Prefeasibility Assessment for Solar PV and Storage for Critical Community Facilities in Chernihiv, Ukraine

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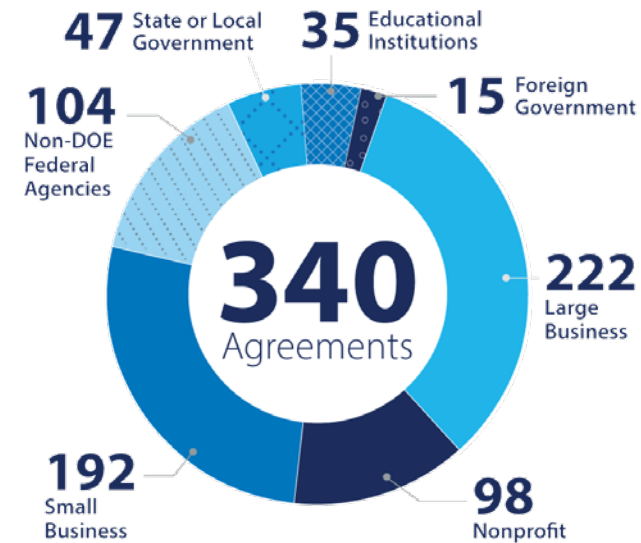
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Photo by Gregory Cooper, NREL 93094

More Than 1,100 Active Partnerships in FY 2023*

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35 Educational Institutions

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104 Non-DOE Federal Agencies

340 Agreements

222 Large Business

98 Nonprofit

192 Small Business

*Agreements by business type

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Energy challenges are complex and integrated

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Overview

- Staff from NREL are supporting the development of renewable energy microgrids in Ukraine.

- Funding is provided by USAID and the U.S. Department of Energy's Net Zero World Initiative.

- This report presents the conceptual design, costs, and benefits of integrating solar photovoltaics (PV) and battery energy storage systems (BESS) into critical community facilities in Chernihiv, Ukraine.

- Conceptual designs, economic metrics, and resilience benefits are presented for the following facilities:

  - Hospital No. 2

  - Maternity Hospital

  - Secondary School No. 11

  - Preschool No. 4.

- Chernihiv community members and NREL subject matter experts have contributed to the development of the conceptual designs.

- This report is intended to inform detailed feasibility studies and investment mobilization.

- Business and Legal Feasibility Disclaimer: This report describes "desktop" analyses. These analyses serve as foundational studies on which further viability analyses could be conducted. We did not assess the regulatory and legal requirements for operating solar PV and energy storage in the Ukrainian context nor examine the facilities' conditions for developing detailed design and cost estimates.

Background and Motivation

- A group of U.S. volunteers led by Rotary Club of Babcock Ranch reached out to NREL and the Net Zero World Initiative to collaborate on advancing renewable energy deployment in the city of Chernihiv.

- In collaboration with Ukrainian and U.S. renewable energy experts, NREL provided a prefeasibility analysis for clean energy deployment at four critical facilities in Chernihiv.

- The motivation of this work is to demonstrate the potential for solar PV and battery energy storage to support critical facility energy resilience in Ukraine, and specifically to support decision-making in the Chernihiv community.

- This work supports the goal of Government of Ukraine for greater deployment of distributed energy resources and decentralized energy systems.

Chernihiv Community Microgrids Development Team and Partners

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Rotary Club of Babcock Ranch, President, Courtney Strong Inc.

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Development of Conceptual Designs

- NREL's REopt®[1] techno-economic model was used to determine system component capacities and life cycle cost metrics.
- NREL's Energy Resilience Performance capability was used to estimate the probability of serving critical facility loads during loss of grid power.
- NREL subject matter experts developed multiple potential courses of action for integrating solar PV and energy storage into the facilities' electrical systems.
- Outcomes for each facility:
    - System architecture
    - Probability of serving critical loads during loss of grid power
    - Capital cost, operating cost, and life cycle cost estimates
    - Net-present value, internal rate of return, and simple payback period estimates.

[1] See https://reopt.nrel.gov/.

Requirements   Data

Discussion   Analysis
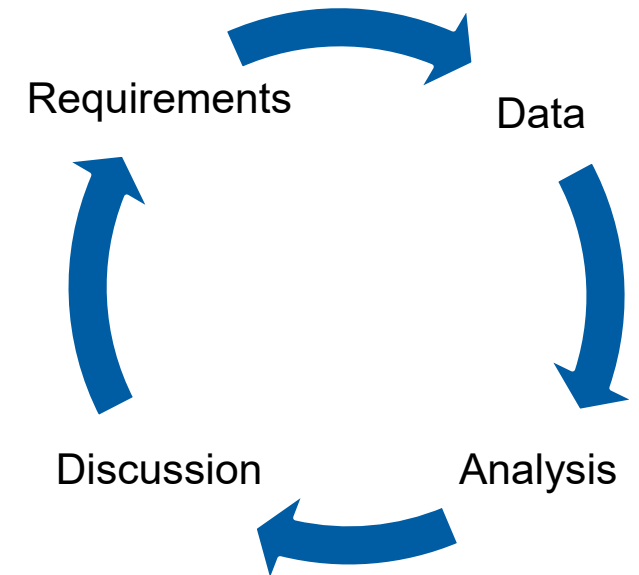
Description of Analyses

- Modeling considers the costs and benefits of integrating solar PV and BESS behind the meter for each facility.

- This analysis estimates the impact of distributed energy resources on **electric utility costs** and the potential of distributed energy resources to provide **backup power** during grid emergencies.

