PSCC'2022

LIÈGE université

Computing Necessary Conditions for Near-Optimality in Capacity Expansion Planning Problems

Antoine Dubois* and Damien Ernst*†

* Department of Electrical Engineering and Computer Science, ULiège, Liège, Belgium

† LTCI, Telecom Paris, Institut Polytechnique de Paris, Paris, France

Observation

To plan the energy transition and **decide which capacity investments** to make

→ Detailed optimisation model

However ⇒ **focus on cost-based optimums**

- Too restrictive for decision-makers
- **Do not encompass all their requirements** (including political and social challenges)

[3] X. Yue, S. Pye, J. DeCarolis, F. G. Li, F. Rogan, and B. Ó. Gallachóir, “A review of approaches to uncertainty assessment in energy system optimization models,” Energy strategy reviews, vol. 21, pp. 204–217, 2018.
[4] E. Trutnevyte, “Does cost optimization approximate the real-world energy transition?” Energy, vol. 106, pp. 182–193, 2016.
[5] E. D. Brill Jr, “The use of optimization models in public-sector planning,” Management Science, vol. 25, no. 5, pp. 413–422, 1979.

Our solution

Step aside the optimum

Provide ***necessary conditions*** for ***epsilon-optimality***:

- guaranteeing a **constrained suboptimality**;
- delivering **a common ground** on which decision-makers can settle and create solutions that accommodate their needs.

E.g.:

- What is the minimum amount of transmission capacity that needs to be installed to ensure a maximum cost deviation of 10% from the cost optimum?
- Are some technologies - e.g. Li-Ion batteries, wind turbines, PV - necessary for a cost-efficient transition?

Background

1. **Multi-objective optimisation**
   - Model the trade-offs between specific objectives
   - **!** Need to know which objectives are at stake prior to modelling
   - **!** Need to be able to model those objectives in some form

2. **Modelling to Generate Alternatives (MGA)**
   - Exploring solutions located in the **suboptimal region**
   - This region **might** contain **solutions that are better in** terms of some **unmodeled objectives**

---

[6] M. Ehrgott, Multicriteria optimization. Springer Science & Business Media, 2005, vol. 491.
[7] D. Brill, S.-Y. Chang, and L. Hopkins, “Modeling to generate alternatives: The HSJ approach and an illustration using a problem in land use planning,” Management Science, vol. 28, no. 3, pp. 221–235, 1982.
[8] J. F. DeCarolis, “Using modeling to generate alternatives (MGA) to expand our thinking on energy futures,” Energy Economics, vol. 33, no. 2, pp. 145–152, 2011.

Background

MGA studies **focus** on showing the **variety of solutions** that can be extracted

We propose to **focus** on **conditions that are respected by all these solutions**.

To this aim:

- We **formalize** the concepts of **epsilon-optimal regions.**
- We **define** the concept of **non-implied necessary conditions.**

⇒ Applied to a case study of expansion planning

[9] P. James and K. Ilkka, "Modelling to generate alternatives: A technique to explore uncertainty in energy-environment-economy models," Applied Energy, vol. 195, pp. 356–369, 2017.
[10] F. G. Li and E. Trutnevyte, "Investment appraisal of cost-optimal and near-optimal pathways for the UK electricity sector transition to 2050," Applied energy, vol. 189, pp. 89–109, 2017.
[11] L. Nacken, F. Krebs, T. Fischer, and C. Hoffmann, "Integrated renewable energy systems for Germany–A model-based exploration of the decision space," in 2019 16th International Conference on the European Energy Market (EEM). IEEE, 2019, pp. 1–8.
[12] J.-P. Sasse and E. Trutnevyte, "Distributional trade-offs between regionally equitable and cost-efficient allocation of renewable electricity generation," Applied Energy, vol. 254, p. 113724, 2019.
[13] F. Neumann and T. Brown, "The near-optimal feasible space of a renewable power system model," Electric Power Systems Research, vol. 190, p. 106690, 2021.

