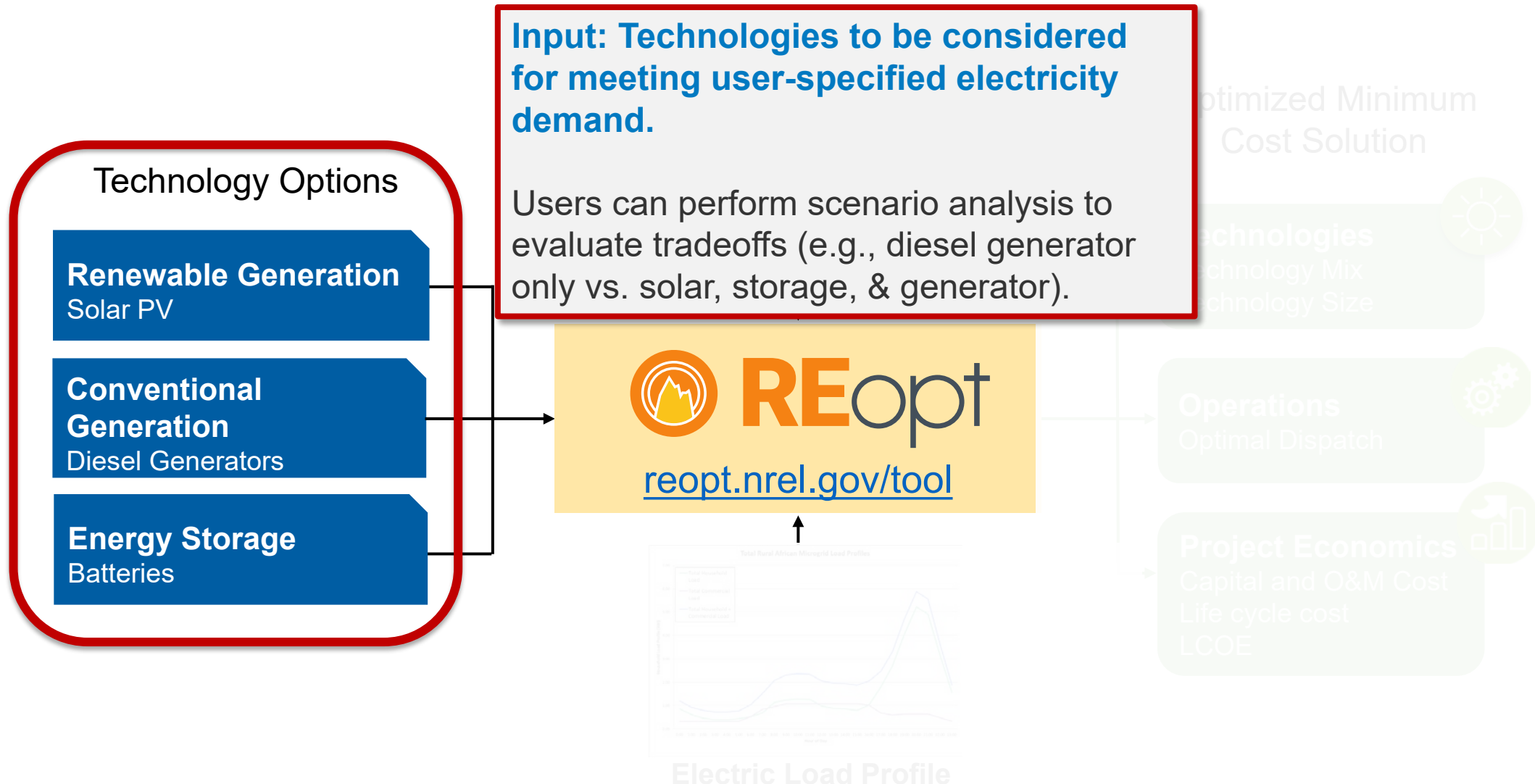
Can estimate based on:

- Technologies to be powered and their timing of use
- Building type(s) to be powered
- Metered data for existing systems

REopt users can specify:

- A minimum load met < 100 % to allow for load shedding.
- A load operating reserve requirement to improve reliability.