- Chernihiv city officials indicated that each facility has an existing emergency generator serving critical loads. Information about existing generator capacities and critical loads are provided by Chernihiv city officials.

- Resilience specification per Chernihiv officials: BESS shall provide **4 hours of backup power to the critical load** at each facility.

- Each facility's constant critical load is shown in the table.

Facility	Critical Load (kW)
Hospital No. 2	60
Maternity Hospital	23
Secondary School No. 11	10
Preschool No. 4	10

Executive Summary

Executive Summary

- Installing PV at each facility appears cost-effective for reducing electric utility costs.

- While BESS was not found cost-effective for enabling higher shares of PV consumption or for other utility bill savings, because of a need for redundancy in emergency generators, BESS is included for each facility's most critical loads for 4 hours.

- The recommended system sizes and estimated costs and benefits over the 25-year analysis period are shown in the table.

Item or Metric*	Hospital No. 2	Maternity Hospital	Secondary School No. 11	Preschool No. 4
PV Capacity	284 kW-DC	131 kW-DC	15 kW-DC	14 kW-DC
BESS Capacity	60 kW | 4-hour	25 kW | 4-hour	10 kW | 4-hour	10 kW | 4-hour
Capital Cost (USD)	$399,700	$186,100	$46,600	$45,800
First-Year Bill Savings (USD)	$52,100	$20,100	$1,930	$1,870
Simple Payback (years)	7.3	8.6	18.2	18.3
Internal Rate of Return	16%	13%	4%	4%
Net Present Value (USD)	$205,000	$43,300	-$29,600	-$29,300
Year 1 Renewable Generation	270 MWh	125 MWh	14.3 MWh	13.3 MWh
PV Fraction of Annual Facility Electrical Use	18%	26%	15%	25%

* Capital costs are rounded to four significant digits; first-year bill savings and net present value are shown to three significant digits.

Executive Summary (cont.)

- With existing backup generator and additional BESS, the probability of serving critical loads is estimated to exceed 99% for 4-hour outages at Hospital No.2 and the Maternity Hospital.

- The analysis considers several electrical configurations for the PV and BESS. Given the existing emergency generator and inclusion of battery backup, integrating PV with battery backup circuit provides modest additional benefit and may incur additional costs.

- Capital and maintenance cost estimates provided by Atmosfera, a Ukrainian company and project conceptualization participant, were used to identify the optimal technology mix.

- Results are based on a remote "desktop" analysis using Atmosfera's cost estimates. Detailed assessment of facility-specific conditions are needed to:
  - Improve cost estimates
  - Refine PV hosting capacity
  - Inform how to electrically integrate backup battery and solar PV into the facility.

- Vendor availability of components, site conditions, and final costs will likely result in refinement of PV sizing for each facility.

Next Steps: Feasibility Assessment

- Subject matter experts should visit each facility to perform a feasibility assessment to inform the best course of action for integrating PV and backup BESS.
- Experts should determine the technical capacity of the facility to host PV:
  - Confirm weight-bearing capacity of roof
  - Develop rooftop system layout options and racking configuration to make best use of the roof area
  - Finalize PV system size.
- Experts should identify the best option for electrical interconnections. This may entail:
  - Determining if critical loads are on a single circuit or multiple circuits and how to add integrate BESS
  - Confirming the peak and typical daily load profile for the critical loads
  - Determining point of interconnection for PV system(s) to maximize bill savings and to leverage, as possible, the resiliency benefits of solar
  - Identifying the maximum size PV that can connect to critical load circuit(s)
  - Identify routing for electrical interconnection from rooftop PV to electrical main points of interconnection and, if selected, to critical load circuit(s).
- Refine cost estimates for fundraising and donor budgeting.

Details and Further Discussion

Capital Cost Breakdown

- The accompanying table shows the breakdown of the capital costs (CAPEX) by item for each facility: PV, BESS, and assumed cost to integrate the backup battery into the emergency circuit.

- Costs estimates were provided by Atmosfera, a Ukrainian solar company.

- Also shown in the table is a cost for an assumed BESS replacement in Year 10. This cost is included in the life cycle cost analyses and is presented here so that Chernihiv city officials can plan for this future expense.

| Item or Metric	Hospital No. 2	Maternity Hospital	Secondary School No. 11	Preschool No. 4
CAPEX, Total Initial ($)	$399,680	$186,050	$46,630	$45,780
CAPEX Emergency Circuit Integration ($)	$15,000	$15,000	$10,000	$10,000
CAPEX PV ($)	$241,400	$111,350	$12,750	$11,900
CAPEX BESS ($)	$143,280	$59,700	$23,880	$23,880
CAPEX in Year 10 for BESS Replacement ($)	$100,380	$41,825	$16,730	$16,730

Courses of Action for Electrical Integration and Estimated Impact on Probability of Serving Critical Load

Possible Courses of Action for Electrical Integration

- Given the unknowns of emergency circuits configuration, three possible courses of action (COAs) for implementation were identified by the NREL team (provided in the table below).

- An on-site feasibility assessment (beyond the scope of this analysis) is needed to inform the most appropriate configuration.

- The next three slides show each COA schematically.