Formulation - Original problem

The original problem is $\min_{x \in \mathcal{X}} f(x)$ with

- a feasible space $\mathcal{X}$
- an objective function $f : \mathcal{X} \rightarrow \mathbb{R}^+$

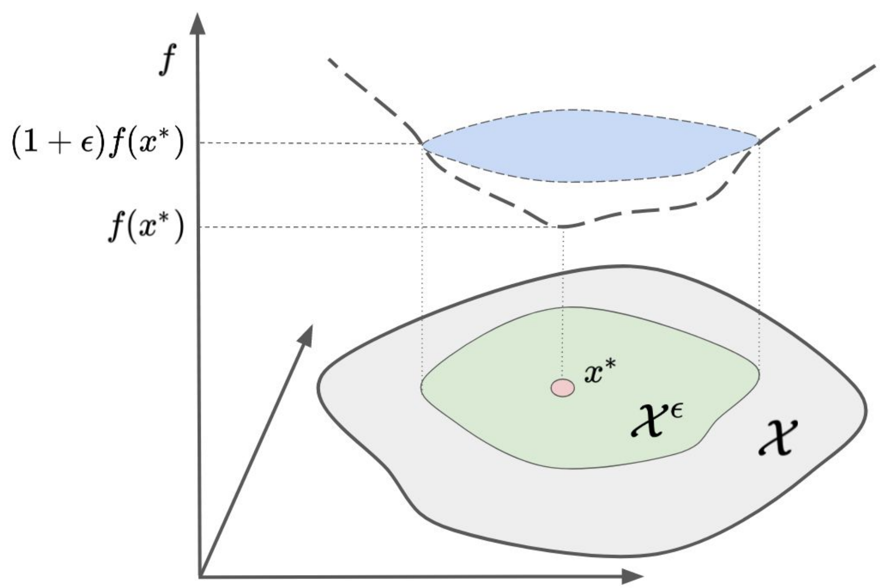
E.g. Minimise cost over a feasible space defined by linear constraint

Formulation - Epsilon-optimal space

Let x^* be an optimal solution of the problem.

An **epsilon-optimal space** is defined as:

$$\mathcal{X}^\epsilon = \{x \in \mathcal{X} \mid f(x) \leq (1+\epsilon) f(x^*), \epsilon \geq 0\}$$



Formulation - Necessary conditions

Let Φ be a set of conditions $\phi : \mathcal{X} \rightarrow \{0, 1\}$

Let $I_\phi = \{x \in \mathcal{X} \mid \phi(x) = 1\}$ be the space over which ϕ is true.

A **necessary condition** for **epsilon-optimality** is a condition which **holds true** for every solution $\mathcal{X}^\epsilon$, i.e. $\mathcal{X}^\epsilon \subset I_\phi$

A condition ϕ_1 is said to be implied by another condition ϕ_2 if $I_{\phi_2} \subset I_{\phi_1}$

A **non-implied necessary condition** is a necessary condition that is not implied by any other necessary condition.

