Optimal integration of flexible loads and PV power generation in an isolated grid

Master´s thesis
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Energy technologies - ENTECH

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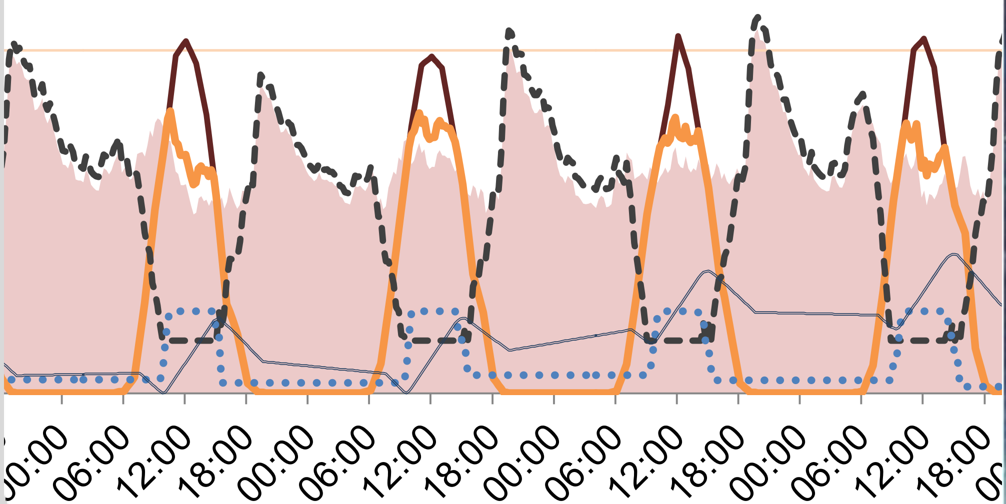

Structure

- 1 Introduction & motivation
- 2 Energy setup & model of an isolated grid
- 3 Case study: Ha’apai, Tonga
- 4 Computational results
- 5 Conclusion & outlook

1 Introduction

- Climate change conference in Paris
  - Alliance of small island states (39 islands states)
  - Restriction of global warming to under 1.5 °C

- Strong interest to implement renewable energies themselfs
  - Isolated grid: Special conditions for energy supply
  - Dependent on diesel generators (DG) & expensive fuel
  - ➡ Cost reduction
  - ➡ Reduce dependency on foreign fuel supply & global oil price
  - ➡ Reduce greenhouse gas emissions

1 Motivation

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- Increase penetration of renewable energies by utilizing flexible loads by DSM
  - Decentral integration over price signal transmitted by electricity frequency

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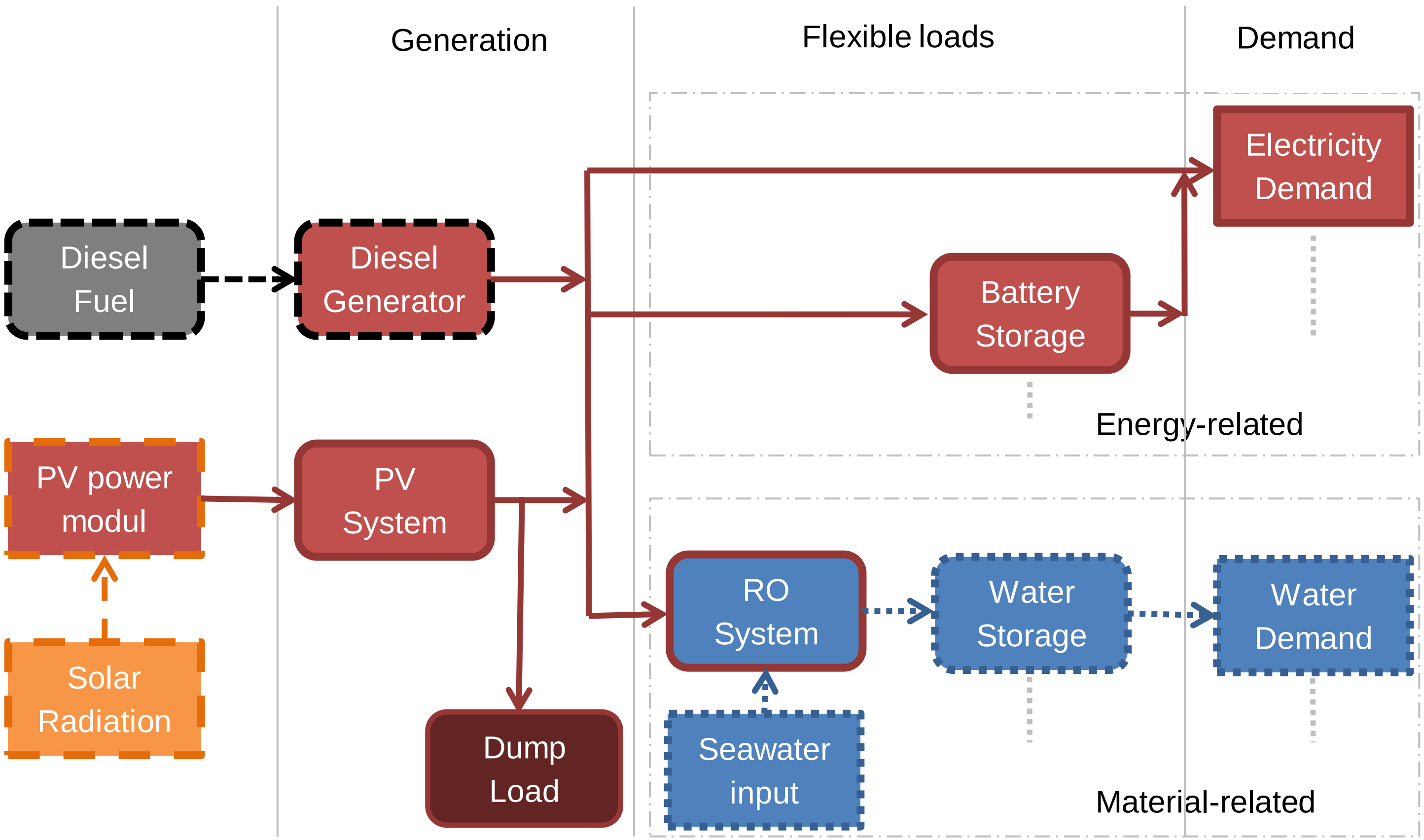
- How does the integration of a PV system influence the energy supply system and what is the capacity of the economically most beneficial PV system?
- How do flexible loads influence the utilization of the PV system and the optimal PV size capacity?
- What is the impact of the decentral integration of flexible loads on the overall energy supply system?
- What are the most important uncertain input or system parameters?

