Merefa Community Microgrid: Conceptual Design and Sequence of Operations

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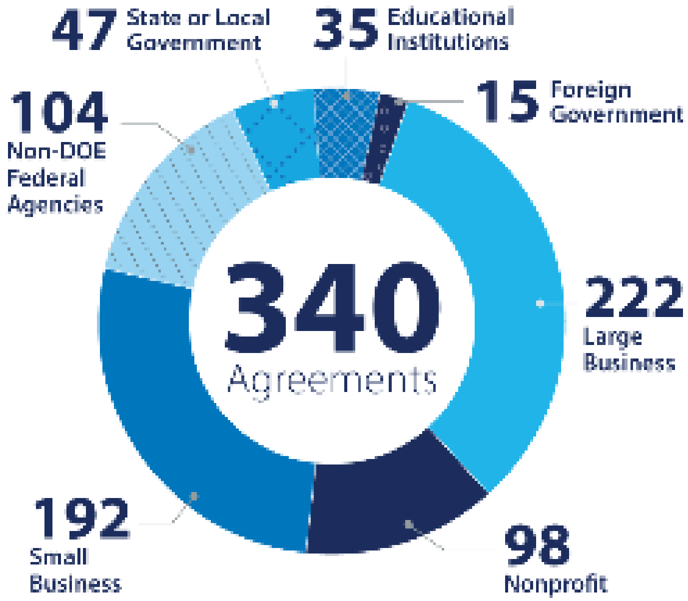

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- Leveraging significant U.S. DOE investment
- Energy challenges are complex and integrated
- Technical leadership and global reputation
- Complementing USAID implementing partners

Overview

- Staff from NREL are supporting the development of renewable energy microgrids in Ukraine.
- Funding is provided by DOE's Net Zero World initiative and USAID.
- This report presents the conceptual design of the Merefa Community Microgrid (MCM).
- Merefa community members, SK-Monolith LLC (the microgrid developer), and NREL subject matter experts have contributed to the development of the conceptual design and this report.
- This report is intended to inform business plan refinement and investment mobilization.
- Business and Legal Feasibility Disclaimer: This report describes a techno-economic analysis. The authors do not claim or deny that there exists a viable business model for this or any other microgrid. This analysis serves as a foundational study on which further business viability analyses could be conducted. We did not assess the regulatory and legal requirements for operating this microgrid in the Ukrainian context.

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Accelerating Global Energy System Decarbonization

Background and Motivation

- The Ministry of Energy of Ukraine reached out to the Net Zero World Initiative seeking support for reconstruction of the energy system in the Merefa, Ukraine.
- The Ministry of Energy identified SK-Monolith as a local industry partner with experience installing and operation clean energy projects in Merefa.
- The Net Zero World Initiative partnered with NREL staff supporting USAID/Ukraine to provide a feasibility analysis for a clean energy microgrid in Merefa.
- The motivation of this work is to demonstrate the feasibility of microgrids in Ukraine to support energy system resilience.
- This analysis is intended to support decision-making in the Merefa community on next steps for its energy system recovery.
- This work supports the goal of Government of Ukraine for greater deployment of distributed energy resources and decentralized energy systems.

Merefa Community Microgrid Development Team & Partners

Andriy Pavlov

SK Monolith

Co-owner

20+ years of experience in Telecom projects as project manager and head of PM team

Dr. of Engineering Oleksandr Moroz

SK Monolith, State Biotechnological University

Professor of the Department of Power Supply and Energy Management

Dr. of Engineering Oleksandr Miroshnyk

SK Monolith, **State Biotechnological University**

Head of the Department of Power Supply and Energy Management

Volodymyr Pazii

SK Monolith, **State Biotechnological University**

Senior Lecturer of the Department of Power Supply and Energy Management

Dr. Yulia Rybak

Senior Advisor to the Ministry of Energy of Ukraine

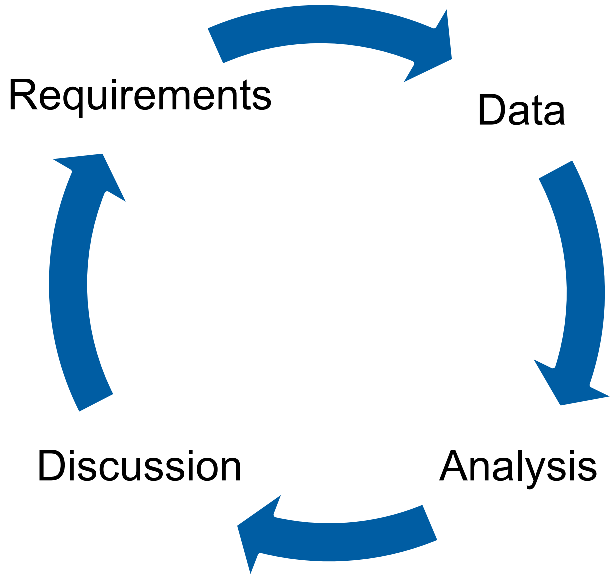
Strong support as a national security priority and blueprint for future projects. CS-WEL program participant.

Merefa Municipality Government

The Deputy Mayor and the Head of International Relations and Project Investment Activities Department of the municipal council

Development of Conceptual Design

- NREL's REopt® [1] techno-economic model was used to determine system component capacities and lifecycle cost of service.
- NREL's Energy Resilience Performance capability was used to estimate the probability of serving critical customer loads during loss of grid power.
- NREL subject matter experts reviewed the distribution system design and advised on switching, microgrid control logic, and sequence of operation.
- Outcomes:
  - System architecture
  - Sequence of operations during local grid emergencies
  - Probability of serving microgrid customers' critical loads during loss of grid
  - Initial capital costs, operating cost, and life cycle cost (LCC) estimates
  - Minimum viable tariff for MCM customers, renewable contribution, market imported and exported energy estimates
  - Example tariffs with indicative financial net-present value, internal rate of return (IRR), and simple payback period.



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

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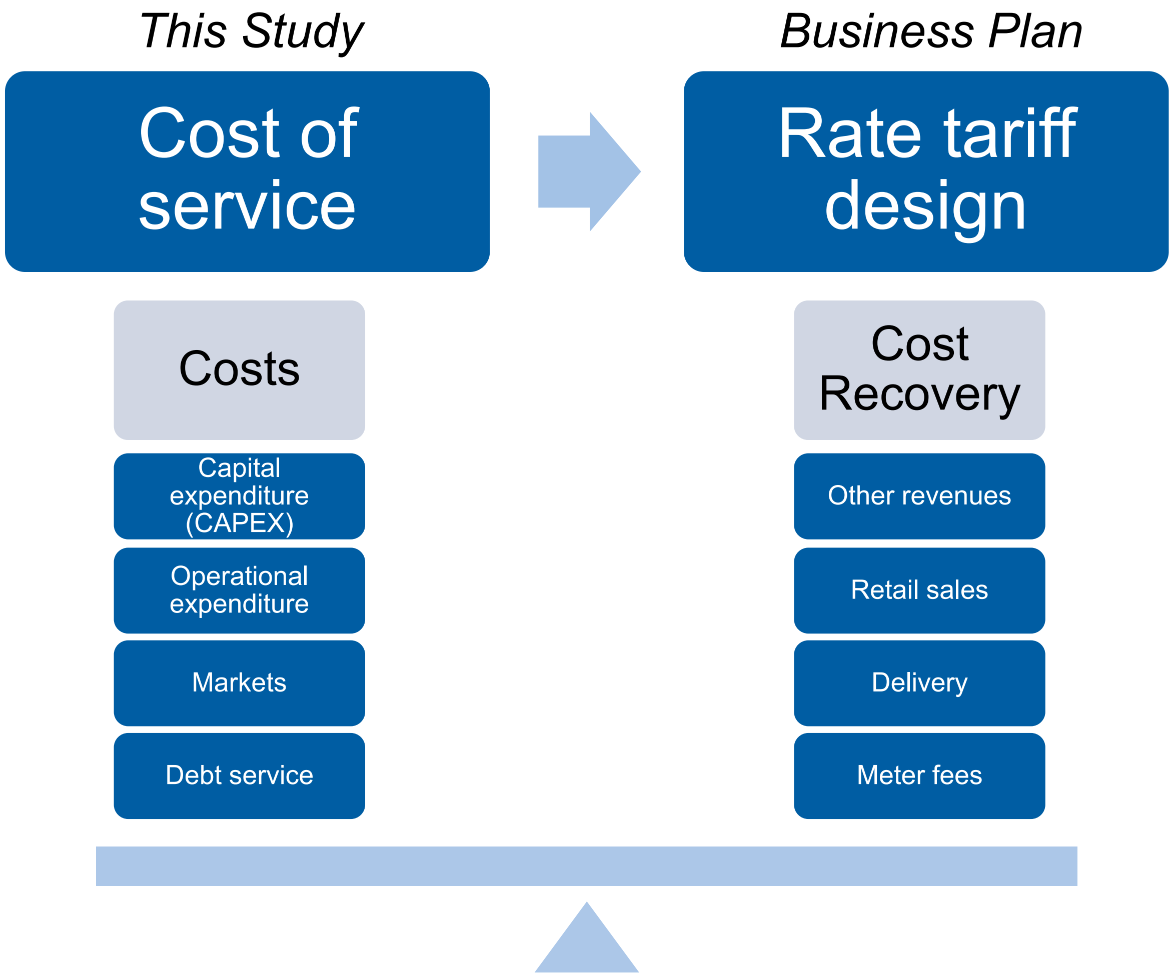
Initial System Design Overview

- REopt determines MCM's cost of service for serving loads of microgrid customers during normal blue-sky operations and during grid emergencies.
- The analysis establishes a minimum viable tariff and potential rates of return.
- Analysis outputs can be used to determine business-viable rate tariff structures to refine cashflow and IRR.



Executive Summary

Executive Summary

- The conceptual design co-developed by SK Monolith and NREL staff will provide affordable and resilient power to critical Merefa community loads.
- SK Monolith has existing solar photovoltaic (PV) plants and utility interconnection capacity that could enable relatively fast development of the microgrid.
- SK Monolith has identified five customers and estimated their total typical daily loads and critical loads to be served during grid outages.
- Results from the analysis recommend microgrid assets of these sizes:
  - 6,060 kW-DC total solar PV; 4,375 kW-DC of PV is already operational or currently under construction
  - 2,447-kW, 4-hour battery energy storage system (BESS)
  - Two 532-kW natural gas reciprocating engine generators, for a total of 1,064 kW
  - Balance-of-plant equipment, microgrid protection and control system.
- These sizes are model outputs; actual sizes will be adjusted to match commercially available best-price offers.
- Capital and investment cost estimates provided by SK Monolith were used to identify optimal technology mix.
- Total estimated capital cost investment is $9,850,000 USD for the conceptual design.
  - Detailed design may reveal additional costs, such as for electrical protection equipment.
- Total estimated annualized operations and maintenance (O&M) is $1,020,000 USD per year.
  - Non-fuel, $443,000 (annualized)
  - Natural gas, $578,000 (annualized).
- Distribution system operator (DSO) interaction for optimizing microgrid costs:
  - During normal grid operation, DSO at times provides low-cost wholesale power.
  - At other times, the microgrid exports power to the DSO when wholesale market prices are high.

Executive Summary (cont.)

- During loss of DSO power, the MCM resources will provide power to customer's critical loads; estimated probability of serving critical load during a 96-hour outage is 87%. See Slide 37 for methodology.
- PV is cost-effective. 6,060 kW-DC is the maximum size that the existing MCM parcel can host.
- BESS provides:
  - Arbitrage value for selling excess PV generation during high wholesale rate periods
  - Black-start redundancy with natural gas generators
  - Greater utilization of PV during MCM islanding events
  - Ability to serve loads solely from PV + BESS during low load periods.
- Natural gas generation:
  - Provides economic value when grid is available during periods of high wholesale market prices. During non-outage periods, the model operates the generators when wholesale market prices exceed marginal cost (fuel cost + wear) of generation.
  - This market revenue "subsidizes" increasing generation capacities to achieve higher probabilities for serving critical loads during grid emergencies.
- As a "front-of-the-meter" microgrid, MCM will service customers through MCM distribution, not the local utility's system.
- Microgrid could be expanded by adding additional engine generators, BESS, and distributed PV.
- While this summary describes the final conceptual design, other configurations, utility cost, and net load scenarios were analyzed. These other results are included in an appendix to this report for completeness.
- Potential legal structure and contractual arrangement are to be resolved in a later phase.

Executive Summary (cont.)

- A fixed energy-only tariff of $0.166/kWh over 20 years provides 8% IRR on investment.
  - This is the minimum viable tariff.
- Current retail rates are approximately $0.20/kWh.
- MCM could consider including a premium charge on tariff for access to resilient power.
- Two simple tariffs are shown in the table below as examples to generate indicative net-present value, IRR, and simple payback. These values assume project is 100% financed with equity.

Tariff Year 1 Rate (USD)	$0.18/kWh	$0.20/kWh
Tariff Annual Escalator	2%	2%
Net-Present Value (USD)	$5,090,000	$7,860,000
IRR	14.2%	17.2%
Simple Payback	6.7 years	5.7 years

Item or Metric	Value
PV Capacity	6,060 kW-DC
BESS Capacity	2,447 kW | 4-hour
Engine Generator Capacity	1,068 kW
Capital Cost ($M)	$ 9.85
O&M Annualized ($M)	$ 1.02
DSO Purchases, Annualized ($M)	$ 0.94
DSO Sales, Annualized ($M)	$ 0.94
LCC ($M)*	$19.84
Minimum Viable Tariff	$0.166/kWh, fixed
96-hour Outage Survival Probability	87%
Annual Renewable Generation	5,957 MWh
PV Fraction of Customer Load**	48%

* Net-present cost calculated over 20-year analysis period. Used to determine minimum viable tariff. Includes market purchase and sales. Does not include revenues for retail sales to MCM customers.
**Total PV generation divided by total customer loads; does not account for PV energy that might be exported versus consumed by MCM customers.

