Héloïse DUTRIEUX

Méthodes pour la planification pluriannuelle des réseaux de distribution. Application à l'analyse technico-économique des solutions d'intégration des énergies renouvelables intermittentes.

- Doctoral advisors
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- Project ANR APOTEOSE (**A**nalyse **P**robabiliste et nouveaux **O**ptimums **T**echnico-**E**c**O**nomiques des **S**ystèmes **E**lectriques en présence de taux de pénétration élevés d'énergies intermittentes)

F R Q WHQ WV

FRQWHQWV

1. Scope and motivation
2. Novel framework for the study of RES-integration solutions in multi-year distribution planning
3. Approximation methods for computing the multi-year electrical network state
4. Case studies
5. Conclusion and further work

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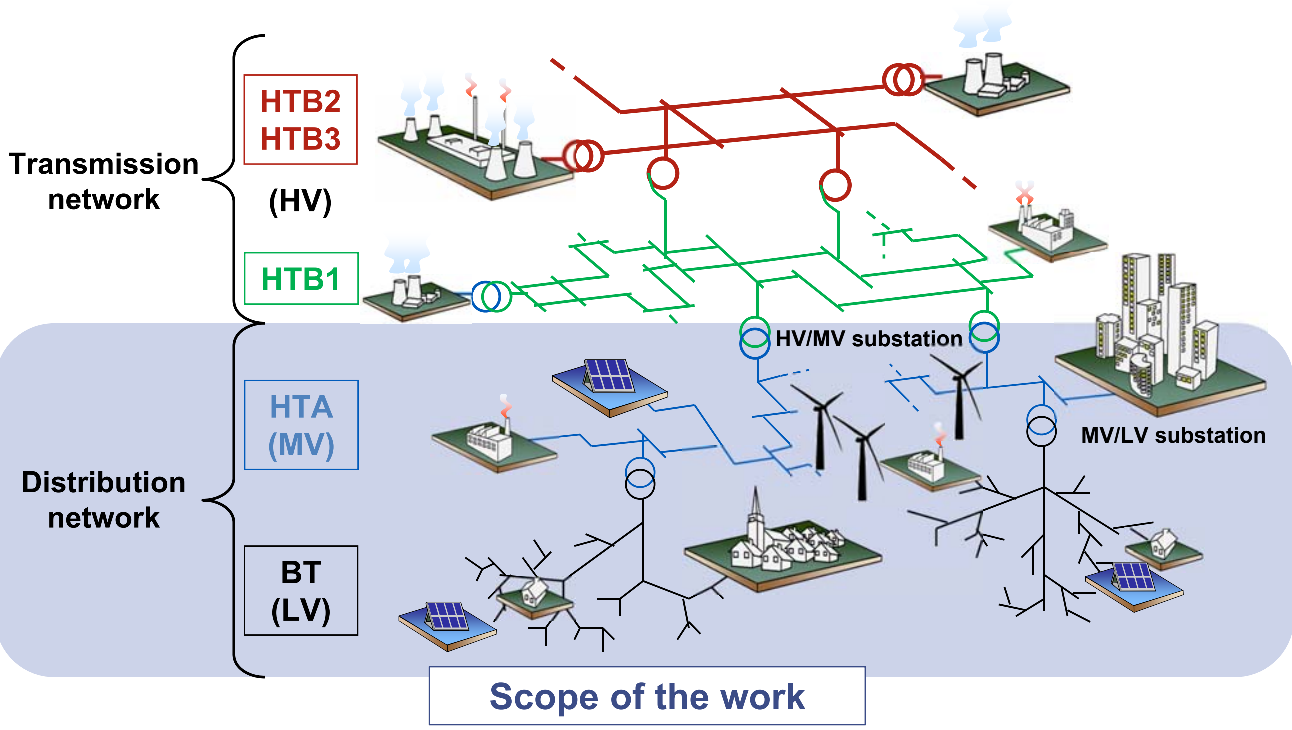
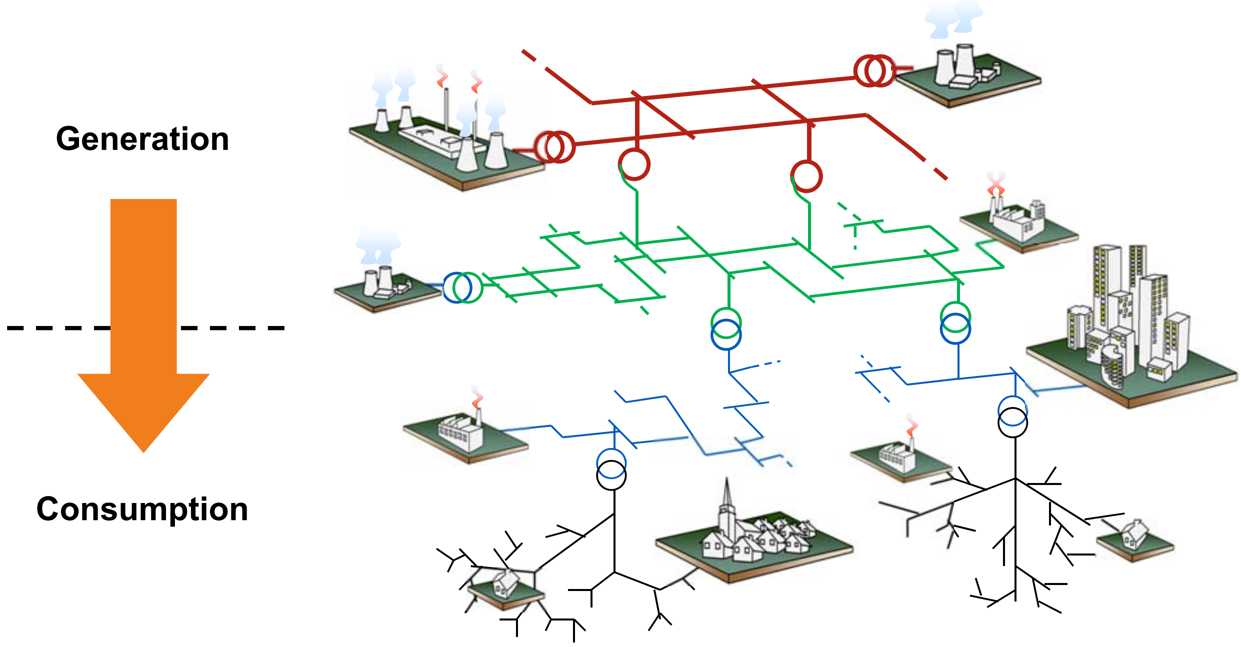
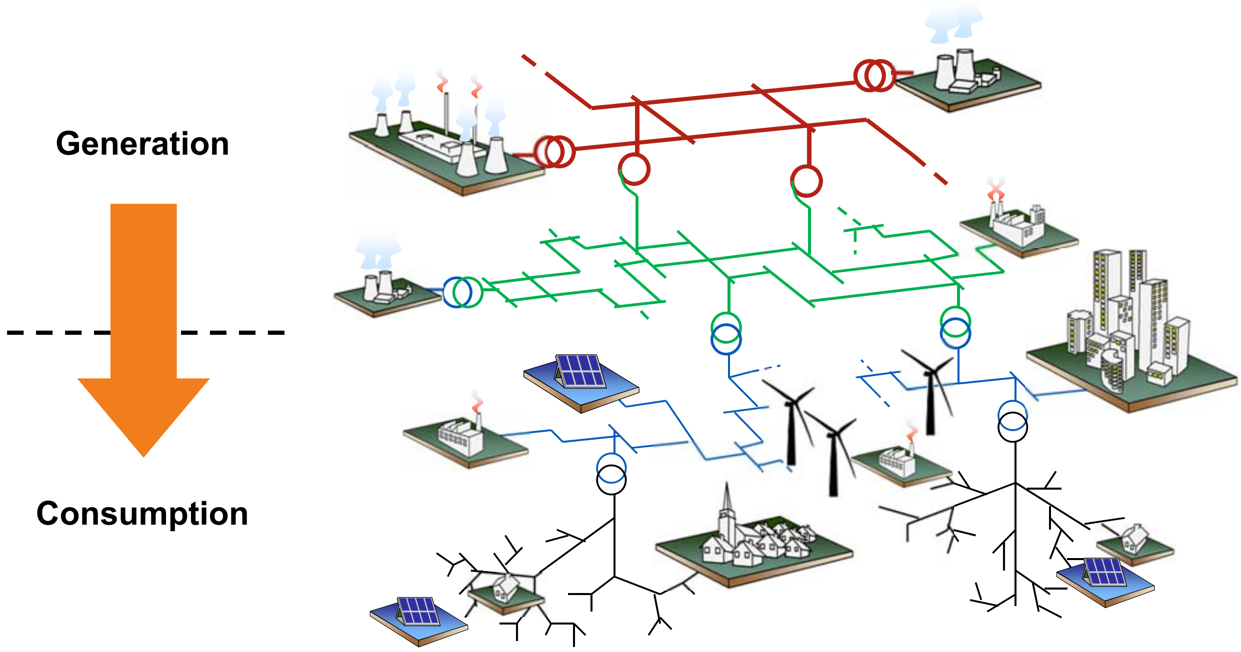


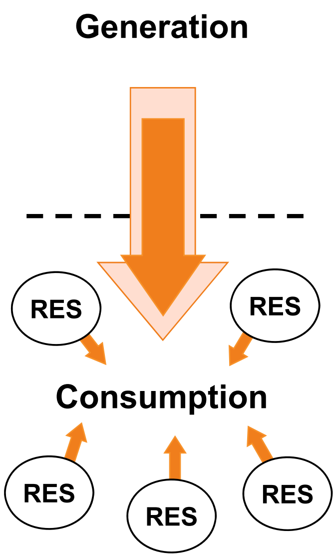
Historically, electricity was mainly produced by central plants connected to the transmission network.

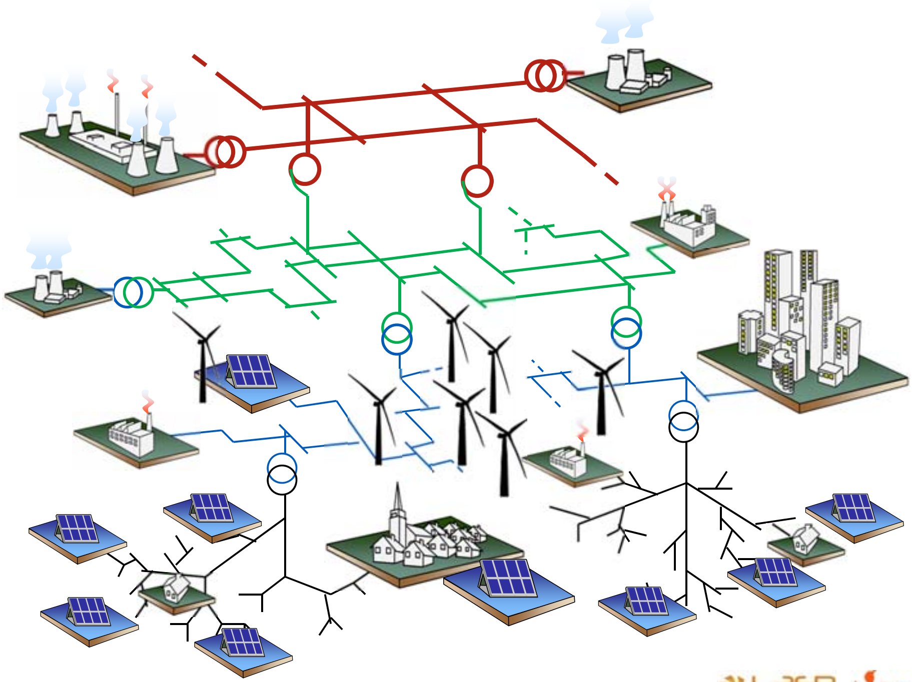


Since the 2000s, more and more Renewable Energy Sources (RES) have been connected to the distribution networks.

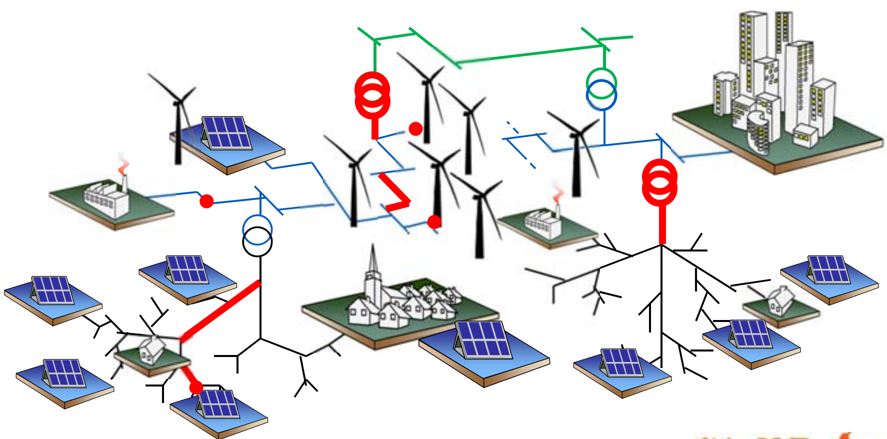


In the near future, a massive integration of RES is expected in the distribution networks.





➩ Risk of voltage/current constraints



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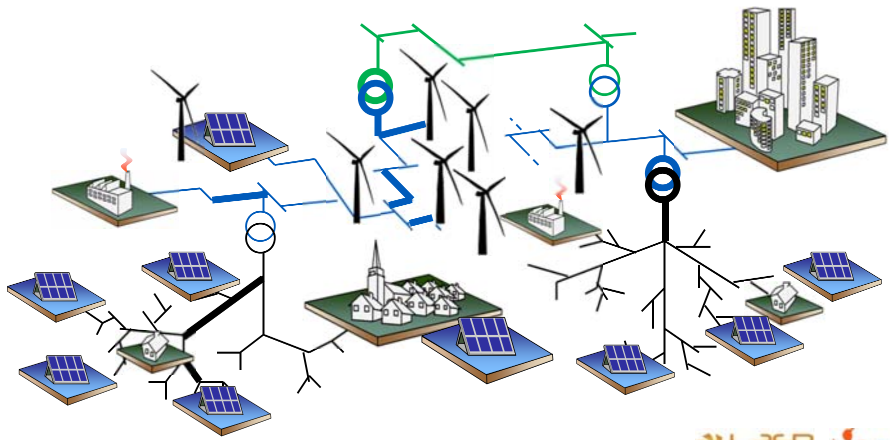
- Risk of voltage/current constraints
- **Network reinforcement** ⇨  **+** **!!!**

Network investments to connect 25 GW by 2030:
300 k€/MW of photovoltaic generation
100 k€/MW of wind generation



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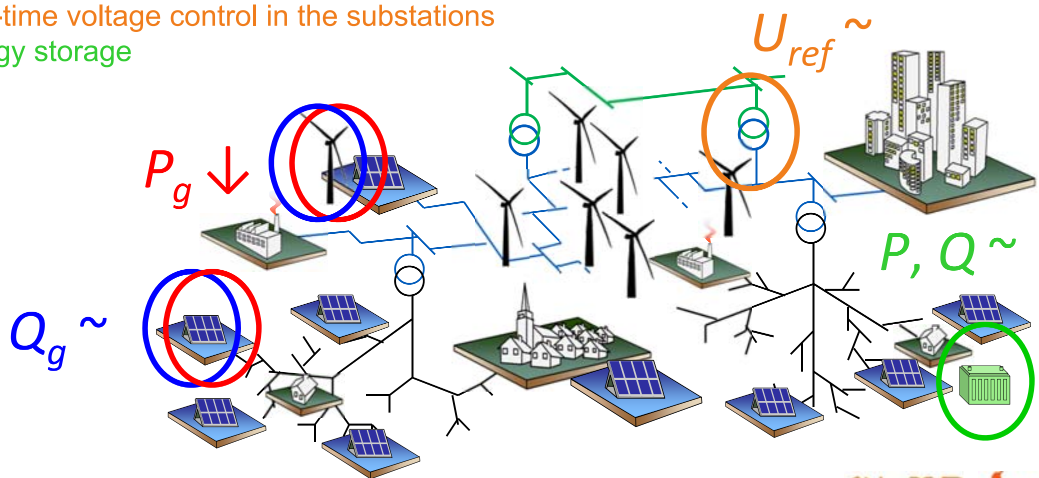
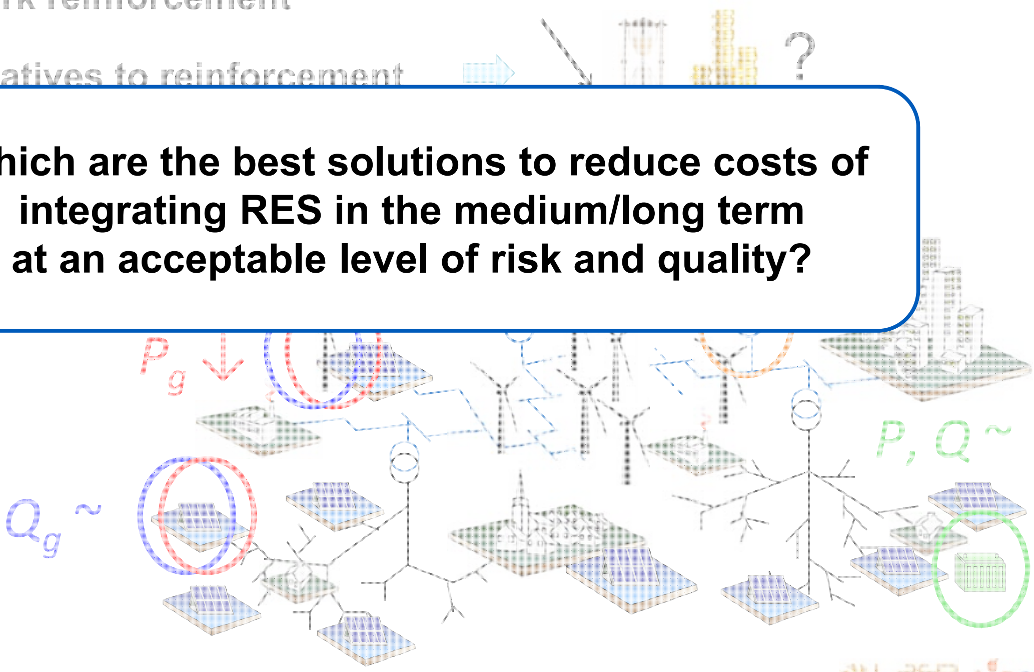
- Risk of voltage/current constraints
- **Network reinforcement**
- **Alternatives to reinforcement** ⇨ ↘  ?
  - Advanced reactive power control of generators
  - Generation curtailment
  - Real-time voltage control in the substations
  - Energy storage
  - …



- Risk of voltage/current constraints
- Network reinforcement
- Alternatives to reinforcement



Which are the best solutions to reduce costs of integrating RES in the medium/long term at an acceptable level of risk and quality?

		Current planning
RES-integration solutions	Operating limits?	No
	Operating costs?	Power losses Energy not supplied
Network planning methods	Studied scenarios	« Worst case »
	Constraint indicators	Boolean (yes or no)
	Objective	Prevent 100 % of the networks constraints

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		Current planning	Requirements with RES
RES-integration solutions	Operating limits?	No	**Yes**, in energy and/or duration
	Operating costs?	Power losses Energy not supplied	**+ Non-negligible costs depending on the constraints**
Network planning methods	Studied scenarios	« Worst case »	
	Constraint indicators	Boolean (yes or no)	
	Objective	Prevent 100 % of the networks constraints	

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		Current planning	Requirements with RES
RES-integration solutions	Operating limits?	No	**Yes**, in energy and/or duration
	Operating costs?	Power losses Energy not supplied	**+ Non-negligible costs depending on the constraints**
Network planning methods	Studied scenarios	« Worst case »	**Multi-year profiles** of generation/consumption
	Constraint indicators	Boolean (yes or no)	**Statistical** (frequency, severity, duration)
	Objective	Prevent 100 % of the networks constraints	Reach a **tradeoff** between costs and quality of supply

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Need to modify the current planning methods to assess the techno-economic impacts of the RES-integration solutions

Extensive literature review on the planning approaches taking into account RES-integration solutions

Main limits of the existing planning approaches:

- Inappropriate time sampling: too small time period and/or time step
- Future events sometimes assumed to be perfectly known
- Interactions between MV and LV networks generally neglected
- Economic analysis sometimes incomplete or missing

1. Scope | 2. Framework | 3. Approximation | 4. Case studies | 5. Conclusion

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Need to modify the current planning methods to assess the techno-economic impacts of the RES-integration solutions

Extensive literature review on the planning approaches
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The limits of the existing planning approaches can distort the assessment of the techno-economic impacts of the RES-integration solutions.

