Optimal design & energy management of islanded hybrid microgrids

For isolated communities with no external power exchange

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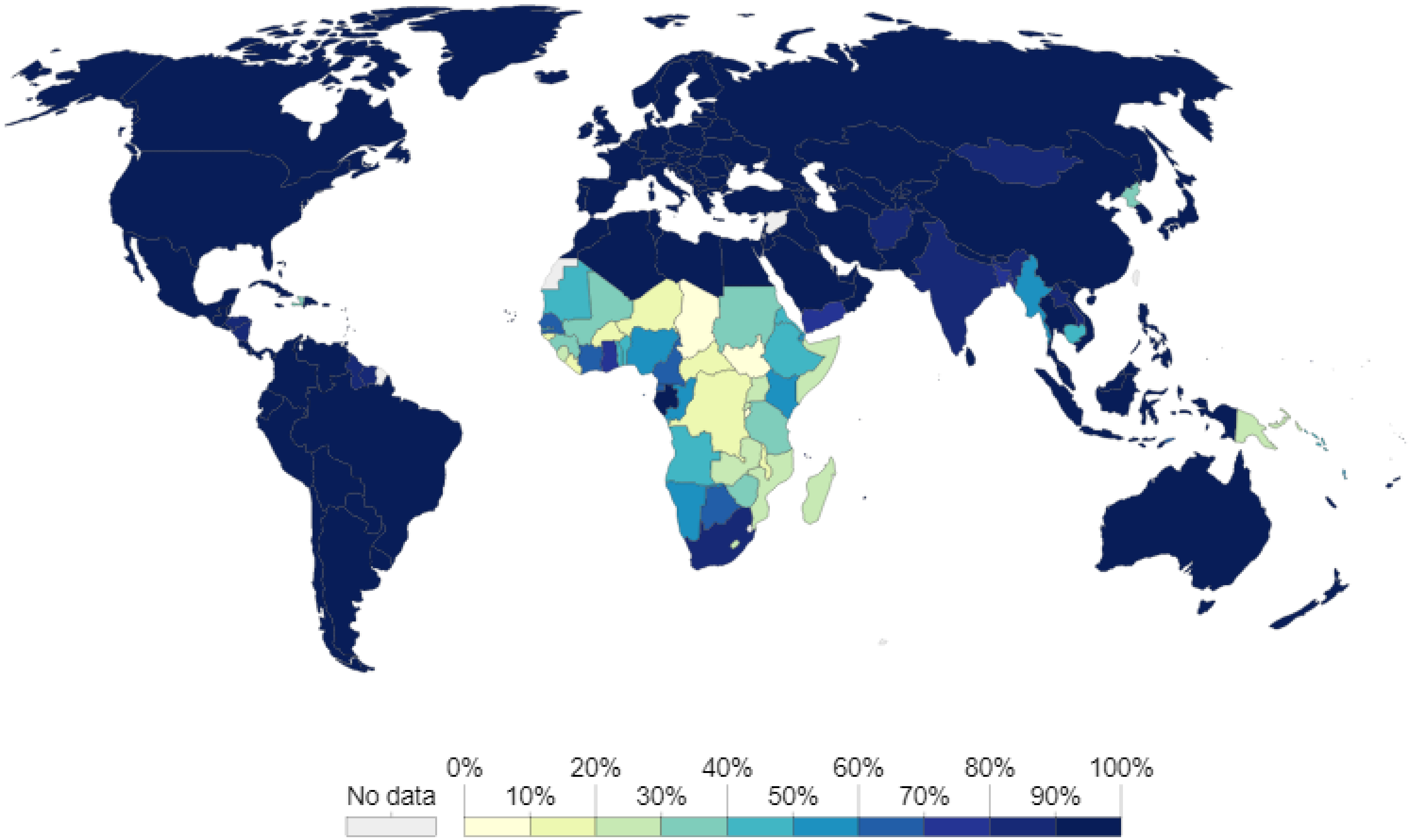
Presentation Outline

- Motivation: Problem statement and solution
- System description
- Methodology
- Selected design and sizing optimization results
- Selected dispatch optimization results
- Conclusions
- Future work: Areas for model improvement
- Appendix

Motivation: Problem statement

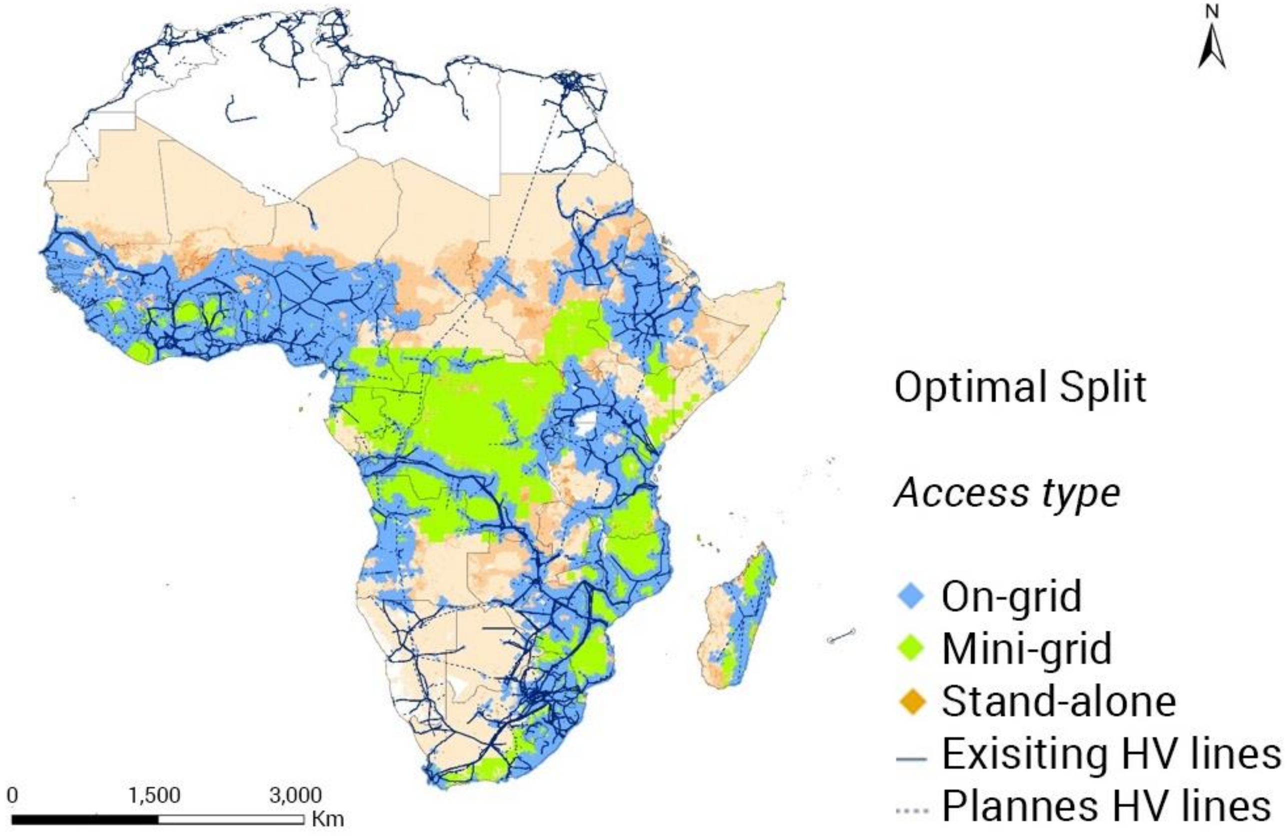
- >1 billion people lack access to electricity
- Remote rural villages located far from traditional 'macrogrids' & large thermal power plants
- High costs of conventional T&D infrastructure
- Other resource-constrained applications



Source: World Bank, Our World in Data

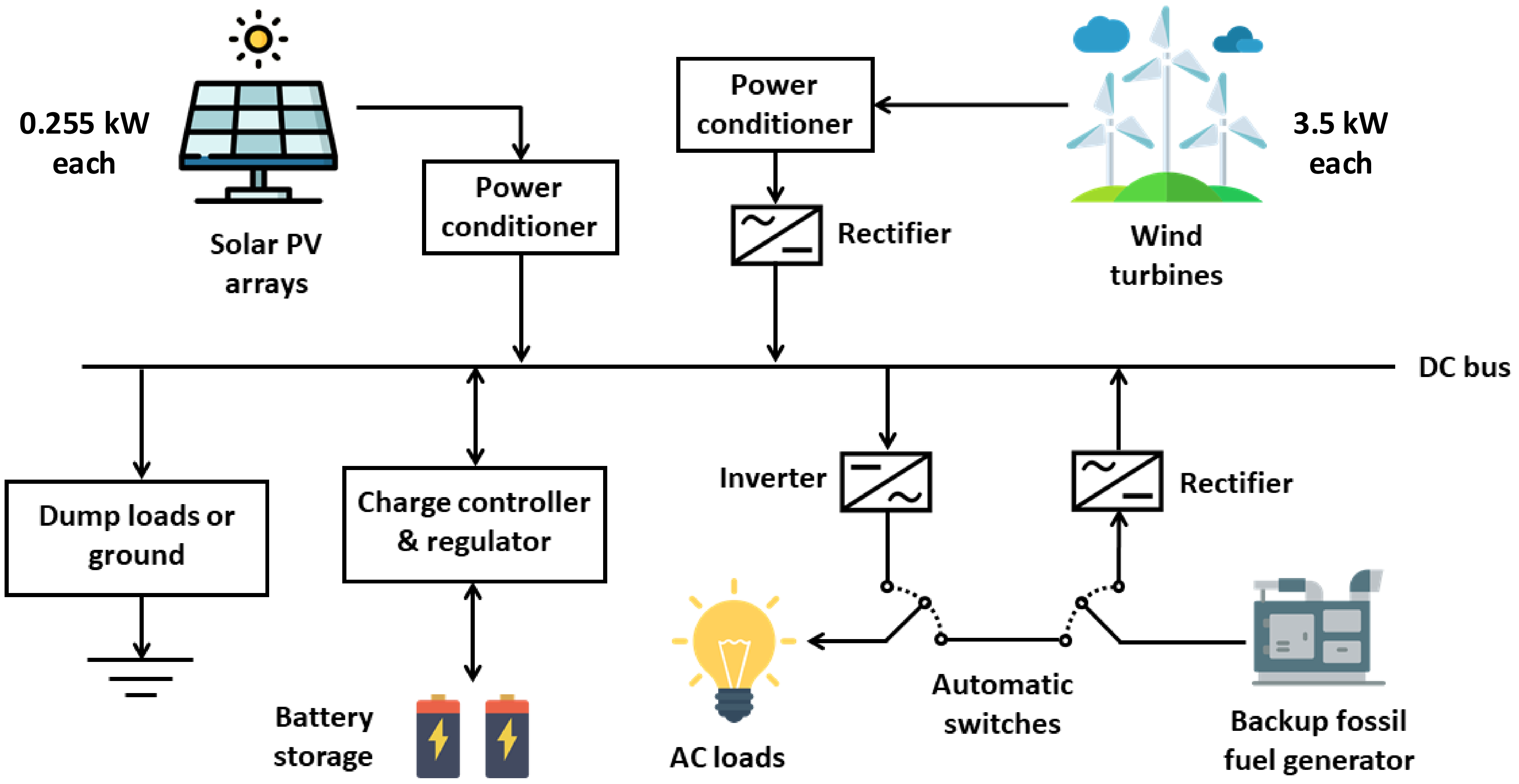
Solution: Microgrids!

