International Conference Energy & Meteorology

Electricity system response to the flexibility costs induced by high variable renewable energy penetration

Samouro Dansokho - 29/06/2023

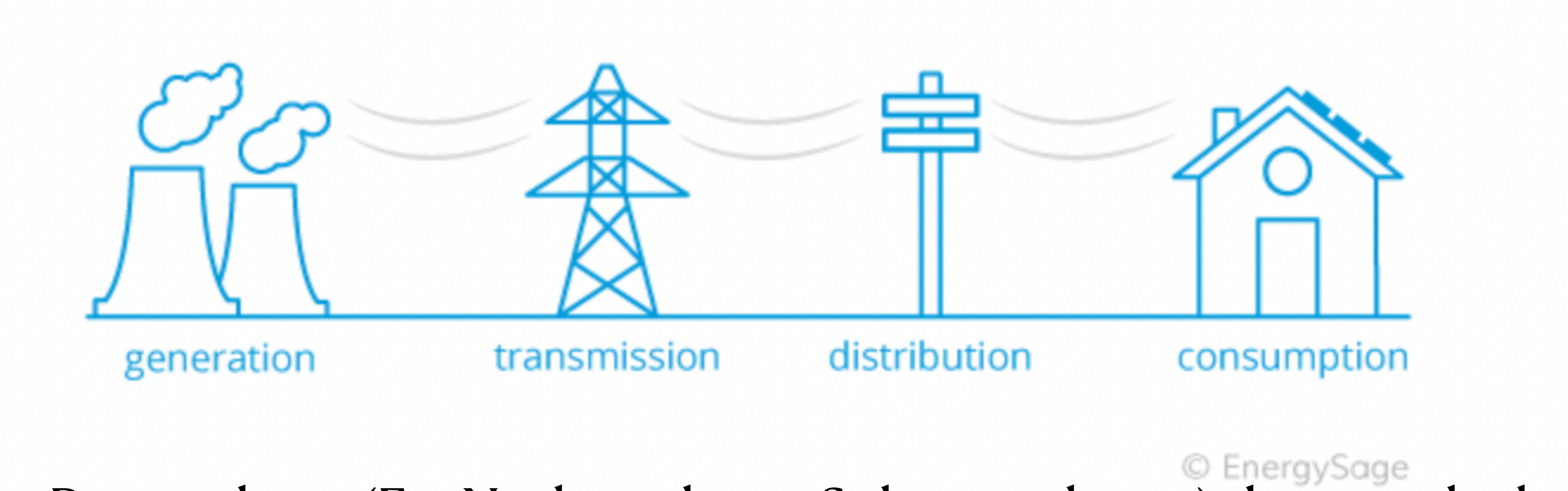
Outline

- Introduction
- Impact of start-ups on the System Costs
- Impact of renewable energies distribution on start-ups
- Conclusion

Introduction

Electricity System

An electric power system is a complex network of electrical components deployed to supply, transfer, and use electric power.



Generation: Power plants (Ex: Nuclear plants, Solar panels, etc) that supply the power

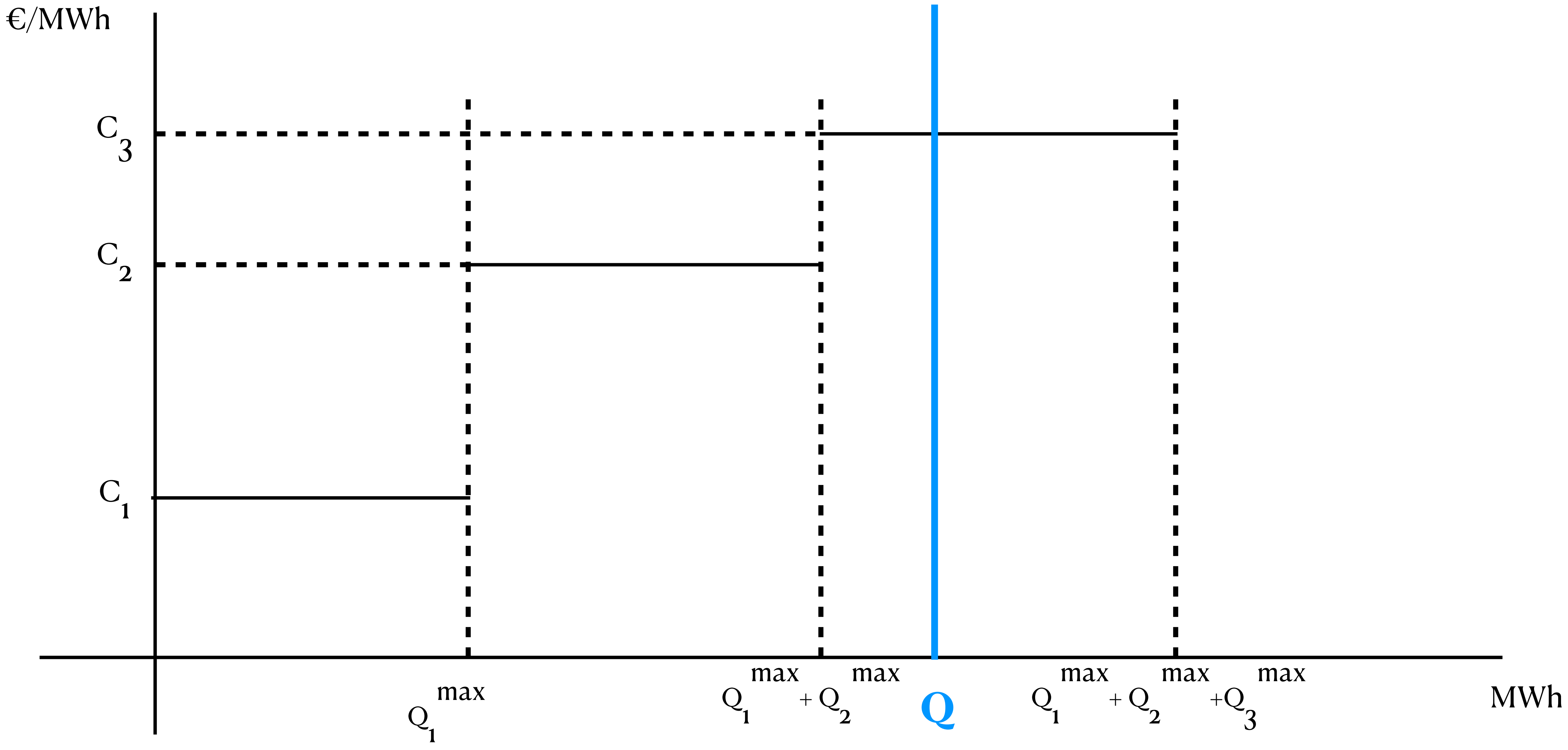
Consumption: Loads that perform a function (Ex: Toasters, Cement Dryer, etc)

Transmission (HV)- Distribution (LV): Carry power from the generators to the load

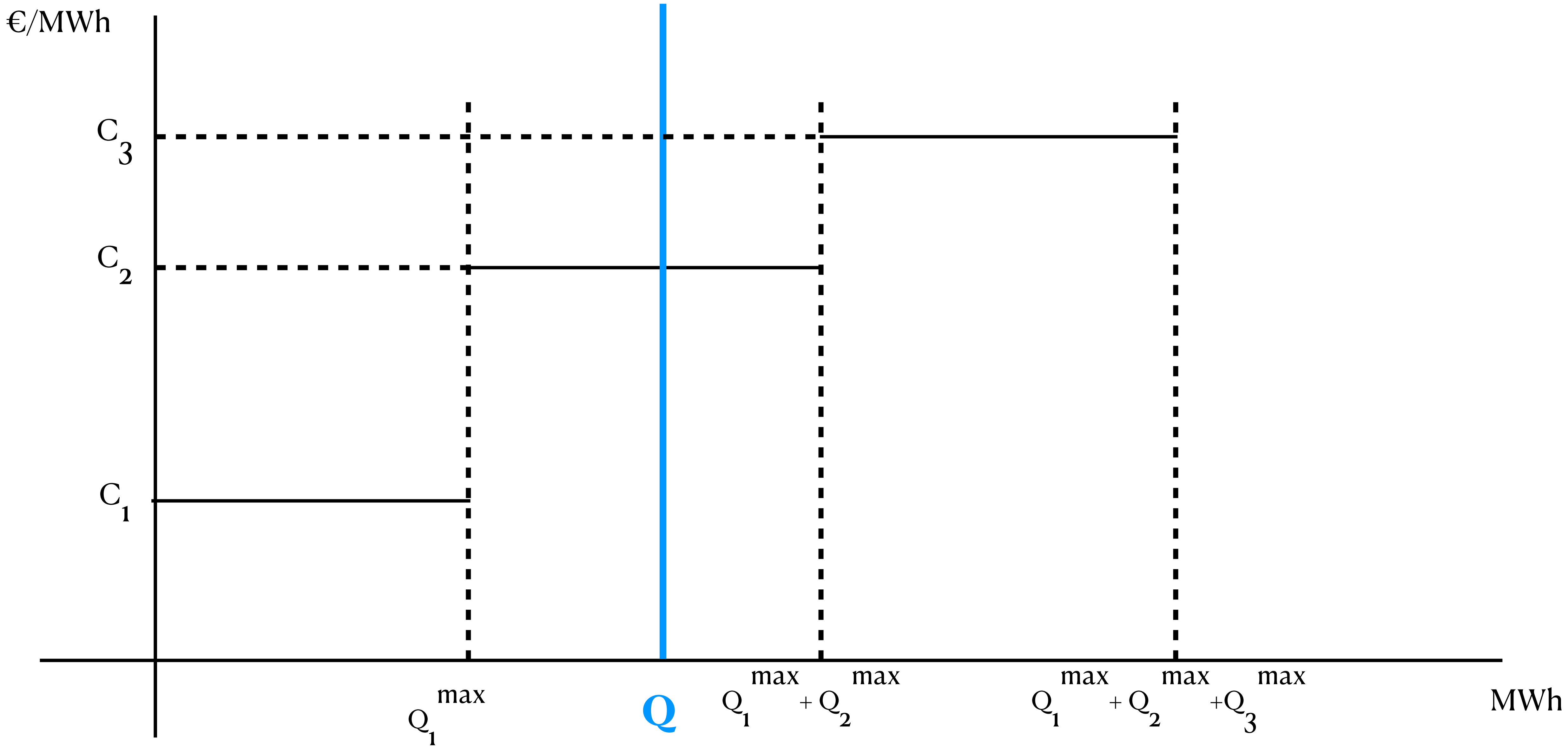
Introduction

Electricity wholesale market

Merit Order Dispatching: the dispatching of power ordered from the least marginal cost power plant to those with higher marginal costs to meet a given load.



Cost minimisation with three plants
all three plants are necessary

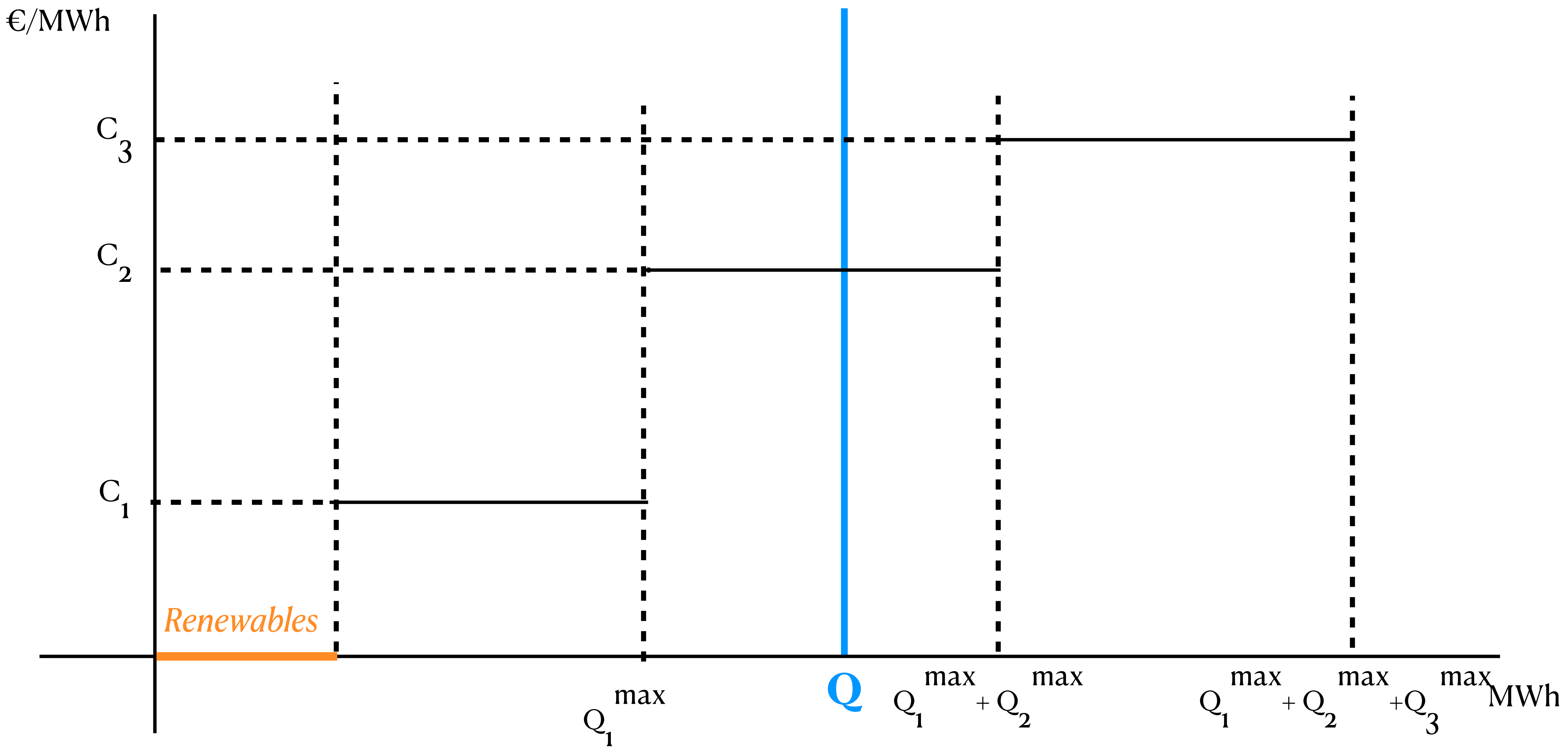


Cost minimisation with three plants
two plants are sufficient

Introduction

Variable renewable energies in the wholesale market

- Renewable generators (solar and wind) are nearly entirely capital and other fixed costs. They have no marginal costs, as they produce when their cost-less fuel source (the sun and the wind) is available.



- Regulations also require VREs be used first

Net Load: the electric demand in the system minus variable renewable generation

Introduction

Flexibility

Supply-demand balance

On the short term

$\leq$ 1 hour

Technical constraint

Frequency stability

(50 or 60 Hz)

On the long term

$\geq$ 1 year

Socio-economic policies

"Critère de défaillance"

(3hr/yr in France)

Flexibility := The ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales, from ensuring instantaneous stability of the power system to supporting long-term security of supply.

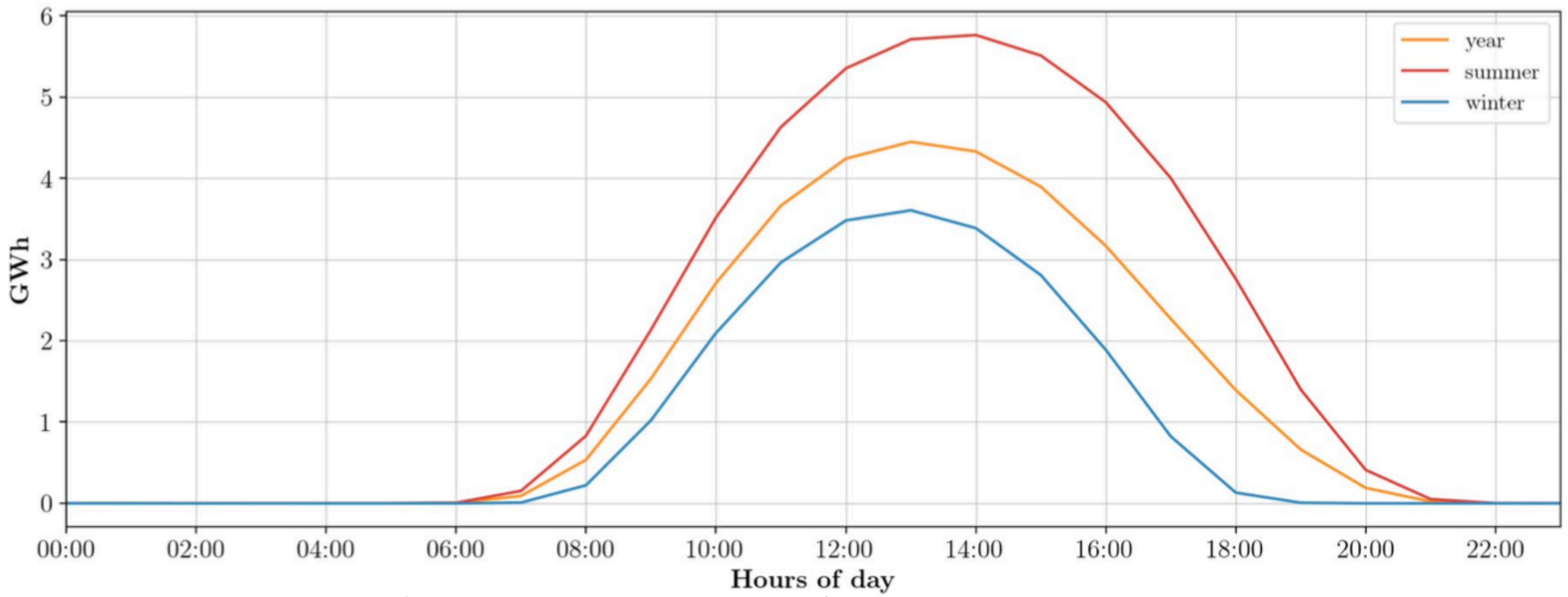
IEA

Introduction

Variable Renewable Energies characteristics

They are characterised by the:

- Limited controllability of variations over time of the generation resource
- Partial ability to determine ahead of time the availability of the generation resource
- Specific location of the generation resource