Main

- Ina
- Future events sometimes assumed to be perfectly known
- Interactions between MV and LV networks generally neglected
- Economic analysis sometimes incomplete or missing

OBJECTIVES

- **Provide a suitable framework for the study of RES-integration solutions in the medium/long run**
- **Address the main limits of the existing planning approaches**:
  - Distribution System Operator (DSO)'s behavior
  - Uncertainty on the arrivals of new RES
  - Interactions between MV and LV networks

SCOPE

- Methods for medium-term distribution network planning (10 years)
- Network constraints: slow voltage/current variations (10 minutes)
- Quality of supply: voltage limits and weakly-supplied LV consumers
- Network and communication facilities assumed reliable

1. Scope and motivation
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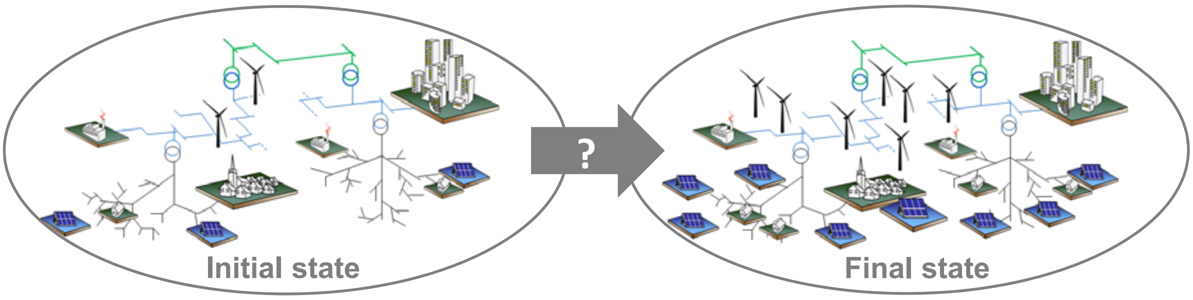
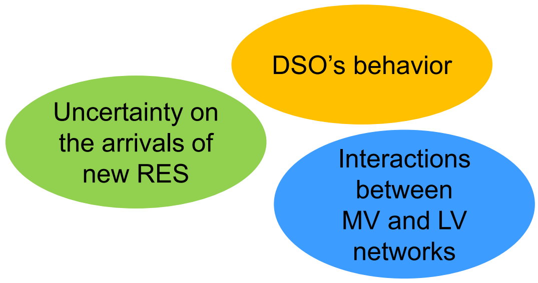
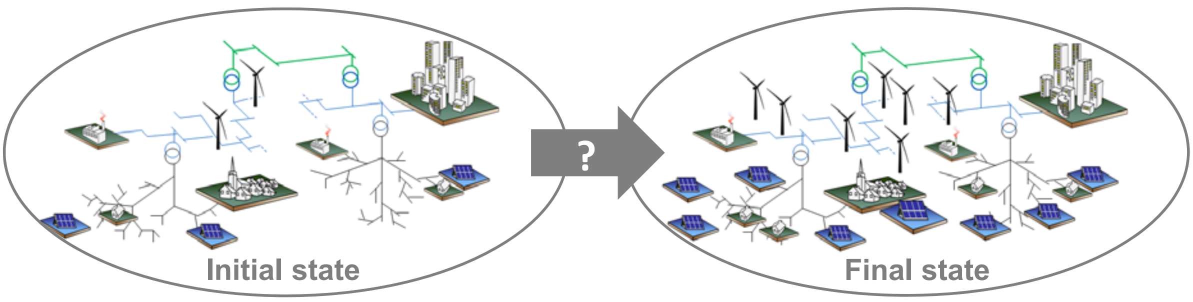
Question



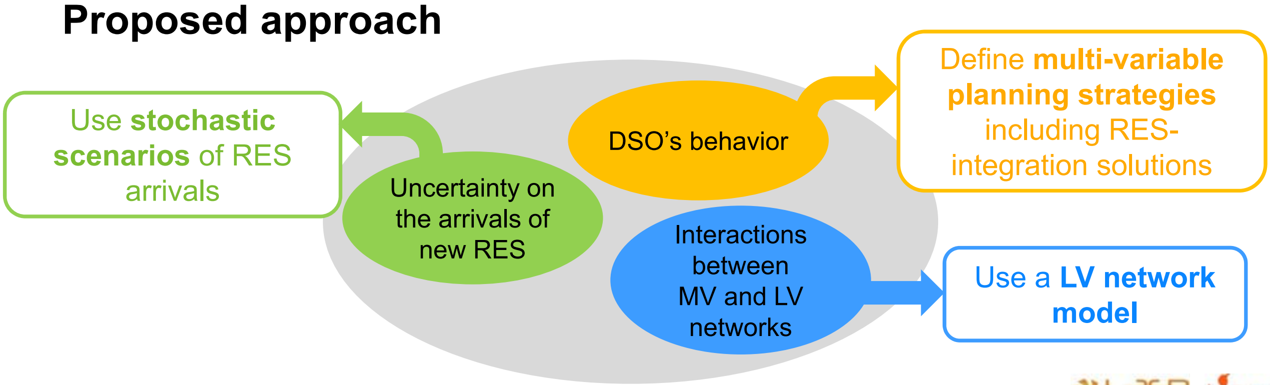
How can we address the main limits of the existing approaches?



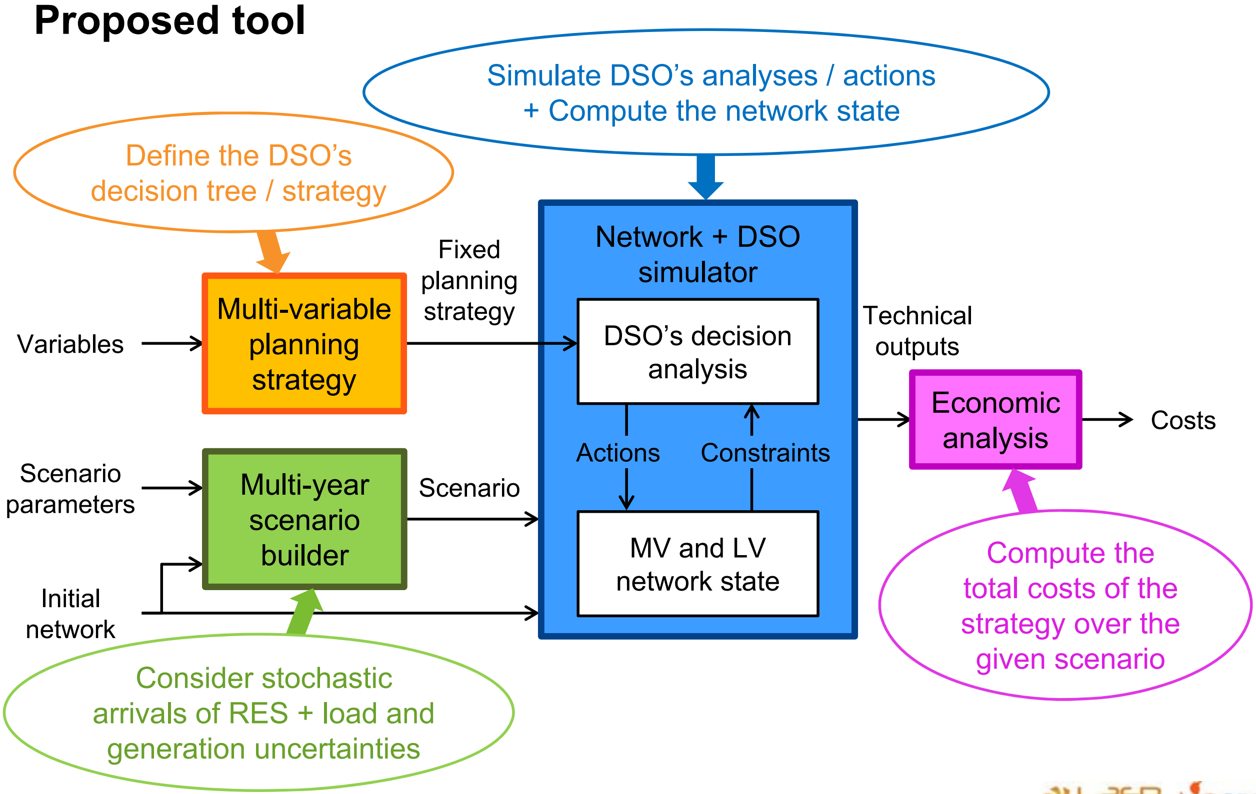
Question

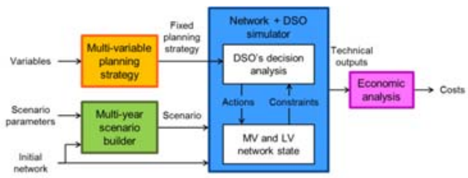


Proposed approach



Proposed tool





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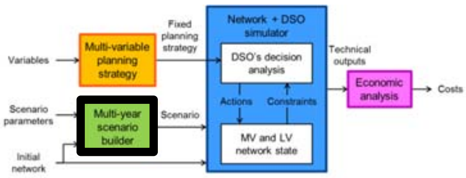
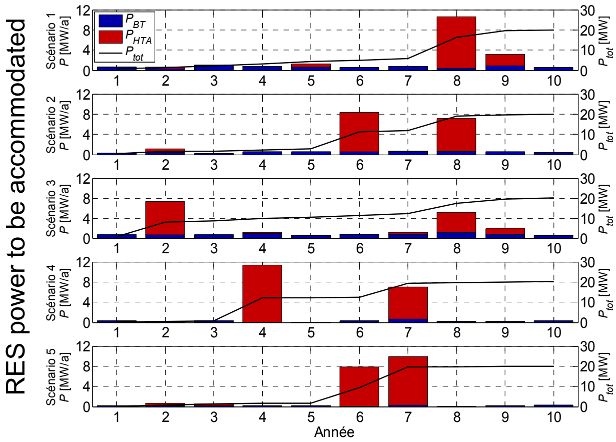
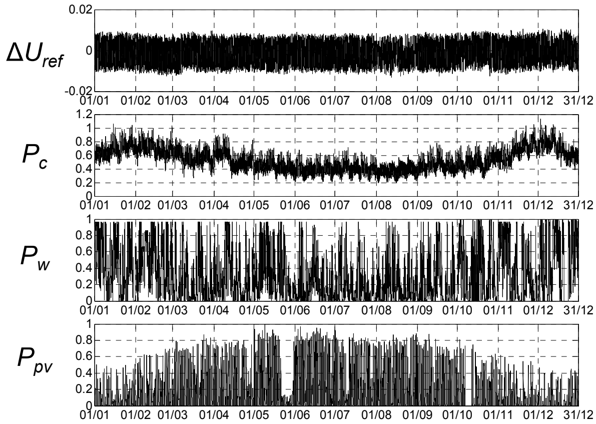
Scenario builder



Generate multi-year scenarios:

- Features of new RES producers
- 10-minute profiles of generation, consumption and voltage reference





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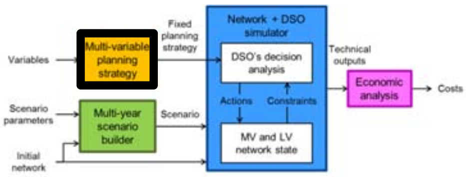
Planning strategy



Model the Distribution System Operator (DSO)'s behavior.

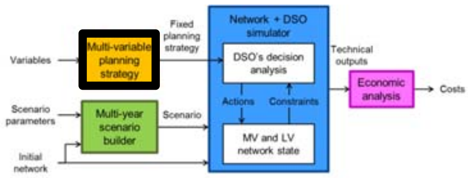
Planning strategy

the sequence of the decision analyses made by the DSO in everyday life, **as well as the associated decisions**, when the DSO notices an event that may require some adaptations of the existing network.

Examples of event

connection of a new user, too many weakly-supplied consumers, constraint limit violations, expected load growth in the coming years, etc.

Planning strategy



Model the Distribution System Operator (DSO)'s behavior.

- Each planning strategy is a **sequence of rules**.
- Each rule describes the **RES-integration solutions** to remove constraints.

<u>Example of the current French strategy</u>:

If the connection of a new MV producer to a feeder supplying loads may cause **overvoltages**, then it is necessary to:

***R1**: decrease the fixed* $\tan(\varphi)$ *reference of the new producer, with* $\tan(\varphi) \geq \tan(\varphi)_{\min}$.

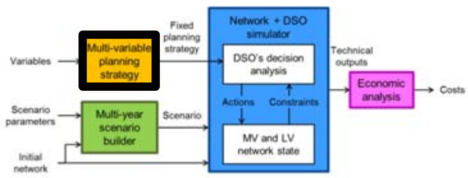
***R2**: decrease the fixed* $\tan(\varphi)$ *reference of the existing MV producers, with* $\tan(\varphi) \geq \tan(\varphi)_{\min,DSO}$.

***R3**: decrease the fixed voltage reference of the on-load tap changer of the HV/MV transformer* U_{OLTC}*, with* $U_{OLTC} \geq U_{OLTC,\min}$.

***R4**: reinforce the MV network.*

$$\theta = \left\{ \tan(\varphi)_{\min}, \tan(\varphi)_{\min,DSO}, U_{OLTC\min} \right\}$$

Planning strategy



Model the Distribution System Operator (DSO)'s behavior.

- Each planning strategy is a **sequence of rules**.
- Each rule describes the **RES-integration solutions** to remove constraints.

<u>Example of a new strategy including generation curtailment</u>:

If the connection of a new MV producer to a feeder supplying loads may cause **overvoltages**, then it is necessary to:

***R1**: decrease the fixed* $\tan(\varphi)$ *reference of the new producer, with* $\tan(\varphi) \geq \tan(\varphi)_{\min}$.

***R2**: decrease the fixed* $\tan(\varphi)$ *reference of the existing MV producers, with* $\tan(\varphi) \geq \tan(\varphi)_{\min,DSO}$.

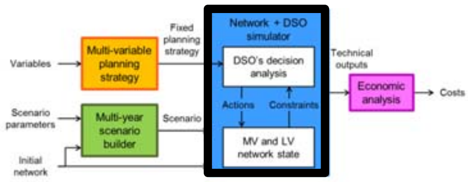
***R3**: decrease the fixed voltage reference of the on-load tap changer of the HV/MV transformer* U_{OLTC}*, with* $U_{OLTC} \geq U_{OLTC,\min}$.

***R5**: limit the active power of the MV producers considering a maximal curtailment rate* $\tau_{curt} \leq \tau_{curt,\max}$.

***R4**: reinforce the MV network.*

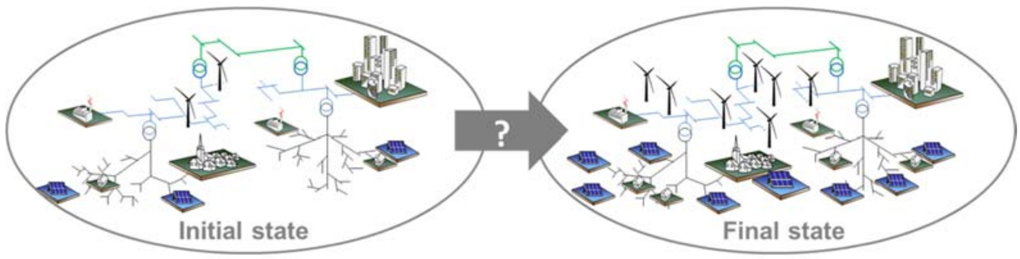
$$\theta = \left\{ \tan(\varphi)_{\min}, \tan(\varphi)_{\min,DSO}, U_{OLTC\min}, \tau_{curt,\max} \right\}$$

Network + DSO simulator

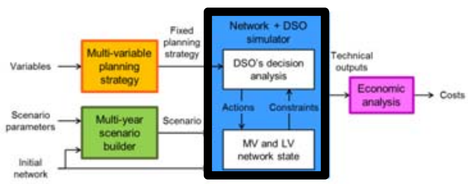


Simulate the network evolutions on a year-by-year basis:

1. Apply the planning strategy at the beginning of the year to remove limit violations and accommodate all LV and MV producers.
2. Estimate the network state over the whole year on the basis of 10-minute generation/consumption profiles.

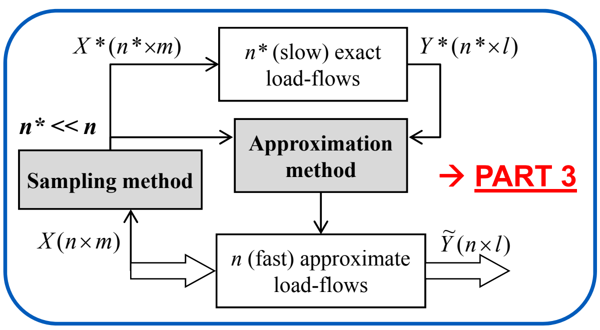


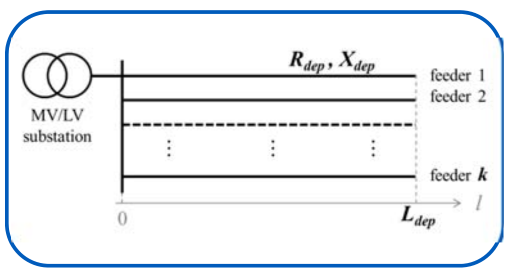
Network + DSO simulator



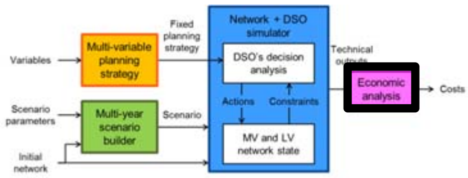
Simulate the network evolutions on a year-by-year basis:

1. Apply the planning strategy at the beginning of the year to remove limit violations and accommodate all LV and MV producers.
2. Estimate the network state over the whole year on the basis of 10-minute generation/consumption profiles.
   a. MV network state: voltages, currents, losses and total apparent power
   b. LV network state: extreme voltages and number of weakly-supplied LV consumers





Economic analysis



Compute the investments and operating costs over the studied period.

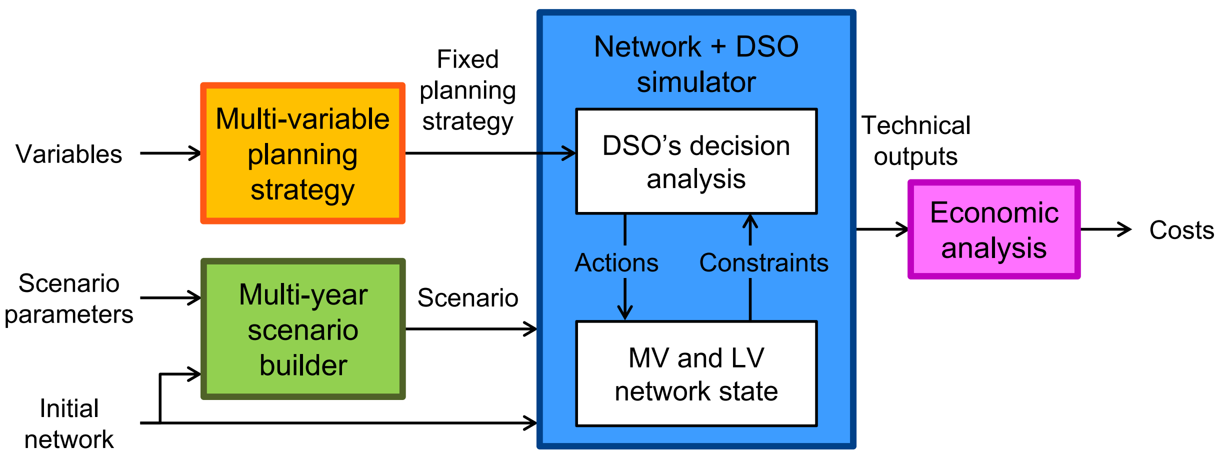
Stake-holders	Investment and operating costs
DSO	Upgraded and new MV lines Upgraded HV/MV transformers Upgraded MV/LV transformers MV line losses
MV producers	Upgraded and new MV lines Upgraded HV/MV transformers Power Conversion System (PCS) oversizing PCS maintenance
LV producers	Only if connected to dedicated feeders: Upgraded MV/LV transformers New LV dedicated feeders (New MV lines)

Gross Present Cost

$$GPC = \sum_{k=1}^{T}\left(\frac{I_k}{(1+i)^{k-1}} + \frac{C_k}{(1+i)^{k-1}}\right)$$

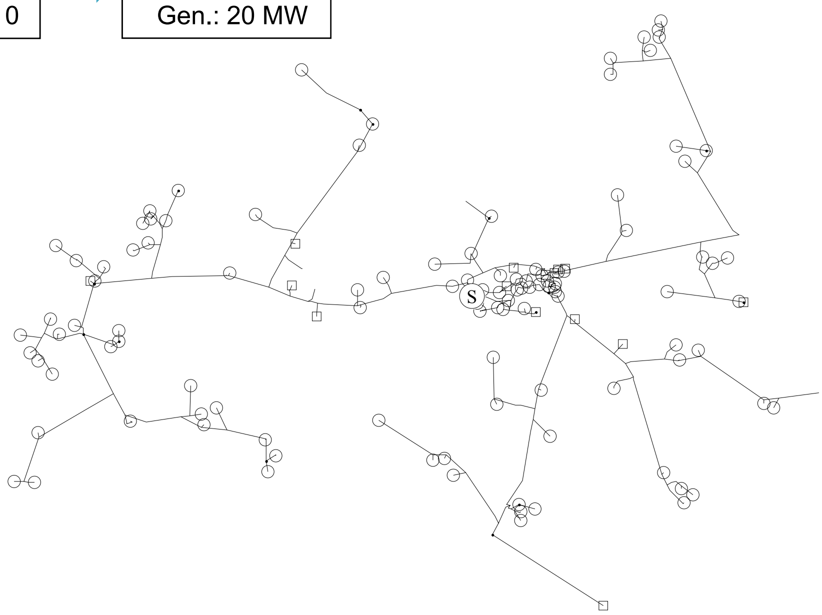
Net Present Cost

$$NPC = \sum_{k=1}^{T}\left(\frac{I_k}{(1+i)^{k-1}} + \frac{C_k}{(1+i)^{k-1}} - \frac{V_k}{(1+i)^{T}}\right)$$



Example of application: the current French planning strategy

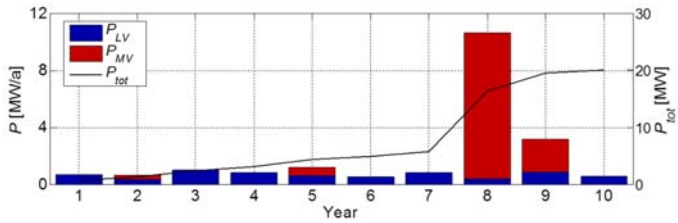
Year 0		Year 10
Load: 11 MVA	→	Load: +2 %/y
Generation: 0		Gen.: 20 MW



Example of application: the current French planning strategy

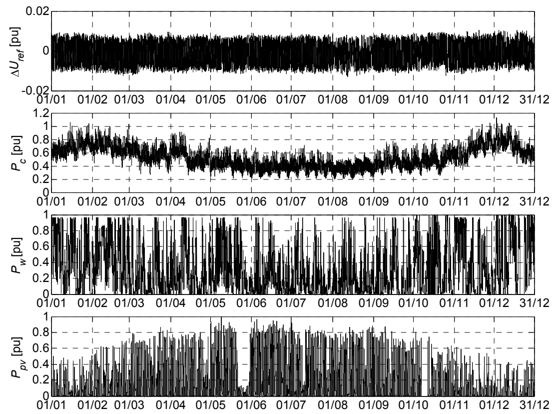
Studied scenario

Features of the new producers



	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Total
Number of new LV producers	115	122	113	126	125	121	124	125	119	130	1220
Number of new MV producers	0	1	0	0	1	0	0	1	1	0	4