Formulation - Necessary conditions

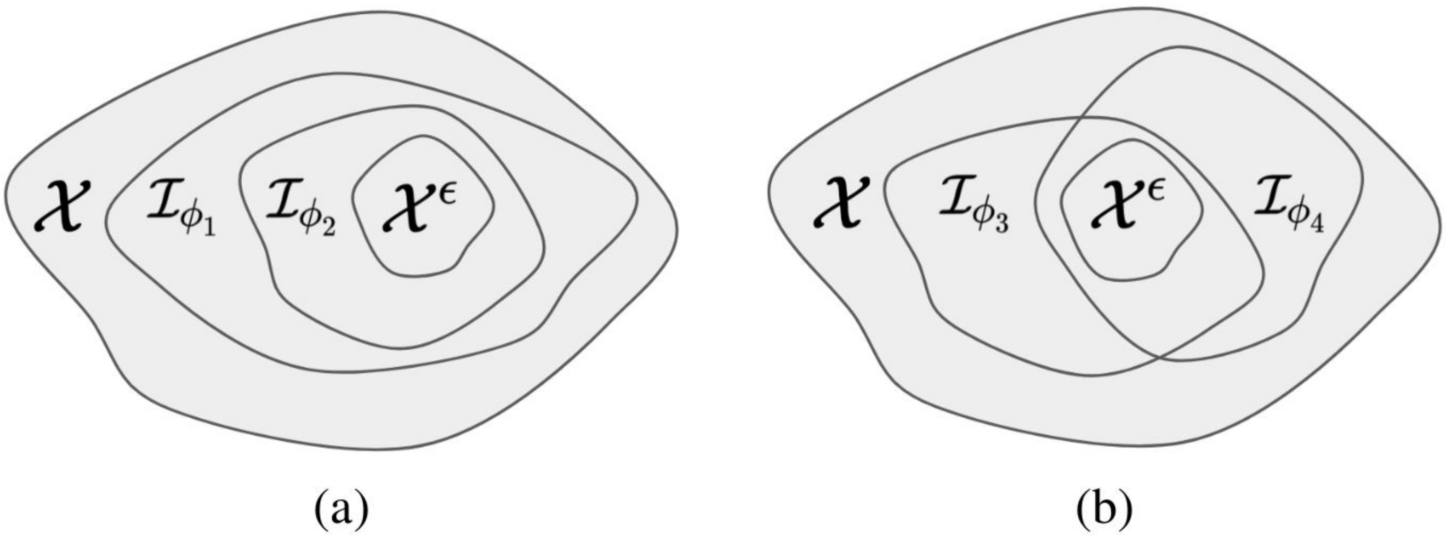


Fig. 2. Graphical illustration of implication using spaces over which conditions are true.

Necessary conditions - Example

Let $\mathcal{X} \subset \mathbb{R}^n$, $f : \mathcal{X} \to \mathbb{R}^+$ and let use conditions of the type:

$$\phi_c(\mathbf{x}) := \sum x_i \geq c$$

E.g. sum over the capacities of all transmission lines

In that case, the only non-implied necessary condition is ϕ_{c^*} where

$$c^* = \min_{x \in \mathcal{X}^\epsilon} \sum x_i$$

The **non-implied necessary condition** in this case will correspond to the **minimum capacity** that **needs to be installed** so that the cost does **not deviate by more than epsilon** from the cost optimum.

Case Study

Capacity expansion planning of the **European** electricity grid

- determine **capacity investments in transmission, generation and storage** assets as well as operation of those assets
- to satisfy **electrical** demand
- while **minimising** capital and marginal **costs**.

Objective of the European Union to be carbon-neutral by 2050.

⇒ 99% reduction of CO_2 compared to 1990

Model:

- PyPSA
- Using linear programming
- One node per country, 2h resolution, 1 year
- Green-field approach for generation (except nuclear) and Li-Ion storage

Case Study

Compute epsilon-optimal space for **epsilons of 0 to 20%**

Conditions are constrained sums of variables: $\phi_c(\mathbf{x}) := \sum x_i \geq c$

Non-implied necessary conditions computed for the capacities:

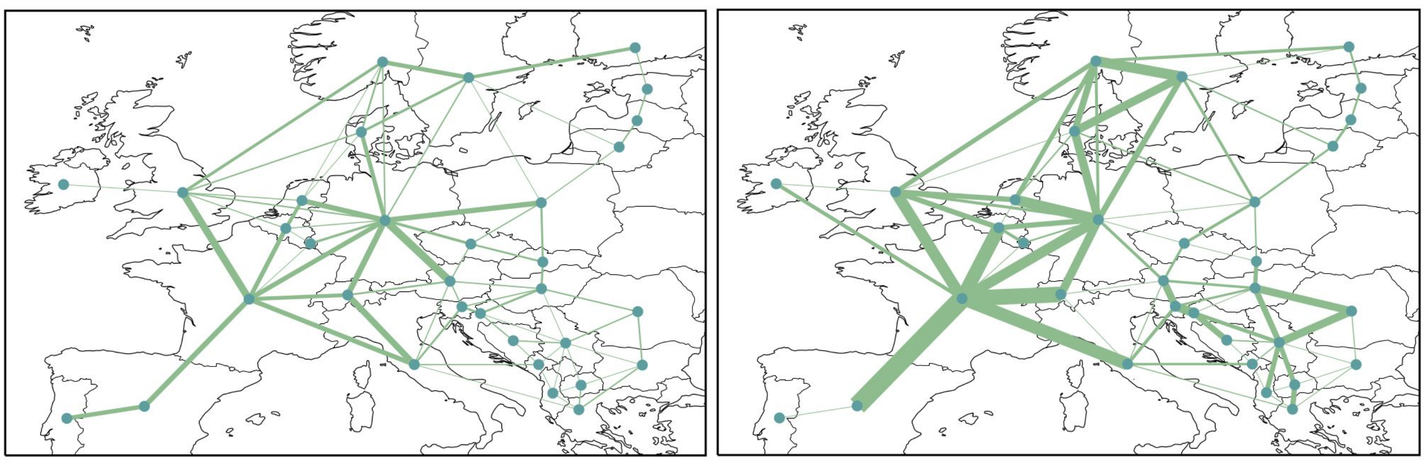
- **Transmission** lines at the European, national and individual-line levels.
- **RES Generation**: Onshore wind, offshore wind, utility-scale PV and their total
- **Li-Ion storage**