2 Energy setup & model of an isolated grid

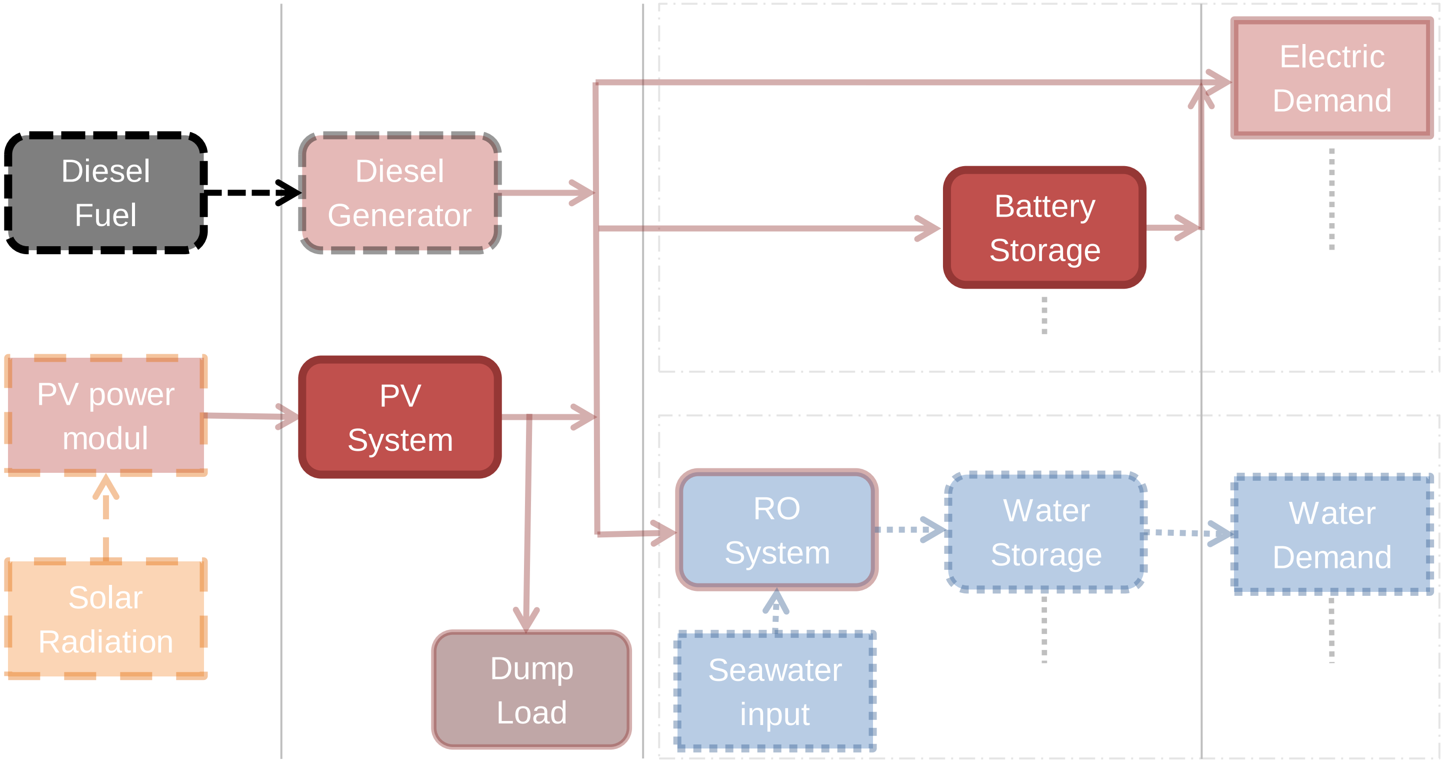
- Formulated as LP/MILP in GAMS, solved with IBM`s Cplex
- 15 min per time step ➡ 35040 time steps for one year



2 Energy setup & model of an isolated grid: Objective

- Minimiziation of total annual costs:
  - Consumed diesel fuel
  - Capacity of PV system (investment as annuity)
  - Capacity of BS (investment as annuity)

$$\min_{\{\text{Decision Variables}\}} cost^{total} = \sum diesel_t^{DG} \cdot c^{diesel} + c^{PV} \cdot A^{PV} \cdot capacity^{PV} + c^{BS} \cdot A^{BS} \cdot capacity^{BS} / L^{BS,dd}$$



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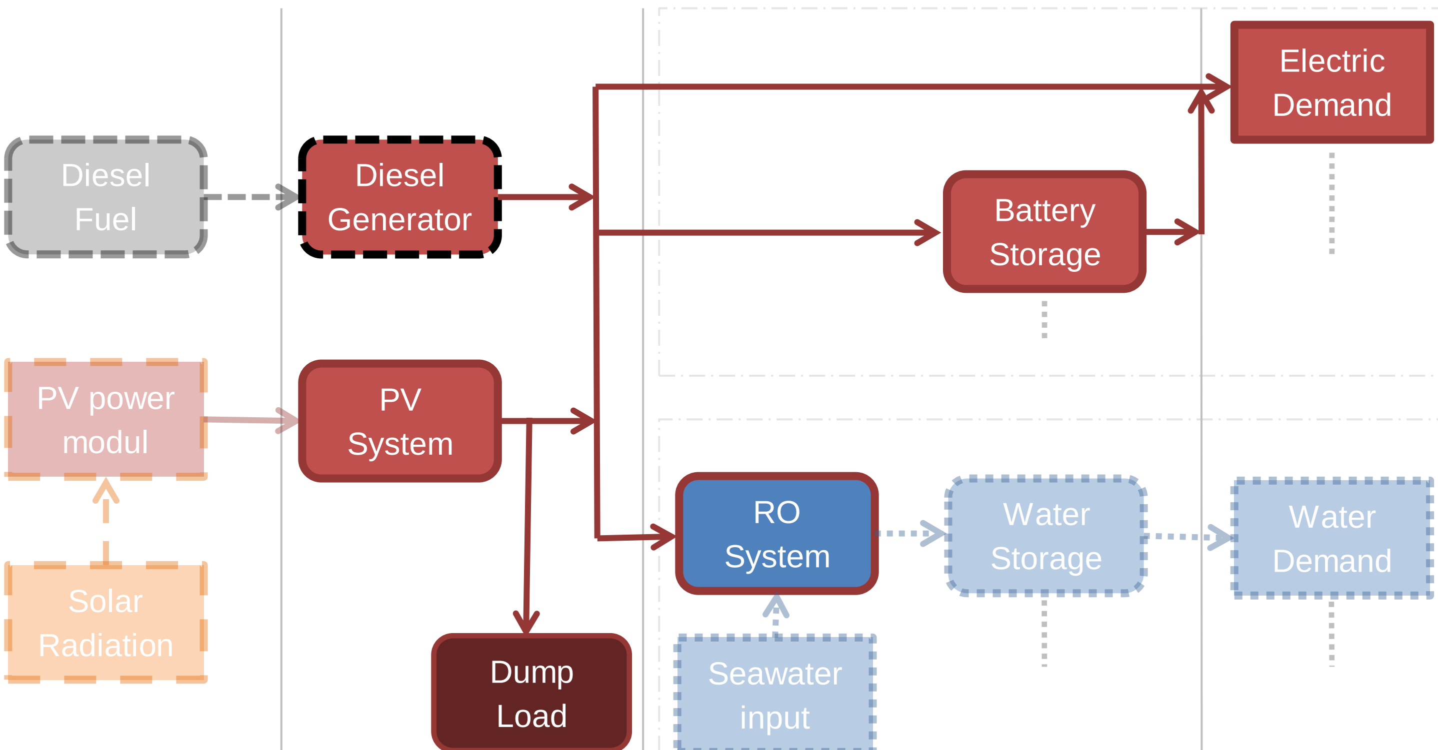
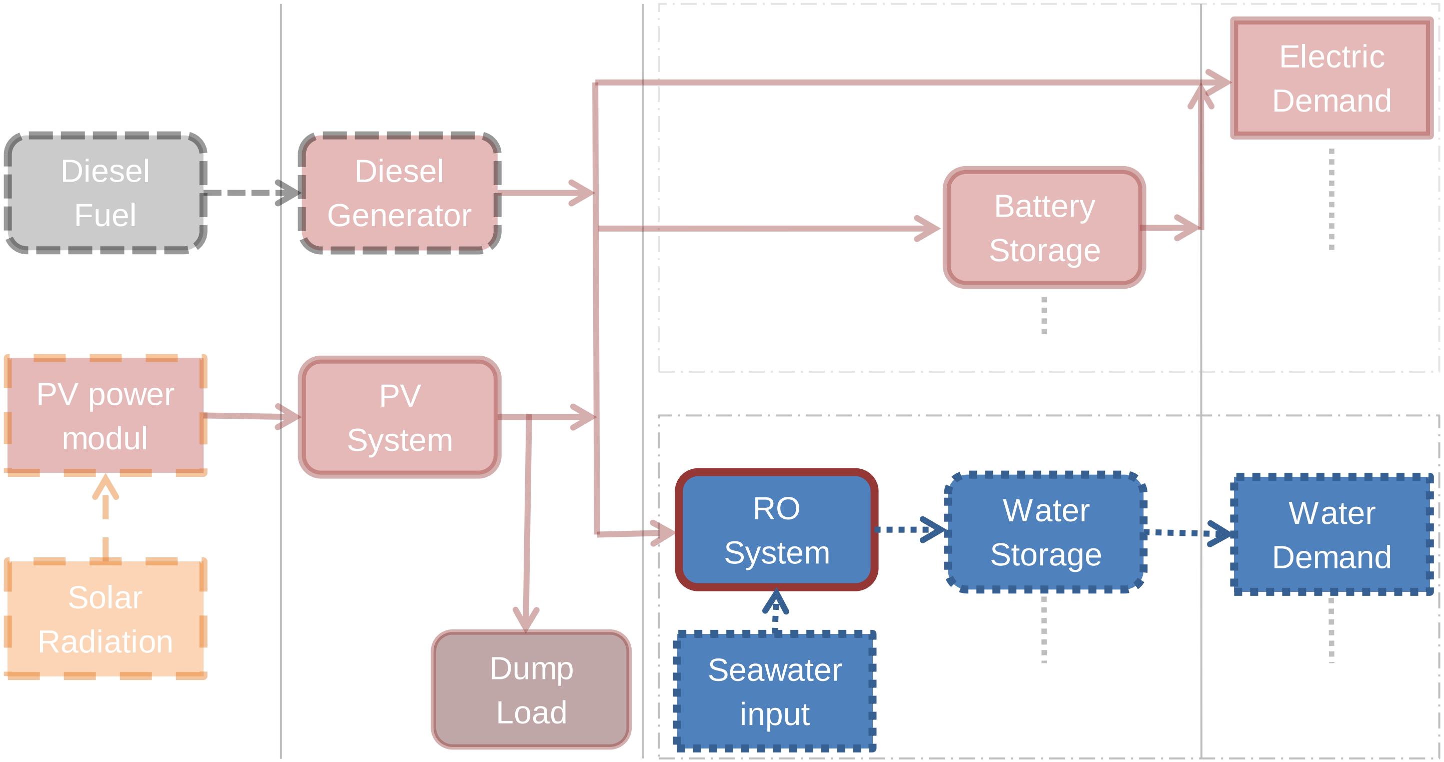
2 Energy setup & model of an isolated grid: Main constraints

