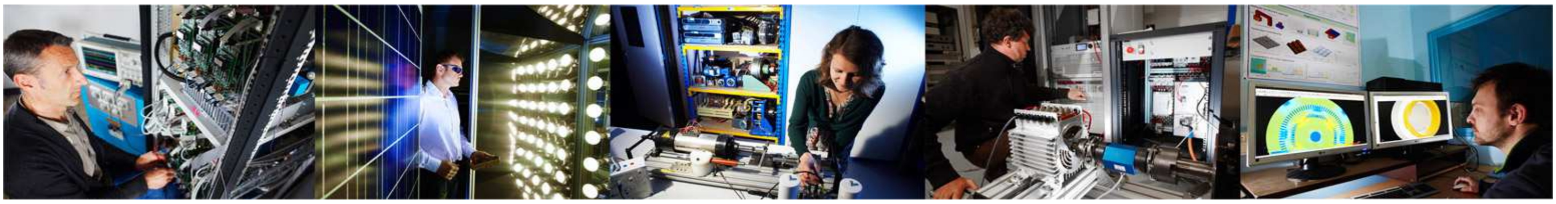


6/23/2021

Stochastic Optimization for Generation Scheduling in a Local Energy Community under Renewable Energy Uncertainty

Xin WEN

Supervisors: Bruno FRANCOIS
Dhaker ABBES

L2EP, Centrale Lille, France

L2EP Laboratoire d'électrotechnique et d'électronique de puissance de Lille

CHINA SCHOLARSHIP COUNCIL 国家留学基金管理委员会 · Université de Lille 1 Sciences et Technologies · Arts et Métiers ParisTech · centralelille · HEI

Part 1 Introduction: Context, objectives and methods

1.1 Context : High penetration ratio of renewable energy sources (RESs) in local energy communities

- Energy and Climate Change

Decarbonization and sustainable development

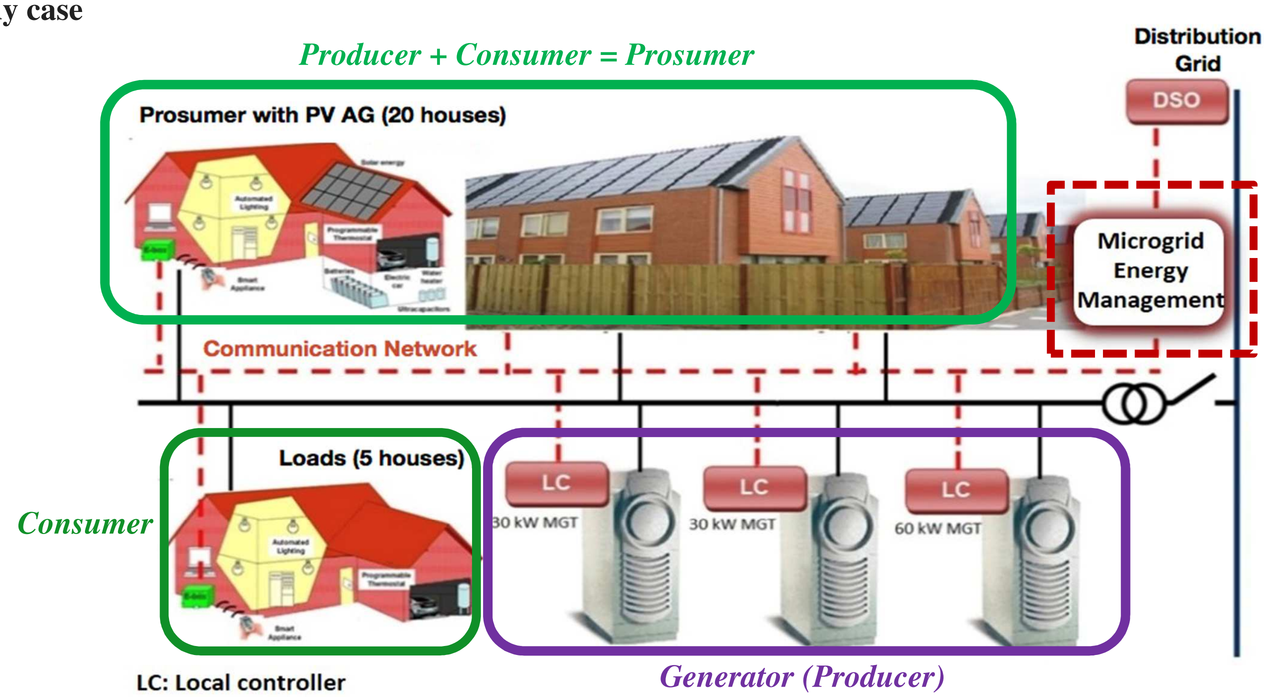
- Increase energy efficiency
  - Reduce power flow transmission losses in a large electrical system
  - Cost saving by reducing agents in commercial and operational transactions
- Reduce environmental impact
  - Substitution by carbon free generation

→ **Local RES based electrical production for local consumption**

- Decarbonization, decentralization and democratization of the electricity generation and management.
- Emerging of Local Energy Communities (related also with islanded networks and microgrids).
- Increasing the participation of RES in the electrical system, introduces **uncertainties** and problems.
  - Local energy balancing
  - Reliability and operational power reserve
  - Economic costs and CO_2 abatement
- How to **integrate RES into operational planning, anticipation and flexibility** in energy management systems?
- Needs for numerical methods that handle **RES uncertainty** in modelling and optimization.

1.2 Context : A local energy community--- An urban microgrid

- **Study case**

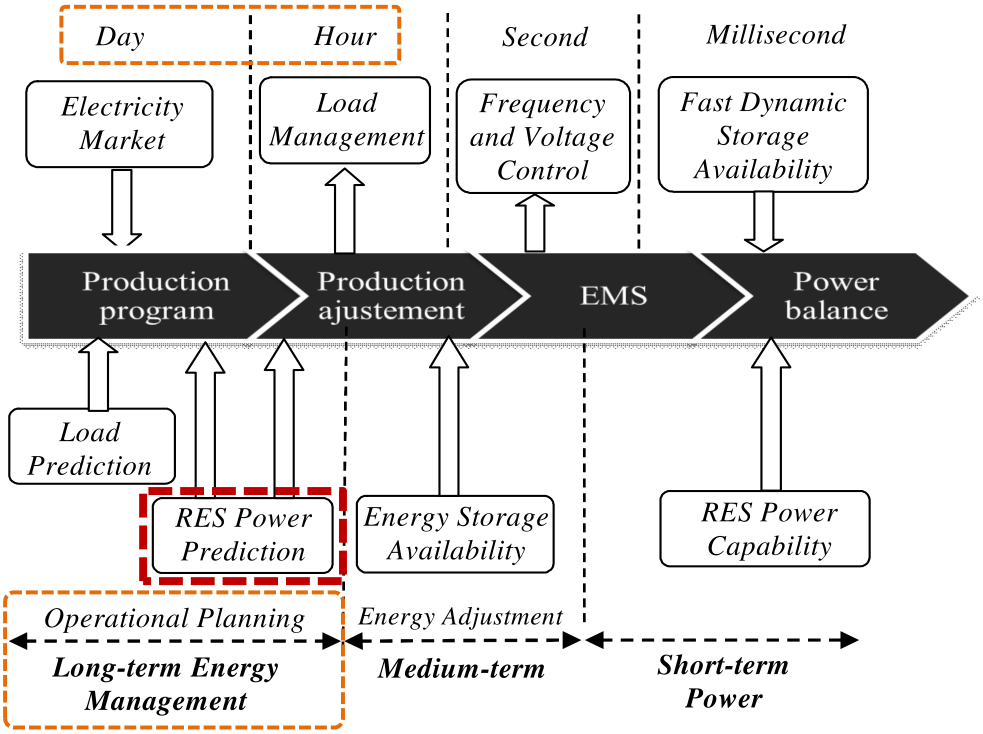


LC: Local controller
MGT: Micro gas turbine
DSO: Distribution system operator
PV AG: Photovoltaic active generator

- Micro Gas Turbines are considered to study impacts of RES on existing generation in electrical systems
- Out of the scope : business plan, socio-economic issues and transaction markets

1.3 General Organization of Energy Management System (EMS)

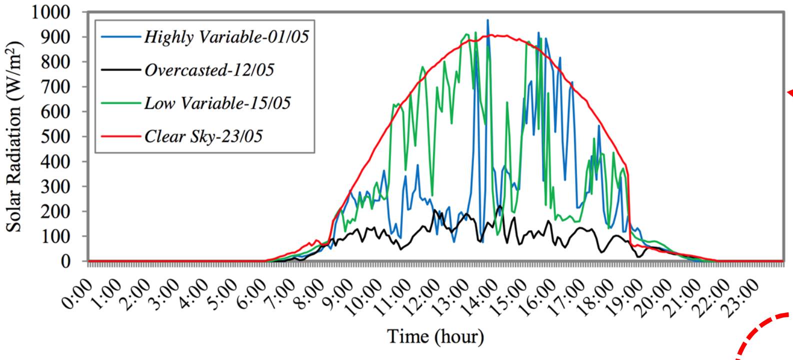
- Organization of a Microgrid supervision in different time scales



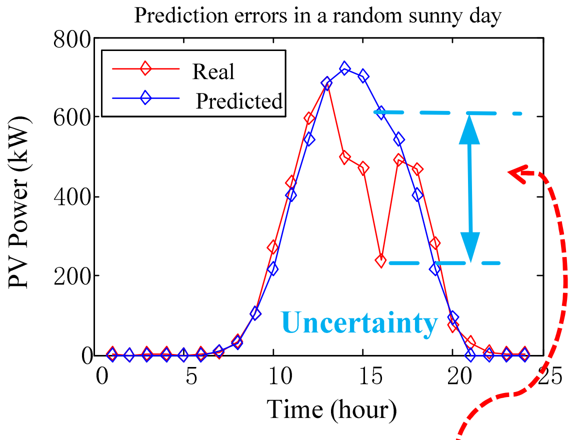
- Focus on day-ahead load and RES predictions, uncertainty analysis, and optimization of the network operation.

1.4 Origin and Characteristics of the Uncertainties

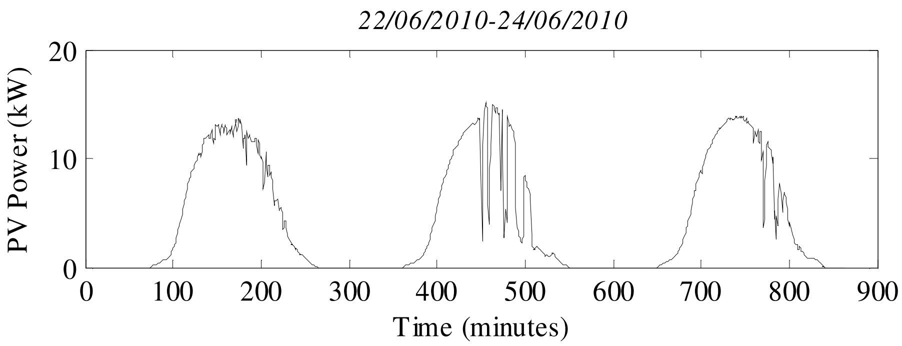
- Solar energy...



Different conditions of irradiance caused by cloudy variations



Uncertainty caused by forecasting errors

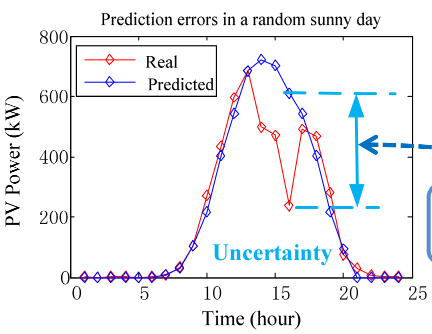


- PV generation is intermittent but predictable
- Unfortunately with errors !

1.5 Deal with uncertainty --- Reserve

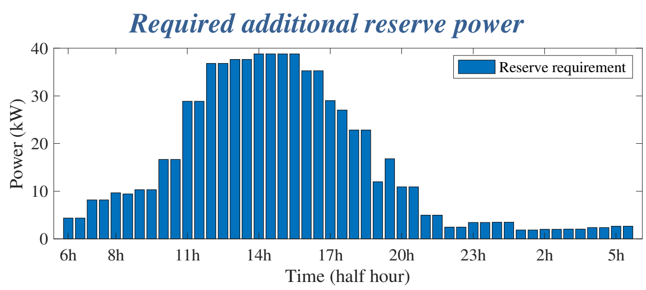
- To deal with this **variable uncertainty, additional reserve power** should be considered (as insurance to against the sudden loss of generation and / or unexpected increase of the demand).
- How **to schedule** the reserve power? How **to dispatch** reserve power on available flexibilities (generators, …) ?

