



### Simulation of Grid-connected PV Systems with Battery Storage

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## Contents

- Battery Model
- Dispatch strategies
  - Peak Shaving
  - Self-Consumption
  - Weak Grid Islanding
- Parametric studies
  - Peak Shaving
  - Self-consumption
- Summary and Outlook



# **Battery Model Overview**

Technologies: Lead-acid and Li-Ion

Battery behavior is simulated as function of:

- Charge/Discharge rate
- Temperature
- Depth of discharge (DoD)



Model determines:

- State of Charge (SOC)
- Battery Voltage
- Battery Losses
- Ageing (State of Wear SOW)

Operating mode (charging/discharging) according to SOC (or Voltage)



# **Dispatch Strategies**

#### Simul. variant: 500 kWp, Peak shaving



#### Simul. variant: 1 MWp, self consumption, small inverters





### **Peak shaving**

PV Array + Storage + Injection power limitation

### Self-consumption

PV Array + Storage + Load Profile

### Weak Grid Islanding

PV Array + Storage + Load Profile + Grid Outages



# **Peak Shaving Mode**

### Aims at recovering curtailed energy generation





Only dispatch strategy where Battery injects into grid

Charge Battery as soon as Production is larger than threshold

Discharge either as soon as possible, or at pre-defined time intervals



# **Peak Shaving Simulation Results**

#### 500 kWp, Peak shaving



EBatDis:	Stored energy (impacts cycling, i.e. battery lifetime)
EBatDis-EBatCh:	Battery storage efficiency (coulombic efficiency, internal resistance, gassing),
CL_Chrg:	Charger efficiency losses
CL_InvB:	Battery inverter efficiency losses
EUnused :	Unused energy, either when the battery is full, or if the charging power exceeds the maximum power of the charger
E_Grid :	Energy ejected into grid



# **Self-Consumption Mode**

# Aims to minimize energy use from grid



### Load profiles must be supplied by user. Examples:



Source: Generic load profiles from BDEW (https://www.bdew.de/energie/standardlastprofile-strom/





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# **Self-Consumption Simulation Results**

Example: Commercial, 1 MWp, self consumption scaled to 2463 MWh/year 2024 kWh/m<sup>2</sup> Horizontal global irradiation +15.2% Global incident in coll. plane -2.72% IAM factor on global EBatDis: Stored energy 2267 kWh/m<sup>2</sup> \* 8693 m<sup>2</sup> coll. Effective irradiation on collectors (impacts battery lifetime) efficiency at STC = 14.78% PV conversion 2913 MWh Array nominal energy (at STC effic.) -0.29% PV loss due to irradiance level 10.74% PV loss due to temperature +0.75% Module quality loss ⇒ -1.10% Mismatch loss, modules and strings CL\_Chrg: ⇒)-1.27% Ohmic wiring loss 2550 MWh Array virtual energy at MPP CL InvB: -2.94% Inverter Loss during operation (efficiency) ₩-1.53% Inverter Loss over nominal inv. power ₩0.00% Inverter Loss due to max. input current E User: → 0.00% Inverter Loss over nominal inv. voltage →-0.01% Inverter Loss due to power threshold ₩0.00 Inverter Loss due to voltage threshold 2438 MWh Available Energy at Inverter Output E Solar: ⇒-1.61% Battery IN, charger loss Stored Direct use Battery Storage grid 41.0% 59.0% consumption Set 1.43% Battery global loss 9.2% (3.57 % of the battery contribution) **EFrGrid**: of time ⇒)-1.88% Battery OUT, inverter loss 159 MWh 2219 MWh 101 NWh Dispatch: user and grid reinjection SolFrac: to user to user to grid

EBatDis-EBatCh: Battery storage efficiency (coulombic efficiency, internal resistance, gassing),

- Charger efficiency losses
  - Battery inverter efficiency losses
- Total energy consumed by user (hourly load profile)
- Consumption coming from PV
- Energy from grid
- "Solar Fraction" (ratio of solar energy, to total consumption) E Grid:
  - the excess energy, injected into the grid



#### **Bruno Wittmer**

from solar

from grid

# Weak Grid Islanding Mode

Like self-consumption, Battery discharge is limited to allow supply during grid outages





With/without grid injection (only PV, not Battery)

Loss of Load is possible!