REopt Overview for Off-Grid Applications



REopt Overview for Off-Grid Applications



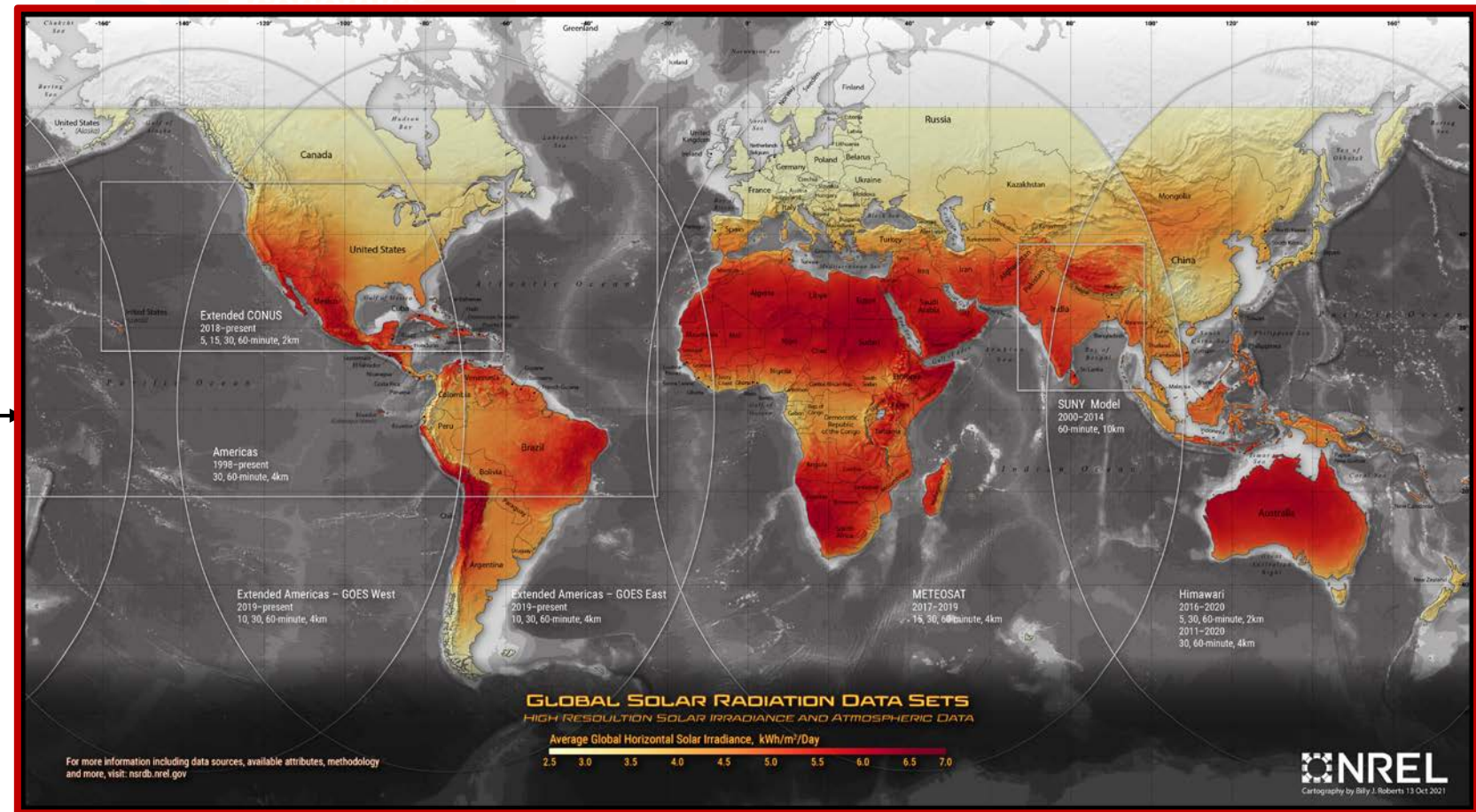
Economic Drivers

Technology Options

Renewable Generation
Solar PV

Conventional Generation
Diesel Generators

Energy Storage
Batteries

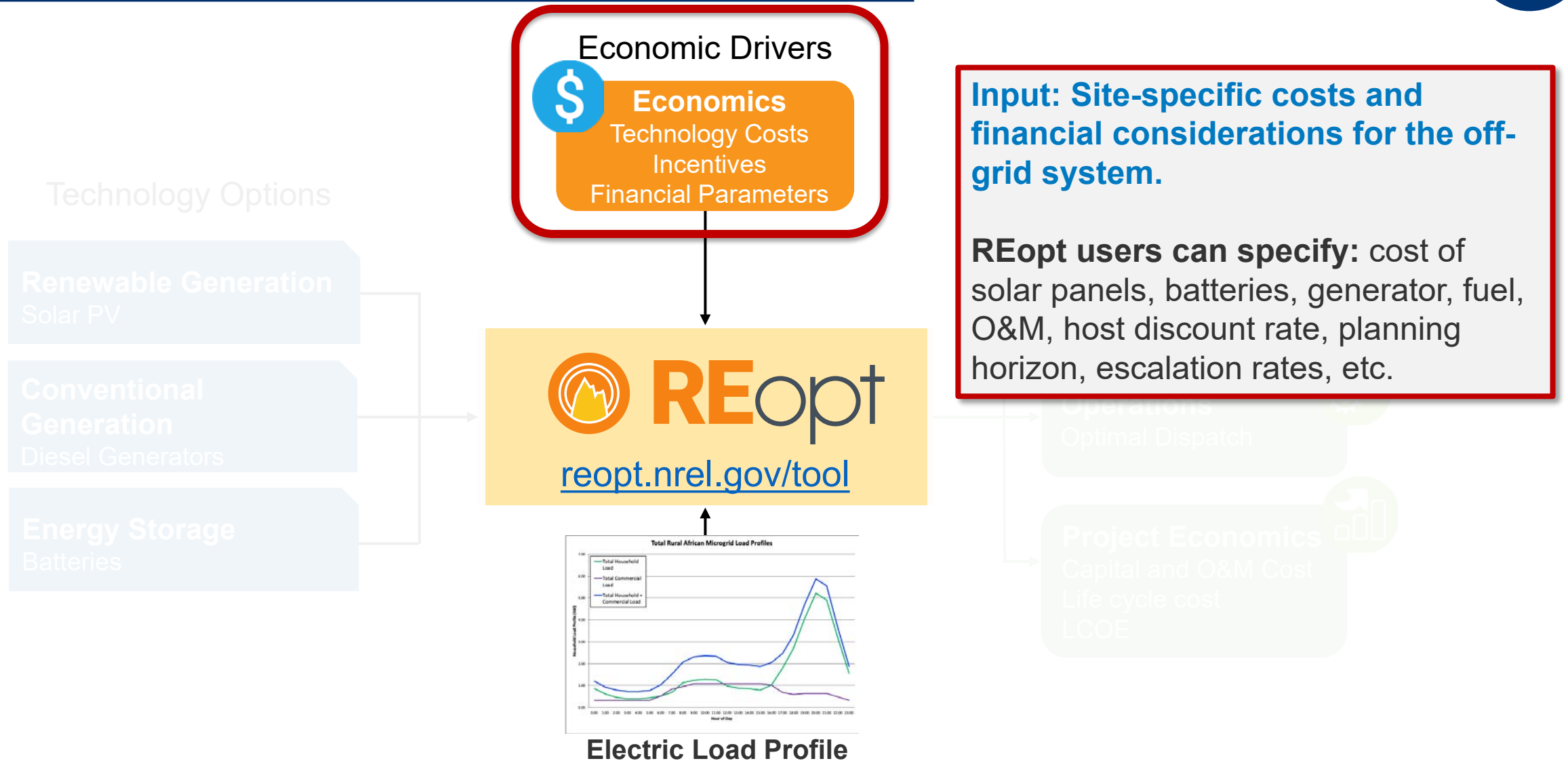


Electric Load Profile



Source: <https://nsrdb.nrel.gov>

REopt Overview for Off-Grid Applications

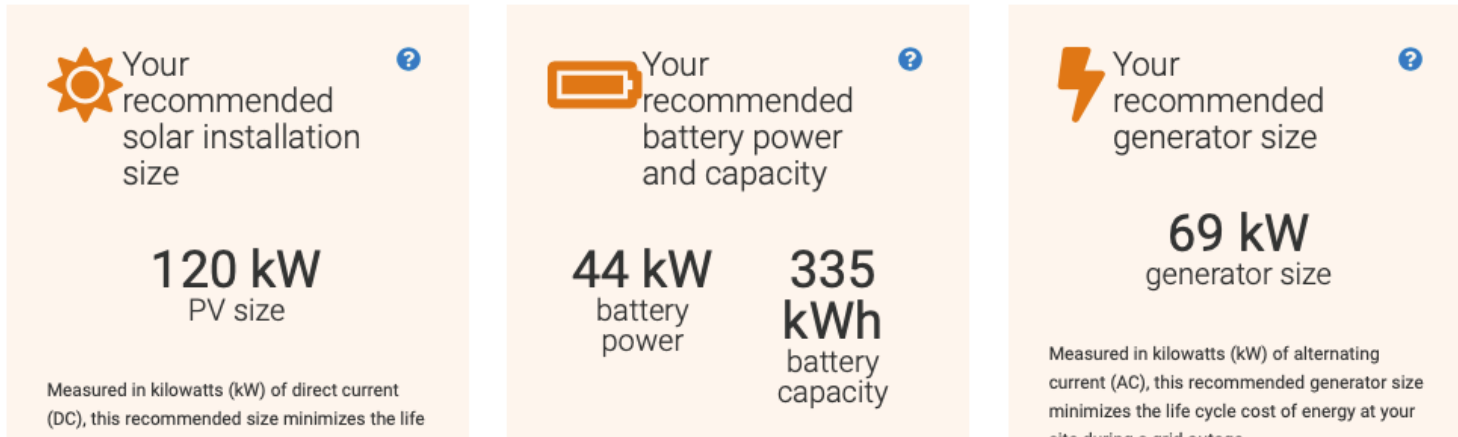