- Low-voltage, localized electricity networks that can disconnect from main grid and operate autonomously
- **Advantages**: More resilient, affordable & sustainable
- **Disadvantages**: Stability issues, deal with stochastic supply & demand



Source: United Nations

System description



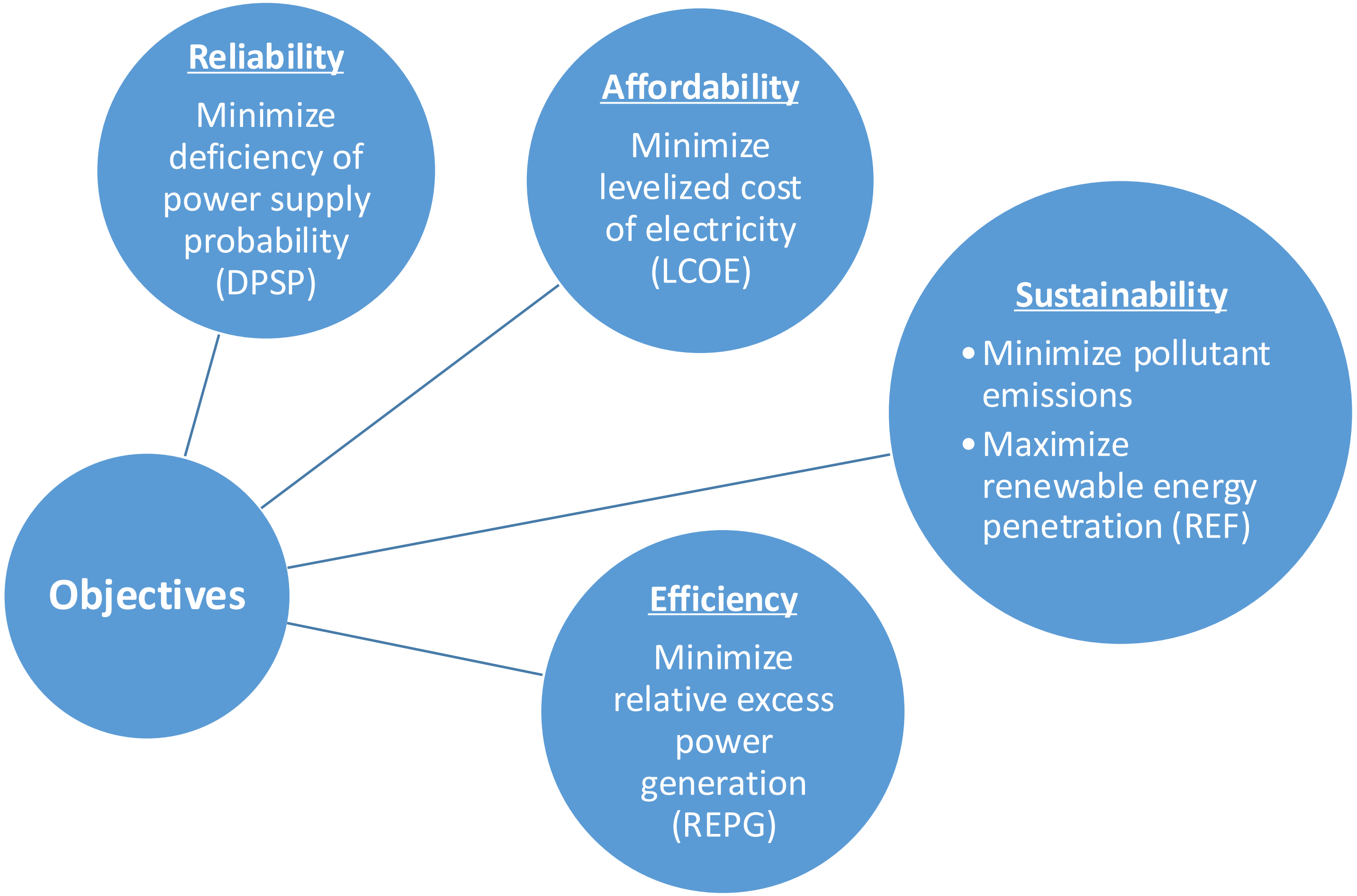
Abbreviations

MG: Microgrid
PV: Solar photovoltaics
WT: Wind turbines
BS: Battery storage
RES: Renewable energy sources
DG: Fossil-fuel distributed generator (for backup)
DE: Diesel engines
MT: Micro gas turbines
LI: Lithium-ion battery
LA: Lead-acid battery

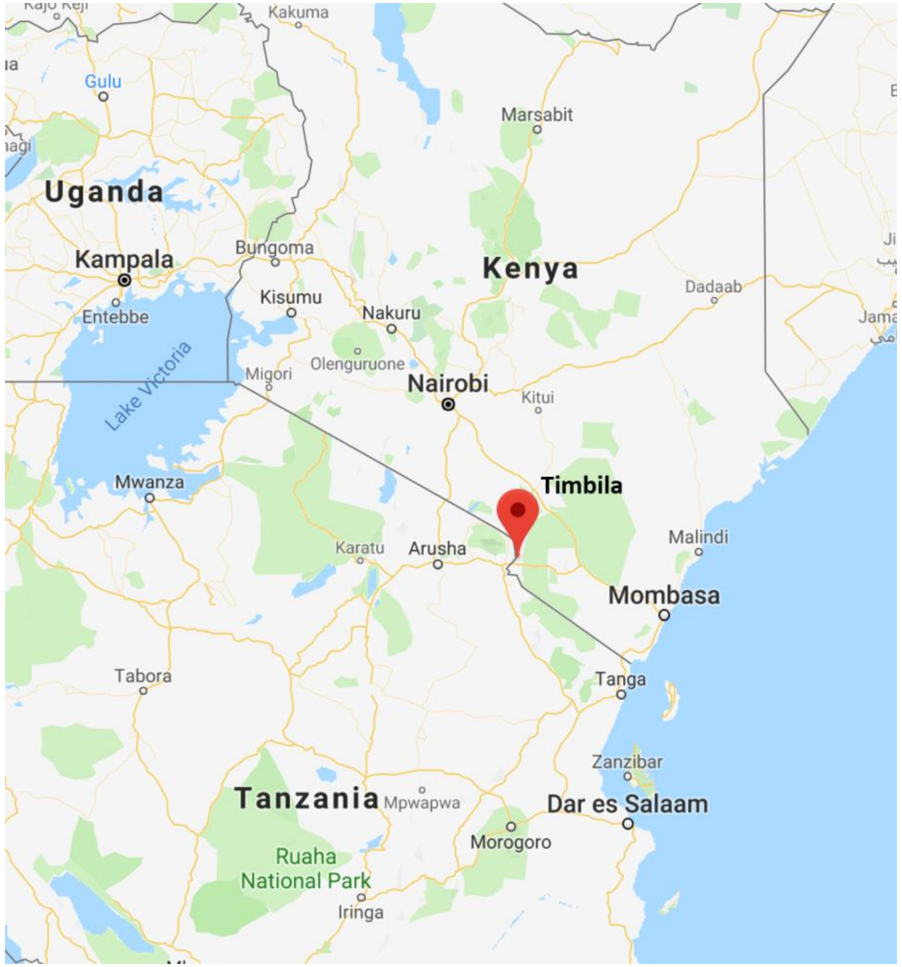
Methodology

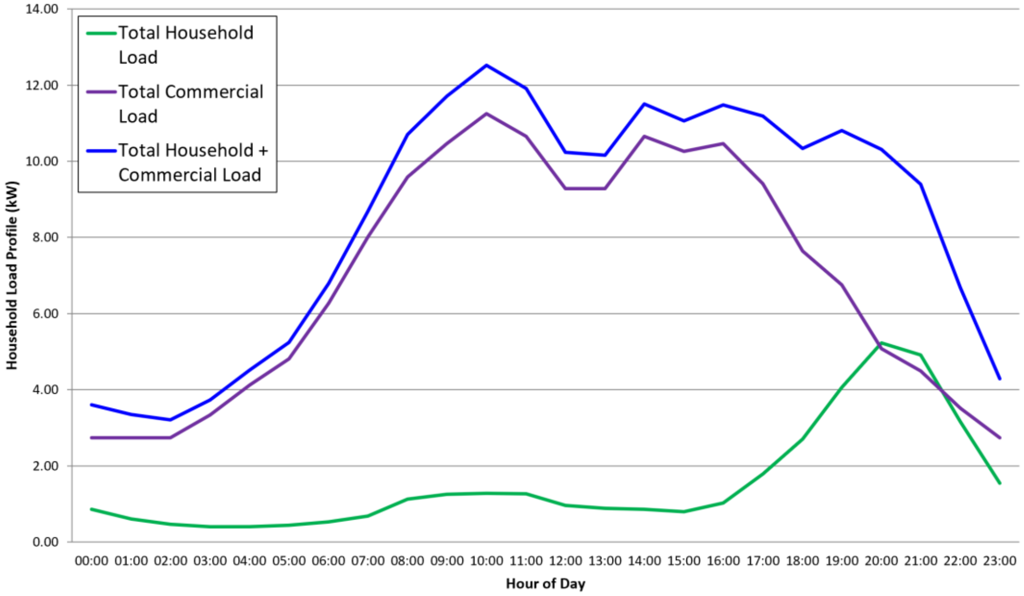
- Weighted multi-objective, multi-period, constrained optimization
- Assumed perfect foresight over climate (solar irradiance, wind speed, temperature) & load data
- LCOE & emissions normalized w.r.t baseline MG running only on fossil-fuelled DG

Parameter	DE system	MT system
LCOE [$\$/kWh$]	0.4968	0.3321
Emissions [kg of pollutants/y]	50,189	48,562
Emissions [kg of pollutants/kWh]	0.6774	0.6555



MG location





Number of households	100
% of high income households	33%
% of medium income households	33%
% of low income households	33%
Number of water pumping operations	6
Number of milling operations	4
Number of small shops	10
Number of schools	1
Number of clinics	3
Number of street lights	30

Methodology: Sizing and design optimization

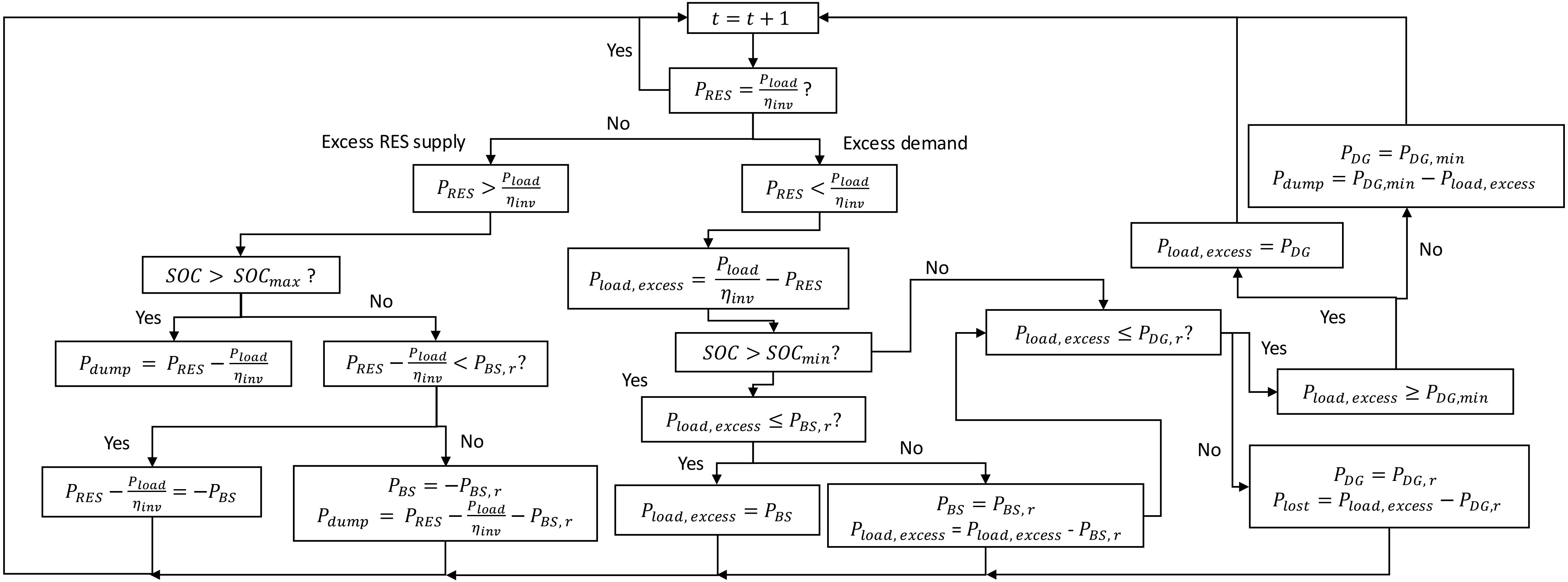
- Determine optimal capacities of solar PV, wind power and battery storage
  - For fixed backup generation capacity
- Simulated MG using hourly time-steps over 1-year period
- Weighted multi-objective function

$$\min_{n_s,\, n_w,\, E_{b,\, init}} w_1 \cdot \frac{LCOE}{LCOE_{base}} + w_2 \cdot \frac{Em}{Em_{base}} + w_3 \cdot DPSP + w_4 \cdot REPG + w_5 \cdot (1 - REF)$$

$$w_1 + w_2 + w_3 + w_4 + w_5 = 1$$

- Used pre-set *load following* dispatch strategy
  - Encoded directly into objective function
  - Positivity constraints on inputs: $n_s,\ n_w,\ E_{b,\, init} \geq 0$
  - All other constraints enforced implicitly