# **Weak Grid Islanding Simulation Results**

EBatDis:

#### 500 kWp, eak grid



rizontal global irradiation obal incident in coll. plane	EBatDis
I factor on global	
ective irradiation on collectors	
conversion	CL_Chrg
ray nominal energy (at STC effic.) loss due to irradiance level	
loss due to temperature	CL_INVB
dule quality loss	
match loss, modules and strings mic wiring loss	E_User:
ray virtual energy at MPP	
erter Loss during operation (efficiency) erter Loss over nominal inv. power	E_Solar:
erter Loss due to max. input current	
erter Loss over nominal inv. voltage erter Loss due to power threshold	EFrGria
erter Loss due to voltage threshold	
ailable Energy at Inverter Output	E Miss:
ttery IN, charger loss ttery Storage	
ttery global loss	SolFrac:
.32 % of the battery contribution)	
used energy (battery full)	
er needs, grid injection and missing energy	E_Grid:
	EUnuse

Stored energy (impacts battery lifetime)

**EBatDis-EBatCh**: Battery storage efficiency (coulombic efficiency, internal resistance, gassing),

- CL\_Chrg:Charger efficiency lossesCL\_InvB:Battery inverter efficiency losses
- E\_User: Total energy need (load profile)
- E\_Solar: Consumption coming from PV
- EFrGrid: Energy from grid (if available)
  - Missing energy (outage & empty batt.)
    - "Solar Fraction" (ratio of solar energy, to total consumption)
    - Energy injected into grid (if possible)
- EUnused: Battery full and no injection possible



# **Parametric Studies (Batch Mode)**

Batch mode allows to run many simulations at once, while varying many (30-40) different simulation parameters

Parameters that are useful in parametric studies with grid storage:

- PV Capacity
- Battery capacity
- Grid injection power limitation
- Self-consumption profile -
- Grid unavailability

# Output variables useful in studies with grid storage:

PV Power	Average SOC	Total battery loss	Solar energy	di
Energy after battery	SOC end of simulation step	SOC energy balance	Load direct from solar	sir Oi
Energy inj. to grid	Charging time	Charging loss	Supplied load	ar
Energy from grid	Discharging time	Discharging loss	Solar fraction	Arr Bai
Energy from Sun	Charged energy	SOW due to cycling	Missing energy	
	Discharged energy	Static SOW	Loss of load	Ene
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PVsyst allows to output ≈ 100 different variables containing simulation results Output of yearly, monthly, daily and hourly values is possible

Grid unavailability

Array and System Battery behavior Energy use

Mar

Apr

May



20 H

23 H

0 H

43 H 11 н

15 H

# **Peak Shaving: Curtailed Energy**

### Overload loss as function of Pnom ratio



### Curtailed energy that can be re-injected





### Peak Shaving: Recovered Energy

### Return = Battery Discharge x FIT Battery cost = Battery Capacity x Battery price / lifetime



1MWp system in sunny desert climate

Vary Battery capacity in batch mode

Battery discharge energy is the additionally sold energy

Assume constant FIT

Battery price : 150 \$/kWh

Battery lifetime: 8 years

More complete calculations would include cost of capital, devaluation, varying FIT, etc.



# Self-Consumption: Generation/Consumption Mismatch

Assume that the battery is used for daily storage (battery transfers energy from day to night)

**Daily** energy consumption that is not covered by direct PV generation. Determines Battery Capacity





Generic load profile for commercial consumers, scaled to 2463 MWh/year Source: BDEW

Difference between **daily** PV overproduction and energy need Determines PV capacity



# **Self-Consumption: Parametric study**

For a given load profile vary PV and Battery Capacity

Commercial, scaled to 2463 MWh/year



Parameters of Example:Consumption2463 MWh/yearElectricity price0.13 \$/kWhPV costs1.4 \$/WpPV lifetime25 yearsBattery cost150\$/kWhBattery lifetime5-7 years(acc. to simulated SOW)

Simple example: No cost of capital considered No ageing propagation from year to year

### Savings:

Avoided energy purchase – System costs (no return for injected energy)



# **Summary and Outlook**

Battery models for Lead-acid and Li-Ion

Three dispatch strategies for grid-tied systems with storage:

- Peak shaving
- Self-consumption
- Weak grid islanding

Parametric scans are possible for detailed studies

- PV capacity
- Battery capacity
- Load profiles
- Power outage periods

Outlook:

- Propagate Battery ageing for multi-year simulations
- Add financial variables to batch output
- Implementation of real components
- Improve tools as understanding grows
- Implement optimization tool for storage