10-minute profiles of generation, consumption and voltage reference



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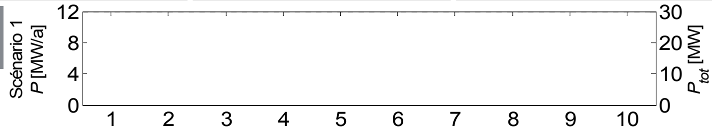
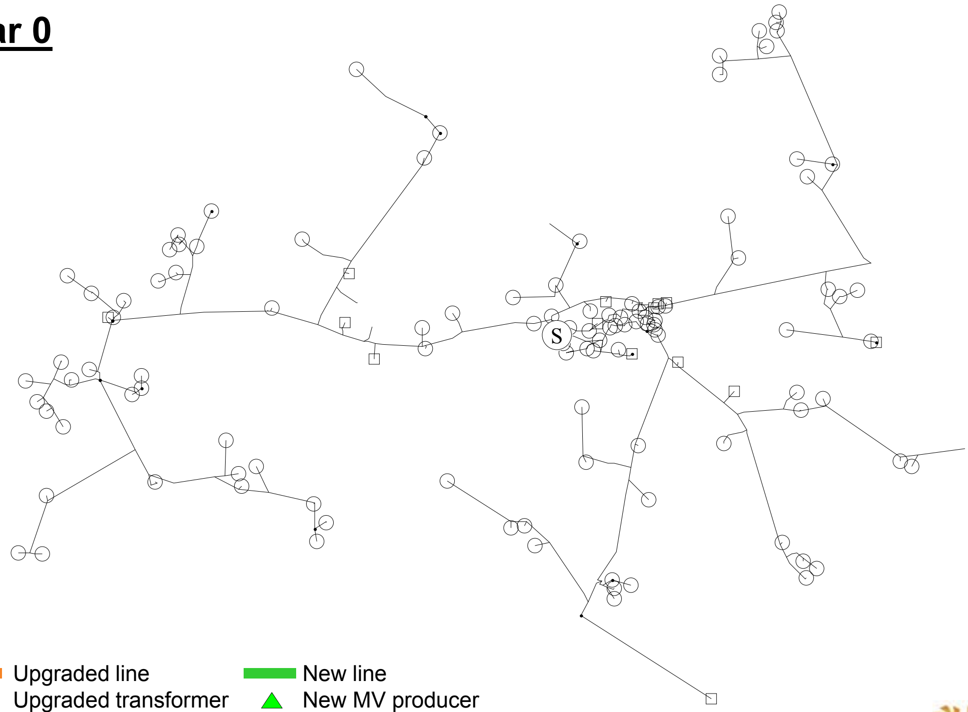


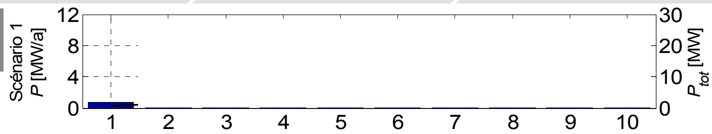
Example of application: the current French planning strategy

Year 0



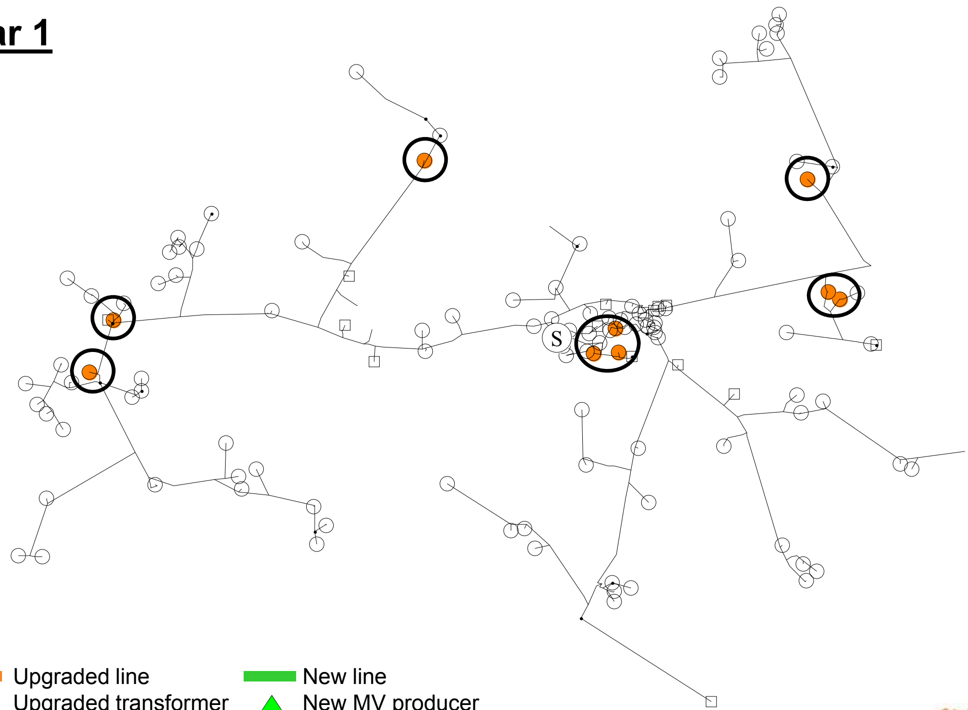
Upgraded line
New line
Upgraded transformer
New MV producer

5 1#Q R Y H O#I U D P H Z R U N



Example of application: the current French planning strategy

Year 1



Upgraded line
New line
Upgraded transformer
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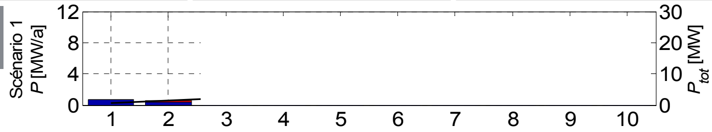
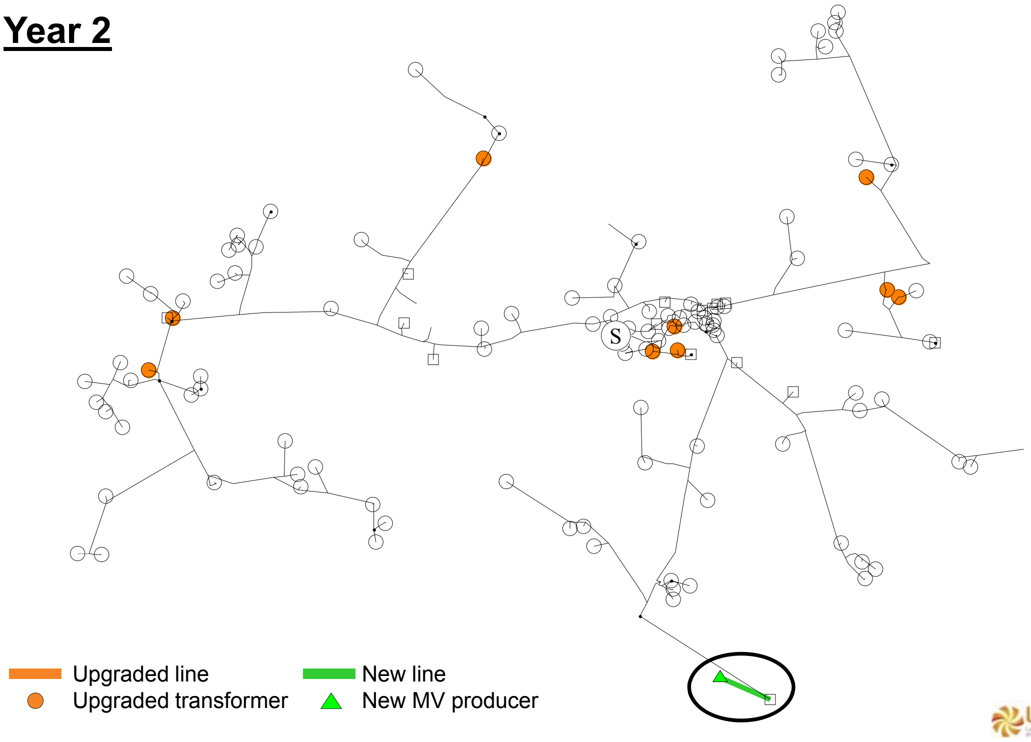


Example of application: the current French planning strategy

Year 2



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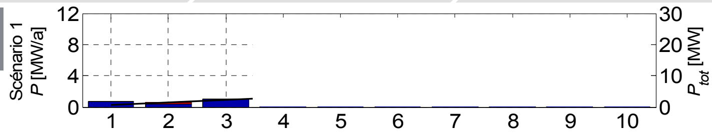
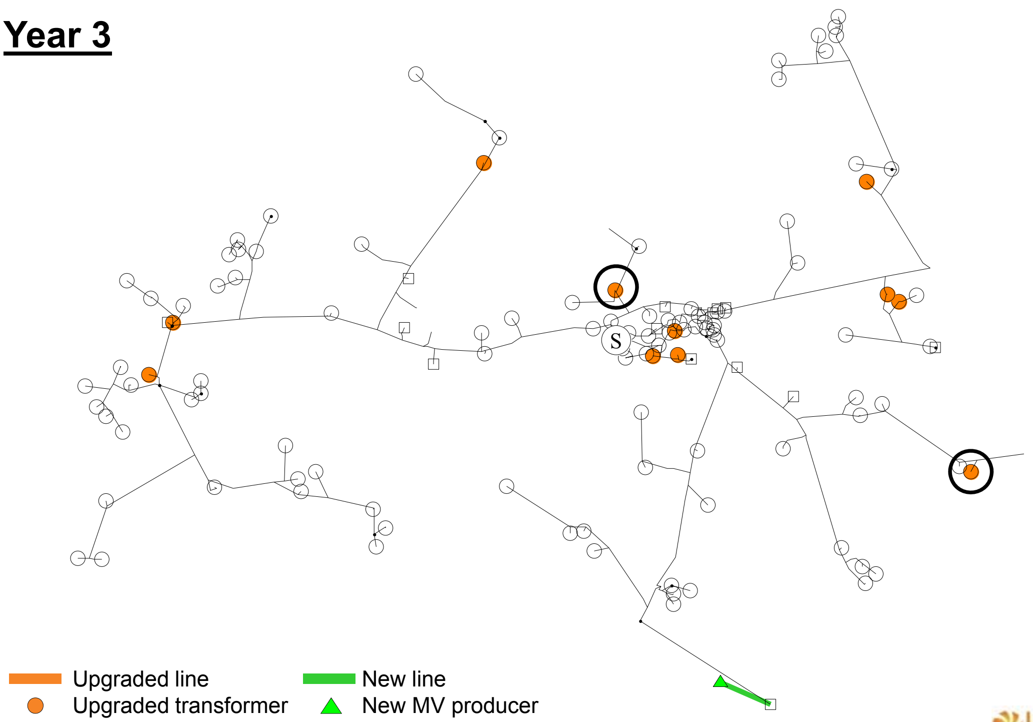


Example of application: the current French planning strategy

Year 3



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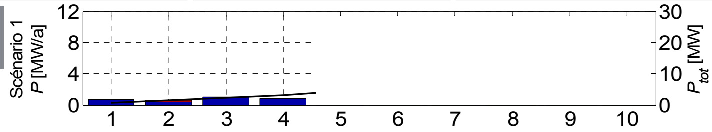
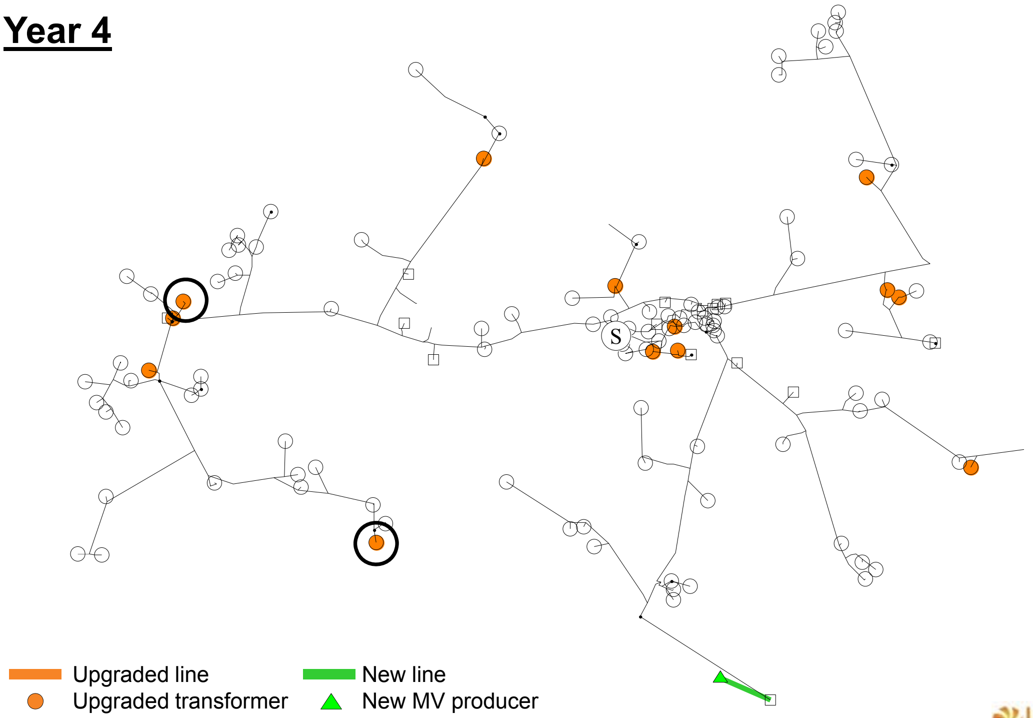


Example of application: the current French planning strategy

Year 4



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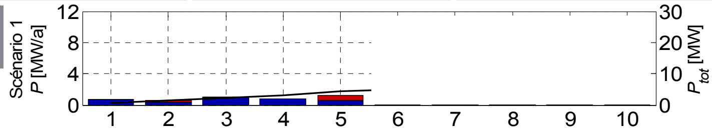
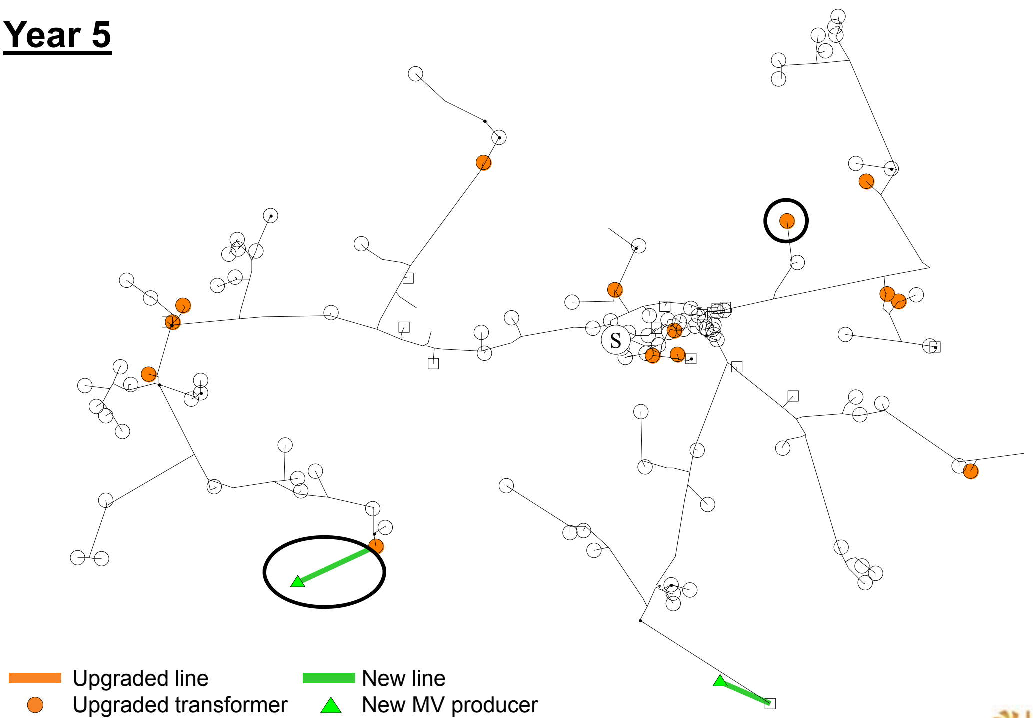


Example of application: the current French planning strategy

Year 5



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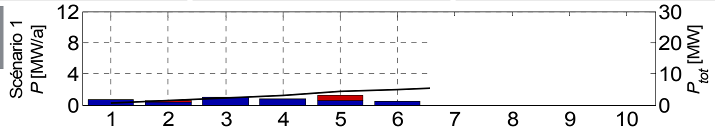
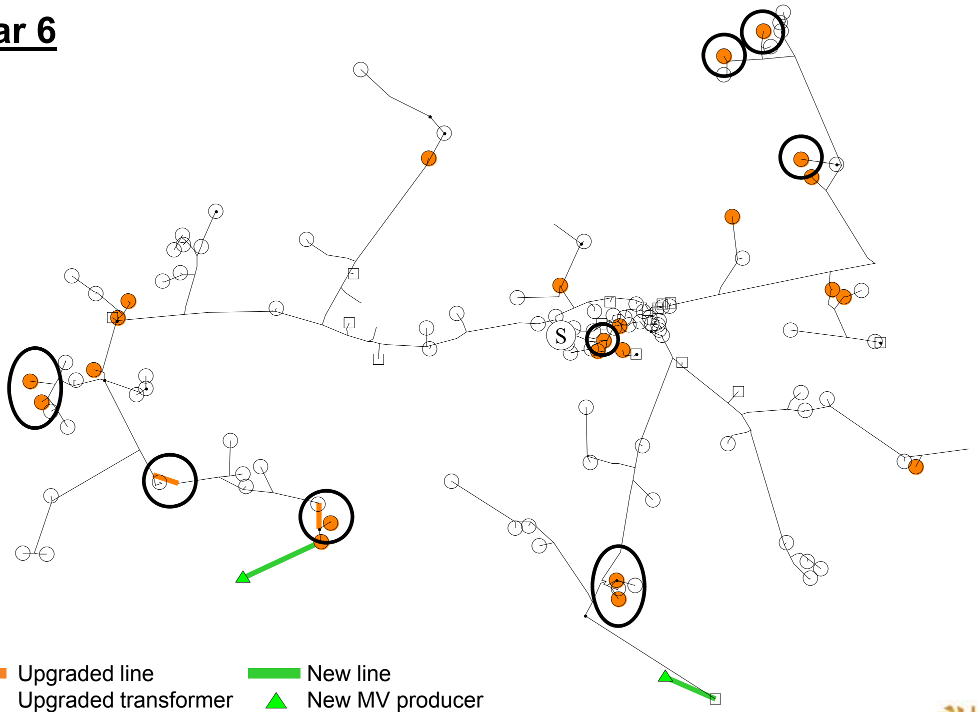


Example of application: the current French planning strategy

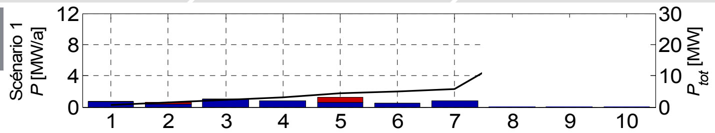
Year 6



Upgraded line
Upgraded transformer
New line
New MV producer

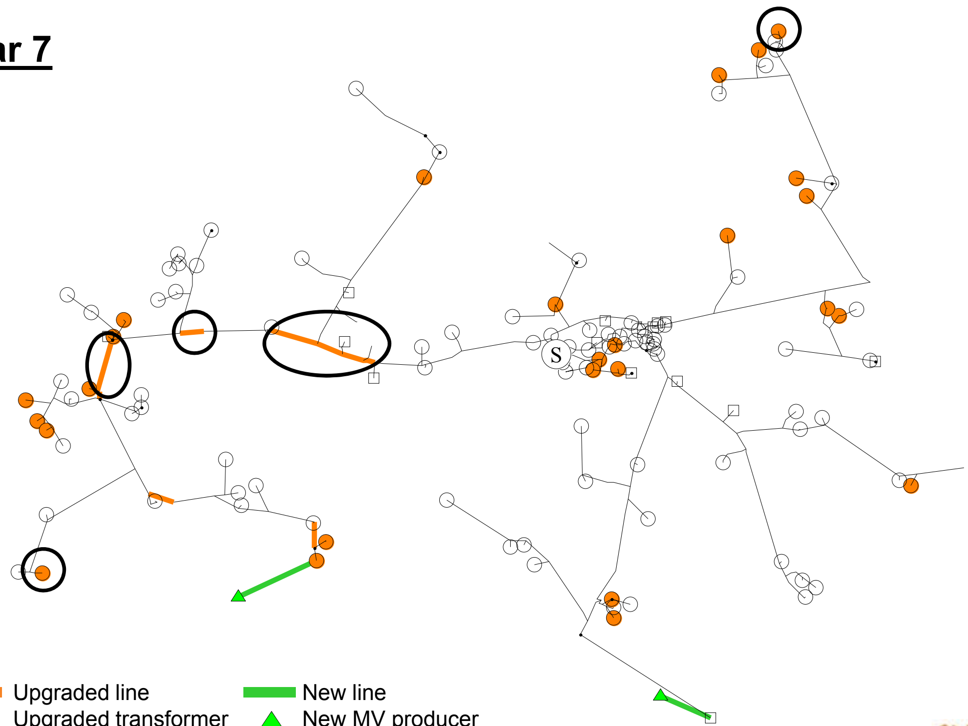
1. Scope 2. Framework 3. Approximation 4. Case studies 5. Conclusion

5 1#Q R Y H O#I U D P H Z R U N



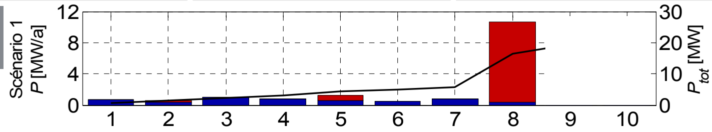
Example of application: the current French planning strategy