Methodology: Encoded dispatch strategy for sizing



Methodology: Dispatch optimization

- Determine optimal scheduling (*unit commitment*) & power flows (*unit dispatch*) of dispatchable generation & storage devices in each time interval
- Simulated MG using hourly time-steps over a day-ahead period
- Used vector-valued variables for both DG & BS powers

$$\min_{P_{DG},\, P_{BS}} w_1 \cdot \frac{COE}{COE_{base}} + w_2 \cdot \frac{Em}{Em_{base}} + w_3 \cdot REPG + w_4 \cdot (1 - REF)$$

$$0 \leq P_{DG} \leq P_{DG,\,rated} \;\forall\; t$$

$$P_{DG,\,min} \leq P_{DG} \; if \; DG \; is \; ON$$

Power limits on DGs

$$SOC_{min} \leq SOC \leq SOC_{max}$$

Battery SOC limits

$$-P_{BS,\,rated} \leq P_{BS} \leq P_{BS,\,rated}$$

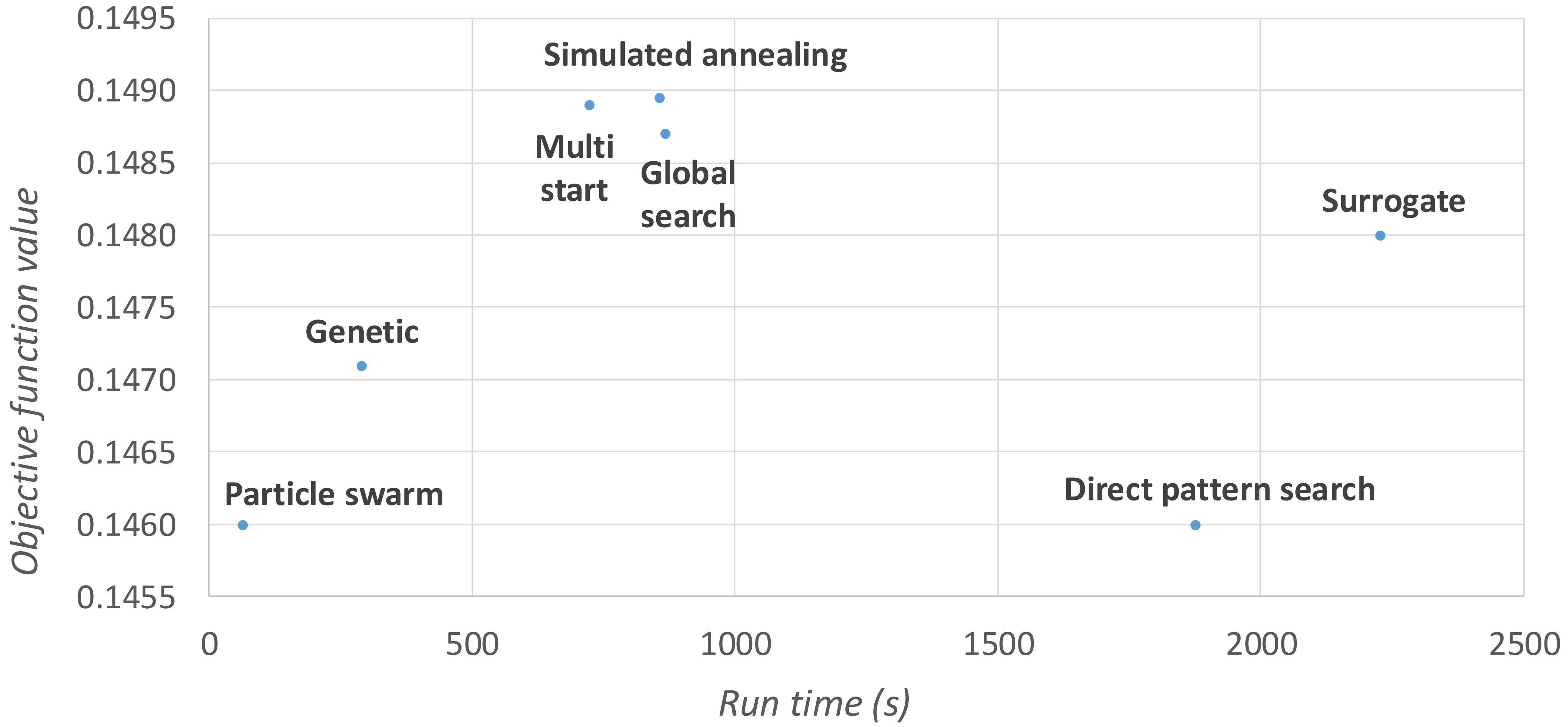
Battery power limits

$$DPSP \leq DPSP_{max}$$

Desired reliability level

$$\Sigma_{i=1}^{i=4} w_i = 1$$

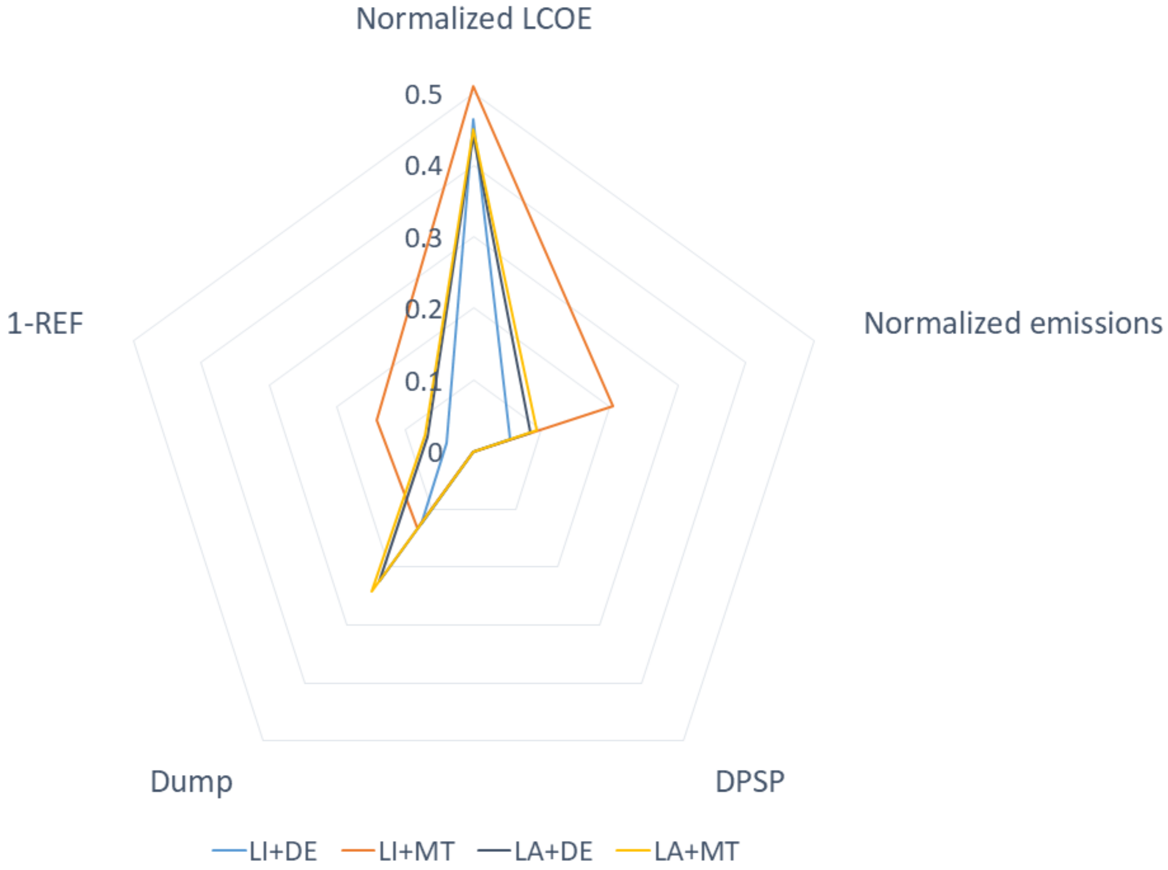
Sizing results: Comparison of MATLAB solvers



Sizing results: Technology selection

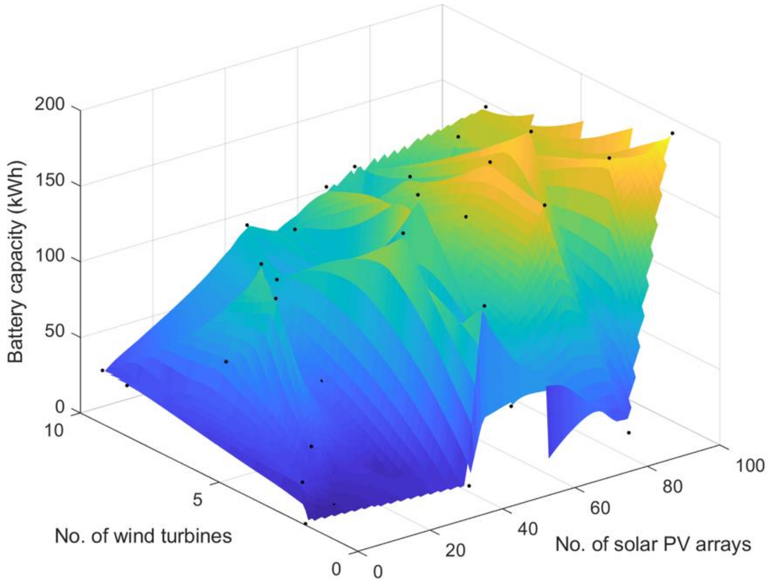
- Initially assumed backup DG rated at 16 kW
- LI + DE system → Most optimal combination
- Significant improvement over baseline system for all objectives except dumped power

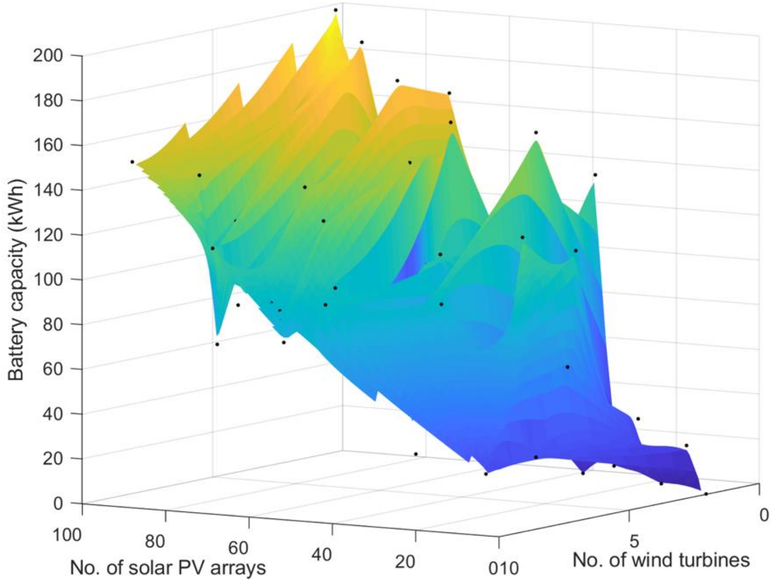
Parameter	(i)	(ii)
$LCOE_{normalized}$	0.4645	0.4585
LCOE $[\$/kWh]$	0.2308	0.2278
$Emissions_{normalized}$	0.0537	0.0613
Annual emissions $[kg/y]$	2695	3077
DPSP	0	0
Dump	0.1252	0.1171
1-REF	0.0399	0.0460
No. of online DE hours $[h/y]$	585	665
No. of LI BS cycles $[/y]$	69	85
Optimal soln.	$[n_s,\ n_w,\ E_{b,\ init}] = [15.12\quad 4.31\quad 106.53]$	$[P_{PV,\ r,\ total},\ P_{WT,\ r,\ total},\ E_{b,\ init}] = [2.51\quad 15.16\quad 85.29]$
Minimum objective	0.1367	0.1366