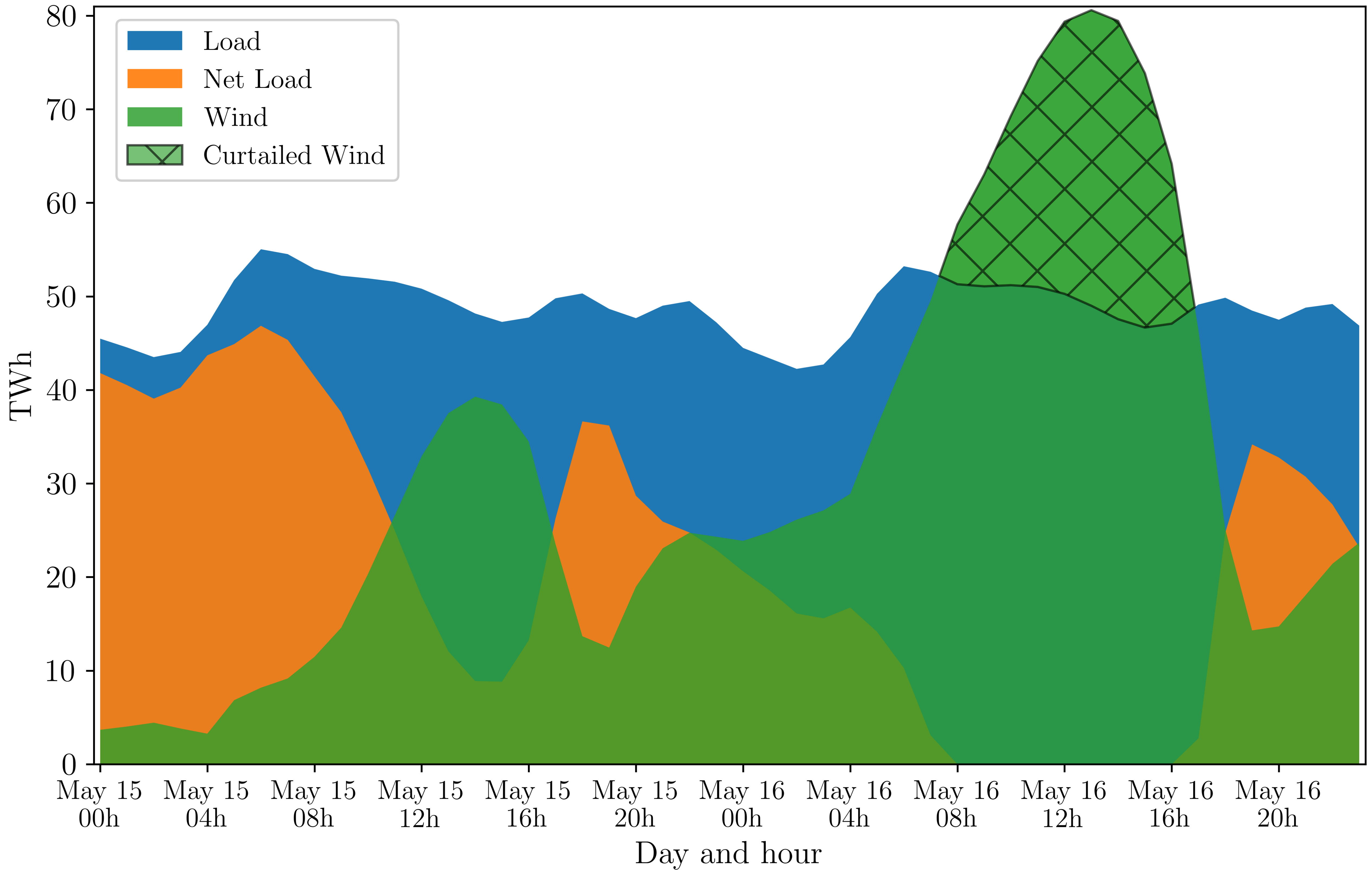


Average hourly solar production in 2019 in France

Eco2Mix data analysis

Introduction

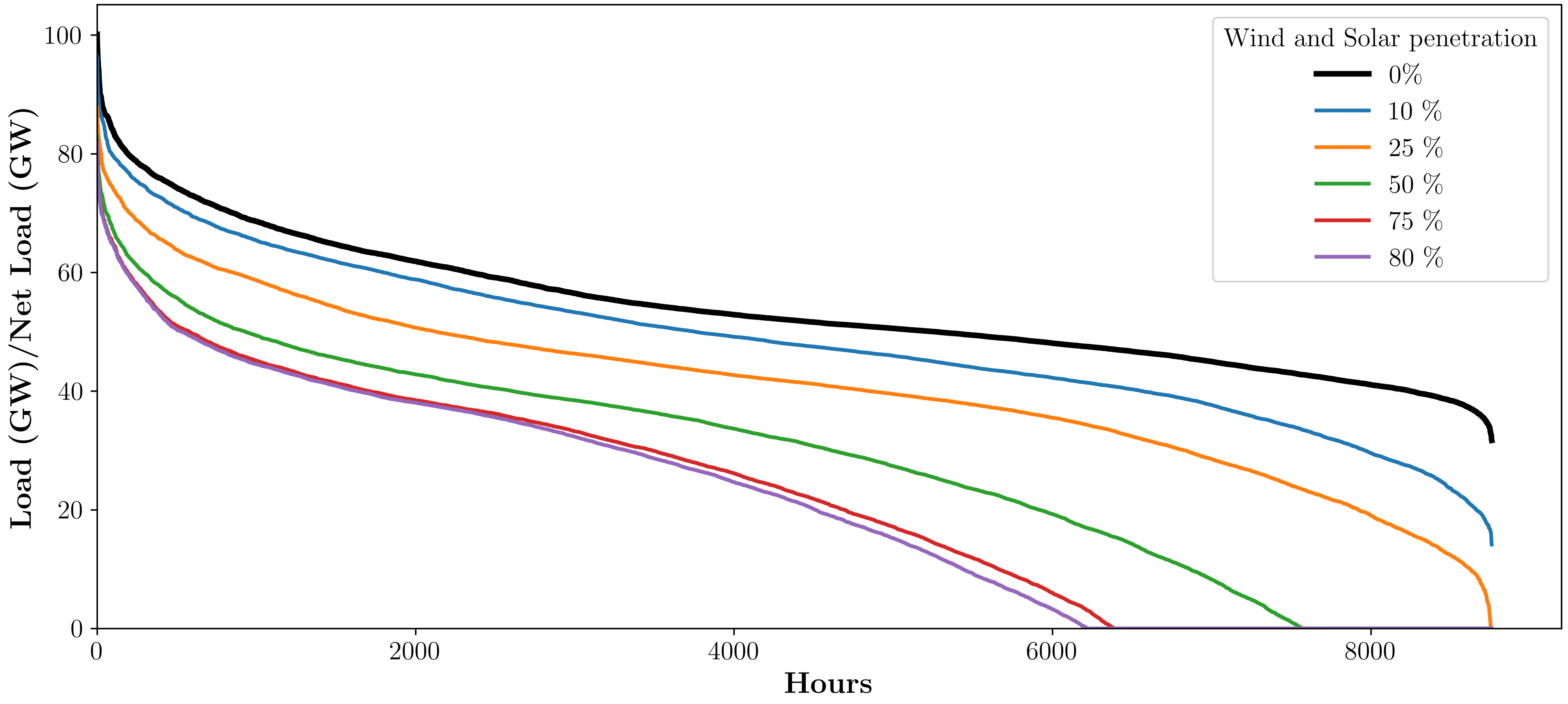
Consequences of VRE introduction on Net Load



Hourly net load changes in response to 50% Wind penetration

Introduction

Load duration curve: Load curve where load data is ordered in descending order of magnitude



Load and net duration curves for different VRE penetrations in e4clim

Observation

Modified dispatchable production with the introduction of VRE.

Research question

What does this imply in terms of flexibility costs for dispatchable producers?

Introduction

Research questions

When flexibility is provided by dispatchable producers only:

1. What is the total system cost response to the flexibility costs change due to VREs integration at the regional scale ?

2. What is the impact of flexibility costs on different dispatchable producers depending on their merit order position ?

3. What is the impact of VREs technological and geographical distribution on dispacthable producers flexibility supply ?

Introduction

Analytical framework

Studying a power system with high VREs penetration requires modelling the system.

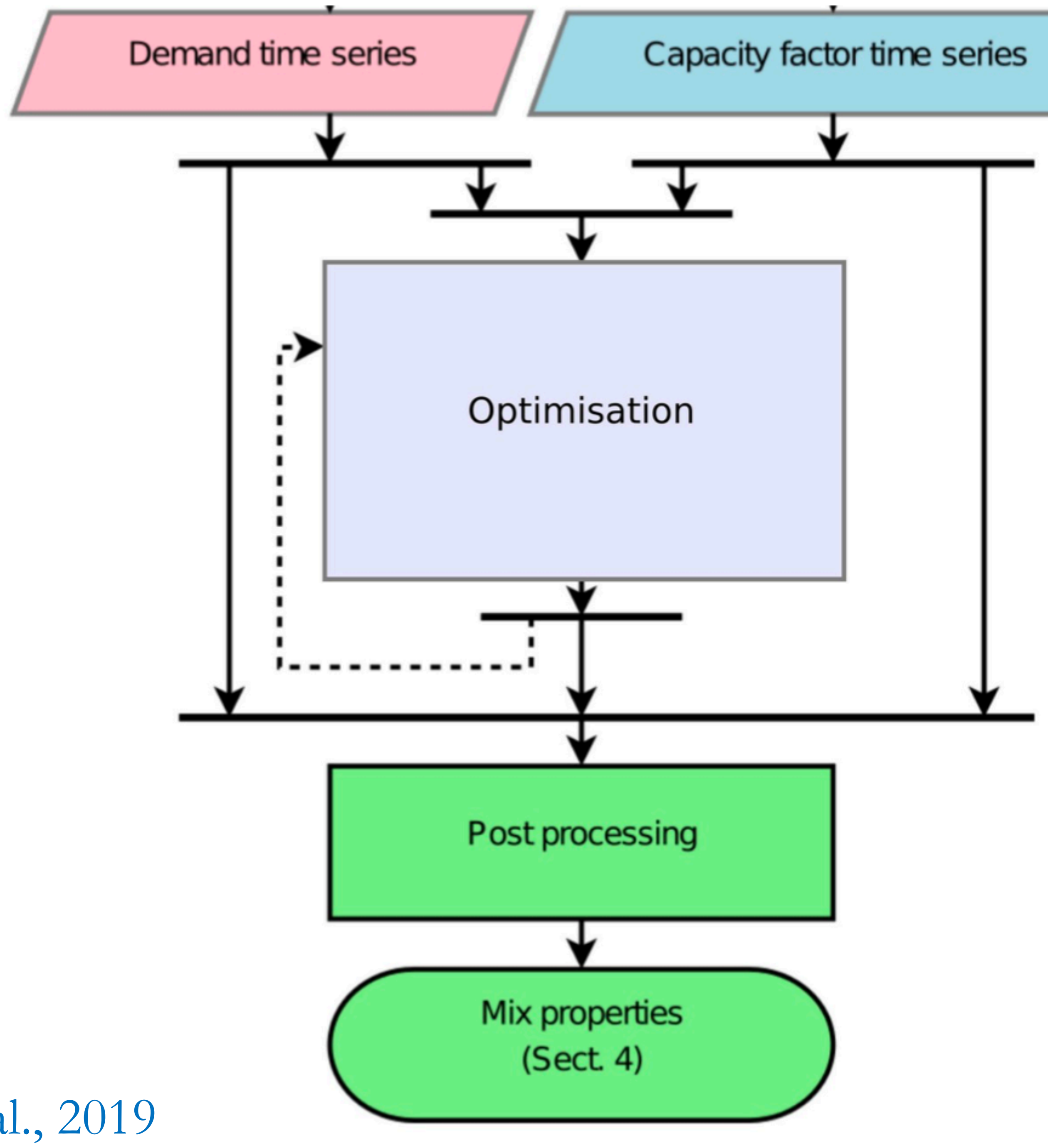
For our research questions, we need a **minimal** model that can be used to:

- understand the different effects of the introduction of VREs in relation with dispatchable generation:
  - by taking into account the temporal and geographical distribution of VREs
  - by allowing to quantify the value of VRE
- carry out sensitivity studies;
  - For different parameters including flexibility parameters

Introduction

e4clim model

Open-source modelling platform for research on energy mixes with a high share of variable renewable energies, allowing sensitivity studies. Allows minimisation of the system cost of investment in capacity by taking into account the response of conventional to the introduction of renewable energy.



Tantet and al., 2019

STC

=

Dispatch Fixed costs

+

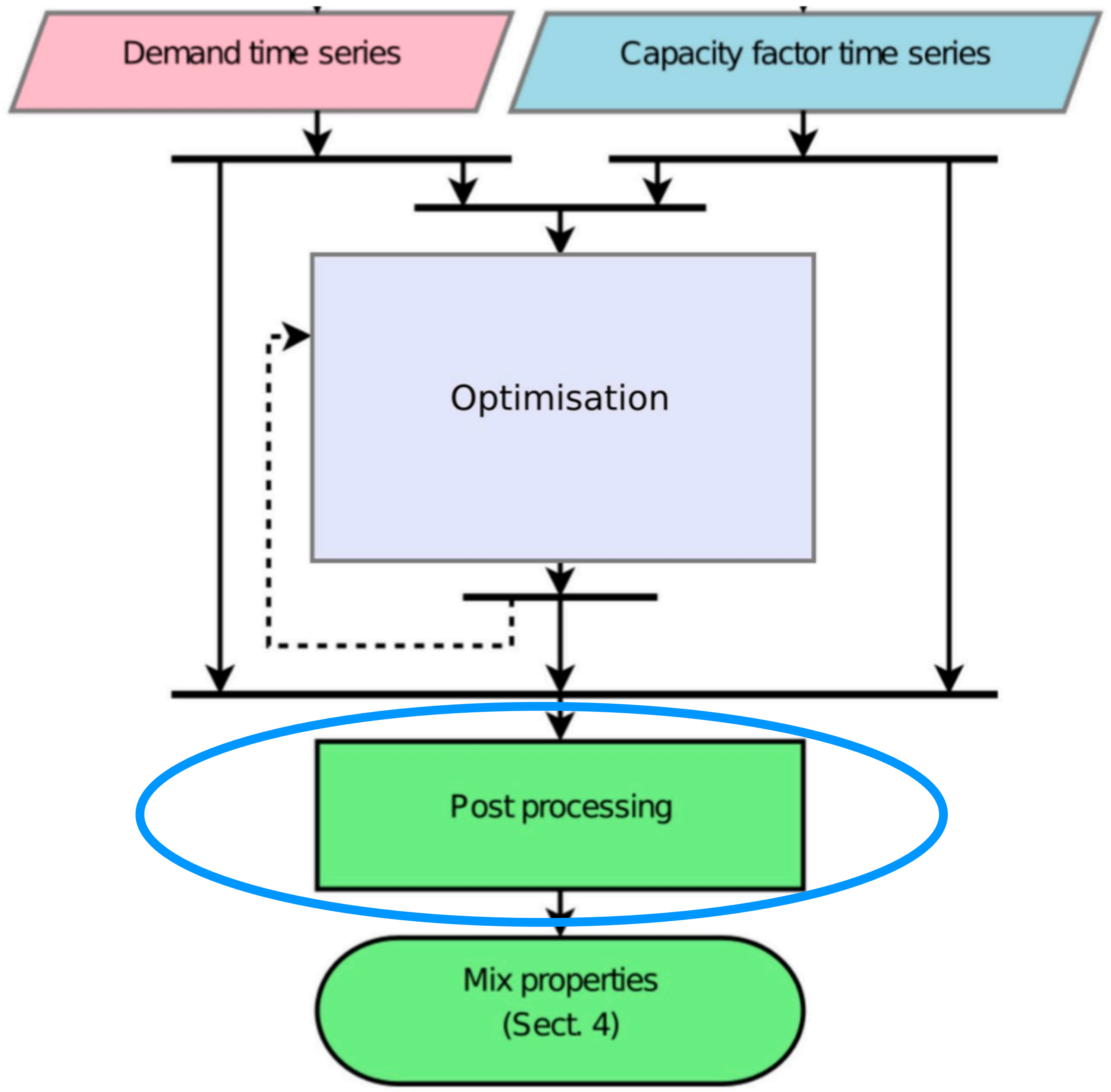
VRE Fixed Costs

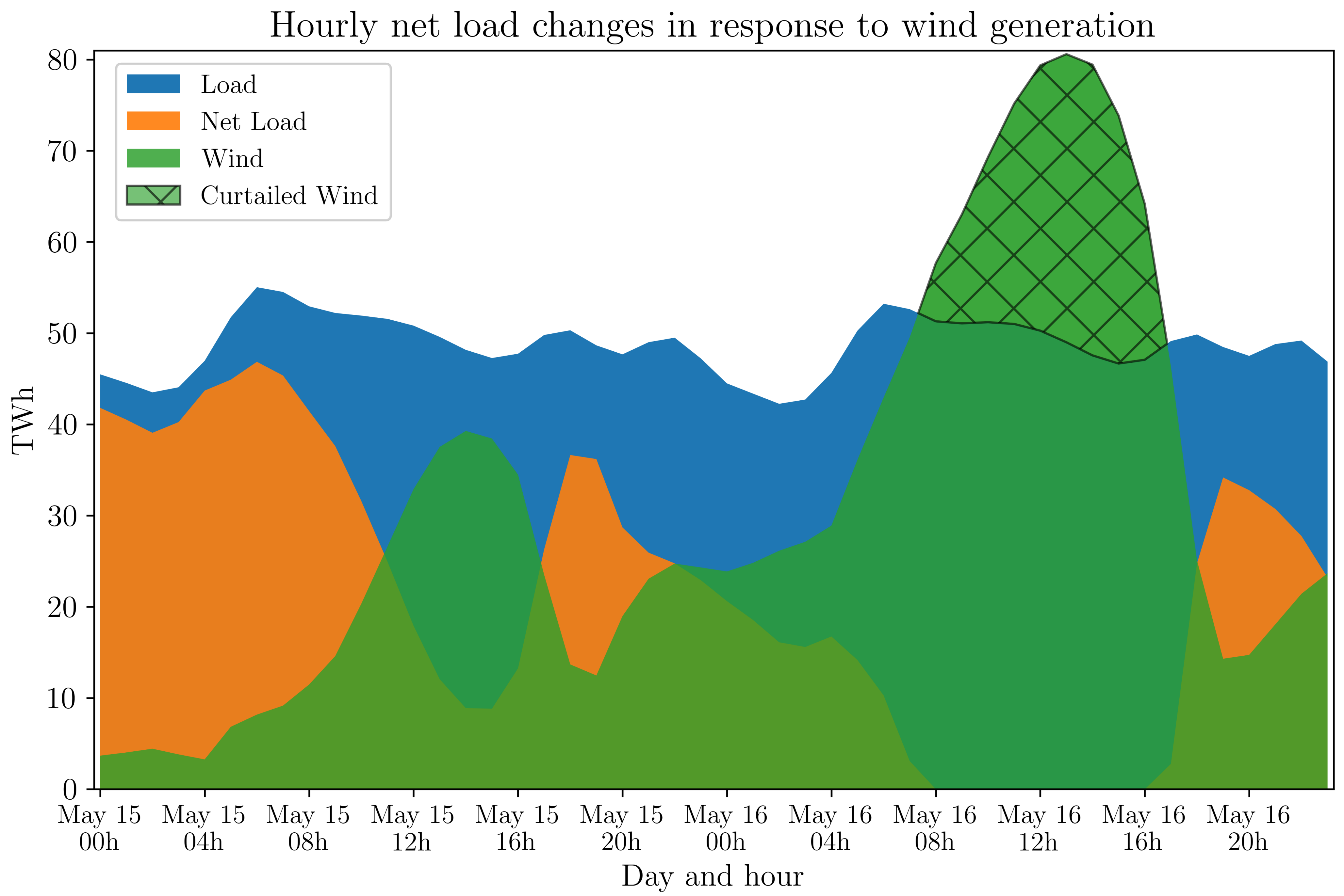
+

Dispatch Variable costs of production

Impact of start-ups on the System Costs

Method





We use the dispatch hourly generation for a period of 20 years

More flexible operation increase the need of Operation and Maintenance and/or reduce the lifetime of the means of production. Therefore, their costs can be seen as additional maintenance cost that add a variable part to the O&M Costs.