Year 7



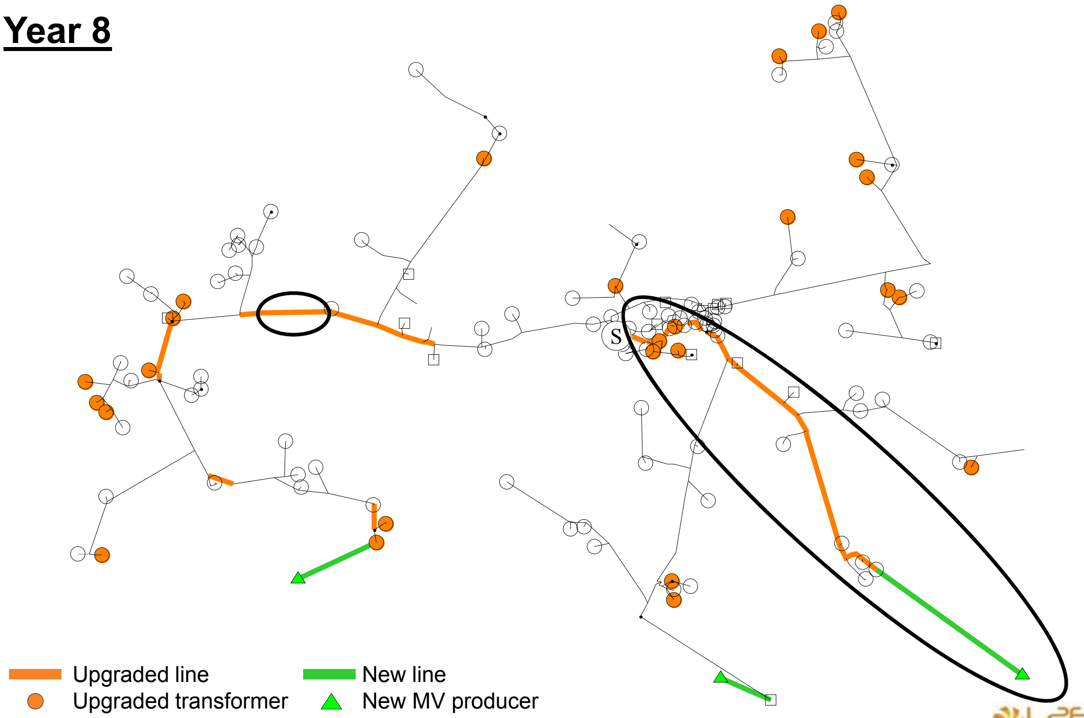
Upgraded line
Upgraded transformer
New line
New MV producer

5 1#Q R Y H O#I U D P HZ R U N

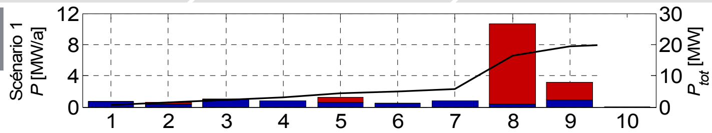


Example of application: the current French planning strategy

Year 8

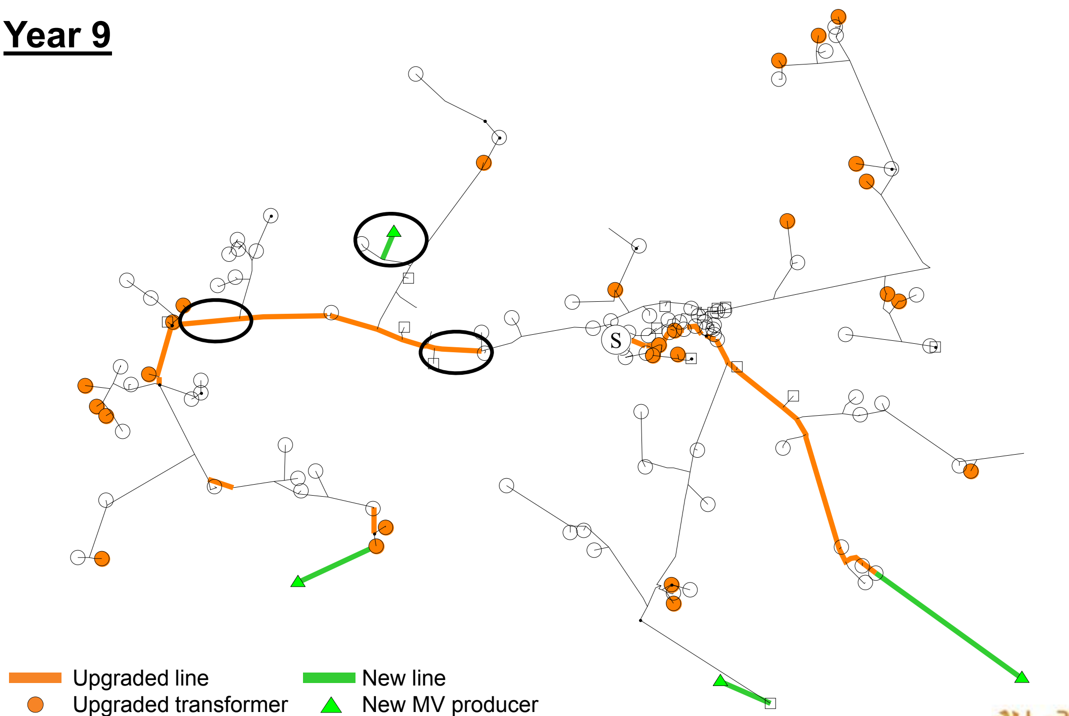


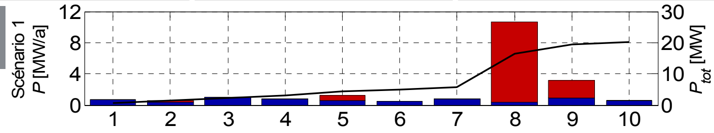
5 1#Q R Y H O#I U D P HZ R U N



Example of application: the current French planning strategy

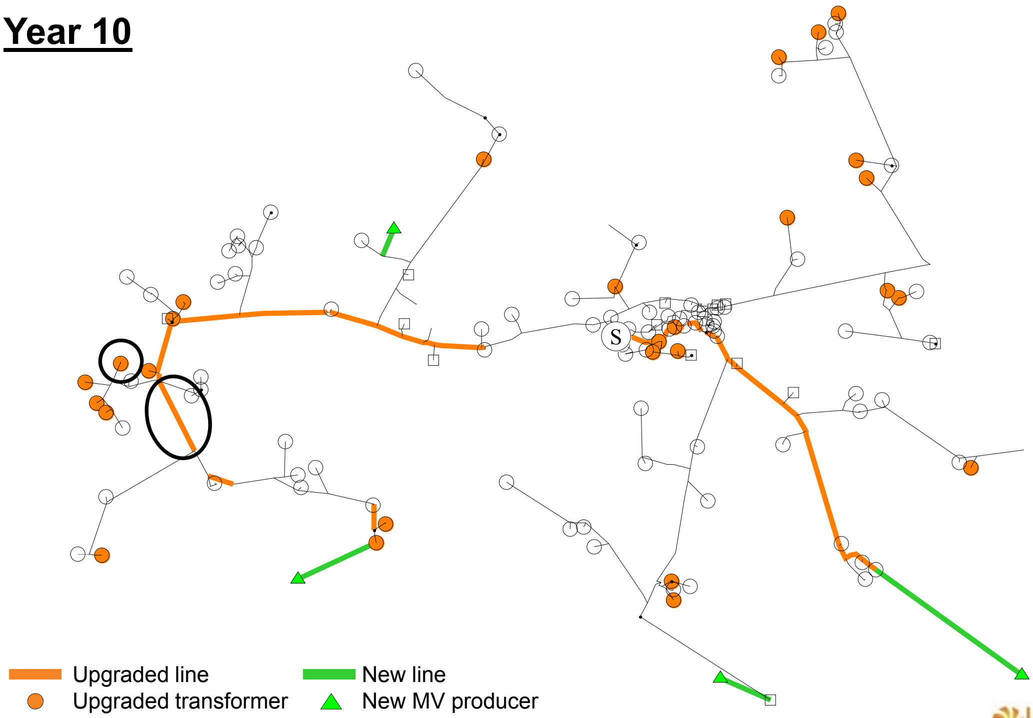
Year 9





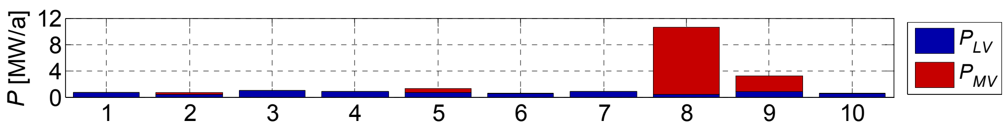
Example of application: the current French planning strategy

Year 10



Example of application: the current French planning strategy

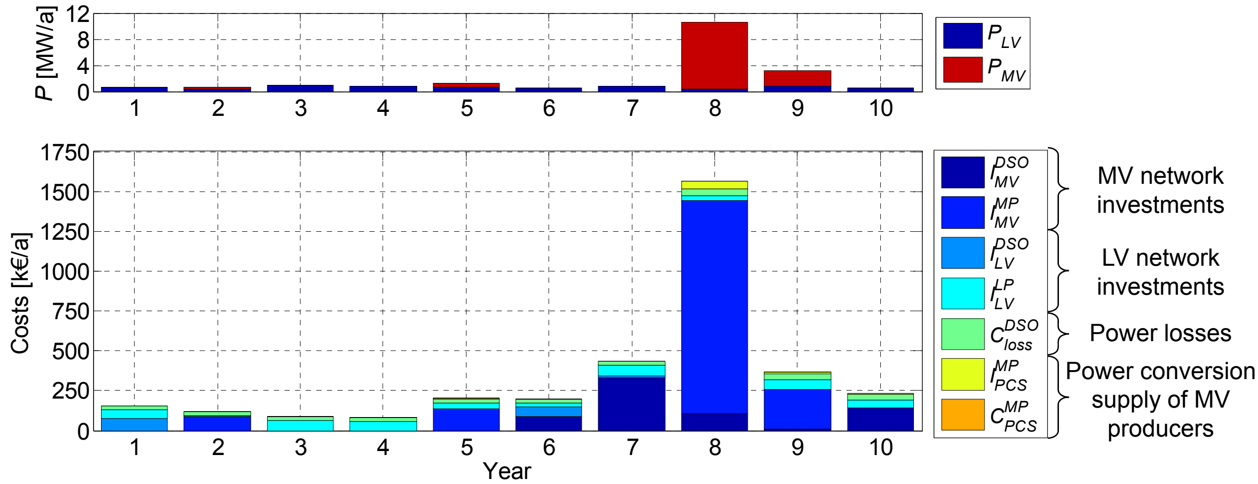
Technical results



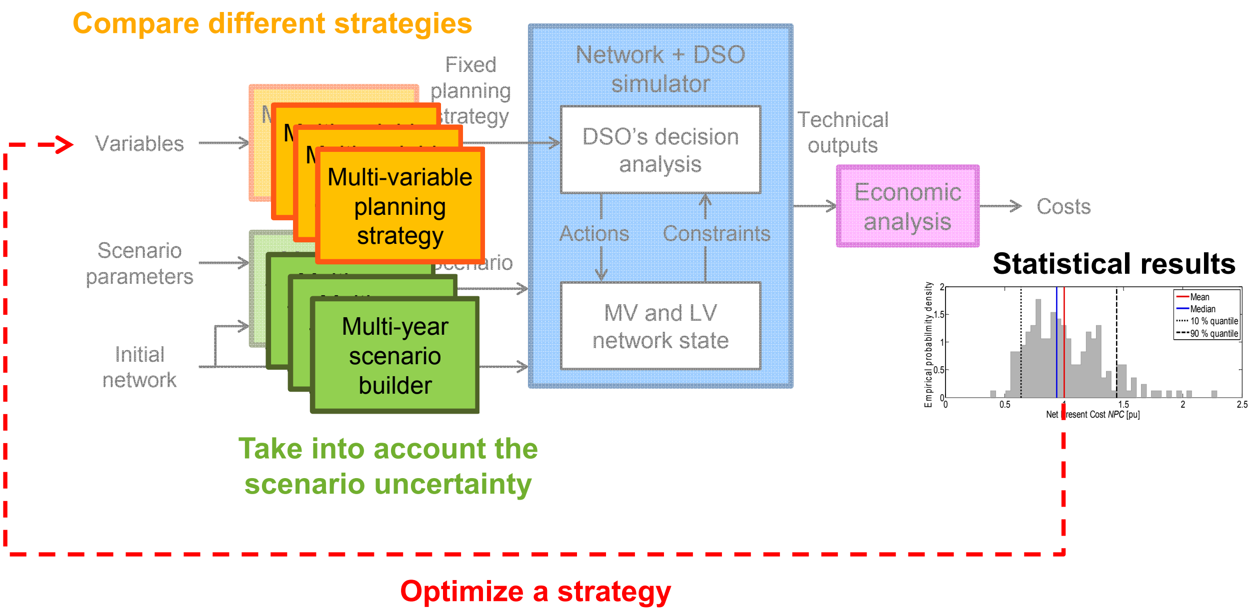
	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Total
Length of upgraded/new MV lines [km]	0	1,2	0	0	1,9	1,2	4,3	15	3,3	2	28,9
Number of upgraded/new MV/LV transformers	9	0	2	2	1	9	4	0	0	1	28
Power losses [MWh]	308	331	353	352	340	352	293	596	528	549	4001
Level of weakly-supplied LV consumers [%]	0,73	0,41	1,05	0,63	0,63	1,81	0,03	0,10	0,19	1,01	–

Example of application: the current French planning strategy

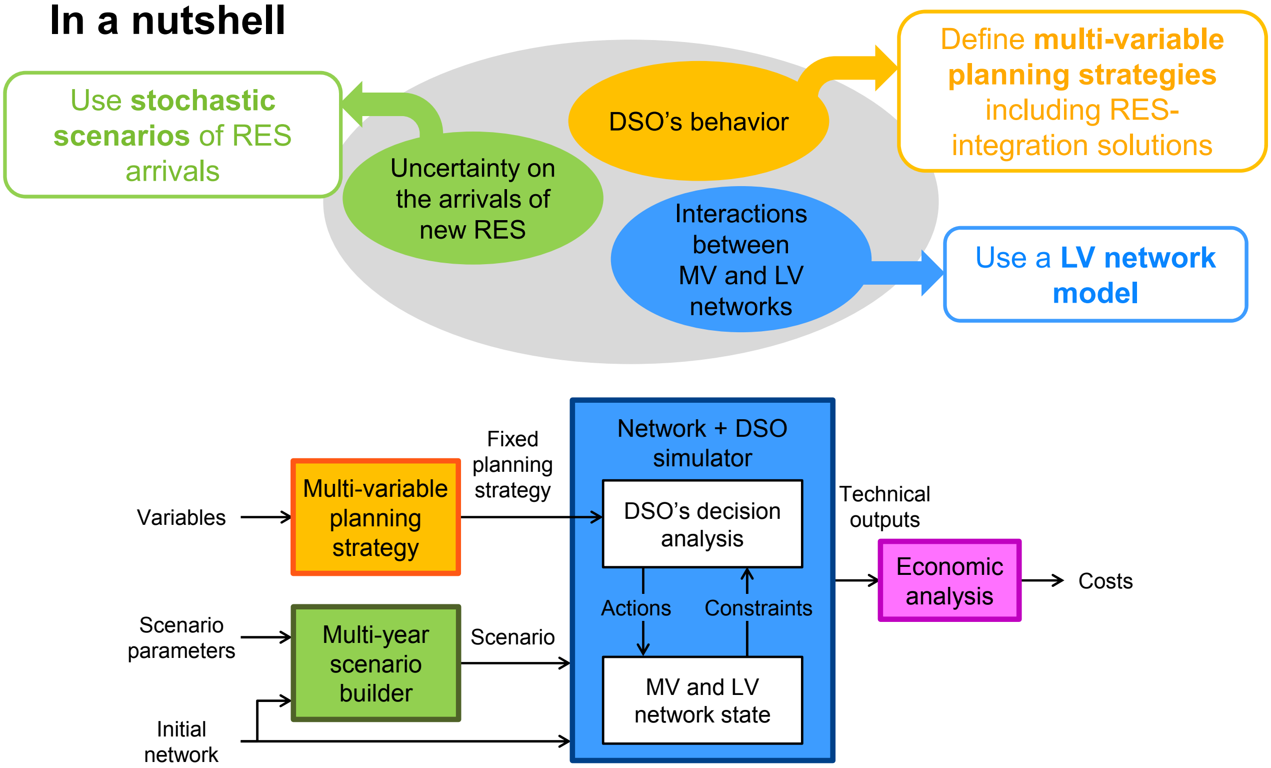
Economic results



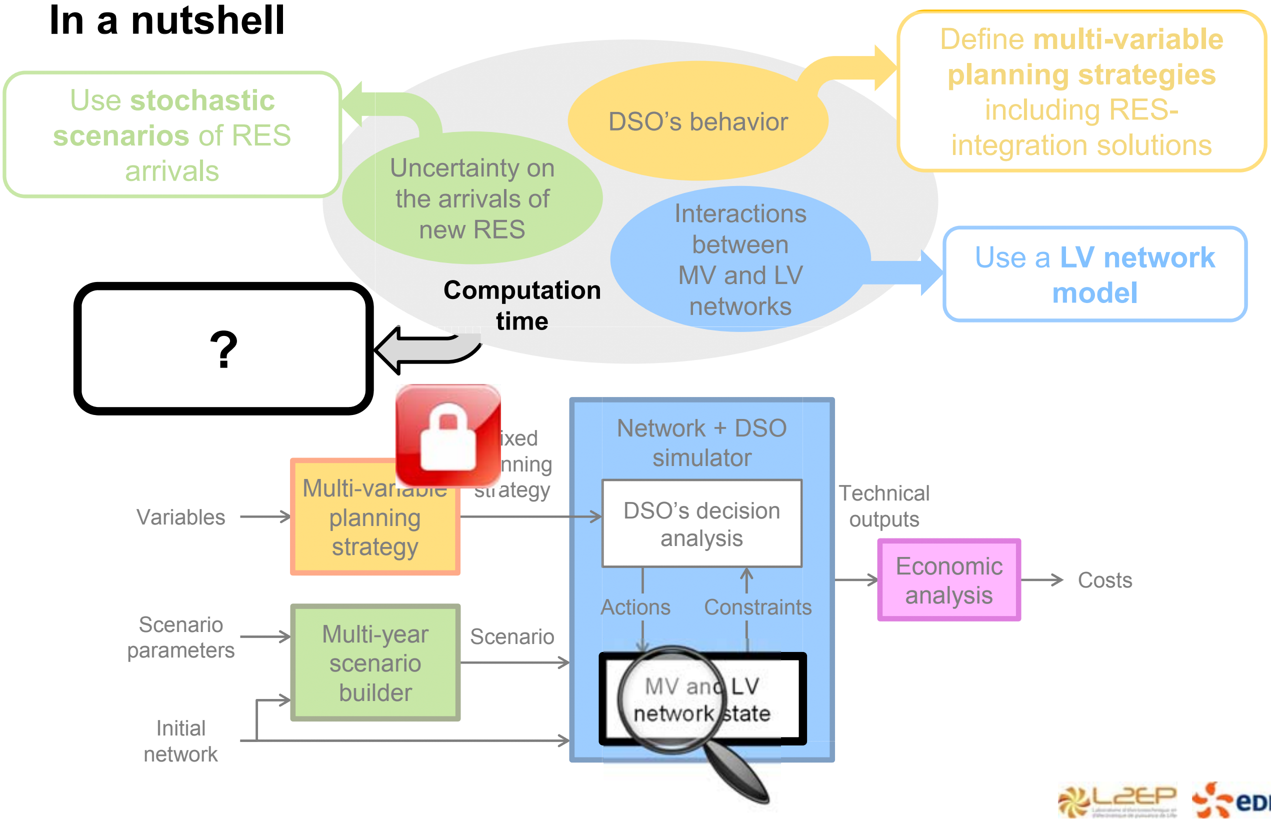
New opportunities to study RES-integration solutions



In a nutshell

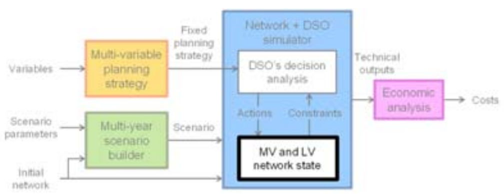


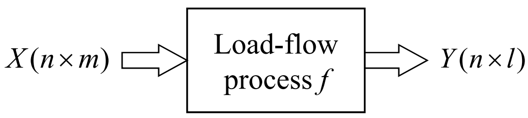
In a nutshell



1. Scope and motivation
2. Novel framework for the study of RES-integration solutions in multi-year distribution planning
3. Approximation methods for computing the multi-year electrical network state
4. Case studies
5. Conclusion and further work

Problem of the computation time in network planning





m = number of input variables
l = number of output variables
n = number of time steps = number of load-flows

Which time step size for studying RES-integration solutions?
The smallest as possible because:
- network constraints are defined over 10 minutes
- RES power can vary in a few seconds/minutes

Time step size considered here: ΔT = **10 minutes** ⇒ n = 52560 load-flows per year ⇒ t_{comput} **≈ 3 minutes** per year

Problem of the computation time in network planning

t_{comput} ≈ **3 minutes** per year

$X(n \times m)$ ⇒ Load-flow process f ⇒ $Y(n \times l)$

m = number of input variables
l = number of output variables
n = number of time steps = number of load-flows

Study a strategy over a 10-year scenario ≈ **30 minutes**

Study a strategy over 200 10-year scenarios ≈ **4 days**

Optimize a multi-variable strategy with 50 candidate points ≈ **6 months**

Compare 10 optimized strategies ≈ **5 years**

1. Scope 2. Framework 3. Approximation 4. Case studies 5. Conclusion
6 1#D SSUR [IP DWIR Q #P HWKRGV

Problem of the computation time in network planning

t_{comput} ≈ **3 minutes** per year

$X(n \times m)$ ⇒ Load-flow process f ⇒ $Y(n \times l)$

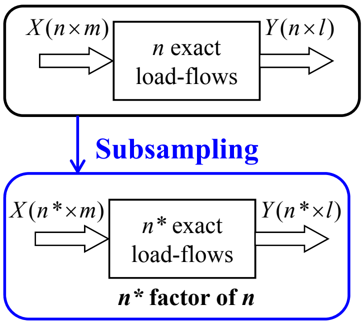
Performing exact load-flows is not suitable.
It is necessary to **reduce computation time while providing accurate results**.