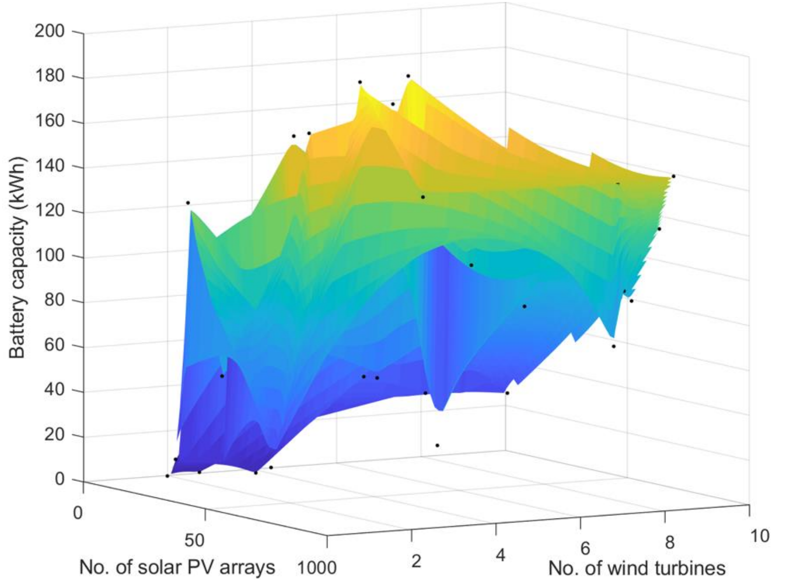


Sizing results: Pareto optimality

- Pareto front generated using genetic and pattern search algorithms
- Shows relationships & trade offs among non-dominated (equally optimal) inputs & output objectives

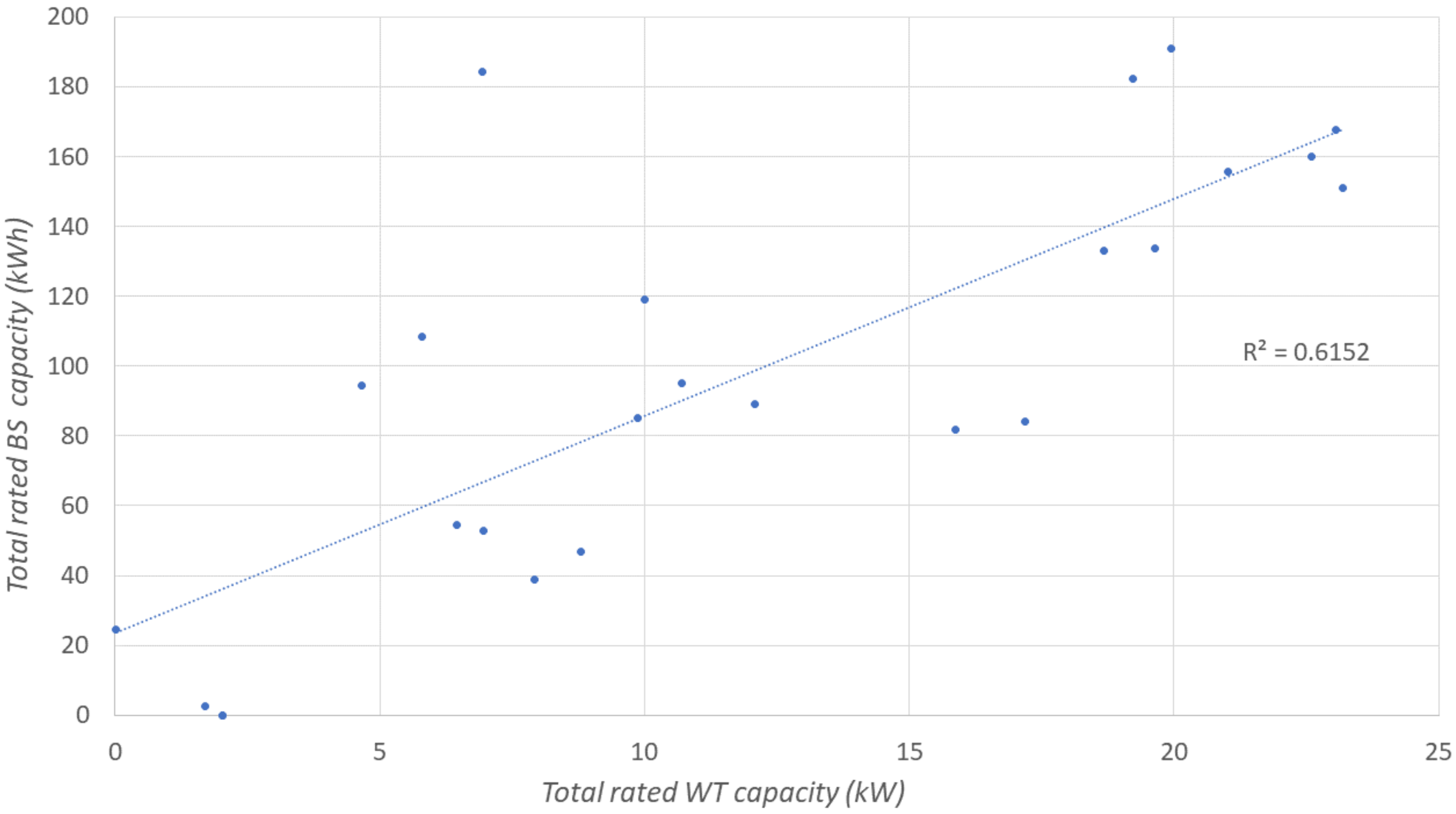




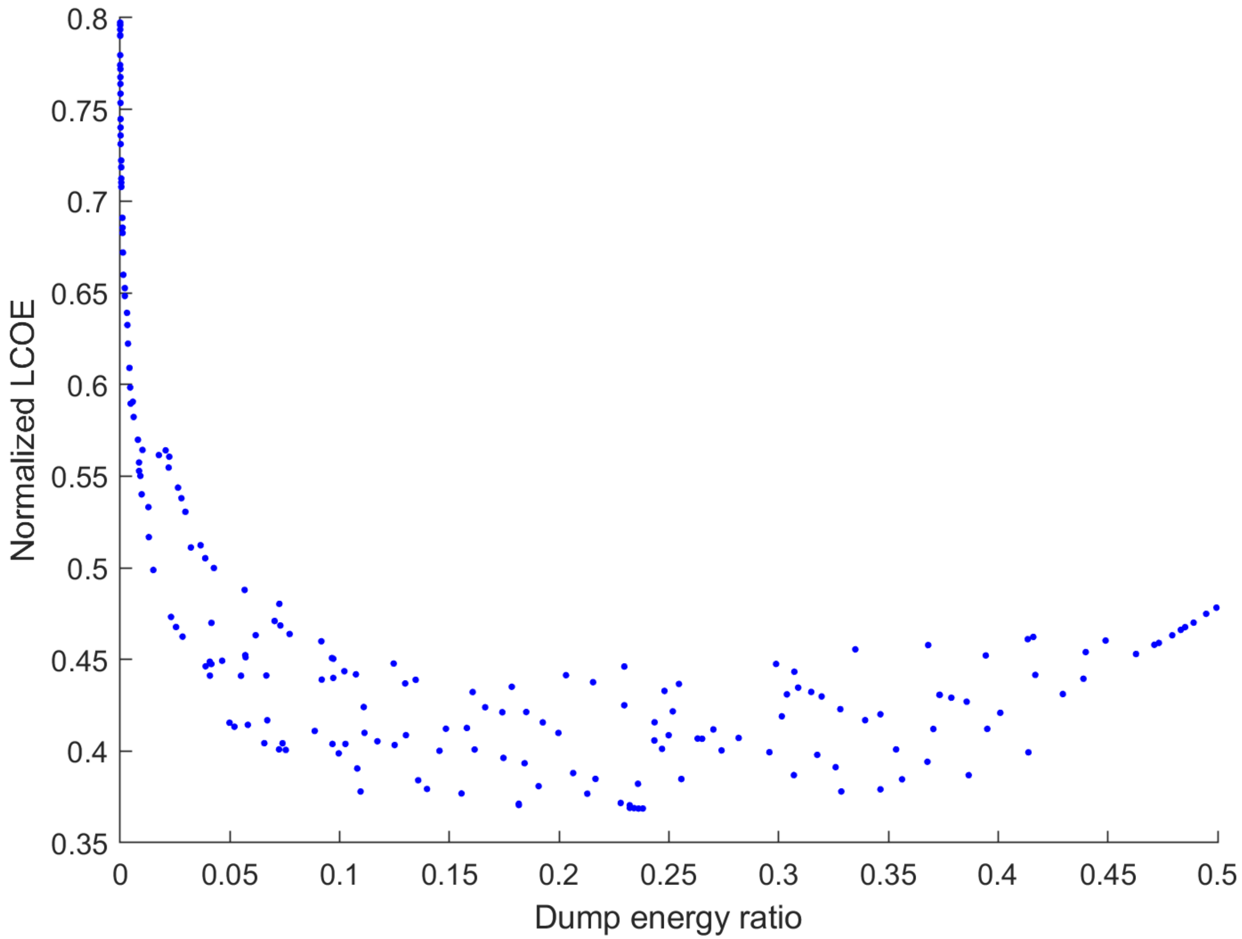


Sizing results: Pareto input relationships

- Each of the 3 input pairs show weakly +ve correlations
- At very high capacities of either PV or WT, they act as substitutes
- Dependence of BS on RES capacity stronger than between PV vs WT
- Due to intermittency of renewables



Sizing results: Pareto output relationships



Sizing results: Break-even distance analysis

- Distance from conventional grid at which off-grid MG becomes cost-effective

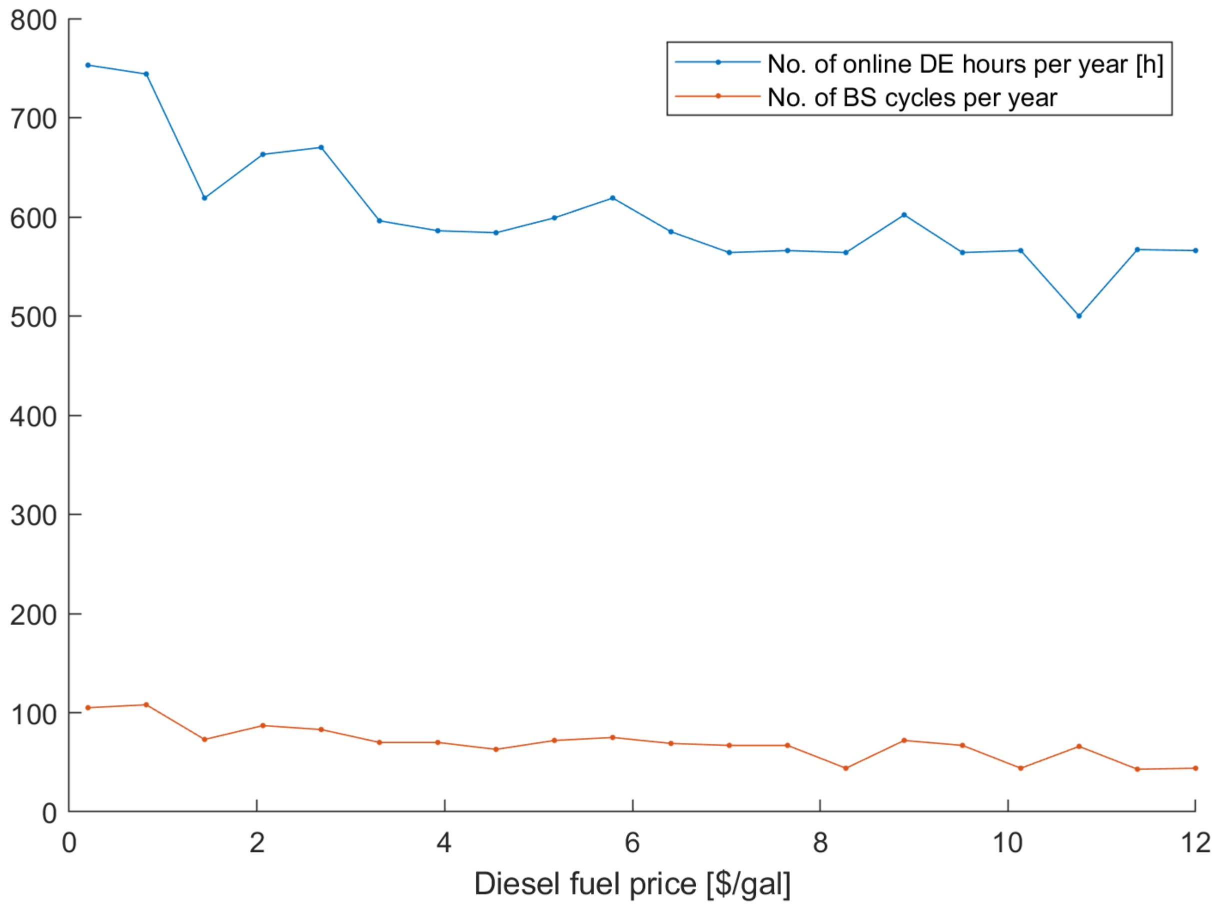
$$BED\ [km] = \frac{[TAC - (LCOE_{grid} \cdot \Sigma_{t=1}^{t=8760}\ E_{load}(t))]}{C_{ext} \cdot CRF}$$