Non-dispatchable renewable energy source

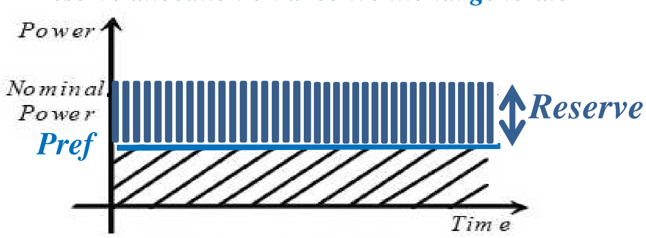


Uncertainty caused by forecasting errors

Required additional reserve power



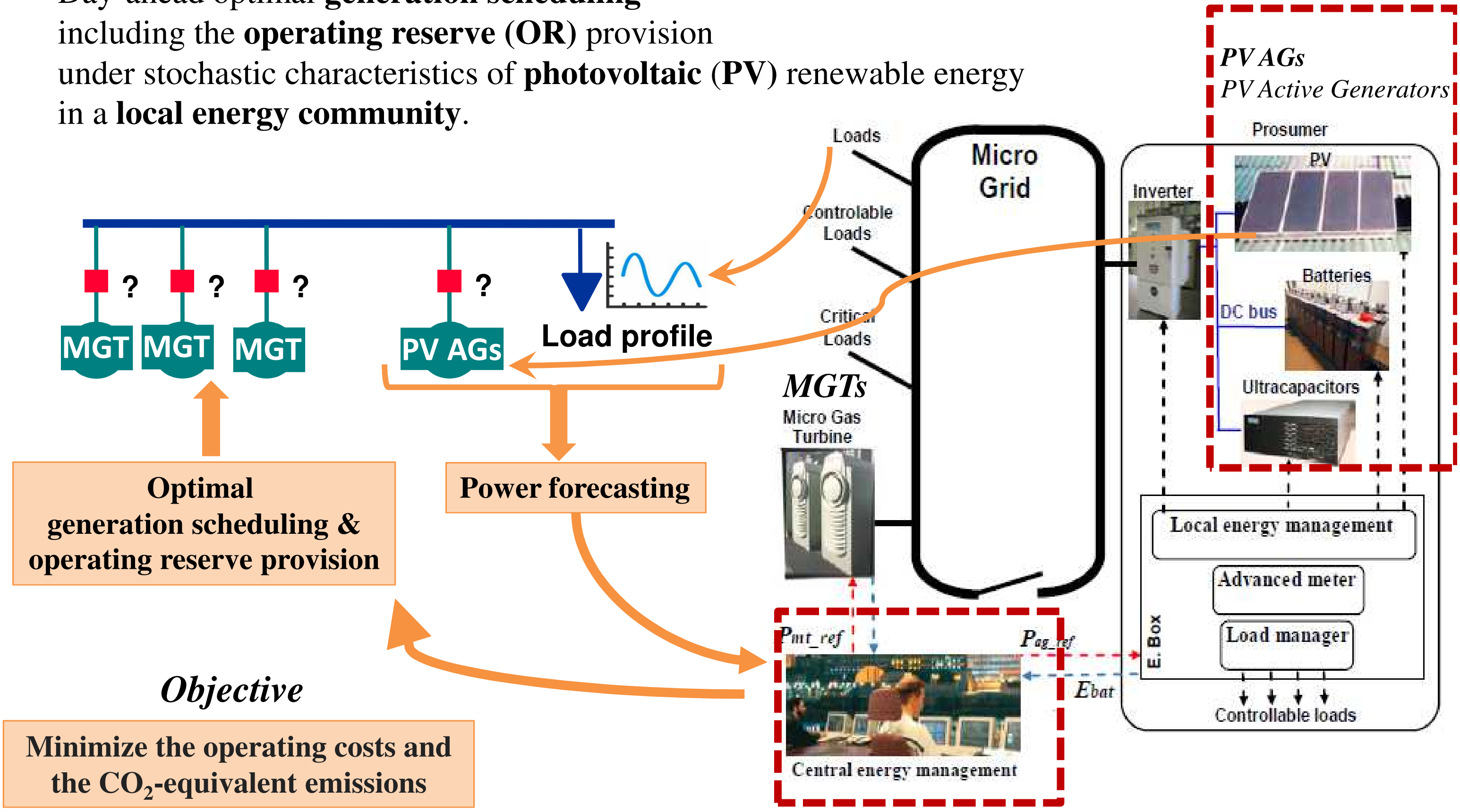
Reserve allocation on a conventional generator



- First, we consider the reserve is only provided by MGTs **already in service** (operating below their rated power), or by offline MGTs **with a fast start-up.**

1.6 Thesis issue

Day-ahead optimal **generation scheduling**
including the **operating reserve (OR)** provision
under stochastic characteristics of **photovoltaic (PV)** renewable energy
in a **local energy community**.



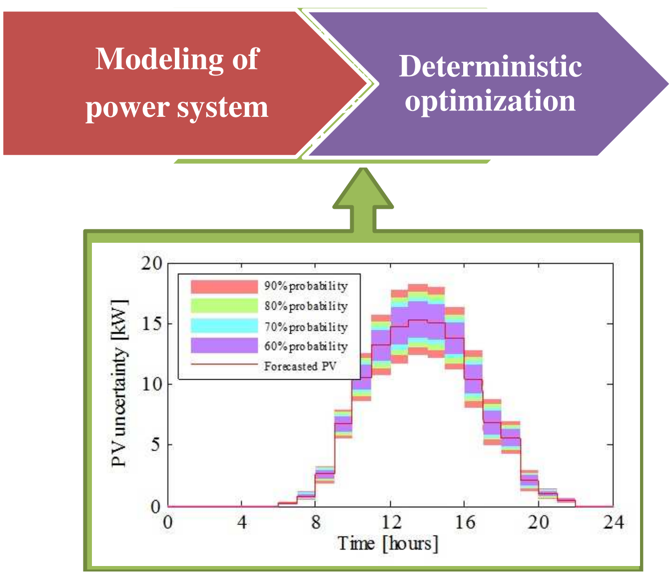
1.7 Previous work

PhD thesis of Hristiyan KANCHEV (L2EP), Jan 2014

Deterministic optimization of the generation scheduling for an urban microgrid.

PhD thesis of Xingyu YAN (L2EP), May 2017

Energy management **under uncertainty:** Deterministic optimization, **uncertainty analysis of past PV forecast, quantification and allocation of power reserve.**



1.8 Research targets / Scientific methods

1) Impacts of uncertainty onto objectives (operational costs and carbon emissions)

-> Propagation of uncertainty with persistent assumption

Uncertainty modelling with pdf of past data
Probabilistic-Based Deterministic Optimization

Uncertainty propagation analysis with probabilistic methods

2) Consideration of future uncertainties

->Integration of uncertainty in the solution search

Uncertainty modelling with future probable scenarios
Multi-Objective Stochastic Optimization

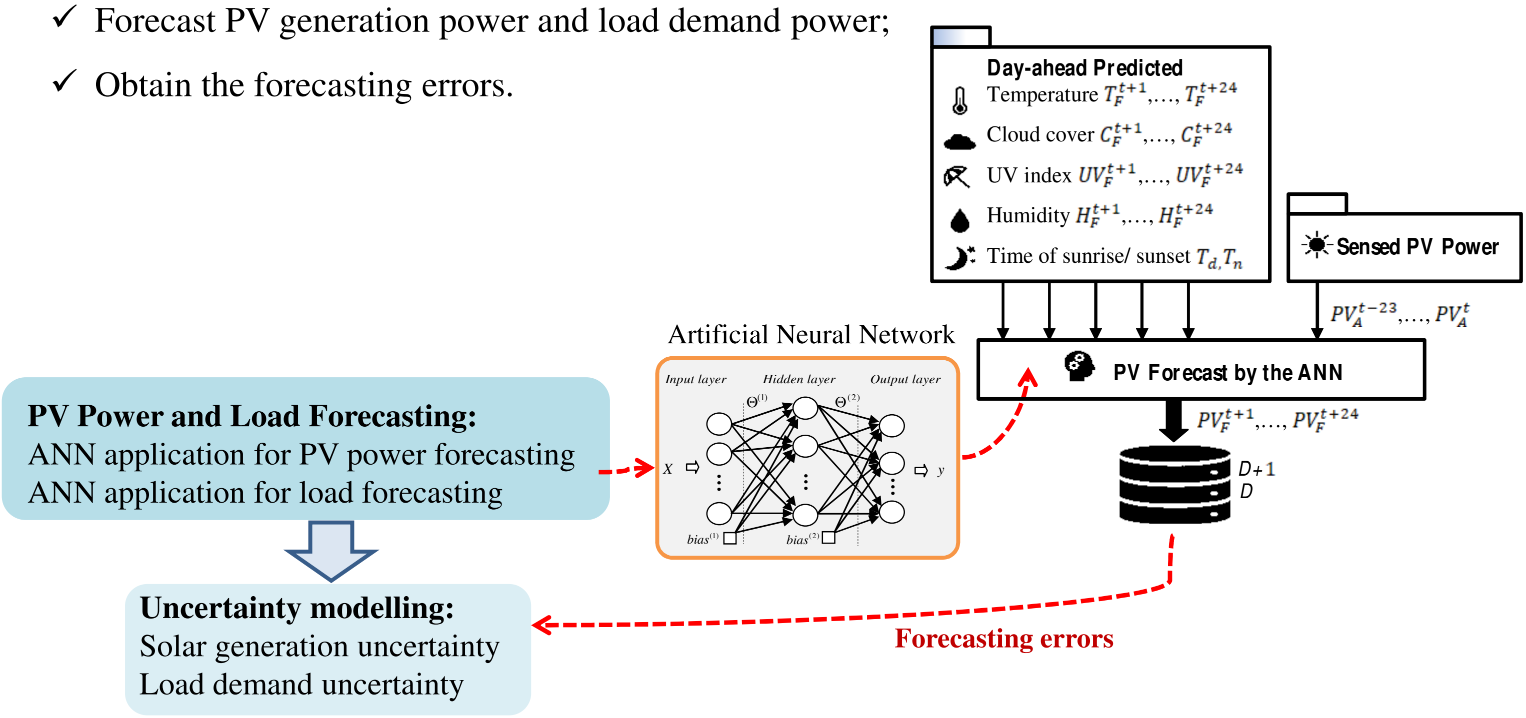
Scenario-based stochastic optimization approach
- Chance-constrained optimization
- Robust optimization with uncertainty set