COA	Description	Pros	Cons
1	PV on the main electrical service for bill savings; BESS on most-critical loads for redundant backup.	BESS provides redundant backup power to emergency generator. Electrically least complex. PV provides bill savings.	PV does not support resiliency.
2	PV split: 1. Most on main electrical service 2. Some interconnected to most-critical loads. BESS on most-critical circuit(s).	BESS and some PV backup the emergency generator. All PV provides bill savings. Some PV serves most-critical loads with BESS during grid emergency. PV on critical circuit can DC-couple with BESS, increasing candidate pool of commercially available products.	Two electrical circuits and routing paths are needed from two rooftop PV systems. Not all the PV is serving most-critical loads. If critical PV is DC-tied to BESS (as standard on some products), potentially a long DC run from roof to location of backup BESS.
3	Connect all PV and BESS to most-critical load circuit.	All PV and BESS can serve all loads during normal operations and most-critical load during loss of grid power.	Building interior critical loads circuit capacity may not be able to support high PV power injection (i.e., 131 kW) and backflow to all facility loads during normal grid operations.

COA 1: Two Independent Systems
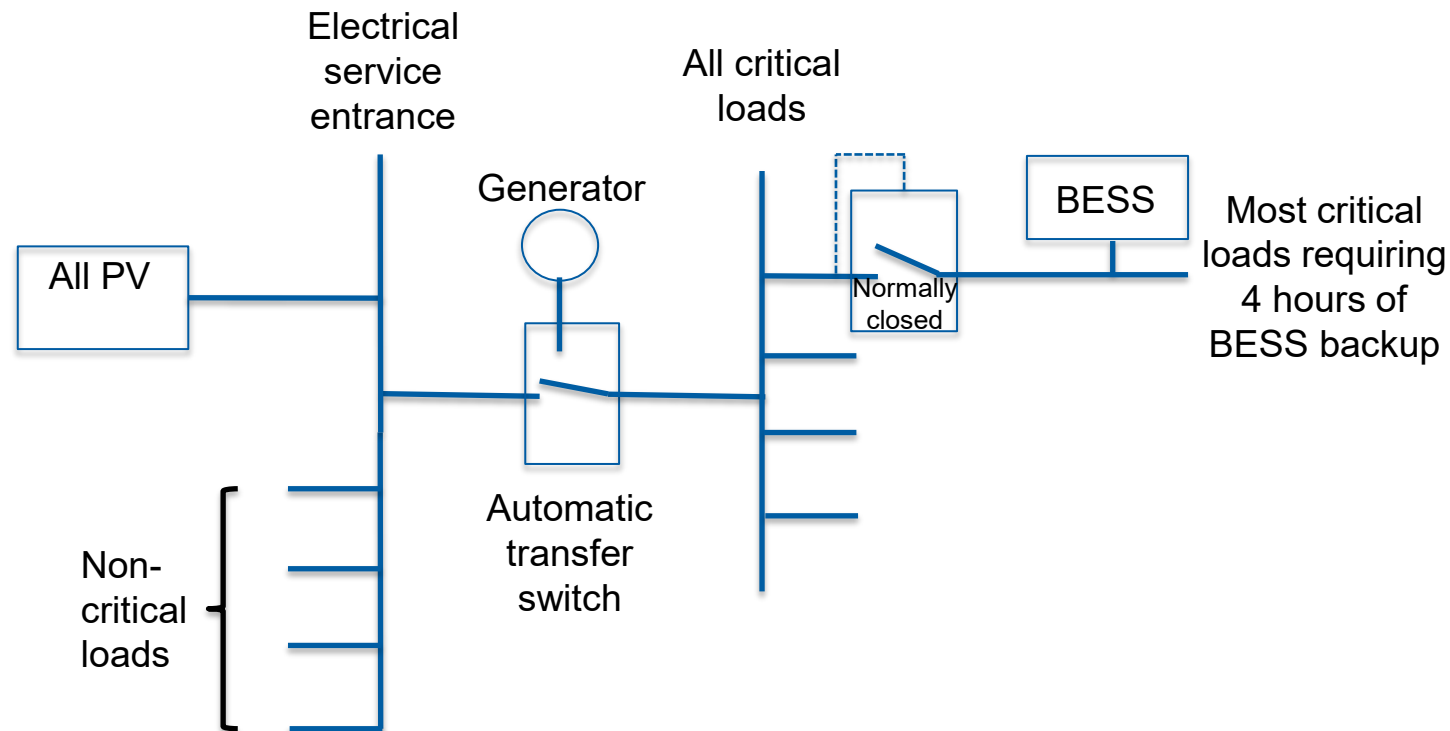
Narrative

- All PV is connected on the main service and serves all loads during normal grid conditions.
- During loss of grid power and activation of the automatic transfer switch:
    - PV system is disconnected from all critical loads.
    - The automatic transfer switch connects to the generator, and all critical loads are served by the backup generator.
- If the backup generator fails, the normally closed switch to the most-critical loads opens, and the BESS provides 4 hours of firm backup to those most critical loads.

Pros:

- BESS provides redundant backup power to emergency generator for most-critical loads.
- Electrically least complex.
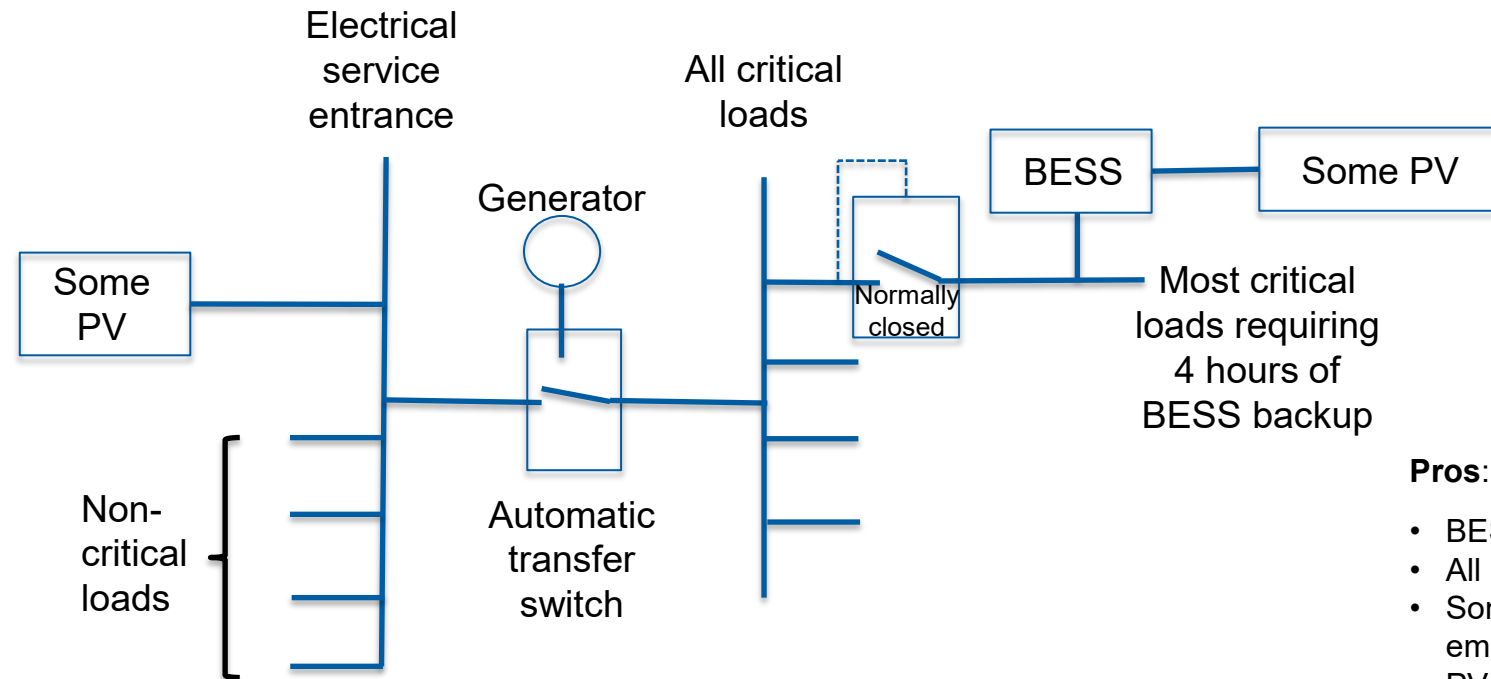- PV provides bill savings.
- Backup BESS for most-critical loads.

Cons:

- PV does not support resiliency.

COA 2: Two Independent Systems

Electrical service entrance

All critical loads

Generator

BESS — Some PV

Some PV

Normally closed

Most critical loads requiring 4 hours of BESS backup

Non-critical loads

Automatic transfer switch

Narrative

- Some portion of the total PV is connected to the main service, and some is connected to the BESS serving the most critical loads. All PV serves all loads during normal grid conditions.
- During loss of grid power and activation of the automatic transfer switch:
  - The portion of the PV connected to the main service is disconnected from all critical loads.
  - The automatic transfer switch connects to the generator, and all critical loads are served by the backup generator and the portion of PV connected to the BESS.
- If the backup generator fails, the normally closed switch to the most-critical loads opens, and the BESS provides 4 hours of firm backup to those most-critical loads and that BESS energy is supplemented by the portion of PV interconnected to it.
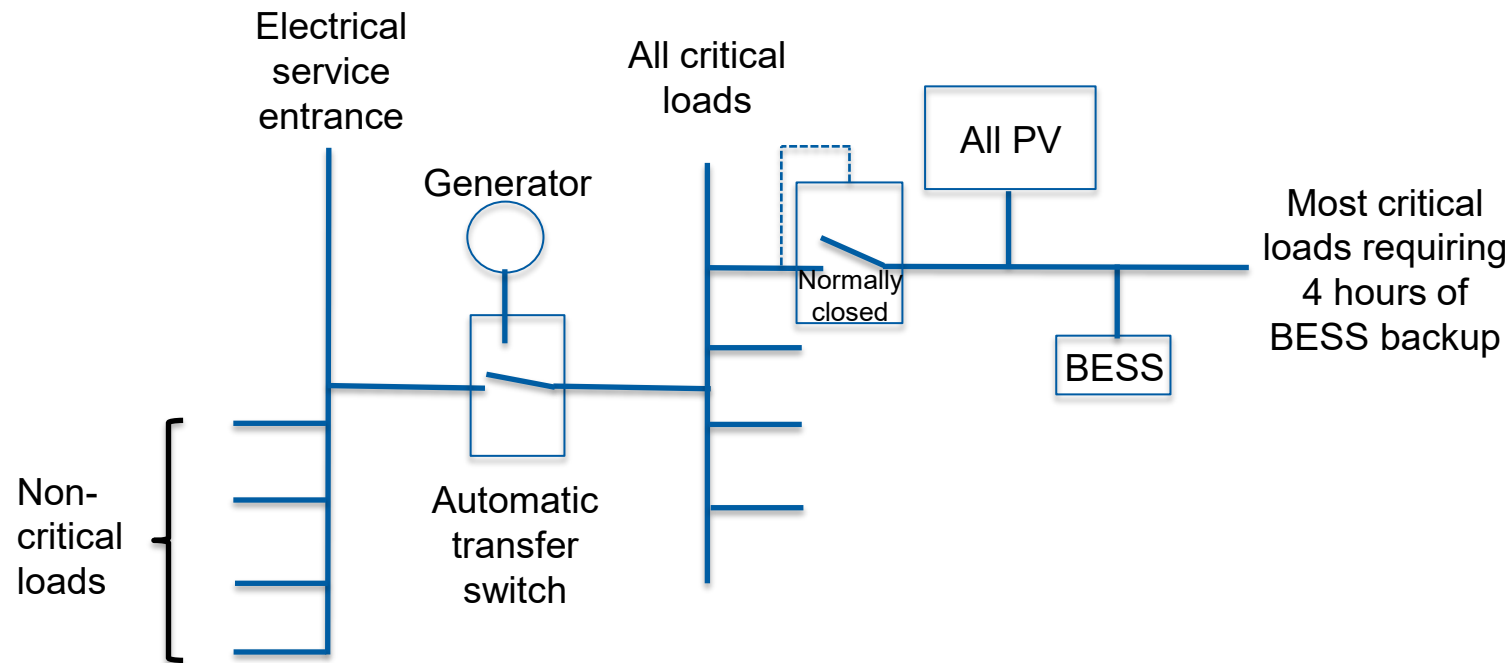
Pros:

- BESS and some PV backup the emergency generator.
- All PV provides bill savings.
- Some PV serves most-critical loads with BESS during grid emergency.
- PV on critical circuit can DC-couple with BESS, increasing candidate pool of commercially available products.

Cons:

- Two electrical circuits and routing paths are needed from two rooftop PV systems.
- Not all the PV is serving most-critical loads.
- If critical PV is DC-tied to BESS (standard on some products), potentially a long DC run from roof to location of backup BESS.

COA 3: All PV on Most-Critical Circuit

Electrical service entrance

Generator

All critical loads

Automatic transfer switch

Normally closed

All PV

BESS

Most critical loads requiring 4 hours of BESS backup

Non-critical loads

Narrative

- All PV is connected to most-critical load circuit and serves all loads during normal grid conditions.
- During loss of normal grid power, the automatic transfer switch connects to the generator, and all critical loads are served by the backup generator and PV.
- If the backup generator fails, the normally closed switch to the most-critical loads opens, and the BESS provides 4 hours of firm backup to those most-critical loads and that BESS energy is supplemented by the all PV.

Pros:

- All PV provides bill savings.
- All PV serves most-critical loads during grid emergency.

Cons:

- Capacity of critical load circuit may not be able to support high PV power injection (i.e., 131 kW) and backflow to all facility loads during normal grid operations. As a result, this could be infeasible or require costly upgrades.

Impact of COA on Probability of Serving Most-Critical Loads

- PV, when tied to the backup battery, can support critical loads during loss of power.

- The tables on the following slides show estimated resilience benefit of interconnecting none, some, or all PV (corresponding to each COA) into the emergency circuits for Hospital No. 2 and the Maternity Hospital.

- For each PV interconnection COA, two scenarios for the reliability of the emergency generator are considered:

  – Standard assumptions for emergency generator reliability

  – Demonstration of how results are impacted when emergency generator reliability metrics are arbitrarily changed to much poorer values.

- Given the presence of existing emergency generator and inclusion of battery backup, **these results demonstrate that integrating PV with battery backup circuit provides modest additional benefit**.

- Estimates are generated using REopt's Energy Resilience Performance capability.

Hospital No. 2 Probability of Serving Most-Critical Loads

- Estimated impact of interconnecting PV to most-critical loads as described for each COA for Hospital No. 2.
- These results use NREL default reliability performance metrics for emergency generators, PV, and BESS and assume that each generator has sufficient fuel supply.

	COA 1	COA 2	COA 3
Scenario Inputs			
Existing Emergency Generator (kW)	160	160	160
PV Total Capacity (kW-DC)	284	284	284
PV on Most-Critical Load (kW-DC)	0	100	284
BESS (kW)	60	60	60
BESS (kWh) (80% available range)	300	300	300
Scenario Results			
Power Outage Duration	**Probability of Serving Most-Critical Load**		
4-hr	99.95%	99.95%	99.95%
12-hr	97.84%	98.06%	98.29%
24-hr	96.78%	96.91%	97.03%

See Model, Inputs, and Assumptions for information on how these results are estimated.

Adding PV to backup BESS only slightly improves probability of serving most-critical load.

With a reliable generator and BESS, probability of serving most-critical load remains high for 24-hr outage.

Hospital No. 2 Probability of Serving Most-Critical Loads

The scenarios on the previous slide are **rerun with considerably poorer assumptions on generator reliability.** Generator reliability assumptions are downgraded from: Availability from 99.5% to 80%, Probability of Failure to start from 0.94% to 5%, and Mean Time to Failure from 1100 to 600 hours. Results assume generator has sufficient fuel supply.

	COA 1	COA 2	COA 3
Scenario Inputs			
Existing Emergency Generator (kW)	160	160	160
PV Total Capacity (kW-DC)	284	284	284
PV on Most-Critical Load (kW-DC)	0	100	284
BESS (kW)	60	60	60
BESS (kWh) (80% available range)	300	300	300
Scenario Results			
Power Outage Duration	**Probability of Serving Most-Critical Load**		
4-hr	99.26%	99.26%	99.26%
12-hr	74.98%	76.57%	79.31%
24-hr	73.49%	73.68%	73.84%

BESS assures high probability of serving most-critical load for 4 hours with unreliable generator.