- BED calculated as 0.855 km for PV-WT MG using LI+DE
- Islanded MG much cheaper than grid extension for community considered

Sizing results: Sensitivity analysis

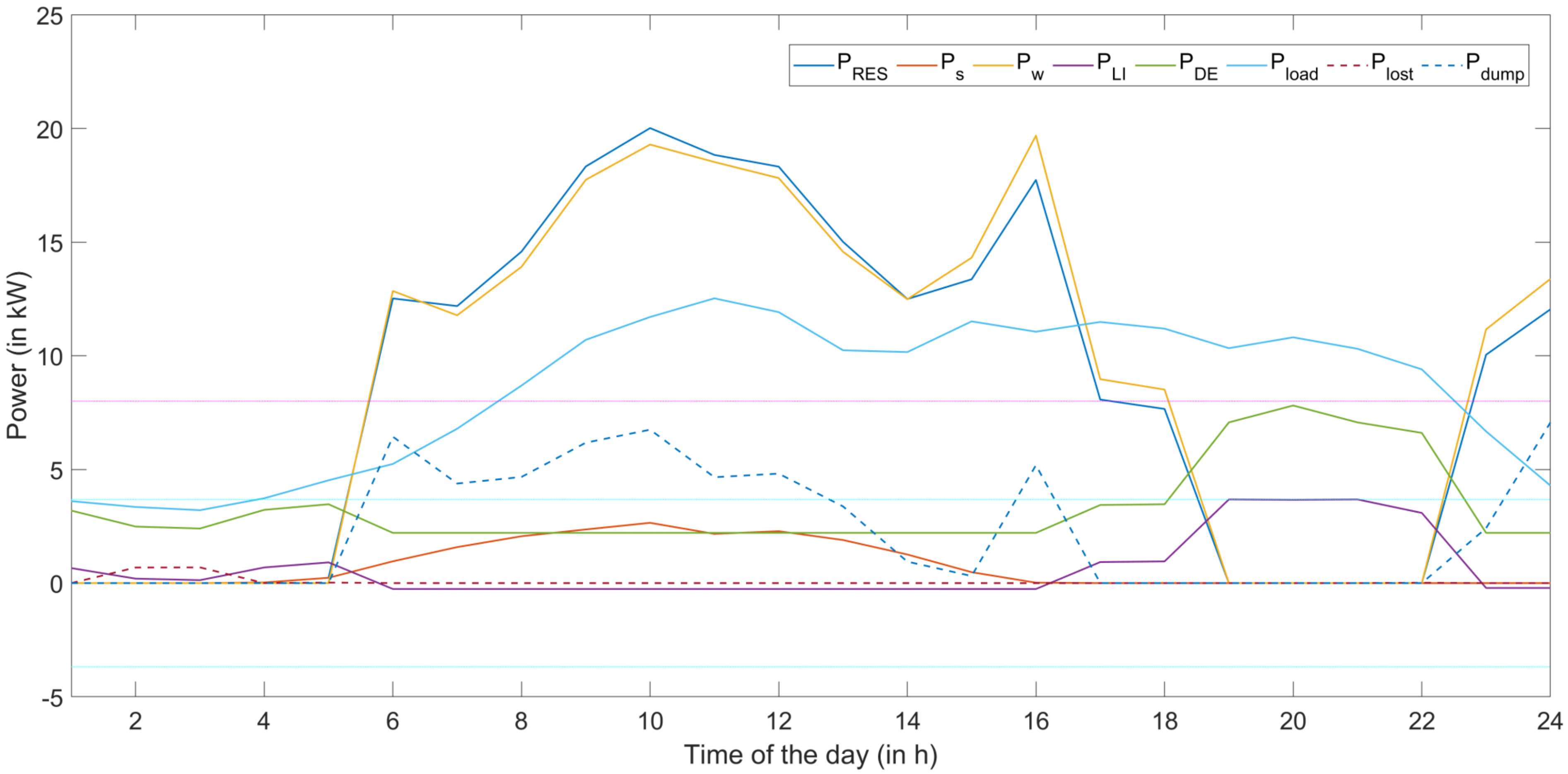
- Independently varied following parameters:
  - Rated power of backup generator
  - Diesel fuel price
  - Nominal interest rate
  - Inflation rate
  - Price of battery storage ($/kWh)
  - Relative weights placed on objectives

Parameter	Default value
DG power rating $[kW]$	16
Diesel fuel price $\$/gal$	3.20
Nominal interest rate (%)	9
Inflation rate (%)	5.70
Price of BS $(\$/kWh)$	300
$[w_1\ w_2\ w_3\ w_4\ w_5]$	[0.2 0.2 0.2 0.2 0.2]