REopt Overview for Off-Grid Applications



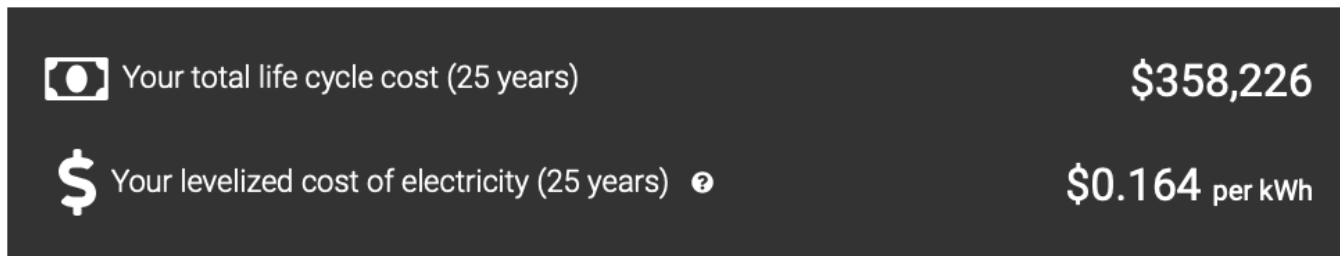
Example Key Outputs:

Recommended System Sizes



Energy Storage Batteries

Total and Levelized Cost



Economic Drivers

Economics Technology Costs

Optimized Minimum Cost Solution

Technologies

Technology Mix
Technology Size

Operations

Optimal Dispatch

Project Economics

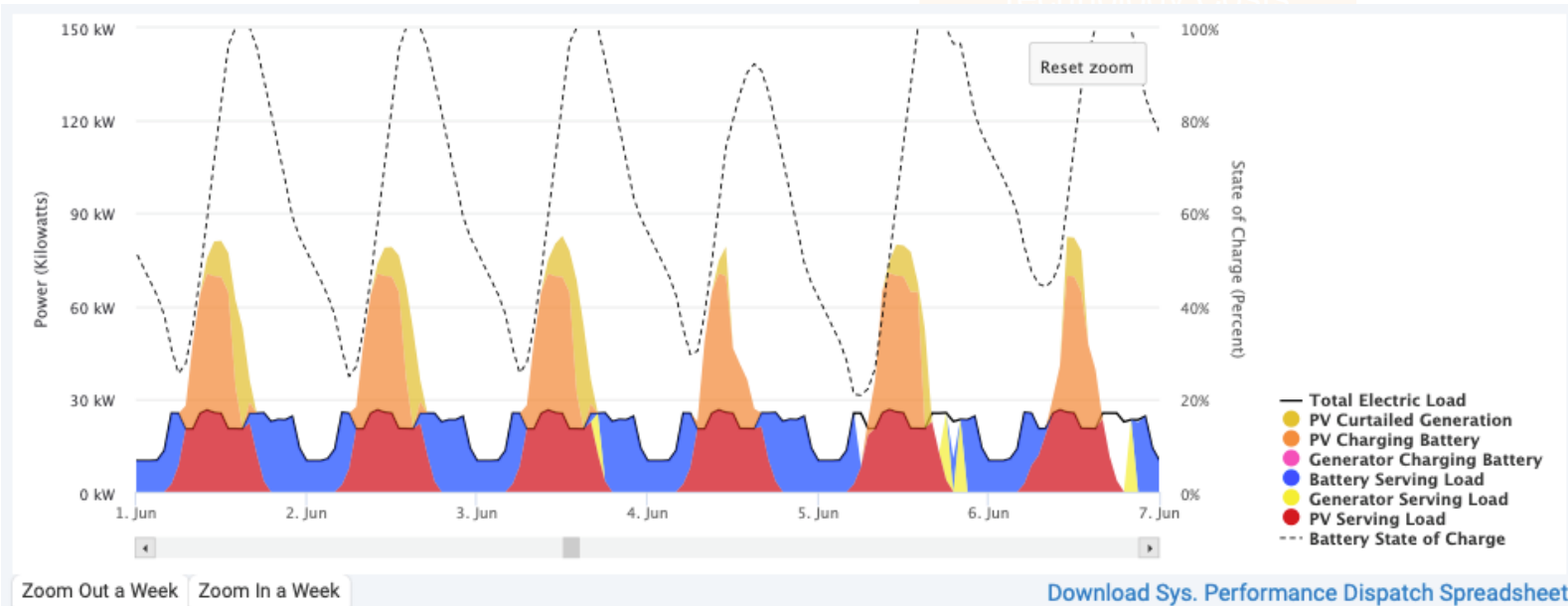
Capital and O&M Cost
Life cycle cost
LCOE