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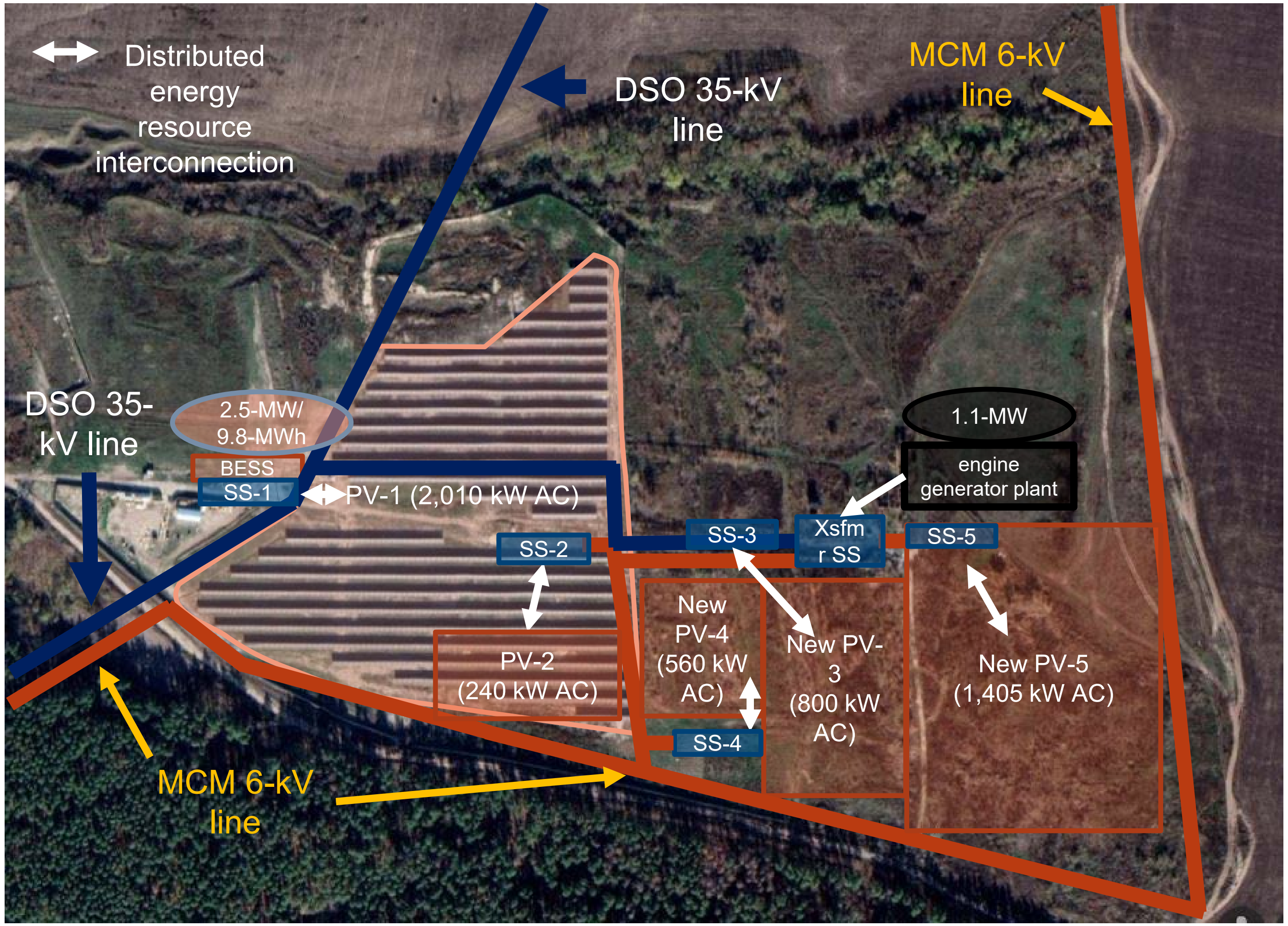
Details and Further Discussion

Major Components Site Layout



- MCM Natural Gas Generator
- MCM Solar PV/BESS
- MCM Substation

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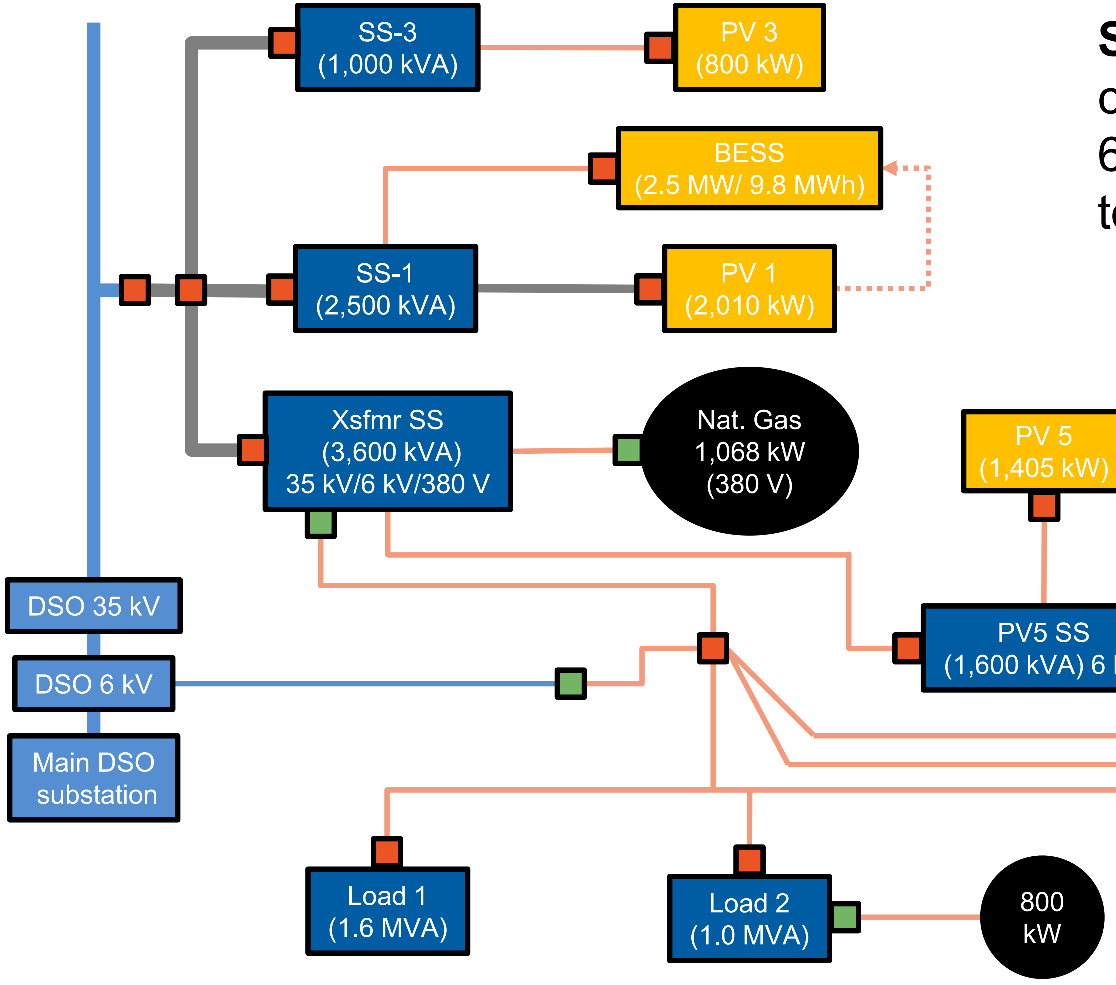
Conceptual Single-Line Diagram



Step 0: Nominal system configuration: DSO 35-kV and 6-kV service supplies power to loads.

- Liquid Fuel Generator
- DSO Substation/Line
- Merefa Solar PV/BESS
- Merefa Substation
- Merefa 35-/6-kV Line
- Open Switch/Breaker
- Closed Switch/Breaker

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Conceptual Sequence of Operation to Electrical Islanding Mode

In the event of a loss of DSO power, the microgrid control system (MCS) will perform the following steps to be completed within a few minutes after the area grid outage:

1. MCS commands all controlled circuit breakers to open.
2. MCS starts the grid-forming BESS.
3. MCS starts and synchronizes the natural gas engine generators (also grid-forming-capable).
4. MCS **energizes selected loads** in a prioritized order. With each added load, the BESS and generators ramp up to match the loads.
5. MCS **energizes any load-shed buildings**; the BESS and generators continue to match the load.
6. MCS monitors microgrid loads and closes the PV-1 system circuit breaker and controls the PV inverters to charge the BESS and serve load.
7. MCS can prioritize PV-1 output, but hot idle of a generator is recommended for greater microgrid stability.
8. MCS continues to dispatch the distributed energy resources (other PV systems) and shed loads if needed and, during daylight hours, prioritizes BESS charging to ensure high state of charge by sunset.
9. MCS disconnects PV arrays overnight to limit inverter loads.
10. When DSO returns utility service, the MCS reverses the microgrid-forming sequence.

Illustration of the sequencing steps is provided in the Sequence of Operation section of the Appendix.

Steps 1 to 5 can be completed withing 5 minutes depending on requirements and selected equipment.

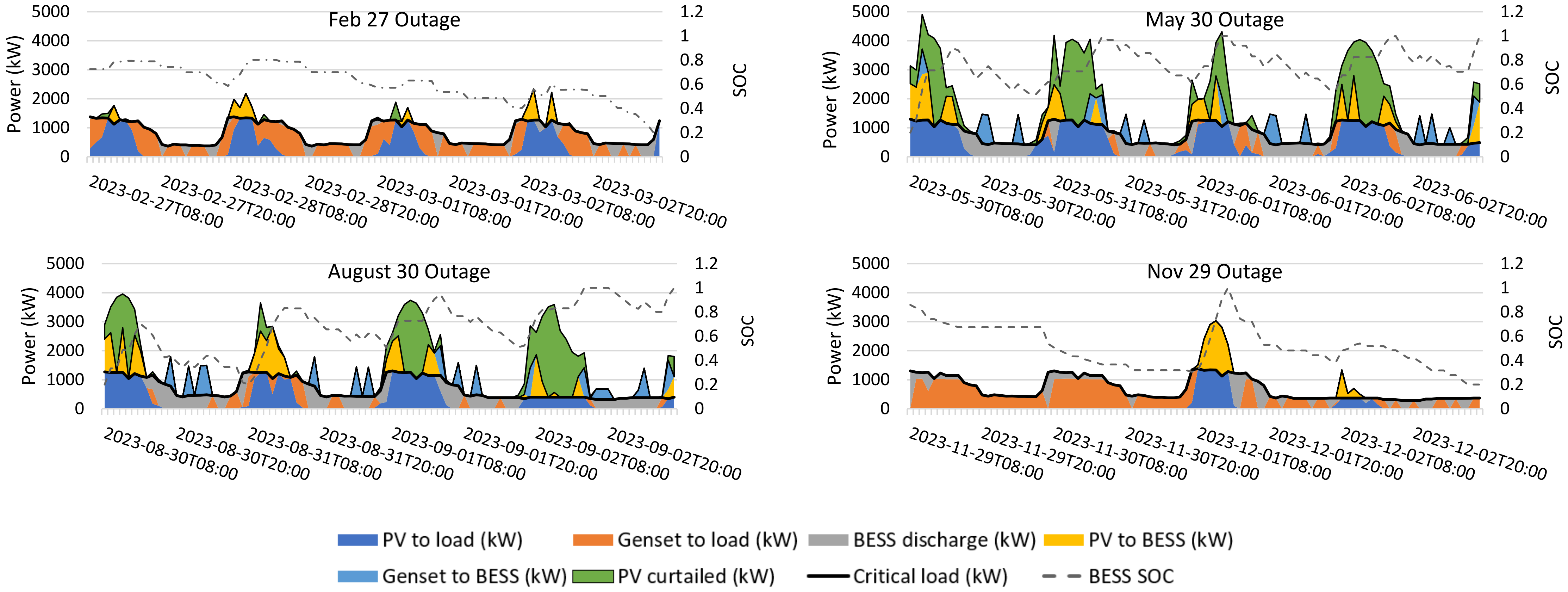
DSO Interaction

- MCM is tied to the local distribution system.
- MCM purchases DSO power when prices are low.
- MCM sells power to market when DSO prices are high and during periods of excess solar energy.

Metric	Market Purchases	Market Sales
Annual Energy	8,494 MWh	4,366 MWh
Annualized Cost and Revenues	$940,000	$943,000
Levelized Costs and Revenues	$0.111/kWh	$0.216/kWh

Dispatch During Loss of Grid Power

The dispatch of MCM assets for four 96-hour outage periods are shown in the figures.



The model occasionally generates periods of simultaneous BESS charging and discharging. This is allowed in the model to reduce complexity. The model team acknowledges that this is a non-physical solution but is not of concern due to the course 1-hour timesteps used in the simulation. Within each timestep, separate periods of charging and discharging would occur.

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Range of Scenarios Modeled

- The table below summarizes the scenarios analyzed, including the selected final conceptual design described in the Executive Summary, Scenario D.
- Summary results for all scenarios are included in the Other Scenarios Modeled section of this report.
- Previous analyses determined that adding 1,686 kW-DC of solar PV, up to the maximum hosting capacity of the site, to the existing SK Monolith PV plants is cost-effective.
- Previous analyses and discussion determined that reciprocating engine generation is needed to meet high reliability needs of microgrid customers.
  - These results determine final rated capacity that when combined with PV and BESS provide high reliability per total investment cost.
  - Generator provides market revenues during non-grid emergencies when wholesale power prices are high.
- Customer generation option is described on a later slide.
- Utilities costs: 5% versus 10% per year cost escalation on wholesale power and natural gas prices.

Selected MCM architecture → Scenario D

Scenario Label	Tech Options	Customer Generation	Engine Generators	Utilities Costs
Scenario A		Yes	(1) 800-kW unit	5% per year
Scenario B		Yes	(1) 266-kW unit	5% per year
Scenario C		No	(2) 800-kW units	5% per year
Scenario D		No	(2) 534-kW units	5% per year
Scenario A’		Yes	(1) 800-kW unit	10% per year
Scenario B’		Yes	(1) 266-kW unit	10% per year
Scenario C’		No	(2) 800-kW units	10% per year
Scenario D’		No	(2) 534-kW units	10% per year

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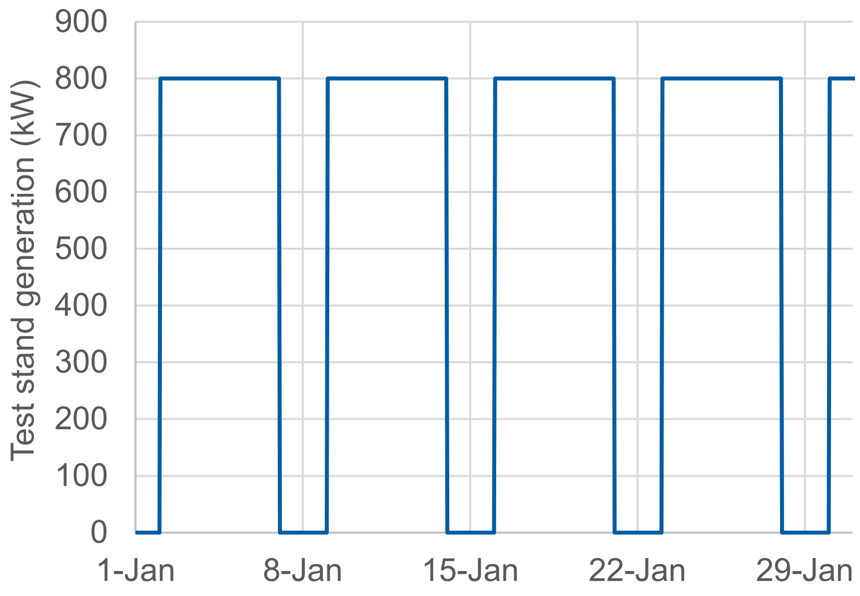
MCM Customer Backup Engine Generator

- One of the identified microgrid customers has 800-kW backup generator capacity.
- The customer has indicated to SK Monolith that this capacity could be included as a possible generation resource for MCM, available 24 hours/day, Monday through Friday.
- The final results presented in the Executive Summary do not assume this potential source of power is utilized. However, it presents both a business and resilience opportunity worth pursuing if an agreement can be reached.
- Some modeled scenarios include this source of power, and the results are described in the Other Modeled Scenarios section of this report:
  - When modeled, the power export is assumed to be 800 kW, 24 hours/day, Monday-Friday.
  - No costs were included in REopt for the supply of this power.
  - The estimated generation profile from the factory's test stand is shown in the figure.