Dispatch results: Baseline conditions

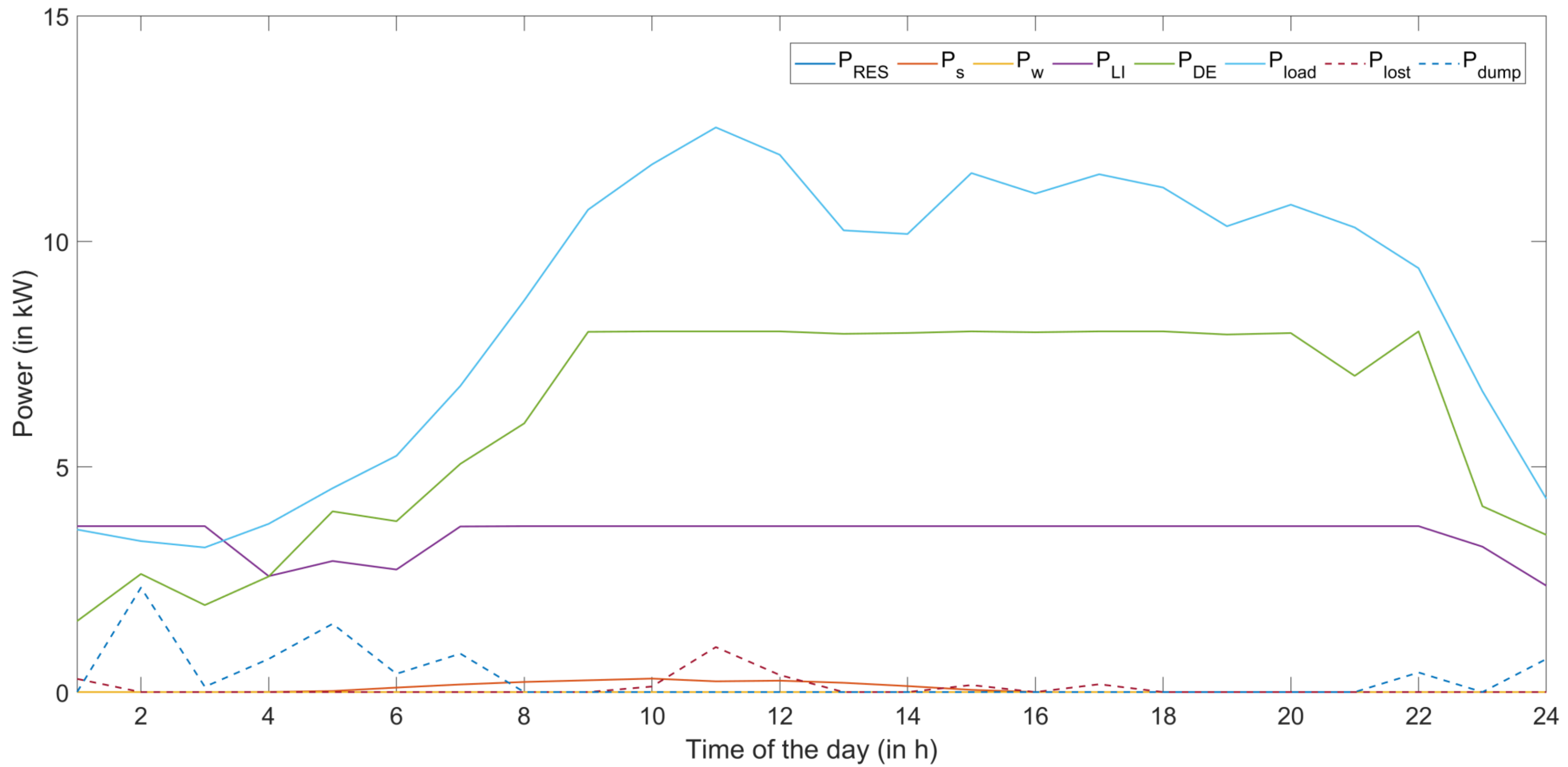
For PV-WT MG using LI & 8 kW backup DE



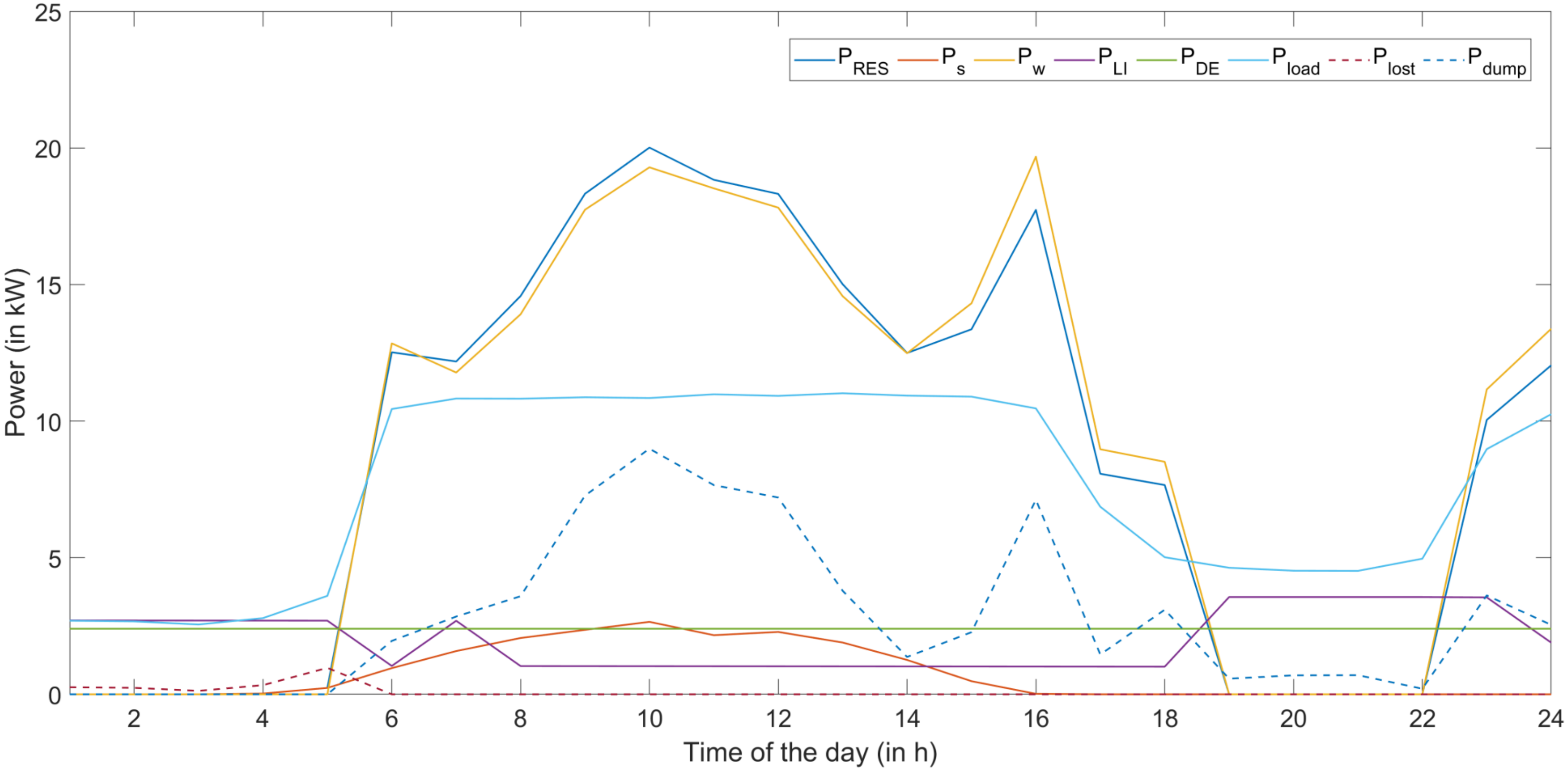
Dispatch results: Robustness analysis

Scenario	Min obj.	COE	Emissions	DPSP	Dump	REF
Low solar radiation	0.2507	0.6793	0.2242	0.007	0.1699	0.8264
Low wind speeds	0.5119	1.047	0.6374	0.009	0	0.1335
Both low solar irradiance and low wind speeds	0.5331	0.9156	0.7	0.010	0.0546	0.0151
Peakier load profile	0.3529	0.8443	0.3565	0.008	0.3196	0.7641
Flatter profile: Load shifting only	0.2055	0.6165	0.1539	0.004	0.1355	0.8824
Flatter profile: Load shifting and curtailment	0.1527	0.3573	0.0524	0.010	0.3042	0.9607

Dispatch results: RES uncertainty



Dispatch results: Stochastic demand



Future work: Areas for potential improvement

- Alternative dispatch strategies at sizing & design stage
- Improve computational efficiency of model
- Simulation using smaller time-steps
- More comprehensive multi-year modelling
- More accurate load and RES output forecasting
- Implementation of DR or DSM programs
- Advanced control techniques like model predictive or receding horizon control

Conclusions

- Isolated MG can provide reliable & affordable supply without depending on external grid
- Hybrid system much more optimal than using only diesel or natural gas
- Reliability depends strongly on sufficient battery storage & backup generation capacity
- Power rating of DG strongly influences sizing of PV, WT & BS components
- Sensitivity analysis reveals effects of external parameters and internal prioritization
- Pareto set generation reveals interesting relations and trade offs among inputs& outputs
- System relatively robust to *short-term* disturbances & uncertainty in demand/supply
    - But performance degraded due to increased reliance on fossil fuels for backup
    - Response to *longer-term* disturbances remains to be seen

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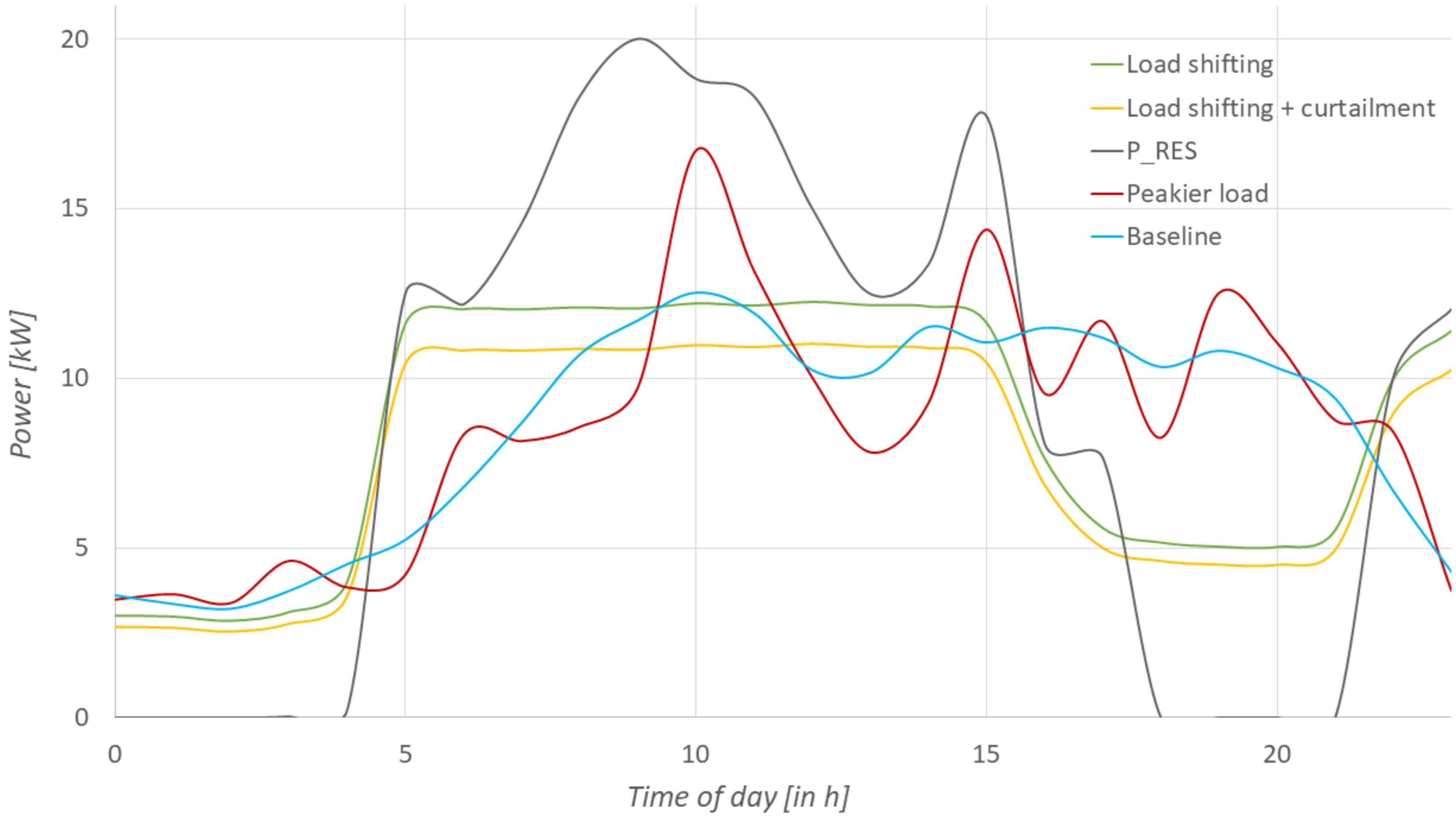
Thank you!

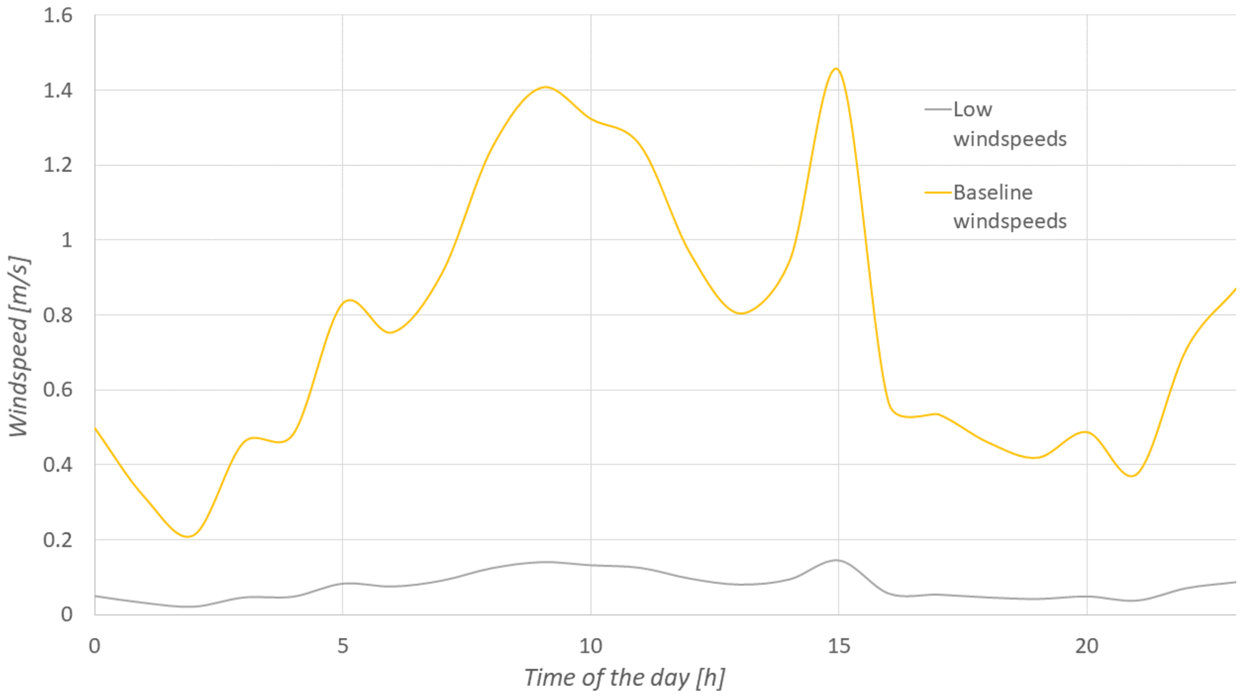
Questions?