REopt Overview for Off-Grid Applications



Example Key Outputs:

Cost-Optimal System Dispatch



Cost Breakdown

Life Cycle Cost Breakdown	
Technology Capital Costs + Replacements, after incentives ?	\$334,706
O&M Costs ?	\$55,683
Generator Fuel Costs ?	\$51,933

Optimized Minimum Cost Solution

Technologies

Technology Mix
Technology Size



Operations

Optimal Dispatch



Project Economics

Capital and O&M Cost
Life cycle cost
LCOE



Renewable Energy & Emissions Accounting



Emissions estimated based on fuel usage

Percent renewable electricity calculated based on relative contribution of solar generation.

Renewable Energy & Emissions Accounting



Emissions and Renewable Energy	
Total CO₂ Emissions in Year 1 ?	11 tons
Lifecycle Costs of Climate Emissions ?	\$12,114
Lifecycle Costs of Health Emissions ?	\$41,584
Annual Renewable Electricity (% of electricity consumption) (%) ?	82%

- REopt reports CO₂ emissions of microgrid systems as this greenhouse gas contributes to climate change.
- REopt reports NO_x, SO₂, and PM_{2.5} emissions as these particulate species can cause local negative health outcomes.

How Can You Use REopt?



Easy-to-use, free web tool

reopt.nrel.gov



Application Programming Interface (API)

<https://github.com/nrel/reopt-api-analysis/wiki>



Open-source codebase

https://github.com/NREL/REopt_API and <https://github.com/NREL/REopt.jl>



Custom NREL analysis



REopt Web Tool User Interface



- **REopt Web Tool** is a free, publicly available, user-friendly web tool
- Optimizes **distributed energy** system sizes and dispatch to **minimize life cycle cost of energy**
- **Resilience mode** optimizes systems to sustain critical load during grid outages
- **Clean energy goals** allow users to consider renewable energy targets and emissions reductions targets
- **Unchecking “Grid”** allow users to model **off-grid microgrids** of solar, storage, wind, and diesel generators

Step 1: Choose Your Energy Goals

Cost Savings \$ Resilience 🛡️ Clean Energy 🌱

Step 2: Select Your Technologies

PV ⚙️ Battery 🔋 Grid ⚡ Wind 🌪️ CHP 🏭

Chilled Water Storage ❄️ Geothermal Heat Pump 🌍

Step 3: Enter Your Site Data

Site and Utility (required) ⊖

* Site location ? 🌐 Use sample site

* Electricity rate ? 📄 Use custom electricity rate ?

Optional inputs 🔄 Reset to default values

Load Profiles (required) ⊕

Financial ⊕

Renewable Energy & Emissions ⊕

PV ⊕

Battery ⊕

[Reset to default values](#)

[Get Results](#) ➔



Transforming ENERGY



Step 1: Choose Your Energy Goals

Cost Savings \$

Resilience

Clean Energy

Step 2: Select Your Technologies

REopt Web Tool Demo

<https://reopt.nrel.gov/tool/>

CHP

Step 3: Enter Your Site Data

Site and Utility (required)

Load Profiles (required)

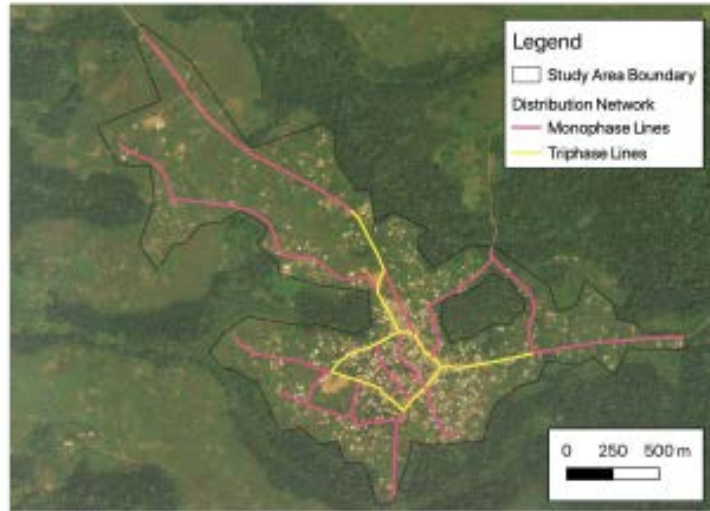
Financial

Renewable Energy & Emissions

PV

What kinds of off-grid solar projects
has REopt been used for?

REopt Analysis for Clean Energy Microgrids in Cameroon



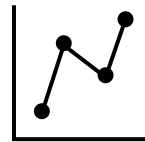
- NREL researchers provided technical assistance to Cameroonian microgrid developer to support sizing and cost estimates for pilot microgrid project
- Developed tools to support planning for wide-scale microgrid deployment



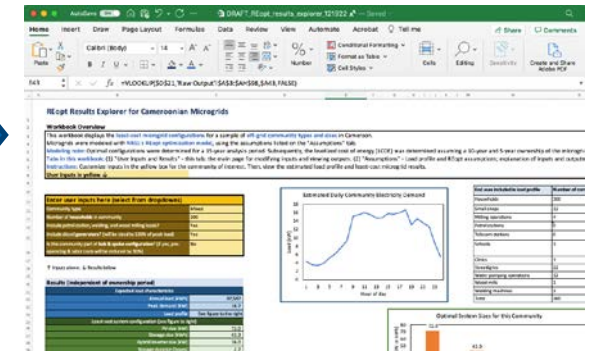
Gathered data from pilot microgrid, developer cost estimates.



Developed set of community types and sizes and load profiles for each.



Used the REopt API (custom hybrid inverter version) to run ~300 scenarios.