- Supply of electricity demand & RO demand: $E_t^{demand} + e_t^{RO} + e_t^{BS} = e_t^{DG} + e_t^{PV} \quad \forall t$
  - Diesel Generator: $diesel_t = e_t^{DG} \cdot F^{DG,B} + {RP^{DG}}/{4} \cdot F^{DG,C} \; ; \; e_t^{DG} \leq {RP^{DG}}/{4} \quad \forall t$
  - PV system: $e_t^{PV} = E_t^{PV1kW_P} \cdot {capacity^{PV}}/{4} - e_t^{DL} \quad \forall t$
  - Battery storage system: $s_t^{BS} = s_{t-1}^{BS} \cdot (1 - L^{BS,sdl}) + e_t^{BS} - e_t^{BS,neg} \cdot (1 - L^{BS,rte}) \quad \forall t$



2 Energy setup & model of an isolated grid: Main constraints

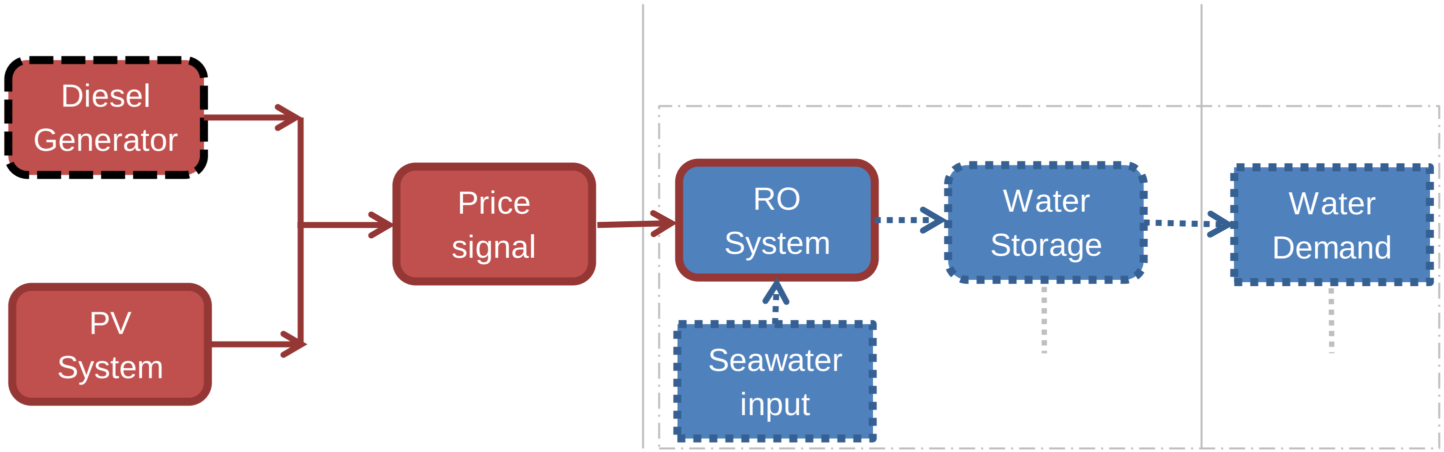
- Supply of water demand: $s_t^{WS} + W_t^{demand} = s_{t-1}^{WS} + w_t^{RO} \quad \forall t$
  - RO system: $e_t^{RO} + L^{RO} \cdot e_t^{RO,neg} = w_t^{RO} \cdot F^{RO} \;;\; e_t^{RO} \leq RP^{RO}/4 \quad \forall t$
  - Water storage: $s_t^{WS} \leq \sum W_t^{demand} \cdot s^{WS,max}/365 \quad \forall t$



2 Energy setup & model of an isolated grid: Decentral integration approach

- Objective: Minimization of RO operation cost: $\min_{\{\text{Decision Variables}\}} \mathbf{cost^{RO}} = P_t^{RO} \cdot e_t^{RO}$
  - Energy consumption of RO plant
- Strong dependency between RO consumption & price signal
- Introduction of time-line ➡ rolling scheduling process
- Price signal as parameter
  - Power production cost: $P_t^{RO} = \text{diesel}_t \cdot C^{\text{diesel}} / E_t^{\text{demand}} \quad \in t = \text{counter}$
  - Price prediction for „future“ out of last three days:

$$P_t^{RO} = {}^1/_3 \cdot P_{t-96}^{RO} + {}^1/_3 \cdot P_{t-188}^{RO} + {}^1/_3 \cdot P_{t-272}^{RO} \qquad \forall t > \text{counter}$$



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3 Case study: Ha’apai, Tonga