Impact of start-ups on the System Costs

Method

Start-ups

$$S_u(t) = \begin{cases} 1 \text{ if } G_j(t-1) = 0 \text{ and } G_j(t) \neq 0 \\ 0 \text{ else} \end{cases}, t \in \mathbb{T}_0$$

STC
=
Dispatch Fixed costs
+
VRE Fixed Costs
+
Dispatch Variable costs of production

+ **Dispatch Variable costs of Start-ups**

Impact of start-ups on the System Costs

Method

The variable costs of start-ups depend on the size of the unit of production and on a marginal cost of start-ups

$$\mathrm{VCSu}_{j,\alpha}(t) = \mathrm{MCSu}_{j,\alpha} \times \mathrm{Su}_j(t) \times x_j$$

That marginal cost of start-ups is proportional to the fixed costs of the unit of production

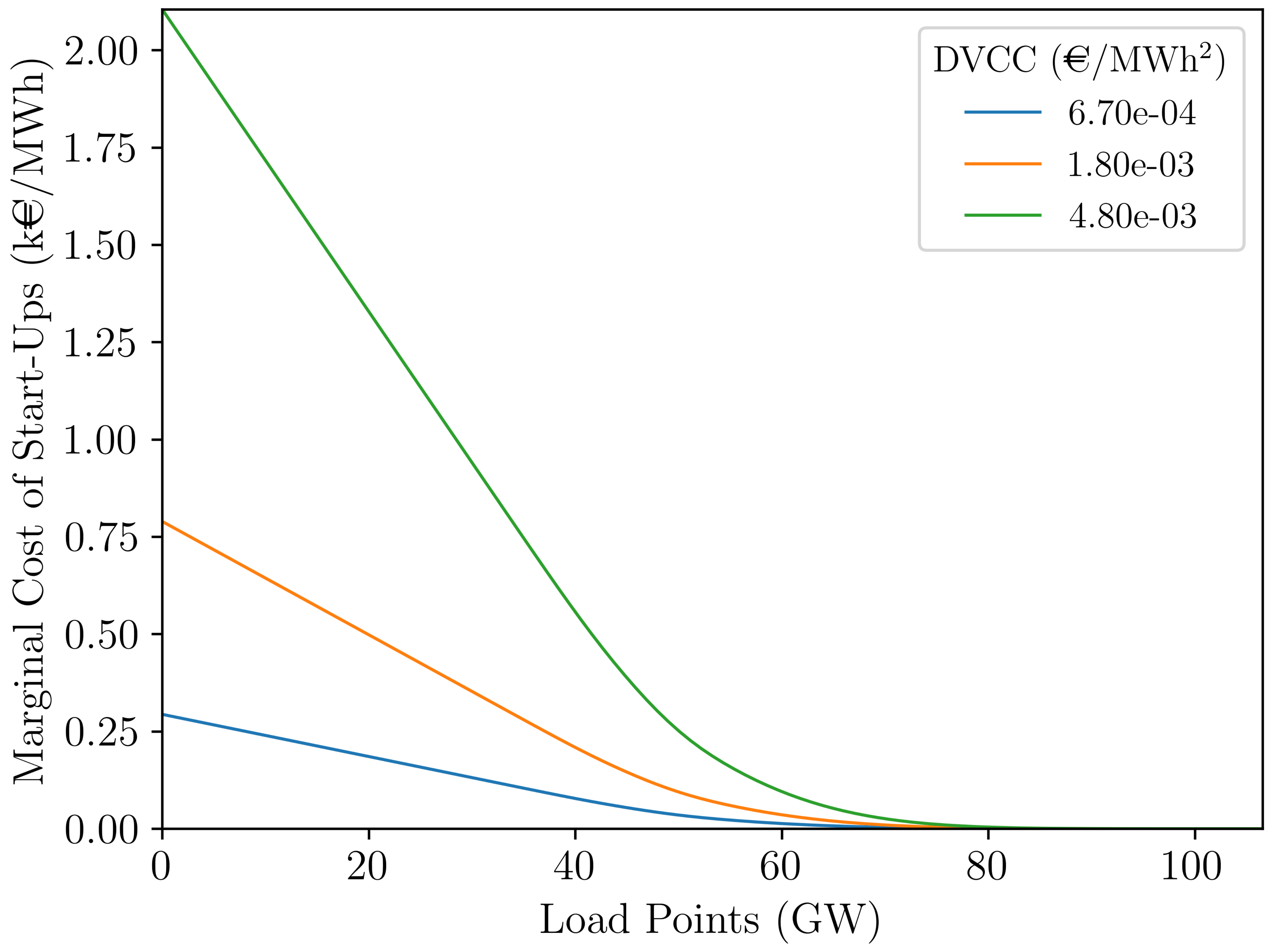
$$\mathrm{MCSu}_{j,\alpha} = K_{Su} \times \mathrm{hRC}_{j,\alpha}$$

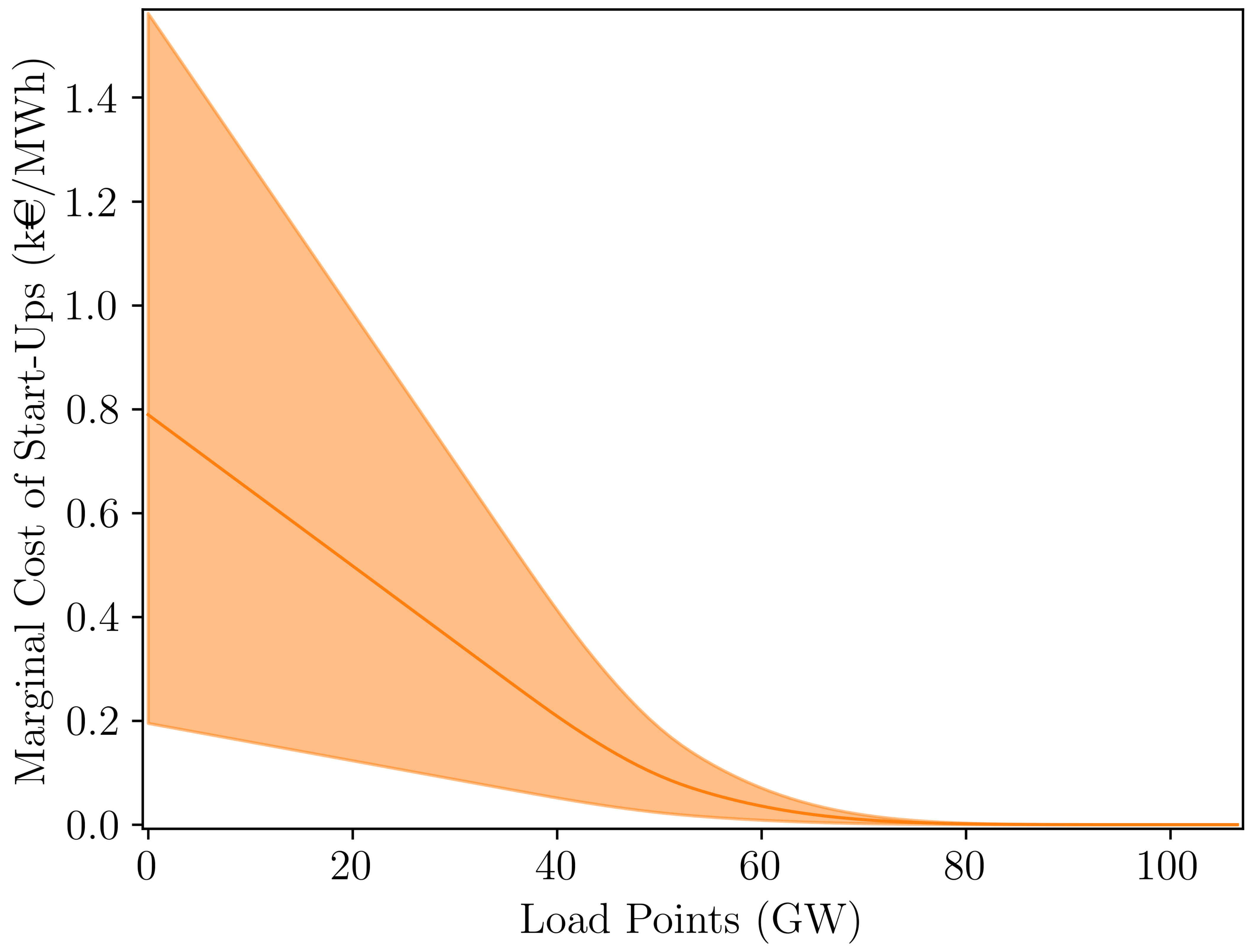
The start-up cost coefficient is derived from real flexibility data (In our case, we use data from the National Renewable Energy Laboratory (NREL))

$$\mathrm{K_{Su}} = \overline{\left(\mathrm{CMC_{NREL}}\right)} \Big/ \overline{\mathrm{hRC}_{.,\alpha}}$$

Impact of start-ups on the System Costs

Method

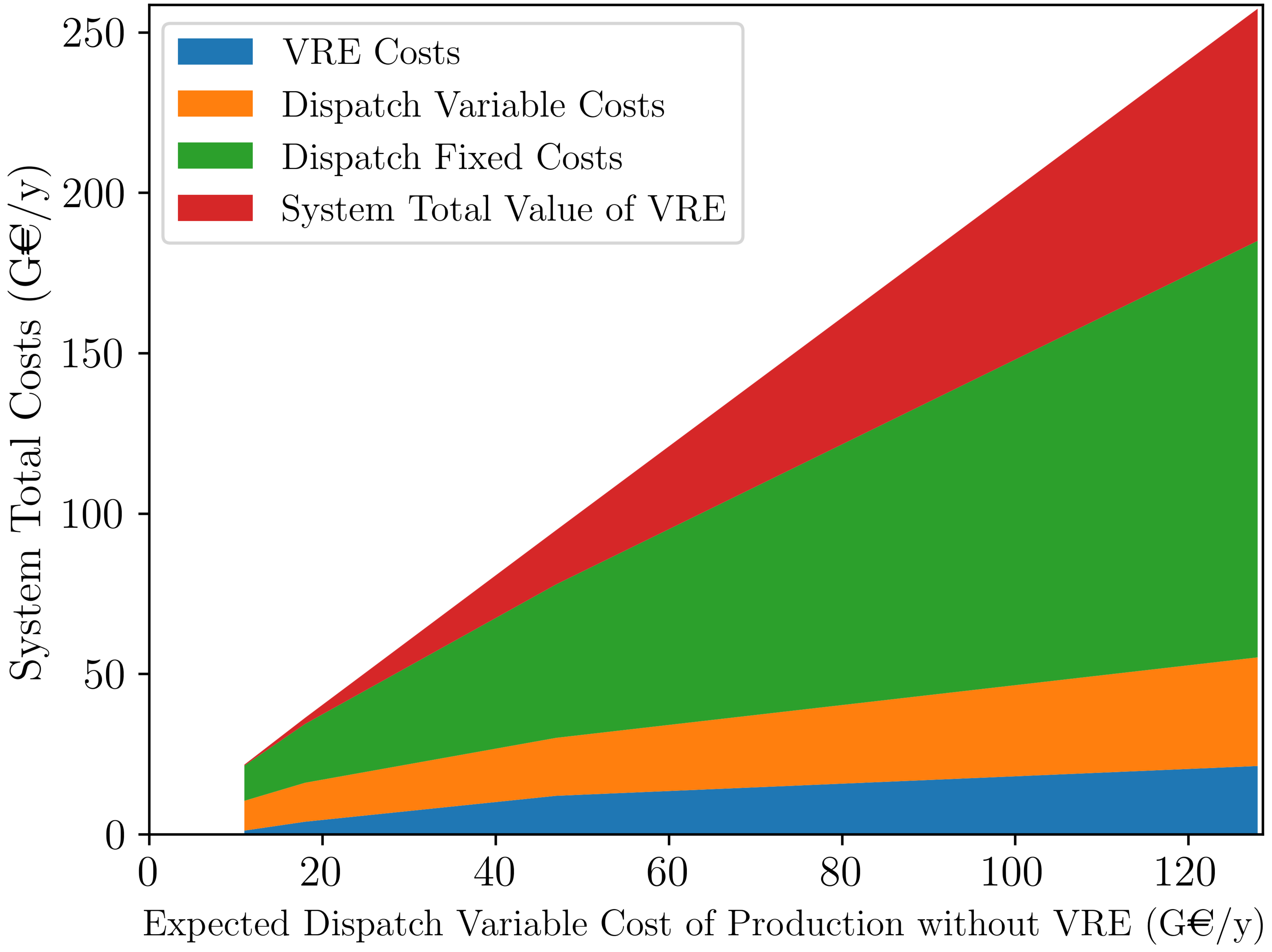


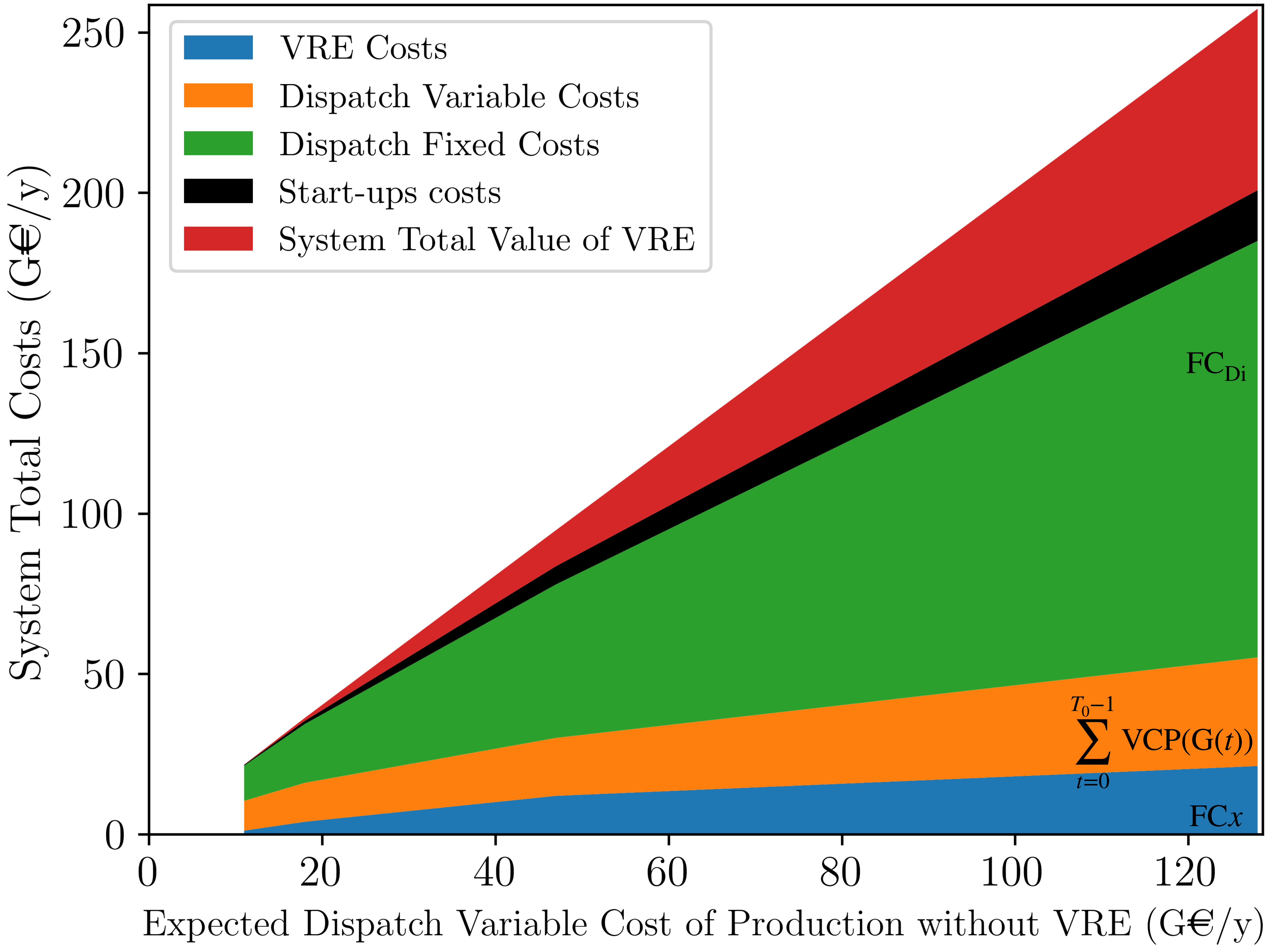


Marginal costs of start-ups variation for $K_{SU}^{min} < K_{SU} < K_{SU}^{max}$ at 50% VRE

Impact of start-ups on the System Costs

Results

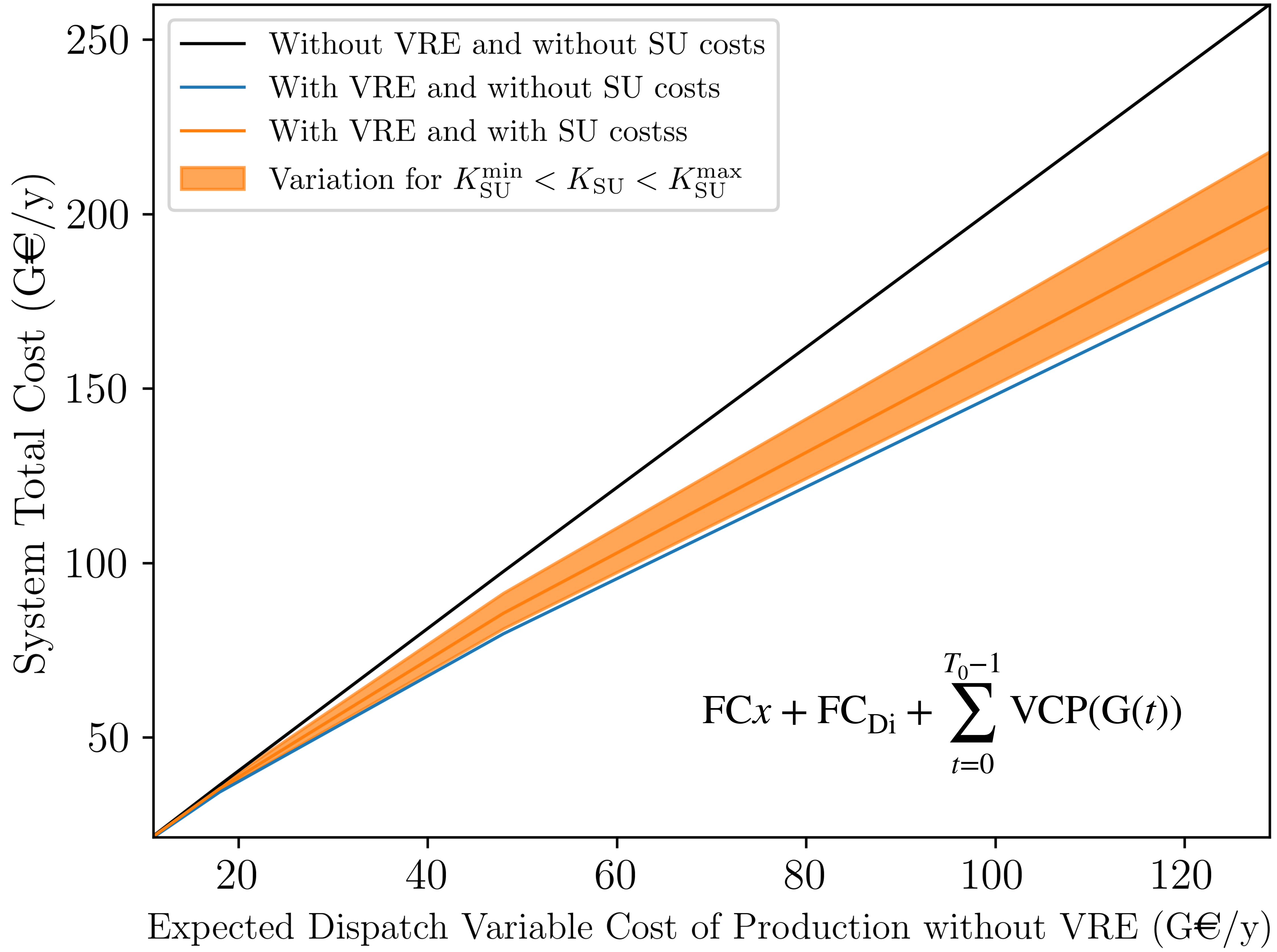




The start up costs account for half of the VRE fixed costs for any given level of penetration

Impact of start-ups on the System Costs

Results



VRE Penetration (%)	20	50	80
Without VCSu	5.3	17.8	28.1
K min	5	17	27
K ref	3	12	22
K max	1.2	7.4	17

VRE values (TSC decrease due to VRE introduction)

The start up costs decrease the VRE value but do not call into question their profitability from the system's point of view

Impact of start-ups on the System Costs

Limits

- We use an hourly scale and do not consider the intra-hour production variation which can lead to under or overestimating the flexibility needs.