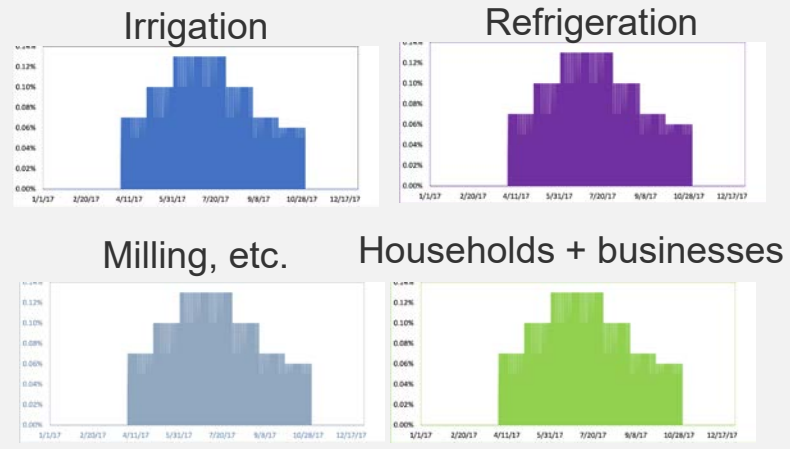
Compiled results into easy-to-use workbook.

Estimating the Impact of Agricultural Productive Use of Energy (PUE) on Microgrid Outcomes in Kenya and Zambia



1

For select 10km² grid cell, we estimate **hourly PUE** and **community electricity demand**...



...and hourly **solar PV production** factors



Using geospatial data, engineering calculations, discussion with in-country subject matter experts.

2

Estimate costs of microgrid components and other financial parameters



3



REopt determines the least-cost microgrid configuration and associated levelized cost of electricity (LCOE)

4

Outputs for each priority grid cell:

- Cost-optimal microgrid technologies and sizes
- Levelized cost of electricity (\$/kWh)
- Calculated for:
 - Community only
 - Community + PUEs

} *Comparison illustrates added value of PUEs*

PV / Hybrid Water Treatment in British Virgin Islands



Techno-economic analysis of a renewable energy hybrid system to help power a reverse osmosis water treatment plant in a remote island in the British Virgin Islands

- NREL's REopt analysis identified cost-effective technologies, sizes, and operating strategies for reducing the life-cycle system operation costs of generating power for the island and for water treatment
- By deploying a 640 kW of PV and 470-kWh of battery, 40% diesel savings could be realized thereby saving money and improving the resilience of energy service for the island community



Anegada, British Virgin Islands

Scenarios Considered in Jamaica Critical Facility Analysis



The scenarios modeled in this analysis are intended to inform the **cost-optimal investments** in **PV and battery systems** at four critical facilities, under varying assumptions:



Resilience:

To survive a **6-hour, 24-hour, vs. 5-day** grid outage



Backup Generation:

Utilizing the site's **existing generator vs. retiring the generator**



PV Net Billing System Size Limits

Assuming **no net billing system size limit** relative to load vs. assuming **PV cannot generate > 120%** of site's load

Review

What data is needed to run a REopt analysis?



- Site location
- Hourly site load (electrical demand) for one year
- Capital and operating costs for each system component
- Expected system lifetimes and replacement costs
- Current cost of fuel and expected cost escalation
- Available area for solar PV
- Financial parameters (e.g., discount rate) for the potential investment
- Desired level of service/operating reserves required (load & PV operating reserves, minimum load met, generator sizing)

The more detailed the inputs the more accurate the results!

REopt is appropriate for...

- Initial estimates of **system sizing**
- Initial estimates of **levelized cost of electricity (LCOE)**
- Evaluating impact of load served, system cost, fuel cost. etc. on outcomes (i.e., **performing sensitivity analysis**)

REopt is not appropriate for...

- **Detailed system design or engineering considerations** (for everything related to the topology and engineering design, see people with the appropriate expertise)
- Planning **distribution networks** (REopt does not account for line capacities, voltage drop, etc.)



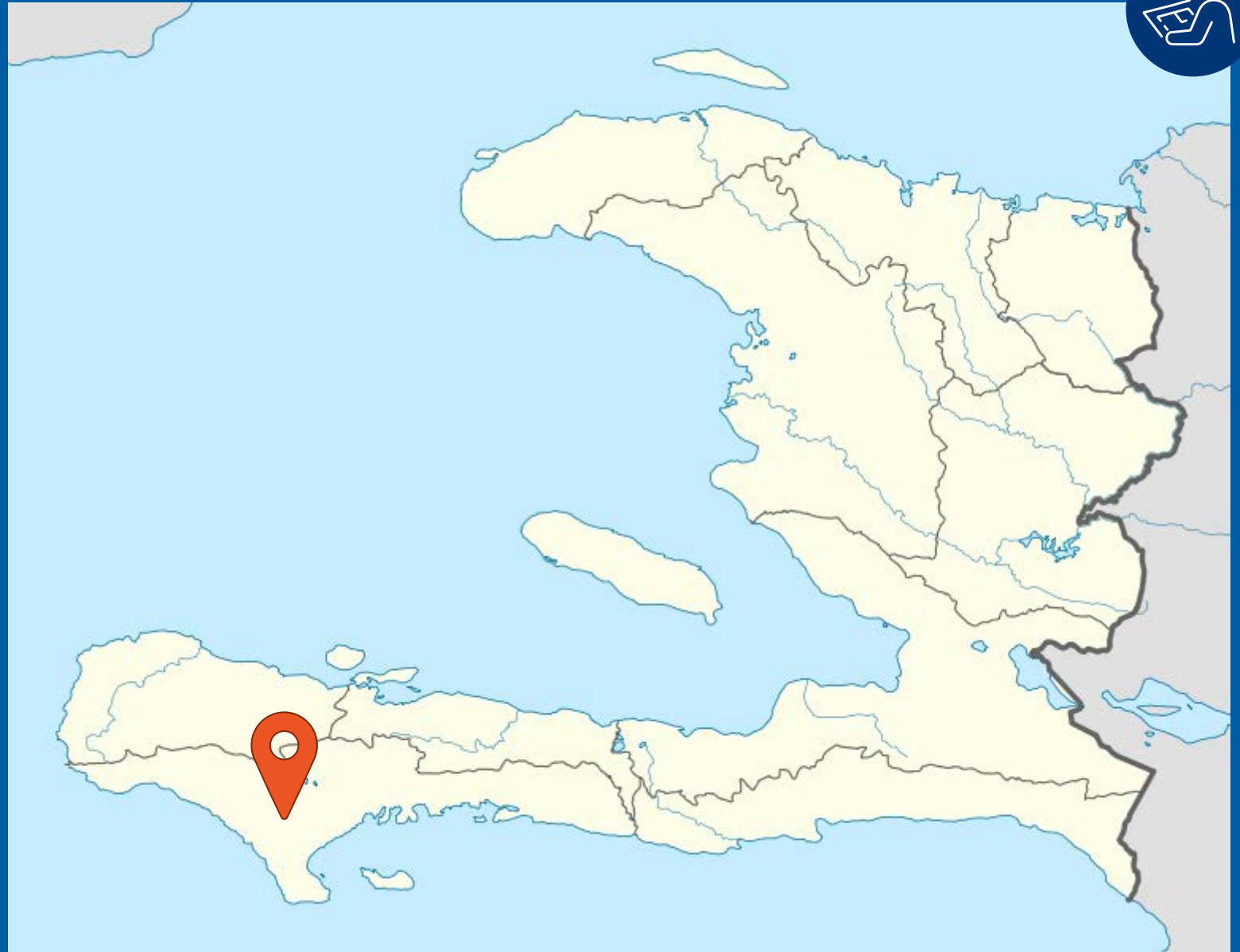
How can REopt be used in Haiti? (Case study for a rural health clinic)