Study a strategy over 200 10-year scenarios ≈ **4 days**

Optimize a multi-variable strategy with 50 candidate points ≈ **6 months**

Compare 10 optimized strategies ≈ **5 years**

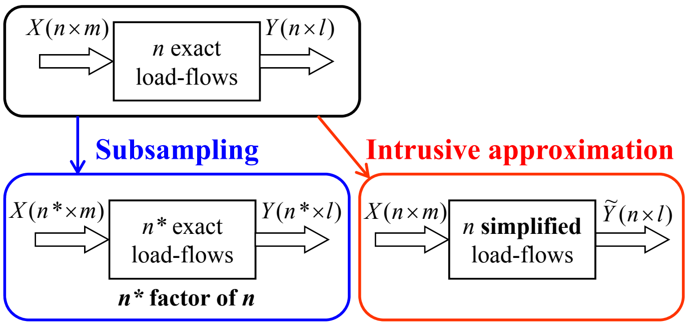
Options to reduce computation time in network planning



Option 1: increase the time step size.

- Commonly used to study RES-integration solutions with $\Delta T = 30$ min or 1 hour.
- Easy to be implemented.
- High loss of accuracy compared with the time saving.

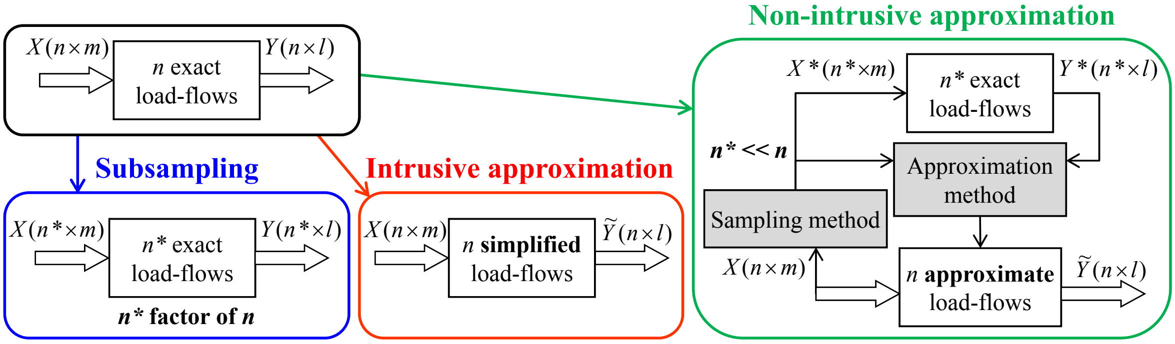
Options to reduce computation time in network planning



Option 2: simplify the load-flow equations using hypotheses and/or intrusive approximation techniques.

- Often used to study network stability and the statistical impacts of input variables.
- Efficiency depending on:
  - the hypotheses,
  - the intrusive approximation techniques.

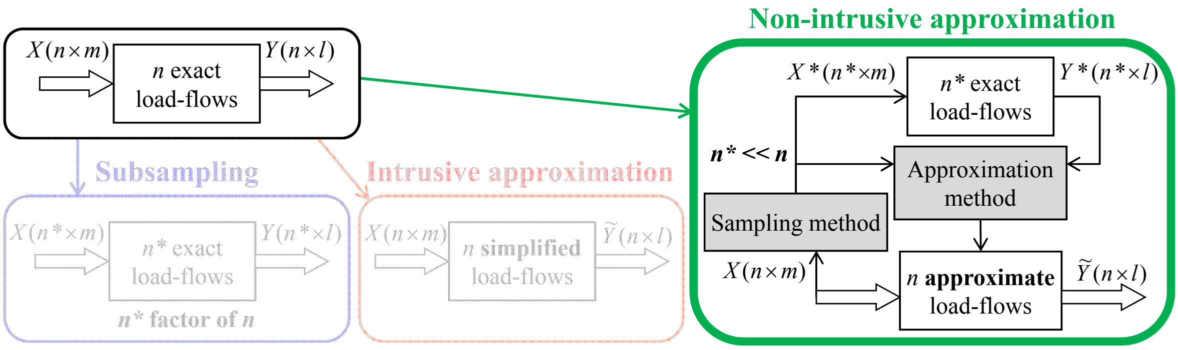
Options to reduce computation time in network planning



Option 3: build a surrogate model of the load-flow process using non-intrusive approximation techniques.

- Often used in application domains when the observed phenomenon is not explicit, but rarely used in network studies.
- Efficiency depending on:
  - the sampling method used to select the points where the exact model has be evaluated,
  - the approximation method used to build the surrogate model based on the evaluation points.

Options to reduce computation time in network planning



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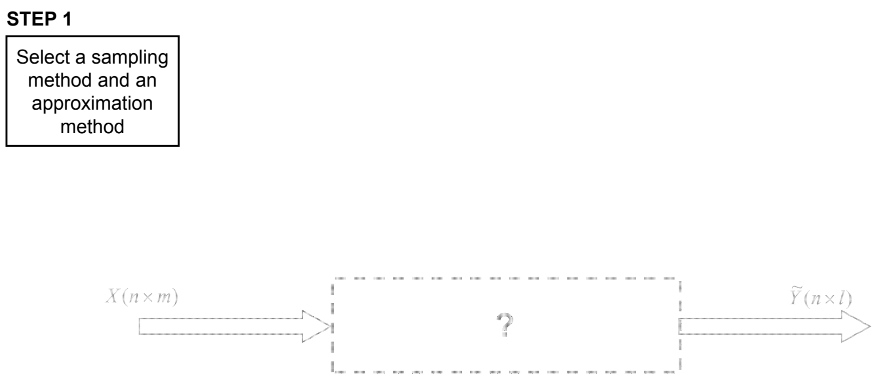
General procedure to estimate a scalar variable $y = f(x)$



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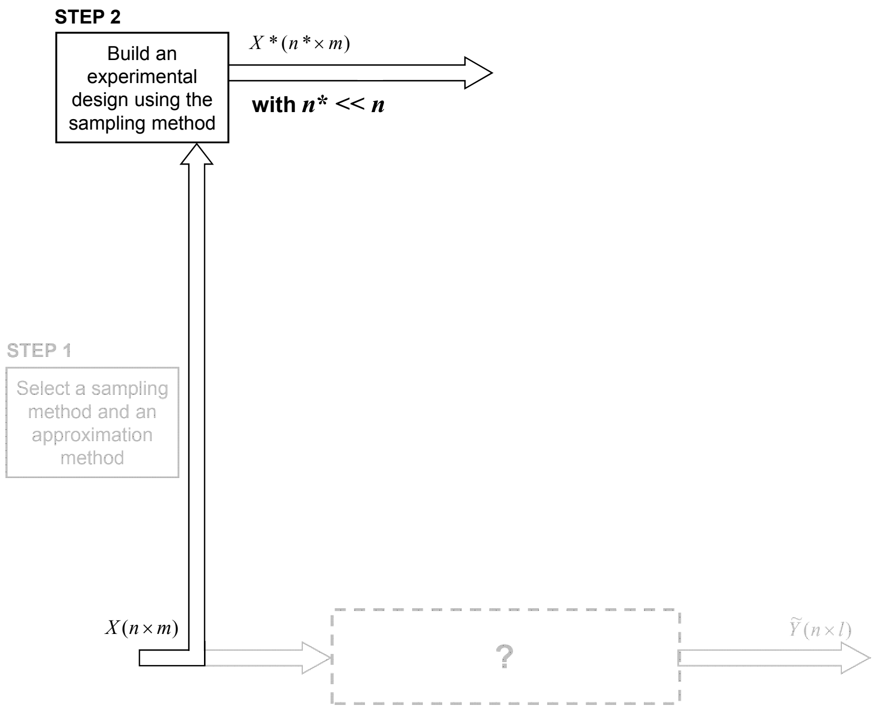

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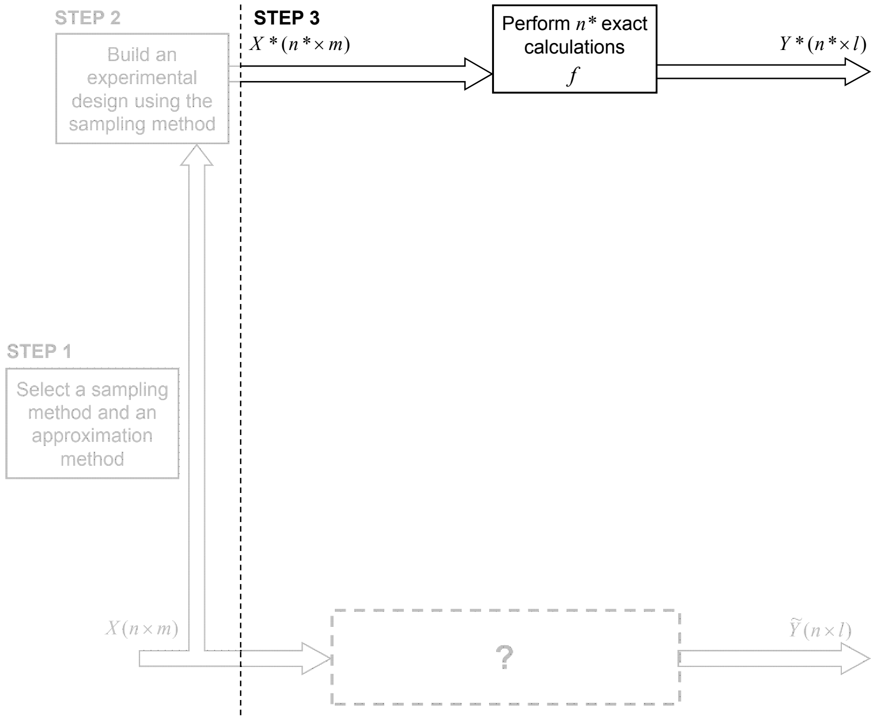

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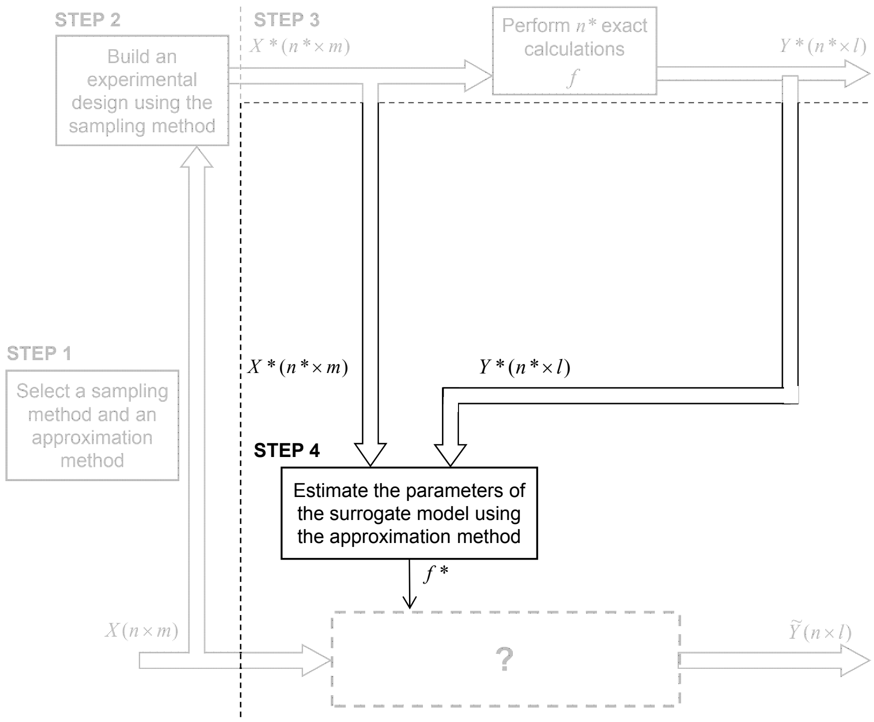

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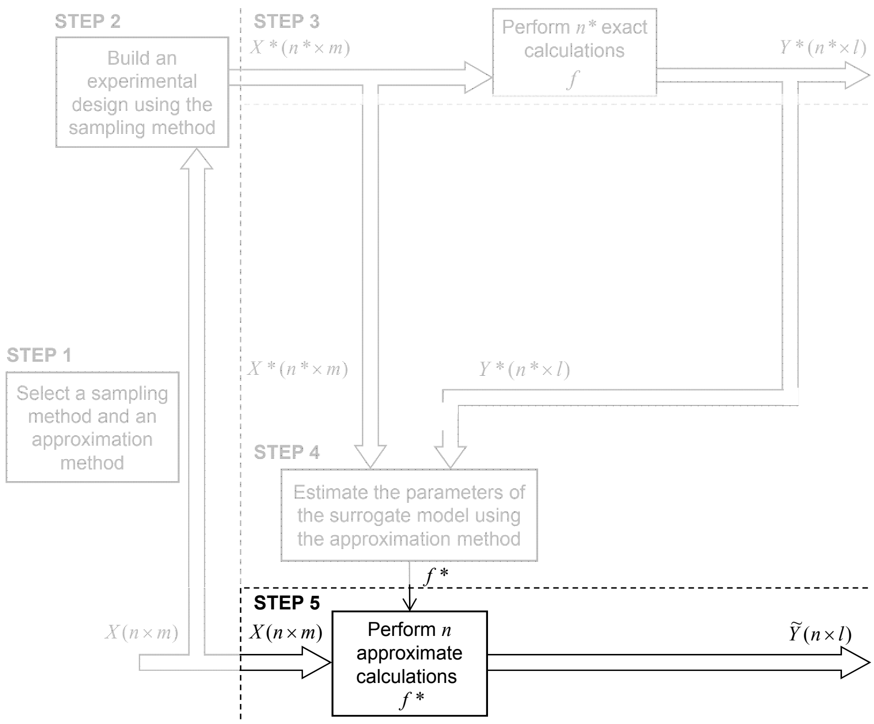
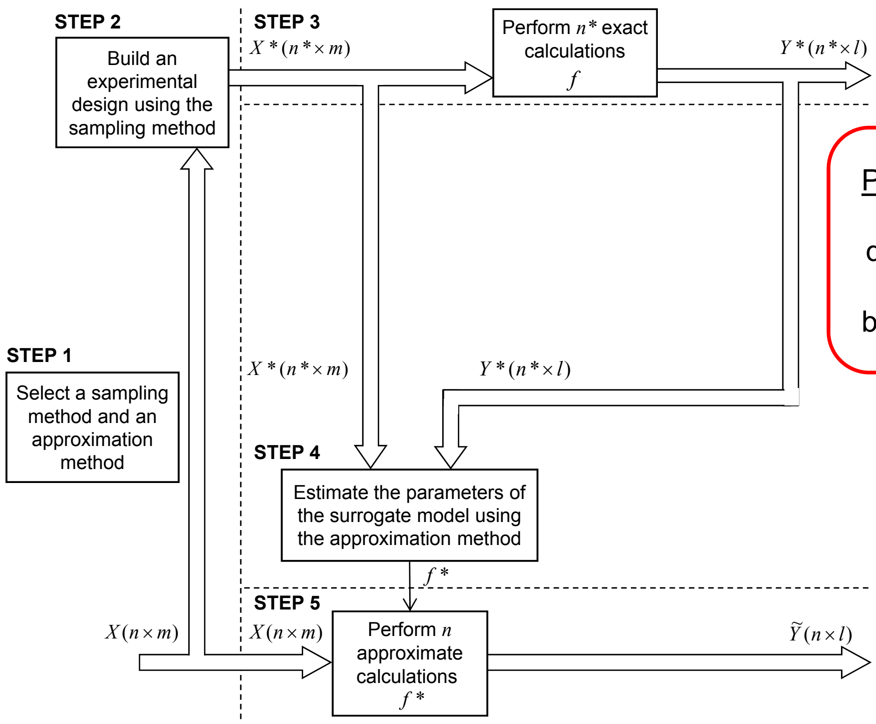
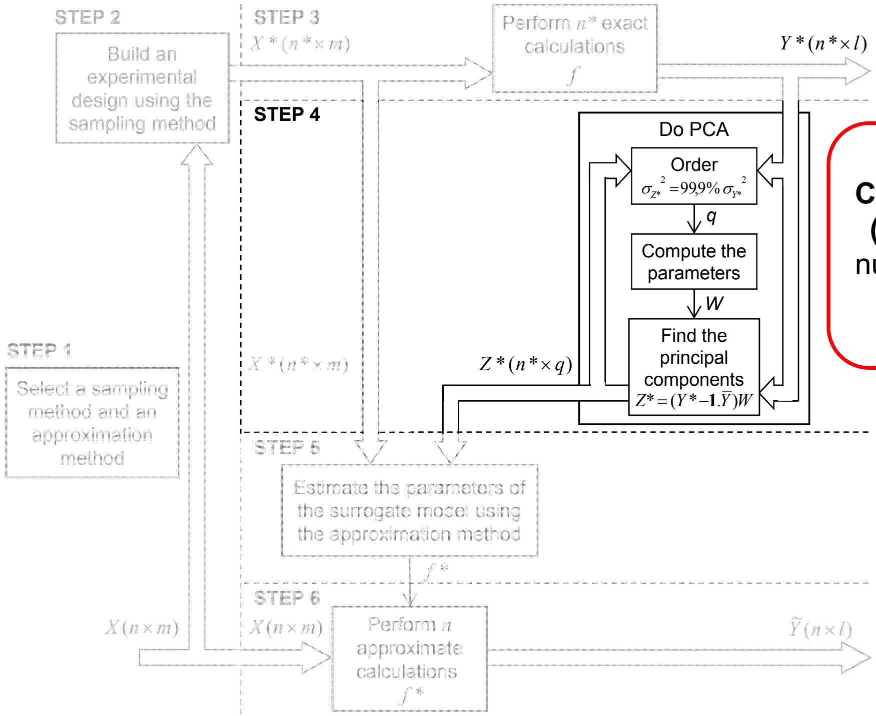


General procedure to estimate a scalar variable $y = f(x)$



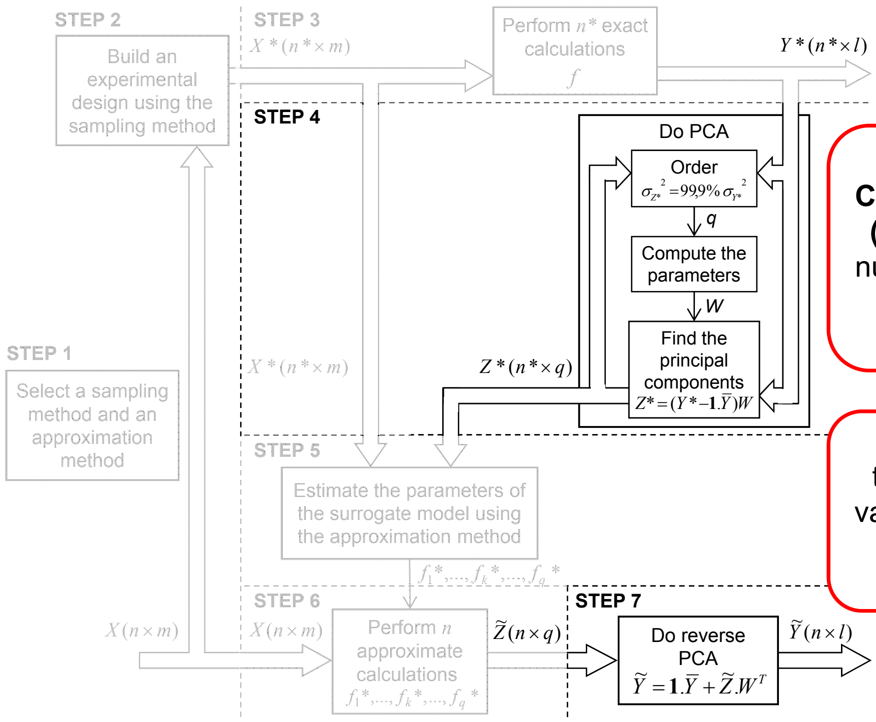
Problem: in our work, *y* is **2(*b*+1)**-dimensional where *b* is the number of buses in the network.

General procedure to estimate a vector variable *y* = *f*(*x*)



Principal Component Analysis (PCA) to reduce the number of variables to be estimated*:*
q* << *l

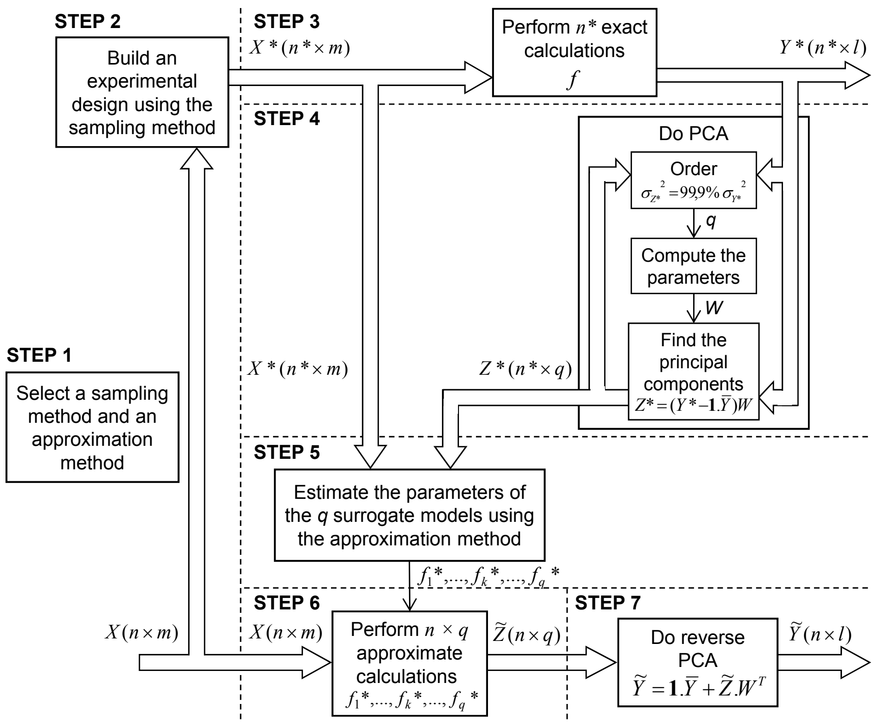
General procedure to estimate a vector variable *y* = *f*(*x*)



Principal Component Analysis (PCA) to reduce the number of variables to be estimated*:*
q* << *l

Reverse PCA
to compute the final variable *y* based on its first principal components *z*.