See Model, Inputs, and Assumptions for information on how these results are estimated.

Adding PV to backup BESS only slightly improves probability of serving most-critical load.

Maternity Hospital Probability of Serving Most-Critical Loads

- Estimated impact of interconnecting PV to most-critical loads as described in for each COA for the Maternity Hospital.
- These results use NREL default reliability performance metrics for emergency generators, PV, and BESS and assume that each generator has sufficient fuel supply.

	COA 1	COA 2	COA 3
Scenario Inputs			
Existing Emergency Generator (kW)	80	80	80
PV Total Capacity (kW-DC)	131	81	131
PV on Most-Critical Load (kW-DC)	0	50	131
BESS (kW)	25	25	25
BESS (kWh) (80% available range)	125	125	125
Scenario Results			
Power Outage Duration	**Probability of Serving Most-Critical Load**		
4-hr	99.95%	99.95%	99.95%
12-hr	97.84%	98.08%	98.25%
24-hr	96.78%	96.92%	97.00%

See Model, Inputs, and Assumptions for information on how these results are estimated.

Adding PV to backup BESS only slightly improves probability of serving most-critical load.

With a reliable generator and BESS, probability of serving most-critical load remains high for 24-hr outage.

Maternity Hospital Probability of Serving Most-Critical Loads

The scenarios on the previous slide are **rerun with considerably poorer assumptions on generator reliability.** Generator reliability assumptions are downgraded from: Availability from 99.5% to 80%, Probability of Failure to start from 0.94% to 5%, and Mean Time to Failure from 1100 to 600 hours. Results assume generator has sufficient fuel supply.

	COA 1	COA 2	COA 3
Scenario Inputs			
Existing Emergency Generator (kW)	80	80	80
PV Total Capacity (kW-DC)	131	81	131
PV on Most-Critical Load (kW-DC)	0	50	131
BESS (kW)	25	25	25
BESS (kWh) (80% available range)	125	125	125
Scenario Results			
Power Outage Duration	**Probability of Serving Most-Critical Load**		
4-hr	99.26%	99.26%	99.26%
12-hr	74.98%	76.98%	78.89%
24-hr	73.49%	73.68%	73.81%

See Model, Inputs, and Assumptions for information on how these results are estimated.

Adding PV to backup BESS only slightly improves probability of serving most-critical load.

BESS assures high probability of serving most-critical load for 4 hours with unreliable generator.

Model, Inputs, and Assumptions

Facility Loads Summary

- Facility electrical load data provided by Chernihiv city officials is shown in the table. Monthly totals were synthesized into hourly values using U.S. Department of Energy Commercial Reference Building models.

- Chernihiv-specificized level and duration of critical load to be supported by BESS is also included.

Item or Metric	Hospital No. 2	Maternity Hospital	Secondary School No. 11	Preschool No. 4
Annual Electricity (MWh)	1,462	385	62.7	37.5
Average Annual Demand (kW)	167	44	7.2	4.3
Annual Peak Demand (kW)	320	134	37	22
Power Rating of Existing Backup Generator (kW)	160	80	10	5
Critical Load Specification for Battery Backup	60 kW for 4 hrs.	23 kW for 4 hrs.	10 kW for 4 hrs.	10 kW for 4 hrs.

Source of Cost and Performance Inputs

- The concept and configuration analyzed were developed by Chernihiv city officials, NREL, and other stakeholders.

- Atmosfera, a Ukrainian solar company, provided capital and maintenance cost inputs for battery energy storage, solar PV, reciprocating engine generators, and balance-of-system components.

- Assumed discount rate, general inflation rate, and electricity cost escalation rate were developed by NREL.

- Additional cost and performance details are provided on the remaining slides in this section.

Economic Parameters and Cost Assumptions

Key Assumptions

Analysis Period	25 years
Technologies Considered	PV, battery storage, existing backup generators
Discount Rate	11.0%
General Inflation Rate	2.5%
Retail Electricity Cost Escalation Rate	5%
Retail Cost of Electricity, Current Year	$0.20/kWh
Value of Exported Solar Electricity	None. Cannot export PV generation.
Financial Incentives	None
Weather Resource and PV Model	NREL's System Advisor Model™, PVWatts® module, and a typical meteorological year National Solar Radiation Database* weather data file for Chernihiv, Ukraine

Electricity Rate Tariff with Assumed 5% Cost Escalation Rate
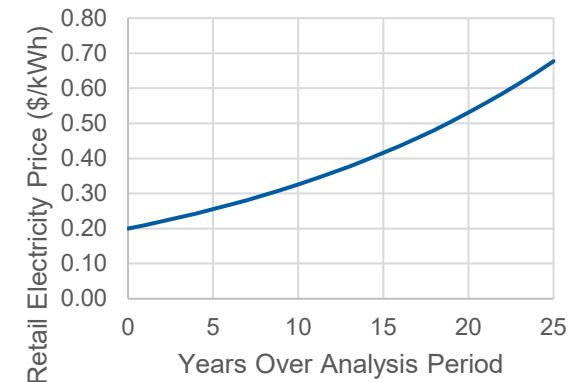
Discount rate and retail electricity costs provided by in-country partners on multiple similar technical assistance activities. Retail electricity cost escalation is an NREL assumption.

* See https://nsrdb.nrel.gov/.

Economic Parameters and Cost Assumptions (cont.)