CONTENTS

2.1 Sources of uncertainty : forecasting errors

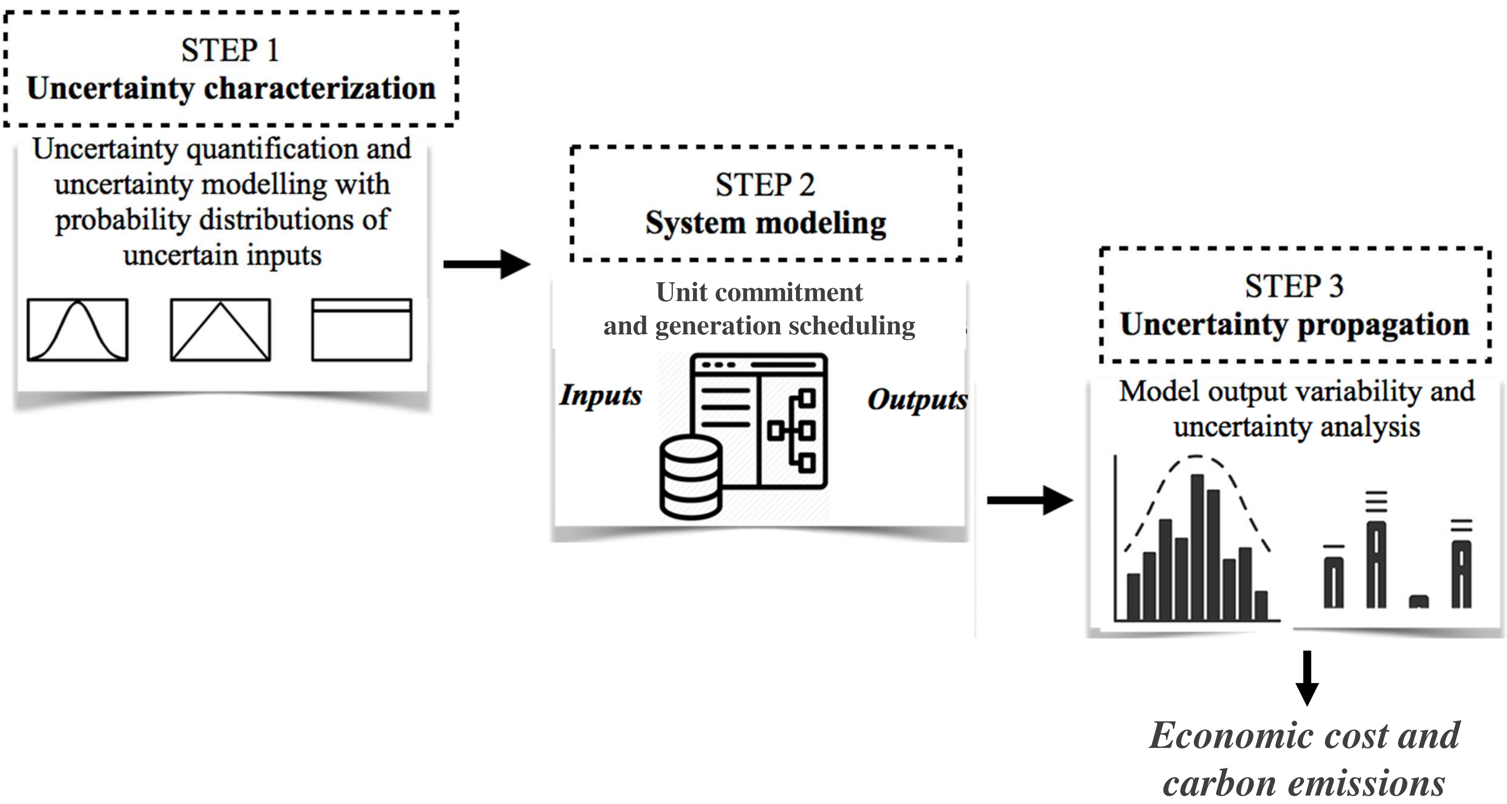
To build a database of forecasting errors, we consider artificial neural network (ANN) to:

- ✓ Forecast PV generation power and load demand power;
- ✓ Obtain the forecasting errors.



2.2 Uncertainty analysis in generation scheduling

Impact of uncertainty onto criteria : economic cost and carbon emissions ?

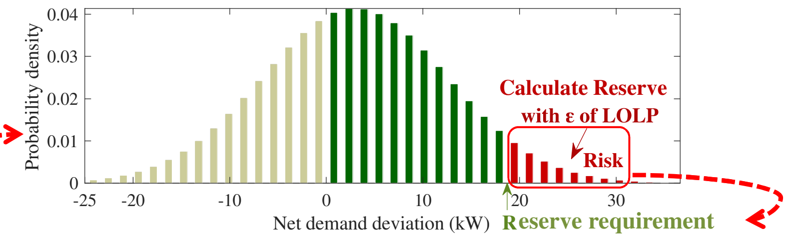


CONTENTS

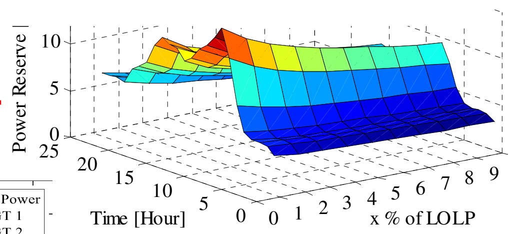
Part 3 Deterministic unit commitment under uncertainty

3.1 Methodology

Uncertainty representation:
PV Power and Load Forecasting Errors

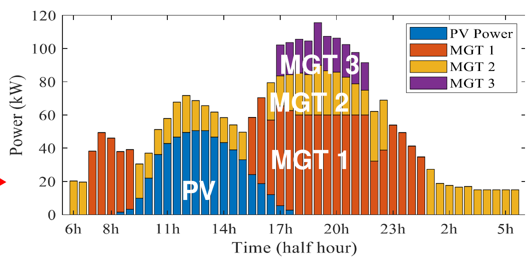


Operating Reserve Quantification:
Risk assessment by Loss of Load probability (LOLP)



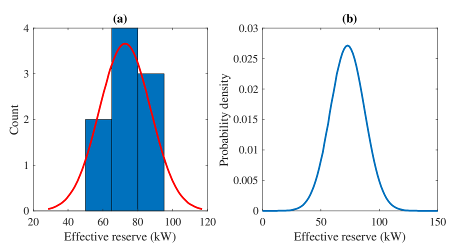
Operating reserve power profile

Day-ahead Generation Scheduling
with Dynamic Programming /
Mixed-integer linear programming



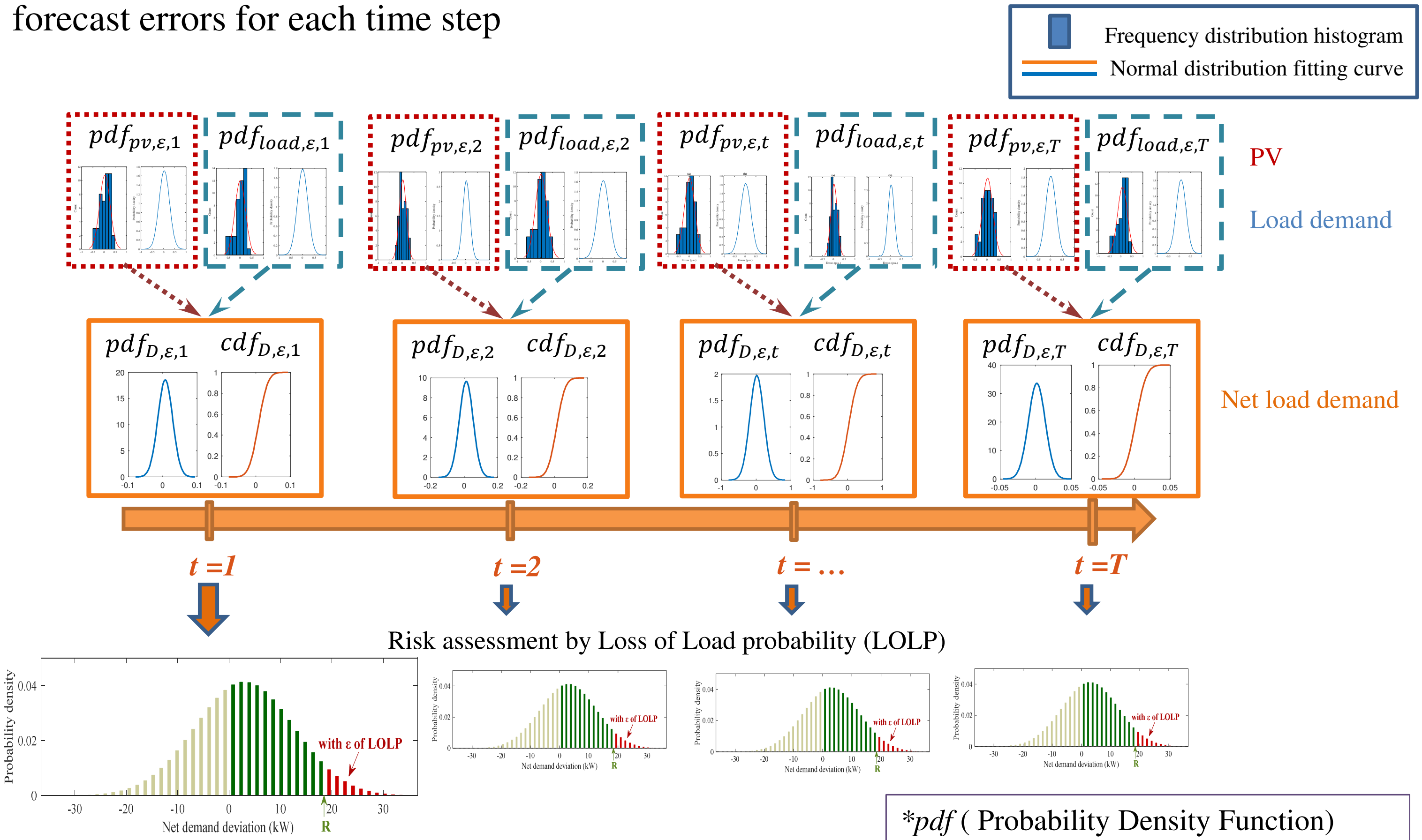
Planning of MGTs

Uncertainty propagation Analysis
regarding PV generation



We are going to detail each step...

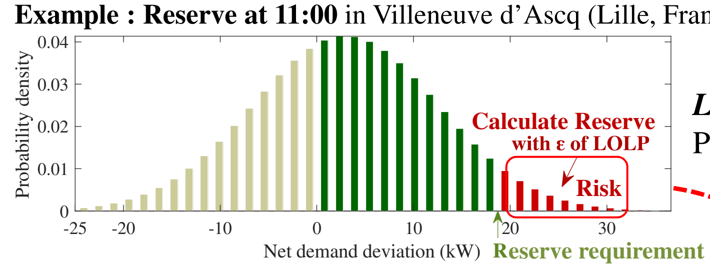
3.2 Reserve quantification from probabilistic analysis of forecast errors for each time step



**pdf* (Probability Density Function)
**cdf* (Cumulative Distribution Function)

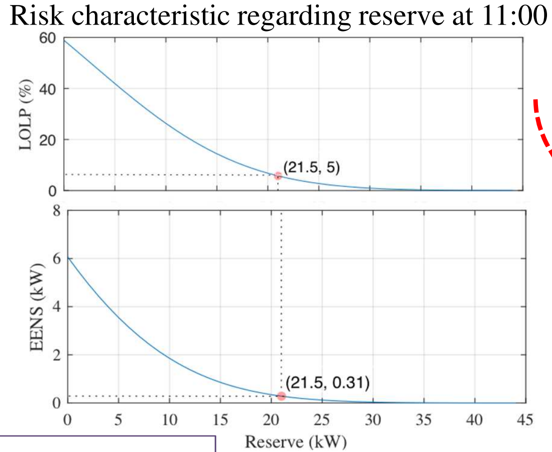
3.3 Reserve quantification from probabilistic analysis with forecast errors

Example : Reserve at 11:00 in Villeneuve d'Ascq (Lille, France) the 23[th] of June, 2020:



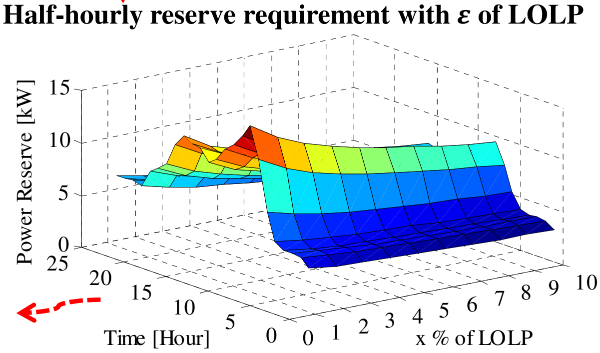
***LOLP* (Loss of Load Probability):**
Probability that load will exceed the available power generation.

Risk characteristic regarding reserve at 11:00



**EENS* (Expected Energy Not Served)

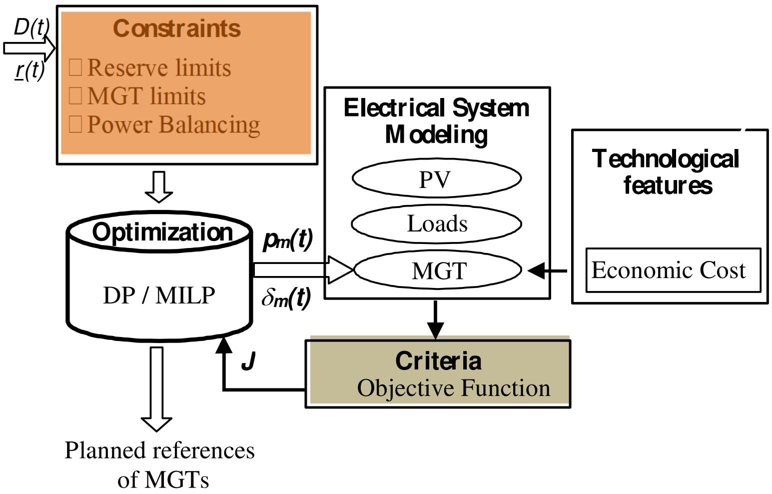
Half-hourly reserve requirement with ε of LOLP



Reserve power is obtained at each time step for tomorrow!

3.4 **Generation Scheduling** with deterministic optimization

- Optimization framework



$m \in \mathcal{M}$ Set of conventional generators

$t \in \mathcal{T}$ Set of time steps.