- The sensitivity of our results to the estimates of the coefficient K_{SU} calls for more empirical studies of the marginal costs of flexibility.

Impact of renewable energies distribution on start-ups

Method

- For each technology, we have a different geographical distribution:
  1. The first one is spread over the whole territory of metropolitan France
  2. The second one is more concentrated in some regions while others remain empty.

FR2019

France actual installed capacities in 2019 are increased proportionally to reach the desired penetration levels.

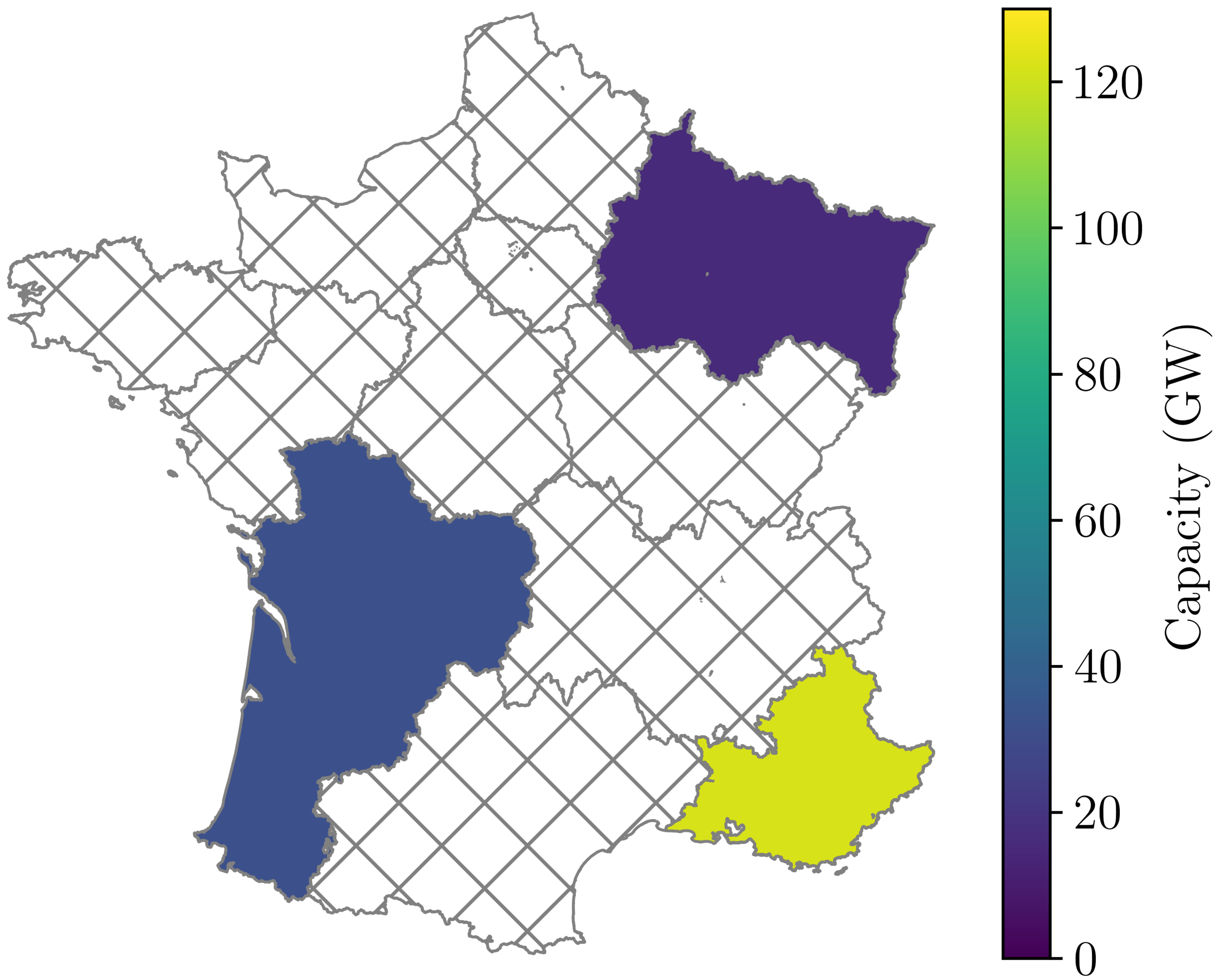
E4CLIM

The e4clim model is launched with no capacity constraints prescribed alpha (α) values to achieve the desired penetrations and

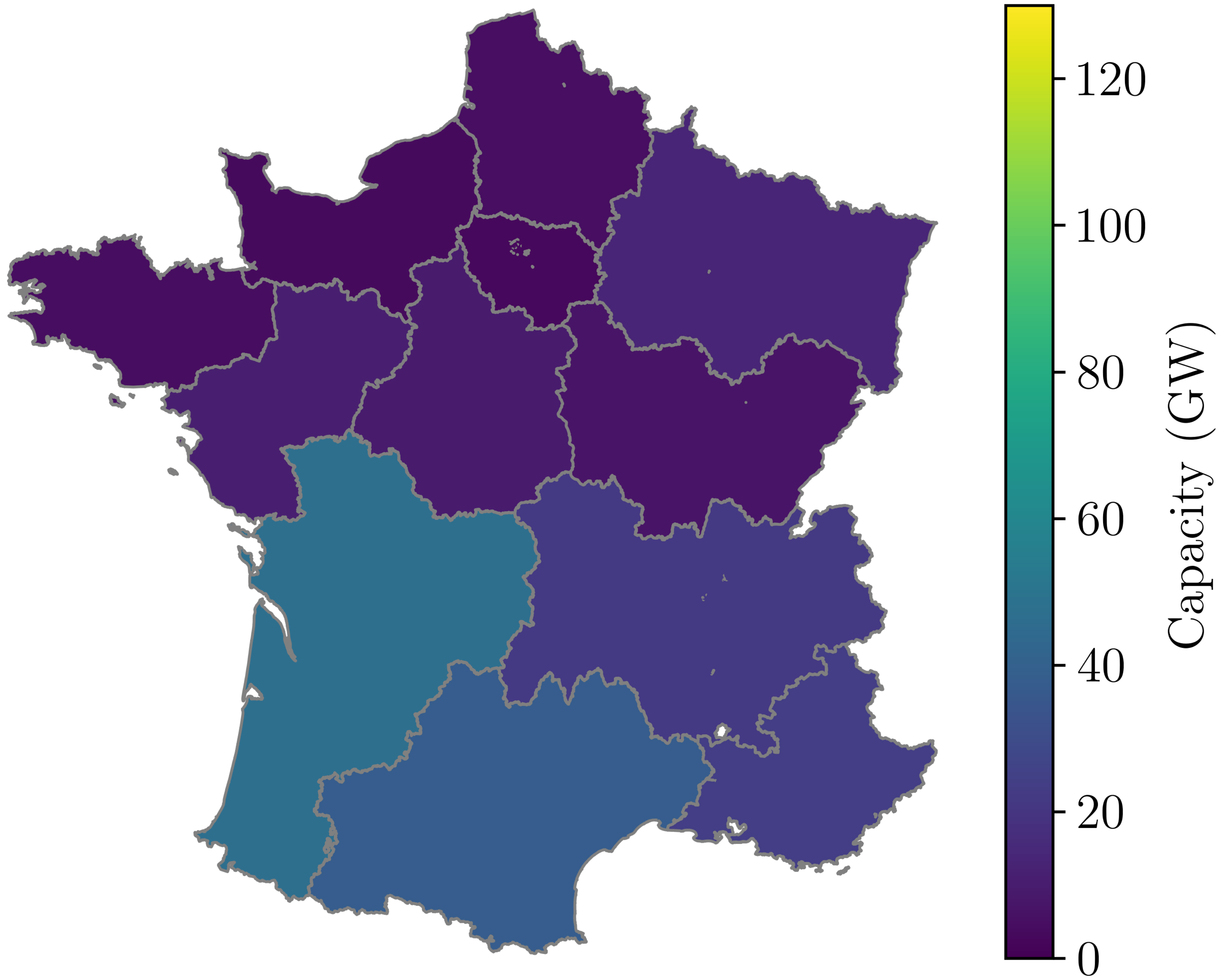
Impact of renewable energies distribution on start-ups

Method

Example: PV - 50% Penetration



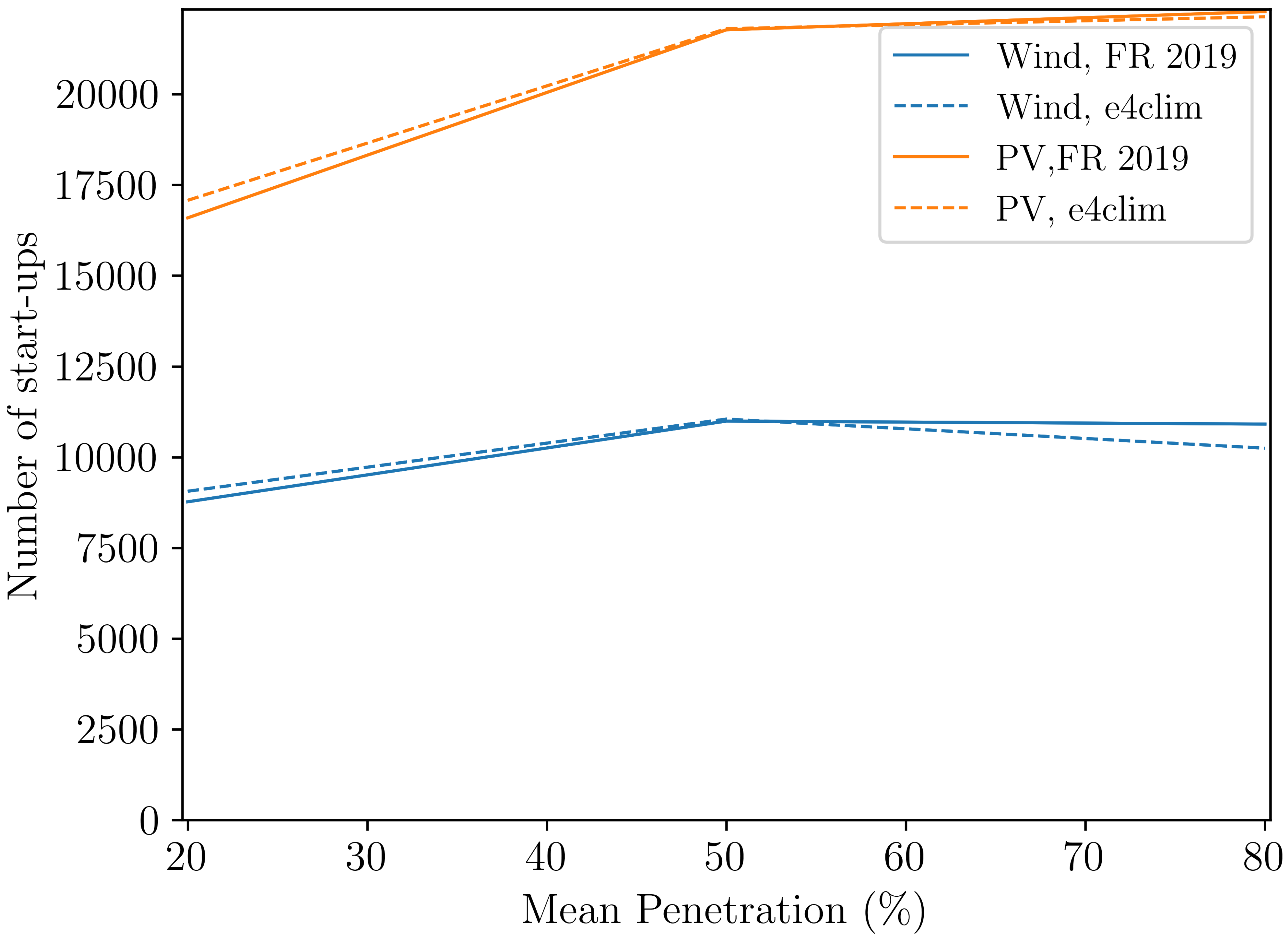
e4clim



FR2019

Impact of renewable energies distribution on start-ups

Results



- For high VRE penetration (>20%) solar PV induces 2 times more start-ups than wind whatever the mix used.
- The geographical distribution has little impact on the total number of start-ups but small impacts can be noted.

Conclusion

1. The costs of start ups impact significantly the total cost of the system (+8%) ie the flexibility effect reduces the economic interest of integrating ERVs.

2. Base producers loose profits while the opposite is true for peak producers.
3. Base producers have a higher variable cost of start-ups than peak producers.

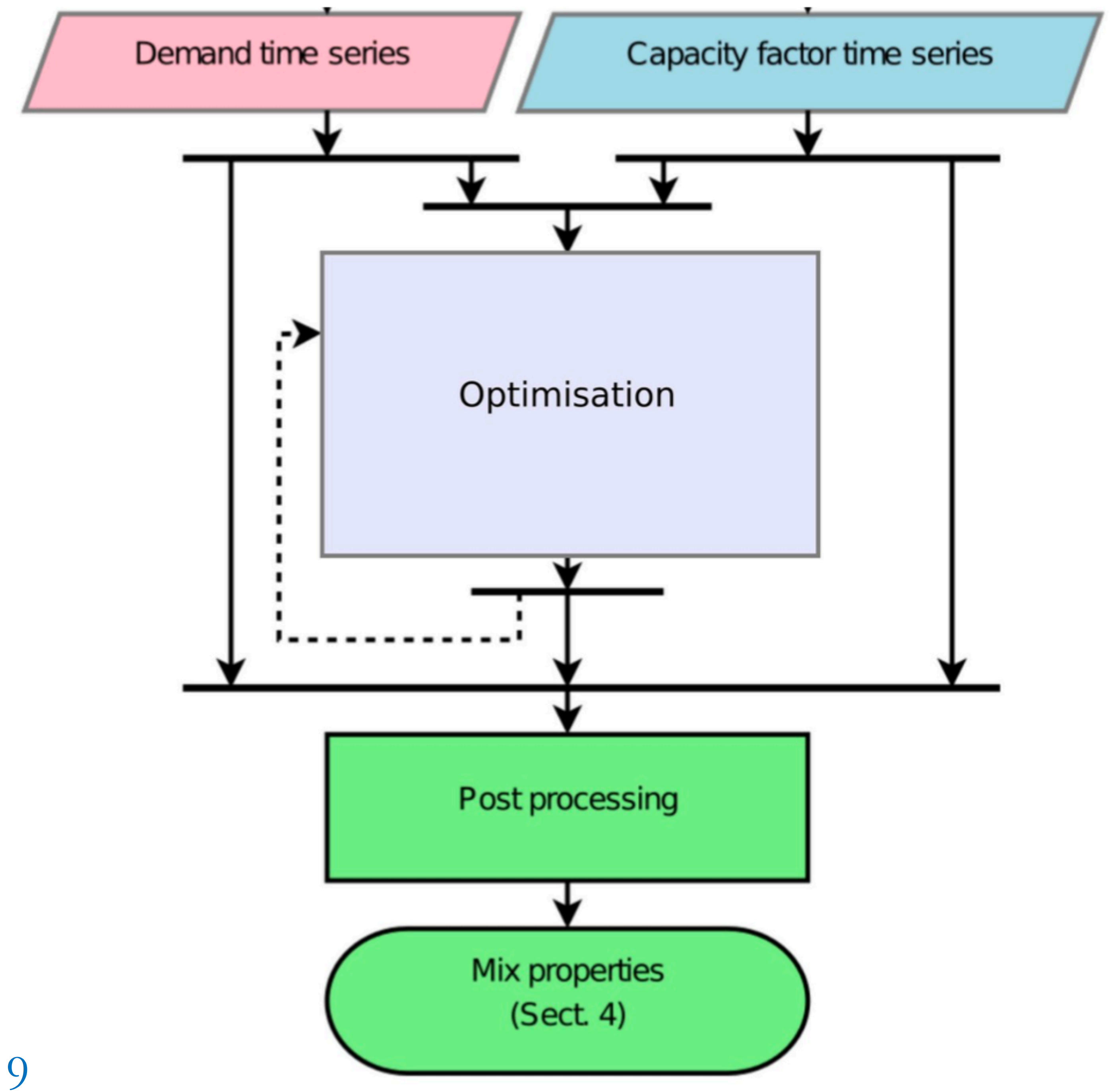
4. PV induces double the number of start-ups compared to Wind
5. The geographical distribution of PV and Wind has little impact on start-ups.