Powering a Dispensaire in Département Sud

A rural dispensaire provides much-needed health services to the surrounding community.

It is isolated from the grid but has an existing diesel generator. They frequently experience fuel shortages and would like to reduce reliance on diesel fuel while maintaining reliability.

This is not based on a real completed project, but instead is meant to be illustrative of the REopt process



Powering a Dispensaire in Département Sud

We are tasked with using **REopt** to evaluate the cost-optimal **PV and battery** system sizing to supplement the existing diesel generator.



Analysis Steps



- Step 1: Determine goals for the site
- Step 2: Estimate hourly electric load for the site
- Step 3: Identify available space for solar panels
- Step 4: Estimate system costs
- Step 5: Establish financial parameters
- Step 6: Establish operating goals and constraints
- Step 7: Input data into REopt for all scenarios of interest

Step 1: Determine Goals



Example Goal: Supplement the dispensaire's existing 5 kW generator with solar and battery storage to improve reliability while minimizing energy costs.

Step 2: Estimate Hourly Electric Load



Remember, there are several approaches to estimating electricity demand for a site, including:

- Considering technologies/appliances on-site and their timing of use
- Using modeled loads for similar building type(s)
- Utilizing metered interval (e.g., hourly) data for existing systems at this or other sites

Step 2: Estimate Hourly Electric Load



Remember, there are several approaches to estimating electricity demand for a site, including:

- Considering technologies/appliances on-site and their timing of use
- Using modeled loads for similar building type(s)
- Utilizing metered interval (e.g., hourly) data for existing systems at this or other sites

We will use this approach in this demonstration.

Step 2: Estimate Hourly Electric Load



Electronic Equipment Used	Quantity
7w Phillips light bulbs	20
80w Tube lights	30
ACS Btu 18	1
Wall fans	5
Ceiling fans	10
Microscopes	2
Toilet lights	10

Step 2: Estimate Hourly Electric Load



Electronic Equipment Used	Quantity	Power (W)
7w Phillips light bulbs	20	7
80w Tube lights	30	80
ACS Btu 18	1	1,800
Wall fans	5	40
Ceiling fans	10	75
Microscopes	2	88
Toilet lights	10	15

Step 2: Estimate Hourly Electric Load



Electronic Equipment Used	Quantity	Power (W)	Peak Power (kW)
7w Phillips light bulbs	20	7	0.14
80w Tube lights	30	80	2.4
ACS Btu 18	1	1,800	1.8
Wall fans	5	40	0.2
Ceiling fans	10	75	0.75
Microscopes	2	88	0.176
Toilet lights	10	15	0.15

Step 2: Estimate Hourly Electric Load



**Utilization Rate Over 1 Day
(fraction of 100% of each hour)**

Electronic Equipment Used	Quantity	Power (W)	Peak Power (kW)	Hour 0	Hour 1	Hour 2	Hours 3-21	Hour 22	Hour 23
7w Phillips light bulbs	20	7	0.14	0.5	0.5	0.5	...	1	1
80w Tube lights	30	80	2.4	0.5	0.5	0.5	...	1	1
ACS Btu 18	1	1,800	1.8	0	0	0	...	0	0
Wall fans	5	40	0.2	0	0	0	...	0	0
Ceiling fans	10	75	0.75	0	0	0	...	0	0
Microscopes	2	88	0.176	0	0	0	...	0	0
Toilet lights	10	15	0.15	0.5	0.5	0.5	...	1	1

Step 2: Estimate Hourly Electric Load



Utilization Rate Over 1 Day
(fraction of 100% of each hour)

Electronic Equipment Used	Quantity	Power (W)	Peak Power (kW)	Hour 0	Hour 1	Hour 2	Hours 3-21	Hour 22	Hour 23
7w Phillips light bulbs	20	7	0.14	0.5	0.5	0.5	...	1	1
80w Tube lights	30	80	2.4	0.5	0.5	0.5	...	1	1
ACS Btu 18	1	1,800	1.8	0	0	0	...	0	0
Wall fans	5	40	0.2	0	0	0	...	0	0
Ceiling fans	10	75	0.75	0	0	0	...	0	0
Microscopes	2	88	0.176	0	0	0	...	0	0
Toilet lights	10	15	0.15	0.5	0.5	0.5	...	1	1

Estimated Load (kW)

7w Phillips light bulbs	0.07	0.07	0.07	...	0.14	0.14
80w Tube lights	1.2	1.2	1.2	...	2.4	2.4
ACS Btu 18	0	0	0	...	0	0
Wall fans	0	0	0	...	0	0
Ceiling fans	0	0	0	...	0	0
Microscopes	0	0	0	...	0	0
Toilet lights	0.075	0.075	0.075	...	0.15	0.15