$p_m(t)$ M decision variables

DP: Dynamic programming

MILP : Mixed Integer Linear Programming

Constraints

Power balancing constraint

$$\sum_{m=1}^{M} p_m(t) = D(t)$$

$D(t)$: net load demand =(Load demand forecast – PV production forecast)

$p_m(t)$: power generated by MGT m at time step t

Reserve constraint

$$\sum_{m=1}^{M} p_m(t) = D(t) + \underline{r}(t)$$

$p_m(t)$: maximum available power of MGT m at time step t

$\underline{r}(t)$: reserve power

Generation limits constraint

$$\underline{p_m}\delta_m(t) \le p_m(t) \le \overline{p_m}\delta_m(t)$$

$\delta_m(t)$: State of the MGT m at time step t

$\underline{p_m}$, $\overline{p_m}$: minimum/maximum power generation limits of MGT m

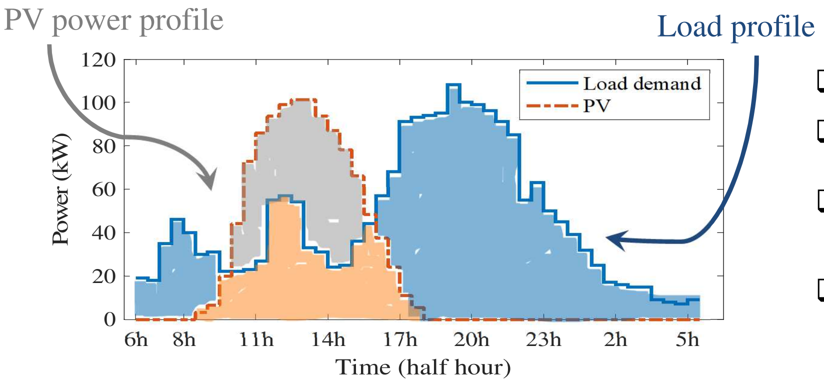
Criteria of optimization (J)

$$J = \min \sum_{t=1}^{T}\sum_{m=1}^{M} c_m\big(p_m(t)\big) + c_m^S s_m(t)$$

$c_m(p_m(t))$: fuel cost of producing $p_m(t)$

$c_m^S s_m(t)$: startup/shutdown penalties

3.5 Studied timing power profiles



- Forecasted daily PV energy is 539 kWh
- Forecasted daily load demand energy is 1082 kWh
- The PV self-consumption rate is about 50%
- The PV self-production rate is about 25%

- Without energy management and optimization during the day, a part of the available PV energy will not be consumed locally and will be lost (when power supply > Load demand).

  -> Hence the PV self-consumption rate and the PV self-production rate will decrease.

- The unused PV power (when the irradiance is high), can be valued by:
  - providing reserve power (scheduled PV limitation or PV curtailment), or
  - being saved in a storage (charging mode) in order to be used later (through a discharging mode),

Part 3 Deterministic unit commitment under uncertainty

3.7 Generation scheduling by considering N-1 criterion

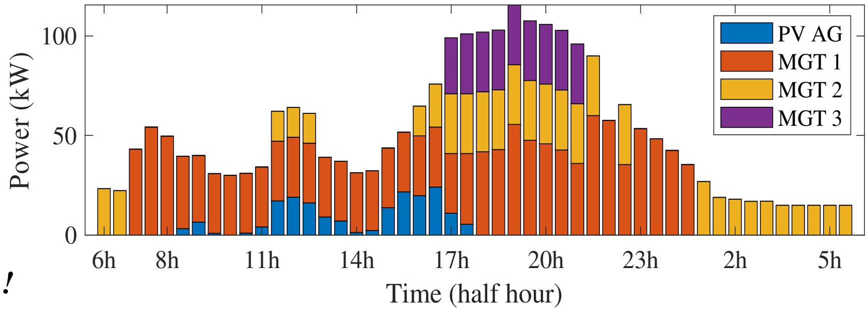
- The classical *N-1* criterion for the reserve quantification is implemented as following :
  1) PV AGs are not seen as reliable generators;
  2) Planning of MGTs commitment is calculated without considering PV generation
  3) For all committed MGTs, power references are reduced in case of PV production

If the minimum power limit of committed MGTs is achieved, the PV production is curtailed (or limited)

- Deterministic generation planning

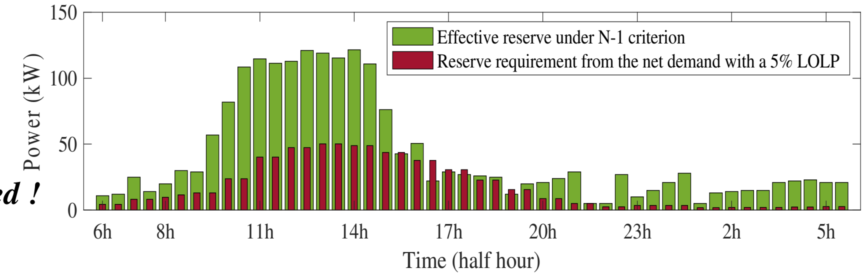
PV self-consumption rate = 17%

PV self-production rate = 9%



A significant part of PV generation is curtailed !

- Obtained effective reserve



Too much unnecessary effective reserve is provided !

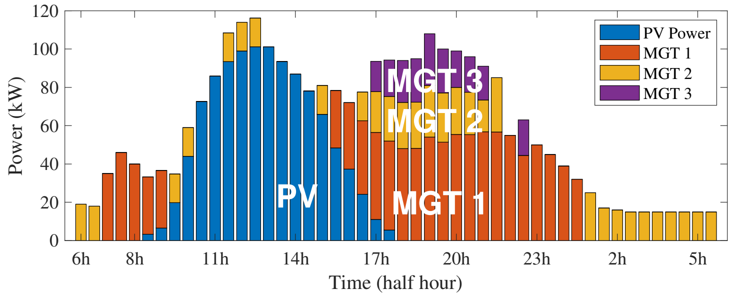
Part 3 Deterministic unit commitment under uncertainty

3.6 **Generation Scheduling** by considering probabilistic reserve provision

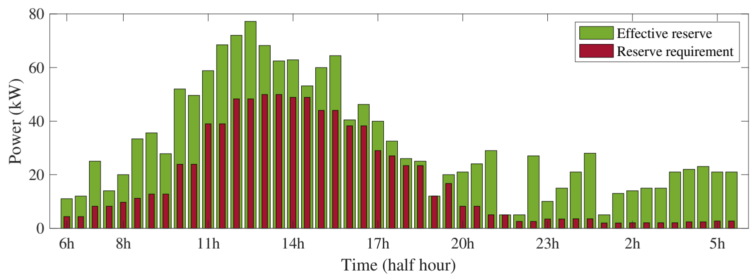
- Optimization method --- Dynamic programming (DP)
- Deterministic generation planning

PV self-consumption rate = 50%

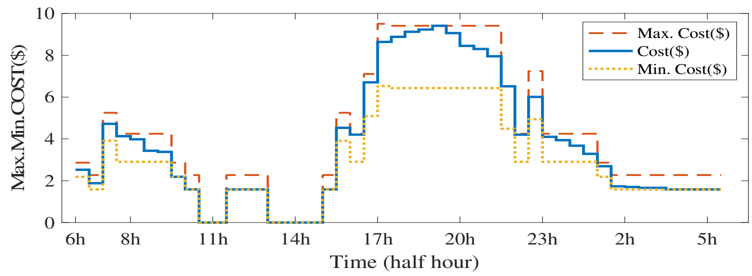
PV self-production rate = 25%



- Obtained effective reserve with a LOLP ≤ 5%

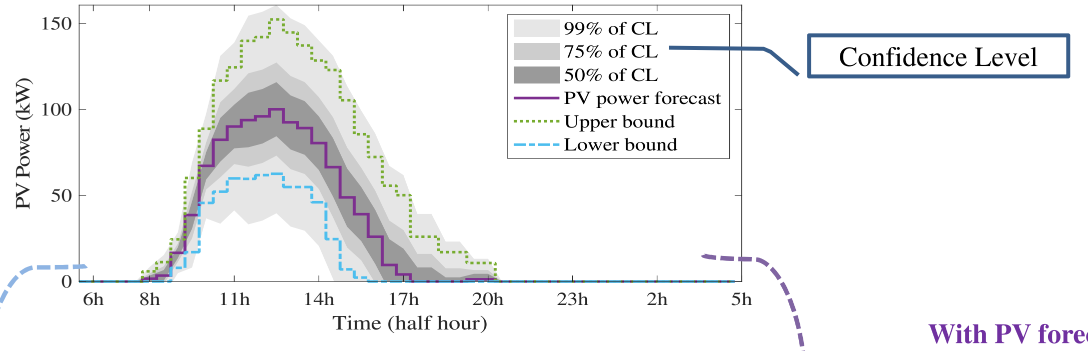


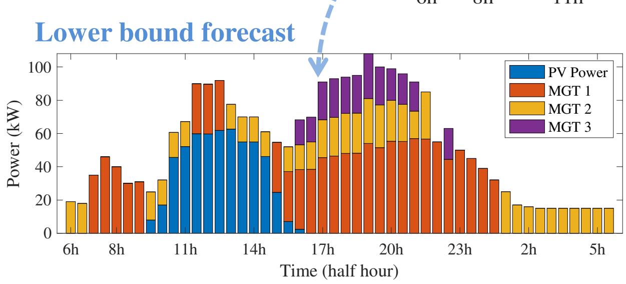
- Cost variation domain
  - Cost with exact forecasted data
  - Cost in case of upper bound:
    PV is less, OR is delivered
  - Cost in case of lower bound:
    PV is more, no delivered OR

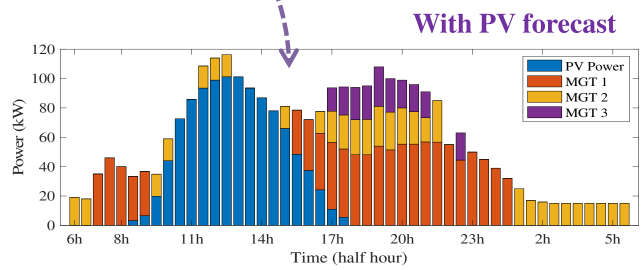


Part 3 Deterministic unit commitment under uncertainty

3.8 Impact of uncertainty in Dynamic Programming Optimization







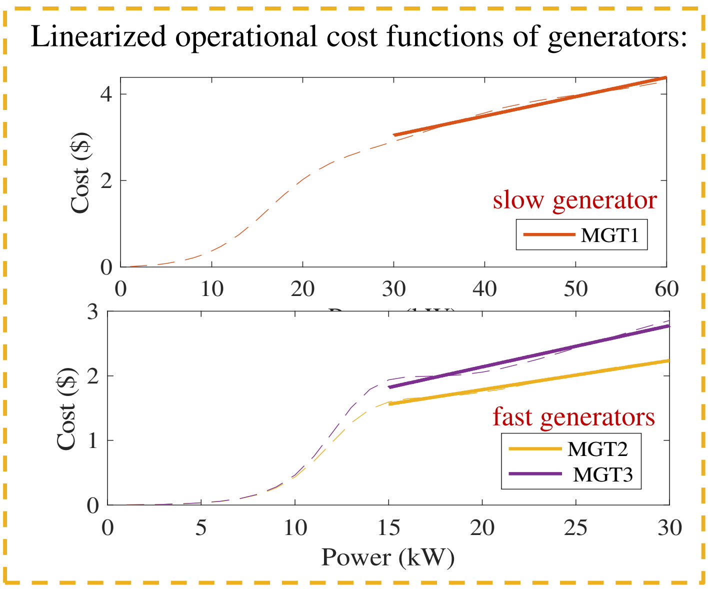
Impact of uncertainty onto cost and reserve variation domain