6. Our results are sensitive to the value of the coefficient K of the marginal cost of start-ups.

Introduction

e4clim model

Open-source modelling platform for research on energy mixes with a high share of variable renewable energies, allowing sensitivity studies. Allows minimisation of the system cost of investment in capacity by taking into account the response of conventional to the introduction of renewable energy.



$$\mathrm{STC}(\boldsymbol{x}, (\mathrm{G}(t))_{t\in\mathbb{T}_0}) := \mathrm{FC}_{\boldsymbol{x}} + \mathrm{FC}_{\mathrm{Di}} + \sum_{t=0}^{T_0-1} \mathrm{VCP}_{\mathrm{Di}}(\mathrm{G}(t))$$

$$\begin{aligned} \min_{\boldsymbol{x}} \quad & \mathbb{E}(\overline{\mathrm{STC}}(\boldsymbol{x})) \\ \text{s.t.} \quad & x_i \leq x_i^{\max}, \quad i \in \{0, \ldots, m-1\} \\ & x_i \geq 0, \quad i \in \{0, \ldots, m-1\}, \end{aligned}$$

$$\begin{aligned} \min_{(\mathrm{G}(t))_{t\in\mathbb{T}_0}} \quad & \mathrm{STC}(\boldsymbol{x}, (\mathrm{G}(t))_{t\in\mathbb{T}_0}) \\ \text{s.t.} \quad & \mathrm{G}(t) + \mathrm{Q}_{\boldsymbol{x}}(t) \geq \mathrm{L}(t) \\ & \mathrm{G}(t) \leq x_{\mathrm{Di}} \\ & \mathrm{G}(t) \geq 0. \end{aligned}$$

Tantet and al., 2019

e4clim model

$$\mathrm{VCP}_{\mathrm{Di}}(\mathrm{G}(t)) = \alpha(\mathrm{G}(t))^2, \quad \mathrm{G}(t) \in [0, x_{\mathrm{Di}}], t \in \mathbb{T}_0$$

$$\mathrm{MCP}_{\mathrm{Di}}(\mathrm{G}(t)) = 2\alpha\mathrm{G}(t), \quad \mathrm{G}(t) \in [0, x_{\mathrm{Di}}], t \in \mathbb{T}_0$$

$$\sum_{j=1}^{J} x_j = \max_{t\in\mathbb{T}_0} \mathrm{L}(t)$$

$$\sum_{j=1}^{J} x_j = xJ$$

$$\mathrm{LP}_j = x(j-1)$$

$$\Longrightarrow x = \frac{\max_{t\in\mathbb{T}_0} \mathrm{L}(t)}{J}$$

$$\mathrm{MCP}_j = 2\alpha\mathrm{LP}_j$$

$$\mathrm{VCP}_j(t) = \mathrm{MCP}_j\mathrm{G}_j(t), \quad \mathrm{G}(t) \in [0, x_{\mathrm{Di}}], t \in \mathbb{T}_0$$

Impact of start-ups on the System Costs

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Start-ups

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$$\mathrm{STC}(\boldsymbol{x}, (\mathrm{G}(t))_{t\in\mathbb{T}_0}) := \mathrm{FC}_{\boldsymbol{x}} + \mathrm{FC}_{\mathrm{Di}} + \sum_{t=0}^{T_0-1} \mathrm{VCP}_{\mathrm{Di}}(\mathrm{G}(t)) + \sum_{t=0}^{T_0-1} \mathrm{VCSu}(t)$$

Introduction

e4clim model

$$\mathrm{STC}(\boldsymbol{x}, (\mathrm{G}(t))_{t\in\mathbb{T}_0}) := \mathrm{FC}_{\boldsymbol{x}} + \mathrm{FC}_{\mathrm{Di}} + \sum_{t=0}^{T_0-1} \mathrm{VCP}_{\mathrm{Di}}(\mathrm{G}(t))$$

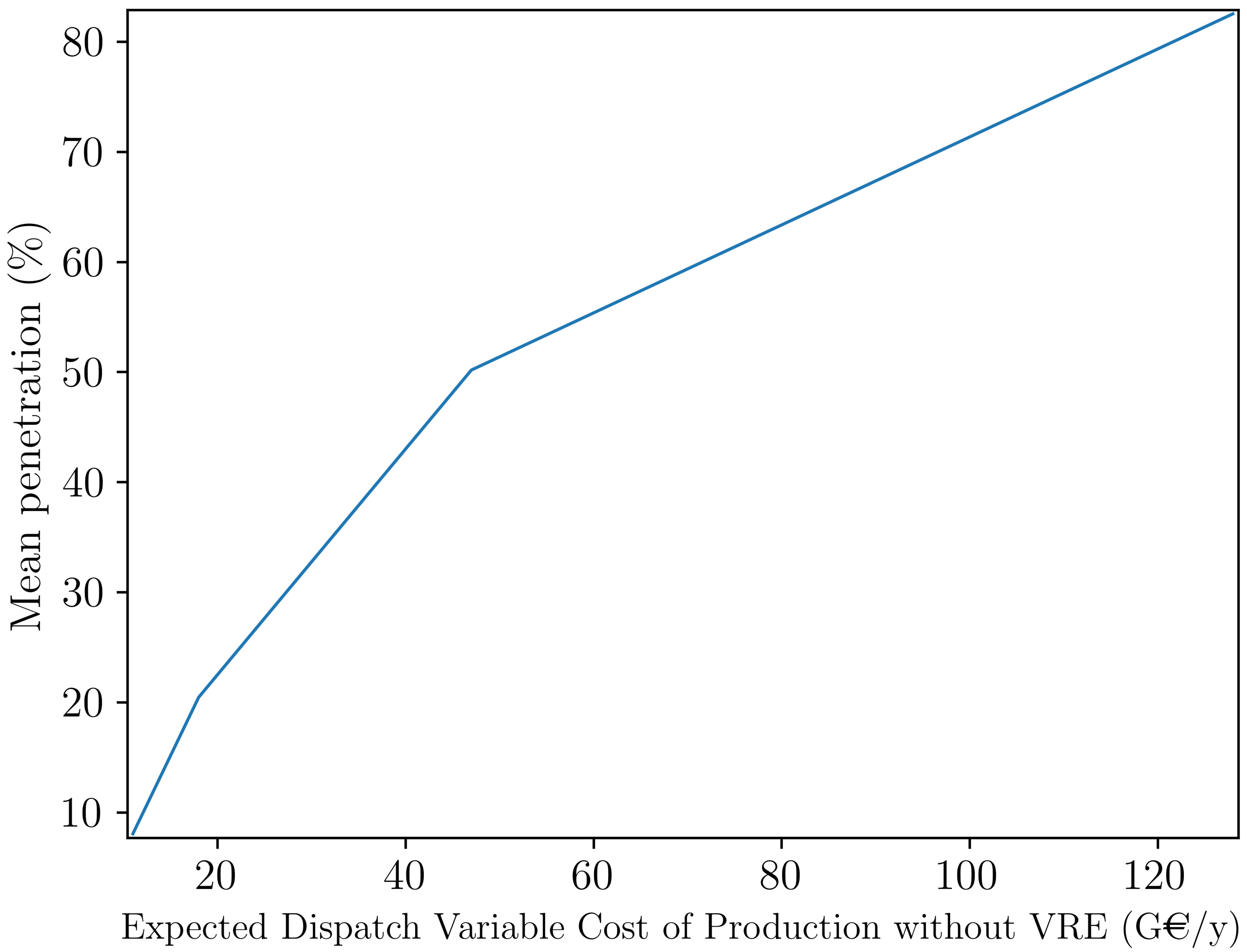
Variable Cost of Production

$$\mathrm{VCP}_{\mathrm{Di}}(\mathrm{G}(t)) = \alpha(\mathrm{G}(t))^2, \quad \mathrm{G}(t) \in [0, x_{\mathrm{Di}}], t \in \mathbb{T}_0$$

Marginal Cost of Production

$$\mathrm{MCP}_{\mathrm{Di}}(\mathrm{G}(t)) = 2\alpha\mathrm{G}(t), \quad \mathrm{G}(t) \in [0, x_{\mathrm{Di}}], t \in \mathbb{T}_0$$

Minimal configuration capturing the increase of the marginal cost with the addition of production from more expensive plants as the load increases (merit order).



Impact of start-ups on the System Costs

Results

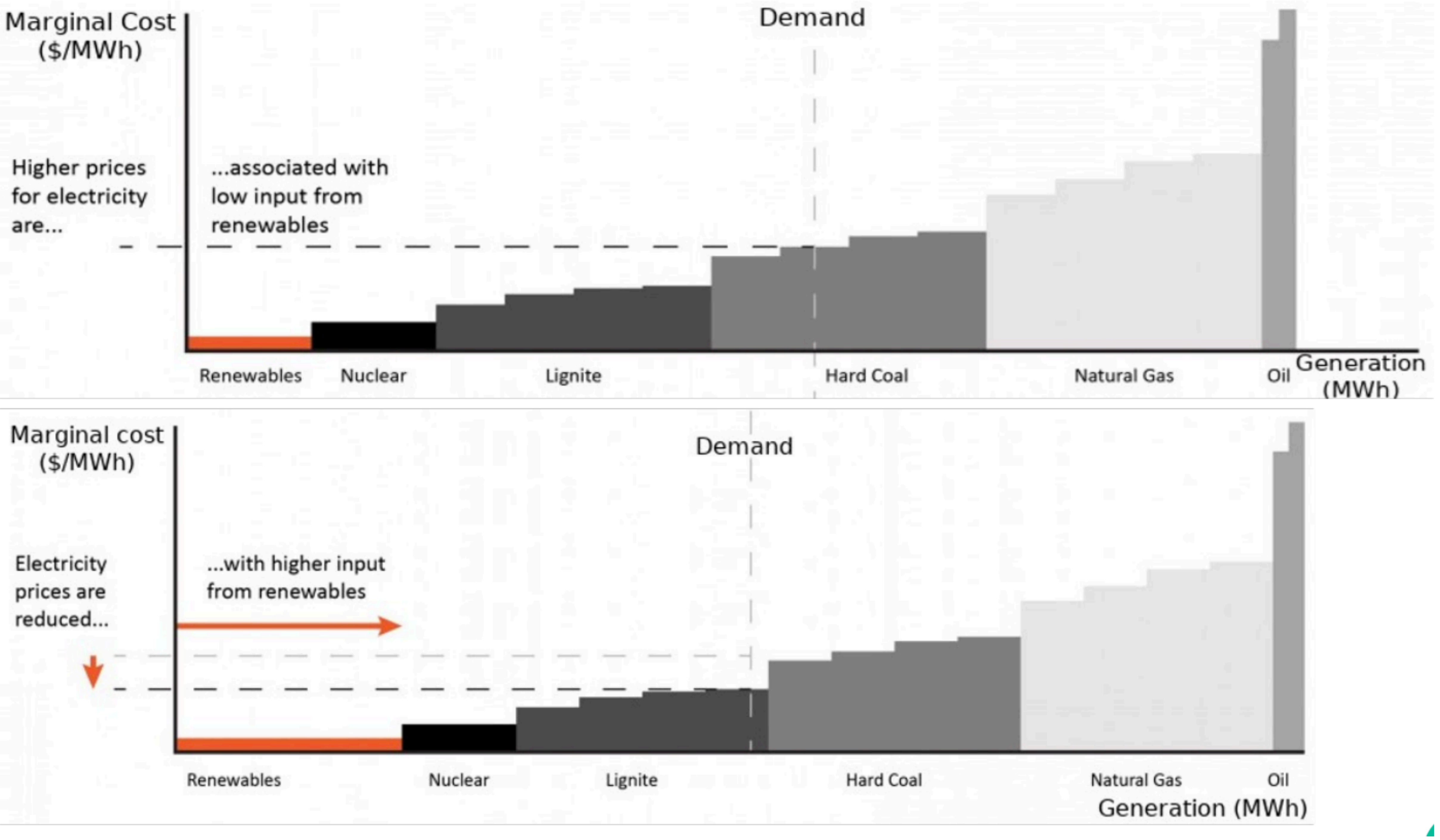
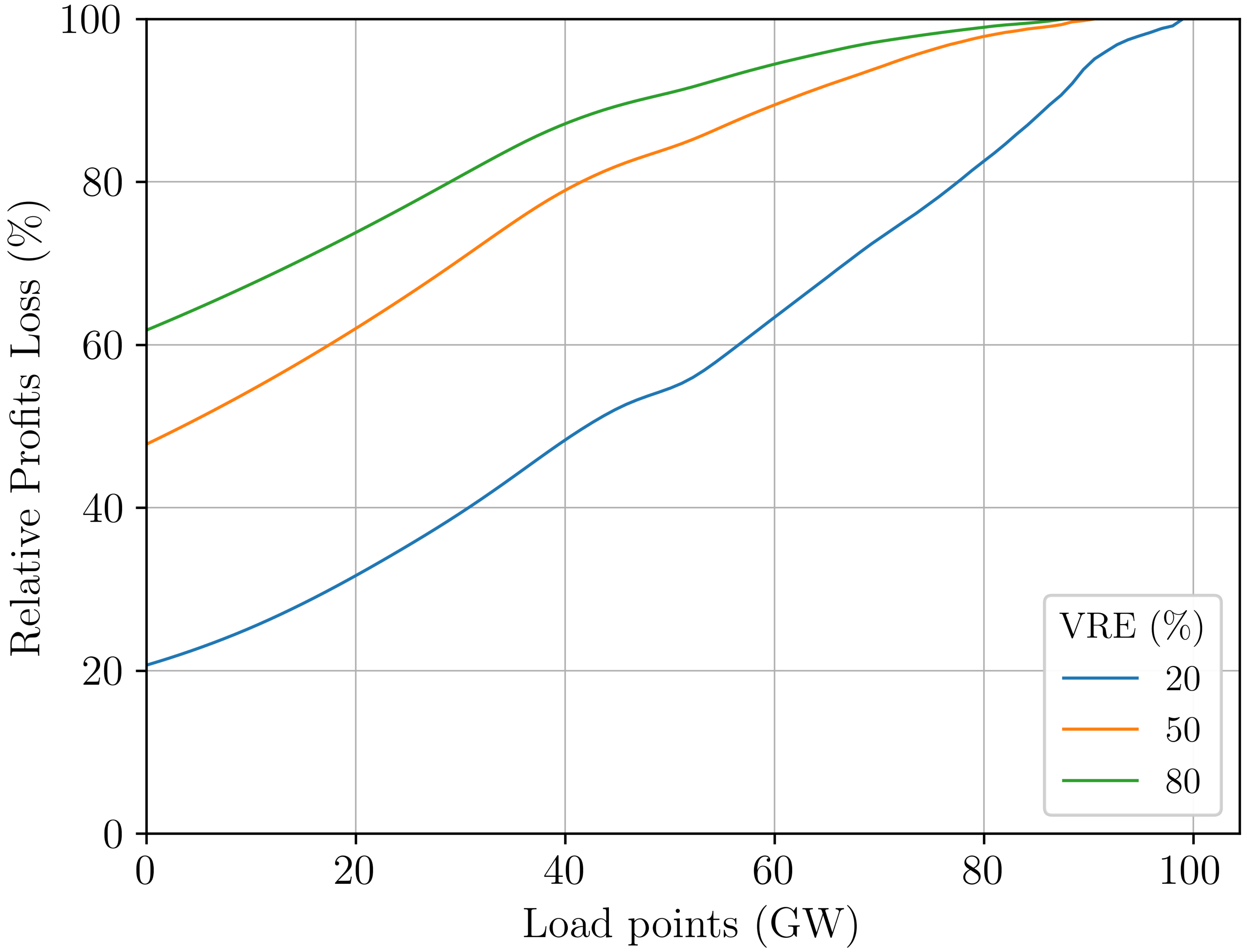


Illustration of the order of merit of the wholesale market



Relative Loss of Conventional producers due to utilisation and wholesale price effects

Impact of start-ups on the System Costs

Results

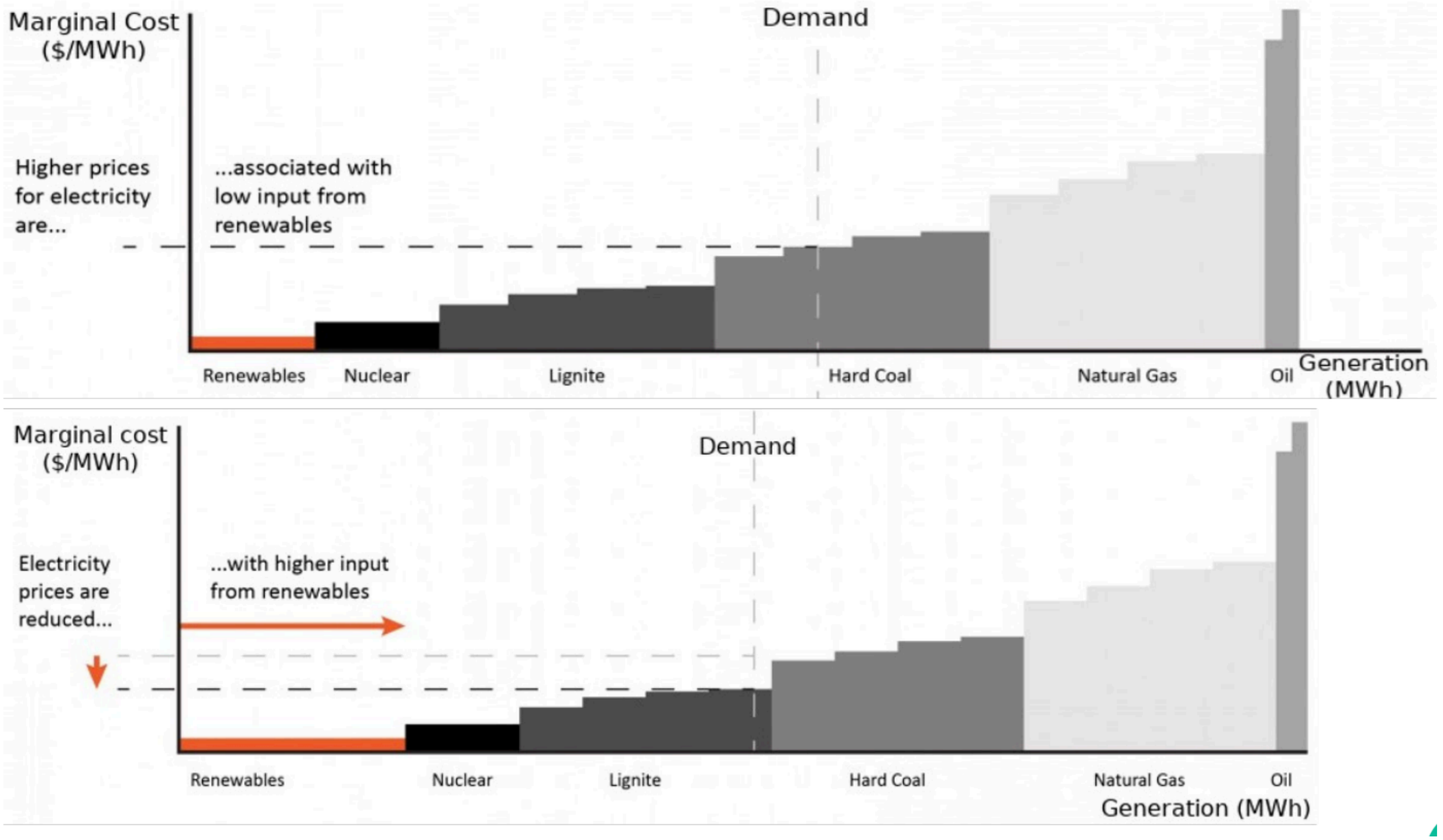
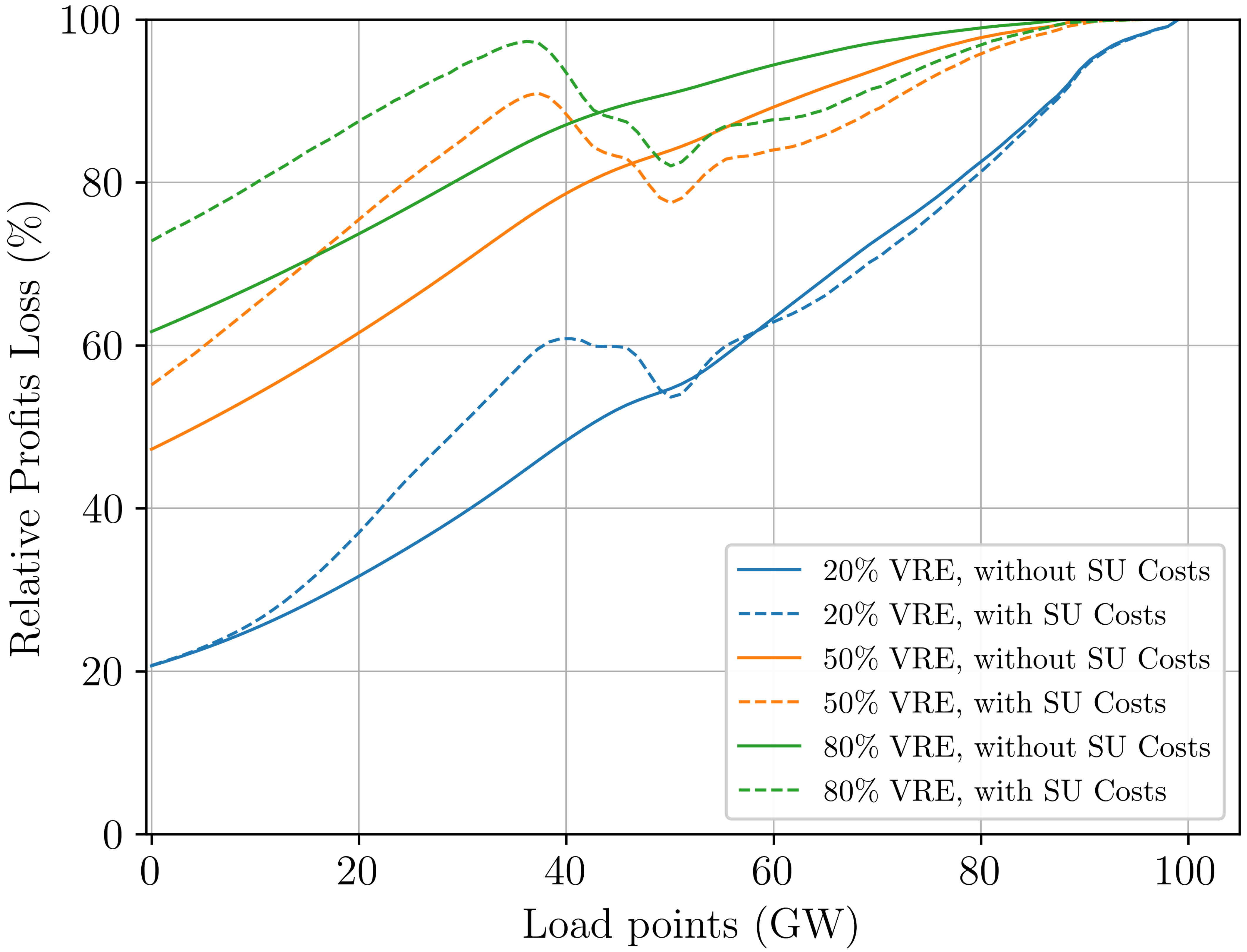