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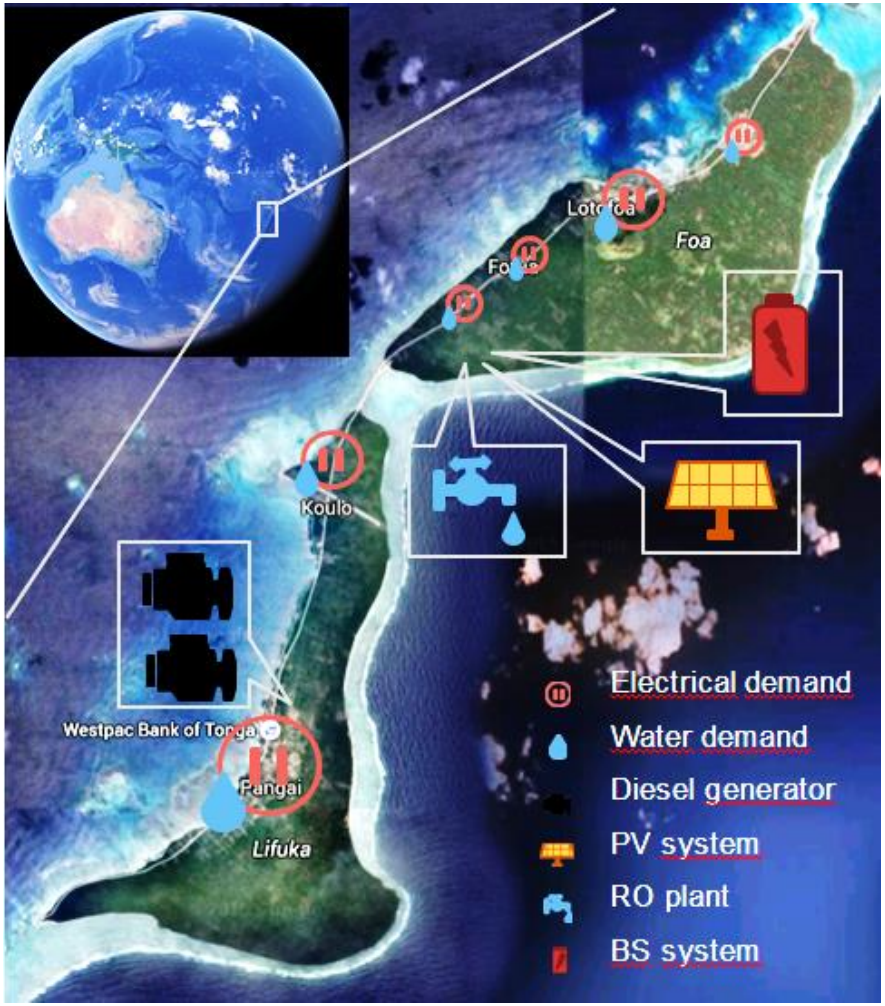
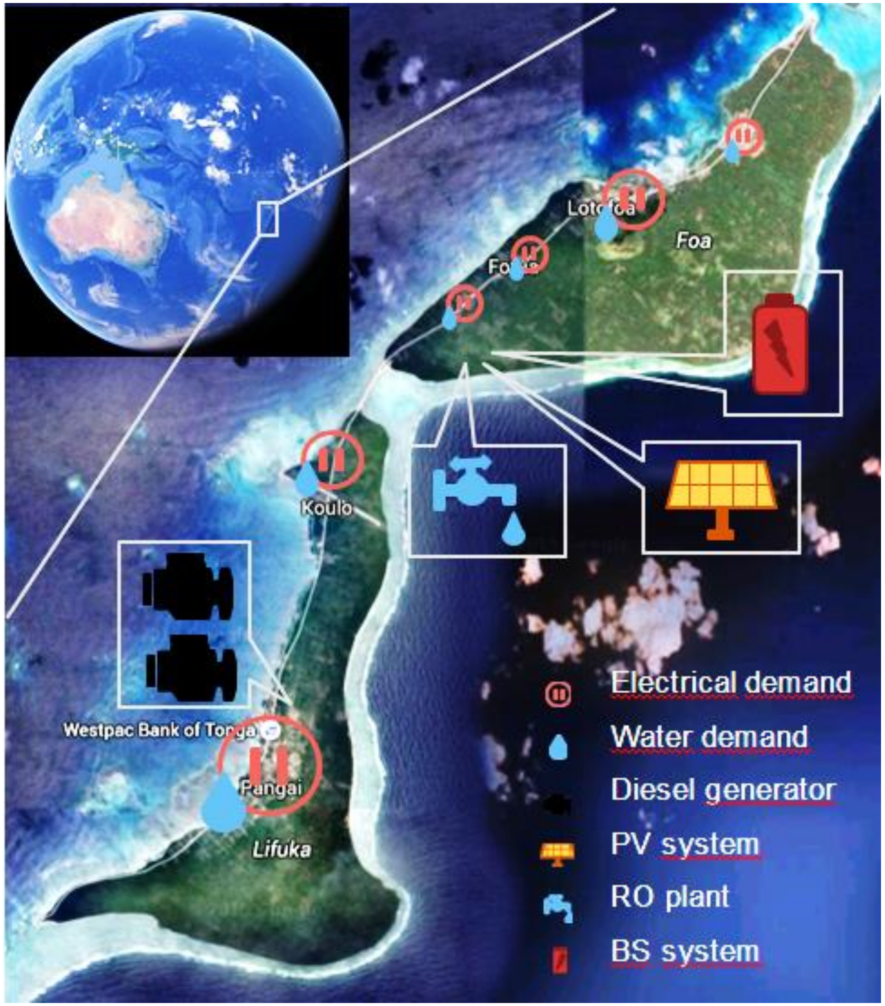
- Energy supply
  - Two DG each: 186 kW
  - SFC(DG): 0.25 l/kWh
  - Cost per liter diesel: 1.2 $

- Energy demand
  - Average: 5000 kWh per day
  - Mean load: 208 kW
  - Peak load: 350 kW