Model, Inputs, and Assumptions

Source of Cost and Performance Inputs

- The concept and configuration analyzed were provided by SK Monolith.
- SK Monolith provided capital and maintenance cost inputs for battery energy storage, solar PV, reciprocating engine generators, and balance of system components. SK Monolith also provided the cost input for natural gas.
- Assumed discount rate, general inflation rate, and electricity and natural gas cost escalation rates were jointly developed by NREL and SK Monolith.
- Additional cost and performance details are provided on the remaining slides in this section.

Economic Parameters and Cost Assumptions

Key Assumptions

Analysis Period	20 years
Technologies Considered	PV, battery storage, natural gas generators
Discount Rate	8.0%
General Inflation Rate	2.5%
Electricity Cost Escalation Rate	0% and 5%
Natural Gas Cost Escalation Rate	0% and 5%
Currency Exchange Rates for Converting Local Currency Wholesale Power Prices to USD	*Wall Street Journal* (https://www.wsj.com/market-data/quotes/fx/UAHUSD/historical-prices) The average daily conversion rate was used for each day's wholesale pricing as described on slide 30.
Natural Gas Cost, Current	$15.36/MMBtu
Tax Rate	0%
Financial Incentives	None
Microgrid Critical Load	50% of nominal load, 96 hours outage duration

Economic Parameters and Cost Assumptions (cont.)

Key Assumptions

PV Capital Costs	Provided by SK Monolith. See PV detailed slide.
PV O&M Costs	$7.54/kW-DC/year
Reciprocating Engine Generator Capital Costs	$879/kW-net
Reciprocating Engine Generator Non-Fuel O&M	$48.63/kW-net/year
BESS Capital Costs	$455/kW + $227.50/kWh
BESS Useful Life	10 years
BESS Replacement Costs (Year 10)	$357.50/kW + $159.00/kWh
Other Controller, Distribution Investment Costs	$1,778,690. See Other Costs detailed slides.
Other Non-Fuel Annual Operations Costs	$247,680/year. See Other Costs detailed slides.

Capital costs estimates are total installed costs. Additional technical and cost details for each resource are provided on later slides.

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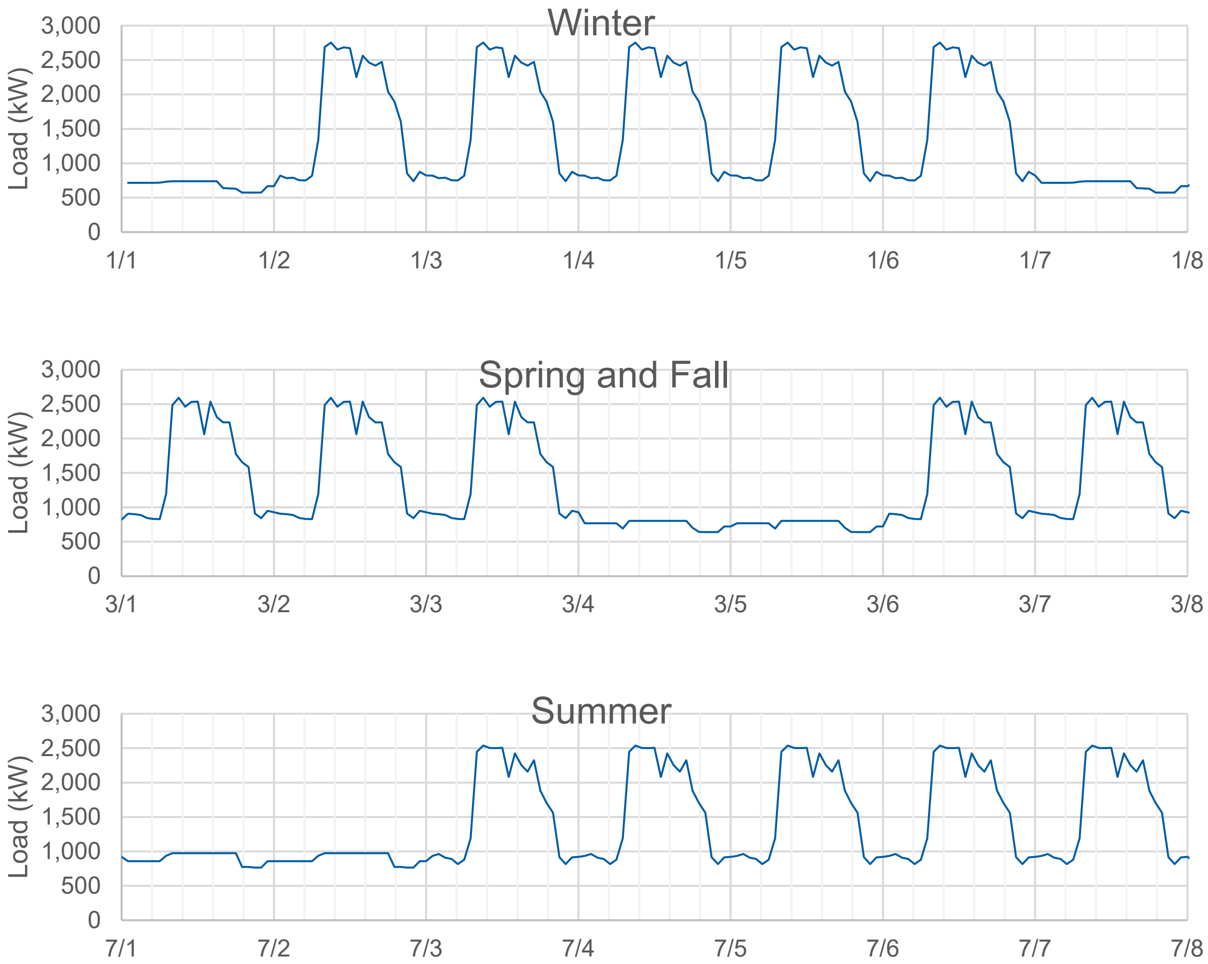
Customer Load Data

- Customers identified and loads estimated by SK Monolith.
- Typical 24-hour load profile provided for weekday and weekend for each season.
- Typical year profile generated.
- This is the gross estimated load; possible self-generation from customers is not included.



Loads	Value
Annual Consumption (MWh)	12,197
Average Demand (kW)	1,392
Maximum Demand (kW)	2,754
Minimum Demand (kW)	575

Existing and Under-Development Solar PV Systems

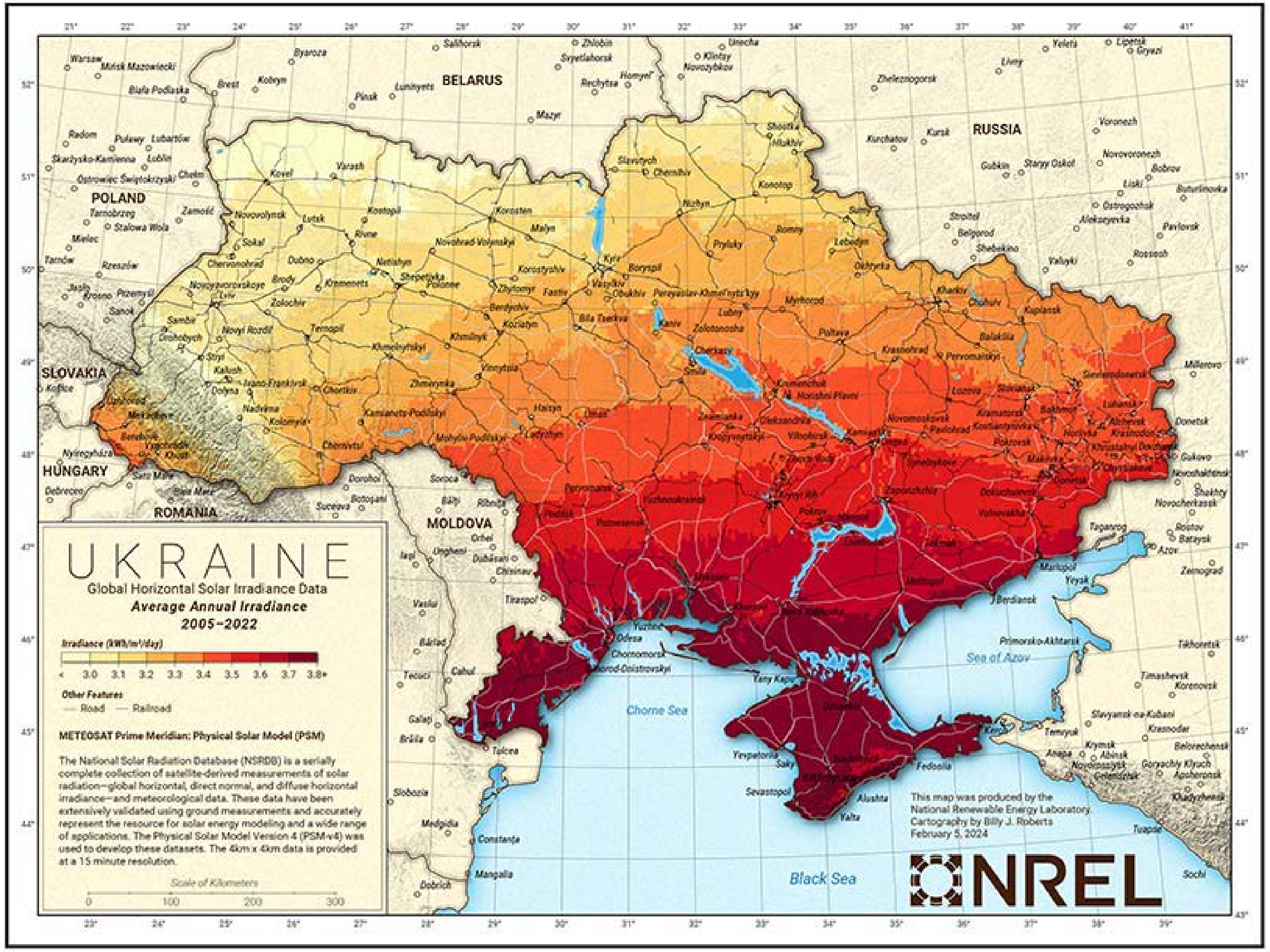
- Existing and under-development PV systems sizes and costs are provided by SK Monolith.
- Analysis results include additional PV. See Executive Summary.
- Systems PV1, PV2, and Ocean Solar are already built. PV1 was hit by an Iskander missile and is operating currently at about 70% of rated capacity. Ocean Solar is a behind-the-meter rooftop system on an MCM customer's roof.
- The initial capital costs for PV1, PV2, and Ocean Solar are considered sunk costs and therefore are not included in the economic analysis; however, PV1 in the model is assumed to be restored to full functionality, and the costs for repair are included in the analysis.
- O&M costs for PV1, PV2, PV3, PV4 are assumed to be $7.50/kW-DC.
  - PV maintenance costs estimated by NREL using REopt default and applying a factor representing the ratio of MCM PV CAPEX estimates to REopt PV CAPEX default, in $/kW-DC.
  - O&M costs for Ocean Solar PV are $0 in the model.

System	Capacity (kW-AC)	Capacity (kW-DC)	CAPEX ($)
PV1	2,010	2,368	$222,720*
PV2	240	270	$0
PV3	800	996	$720,000
PV4	560	680	$525,000
Ocean Solar	50	60	$0
Total	3,660	4,374	$1,199,720

*Estimated cost to repair

Solar Resource

- PV system power output is estimated for each hour of 1 year using NREL's System Advisor Model, PVWatts® module, and a weather data file for Merefa, Ukraine, from 2019.
- NREL's National Solar Resource Database has solar resource data for Ukraine from 2005 through 2022.
- 2019 data and NREL's System Advisor Model's PVWatts solar PV performance module were used to estimate the hourly available power generation of MCM plants.



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Reciprocating Engine Generators

- SK Monolith provided the data sheet for one potential generator model for estimating costs and performance in REopt:
  - 532 kW gross power
  - 504.5 kW power net of generator loads
  - 1,310 kW-fuel consumption.
- Fueled with natural gas; fuel cost provided by Monolith.
- Modeled fuel consumption rate 38.5% equivalent efficiency on net capacity at full rated power.
- NREL estimated average efficiency of 36.2% used in REopt.
- Total CAPEX estimate $2,262,000 per SK Monolith.
- Assume marginal CAPEX $879/kW:
  - Using total costs and net power capacity provided by SK Monolith.
  - Used for REopt sizing of genset plant.
- Non-fuel O&M:
  - $48.63/kW/year
  - Per Monolith, $12,280 monthly cost and net power rating
  - Assumes 240 hrs/month runtime.

BESS

- CAPEX assumed to be 50% of REopt default BESS costs for U.S. installations. This is consistent with cost estimates provided by SK Monolith and other in-country cost data points.
- O&M costs $7.15/kW-year based on SK Monolith estimate for staff, materials, and land tax (excludes “self-consumption” item, which is accounted separately in REopt in BESS efficiency parameters).