Illustration of the order of merit of the wholesale market



Relative Loss of Conventional producers due to utilisation and wholesale price effects and start-ups

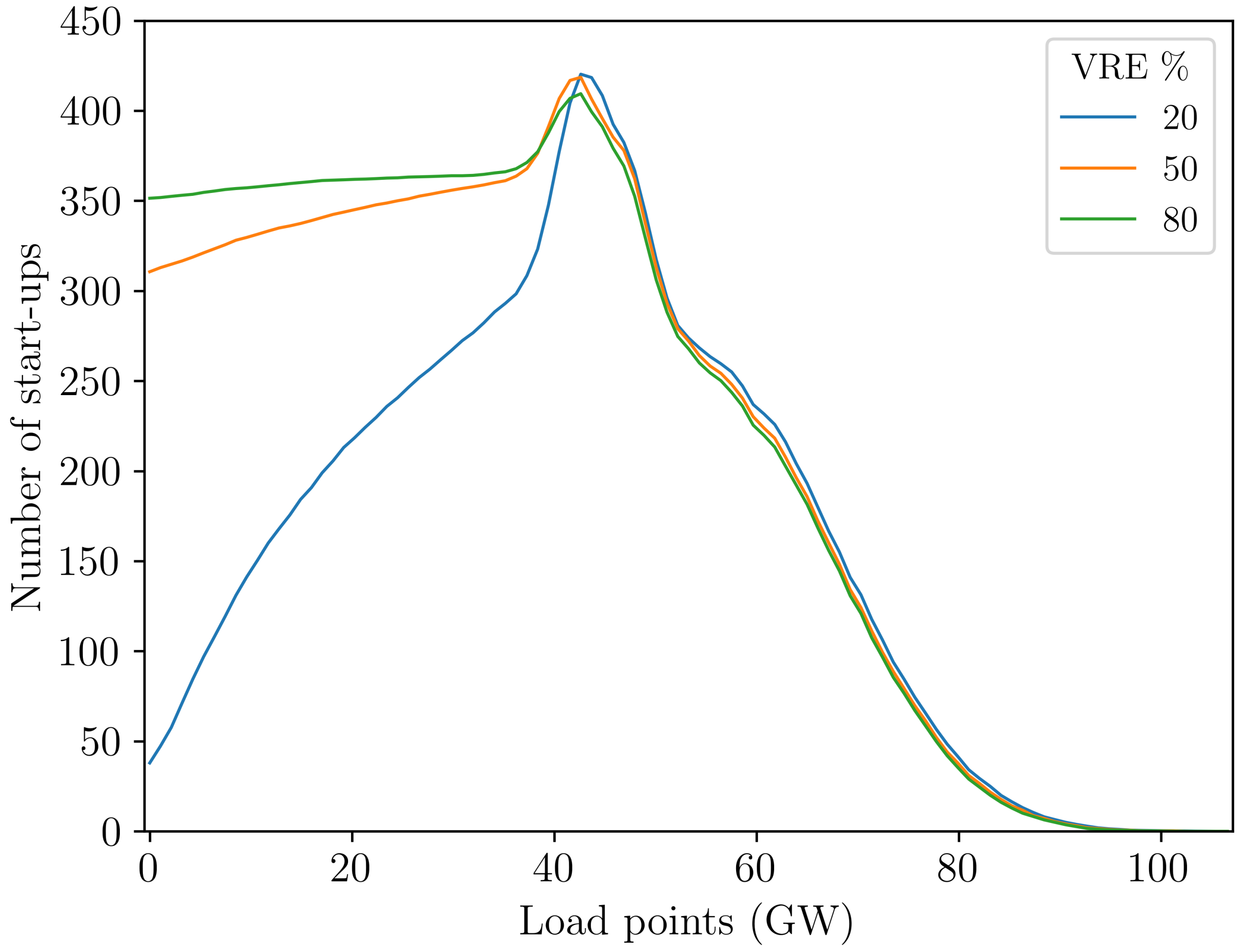
Impact of renewable energies distribution on flexibility needs