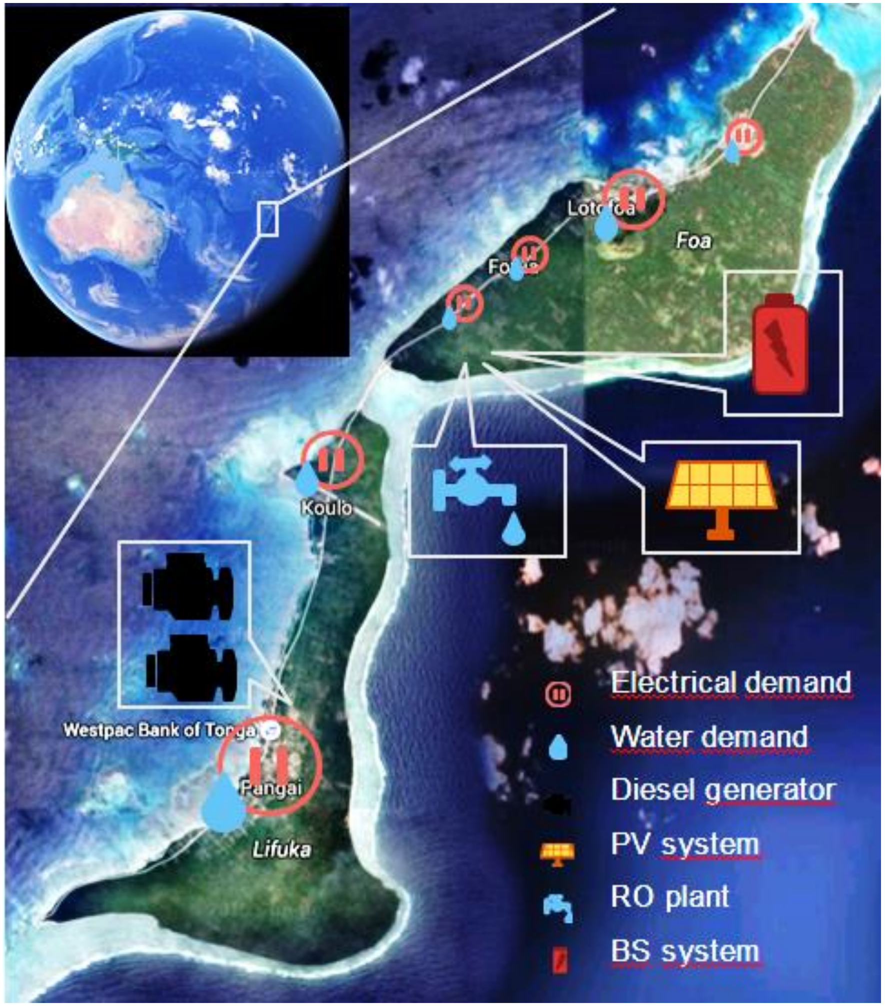
3 Case study: Ha'apai, Tonga

- PV system: mc-Si
  - Irradiation: 800 – 1000 W/m²
  - Module efficiency: 16.37 %
  - Cost per kW_P: 2500 $
  - Life time: 20 years
  - Interest rate: 10 %



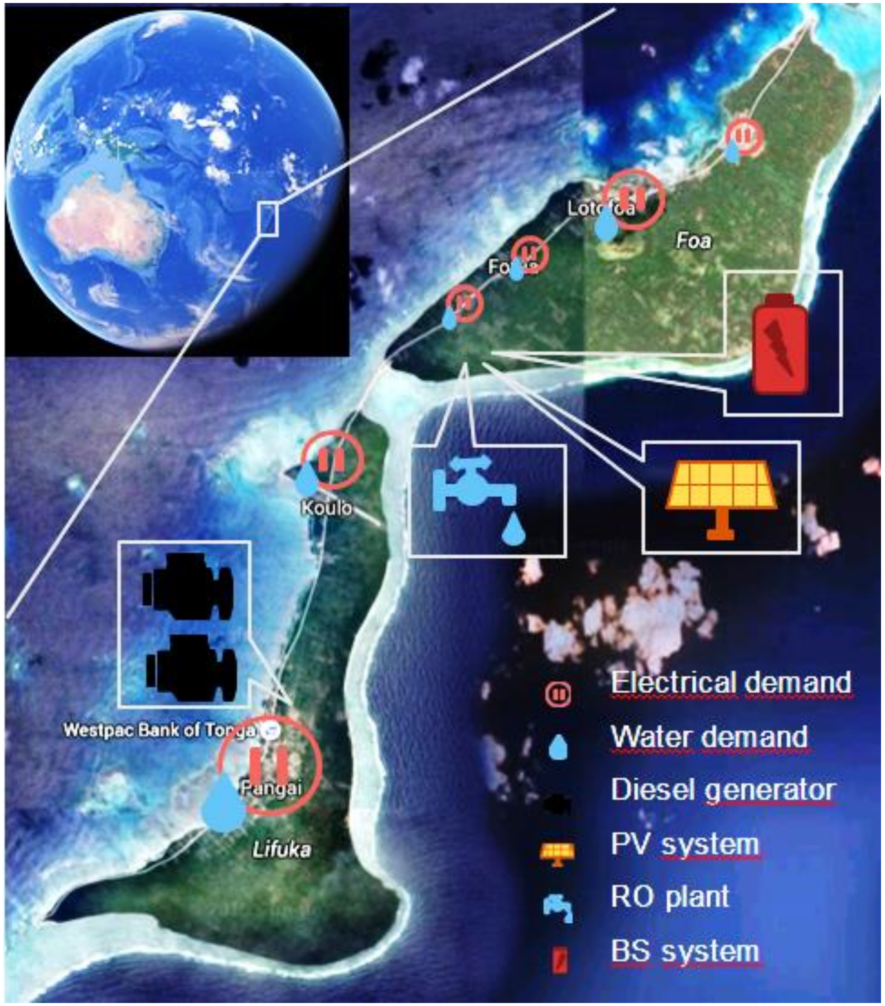
3 Case study: Ha’apai, Tonga

- Battery storage: Li-ion technology
  - Capacity: 1 kWh, 1 kW per unit
  - Cost per unit: 1200 $
  - Round-trip efficiency: 90 %
  - Depth of discharge: 90 %
  - Life time: 10 years
  - Interest rate: 10 %



3 Case study: Ha’apai, Tonga

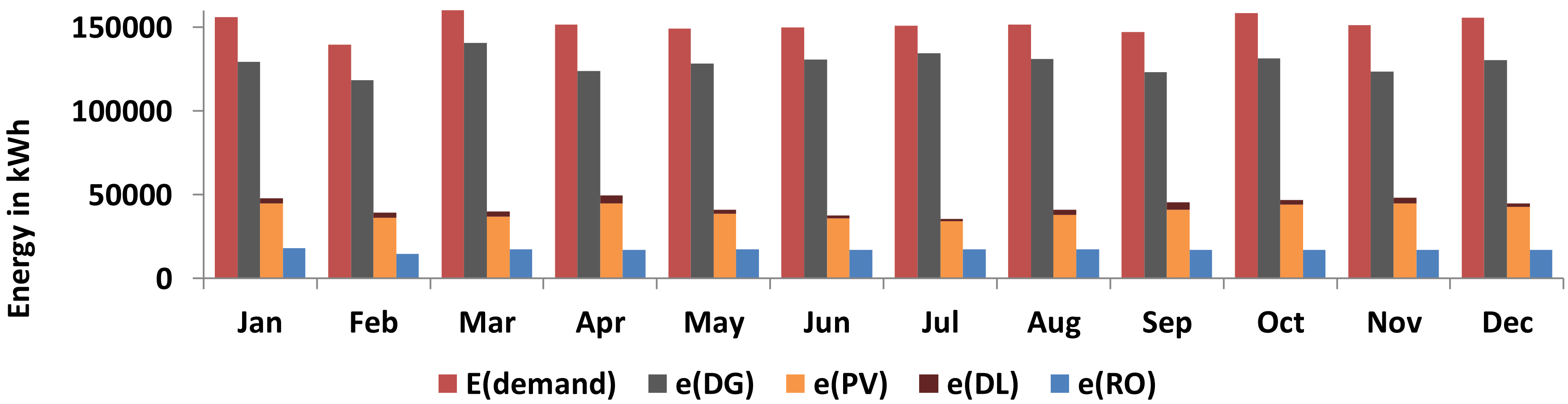
- Variable RO plant
  - Operating range: 18 – 72 kW
  - SEC(RO): 2.5 kWh/m³
- Water storage capacity
  - 2 days
- Water demand
  - 563 kWh per day