Results - Cost optimum

TWkm			GW					
AC	DC	AC+DC	Onshore wind	Offshore wind	Utility PV	CCGT	OCGT	Li-Ion
128	90	218	168	327	367	49	0	249

Total RES : 862 GW

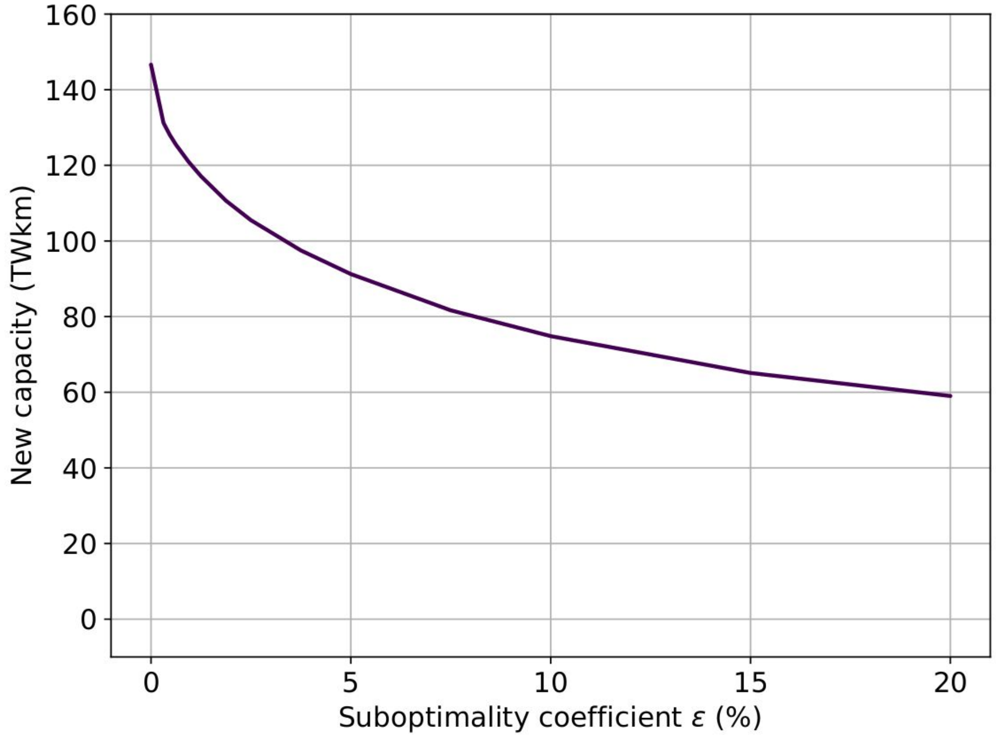
Transmission capacity: 72 initially -> 218 (big investment in Germany and France)