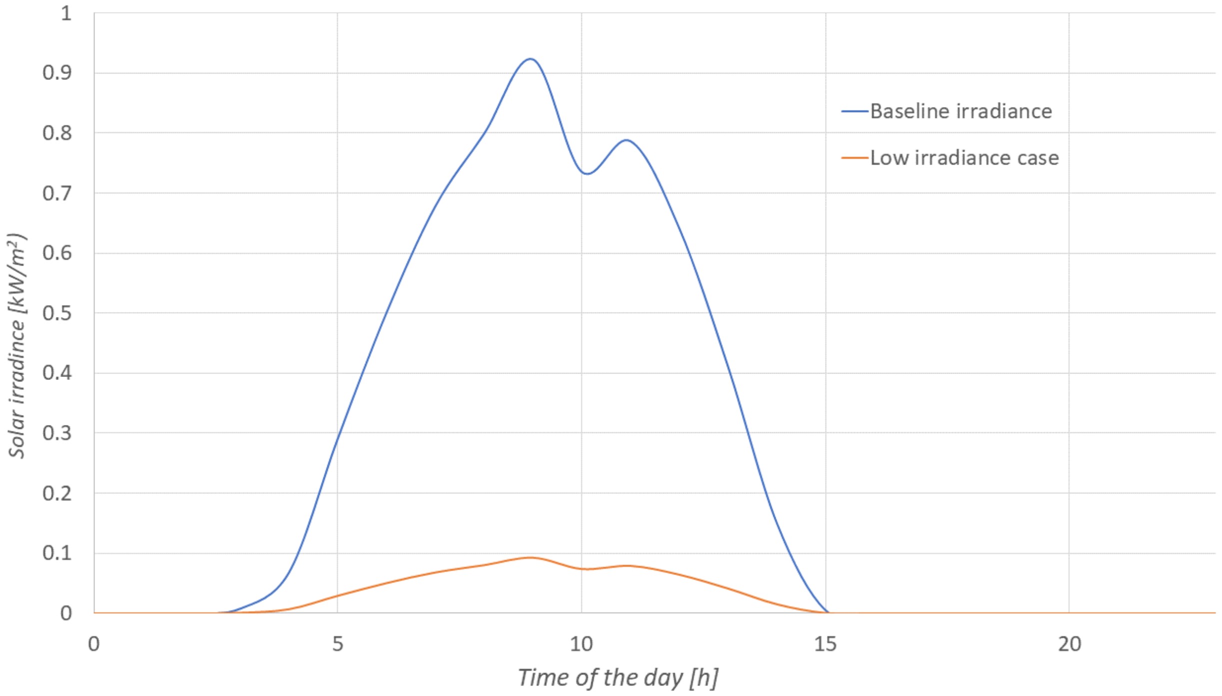
Appendix

Load profiles used

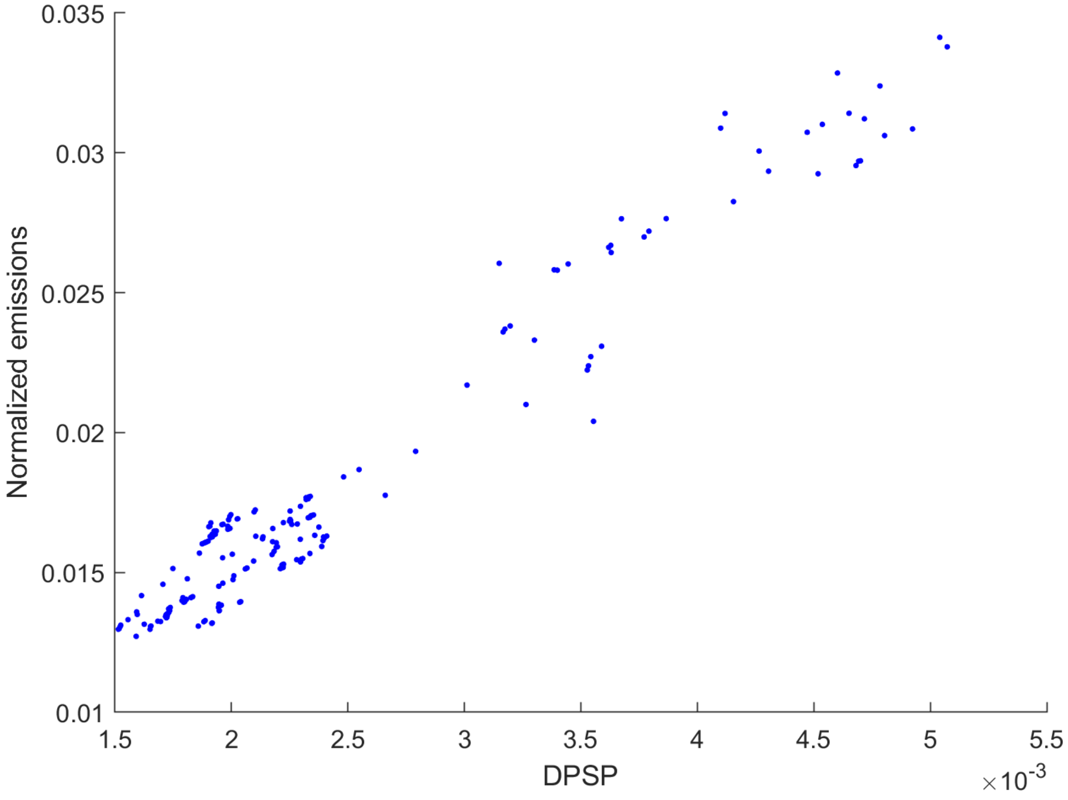


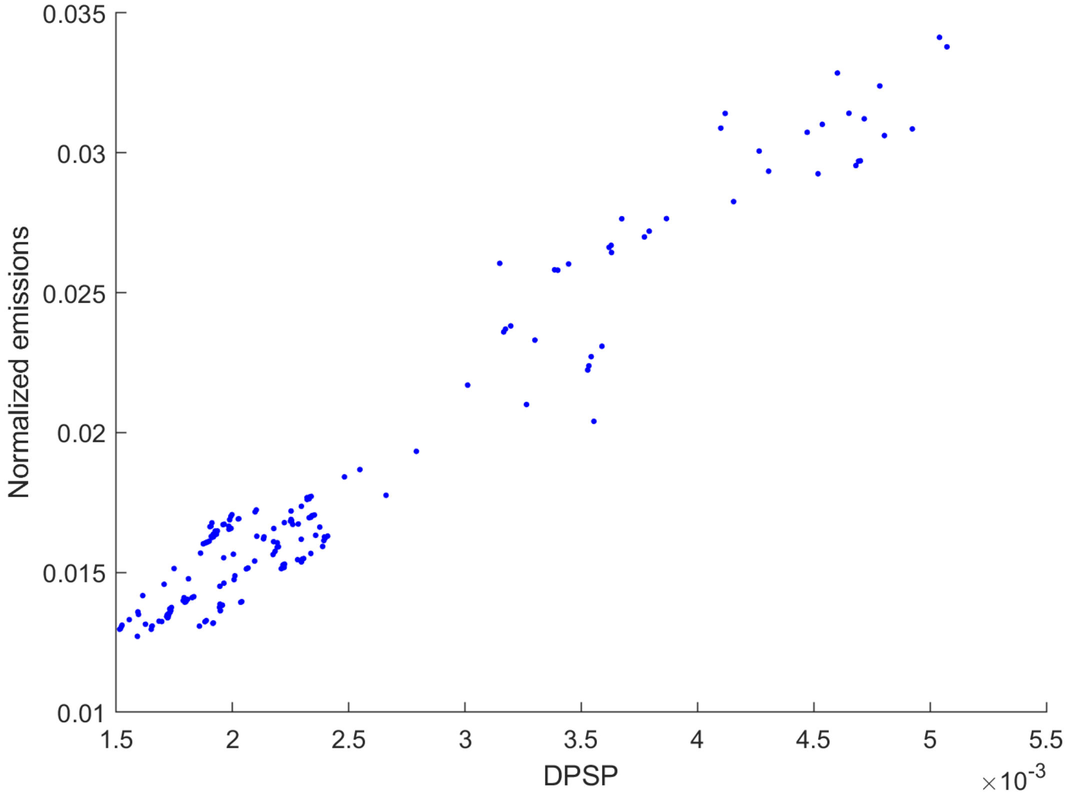
RES profiles used



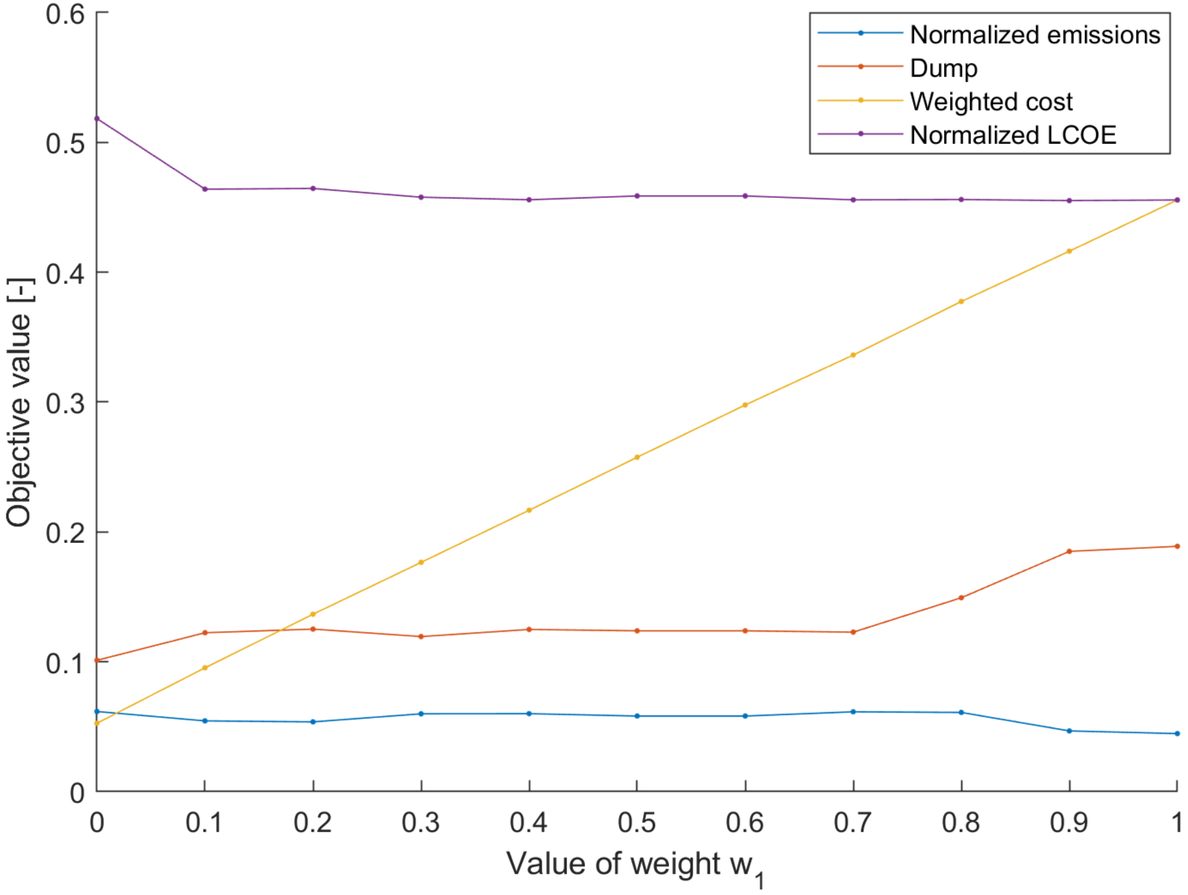


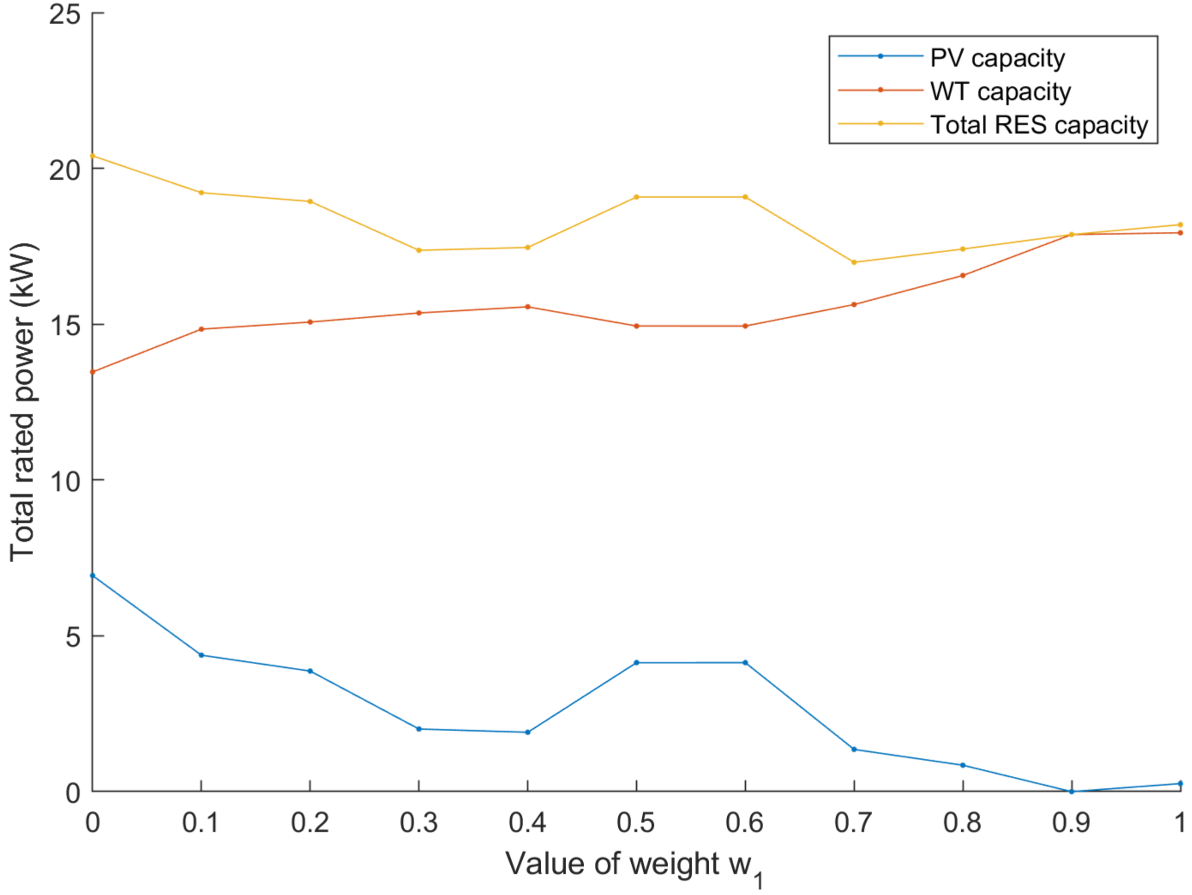
Other Pareto output relationships



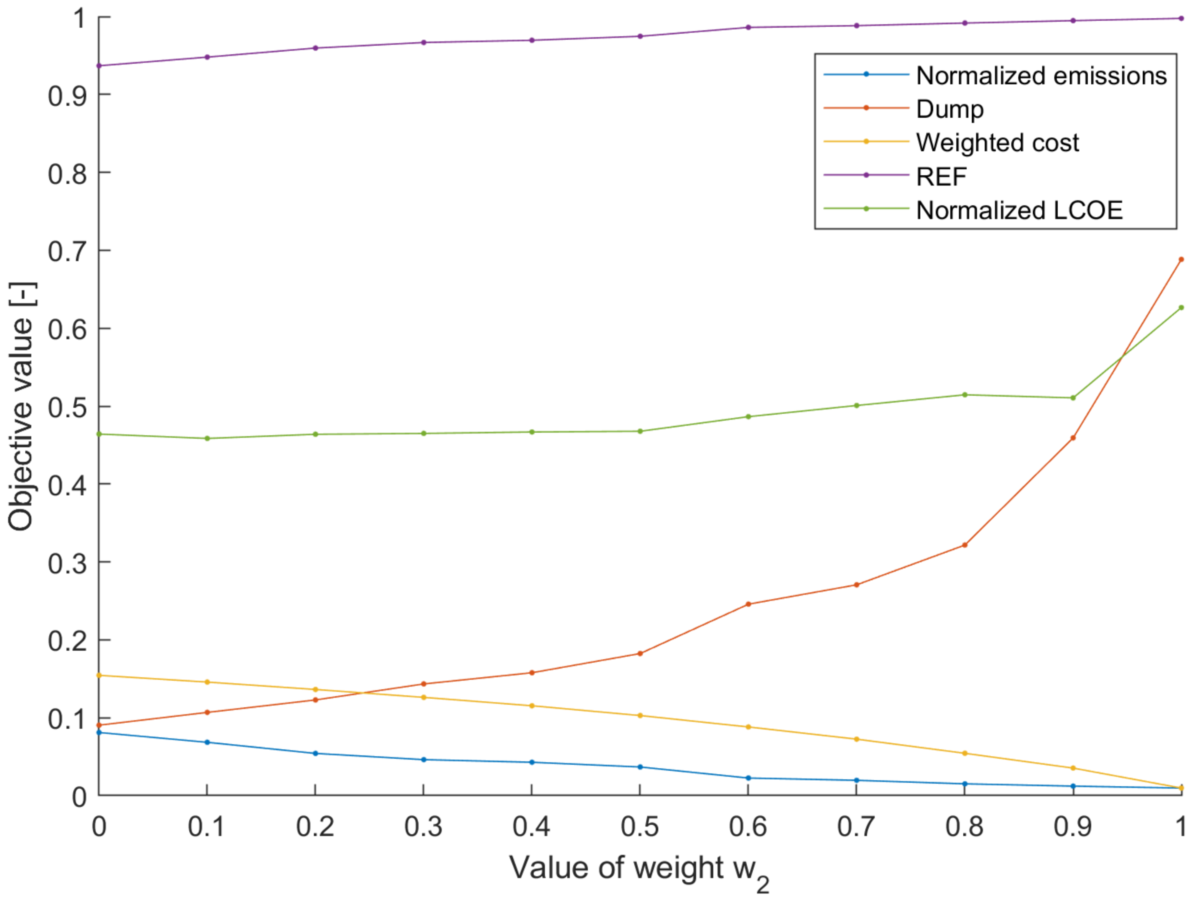