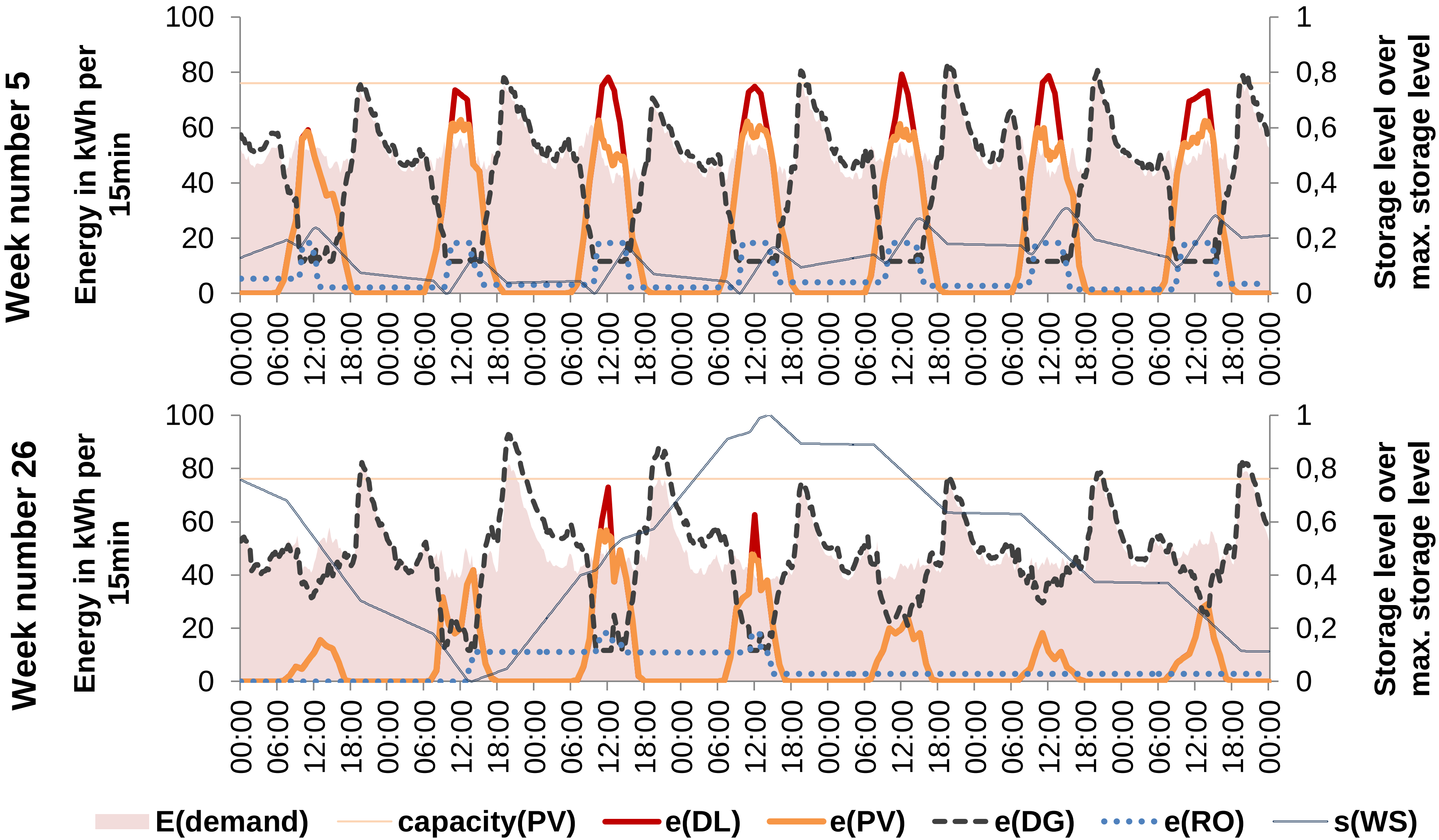
4 Computational results: Optimal energy supply system

Scenario	PV capacity (kW_p)	% PV of energy demand	% of DL on PV	BS (units)	Total cost ($)	PV cost ($)	LCOE ($/kWh)
1. DG only	-	-	-	-	565,117	-	0.310
2. + PV	206.7	17.9 %	7.2 %	-	532,246	60,701	0.292
3. + static RO	237.8	18.5 %	7.0 %	-	586,028	69,840	0.289
4. + variable RO	304.4	23.8 %	6.9 %	-	575,159	89,403	0.284
5. + BS (static RO)	304.4	23.4 %	6.9 %	52.8	593,880	89,403	0.288

4. DG + PV + variable RO



4 Computational results: Control of system components for two example weeks



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4 Computational results: Decentral integration approach

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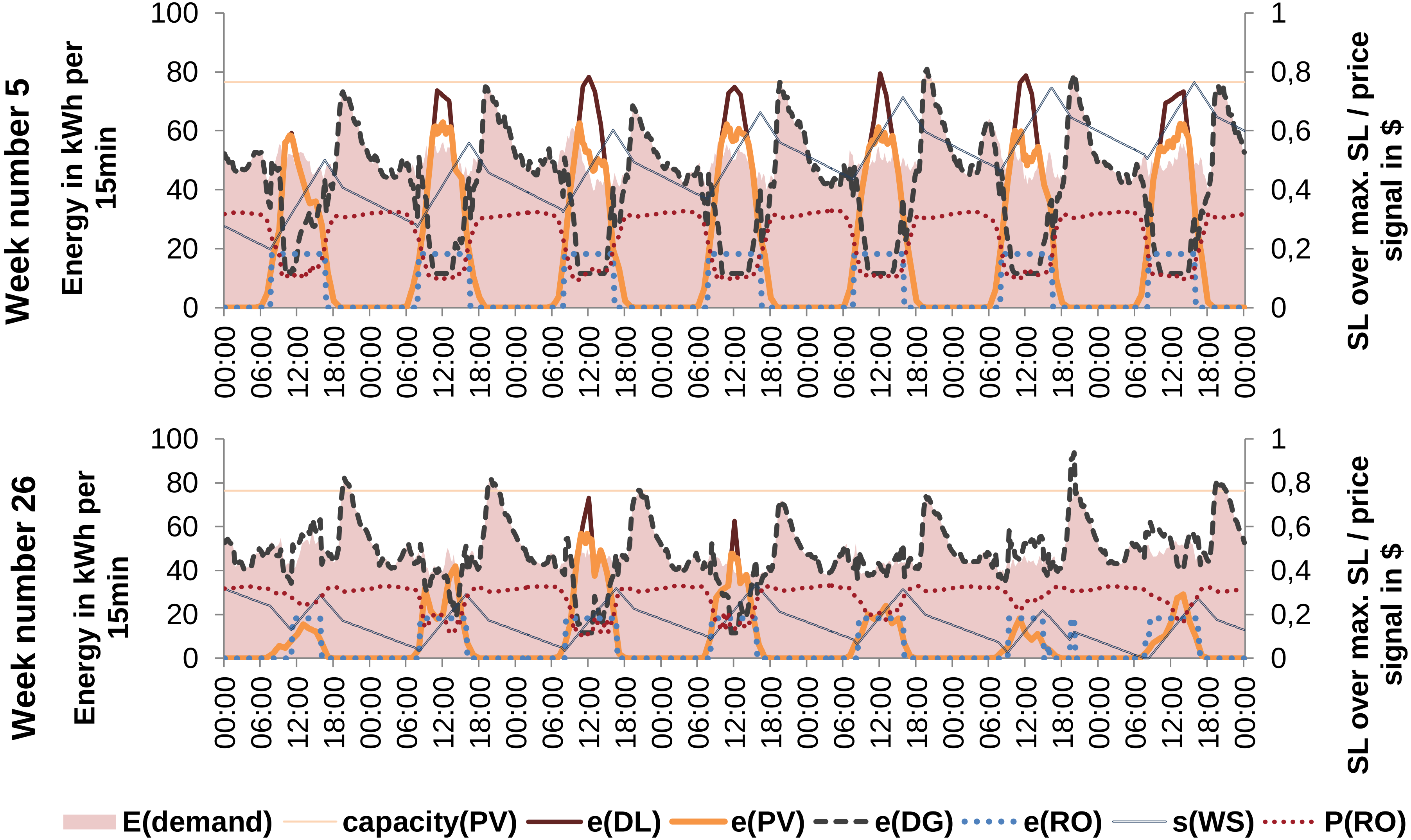
- PV capacity: Obtained from centralized optimization