General procedure to estimate a vector variable *y* = *f*(*x*)



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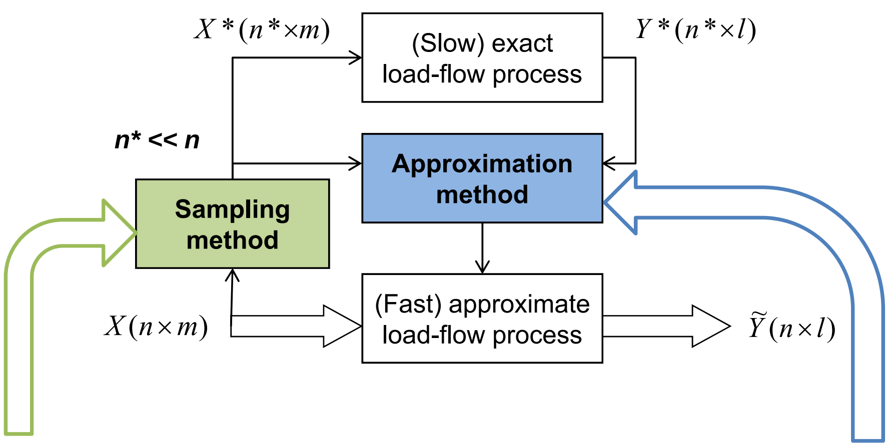
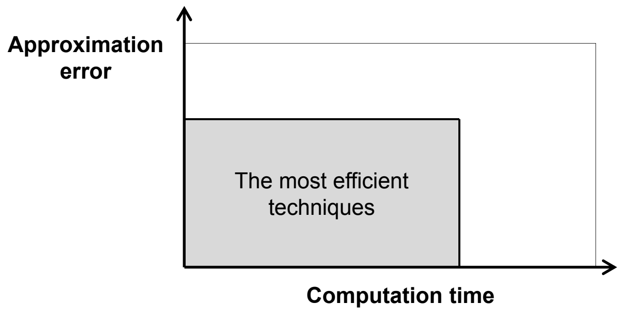


- Pruned Factorial Designs (PFD)
- Mean factorial-based designs (MFD)
- Latin Hypercube Samples (LHS)

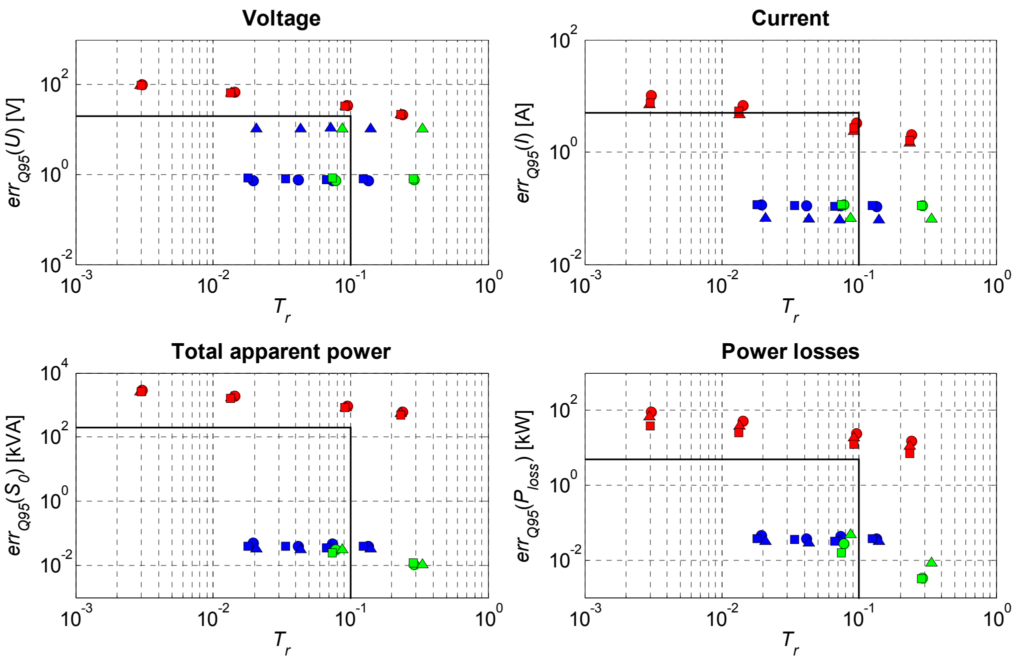
- Nearest-Neighbor Interpolation (NNI)
- Polynomial Regression (PR)
- Kriging (K)

Results of the comparison of the approximation techniques



○ Case 1 — Nearest-Neighbor Interpolation + Mean factorial-based design (red)
△ Case 2 — Polynomial Regression + Latin Hypercube Sample (blue)
□ Case 3 — Kriging + Latin Hypercube Sample (green)

Results of the comparison of the approximation techniques



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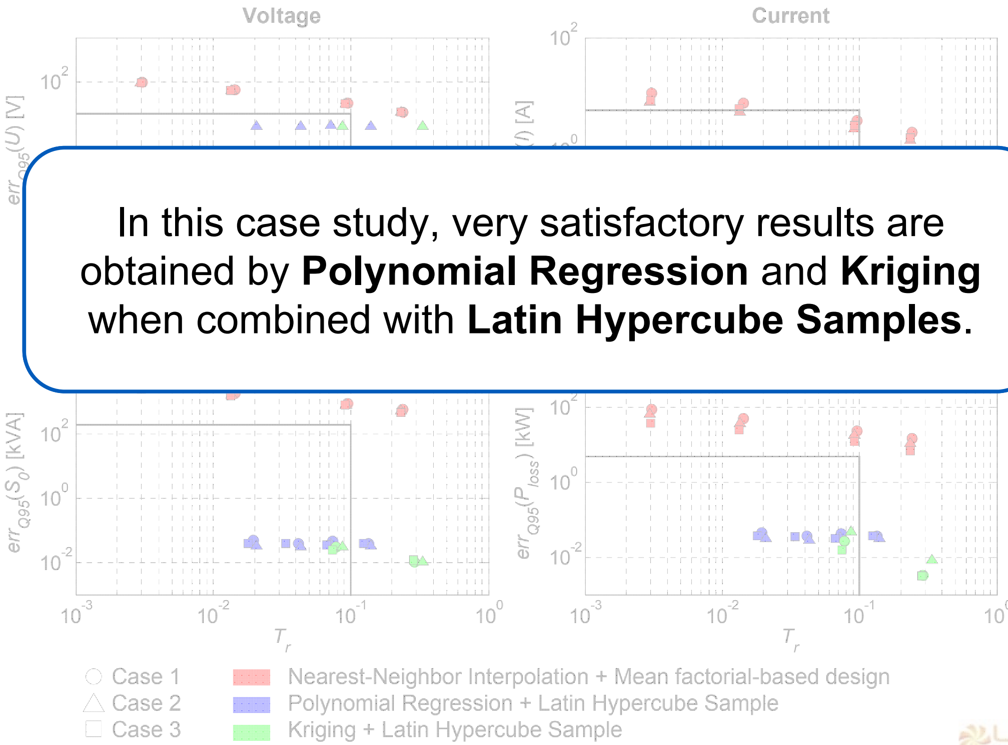
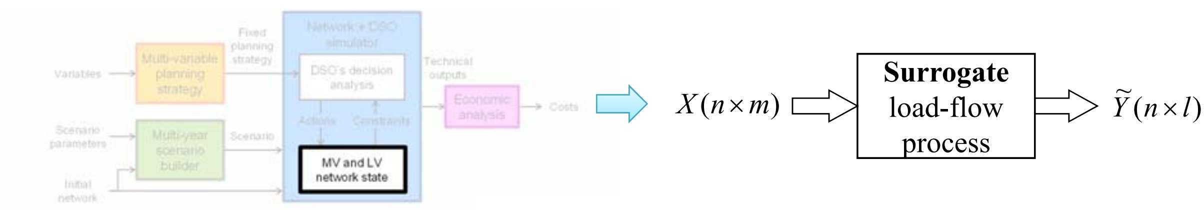
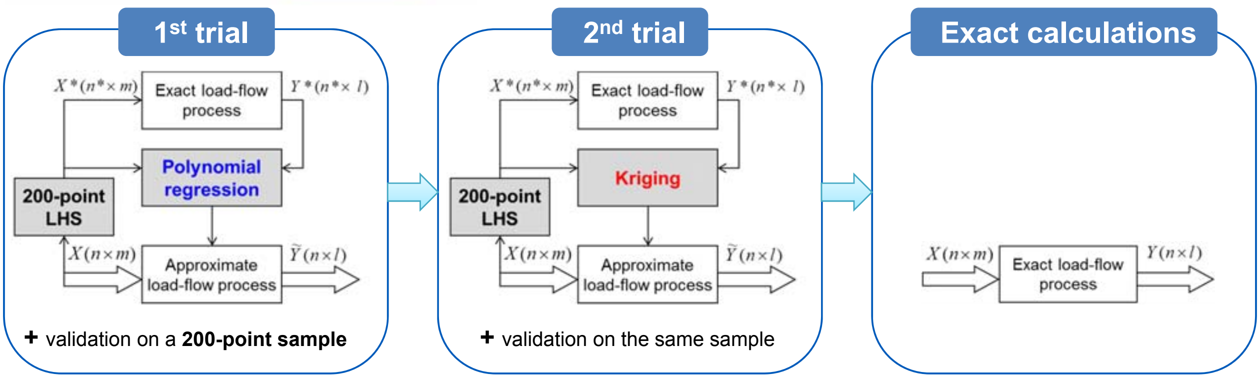


In this case study, very satisfactory results are obtained by **Polynomial Regression** and **Kriging** when combined with **Latin Hypercube Samples**.

Final procedure to estimate the network state over one year





= 400 exact load-flows

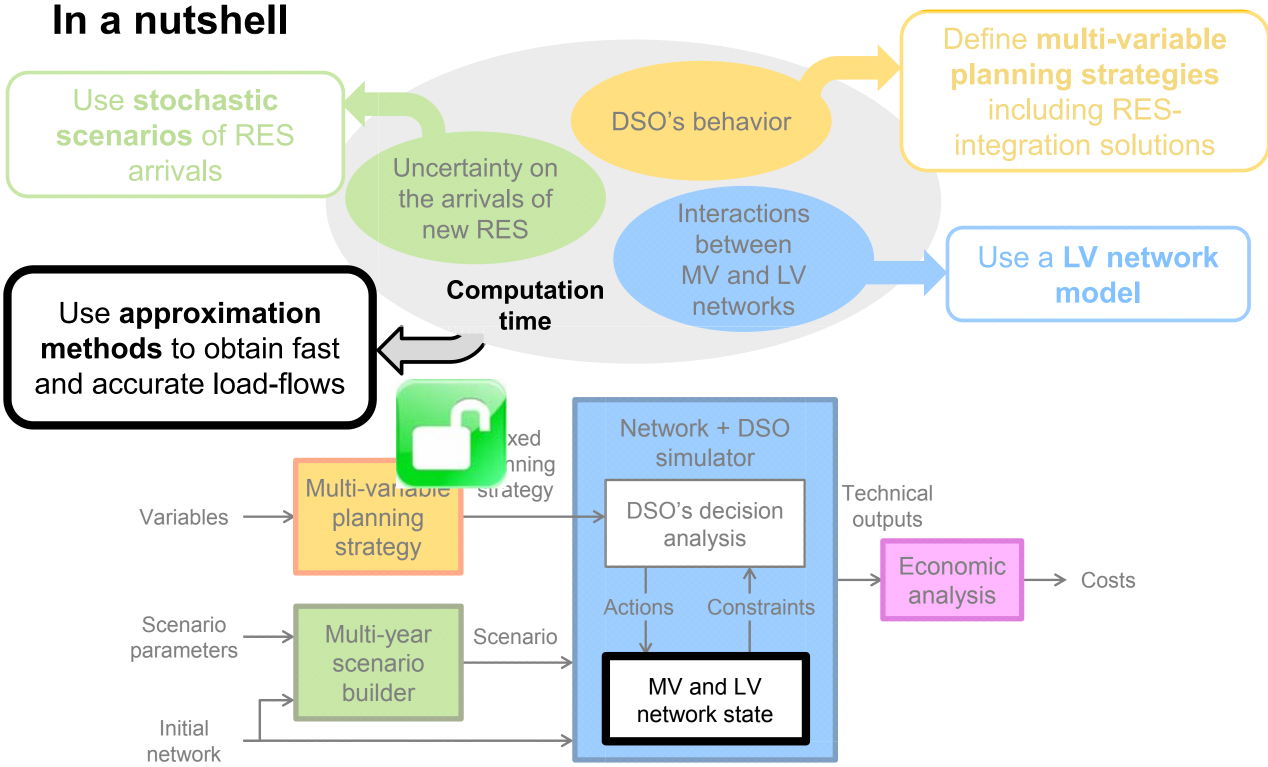
= 200 exact load-flows

= 52 560 exact load-flows

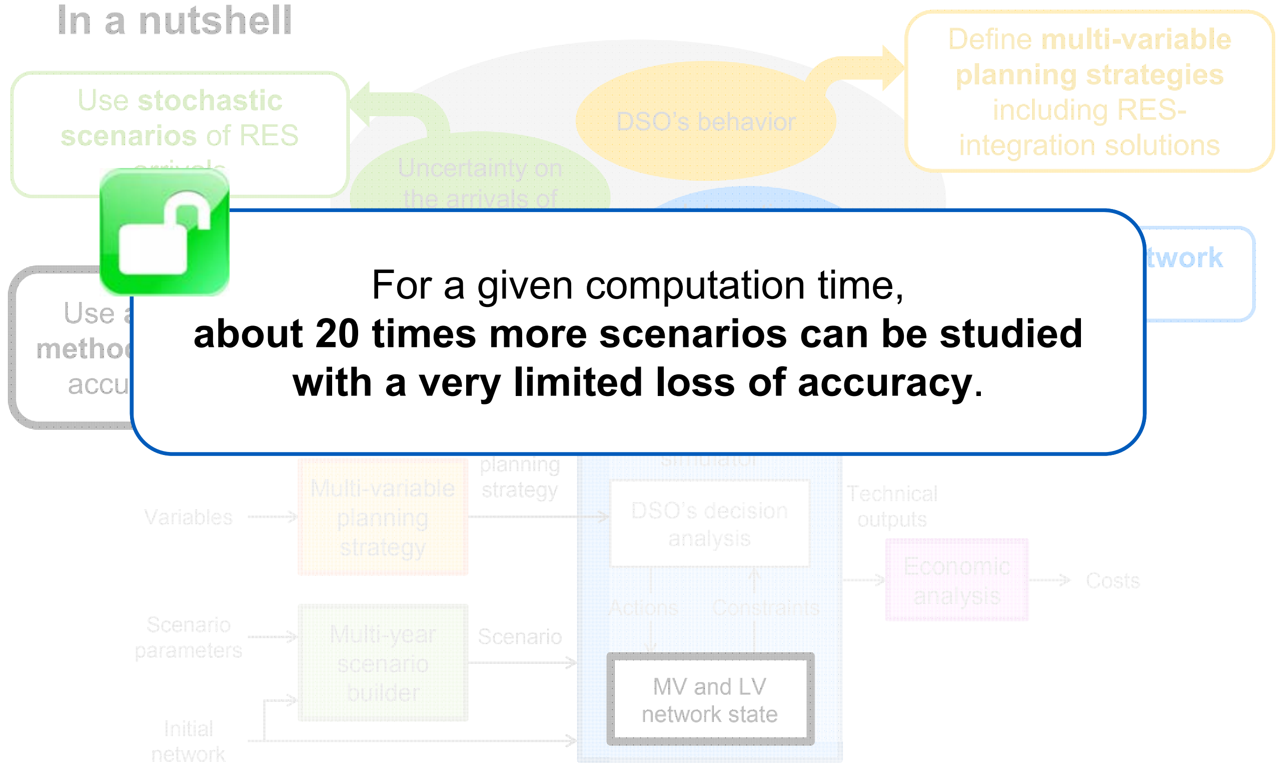
General performances of the proposed procedure

		Proposed procedure	To be compared with:
Error	Voltage	< 150 V	U_n = 20 kV
	Current	< 5 A	185 A < I_n < 615 A
	Power losses	< 1 %	E_{loss} ≈ 200-600 MWh
	Total apparent power	< 200 kVA	20 MVA < S_n < 72 MVA
Time saving		8 to 35!	3 or 6 with time subsampling

In a nutshell



In a nutshell



For a given computation time,
about 20 times more scenarios can be studied with a very limited loss of accuracy.

1. Scope and motivation
2. Novel framework for the study of RES-integration solutions in multi-year distribution planning
3. Approximation methods for computing the multi-year electrical network state
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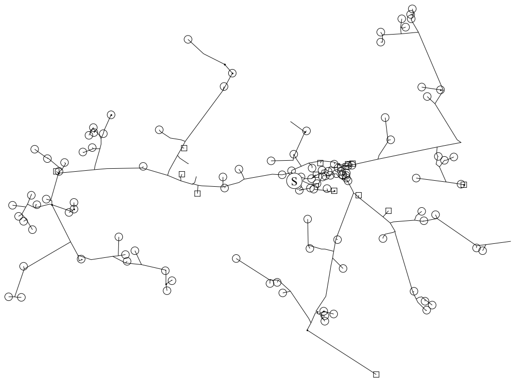
Considered studies



Year 0	→	Year 10
Load: 11 MVA		Load: +2 %/y
Generation: 0		Gen.: 20-22 MW

1. Impact of the minimal tangent phi of the MV producers
2. Impact of the "Last In First Out" generation curtailment
3. Optimization of the current French planning strategy

(1–2) Simulations over **200 scenarios**

(3) Use of an **optimization algorithm**

Study 1: impact of the minimal tangent phi of the MV producers

Variables: $\theta = \tan(\varphi)_{\min} = \tan(\varphi)_{\min,DSO}$

θ → Current planning strategy → Fixed strategy

***R1**: decrease the fixed $\tan(\varphi)$ reference of the new producer, with $\tan(\varphi) \geq \mathbf{tan(\varphi)_{min}}$.*

***R2**: decrease the fixed $\tan(\varphi)$ reference of the existing MV producers, with $\tan(\varphi) \geq \mathbf{tan(\varphi)_{min,\mathit{DSO}}}$.*

Possible impacts

↘ $\tan(\varphi)_{\min}$

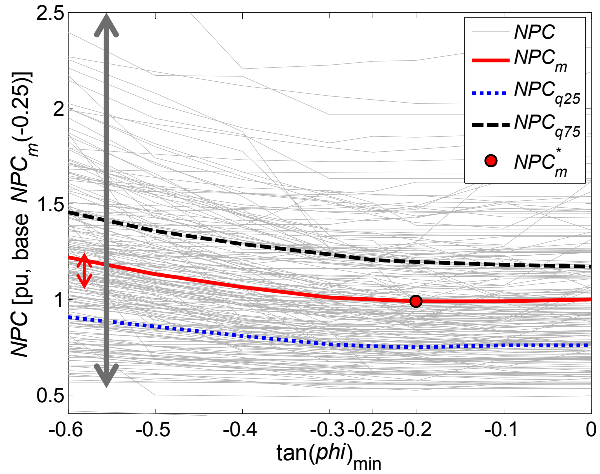
- Less network reinforcement
- More MV producers connected to feeders supplying loads
- More or less power losses
- Bigger power conversion chain for all the MV producers

$$NPC = \sum_{k=1}^{T}\left(\frac{I_k}{(1+i)^{k-1}} + \frac{C_k}{(1+i)^{k-1}} - \frac{V_k}{(1+i)^{T}}\right)$$

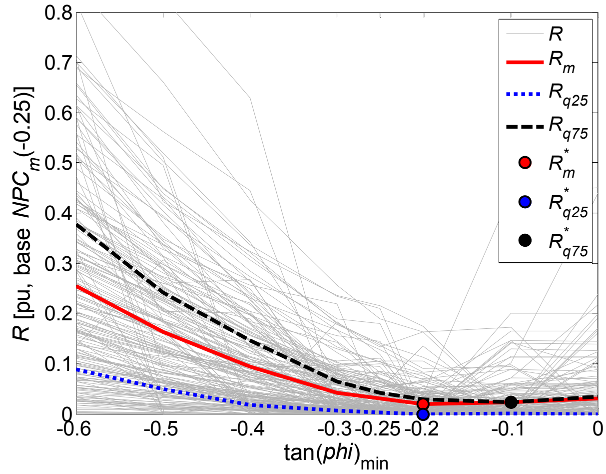
Which impact on the Net Present Cost?

Study 1: impact of the minimal tangent phi of the MV producers

$NPC(\theta,S)$



$R(\theta,S) = NPC(\theta,S) - \min_{\theta\in\Theta}\left(NPC(\theta,S)\right)$

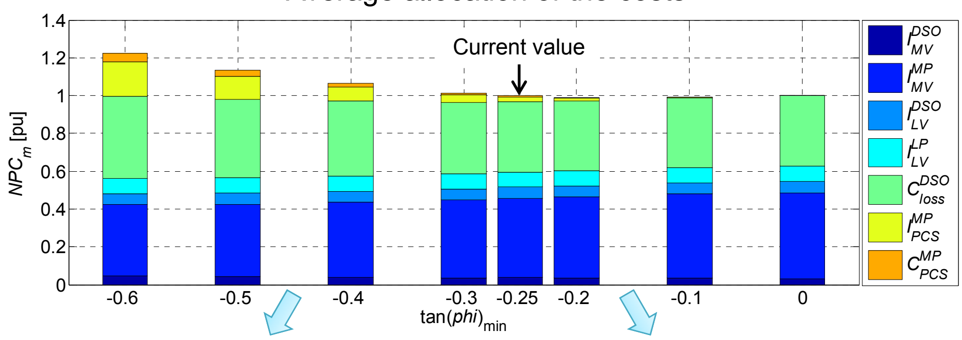


High dispersion of the scenario costs compared with the average cost: impossible to say which value of $\tan(\varphi)_{\min}$ is optimal.