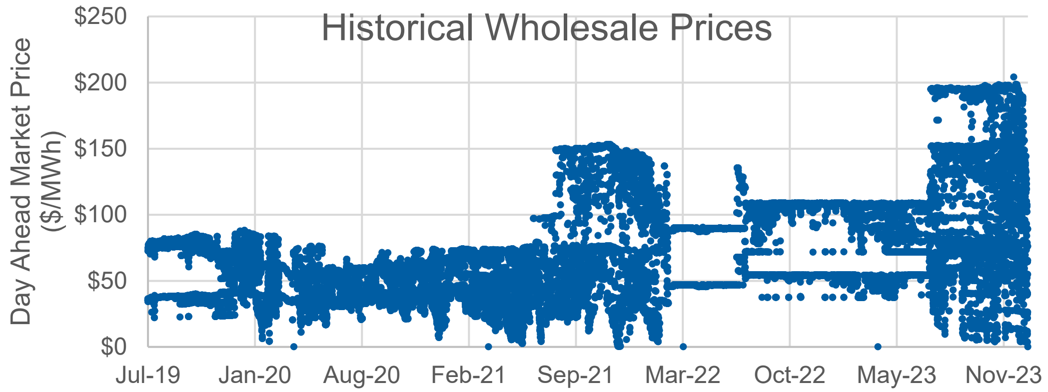
Battery Energy Storage Inputs	Assumptions
Battery Type	Lithium-ion
AC-AC Round-Trip Efficiency	89.9% (includes inverter and rectifier efficiencies of 94.8%)
Initial State of Charge	50%
Minimum State of Charge	20%
Capital Costs	$455.00/kW + $227.50/kWh
Replacement Costs (Year 10)	$357.50/kW + $159.00/kWh

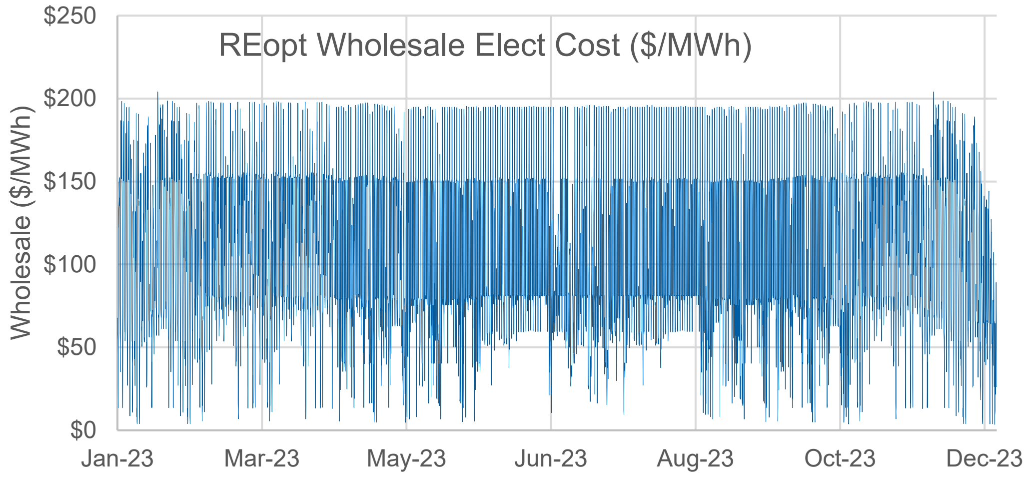
Other Costs for Microgrid Development and Operation

- Costs provided by SK Monolith.
- $1,778,690 microgrid fixed investment costs:
  - $1,191,190 distribution total installed cost
  - $305,500 control system total installed cost
  - $282,000 design and legal.
- Annual fixed microgrid operations:
  - $247,680 per year:
    - SK Monolith estimated $8,130/month for top-level control systems.
    - SK Monolith estimated $12,510/month for microgrid and metering system.
  - $2,993,094 present value of 20-year total, assuming inflation.

Wholesale Power Prices

- MCM can procure and sell excess generation to the wholesale market.
- The costs for buying and selling power are assumed to be the same.
- Historical day-ahead market pricing for Ukraine power market is shown in the top figure from July 2019 through December 2023.
- In the analysis, more-recent pricing is assumed to persist as the baseline; market prices from July 1 through December 31, 2023. Pricing in the model for January through June is filled in using July through December prices. See bottom figure.
- Ukraine market pricing: https://www.oree.com.ua/index.php/graphs_trading?lang=English.
- Ukraine day-ahead market prices in the local currency are converted to USD using daily exchange rates published by *Wall Street Journal*: https://www.wsj.com/market-data/quotes/fx/UAHUSD/historical-prices.





Other Scenarios Modeled: Summary of Results Informing Final Conceptual Design Development

Results Table for All Scenarios

- MCM selected scenario is highlighted in gray box.
- All solutions include 6,060 kW-DC of solar PV.
- No compensation for customer's 800-kW generation is included in model results.

	Scenario				Results								
	Label	Customer Gen. (kW)	MCM Gen. (kW)	Utility Costs	Cost of Service LCC ($M)	BESS (kW)	BESS (hrs)	Survival Probability**	CAPEX* ($M)	Operational Expenditure Non-Fuel LCC ($M)	Natural Gas LCC ($M)	Market Purchases LCC ($M)	Market Sales LCC ($M)
	A	800	(1) 800	5%	$11.42	2,447	4.0	98.2%	$9.63	$4.20	$4.25	$5.81	-$12.47
	B	800	(1) 266	5%	$11.14	2,447	4.0	87.6%	$9.18	$3.90	$1.42	$6.21	-$9.56
	C	0	(2) 800	5%	$20.13	2,447	4.0	98.1%	$10.29	$4.64	$8.51	$8.83	-$12.15
Selected conceptual design →	D	0	(2) 534	5%	$19.84	2,447	4.0	86.9%	$9.85	$4.35	$5.68	$9.22	-$9.26
	A'	800	(1) 800	10%	$9.57	2,754	4.8	98.5%	$10.92	$4.22	$6.88	$9.94	-$22.40
	B'	800	(1) 266	10%	$9.57	2,754	4.8	90.2%	$10.47	$3.93	$2.29	$10.37	-$17.49
	C'	0	(2) 800	10%	$22.96	2,754	4.8	98.5%	$11.59	$4.67	$13.76	$14.54	-$21.61
	D'	0	(2) 534	10%	$22.95	2,754	4.8	90.1%	$11.14	$4.37	$9.18	$14.97	-$16.71

* CAPEX includes an assumed cost for BESS replacement in Year 10, discounted to Year 0.
** Cumulative probability of serving customer critical load for 4-day outage.

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Results Table for All Scenarios (cont.)

Levelized cost of service is the minimum viable tariff, if it was an energy-only scheme, needed for MCM to recover all costs from customers and earn an 8% return.

Scenario				Results								
Label	Customer Gen. (kW)	MCM Gen. (kW)	Utility Costs	Cost of Service LCC ($M)	BESS (kW)	BESS (hrs)	Survival Probability**	CAPEX* ($M)	Operational Expenditure Non-Fuel LCC ($M)	Natural Gas LCC ($M)	Market Purchases LCC ($M)	Market Sales LCC ($M)
A	800	(1) 800	5%	$11.42	2,447	4.0	98.2%	$9.63	$4.20	$4.25	$5.81	-$12.47
B	800	(1) 266	5%	$11.14	2,447	4.0	87.6%	$9.18	$3.90	$1.42	$6.21	-$9.56
C	0	(2) 800	5%	$20.13	2,447	4.0	98.1%	$10.29	$4.64	$8.51	$8.83	-$12.15
D	0	(2) 534	5%	$19.84	2,447	4.0	86.9%	$9.85	$4.35	$5.68	$9.22	-$9.26
A'	800	(1) 800	10%	$9.57	2,754	4.8	98.5%	$10.92	$4.22	$6.88	$9.94	-$22.40
B'	800	(1) 266	10%	$9.57	2,754	4.8	90.2%	$10.47	$3.93	$2.29	$10.37	-$17.49
C'	0	(2) 800	10%	$22.96	2,754	4.8	98.5%	$11.59	$4.67	$13.76	$14.54	-$21.61
D'	0	(2) 534	10%	$22.95	2,754	4.8	90.1%	$11.14	$4.37	$9.18	$14.97	-$16.71

Selected conceptual design → D

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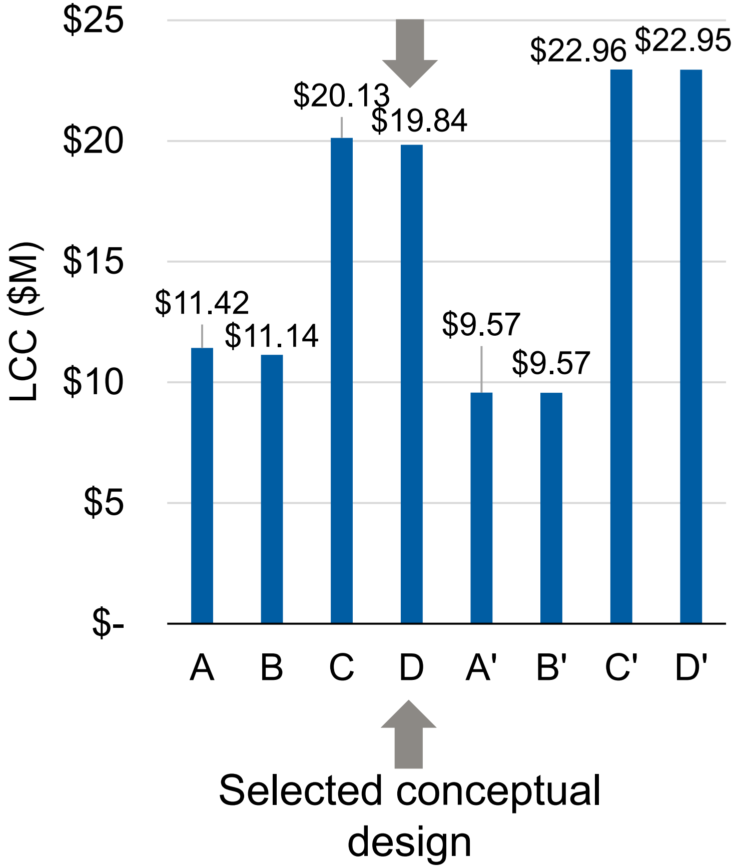
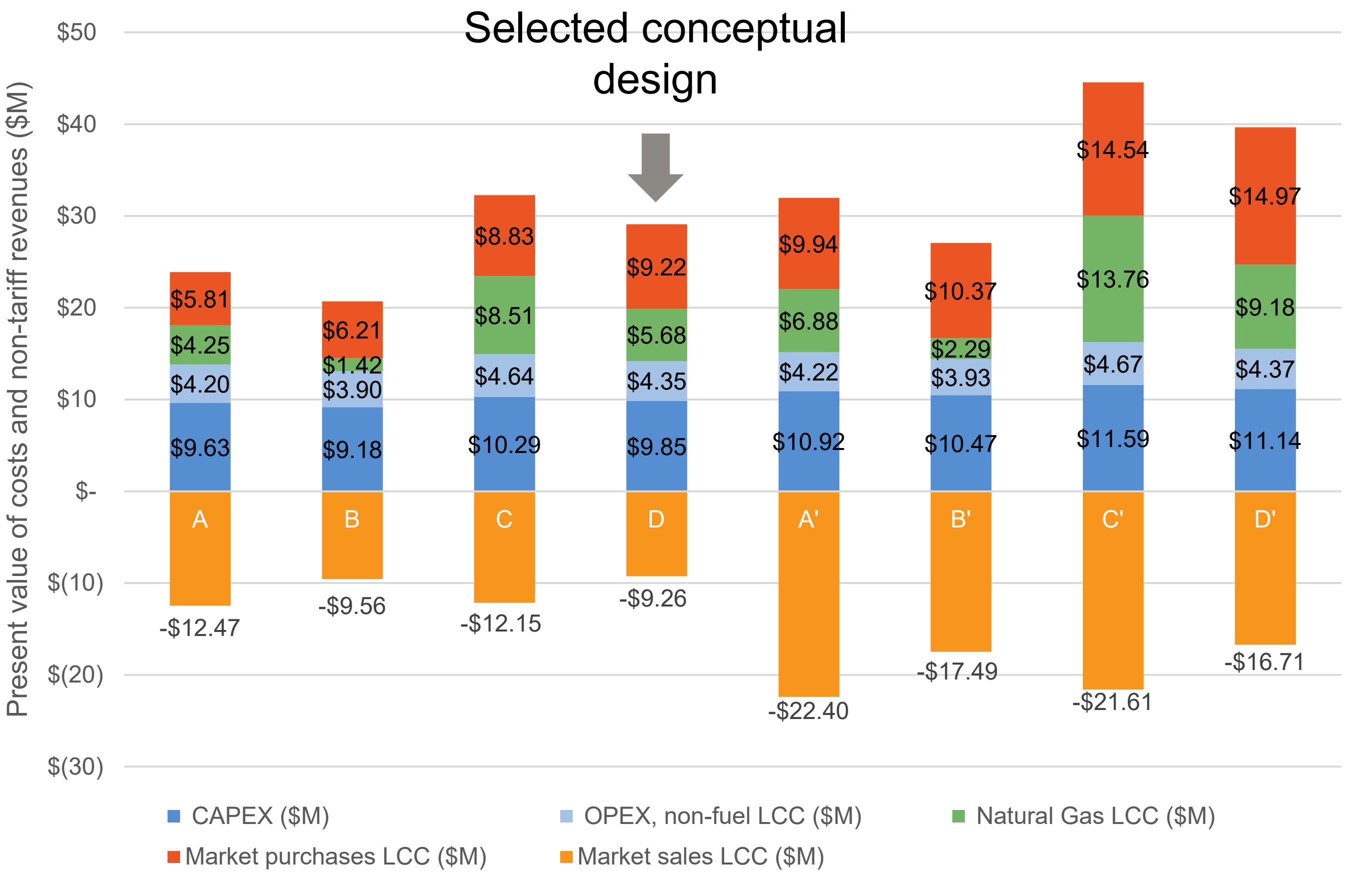
Cost of Service Results Graph for All Scenarios





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Appendix: Reliability Analysis Methods and Assumptions, Microgrid Sequence of Operations, and REopt Model Overview

Reliability Analysis Method and Assumptions

- In addition to the economics for serving MCM loads, 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.