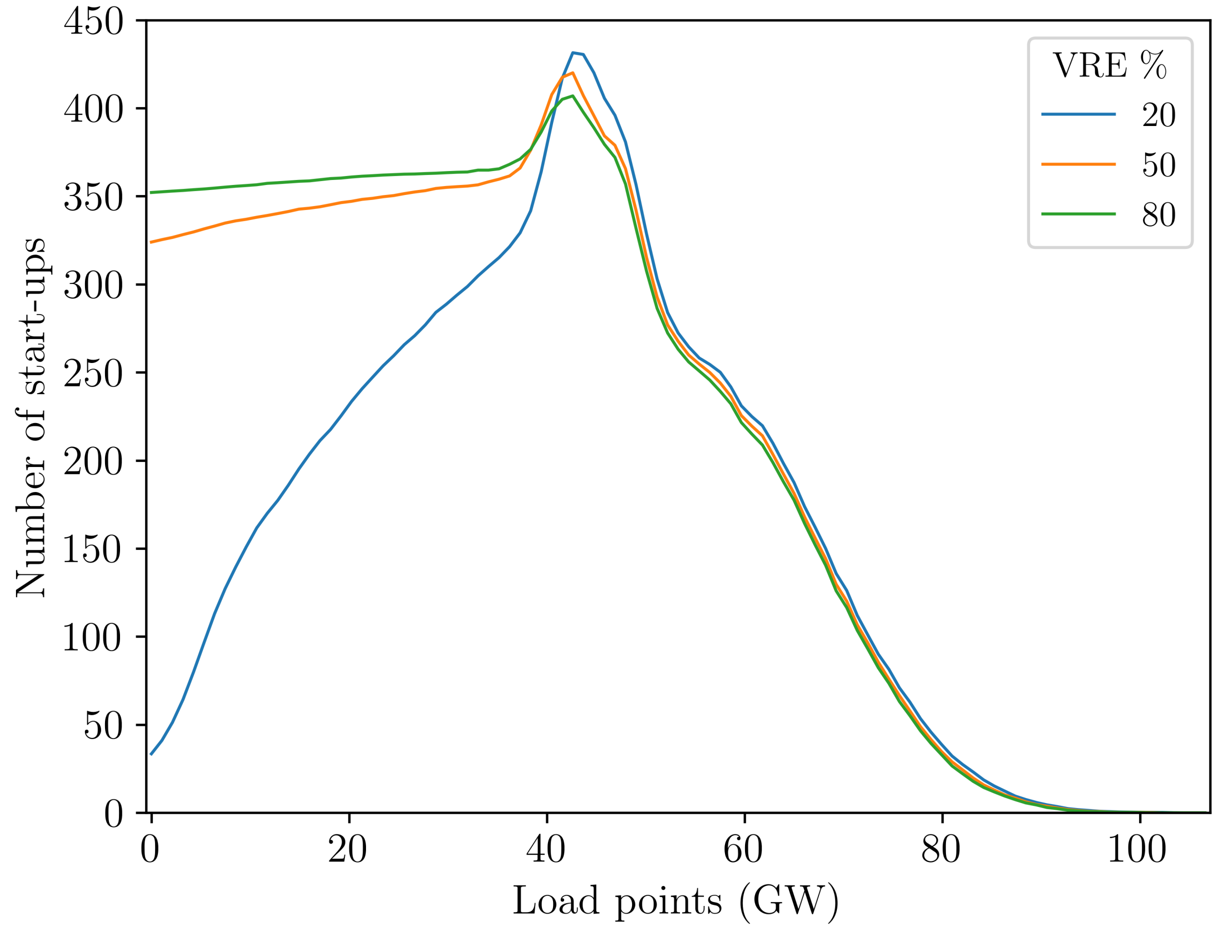
Results

FR2019

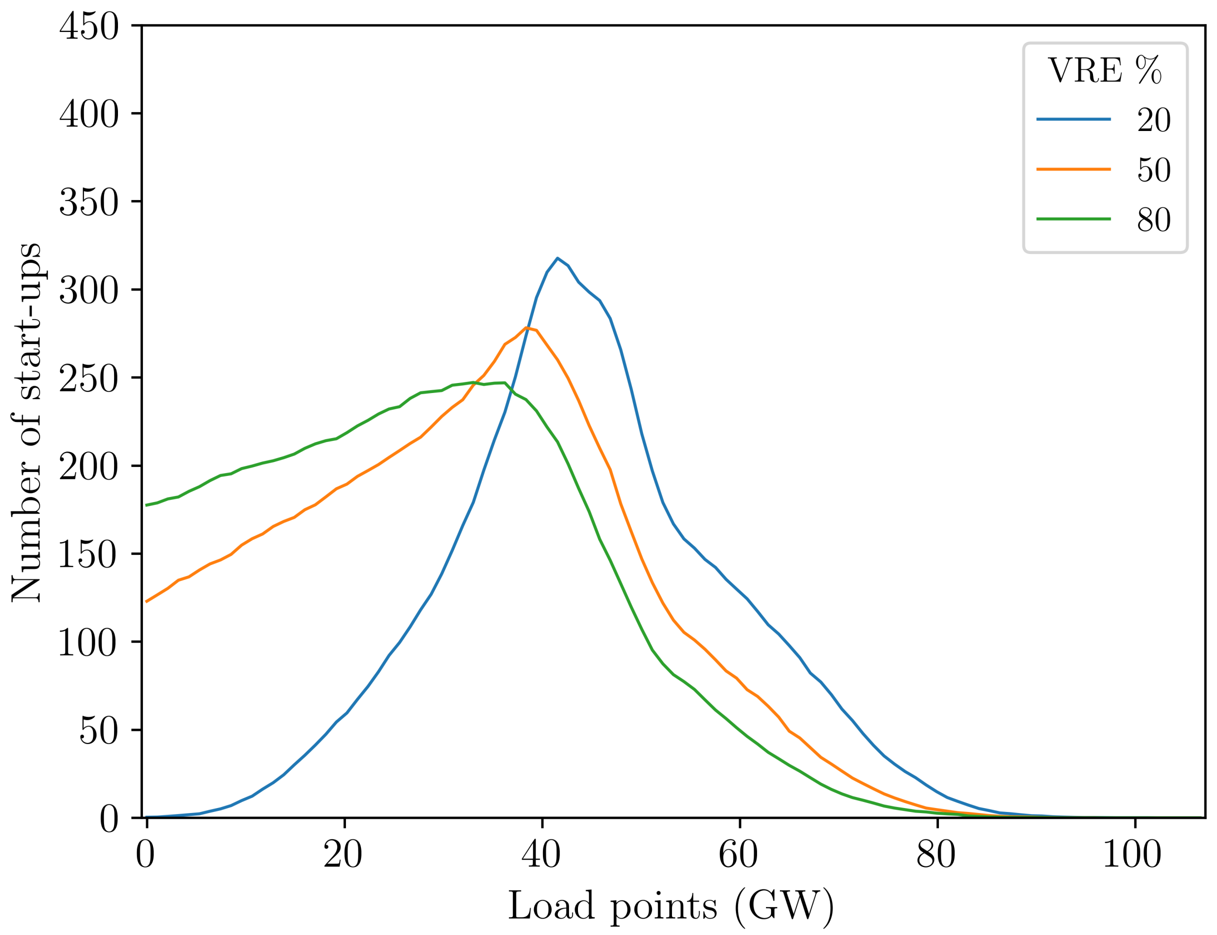
e4clim

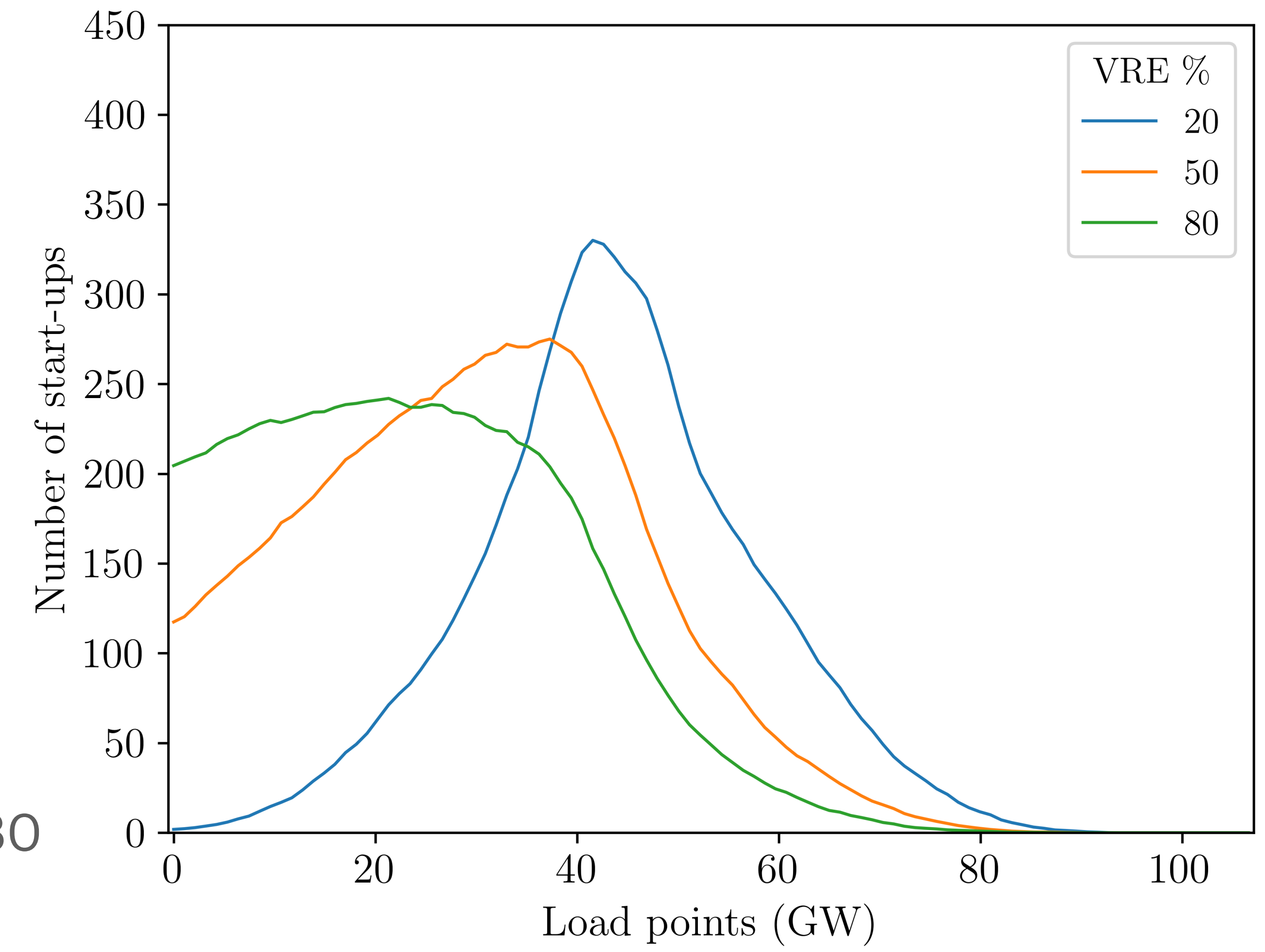
PV

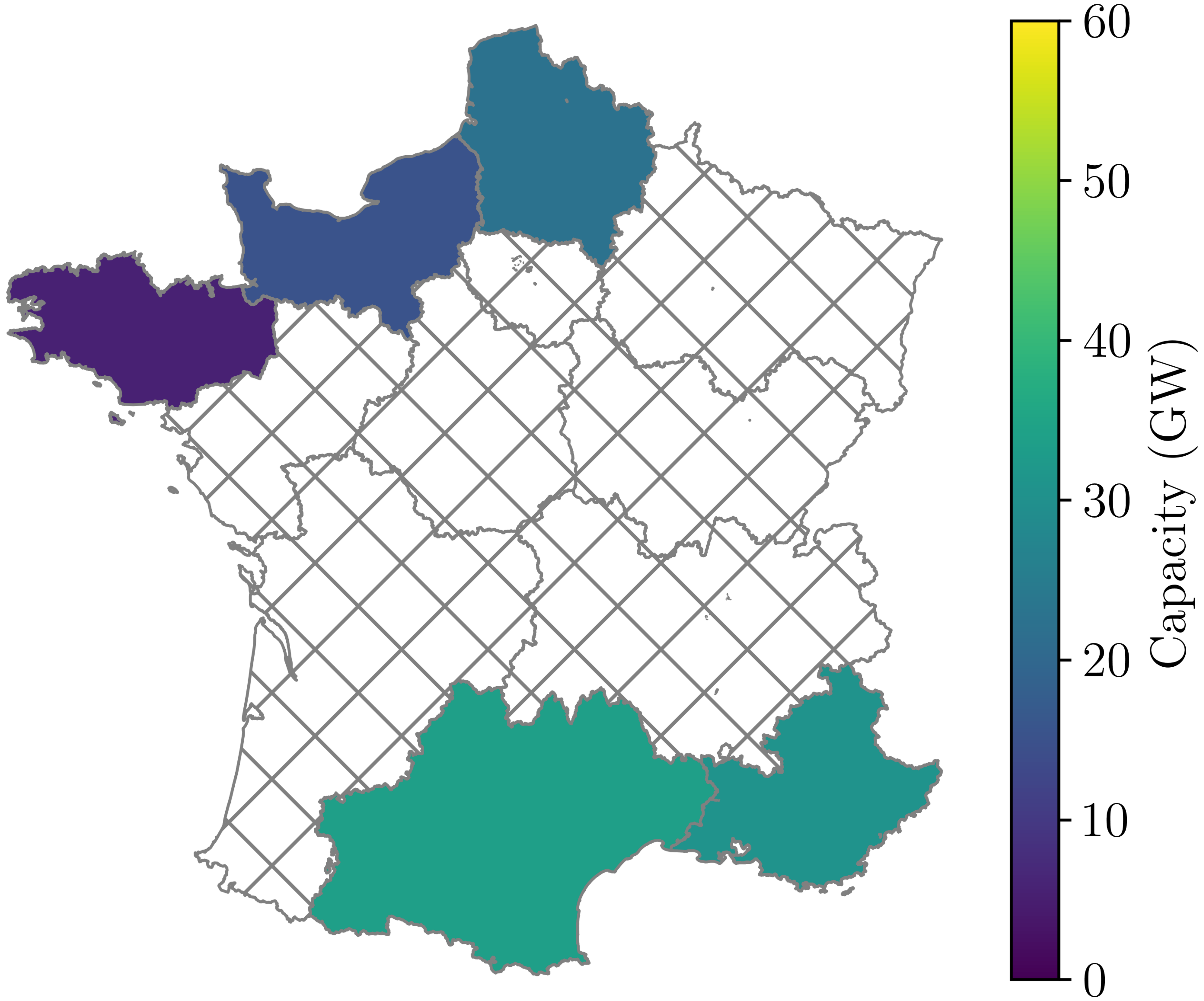


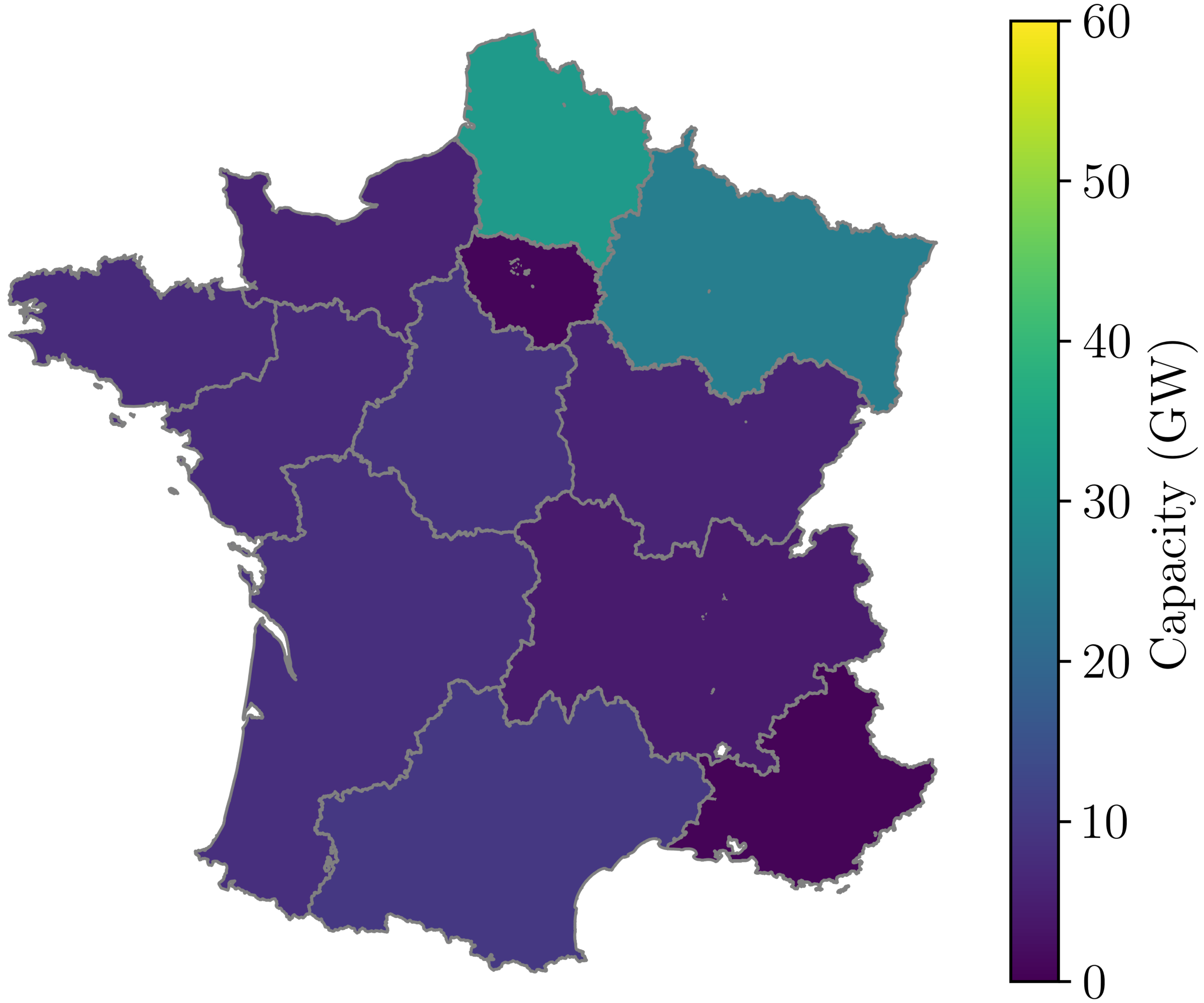


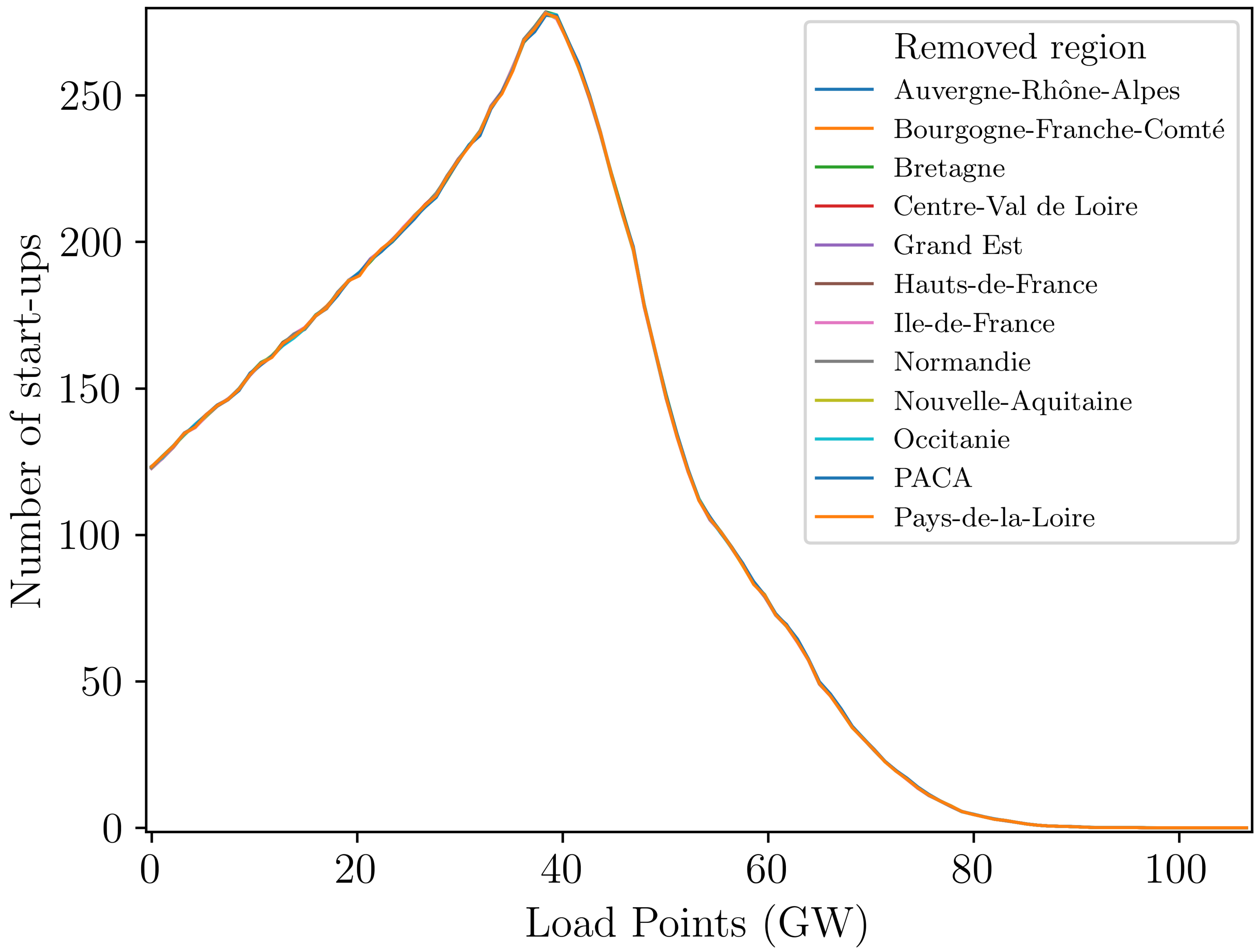
Wind

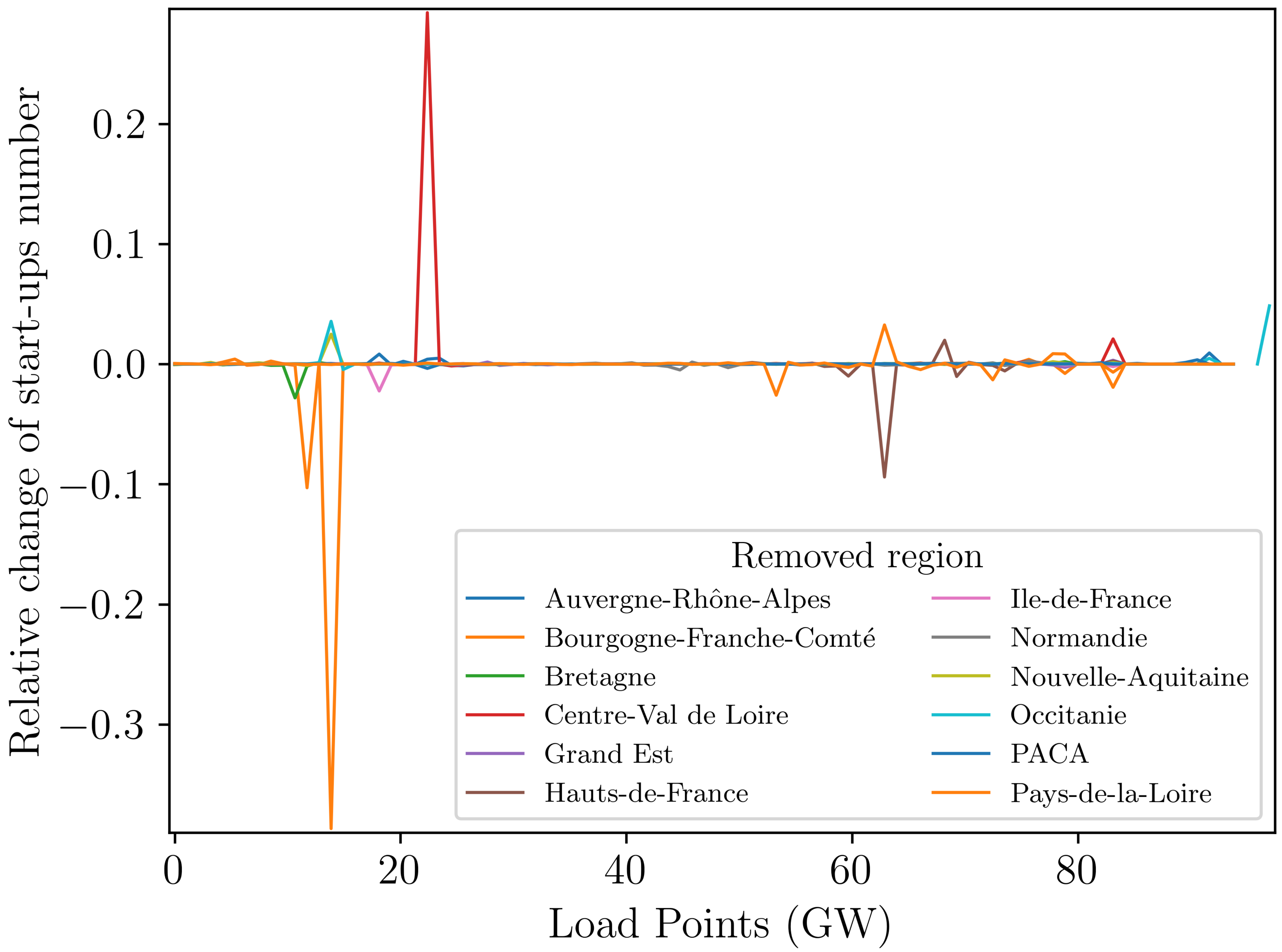


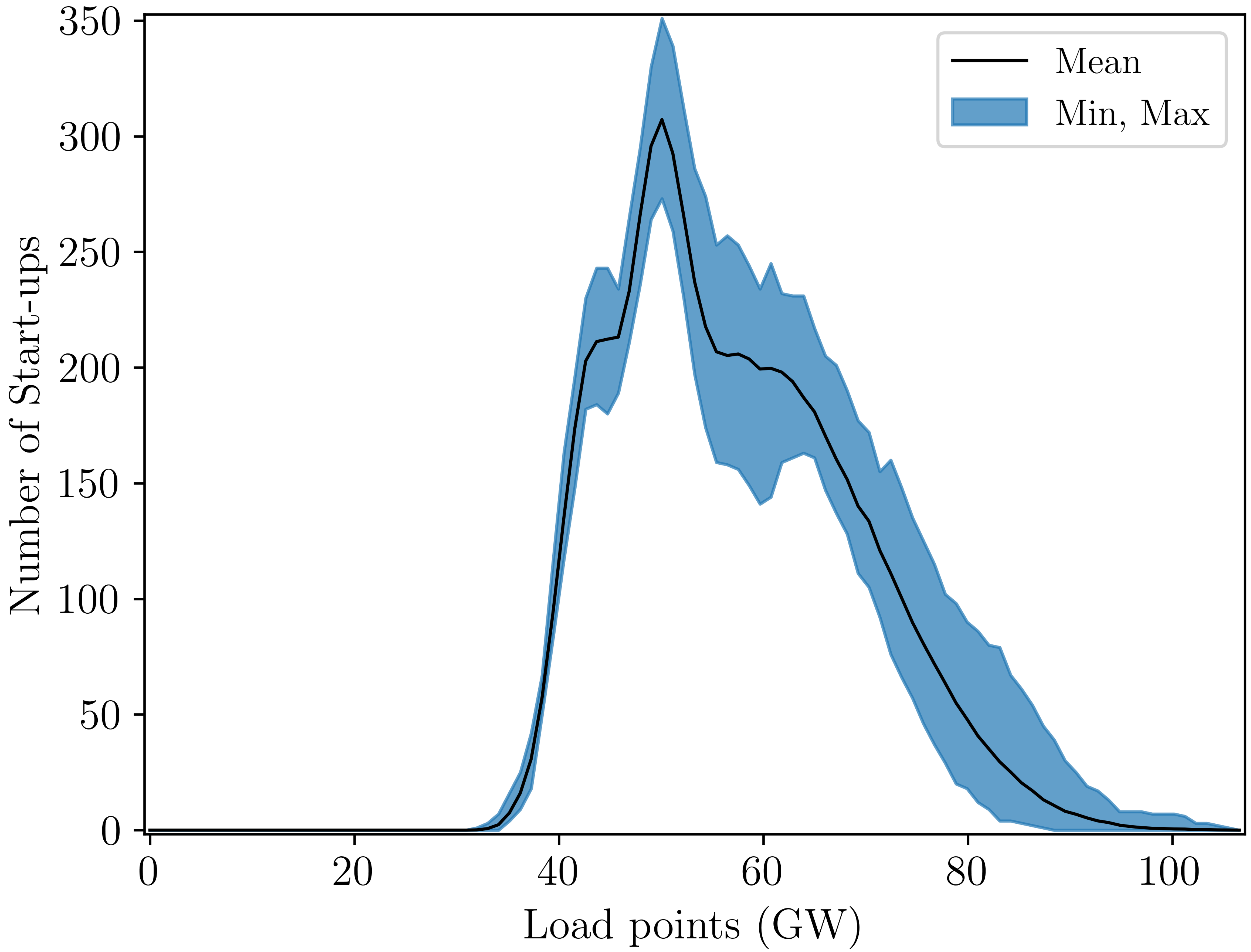


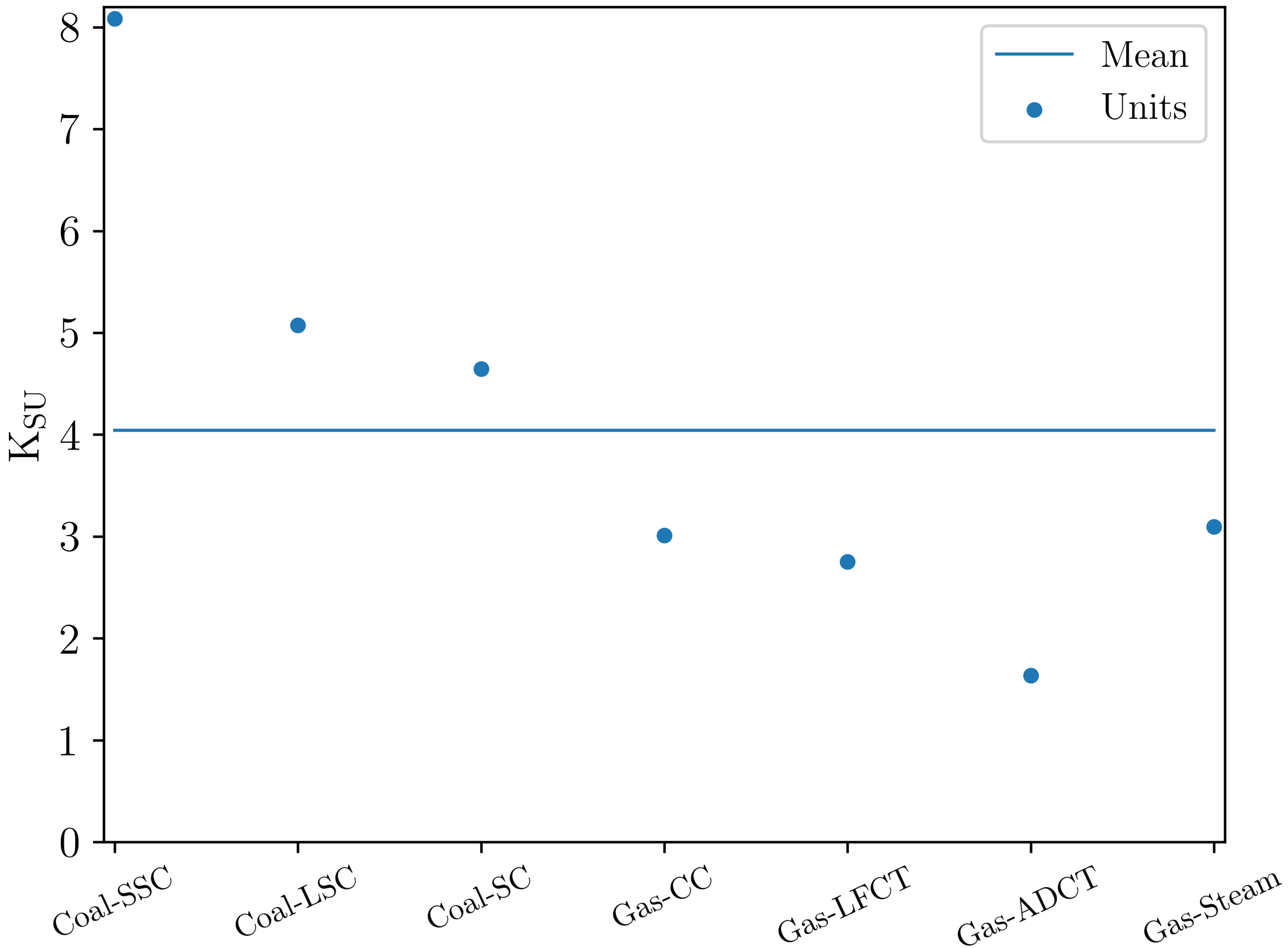

60
50
40
30
20
10
0
Capacity (GW)