Key Assumptions

PV Capital Costs	$850/kW-DC
PV Operations and Maintenance Costs	$15/kW-DC/year, Year 1 (60% of REopt U.S. default)
BESS Capital Costs	$683/kW + $341/kWh
BESS Replacement Year	Year 10
BESS Replacement Costs	$478/kW + $239/kWh (70% of initial cost, estimated)
Emergency Backup Generator Fuel Cost	$5.31/gallon fuel cost
Costs for Integrating BESS and PV Into Emergency Power Circuit	$15,000

Capital costs estimates are total installed costs. PV, initial BESS capital costs, and costs for integrating BESS and PV into emergency power circuit estimates were provided by in-country nonprofits and installers. Operations and maintenance costs, BESS useful life and replacement costs, and emergency generator fuel costs are NREL assumptions.

Solar Resource

- PV system power output is estimated for each hour of 1 year using NREL's System Advisor Model, PVWatts module, and a typical meteorological weather data file for Chernihiv, Ukraine.

- NREL's National Solar Resource Database has solar resource data for Ukraine from 2005 through 2022.

Ukraine global horizontal solar irradiance data. Map illustration by Billy Roberts, NREL

Roof Area Estimates

- Roof area estimates were used to estimate the maximum hosting capacity for rooftop PV at each facility.

- Chernihiv officials provided estimated roof areas for the schools:
  - Preschool No. 4, 1530 m^2
  - Secondary School No. 11, 3259 m^2

- NREL estimated the available roof area for Hospital No. 2 and the Maternity Hospital using satellite imagery accessed through Google Earth.

- A factor of 0.7 is applied to area measurements to conservatively account for setbacks and roof penetrations.

- Hospital No. 2 roof area estimates:
  - East roof 1,720 m^2
  - Northwest roof 930 m^2
  - Southwest roof 1,120 m^2
  - = 3,770 m^2 total * 0.7 = **2640 m^2.**

- Maternity Hospital roof area estimates:
  - South roof 1,410 m^2
  - North roof 470 m^2
  - = 1,880 m^2 total * 0.7 = **1,320 m^2.**
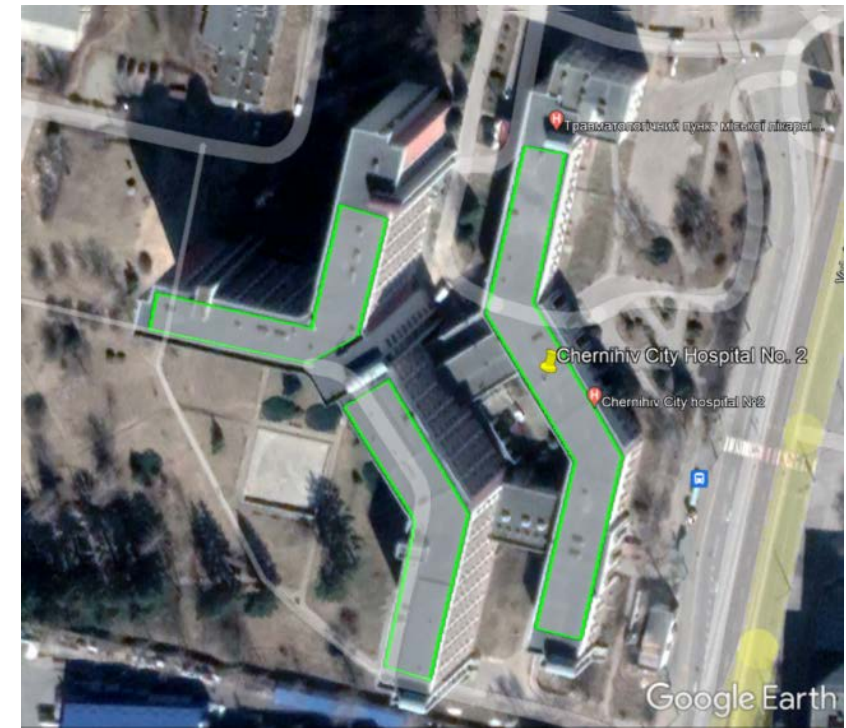
Hospital No. 2 satellite image
Credit: Google Earth

Maternity Hospital satellite image
Credit: Google Earth

PV Technical Performance Assumptions

PV Inputs and Assumptions	Assumptions
Weather File	NREL URDB typical meteorological year data for Chernihiv, Ukraine
PV Performance Model	NREL PVWATTS
Module Type	Standard
Array Type	Rooftop, fixed
Array Tilt	20
DC-to-AC Ratio	1.2
System Losses	14%

BESS and Generator Technical Performance Assumptions

Battery Energy Storage Inputs	Assumptions
Battery Type	Lithium-ion
AC-AC Round-Trip Efficiency	89.9% (includes inverter and rectifier efficiencies of 94.8%)
Initial State of Charge	50%
Minimum State of Charge	20%
Replacement Year	10

Emergency Generator	Assumptions
Generator Type	Reciprocating engine
Specific Efficiency	32.2%
Fuel Higher Heating Value	40.7 kWh/gallon

Appendix: Reliability Analysis Methods and Assumptions and REopt Model Overview

Reliability Analysis Method and Assumptions

- In addition to the economics, reliability performance was estimated.

- Reliability was estimated using a published NREL method (using a Markovian approach).*

- High-level description and defaults are available in the REopt User Manual: https://reopt.nrel.gov/tool/reopt-user-manual.pdf#page=112.

*Marqusee, Jeffrey, William Becker, and Sean Ericson. 2021. "Resilience and Economics of Microgrids with PV, Battery Storage, and Networked Diesel Generators." *Advances in Applied Energy*, 3, 10004. https://www.nrel.gov/docs/fy21osti/78837.pdf.