Step 2: Estimate Hourly Electric Load



Utilization Rate Over 1 Day
(fraction of 100% of each hour)

Electronic Equipment Used	Quantity	Power (W)	Peak Power (kW)	Hour 0	Hour 1	Hour 2	Hours 3-21	Hour 22	Hour 23
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80w Tube lights	30	80	2.4	0.5	0.5	0.5	...	1	1
ACS Btu 18	1	1,800	1.8	0	0	0	...	0	0
Wall fans	5	40	0.2	0	0	0	...	0	0
Ceiling fans	10	75	0.75	0	0	0	...	0	0
Microscopes	2	88	0.176	0	0	0	...	0	0
Toilet lights	10	15	0.15	0.5	0.5	0.5	...	1	1

Estimated Load in Each Hour (kW) = Peak Power (kW) * Utilization Rate (%)

7w Phillips light bulbs	0.07	0.07	0.07	...	0.14	0.14
80w Tube lights	1.2	1.2	1.2	...	2.4	2.4
ACS Btu 18	0	0	0	...	0	0
Wall fans	0	0	0	...	0	0
Ceiling fans	0	0	0	...	0	0
Microscopes	0	0	0	...	0	0
Toilet lights	0.075	0.075	0.075	...	0.15	0.15

Step 2: Estimate Hourly Electric Load



Estimated Load (kW)

7w Phillips light bulbs	0.07	0.07	0.07	...	0.14	0.14
80w Tube lights	1.2	1.2	1.2	...	2.4	2.4
ACS Btu 18	0	0	0	...	0	0
Wall fans	0	0	0	...	0	0
Ceiling fans	0	0	0	...	0	0
Microscopes	0	0	0	...	0	0
Toilet lights	0.075	0.075	0.075	...	0.15	0.15
Total Load	1.345	1.345	1.345	...	2.69	2.69

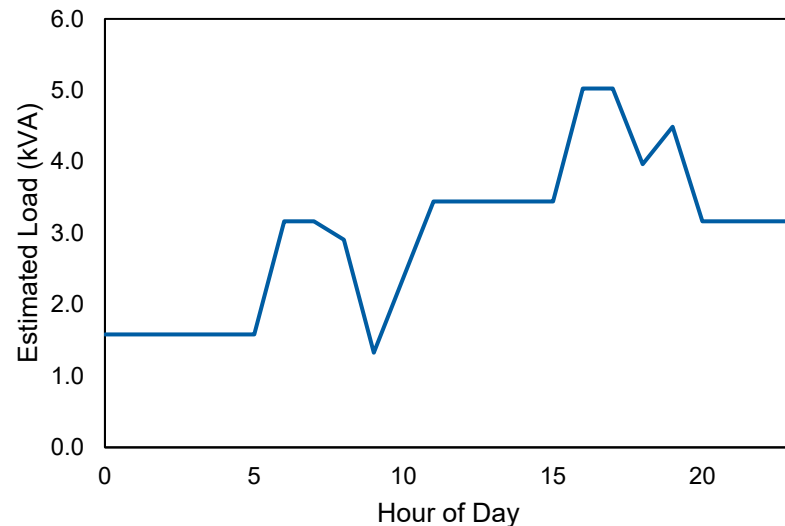
Step 2: Estimate Hourly Electric Load



Estimated Load (kW)

7w Phillips light bulbs	0.07	0.07	0.07	...	0.14	0.14
80w Tube lights	1.2	1.2	1.2	...	2.4	2.4
ACS Btu 18	0	0	0	...	0	0
Wall fans	0	0	0	...	0	0
Ceiling fans	0	0	0	...	0	0
Microscopes	0	0	0	...	0	0
Toilet lights	0.075	0.075	0.075	...	0.15	0.15
Total Load	1.345	1.345	1.345	...	2.69	2.69

Estimated Load For One Day



Step 2: Estimate Hourly Electric Load

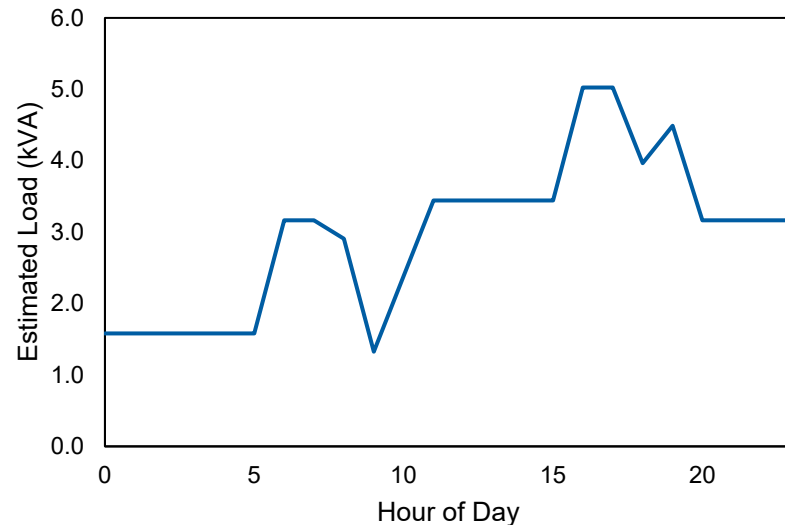


Estimated Load (kW)