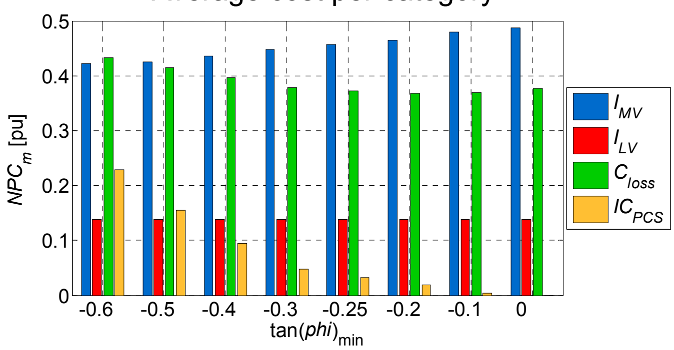
The values of $\tan(\varphi)_{\min}$ between –0.2 and 0 have a similar average impact on the costs.

Study 1: impact of the minimal tangent phi of the MV producers

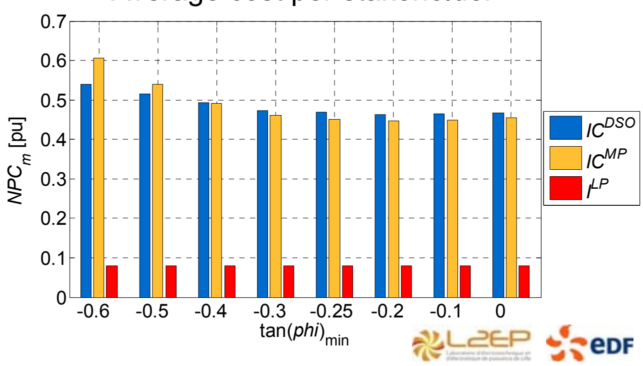
Average allocation of the costs



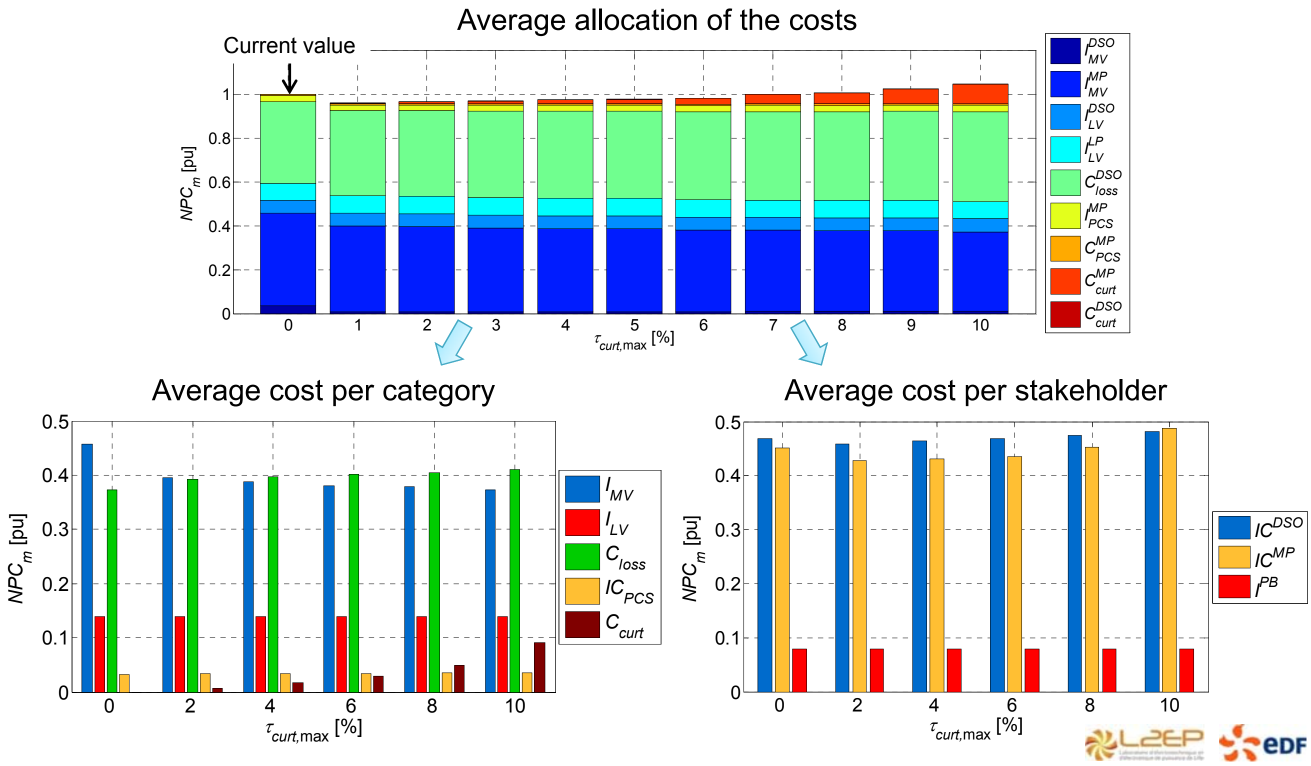
Average cost per category



Average cost per stakeholder



Study 2: impact of the "Last In First Out" generation curtailment



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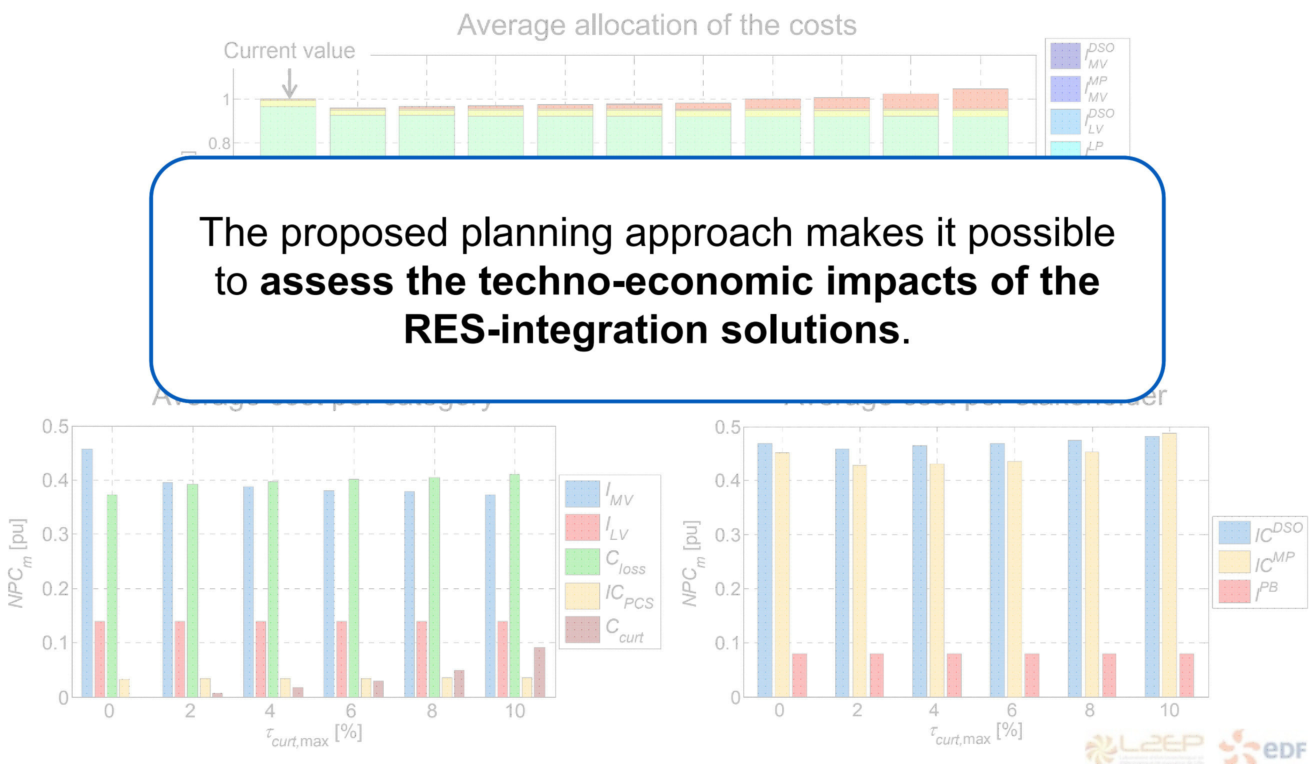
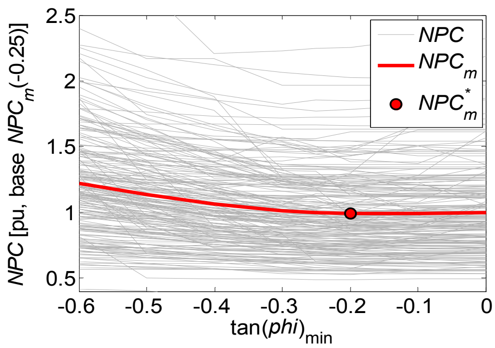


The proposed planning approach makes it possible to **assess the techno-economic impacts of the RES-integration solutions**.

Study 3: optimization of the current planning strategy

Why should we use an optimization process?



Accuracy on the average cost: δ = 2 %

N = 200 scenarios per candidate point

t_{comput} ≈ 4 hours per candidate point

Considering 10 candidate values for each decision variable:

- Optimize a 1-variable strategy ≈ **40 hours**
- Optimize a 2-variable strategy ≈ **16 days**
- Optimize a 3-variable strategy ≈ **5 months**

Study 3: optimization of the current planning strategy

General problem

$$\begin{pmatrix} \min_\theta f(\theta) \\ \text{s.t. } g(\theta) \leq 0 \end{pmatrix}$$

Objective f

- Economic: Net Present Cost, Regret...
- Quality: Number of weakly-supplied consumers...
- Scenario uncertainty: Mean, Quantile…

Constraints g

- Finite space of the decision variables,
- Quality on the network…

Decision variables θ

- Number of variables
- Continuous or discrete

Study 3: optimization of the current planning strategy

General problem

$$\begin{cases} \min_\theta f(\theta) \\ \text{s.t. } g(\theta) \leq 0 \end{cases}$$

Objective f

- Economic: Net Present Cost, Regret...
- Quality: Number of weakly-supplied consumers...
- Scenario uncertainty: Mean, Quantile…

Constraints g

- Finite space of the decision variables,
- Quality on the network…

Decision variables θ

- Number of variables: 1
- Continuous or discrete

Studied problem

$$f(\theta) = E_{S\in\mathbf{S}}\left(NPC(\theta,S)\right)$$

$$\theta = \tan(\varphi)_{\min} \in \left[-0.6\ ;\ 0\right]$$

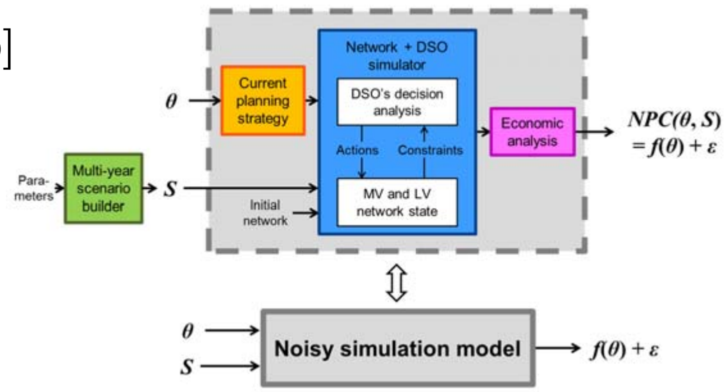
Study 3: optimization of the current planning strategy

Studied problem

$$\min_{\theta\in\boldsymbol{\Theta}} f(\theta) \begin{cases} f(\theta) = E_{S\in\mathbf{S}}\left(NPC(\theta,S)\right) \\ \theta = \tan(\varphi)_{\min} \\ \boldsymbol{\Theta} = \left[-0.6\ ;\ 0\right] \end{cases}$$

Problem particularities?

- No explicit formulation of f
- Noisy evaluation results
- Expensive-to-evaluate model



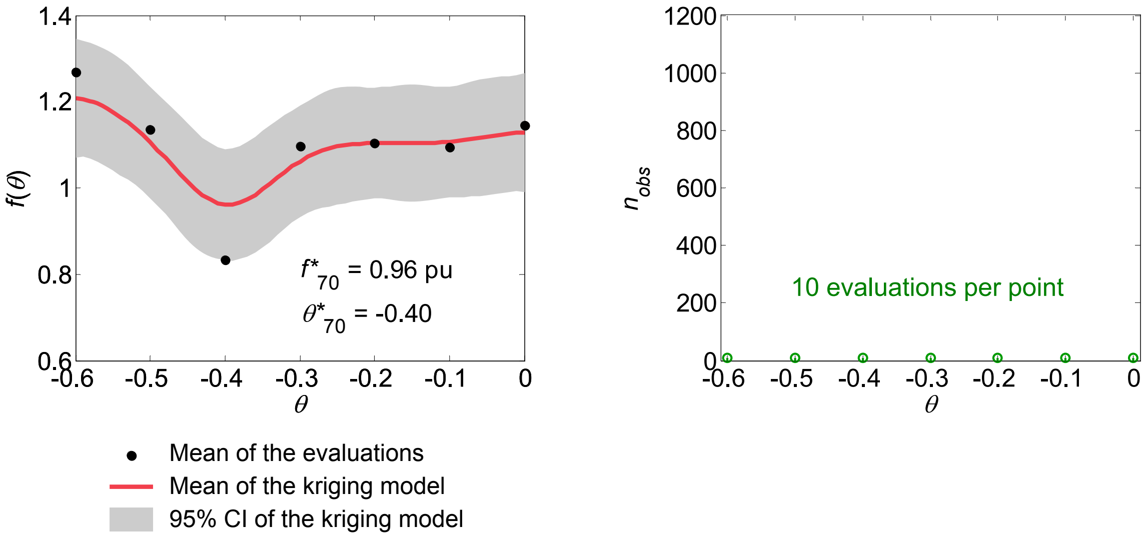
Optimization algorithm used:

Informational Approach to Global Optimization (IAGO)

Study 3: optimization of the current planning strategy

After 70 evaluations:

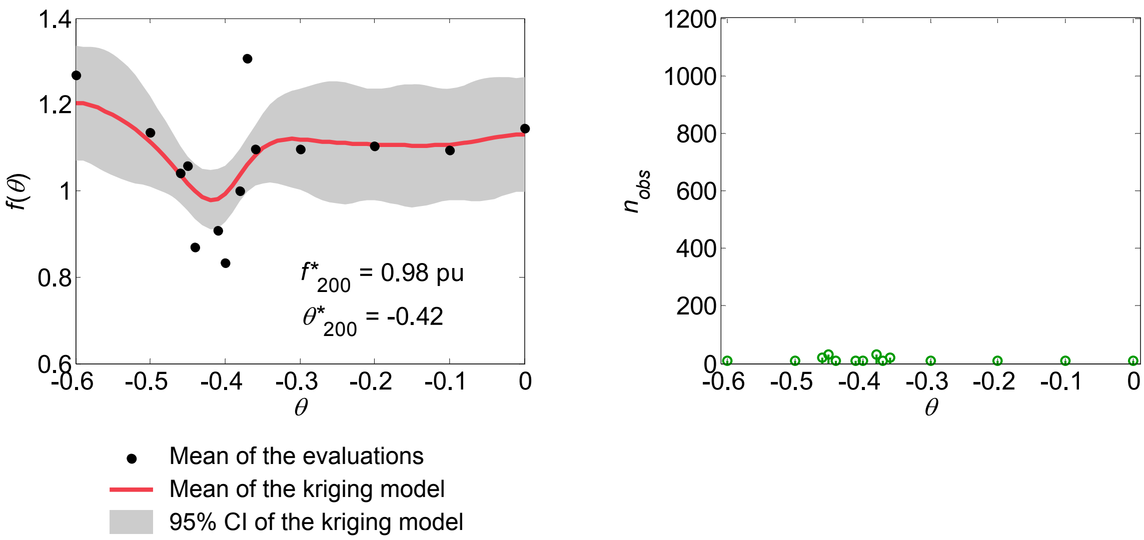
Estimation of the objective function **Allocation of the evaluations**



Study 3: optimization of the current planning strategy

After 200 evaluations:

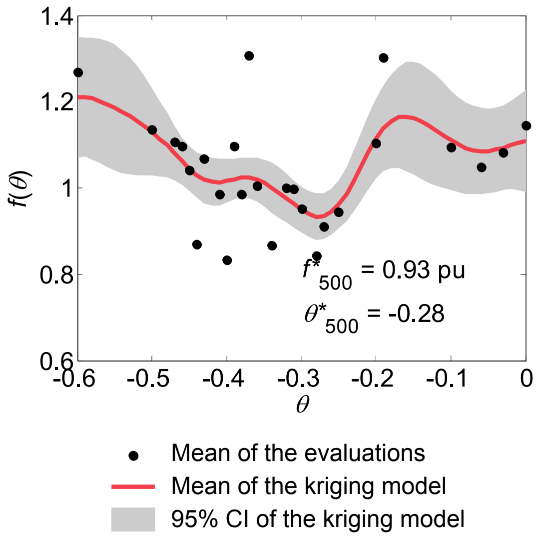
Estimation of the objective function **Allocation of the evaluations**



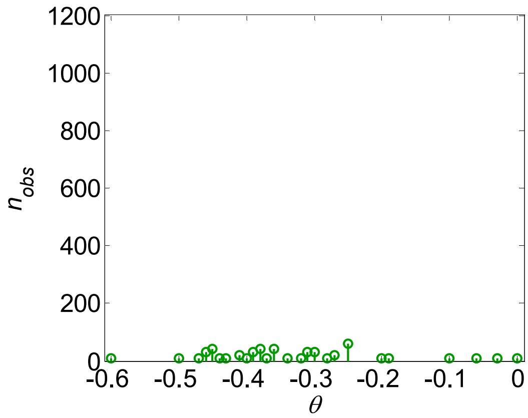
Study 3: optimization of the current planning strategy

After 500 evaluations:

Estimation of the objective function



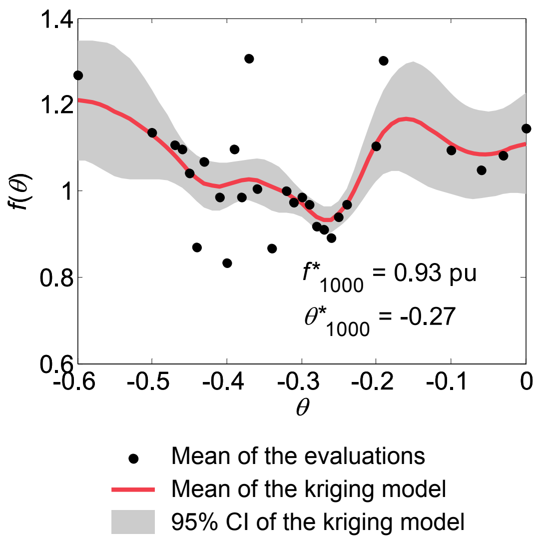
Allocation of the evaluations



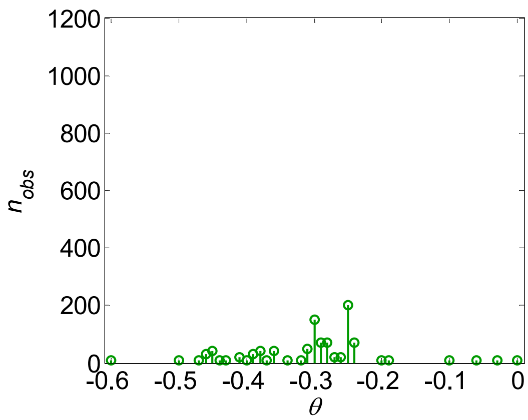
Study 3: optimization of the current planning strategy

After 1 000 evaluations:

Estimation of the objective function



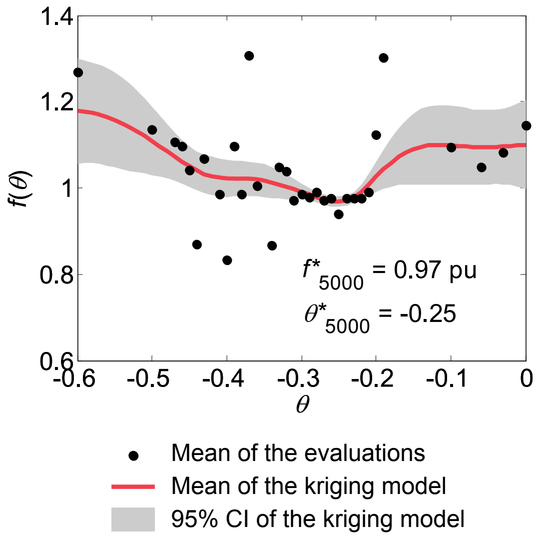
Allocation of the evaluations



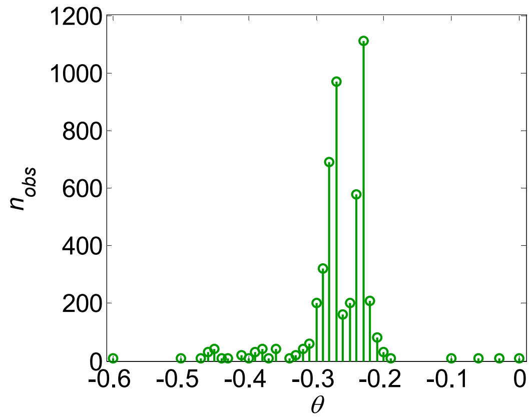
Study 3: optimization of the current planning strategy

After 5 000 evaluations: ⟺ **83 scenarios** per candidate point without optimization

Estimation of the objective function



Allocation of the evaluations



1. Scope 2. Framework 3. Approximation 4. Case studies 5. Conclusion
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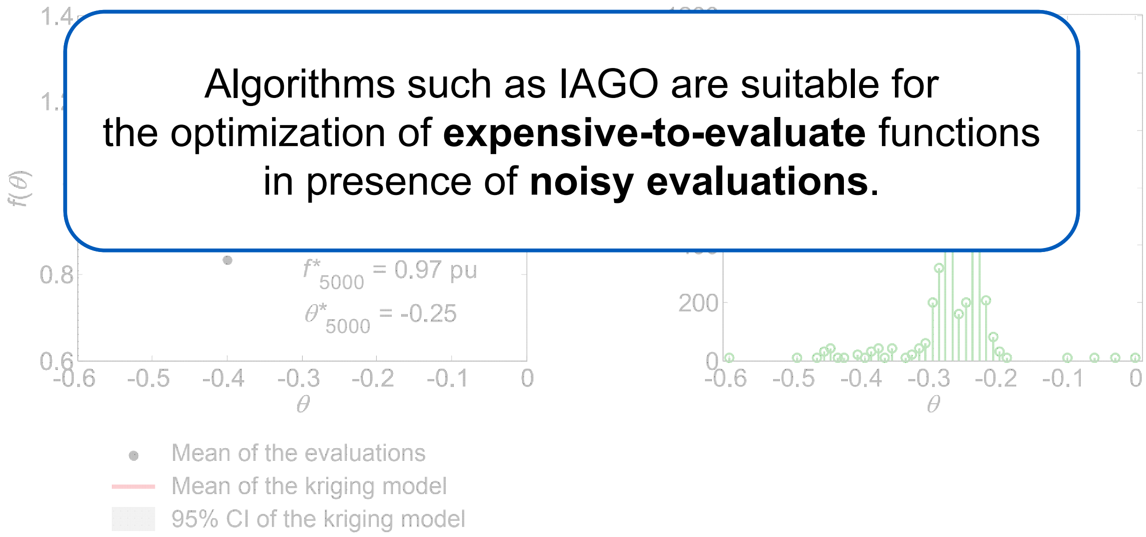
Study 3: optimization of the current planning strategy

After 5 000 evaluations: ⟺ 83 scenarios per candidate point without optimization

Estimation of the objective function

Allocation of the evaluations



Algorithms such as IAGO are suitable for the optimization of **expensive-to-evaluate** functions in presence of **noisy evaluations**.