Results - Non-implied necessary conditions

Total transmission capacity

- Divided by 2 at 10% sub-optimality

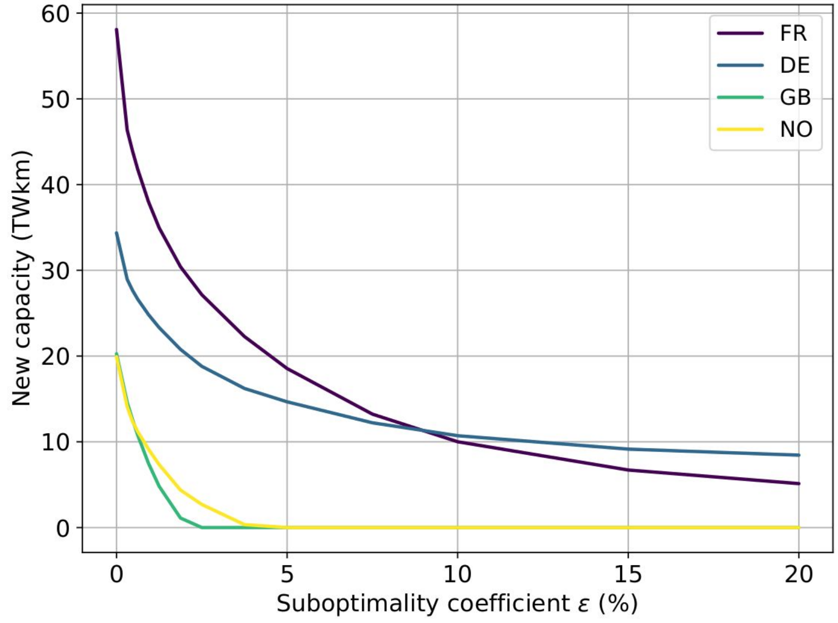


(a) Sum of the capacities of all lines.

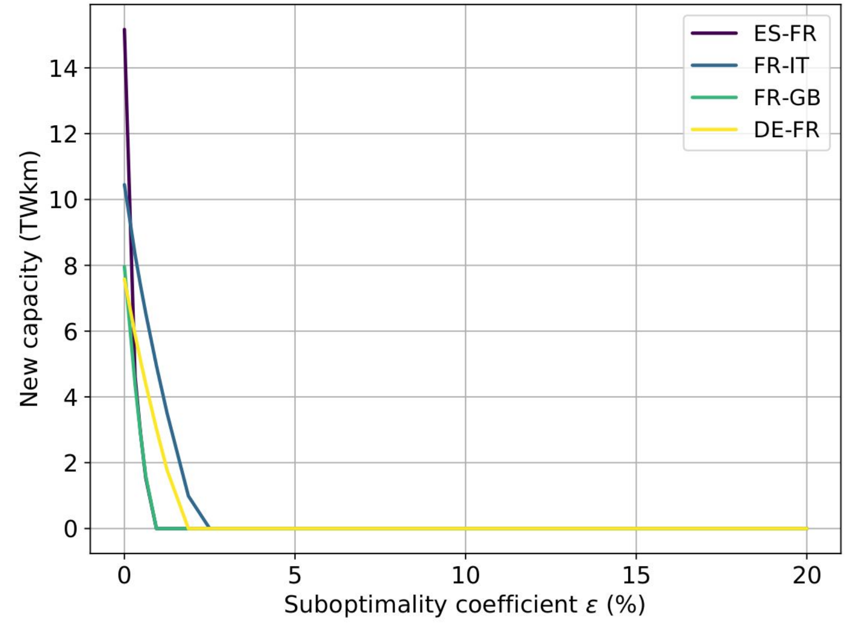
Results - Non-implied necessary conditions