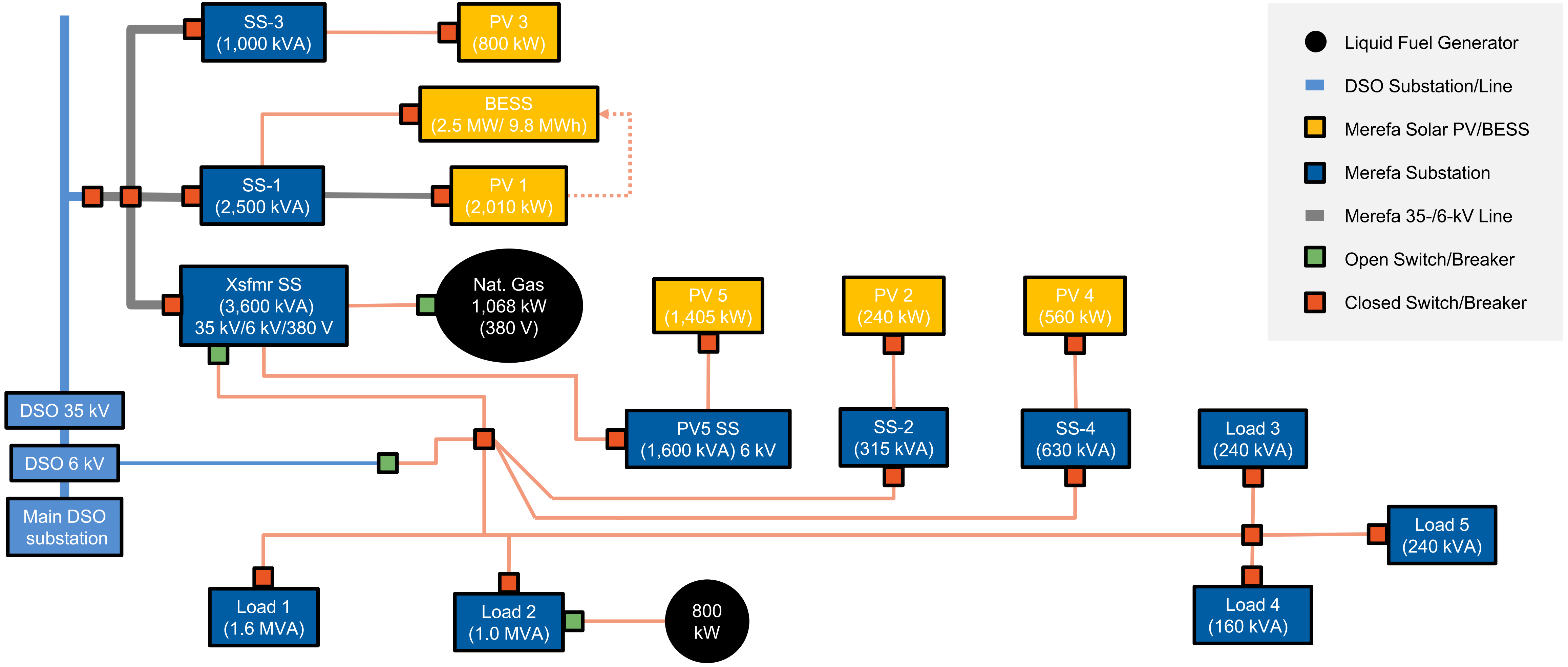
Microgrid Control Sequence of Operations

Microgrid Control Sequence of Operation

- The next 14 slides graphically illustrate the conceptual sequence of operations that the microgrid could employ when power is lost on the local distribution system.
- These slides illustrate the sequence of operations described on slide 16.
- The slides are intended to illustrate how the microgrid will respond, through a sequence of actions, to loss of local grid power:
  - Sense outage and then electrically isolate, or ‘island’, from the utility grid
  - ‘Form’ the microgrid by establishing voltage and frequency using microgrid assets
  - Energize MCM customer loads in a prioritized fashion
  - Monitor and manage loads and generation to keep power balanced
  - Return to normal grid-connected mode once power on the utility grid is restored

Step 0: Proposed Utility-Tied Configuration: DSO Supplies 35 kV and 6 kV via 35-kV Merefa/SK Monolith Line

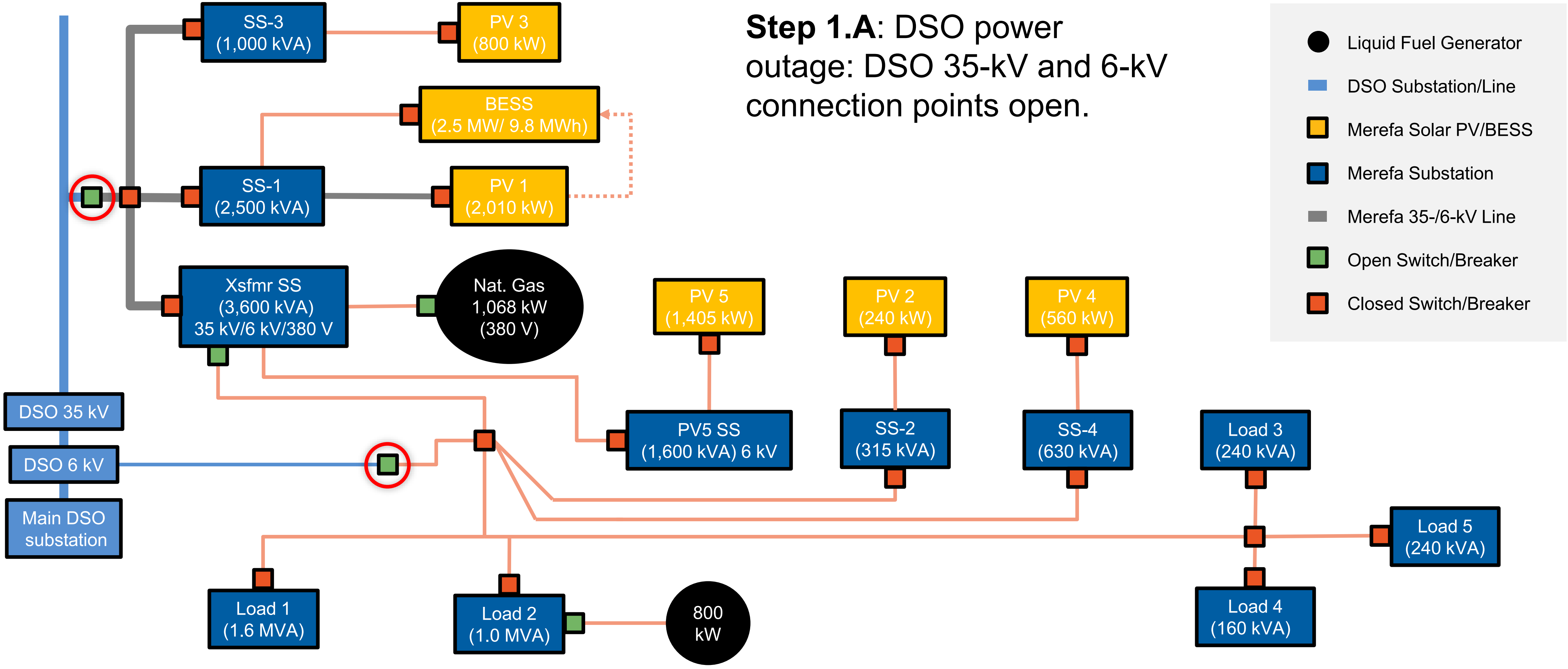
MG = Microgrid	
MG Gen Capacity	0 MW
MG Max Load	0 MW



Step 1.A: DSO Utility Outage:
DSO Distribution/Generation Outage

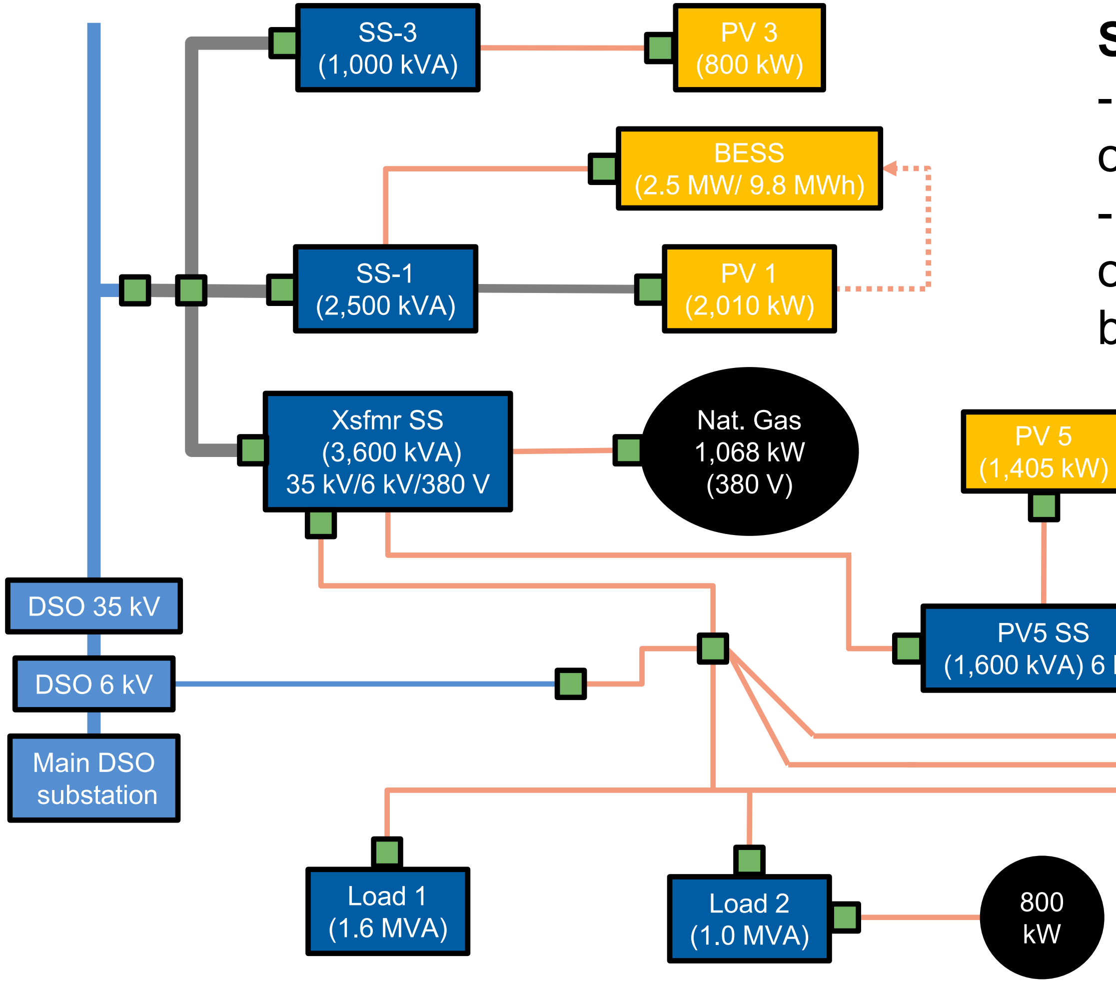
MG = Microgrid	
MG Gen Capacity	0 MW
MG Max Load	0 MW

Step 1.A: DSO power outage: DSO 35-kV and 6-kV connection points open.



Step 1.B: DSO Utility Outage: All Breakers Trip/Open Upon Utility Loss, MCS Opens all Breakers and Confirms Separation From DSO

MG = Microgrid	
MG Gen Capacity	0 MW
MG Max Load	0 MW



Step 1.B: DSO power outage:
- All breakers open upon loss of utility.
- MCS verifies loss of utility, opens all controlled breakers/switches.

Liquid Fuel Generator
DSO Substation/Line
Merefa Solar PV/BESS
Merefa Substation
Merefa 35-/6-kV Line
Open Switch/Breaker
Closed Switch/Breaker

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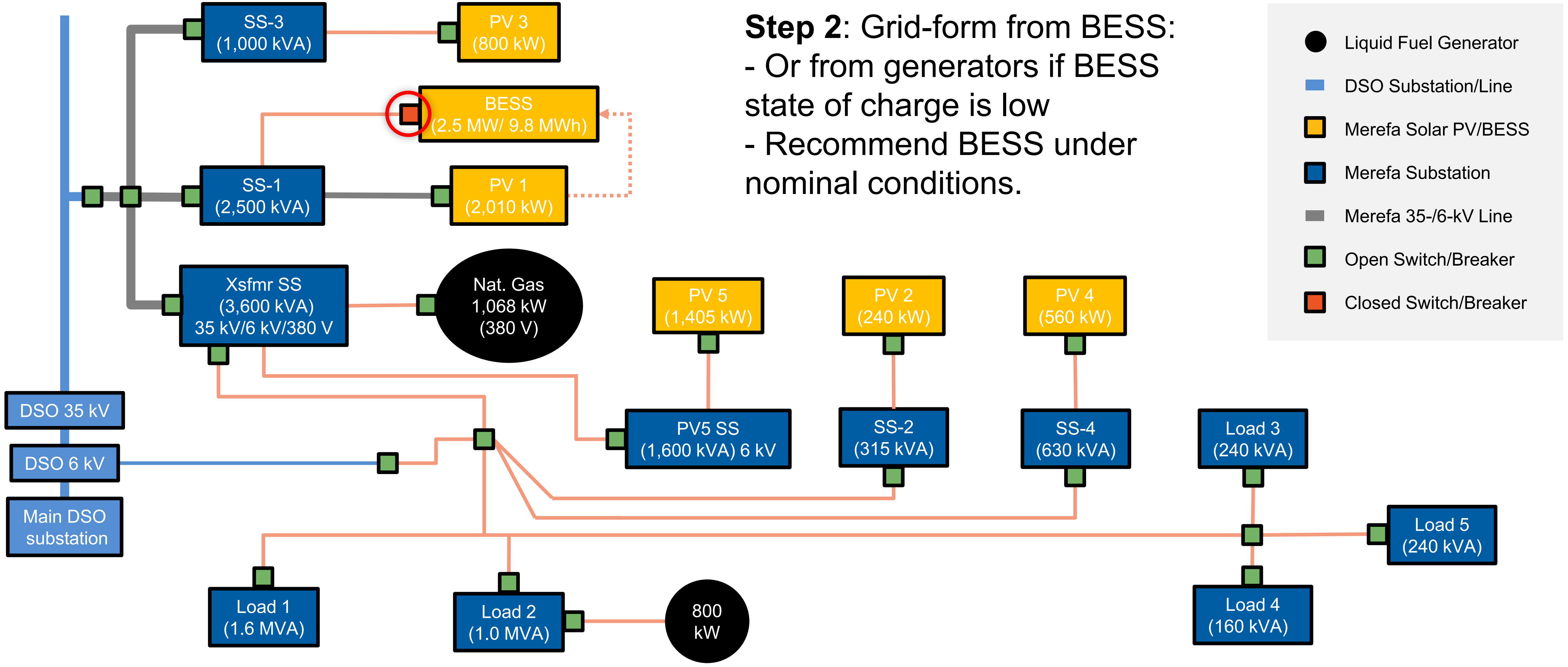
Step 2: Form Merefa Microgrid:
Grid-Form From BESS or Natural Gas Generators

MG = Microgrid	
MG Gen Capacity	2.5 MW
MG Max Load	0 MW



Step 2: Grid-form from BESS:
- Or from generators if BESS state of charge is low
- Recommend BESS under nominal conditions.