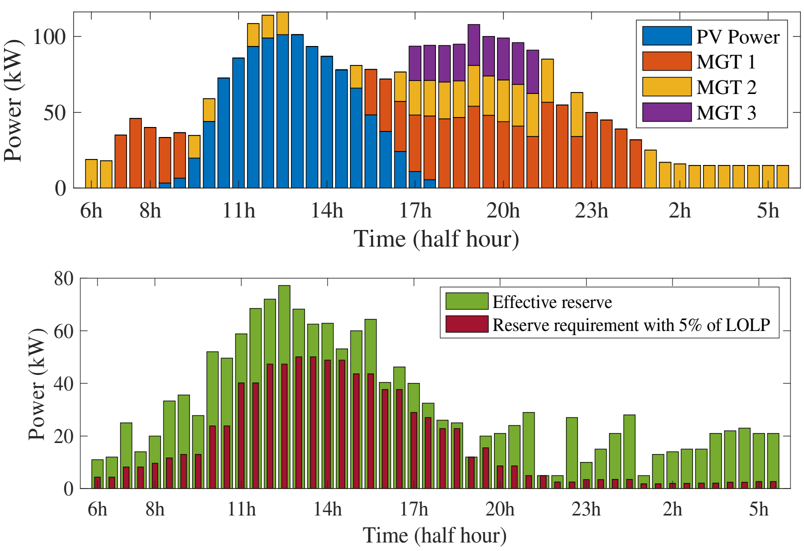
Scenarios	Daily Net Demand (kWh)	Daily PV (kWh)	Daily Reserve (kWh)		Daily Cost ($)		
			Positive OR (up power margin)	Negative OR (down power margin)	Max. Cost (up margin)	Cost	Min. Cost (down margin)
PV lower bound	1230	279	712	490	236	211	164
PV predicted	1017	539	763	401	202	179	141
PV upper bound	833	938	842	336	176	159	128

Part 3 Deterministic unit commitment under uncertainty

3.9 From Dynamic Programming to Mixed-Integer Linear Programming

- To reduce the computational time, we simplify models of nonlinear MGTs' characteristics.
- Optimization method --- Mixed-integer linear programming (MILP)





- Comparison of DP and MILP

	DP	MILP
Objective Function Type	Quadratic	Linear
Computational Time (s)	4.39	2.53
Optimal operational cost ($)	179	180

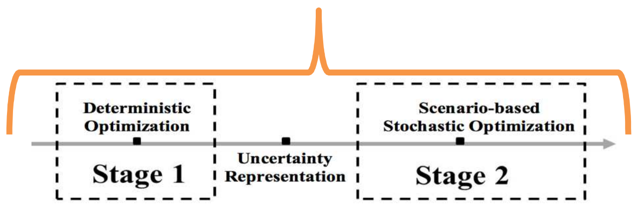
Acceptable errors

CONTENTS

4.1 Evolution: From deterministic to stochastic optimization

Probabilistic-Method for Risk Based Quantification of the reserve

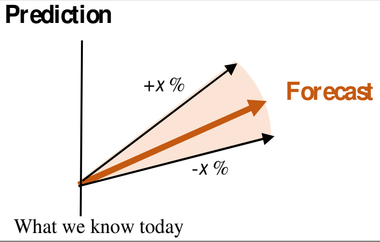
Part 3

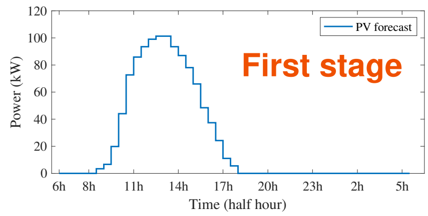


	Stage 1	Stage 2
Uncertainty modelling	Historical forecasting errors	Possible future scenarios
Commitment decision	**Slow generators** Fast generators	**Fast generators (flexible)** to erase probable uncertainty if necessary
Reserve quantification	By considering forecasting errors	By anticipating different scenarios
Reserve dispatching	MGTs and PV AGs (limitation)	Only fast MGTs and PV AGs

Part 4 Anticipating uncertainty with a scenario-based stochastic optimization

4.3 Uncertainty represented by scenarios





Using the past and the future to handle the uncertainties

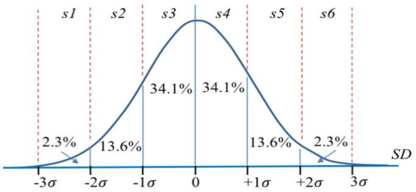
Knowledge from the past — Consider the possible future

Past — **Build probable scenarios** — **Present** — **Impact of scenarios** — **Future**

Certain of what happened

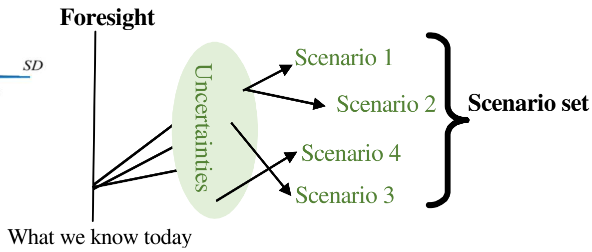
Uncertain it has not happened yet

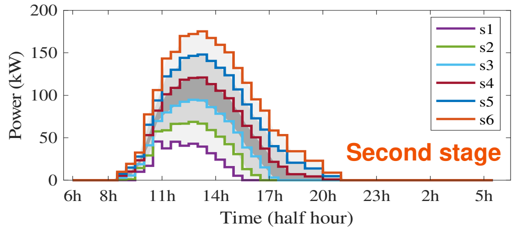
Build probable scenarios



For each time step

Scenario s_ω	s1	s2	S3	S4	S5	s6
Probability π_ω	2.3%	13.6%	34.1%	34.1%	13.6%	2.3%





Part 4 Anticipating uncertainty with a scenario-based stochastic optimization

4.4 Mathematical formulation of scenario-based optimization

Multi-objective: Operational cost and CO_2-equivalent emission cost

$$\min_{\Delta,p,r} \sum_{\omega=1}^{\Omega} \pi_\omega \sum_{t=1}^{T} \sum_{m=1}^{M} \{\delta_{m,\omega}(t)\left[\alpha_c c_m\left(p_{m,\omega}(t)\right) + \alpha_{ce} ce_m\left(p_{m,\omega}(t)\right)\right] + u_{m,\omega}(t)[c_m^u + ce_m^u] + d_{m,\omega}(t)[c_m^d + ce_m^d]\}$$

Parameters for unit normalization; start-up penalties; shutdown penalties

s.t.

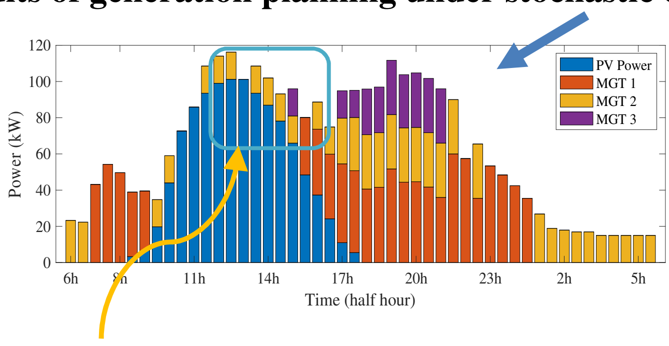
Net demand constraint,

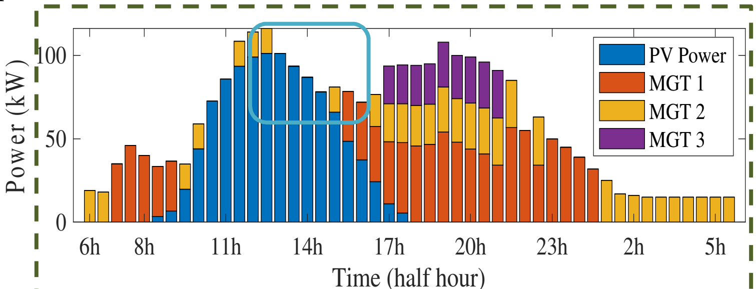
Reserve constraint,

Generator constraint, and the commitment of slow generators in stage 2 should be same as in stage 1

$m \in \mathcal{M}$	Set of conventional generators	$(\mathbf{\Delta}, \mathbf{p}, \mathbf{r}) \in \mathcal{F}$	Set of feasible solutions.
$t \in \mathcal{T}$	Set of time steps.	$\delta_{m,\omega}(t)$	Commitment of generator m with scenario ω at time step t.
$\omega \in \mathcal{W}$	Set of scenarios.	$p_{m,\omega}(t)$	The power generation set point of generator m with scenario ω at time step t.
π_ω	Probability of occurrence of scenario ω.	α_c, α_{ce}	Parameters for normalization
c_m, ce_m	Operational / Emission cost function		

Results of generation planning under stochastic optimization





Deterministic optimization

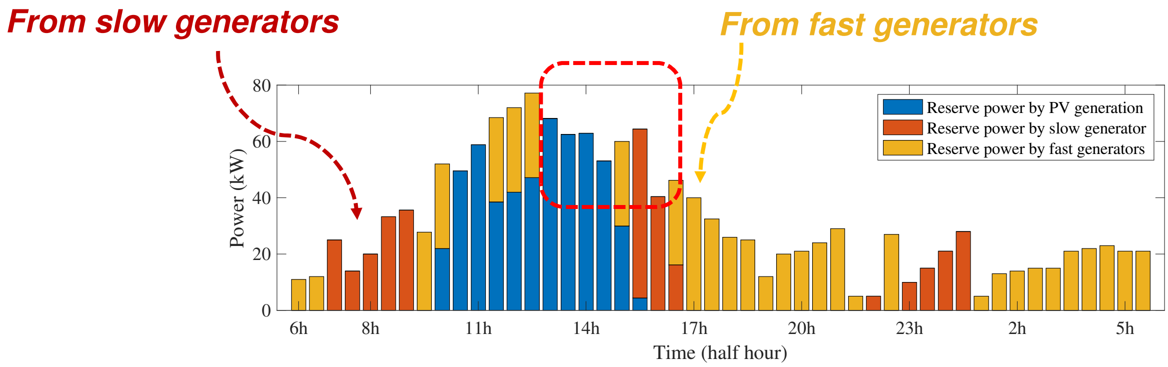
Higher security level by considering uncertainty under different net demand scenarios.

Part 4 Anticipating uncertainty with a scenario-based stochastic optimization

4.5 Obtained effective reserve from slow and fast generators (with a LOLP ≤5%)

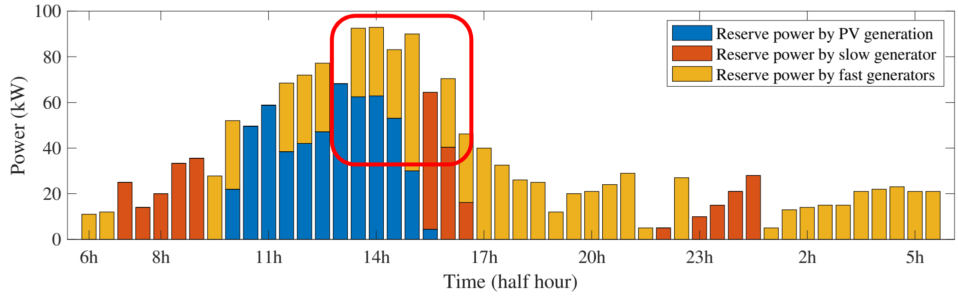
- ❑ **Fast generators : response time less than one time step (1-30 minutes).**
- ❑ **In the second stage, they are used as flexible generators to handle the possible future uncertainty.**

Obtained effective reserve in first stage:



Obtained effective reserve in second stage:

More effective reserve is provided by fast generators in second stage

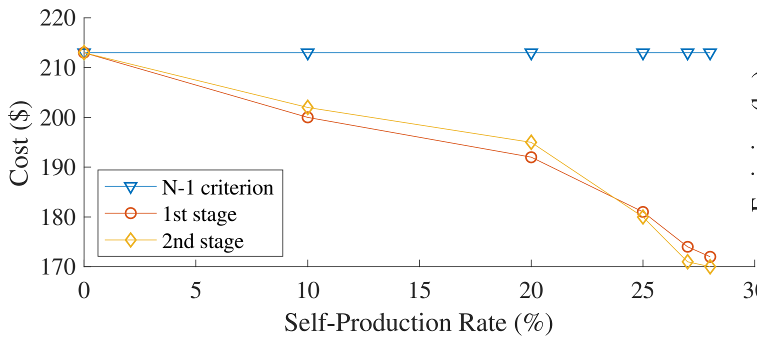


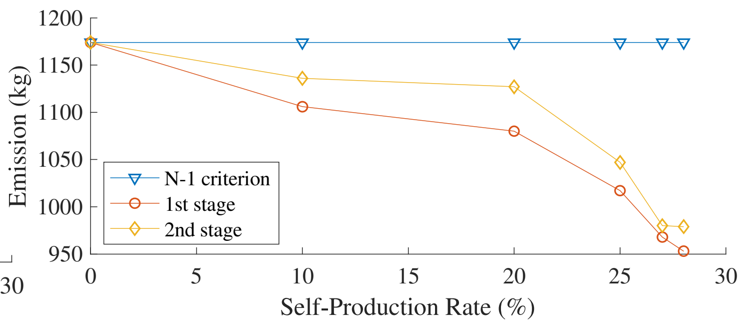
Part 4 Anticipating uncertainty with a scenario-based stochastic optimization