National transmission capacity and capacity of individual lines

- Decreases faster than the total because you have more alternatives



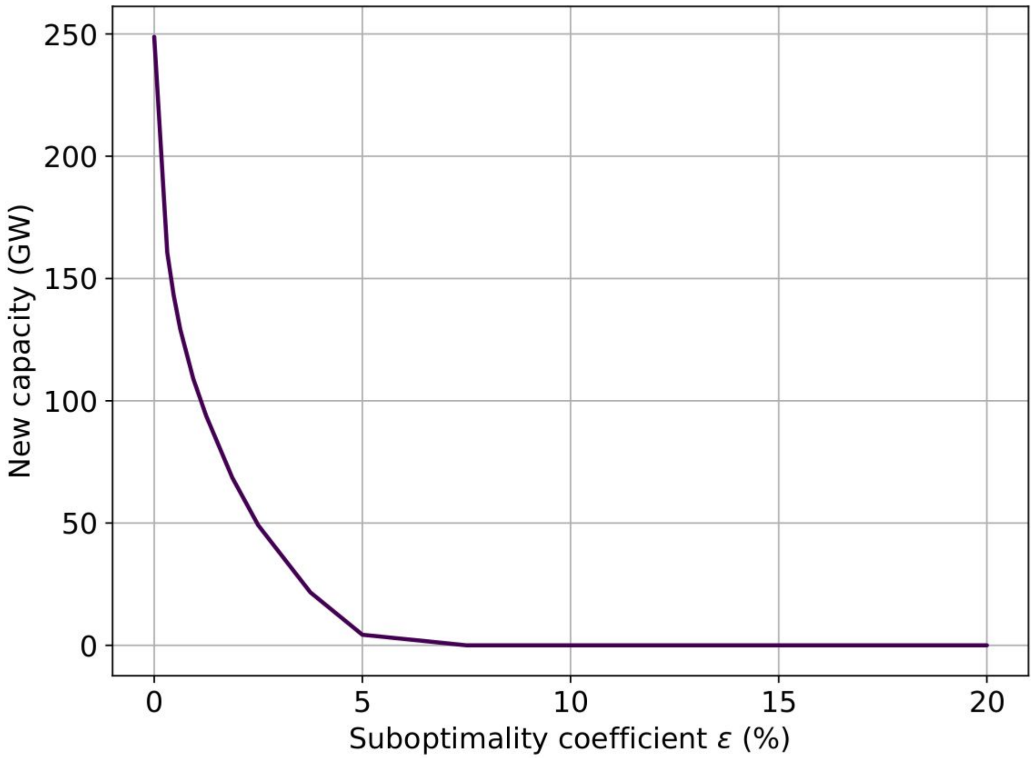
(b) Sum of the capacities of country lines.



(c) Capacity of individual lines.