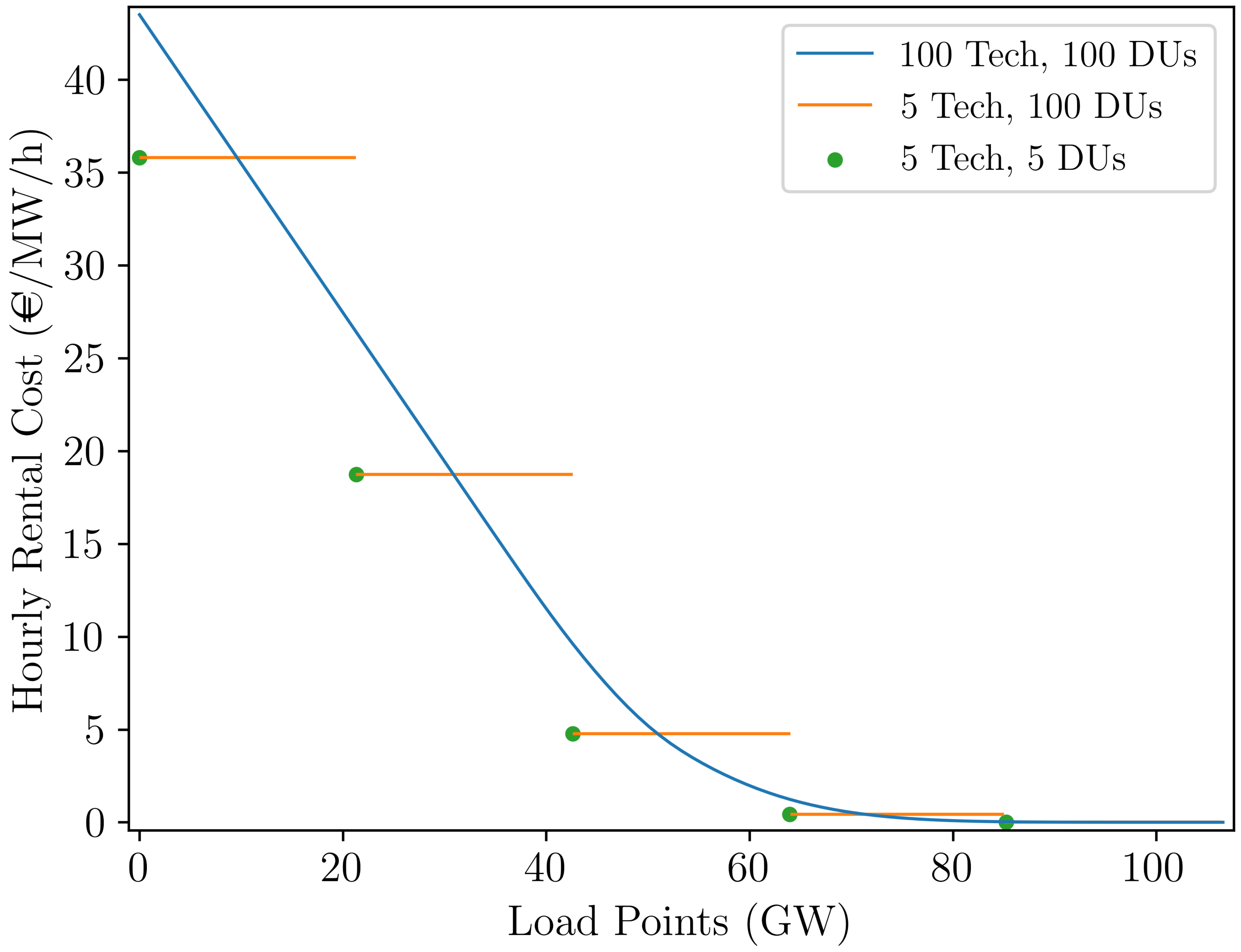

60
50
40
30
20
10
0
Capacity (GW)

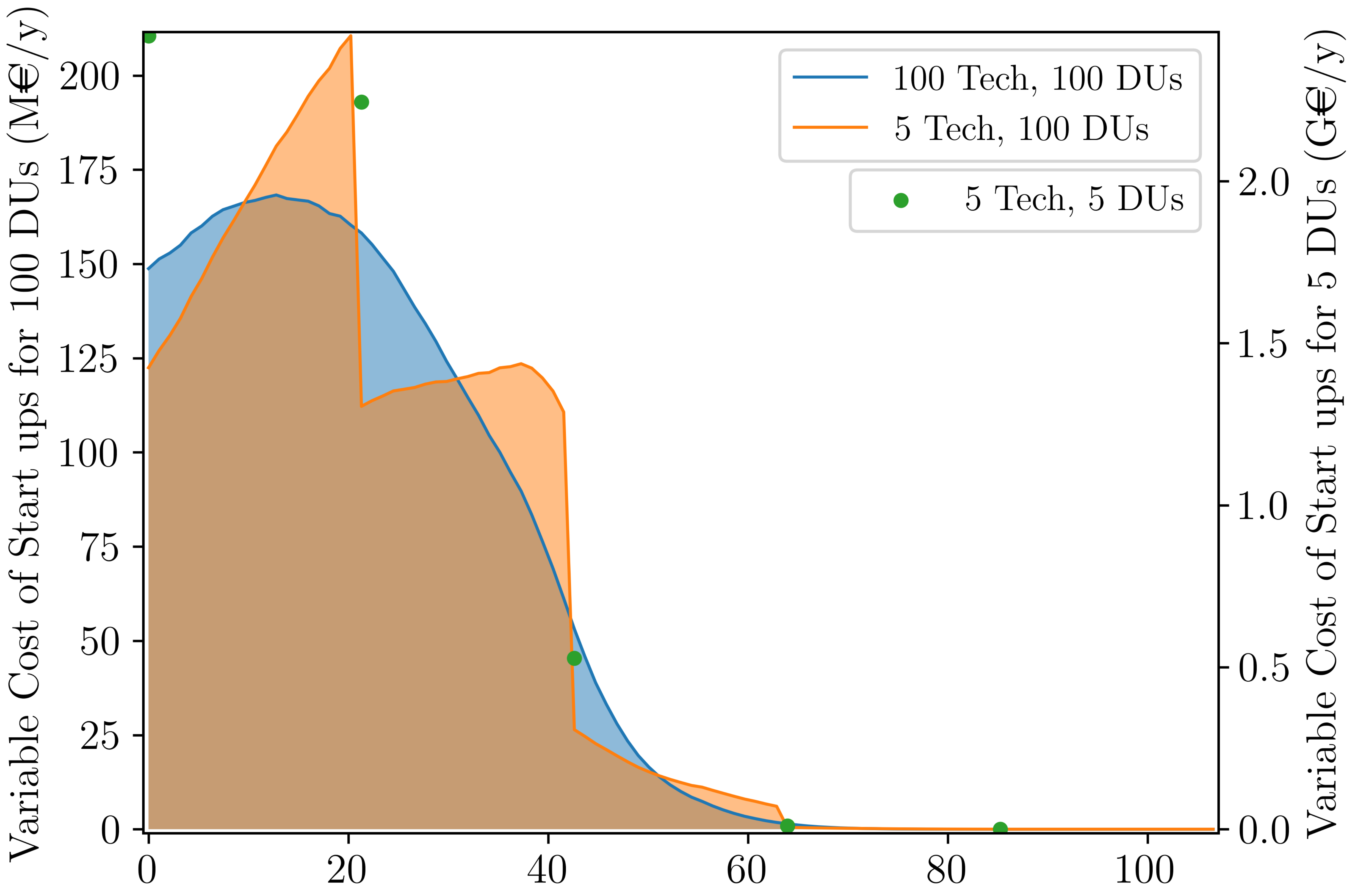

Removed region
Auvergne-Rhône-Alpes
Bourgogne-Franche-Comté
Bretagne
Centre-Val de Loire
Grand Est
Hauts-de-France
Ile-de-France
Normandie
Nouvelle-Aquitaine
Occitanie
PACA
Pays-de-la-Loire
Number of start-ups
Load Points (GW)


Removed region
Auvergne-Rhône-Alpes
Bourgogne-Franche-Comté
Bretagne
Centre-Val de Loire
Grand Est
Hauts-de-France
Ile-de-France
Normandie
Nouvelle-Aquitaine
Occitanie
PACA
Pays-de-la-Loire
Relative change of start-ups number
Load Points (GW)

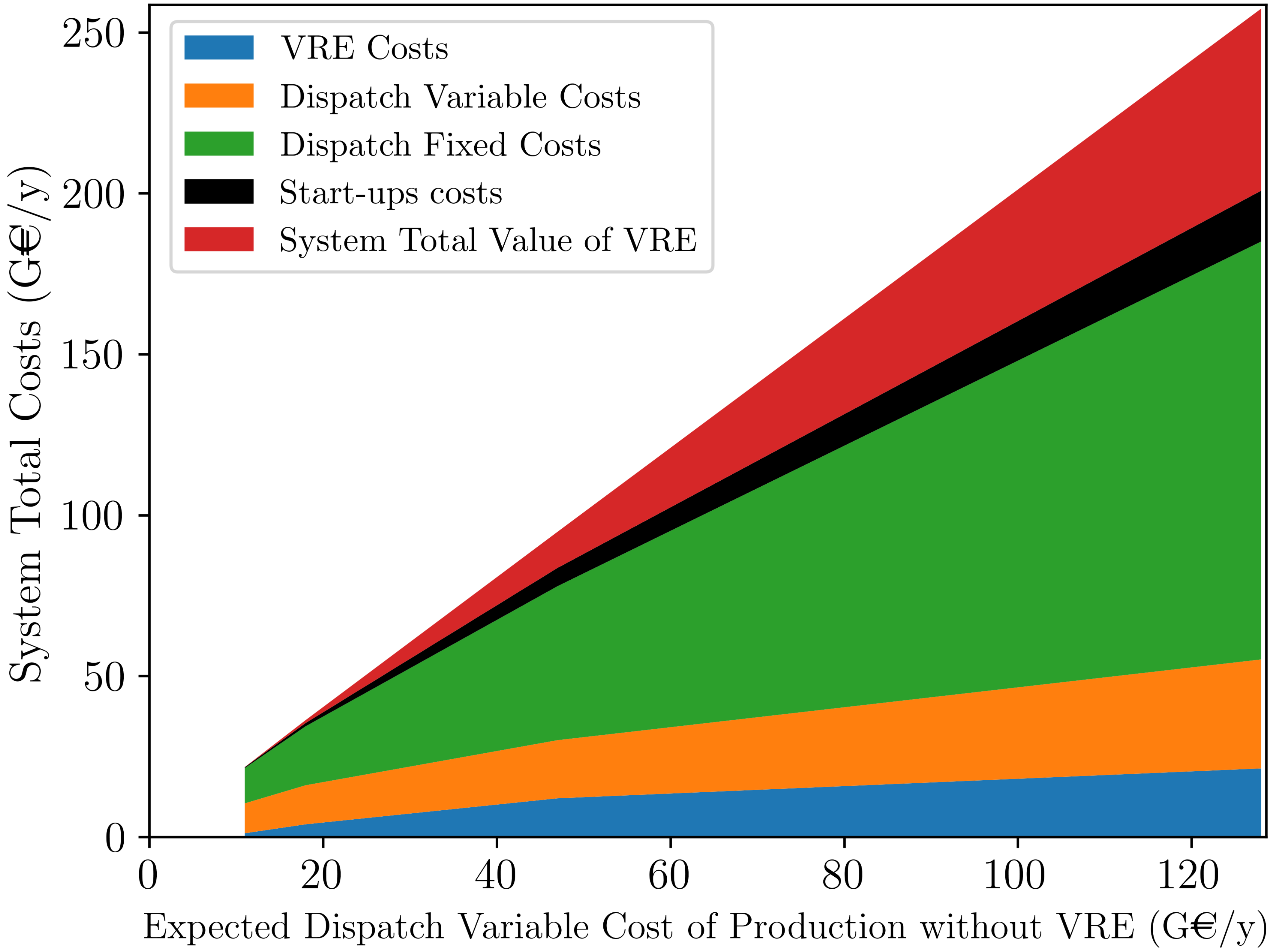

Mean
Min, Max
Number of Start-ups
Load points (GW)
0
50
100
150
200
250
300
350
0
20
40
60
80
100


Mean
Units
K_{SU}
0
1
2
3
4
5
6
7
8
Coal-SSC
Coal-LSC
Coal-SC
Gas-CC
Gas-LFCT
Gas-ADCT
Gas-Steam


Hourly Rental Cost (€/MW/h)
Load Points (GW)
100 Tech, 100 DUs
5 Tech, 100 DUs
5 Tech, 5 DUs
0
5
10
15
20
25
30
35
40
0
20
40
60
80
100


Variable Cost of Start ups for 100 DUs (M€/y)
Variable Cost of Start ups for 5 DUs (G€/y)
100 Tech, 100 DUs
5 Tech, 100 DUs
5 Tech, 5 DUs
0
25
50
75
100
125
150
175
200
0.0
0.5
1.0
1.5
2.0
0
20
40
60
80
100

$$\mathrm{STC}(\boldsymbol{x}, (\mathrm{G}(t))_{t\in\mathbb{T}_0}) := \mathrm{FC}_{\boldsymbol{x}} + \mathrm{FC}_{\mathrm{Di}} + \sum_{t=0}^{T_0-1} \mathrm{VCP}_{\mathrm{Di}}(\mathrm{G}(t))$$

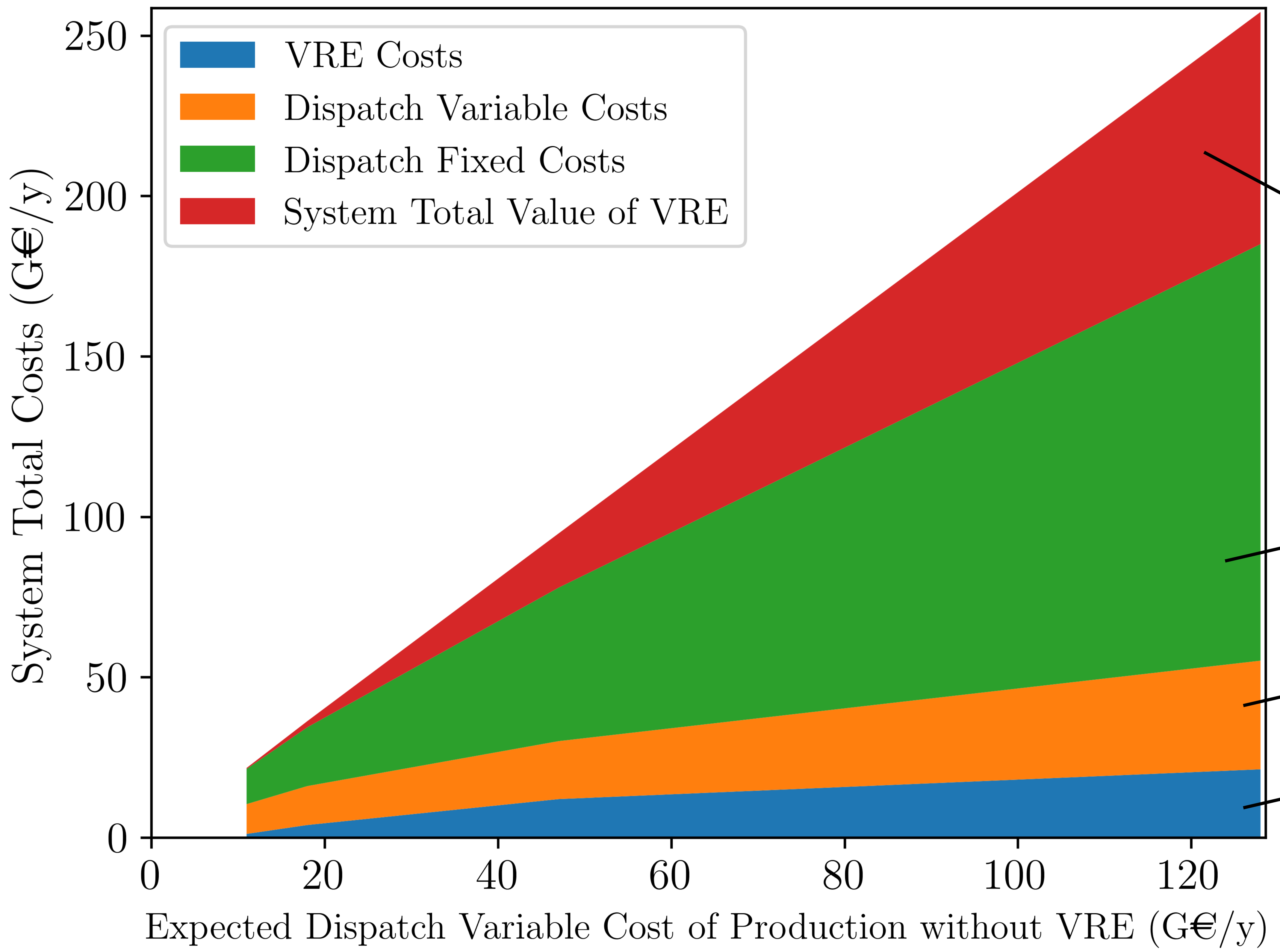


VRE Penetration (%)	20	50	80
VRE Value (%)	3	12	22
Start-up Costs (%)	**3**	**7**	**8**
FC Dispatch (%)	52	57	65
VC Dispatch (%)	34	22	17
FC VRE (%)	11	14	11

Decomposition of the System Total Cost (STC) for different level of VRE penetration

Materials and Methodology

e4clim model - STC



VRE Penetration (%)	20	50	80
VRE Value (%)	5.3	17.8	28.1
FC Dispatch (%)	53	64	70
VC Dispatch (%)	35	23	18
FC VRE (%)	11	15	12

Decomposition of the System Total Cost (STC) for different level of VRE penetration

Materials and Methodology

Flexibility costs data

Table 1-1: Typical lower bound costs of cycling and other data for various generation types

Unit Types	Coal - Small Sub Critical	Coal - Large Sub Critical	Coal - Super Critical	Gas - CC [GT+HRSG+ST]	Gas - Large Frame CT	Gas - Aero Derivative CT	Gas - Steam
Cost Item/							
Typical Hot Start Data							
-C&M cost ($/MW cap.)							
Median	94	59	54	35	32	19	36
~25th_centile	79	39	39	28	22	12	25
~75th_centile	131	68	63	56	47	61	42
-EFOR Impact							
Median	0.0086%	0.0057%	0.0037%	0.0025%	0.0020%	0.0073%	0.0029%
~25th_centile	0.0045%	0.0035%	0.0030%	0.0021%	0.0007%	0.0038%	0.0016%
~75th_centile	0.0099%	0.0082%	0.0065%	0.0070%	0.0142%	0.0186%	0.0060%
Typical Warm Start Data							
-C&M cost ($/MW cap.)							
Median	157	65	64	55	126	24	58
~25th_centile	112	55	54	32	26	12	36
~75th_centile	181	78	89	93	145	61	87
-EFOR Impact							
Median	0.0123%	0.0070%	0.0054%	0.0039%	0.0027%	0.0073%	0.0048%
~25th_centile	0.0058%	0.0041%	0.0037%	0.0023%	0.0007%	0.0038%	0.0026%
~75th_centile	0.0156%	0.0081%	0.0095%	0.0083%	0.0162%	0.0186%	0.0081%
Typical Cold Start Data							
-C&M cost ($/MW cap.)							
Median	147	105	104	79	103	32	75
~25th_centile	87	63	73	46	31	12	54
~75th_centile	286	124	120	101	118	61	89
-EFOR Impact							
Median	0.0106%	0.0088%	0.0088%	0.0055%	0.0035%	0.0088%	0.0060%
~25th_centile	0.0085%	0.0047%	0.0059%	0.0033%	0.0007%	0.0038%	0.0043%
~75th_centile	0.0163%	0.0150%	0.0101%	0.0088%	0.0116%	0.0195%	0.0123%
Startup Time (hours)							
-Typical (Warm Start Offline Hours)	4 to 24	12 to 40	12 to 72	5 to 40 (ST Different)	2 to 3	0 to 1	4 to 48

We assume all start-ups are hot.

Results

Start-ups costs - Producers