4.6 Day-ahead operational planning results comparison

	Deterministic Optimization			
	Without Criterion		*N-1* Criterion	
	Cost ($)	CO_2 (kg)	Cost ($)	CO_2 (kg)
Multi-objective (cost & emission)	149	832	213	1174
Mono-objective (cost)	147	868	211	1221
Mono-objective (emission)	157	818	220	1164
Reserve requirement (kWh)	\		\	
Effective reserve (kWh)	403		554	

❑ **Extension to other profiles (days)**





CONTENTS

Part 5 Participation of storage for operating reserve provision

5.2 Deal with uncertainties--- Storage

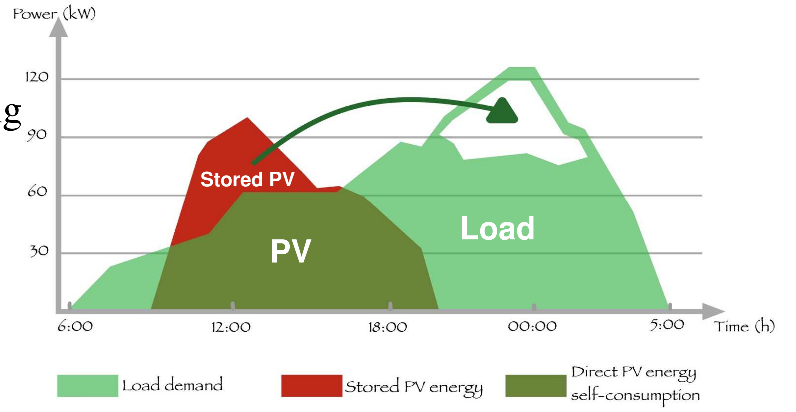
- Multiple storage applications exist
- The main idea is to save the PV curtailed energy
- The stored energy can then be used for various energy services
- Two applications are explored
  - Use of the stored energy to supply the load demand later

    "Renewable energy time-shift "
  - Use of the stored energy to provide "clean" power reserve

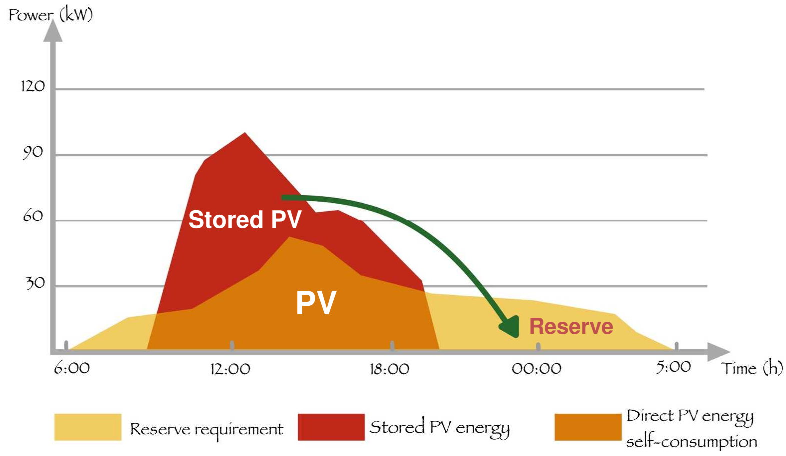
    "Clean technology for the power reserve provision"
- Quantify the reduction of the CO_2-equivalent emission and operating costs

5.3 Storage application benefits

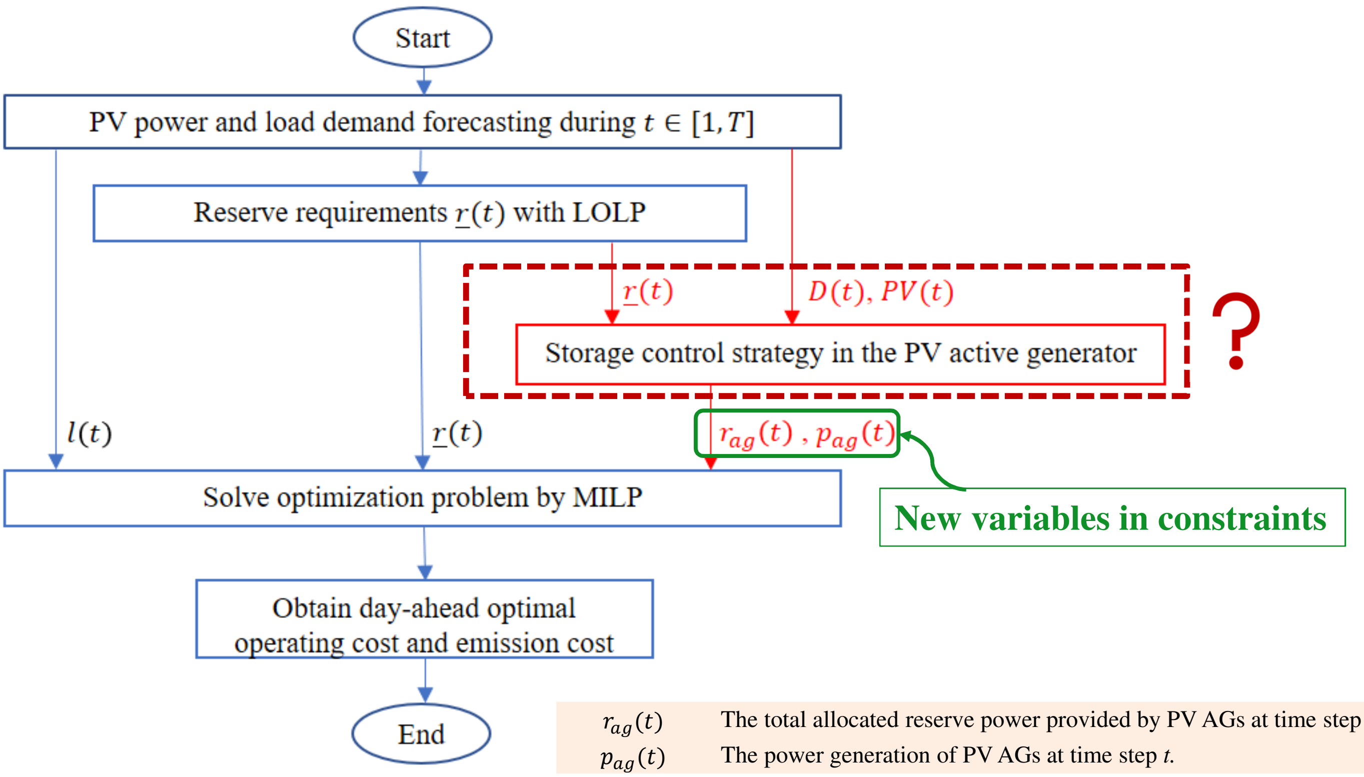
Storage application 1:
Renewable energy time-shift by maximizing solar energy self-consumption rate.



Storage application 2:
Clean technology to provide power reserve



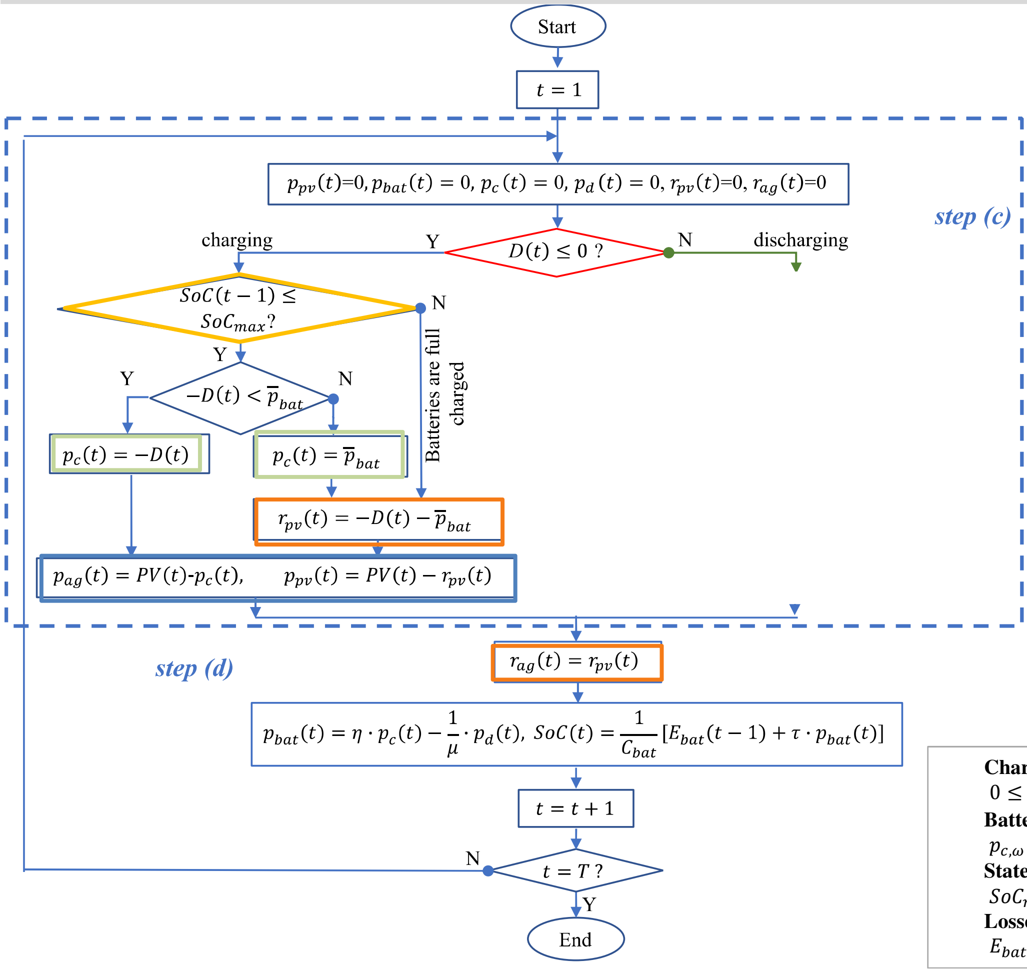
5.4.1 Integration of the ESS control strategy in the generation scheduling



$r_{ag}(t)$	The total allocated reserve power provided by PV AGs at time step *t*.
$p_{ag}(t)$	The power generation of PV AGs at time step *t*.

- The storage control strategy impacts directly the operational planning of MGTs
- Implementation of the control strategy : use case, control of the SoC and rated values, …

Saving the PV power surplus



Charging or discharging at time step t ?

Check the state of charge (SoC)

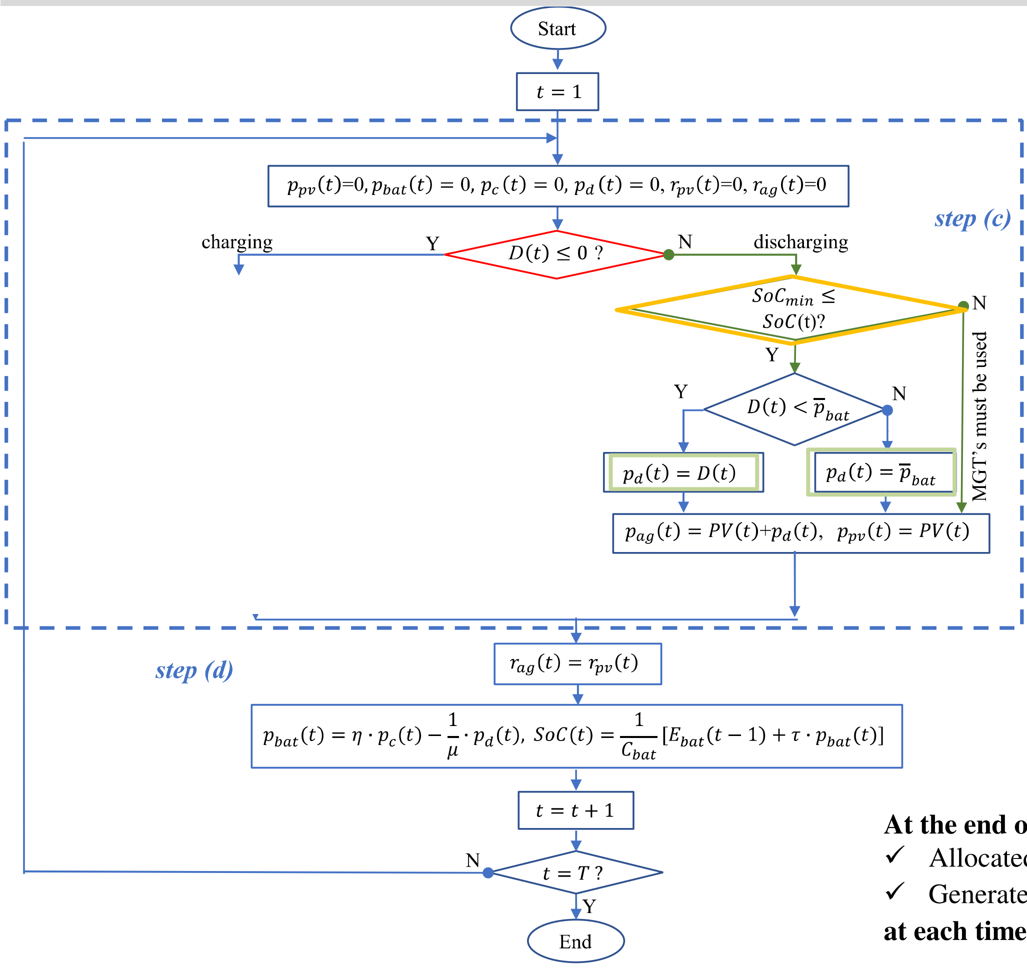
Calculate the charging power

Direct PV power surplus for reserve provision

Calculate the power exchanged with PV AG

Charge and discharge power limits :
$0 \le p_{c,\omega}(t) \le \overline{p}_{bat}, 0 \le p_{d,\omega}(t) \le \overline{p}_{bat},$
Batteries cannot be charged and discharged at the same time:
$p_{c,\omega}(t) \cdot p_{d,\omega}(t) \le 0, \forall t \in \mathcal{T},$
State of charge (SoC) of batteries in a certain interval :
$SoC_{min} \le SoC_{\omega}(t) \le SoC_{max},$
Losses during charging and discharging :
$E_{bat,\omega}(\tau) = E_{bat}(0) + \sum_{t=1}^{\tau} \eta \cdot p_{c,\omega}(t) + \sum_{t=1}^{\tau} 1/\mu \cdot p_{d,\omega}(t)$