Results - Non-implied necessary conditions

Li-Ion batteries (new capacity = total capacity) ⇒ Nearly 0 at 5%

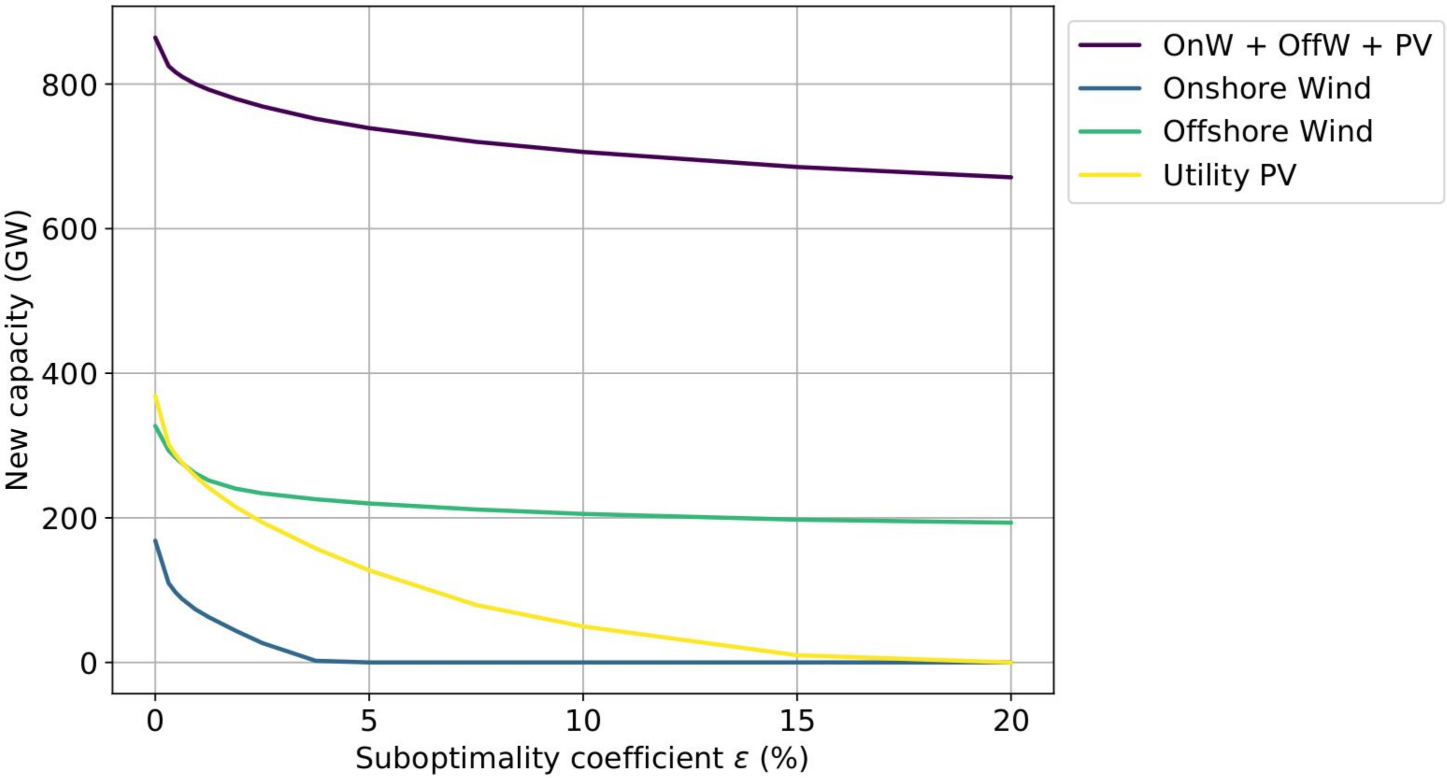


(d) Sum Li-Ion batteries capacities.

Results - Non-implied necessary conditions

RES generation (new capacity = total capacity)

- Total capacity and offshore wind reaches a plateau quickly
- Onshore wind unnecessary at 5% and PV unnecessary at 15%



Future Work

1. This methodology does not yet take into account parametric uncertainty.

2. Explore other types of conditions than constrained sum of variables

3. Extension to other objectives than cost
    a. Either applied to one other objective (e.g. epsilon-optimality in CO_2 emissions)
    b. Or applied in a multi-objective context

4. The methodology could be tested on other problems than expansion planning

Summary

- Cost-based studies are too restrictive

- Our solution: non-implied necessary conditions computed over epsilon-optimal spaces

- Case study shows how flexible the options are for the expansion of the European electrical grid

---

Contact:

- Antoine Dubois, University of Liège, Belgium
- Damien Ernst, University of Liège, Belgium

Code available on GitHub and Zenodo
Data available on Zenodo

PSCC'2022

LIÈGE université

Supplementary slides

Formulation - Necessary conditions

Let Φ be a set of conditions $\phi : \mathcal{X} \to \{0, 1\}$

Necessary conditions for **epsilon-optimality** are conditions which **hold true** for every solution in $\mathcal{X}^{\epsilon}$.

Formulation - Example

Let us consider conditions of the type $\phi_c(x) = x > c$ where

x is the aggregated transmission capacity between two countries (in GW)

$c \in \mathbb{N}$

Let us say that $\phi_2(x) := x > 2$ is true for every solution in $\mathcal{X}^\epsilon$

Then ϕ_2 is a necessary condition.

Formulation - Implication

Using necessary conditions directly can lead to a problem.

If $x > 2$ is true for all epsilon-optimal solutions, then so is $x > 1$ and $x > 0$

ϕ_1 and ϕ_0 are thus necessary conditions.

However, if we know that $\phi_2(x) := x > 2$ is a necessary condition,

Then $x > 1$, $x > 0$ do not provide any further information.

$\Rightarrow$ ϕ_2 **implies** the two other necessary condition.

Formulation - Non-implied necessary conditions

To limit the number of necessary conditions

⇒ the concept of **non-implied** necessary conditions is defined.

In this case, if ϕ_2 is the necessary condition with the largest value of c
i.e. all $x \leq 3$

⇒ it is a non-implied necessary condition because we cannot determine that it is a necessary condition from other necessary conditions.