Scenario	PV capacity (kW_p)	Energy by PV (kWh)	Sum of DL (kWh)	% of PV	% of DL on PV
Centralized optimization	304.4	481694	35532	23.8 %	6.9 %
Decentralized integration	304.4	481549	35677	23.8 %	6.9 %

- Nearly same results for energy supply ⇨ same total costs
- **Different operational characteristics**
  - Similar on/off operation for each day
  - Low PV generation + low price signal for evening peak ⇨ Overload of DG

4 Computational results: Decentral integration approach



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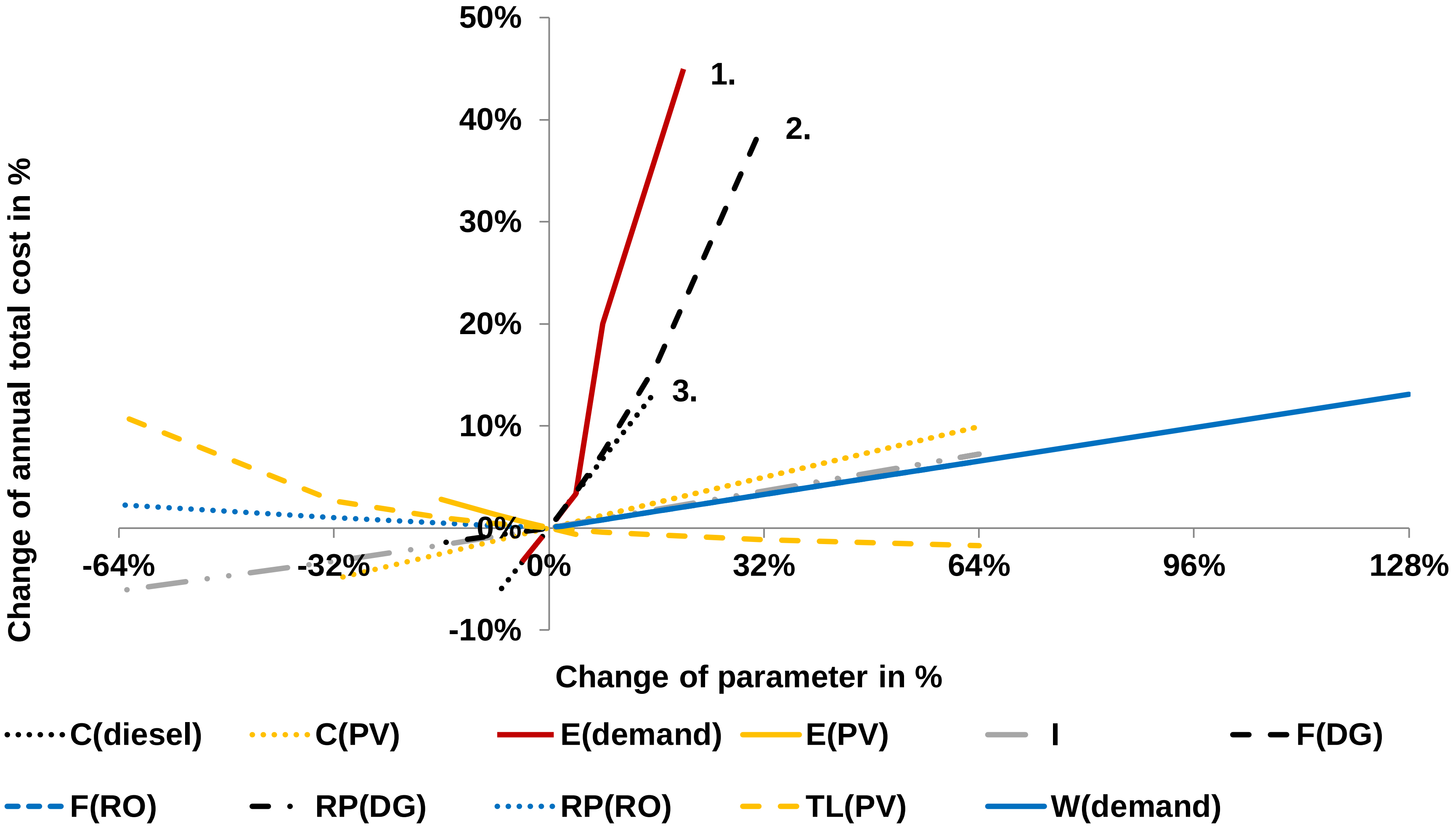
4 Computational results: Most important uncertain parameters



5 Conclusion

- Integration of PV power generation results in lower cost for the energy supply

- Integration of flexible loads results in higher penetration of PV power
  - ⇒ Lower cost of energy supply
  - ⇒ Better utilization of PV power
  - Battery storage not economical at the moment

5 Conclusion

- Decentralized integration approach results in same key figures
  - Different operational charactistics
  - Overload of DG
  - Simple case: integration of one load

- Most important uncertain parameteras related to the DG
  - Electricity demand
  - DG efficiency
  - Diesel price

5 Outlook

- Future research towards higher penetration of renewable energies
  - Wind power
  - High capacities of battery storage to shut down DG

- Future reasearch of decentral integration of flexible loads
  - Several loads
  - Different load/flexibility characteristics
  - Linkage to electricity frequency

Thank you for your attention!
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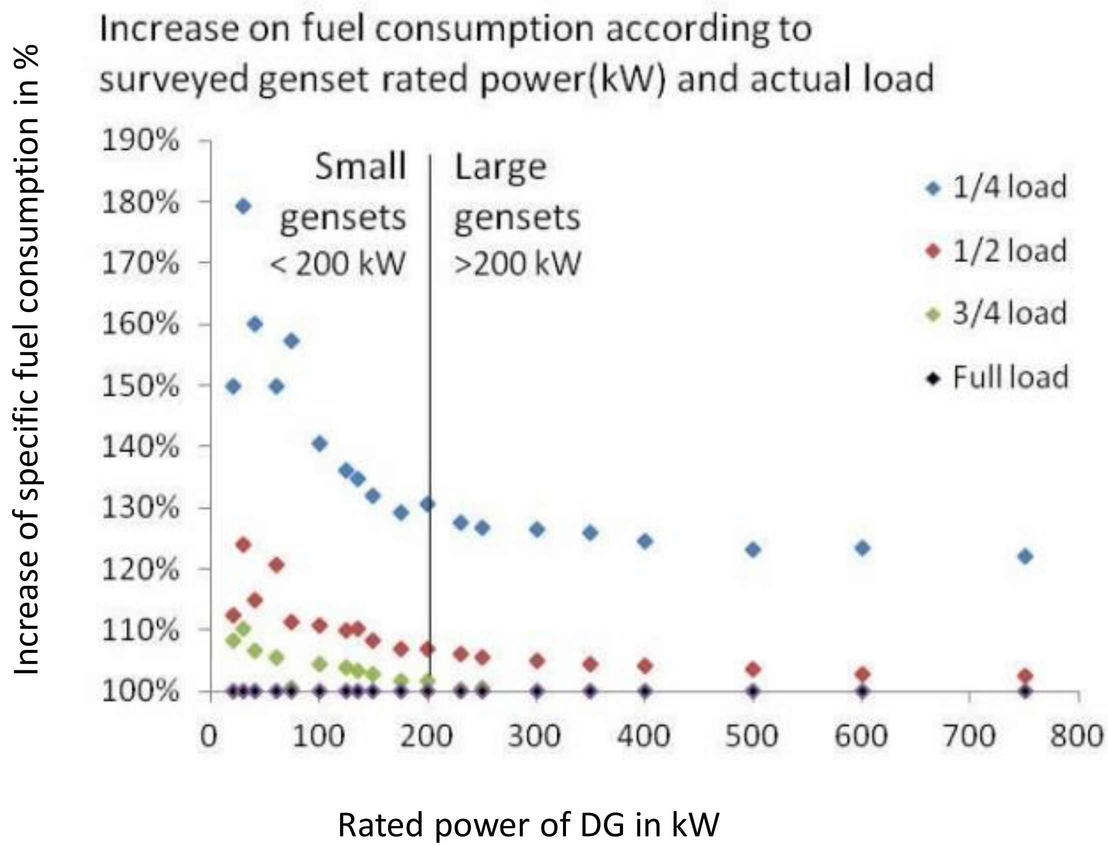
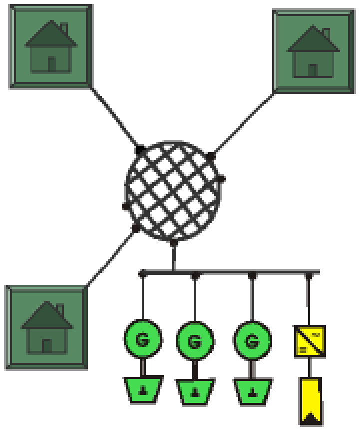
Diesel generator