Discharging for load supply



Check the SoC

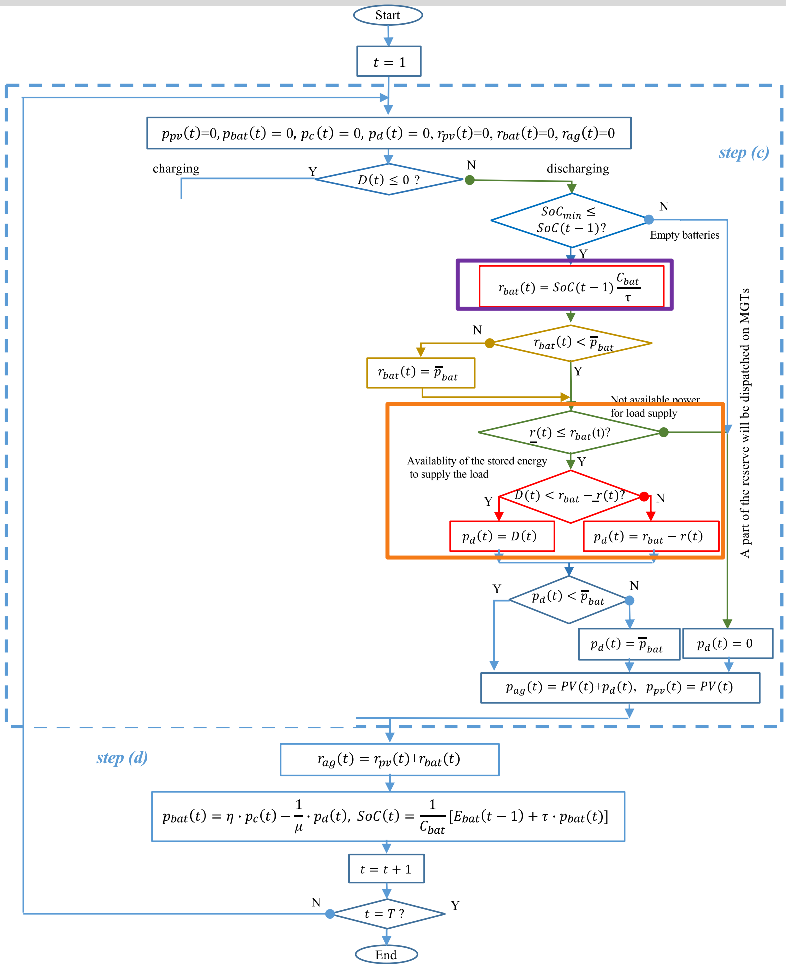
Calculate the discharging power

At the end of ESS control strategy, we know:

- ✓ Allocated reserve power provided by PV AGs $\boldsymbol{r_{ag}(t)}$
- ✓ Generated power of PV AGs $\boldsymbol{p_{ag}(t)}$

at each time step !

5.4.3 ESS control strategy 2 : **Reserve provision**



Another control strategy

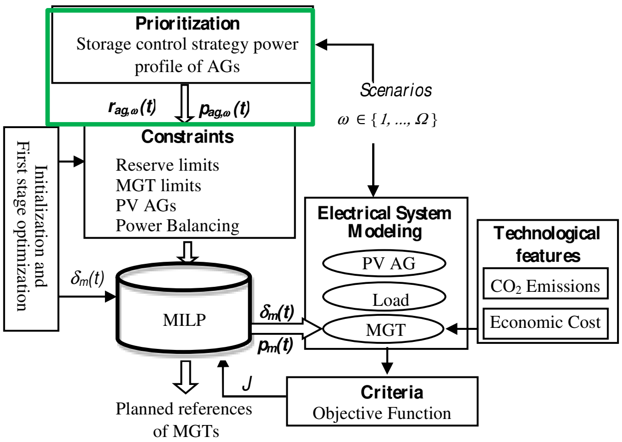
Discharging for power reserve

How much stored energy for reserve provision

After reserve provision, what is the availability of stored energy to supply the load?

5.5 Mathematical formulation of scenario-based optimization with storage

- Optimization framework



Multi-objective: Operational cost and CO_2-equivalent emission cost

$$\min_{\Delta,p,r} \sum_{\omega=1}^{\Omega} \pi_\omega \sum_{t=1}^{T} \sum_{m=1}^{M} \{\delta_{m,\omega}(t) \left[\alpha_c c_m \left(p_{m,\omega}(t)\right) + \alpha_{ce} ce_m \left(p_{m,\omega}(t)\right)\right] + u_{m,\omega}(t)[c_m^u + ce_m^u] + d_{m,\omega}(t)[c_m^d + ce_m^d]\}$$

s.t.

(New variables are added in constraints because of the participation of storage)

Reserve constraint: $r_{mgt,\omega}(t) = \underline{r}_\omega(t) - r_{ag,\omega}(t)$ → total allocated reserve power provided by PV AGs

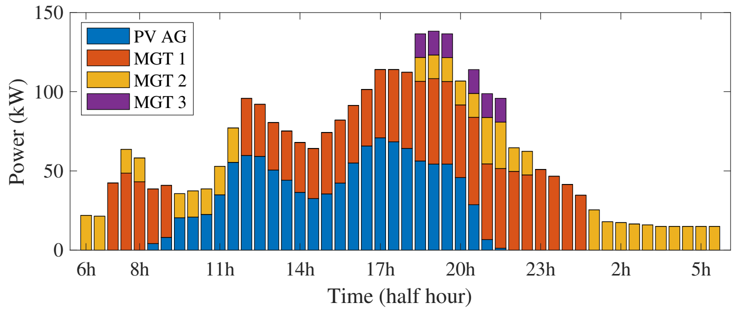
Net demand constraint: $\sum_{m=1}^{M} p_{m,\omega}(t) = l_\omega(t) - \sum_{a=1}^{A} p_{ag,\omega}(t) + r_{mgt,\omega}(t)$

→ power generation of PV AGs

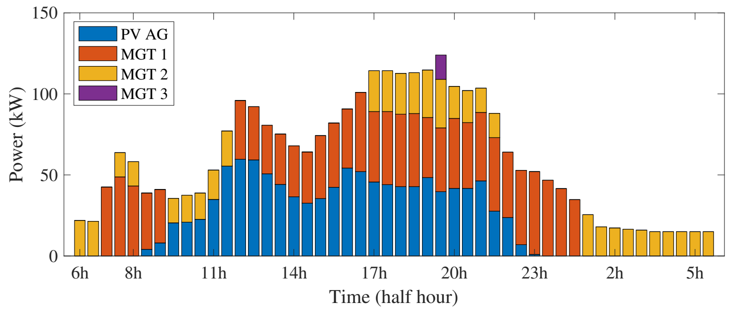
Generator constraint: $\underline{p}_m\, \delta_{m,\omega}(t) \leq p_{m,\omega}(t) \leq \overline{p}_m \delta_{m,\omega}(t)$, and commitment of slow genereator keep unchange

5.5.1 Results of stochastic optimization under two storage control strategies

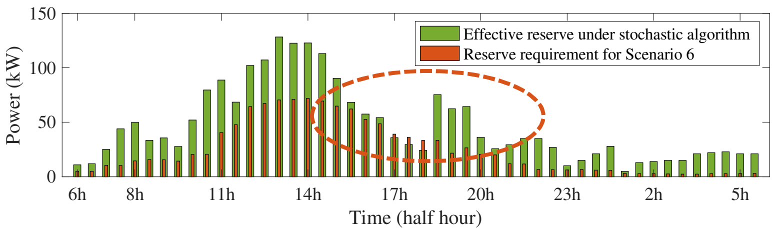
Storage control strategy 1: Renewable energy time-shift

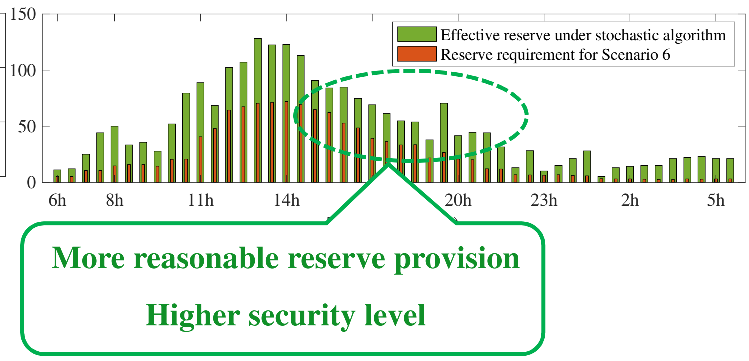


Storage control strategy 2: Reserve provision



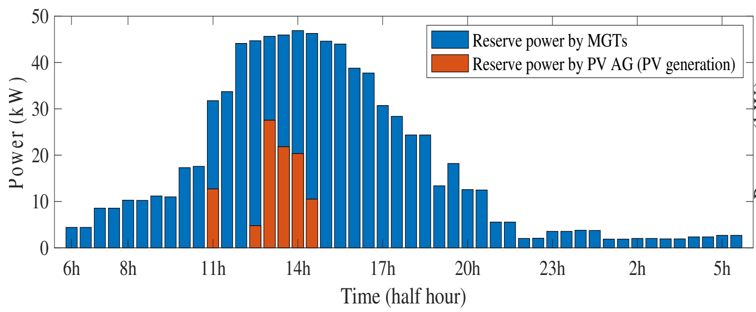
Under WORST CASE (scenario 6): Reserve requirement and obtained effective reserve with a *LOLP* ≤ 5%