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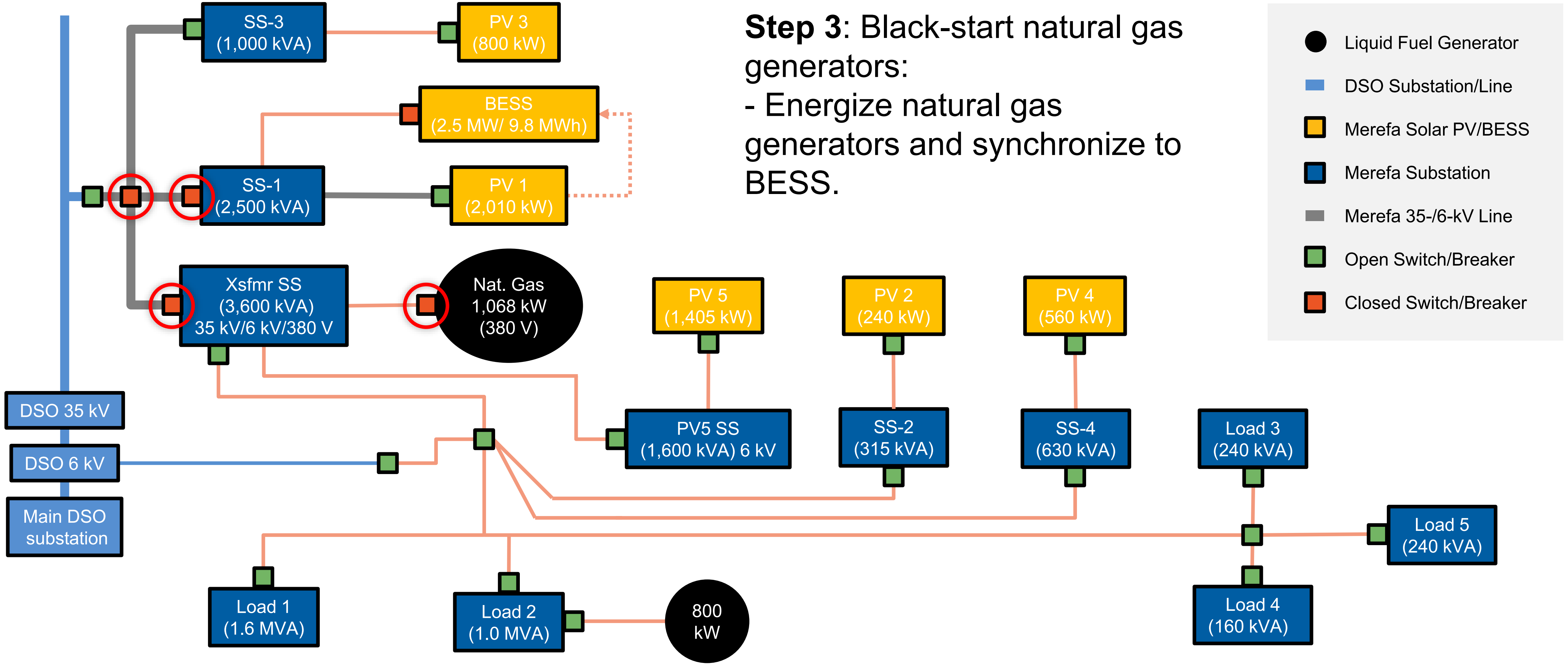
Step 3: Form Merefa Microgrid: Grid-Form From BESS or Natural Gas Generators

MG = Microgrid	
MG Gen Capacity	3.6 MW
MG Max Load	0 MW



Step 3: Black-start natural gas generators:
- Energize natural gas generators and synchronize to BESS.

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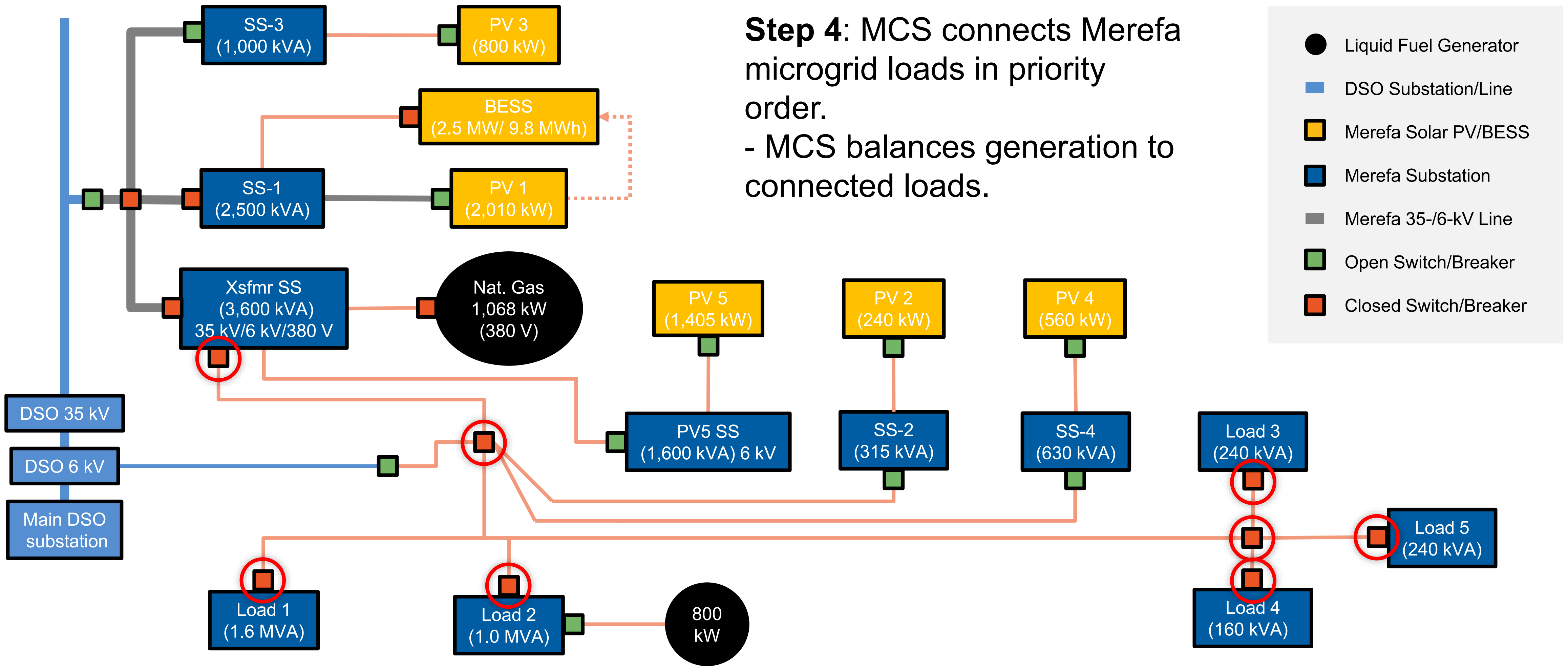
Step 4: Energize Merefa Microgrid:
Connect Merefa Microgrid Loads and Balance System

MG = Microgrid	
MG Gen Capacity	3.6 MW
MG Max Load	1.5 MW

Step 4: MCS connects Merefa microgrid loads in priority order.
- MCS balances generation to connected loads.



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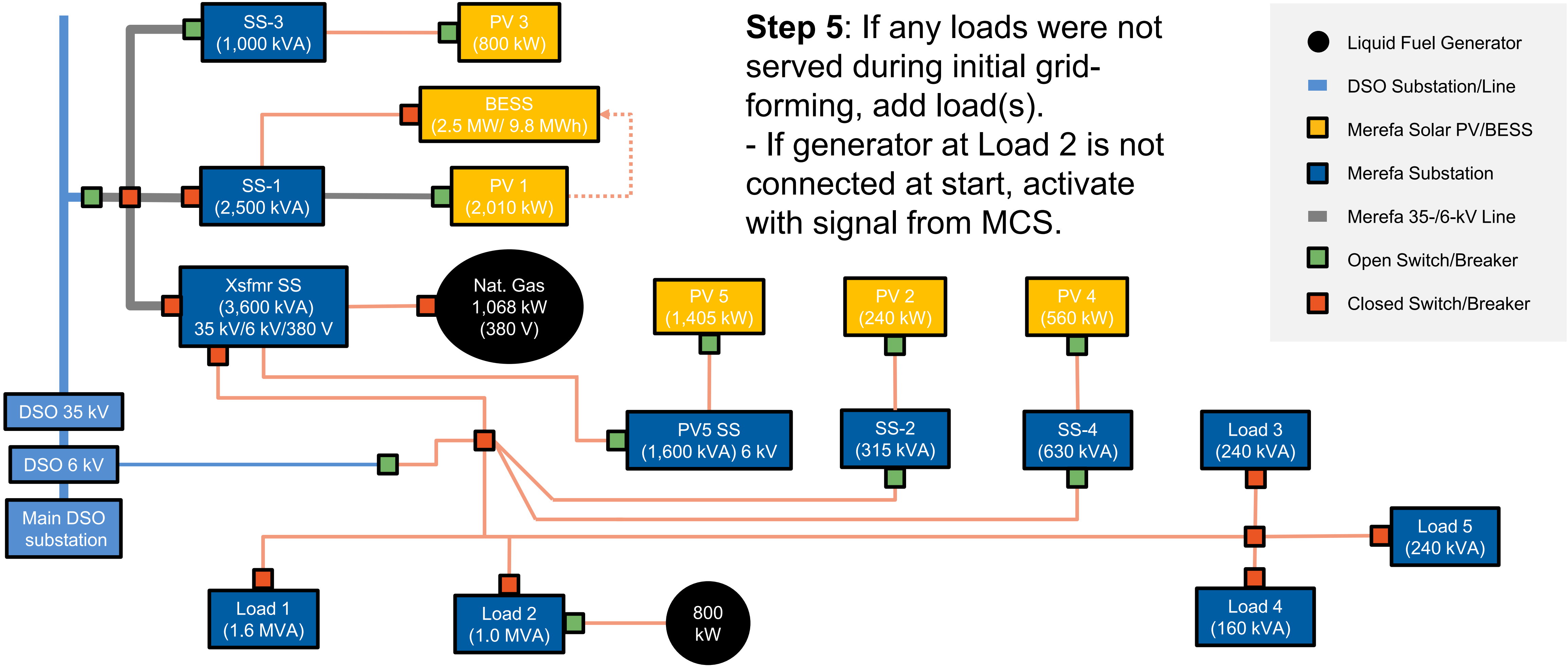
Step 5: Energize Remaining loads as Desired if any Loads Were Not Connected During Initial Grid-Forming

MG = Microgrid	
MG Gen Capacity	3.6 MW
MG Max Load	1.5 MW

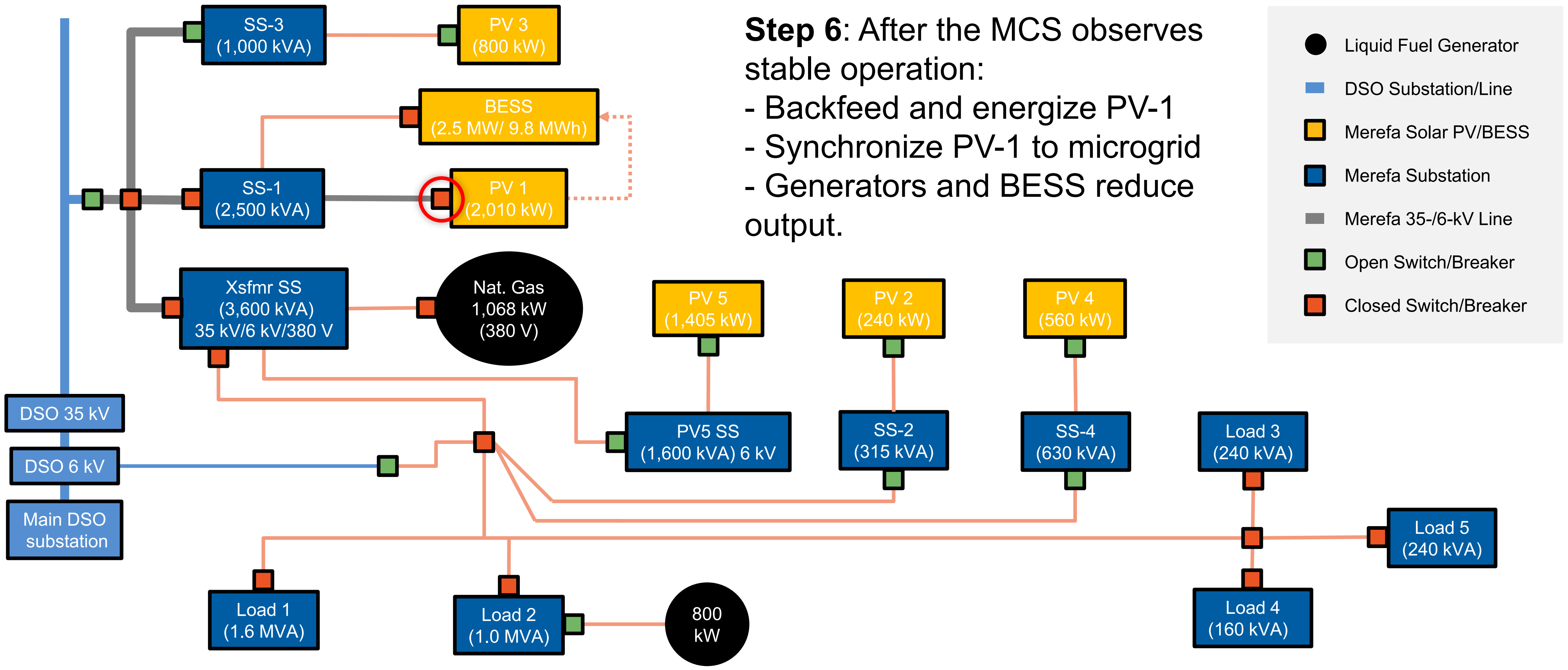
Step 5: If any loads were not served during initial grid-forming, add load(s).
- If generator at Load 2 is not connected at start, activate with signal from MCS.



Step 6: Energize PV-1: After Observing Stable Microgrid operation, Backfeed, Energize, Synchronize PV-1

MG = Microgrid	
MG Gen Capacity	3.6 MW
MG Max Load	1.5 MW

Step 6: After the MCS observes stable operation:
- Backfeed and energize PV-1
- Synchronize PV-1 to microgrid
- Generators and BESS reduce output.