Marqusee, Jeffrey, Sean Ericson, and Donald Jenket. 2021. "Impact of Emergency Diesel Generator Reliability on Microgrids and Building-Tied Systems." *Applied Energy* 285, 116437. https://www.nrel.gov/docs/fy21osti/78837.pdf.

REopt Model Overview

REopt Modeling Overview

Model overview: Developed by NREL, REopt[1] is an open-source, techno-economic, mixed-integer linear optimization model used to determine cost-optimal system sizing, economic dispatch, and net value of distributed energy systems.

Model objective: Minimize the life cycle cost of electricity for the grid-connected microgrid over the planning horizon.
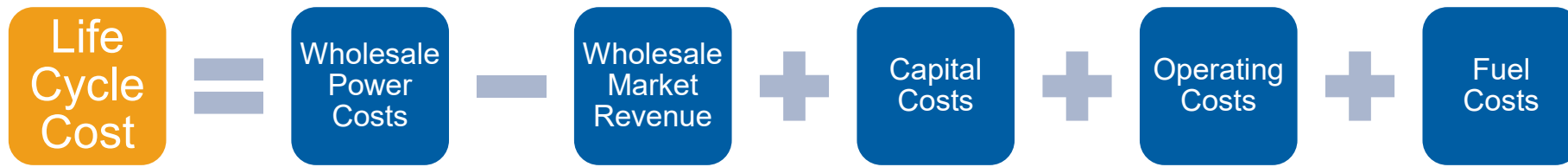

Decision variables: (1) Installed capacity of solar, batteries, and natural gas generators; and (2) economic dispatch of each technology.

Key inputs: Overview on subsequent slide; detailed in Model, Inputs, and Assumptions section.

REopt Energy Planning Platform

Formulated as a mixed-integer linear program, REopt provides an integrated, cost-optimal energy solution.
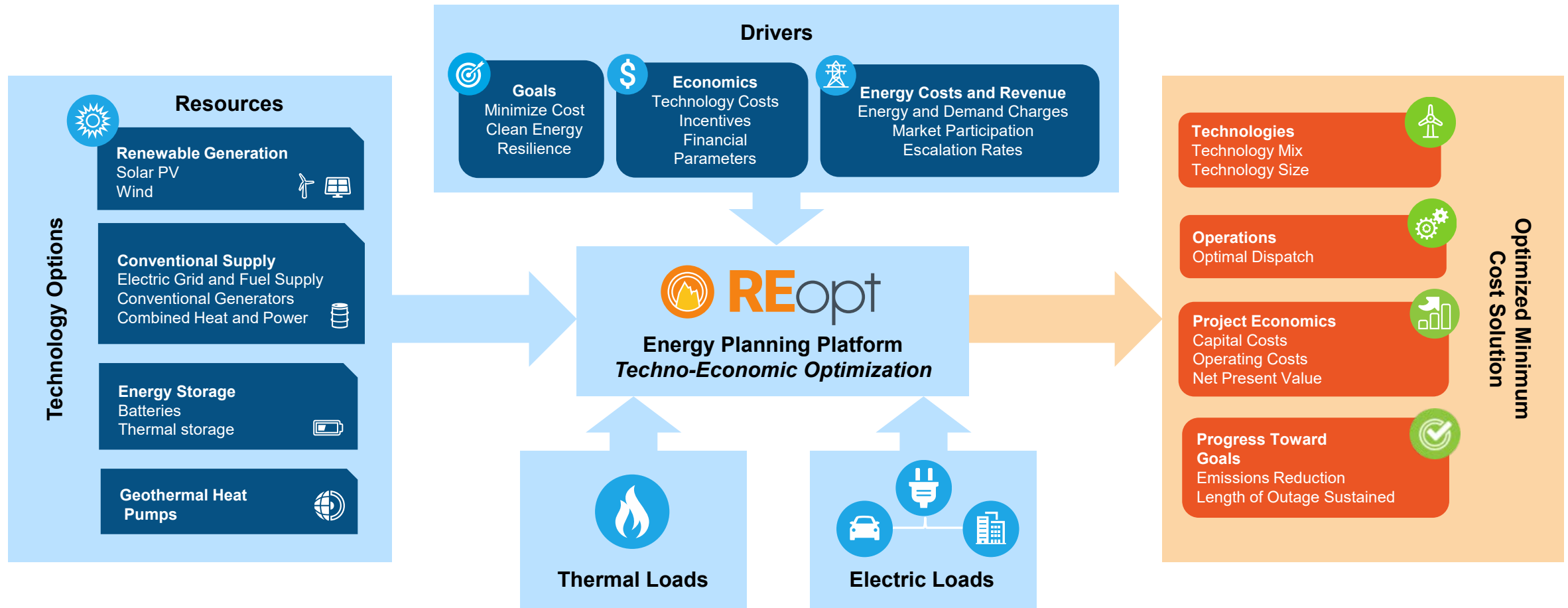
Thank you!

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- This analysis relies on site information provided to NREL that has not been independently validated by NREL.

- The analysis results are not intended to be the sole basis of investment, policy, or regulatory decisions.

- This analysis was conducted using the NREL REopt Model (http://www.reopt.nrel.gov). REopt is a techno-economic decision-support model that identifies the cost-optimal set of energy technologies and dispatch strategy to meet site energy requirements at minimum life cycle cost, based on physical characteristics of the site and assumptions about energy technology costs and electricity and fuel prices.

- The data, results, conclusions, and interpretations presented in this document have not been reviewed by technical experts outside NREL.