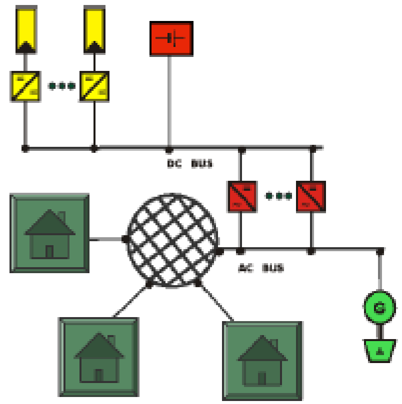


Grid configuration

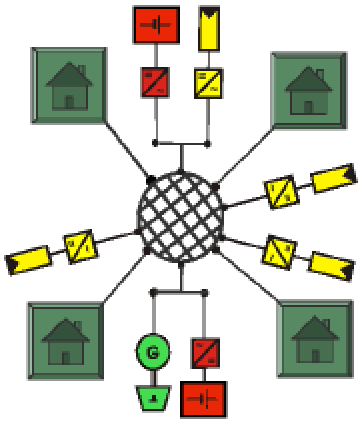
multi-master DG dominated grid:



single switching master grid:



multi-master inverter dominated grid:



- Annuity factor: $A^{PV} = \frac{(1+I)^{LT^{PV}} \cdot I}{(1+I)^{LT^{PV}} - 1}$
- Diesel generator
  - $F^{DG,C} = L^{DG} \cdot F^{DG,A}/3$
  - $F^{DG,B} = F^{DG,A} - F^{DG,C}$
  - $diesel_t = e_t^{DG} \cdot F^{DG,B} + F^{DG,C} \cdot b_t^{DG} \cdot {RP^{DG}}/{4} \qquad \forall t$
  - $e_t^{DG} \leq b_t^{DG} \cdot {RP^{DG}}/{4} \qquad \forall t$
  - $e_t^{DG} \geq b_t^{DG} \cdot {RP^{DG}}/{16} \qquad \forall t$

- Battery storage:
  - $e_t^{BS} = e_t^{BS,pos} - e_t^{BS,neg} \qquad \forall t$
  - $s_t^{BS} \leq capacity^{BS} \cdot S^{BS,cap} \qquad \forall t$
  - $e_t^{BS} \leq capacity^{BS} \cdot E^{BS,cap}/_4 \qquad \forall t$
  - $e_t^{BS} \geq -capacity^{BS} \cdot E^{BS,cap}/_4 \qquad \forall t$

- Grid stability:
  - $g_t^{BS}/_2 + e_t^{DG} \geq RP^{DG}/_4 \qquad \forall t$
  - $g_t^{BS} \leq s_t^{BS} \qquad \forall t$
  - $g_t^{BS} \leq capacity^{BS} \cdot E^{BS,cap} \qquad \forall t$

- RO system:
  - $e_t^{RO} - e_{t-1}^{RO} = e_t^{RO,pos} - e_t^{RO,neg} \qquad \forall t$
  - $e_t^{RO} \leq {RP^{RO}}/{4} \cdot b_t^{RO} \qquad \forall t$
  - $e_t^{RO} \geq {RP^{RO}}/{16} \cdot b_t^{RO} \qquad \forall t$

Different scenarios for variable RO integration

Scenario	PV capacity (kW_p)	% PV of energy demand	% of DL on PV	BS (units)	Total cost ($)	PV cost ($)	LCOE ($/kWh)
Variable	237.8	19.7 %	1.0 %	-	579,084	69,840	0.286
Variable	304.4	23.8 %	6.9 %	-	575,159	89,403	0.284
Var.+2*WD	304.4	21.6 %	6.9 %	-	634,112	89,403	0.284
2*Var.	357.8	28.8 %	4.1 %	-	561,720	105,058	0.277
2*Var.+2*WD	402.4	28.0 %	6.8 %	-	618,171	118,181	0.277

Binary RO system: Results/operational characteristics

Scenario	PV capacity (kW_p)	% PV of energy demand	% of DL on PV	BS (units)	Total cost ($)	PV cost ($)	LCOE ($/kWh)
Variable	304.4	23.8 %	6.9 %	-	575,159	89,403	0.284
Binary1	303.2	23.7 %	6.8 %	-	575,177	89,034	0.284
Binary2	304.4	23.8 %	6.9 %	-	575,160	89,403	0.284

Scenario	System shut down ($e_t^{RO} = 0$)	Invalid operation range ($0 < e_t^{RO} < 4.6$)	Valid variable operation range ($4.6 < e_t^{RO} < 18.4$)	Full load operation ($e_t^{RO} = 18.4$)
RO3	68.8 days	126.0 days	136.2 days	34.0 days
RO3bin1	126.3 days	-	203.7 days	35.0 days
RO3bin2	122.9 days	-	208 days	34.1 days

Economical numbers for RO system / operational characterstics decentral integration

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Scenario	RO capacity (m³/d)	$cost^{RO}$ ($)	$cost^{total}$ ($)	$cost^{total+RO}$ ($)
Fix RO	225	31,714	586,028	617,742
Variable RO	700	98,666	575,159	673,825

Scenario	System shut down ($e_t^{RO} = 0$)	Invalid operation range ($0 < e_t^{RO} < 4.6$)	Valid variable operation range ($4.6 < e_t^{RO} < 18.4$)	Full load operation ($e_t^{RO} = 18.4$)
Central	68.8 days	126.0 days	136.2 days	34.0 days
Decentral	246.9 days	0.7 days	1.0 days	116.4 days

Ranking of uncertain parameter

Parameter	Maximal absolute deviation of the annual total cost	Ranking of the importance of the parameter
C^{diesel}	13.5 %	3.
C^{PV}	10.0 %	6.
$\sum E_t^{demand}$	45.0 %	1.
$\sum e_t^{PV+DL}$	2.8 %	9.
$F^{DG,A}$	39.7 %	2.
F^{RO}	6.7 %	8.
I	7.3 %	7.
LT^{PV}	11.1 %	5.
RP^{DG}	1.4 %	11.
RP^{RO}	2.3 %	10.
$\sum W_t^{demand}$	13.1 %	4.