1. Scope and motivation
2. Novel framework for the study of RES-integration solutions in multi-year distribution planning
3. Approximation methods for computing the multi-year electrical network state
4. Case studies
5. Conclusion and further work

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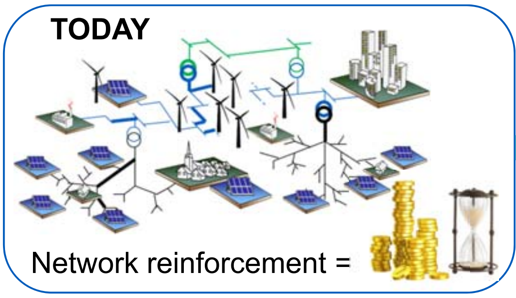
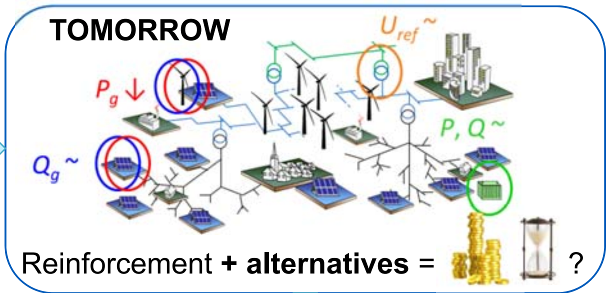
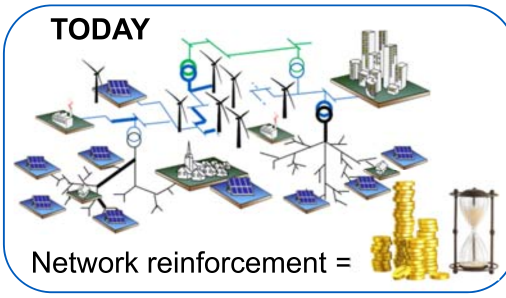




Need to modify the distribution planning methods to assess the techno-economic impacts of RES-integration solutions.

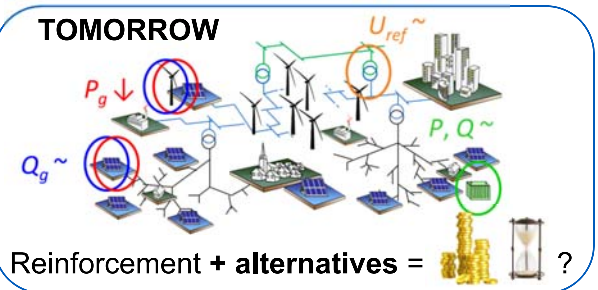
8 1#F R Q F OX VIR Q #D Q G #I X UWK HU #Z R UN

TODAY



Network reinforcement =

TOMORROW



Reinforcement **+ alternatives** = ?

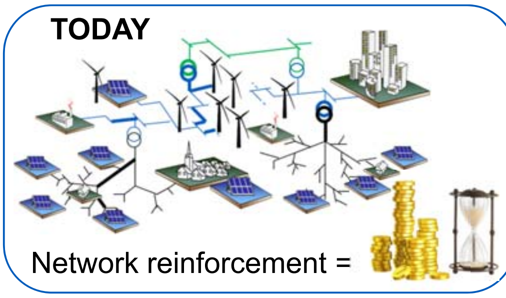
Points often neglected in the existing planning approaches

- Uncertainty on the arrivals of new RES
- DSO's behavior
- Interactions between MV and LV networks

1. Scope | 2. Framework | 3. Approximation | 4. Case studies | 5. Conclusion

8 1#F R Q F OX VIR Q #D Q G #I X UWK HU #Z R UN

TODAY



Network reinforcement =

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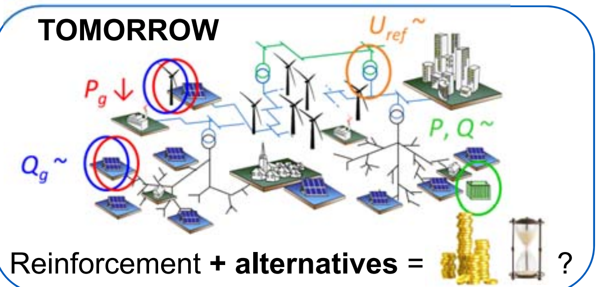

Reinforcement **+ alternatives** = ?

Proposed planning approach

- Uncertainty on the arrivals of new RES → Use **stochastic scenarios** of RES arrivals
- DSO's behavior → Define **multi-variable planning strategies**
- Interactions between MV and LV networks → Use a **LV network model**

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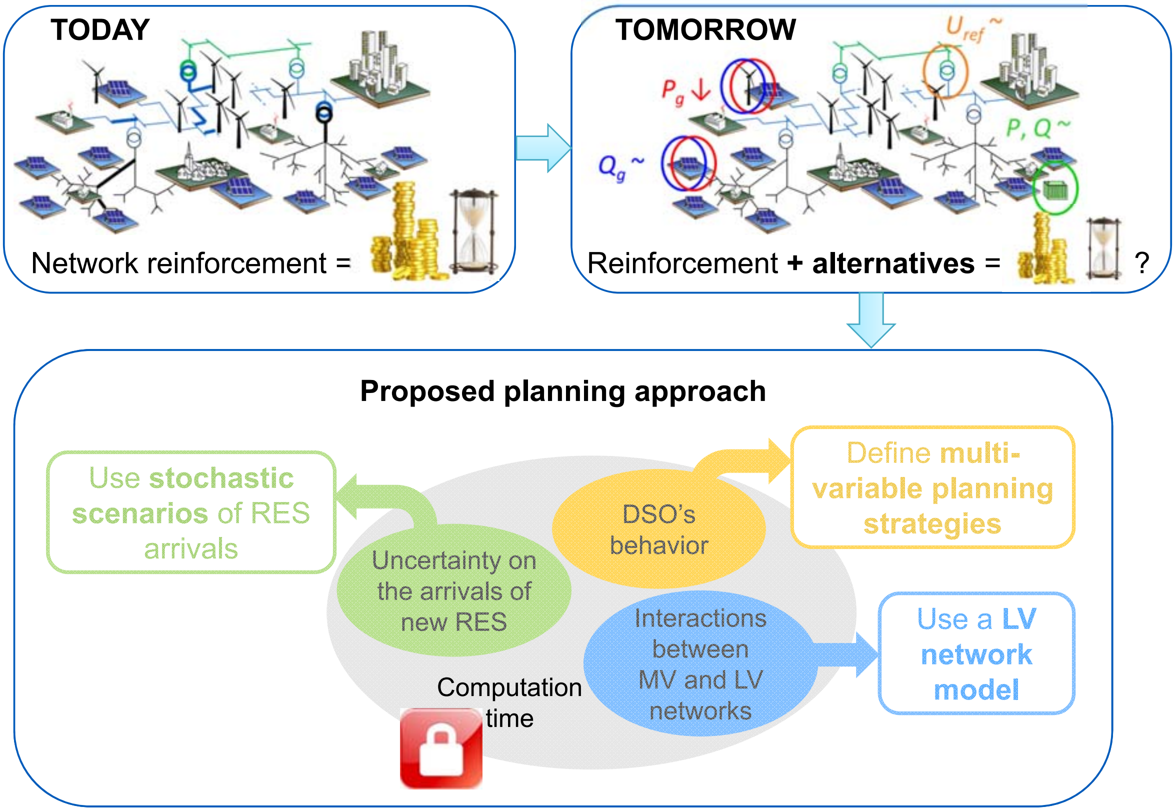

1. Scope 2. Framework 3. Approximation 4. Case studies 5. Conclusion

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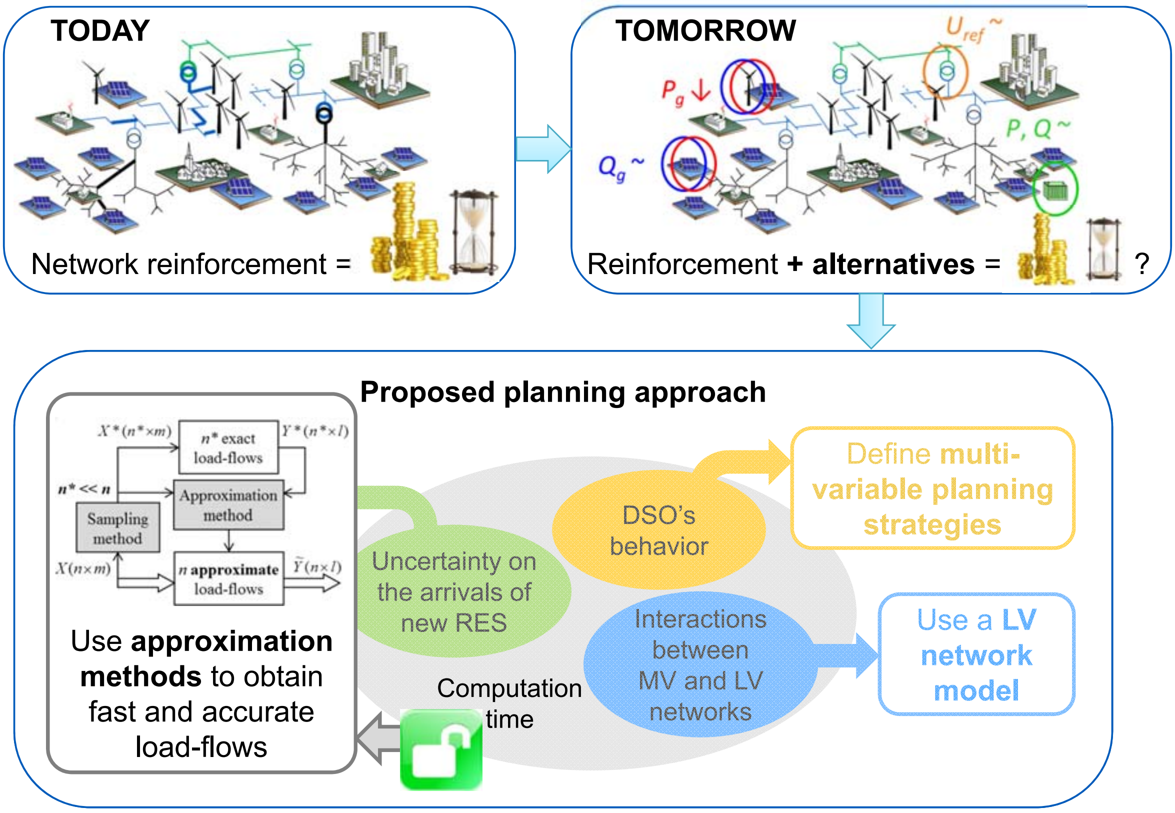

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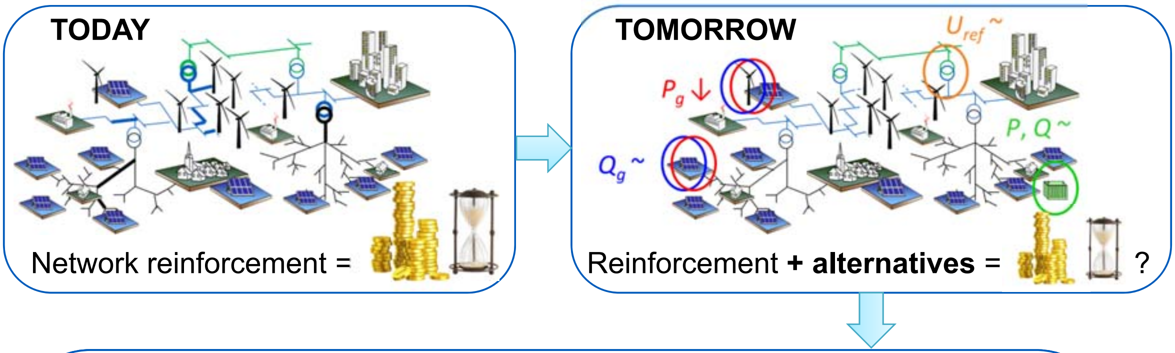

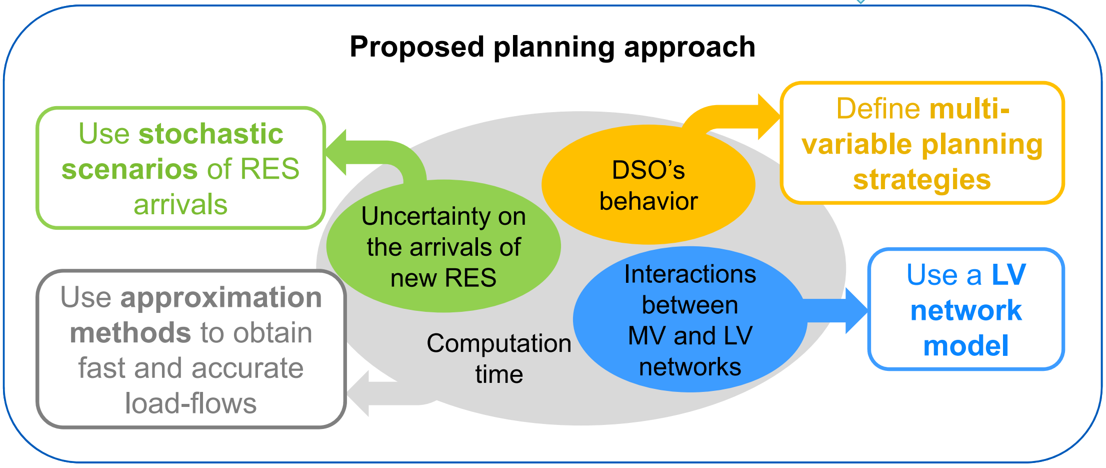

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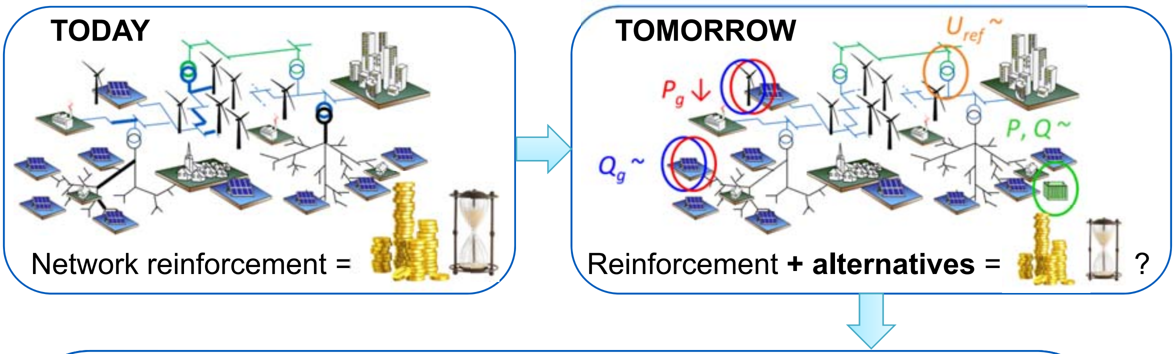
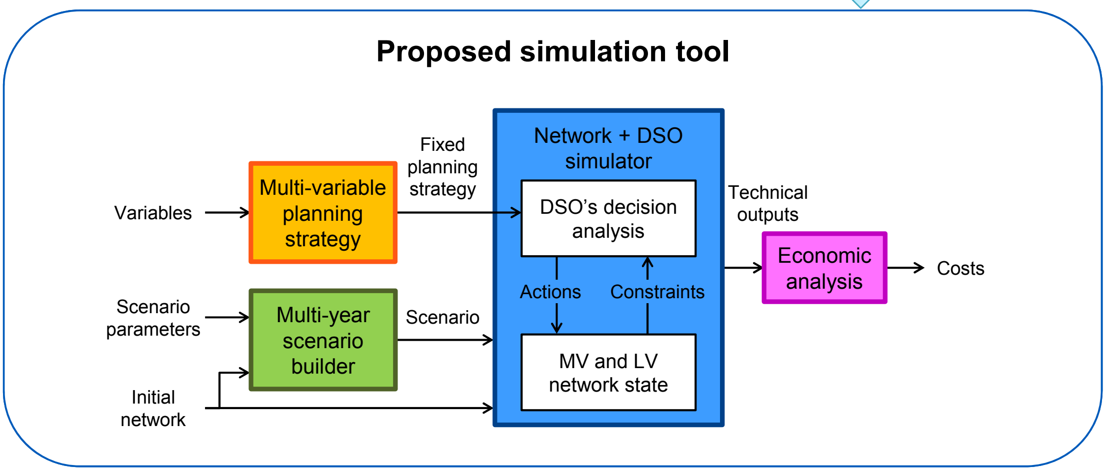
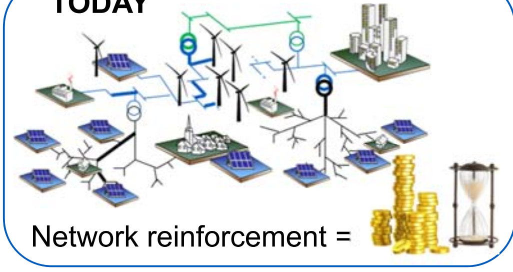


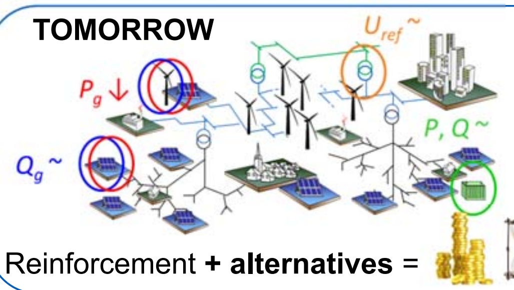


TODAY



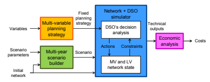
Network reinforcement =

TOMORROW

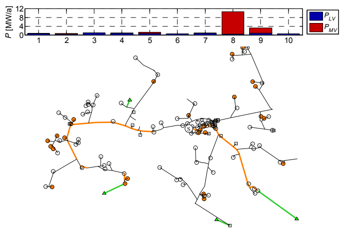


Reinforcement **+ alternatives** = ?

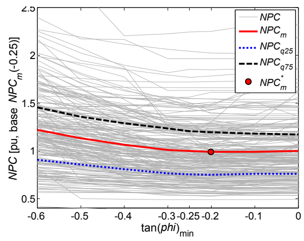
Possible case studies



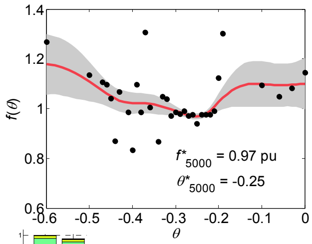
Study one RES scenario



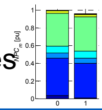
Study parameter impacts



Optimize a strategy

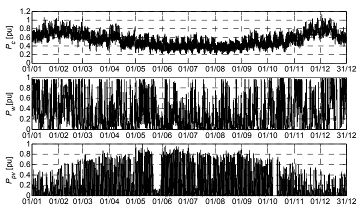


Compare different strategies

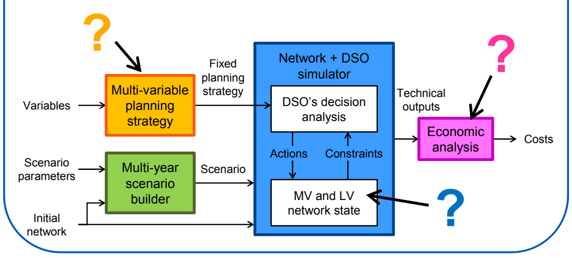


Further work

Improve the procedure used to create profiles of consumption/generation



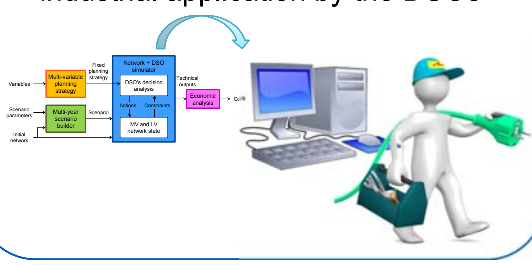
Take into account novel RES-integration solutions



Tackle complex optimization problems

$$\min_{\theta} f(\theta)$$
$$\text{s.t. } g(\theta) \leq 0$$

Adapt the proposed methods for an industrial application by the DSOs



- H. Dutrieux, G. Delille et B. François, “An innovative method to assess solutions for integrating renewable generation into distribution networks over multi-year horizons”, *Proc. 23rd International Conference on Electricity Distribution (CIRED)*, article 1103, juin 2015.

- H. Dutrieux, I. Aleksovska, J. Bect, E. Vazquez, G. Delille et B. François, “The Informational Approach to Global Optimization in presence of very noisy evaluation results. Application to the optimization of renewable energy integration strategies”, *Proc. 47èmes Journées de Statistique de la SFdS (JDS)*, article 199, juin 2015.

- H. Dutrieux, G. Delille, B. François et G. Malarange, “Assessing the Impacts of Distribution Grid Planning Rules on the Integration of Renewable Energy Sources”, *Proc. IEEE PowerTech*, article 464270, juillet 2015.

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