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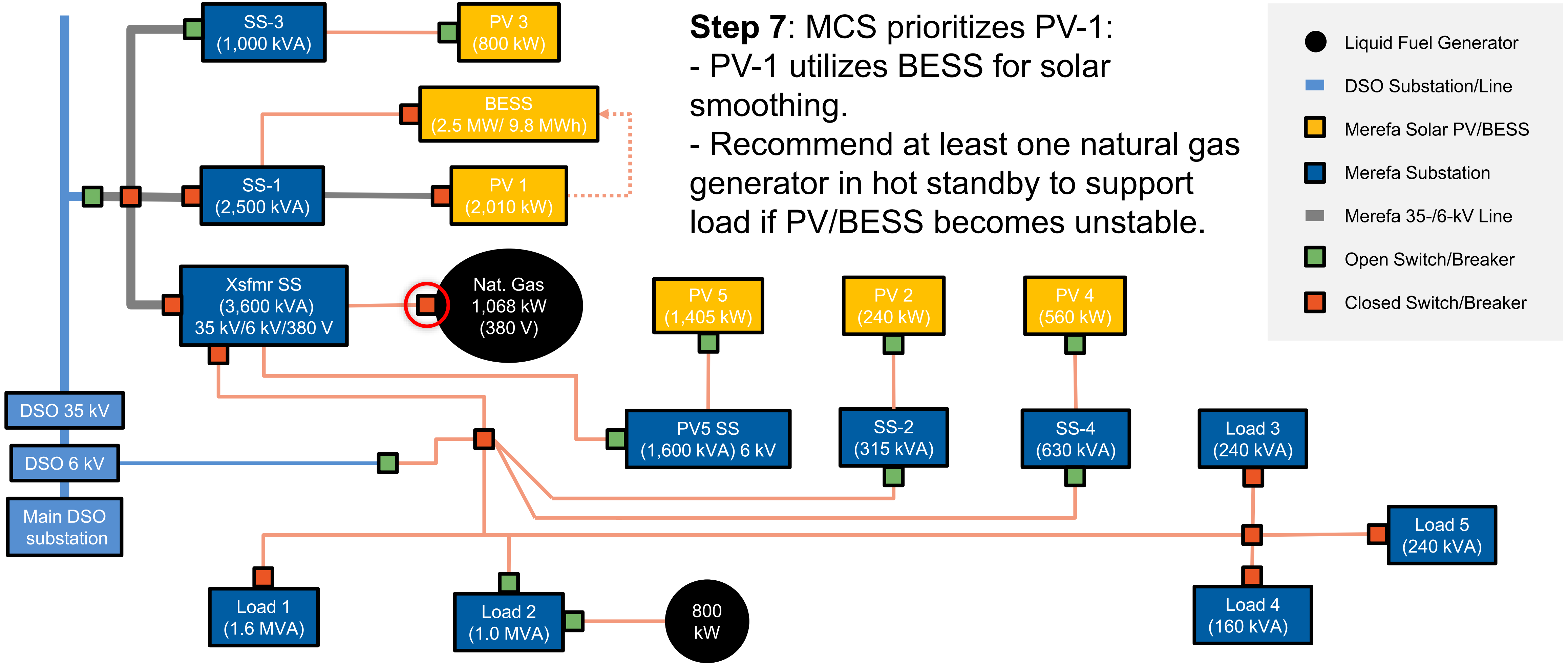
Step 7: MCS Prioritizes PV-1 Output: PV-1 Utilizes BESS for Solar Smoothing

MG = Microgrid	
MG Gen Capacity	3.6 MW
MG Max Load	1.5 MW

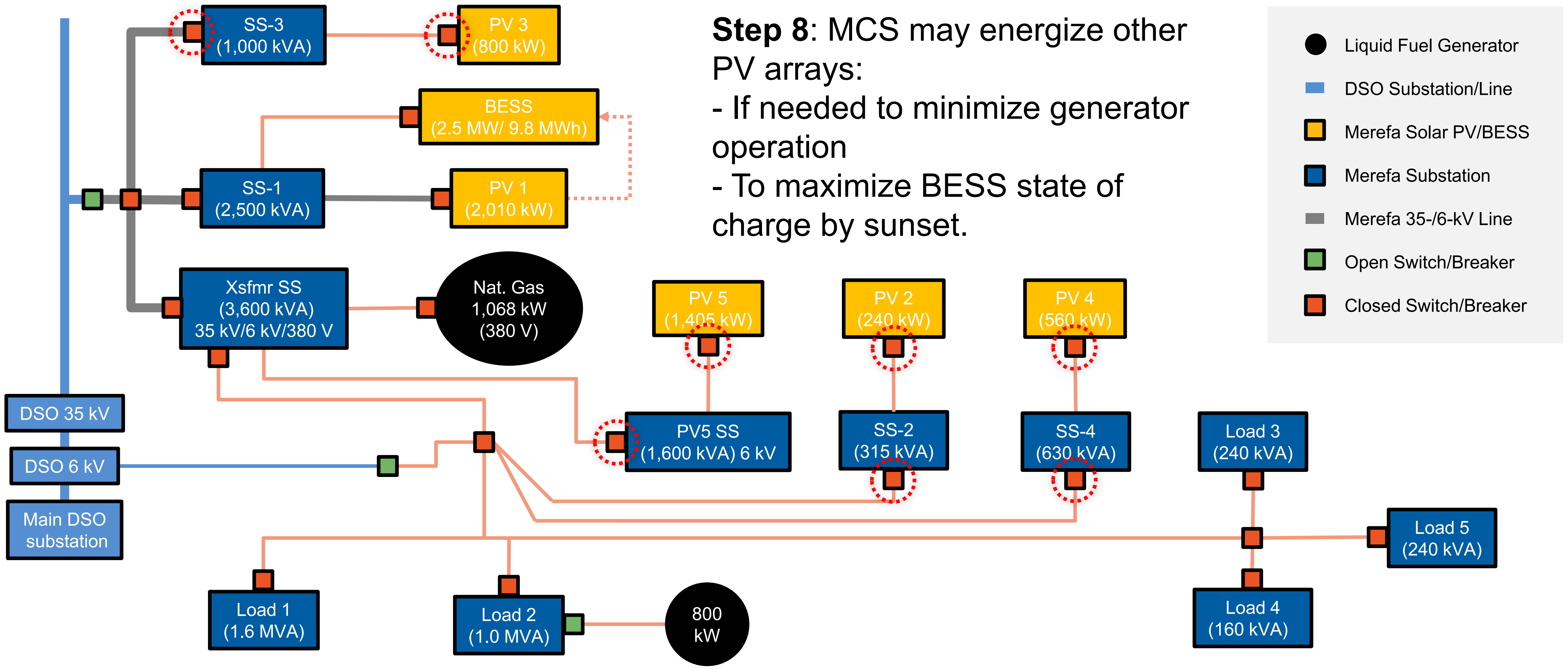


Step 7: MCS prioritizes PV-1:
- PV-1 utilizes BESS for solar smoothing.
- Recommend at least one natural gas generator in hot standby to support load if PV/BESS becomes unstable.

Step 8: MCS May Energize Other PV Arrays if Needed to Minimize Generator Use and Maximize BESS Charge by Sunset

MG = Microgrid	
MG Gen Capacity	8.6 MW
MG Max Load	1.5 MW

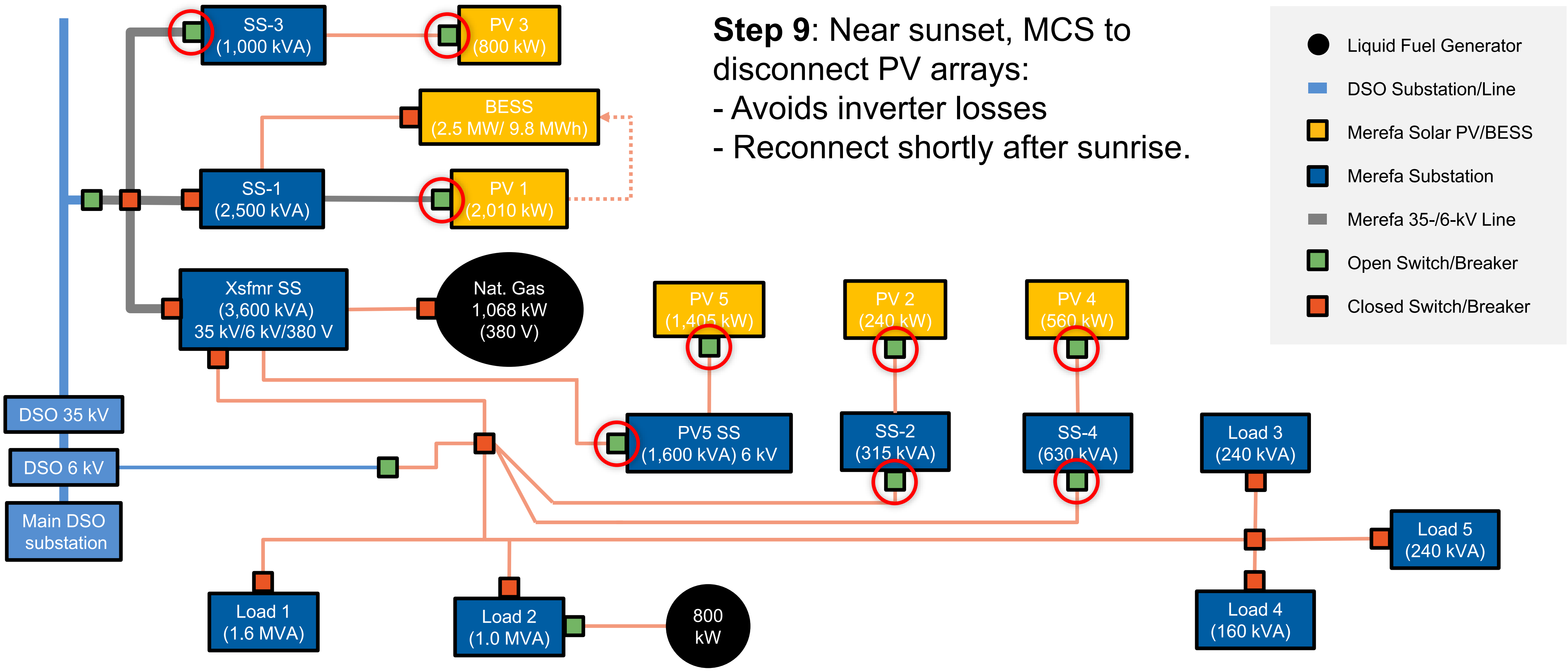
Step 8: MCS may energize other PV arrays:
- If needed to minimize generator operation
- To maximize BESS state of charge by sunset.



Step 9: MCS To Disconnect PV Arrays Near Sunset To Limit Inverter Losses Overnight

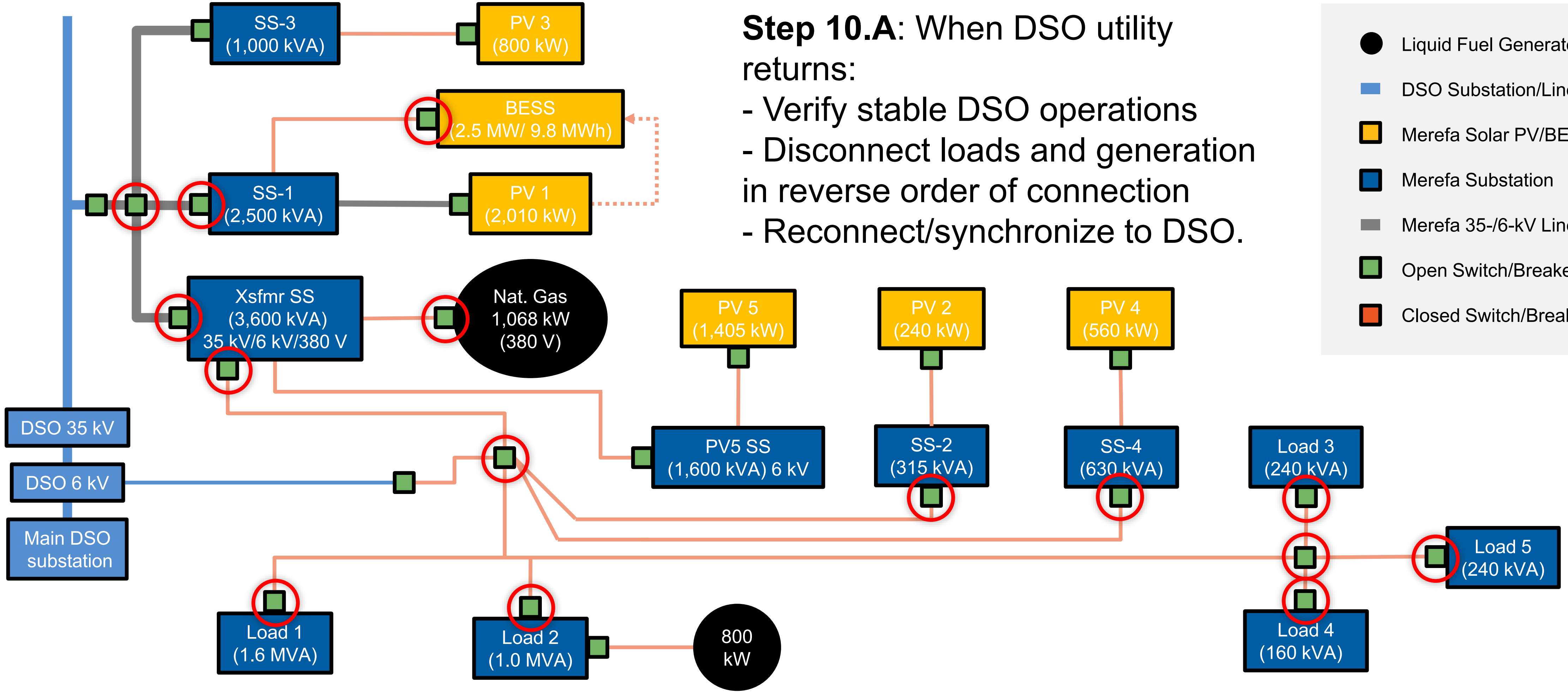
MG = Microgrid	
MG Gen Capacity	3.6 MW
MG Max Load	1.5 MW

Step 9: Near sunset, MCS to disconnect PV arrays:
- Avoids inverter losses
- Reconnect shortly after sunrise.