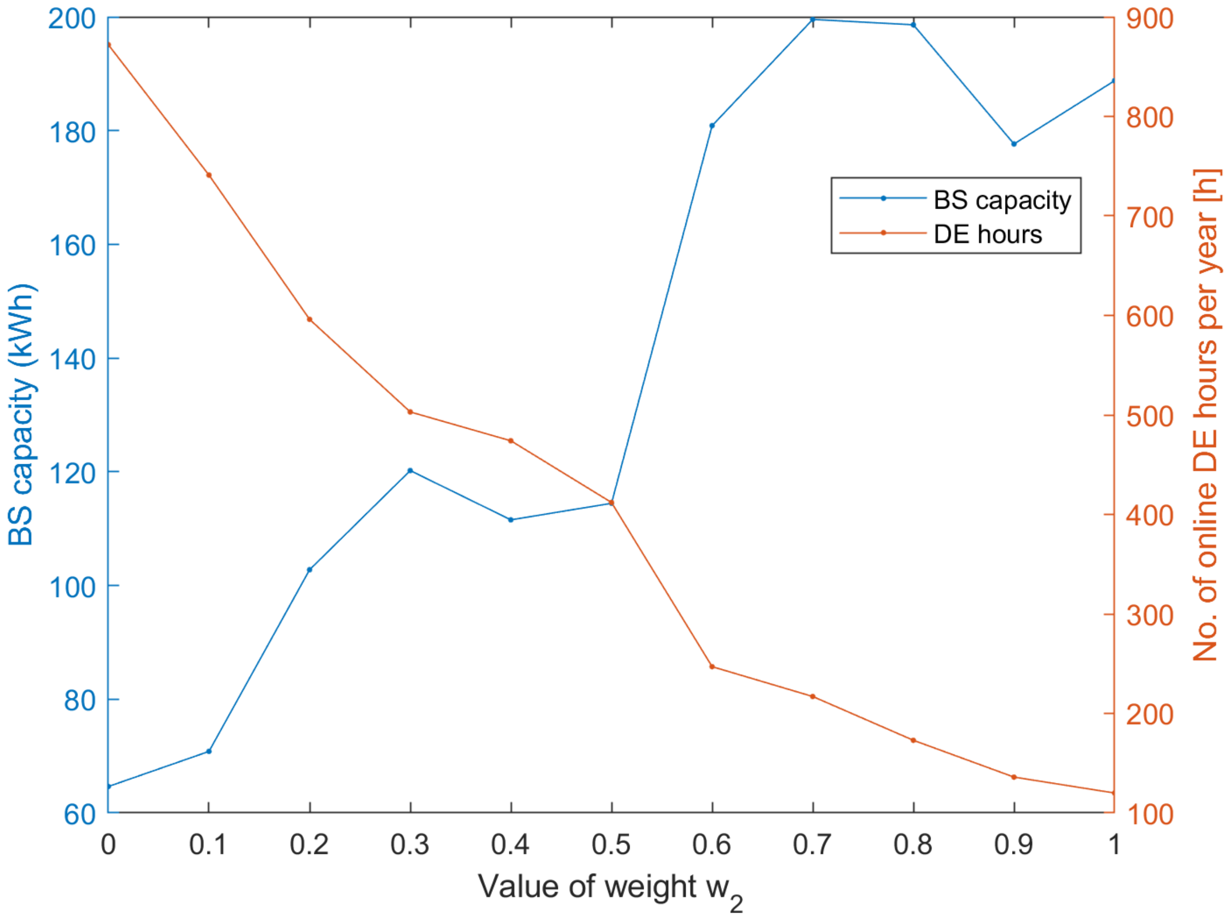
Few other sensitivity analysis results: Vary w1



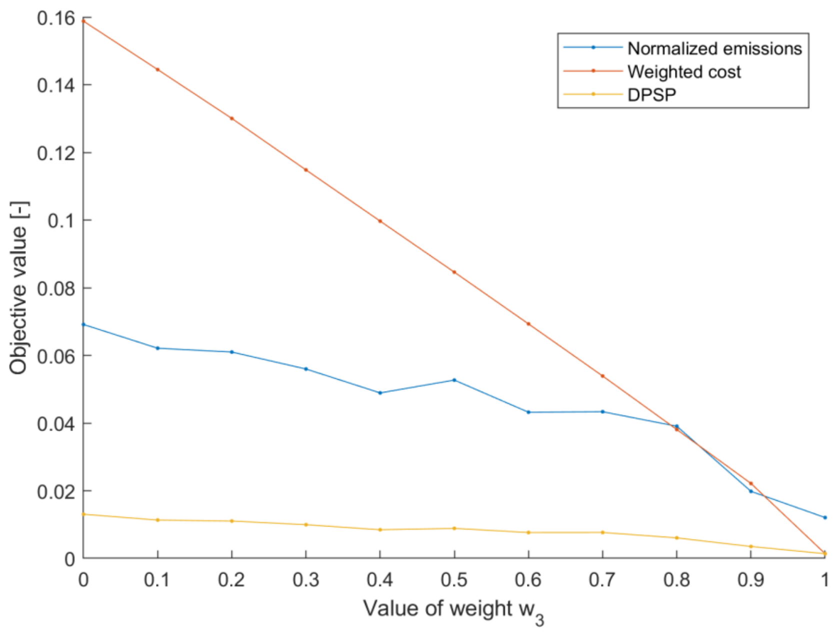


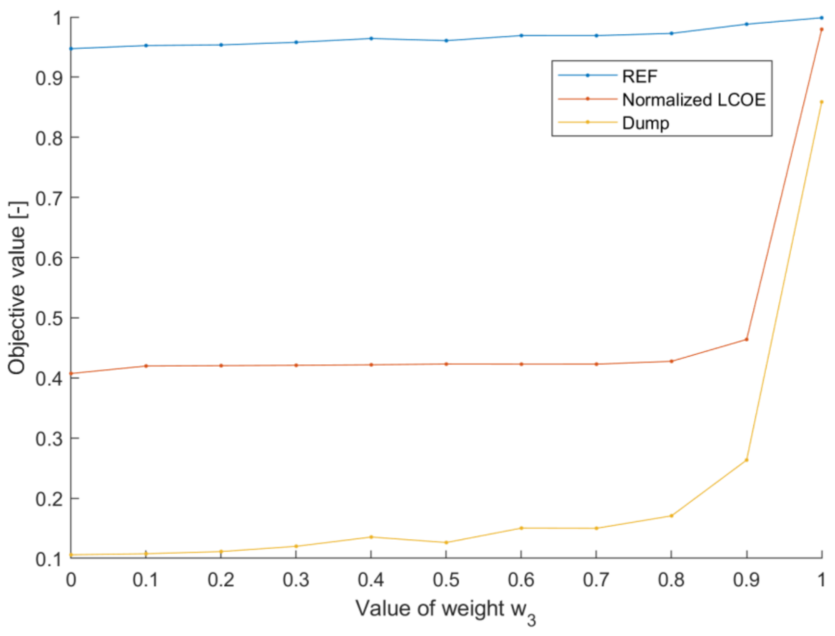
Few other sensitivity analysis results: Vary w2

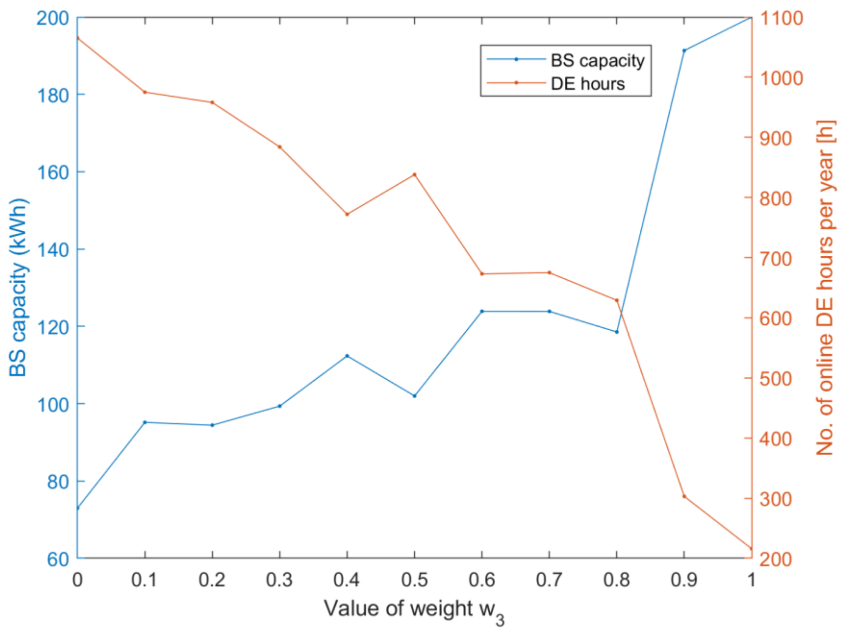




Few other sensitivity analysis results: Vary w3







Few other sensitivity analysis results: Vary w4