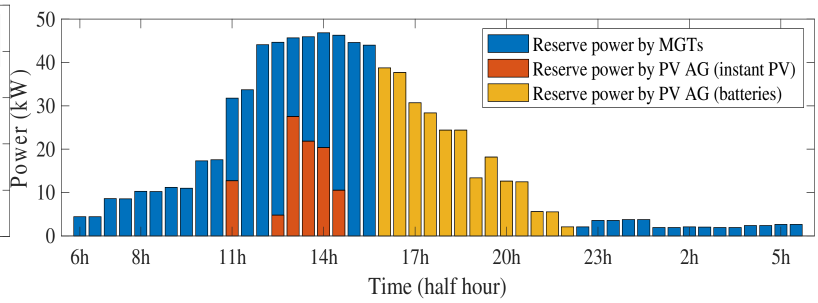


5.5.2 Results of stochastic optimization under two storage control strategies

Storage control strategy 1: Renewables energy time-shift



Storage control strategy 2: Reserve provision



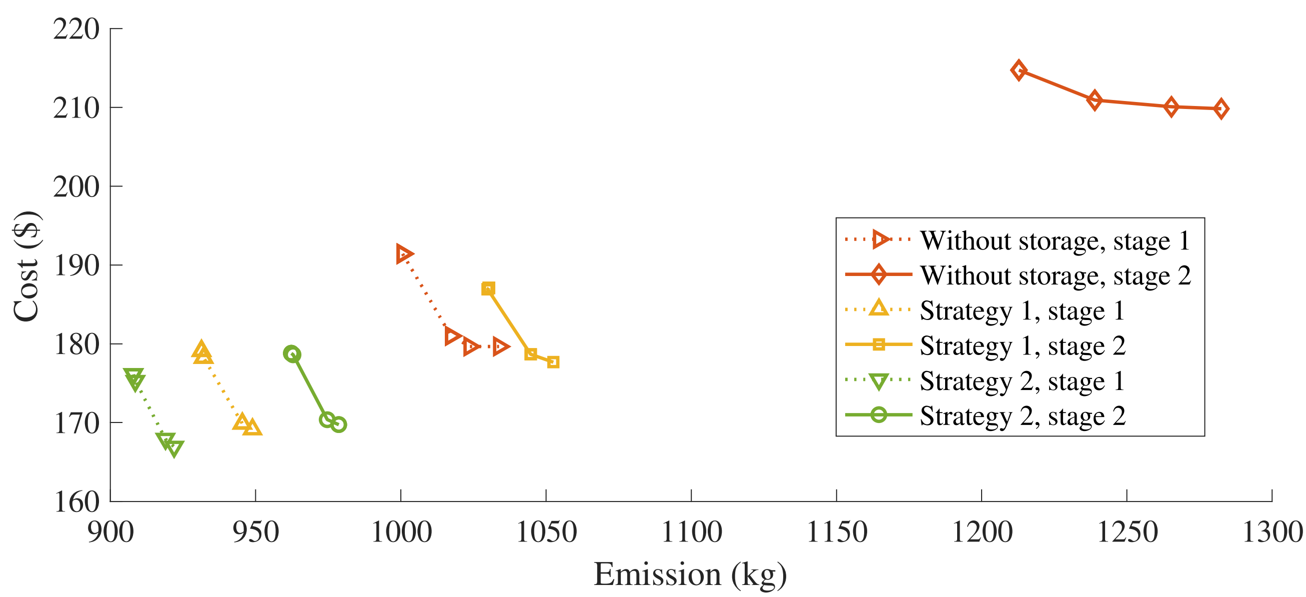
Storage control strategy	Reserve energy sources (kWh)		Scenario S 1
Strategy 1	Reserve energy from PV AGs	PV limitation	0
		Batteries	0
	Reserve energy from MGTs		151.2
Strategy 2	Reserve energy from PV AGs	PV limitation	0
		Batteries	51.1
	Reserve energy from MGTs		100.2

5.6 Day-ahead operational planning results comparison

Storage control strategy	Objective	Scenario-based Stochastic Optimization			
		Fuel Cost (€)	CO_2 Cost (kg)	Possibility of risk under worst-case (S6)	Possibility of risk under S4
No storage	Multi-objective (cost & emission)	211	1239	≤16.7% of time steps	≤2.1% of time steps
	Mono-objective (cost)	209	1283	≤3.6% of daily reserve energy deficit (21.2 kWh / 591.5 kWh)	≤0.2% of daily reserve energy deficit (0.7 kWh / 411.7 kWh)
	Mono-objective (emission)	215	1213		

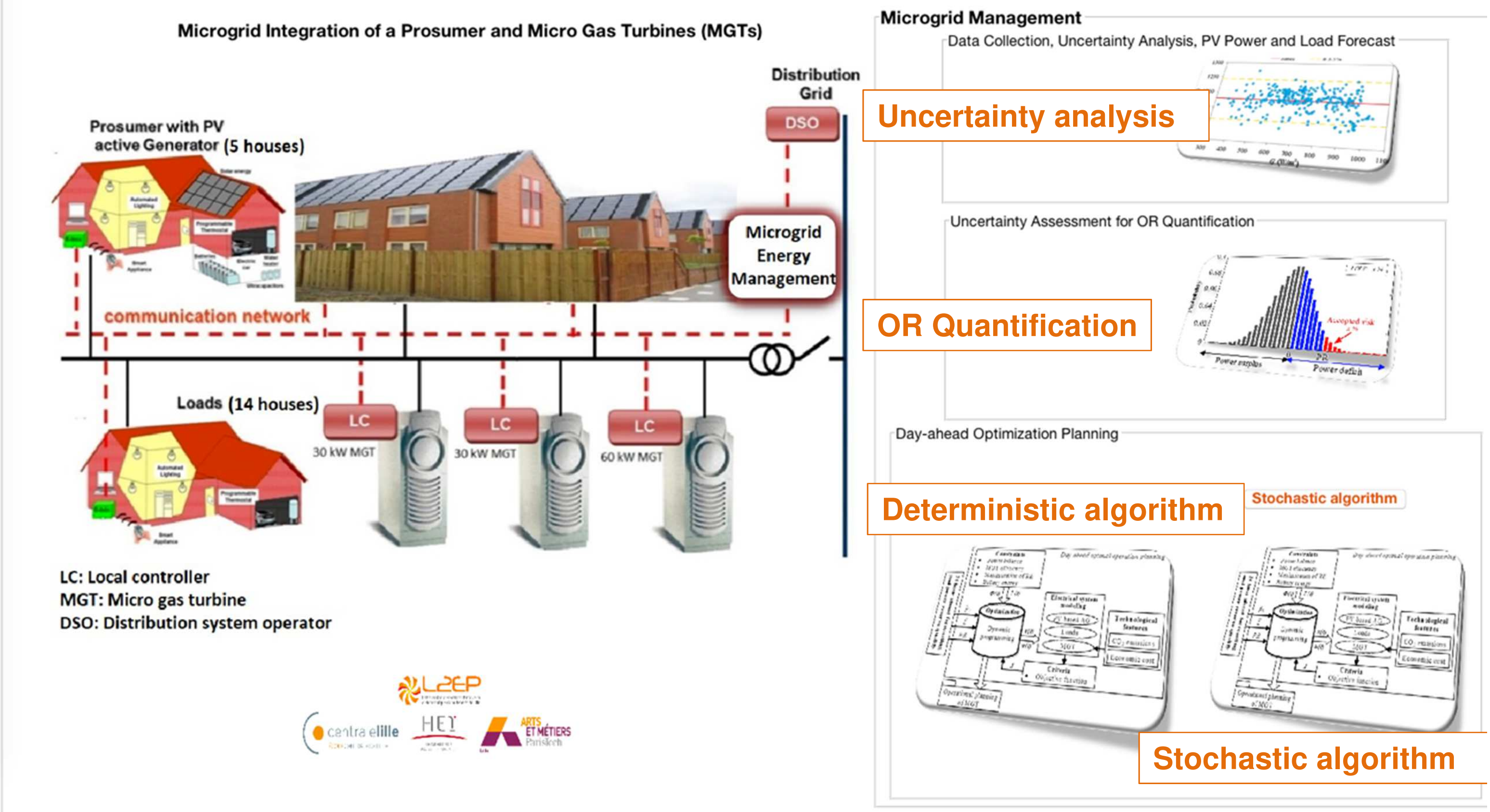
5.7 **Pareto-optimal fronts** for the multi-objective optimization

Pareto-optimal fronts: CO_2 equivalent emission vs. operational cost



6.1 Four main interfaces in the presented energy management system (EMS)

Generation scheduling using probabilistic & stochastic strategies in a MG including PV active generator



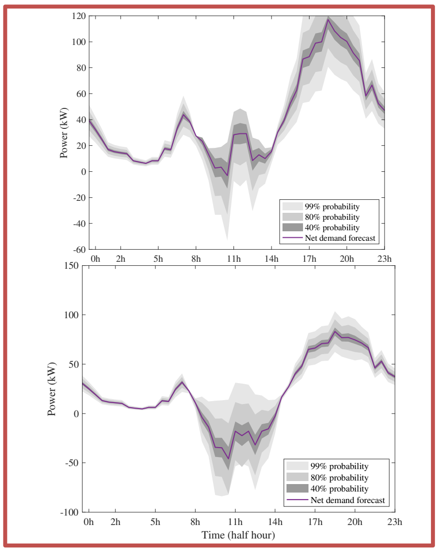
Part 6 Microgird central energy management system interface design

6.2 Main interfaces and function modules

Part 5 Participation of storage for operating reserve provision

5.8 Sizing of storage under uncertainty: *pdf*-based probabilistic analysis

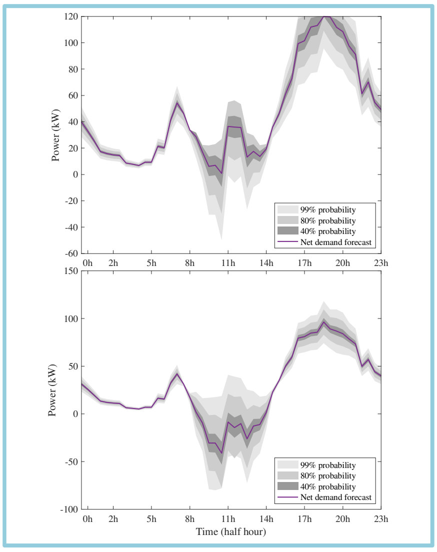
Non-workday ← **Net load profile** → **Workday**



Let's take winter and spring as examples…

← Winter →

← Spring →



Seasons	Spring		Summer		Autumn		Winter	
Workdays / non-workdays (w / n)	n	w	n	w	n	w	n	w
Mean value of renewable energy surplus (kWh)	129	98	113	82	9	9	2	0
Renewable energy surplus within 40% of probability (kWh)	179	146	158	126	22	26	11	6
Renewable energy surplus within 80% of probability (kWh)	278	246	250	217	59	83	45	36

Sizing of battery:

280 kWh of capacity → 350 kWh of storage size (considering a 20% of minimum allowable state of charge)

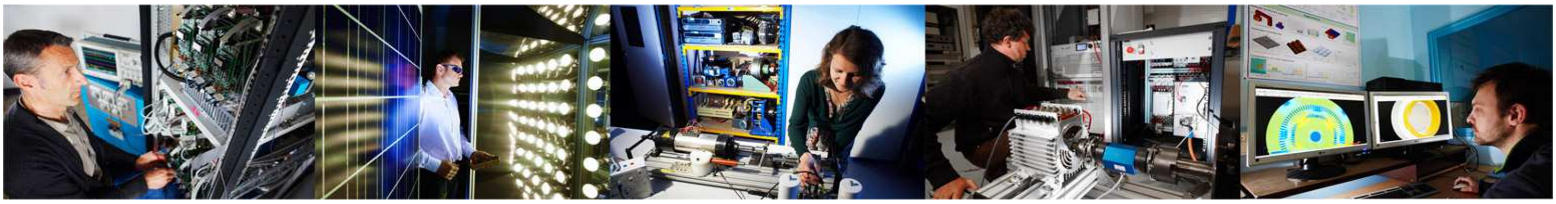
Conclusion & Perspective

❑ Conclusion

- ❑ A scientific method to **build scenarios and anticipate uncertainties**.
- ❑ Minimization of **CO_2 equivalent emissions and operational costs**.
- ❑ **Impact analysis** of stochastic optimization **on operating reserve**.
- ❑ Use of **storage as energy flexibility** for **both power balancing** and **reserve provision.**
- ❑ **Inclusion of storage control strategies** into the stochastic optimization.

❑ Perspective

- ❑ Impact of seasonal factor on generation scheduling.
- ❑ Investigation on both CAPEX and OPEX of storage.
- ❑ Sensitivity analysis.



Thank you for your attention!

Publication:

Journals:

WEN Xin, ABBES Dhaker, FRANCOIS Bruno, "Modelling of Photovoltaic Power Uncertainties for Impact Analysis on Generation Scheduling and Cost of an Urban Micro Grid", Mathematics and Computers in Simulation, 04/2020. ISSN 0378-4754, https://doi.org/10.1016/j.matcom.2020.02.023.

Conferences:

WEN Xin, ABBES Dhaker, FRANCOIS Bruno, "Day-Ahead Generation Planning and Power Reserve Allocation with Flexible Storage Strategy", International Conference on Electricity Distribution CIRED 2020, 22-23 September 2020, Berlin, 09/2020.

WEN Xin, ABBES Dhaker, FRANCOIS Bruno, "Impact of Photovoltaic Power Uncertainties on Generation Scheduling and Cost of an Urban Micro Grid", 13th international conference of IMACS TC1 Committee (ELECTRIMACS). 20-23 mai 2019. Salerne, Italie, 05/2019.

YAN Xingyu, WEN Xin, FRANCOIS Bruno, ABBES Dhaker, "Management of distributed operating power reserve in an urban microgrid beyond DSO risk decision", International Conference on Electricity Distribution CIRED 2018, 7-8 June 2018,Lubjana, Slovenia, 06/2018.