Step 10.A: If MCS or Supervisory Control and Data Acquisition Detects Return of Utility, Reverse Microgrid-Forming Sequence To Return to DSO

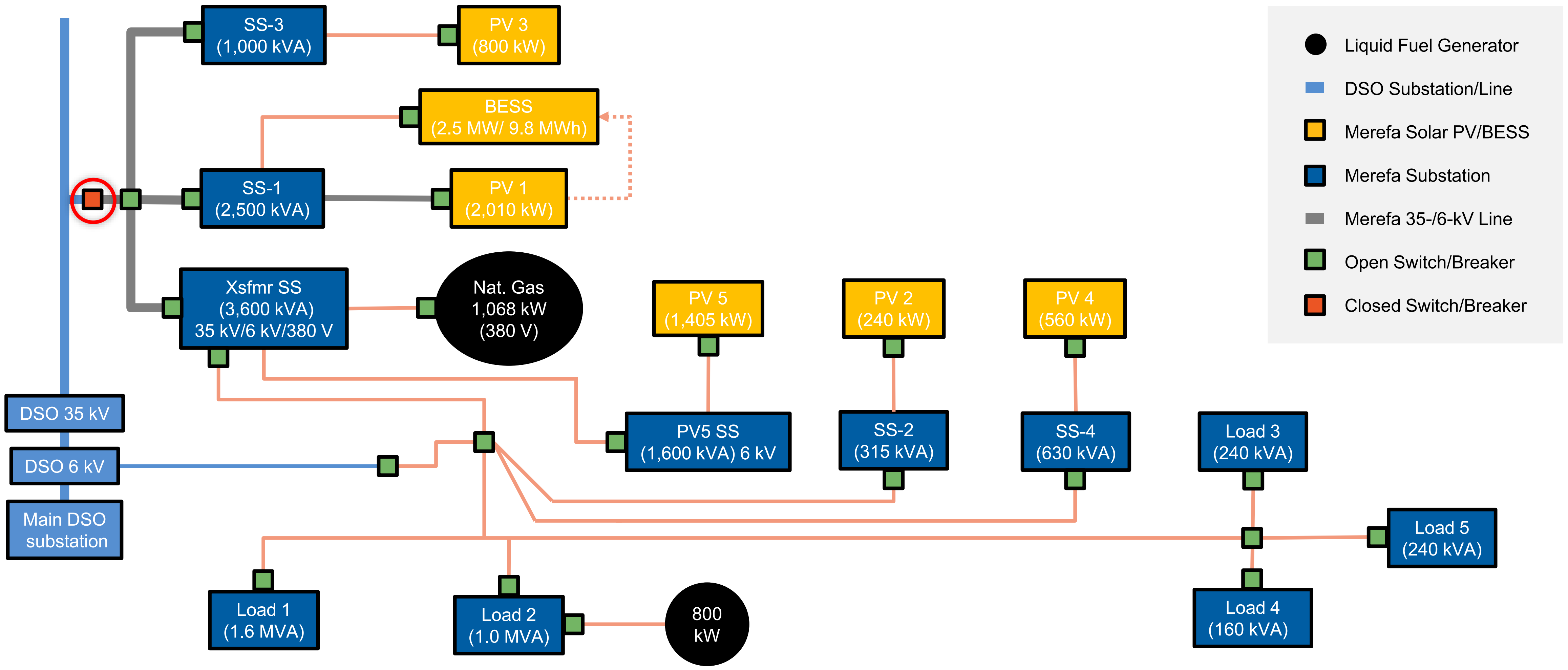
MG = Microgrid	
MG Gen Capacity	0 MW
MG Max Load	0 MW



Step 10.A: When DSO utility returns:
- Verify stable DSO operations
- Disconnect loads and generation in reverse order of connection
- Reconnect/synchronize to DSO.

MG = Microgrid	
MG Gen Capacity	0 MW
MG Max Load	0 MW

Step 10.B: Reconnect to DSO Utility Service



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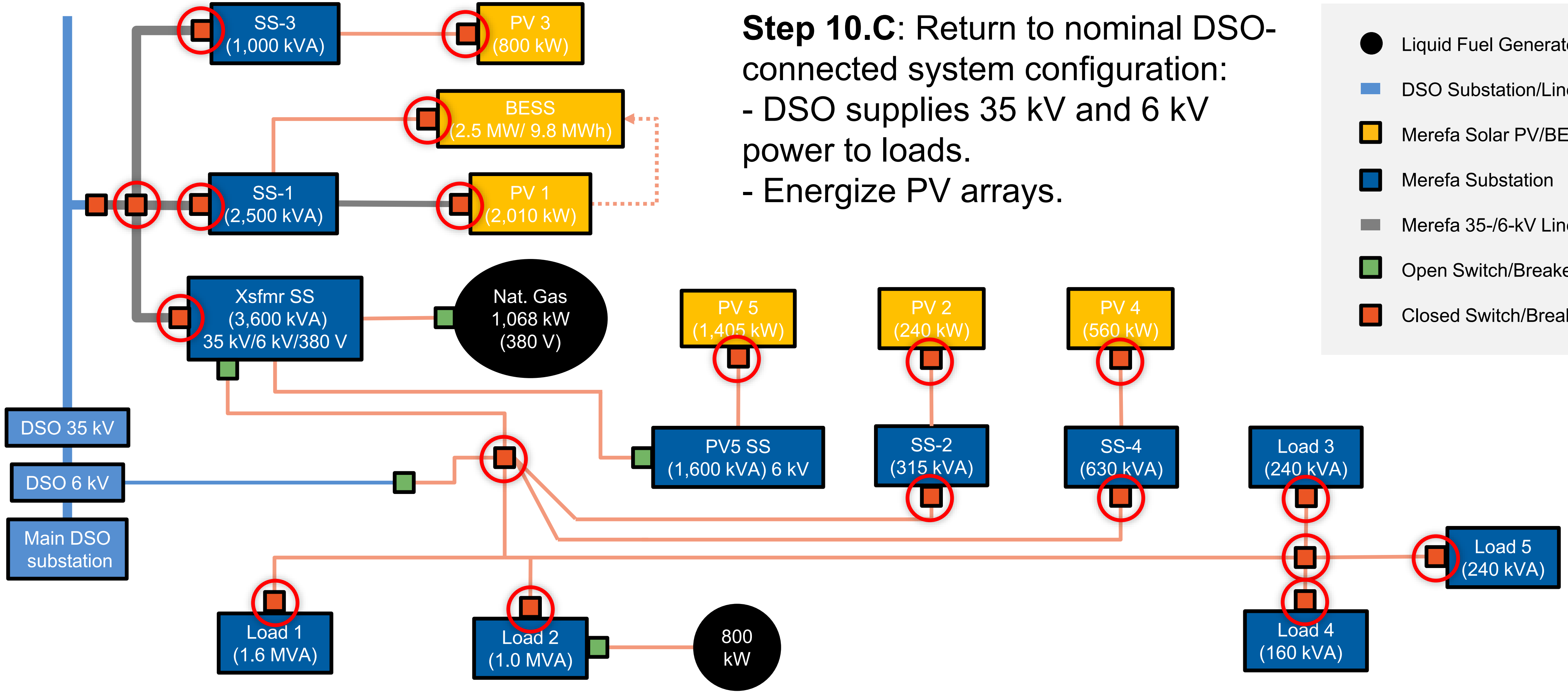
Step 10.C: Return to DSO Utility Service, Nominal Configuration

MG = Microgrid	
MG Gen Capacity	0 MW
MG Max Load	0 MW



Step 10.C: Return to nominal DSO-connected system configuration:
- DSO supplies 35 kV and 6 kV power to loads.
- Energize PV arrays.

- Liquid Fuel Generator
- DSO Substation/Line
- Merefa Solar PV/BESS
- Merefa Substation
- Merefa 35-/6-kV Line
- Open Switch/Breaker
- Closed Switch/Breaker

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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 LCC of electricity for the grid-connected microgrid over the planning horizon.

LCC = Wholesale Power Costs − Wholesale Market Revenue + Capital Costs + Operating Costs + Fuel Costs

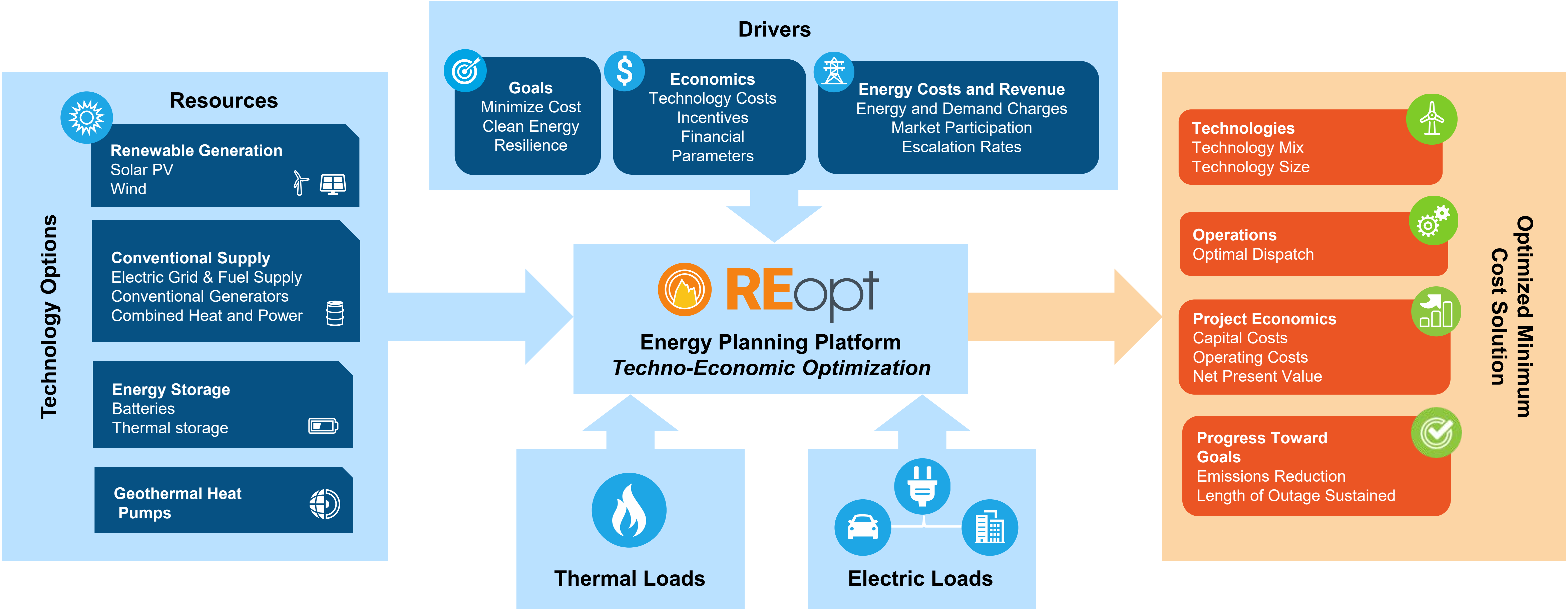
Decision variables: (1) Installed capacity of solar, batteries, and natural gas generators; and (2) economic dispatch of each technology.

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

[1] REopt web tool: reopt.nrel.gov. Open-source REopt codebase: https://github.com/NREL/REopt.jl.

REopt Energy Planning Platform

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



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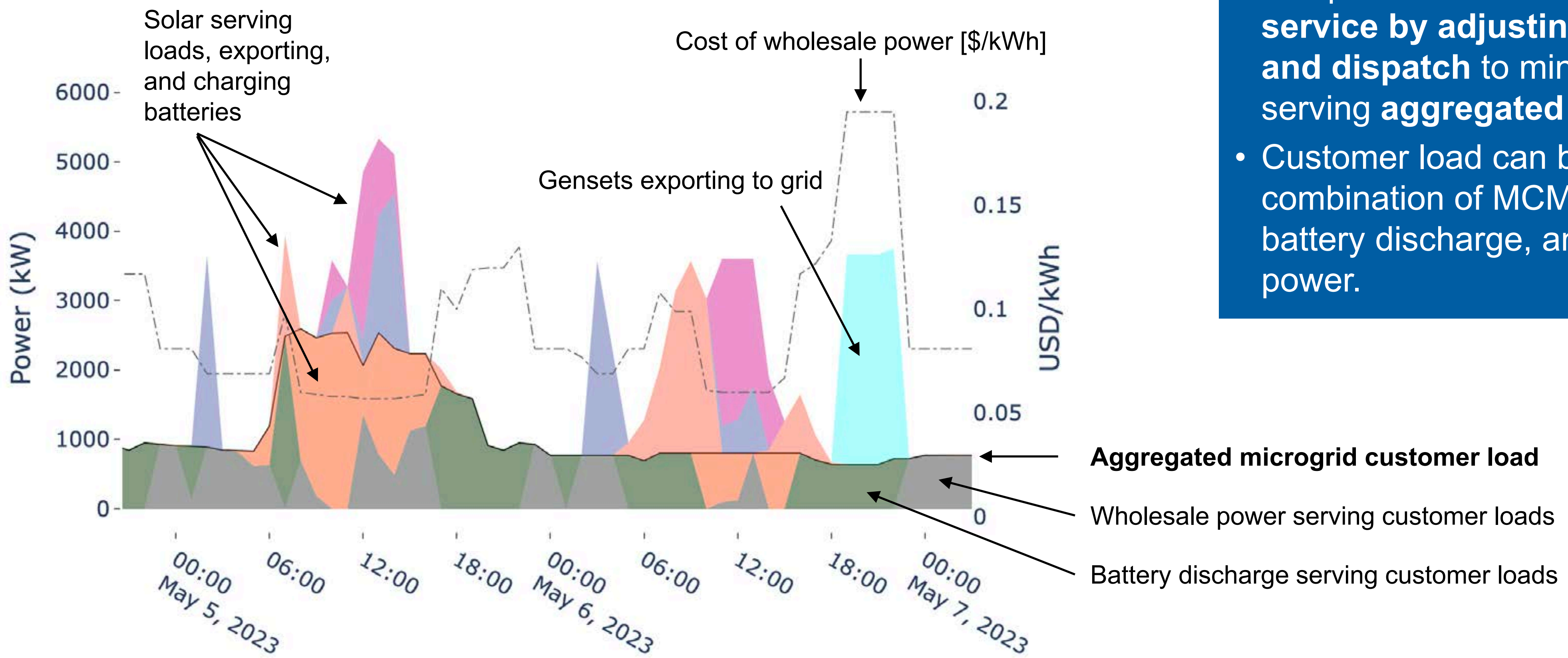
Determining the Lowest-Cost-of-Service System



- REopt finds the **lowest cost of service by adjusting system sizes and dispatch** to minimize LCCs for serving **aggregated customer load.**
- Customer load can be met by a combination of MCM generation, battery discharge, and wholesale power.

Thank you!

Corresponding author: Dan Olis, dan.olis@nrel.gov.

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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 lifecycle 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.