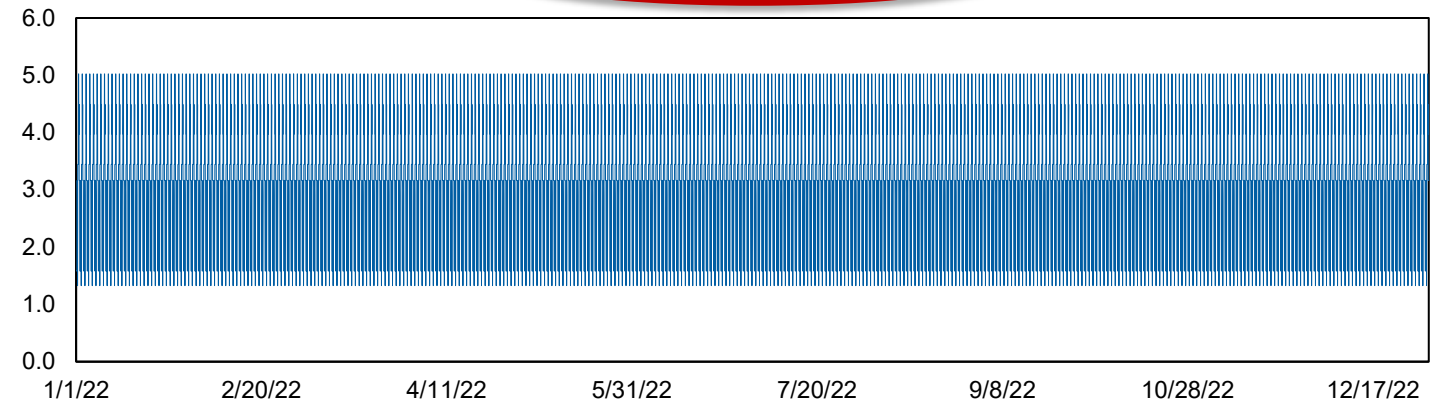
7w Phillips light bulbs	0.07	0.07	0.07	...	0.14	0.14
80w Tube lights	1.2	1.2	1.2	...	2.4	2.4
ACS Btu 18	0	0	0	...	0	0
Wall fans	0	0	0	...	0	0
Ceiling fans	0	0	0	...	0	0
Microscopes	0	0	0	...	0	0
Toilet lights	0.075	0.075	0.075	...	0.15	0.15
Total Load	1.345	1.345	1.345	...	2.69	2.69

Required for REopt: Estimated load for 1 calendar year at hourly resolution.

Estimated Load For One Day



Estimated Load for One Year



Step 3: Identify Available Space



- Can use site visit or geospatial tool such as Google Earth
- Avoid obstructions and shading
- Consider suitability of roof to support solar loads



Hypothetical Scenario:

Land Available: **0.3 acres**

Roof Space Available:
1,890 ft²

Source: Google Earth

Step 4: Estimate System Costs



Input	Value
Solar Panels	\$430 / kW
PV Racking	\$560 / kW
PV Inverters	\$591.23 / kW
Total PV Capital Cost	\$1,581 /kW
Battery Inverter Cost	\$510 / kW
Battery Energy Cost	\$562 / kWh
Other Materials	\$888 / peak kW load
Installation Labor	\$1,307 / peak kW load
Annual Labor	\$87.15 / peak kW load / year
Diesel Fuel Cost	\$1.48 / liter

Costs were sourced from generalized information on past microgrid project bids in Haiti as an example – these costs have likely increased substantially in the past few years, but REopt users can adjust costs in the online tool. It will be important to talk to suppliers to understand the current costs

Step 5: Establish Financial Parameters



Input	Value
Project Life	20 years
Off-taker (Host) Discount Rate (nominal)	15%
O&M & Fuel Cost Escalation Rate (nominal)	34%/year (World Bank ; 2022 Inflation Rate)
Host Effective Tax Rate	0% (not considering tax implications of O&M expenses)

These parameters are selected based on a hypothetical project in Haiti, but should be adjusted to specific project context

Step 6: Establish Operating Goals



Input	Value
Minimum Annual Load Met [%]	97%
Load Operating Reserve Requirement [%]	10%
Solar PV Operation Reserve Requirement [%]	25%
Battery Minimum Turndown [%]	20%
Generator Minimum Turndown [%]	15%
Generator Annual Fuel Availability [liters / year]	2,500 liters / year

These parameters are selected based on a hypothetical project in Haiti, but should be adjusted to specific project context

Step 7: Input Data Into REopt Web Tool for Each Scenario




- **Scenario 1:** Cost-optimal solution considering historical inflation (34%)
- **Scenario 2:** Cost-optimal solution considering less inflation (10%)

Results




Inflation = 34%

 Your recommended solar installation size

18 kW
PV size

Measured in kilowatts (kW) of direct current (DC), this recommended size minimizes the life cycle cost of energy at your site.


This optimized size may not be commercially available. The user is responsible for finding a commercial product that is closest in size to this optimized size.

 Your recommended battery power and capacity

9 kW battery power
55 kWh battery capacity

This system size minimizes the life cycle cost of energy at your site. The battery power (kW-AC) and capacity (kWh) are optimized for economic performance.


This optimized size may not be commercially available. The user is responsible for finding a commercial product that is closest in size to this optimized size.

 Your recommended generator size


5 kW
generator size
(0 kW new + 5 kW existing)

Measured in kilowatts (kW) of alternating current (AC), this recommended generator size minimizes the life cycle cost of energy at your site during a grid outage.

This optimized size may not be commercially available. The user is responsible for finding a commercial product that is closest in size to this optimized size.

 Your total life cycle cost (20 years)


\$186,245

 Your levelized cost of electricity (20 years)

\$1.403 per kWh

<https://reopt.nrel.gov/tool/results/88f9bf6c-c308-4d17-bed6-3930a46b99bf>


Inflation = 10%

 Your recommended solar installation size

16 kW
PV size

Measured in kilowatts (kW) of direct current (DC), this recommended size minimizes the life cycle cost of energy at your site.


This optimized size may not be commercially available. The user is responsible for finding a commercial product that is closest in size to this optimized size.

 Your recommended battery power and capacity

7 kW battery power
44 kWh battery capacity

This system size minimizes the life cycle cost of energy at your site. The battery power (kW-AC) and capacity (kWh) are optimized for economic performance.


This optimized size may not be commercially available. The user is responsible for finding a commercial product that is closest in size to this optimized size.

 Your recommended generator size


5 kW
generator size
(0 kW new + 5 kW existing)

Measured in kilowatts (kW) of alternating current (AC), this recommended generator size minimizes the life cycle cost of energy at your site during a grid outage.

This optimized size may not be commercially available. The user is responsible for finding a commercial product that is closest in size to this optimized size.

 Your total life cycle cost (20 years)

\$82,733

 Your levelized cost of electricity (20 years)

\$0.623 per kWh

<https://reopt.nrel.gov/tool/results/ad9cdb63-28c4-434d-a3c3-596510690c68>

Thank you



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