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# Addressing supply risks in energy system models with multi-objective optimisation

**Jonas Finke**, Gianvito Colucci, Laura Savoldi, Valeria Di Cosmo, Valentin Bertsch

Ruhr-Universität Bochum | jonas.finke@rub.de
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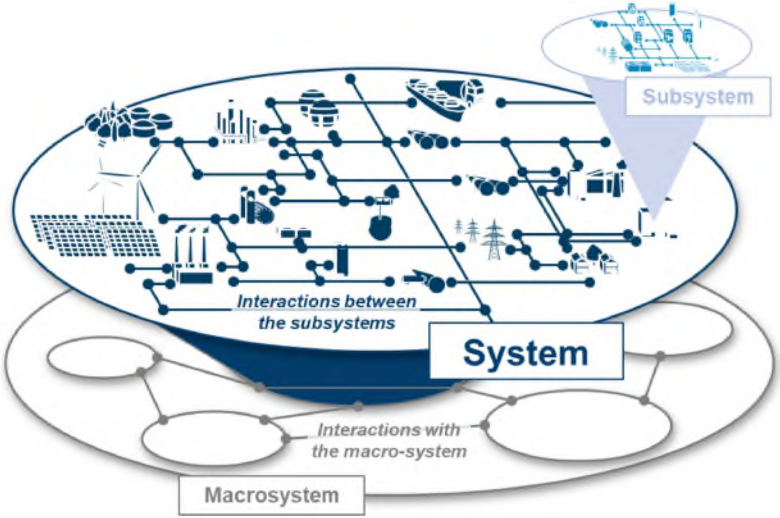
# Why is it relevant?



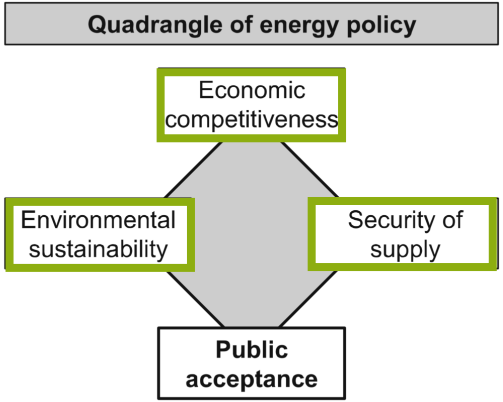
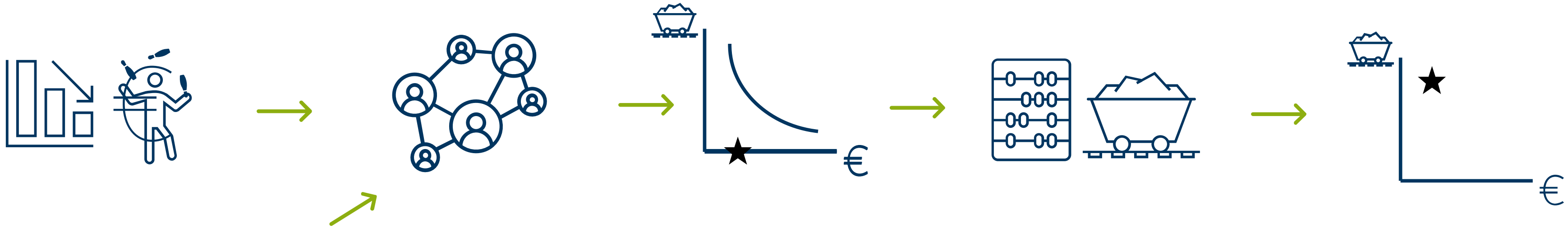






Figure (left) taken from Kotzur et al. *A modeler's guide to handle complexity in energy systems optimization*, Advances in Applied Energy 2021. https://doi.org/10.1016/j.adapen.2021.100063
Figure (right) taken from Betsch and Fichtner, *A participatory multi-criteria approach for power generation and transmission planning*, Ann Oper Res 2016. https://doi.org/10.1007/s10479-015-1791-y

# How is it done?



# Material and energy supply risk metrics

# Material supply risk metric

Input data for model

$$SR_M(-) = \sum_{p=y_{start}}^{y_{end}} \sum_{t=1}^{N_{tech}} SR_t\left(\frac{1}{cap}\right) V\_Capacity_{t,p}\,(cap)$$

Supply risk for technology t

Decision variable for capacity investment

$$SR_t\left(\frac{1}{cap}\right) = \sum_{m=1}^{N_{mat}^{tech}} \frac{f_{m,t}\left(\frac{t}{cap}\right)}{cons_m^{yref}(t)} SR_m(-)$$

Supply risk for material m

$$SR_m(-) = f\left(HHI_m\,(-), IR_m\,(-)\right)$$

Herfindahl-Hirschman-Index for material m

Import reliance for material m

$$HHI_m(-) = \sum_{c=1}^{N_{countries}^{mat}} g_c(-) \cdot S_{c,m}^2(-)$$

$$IR_m(-) = \frac{NetImport_m(t)}{DomProd_m(t) + NetImport_m(t)}$$



This case study is based on Colucci, G., Finke, J., Di Cosmo, V., Bertsch, V., Savoldi, L. *Combined assessment of material and energy supply risks in the energy transition: a multi-objective energy system optimization approach* (Under review)

# Energy supply risk metric

Decision variables for net energy import

$$SR_E(-) = \sum_{p=y_{start}}^{y_{end}} \sum_{e=1}^{N_{en}} HHI_e(-) \cdot \frac{\left(V\_flow_{e,p}^{import}(PJ) - V\_flow_{e,p}^{export}(PJ)\right)}{cons_{energy}^{yref}(PJ)}$$

Input data for model



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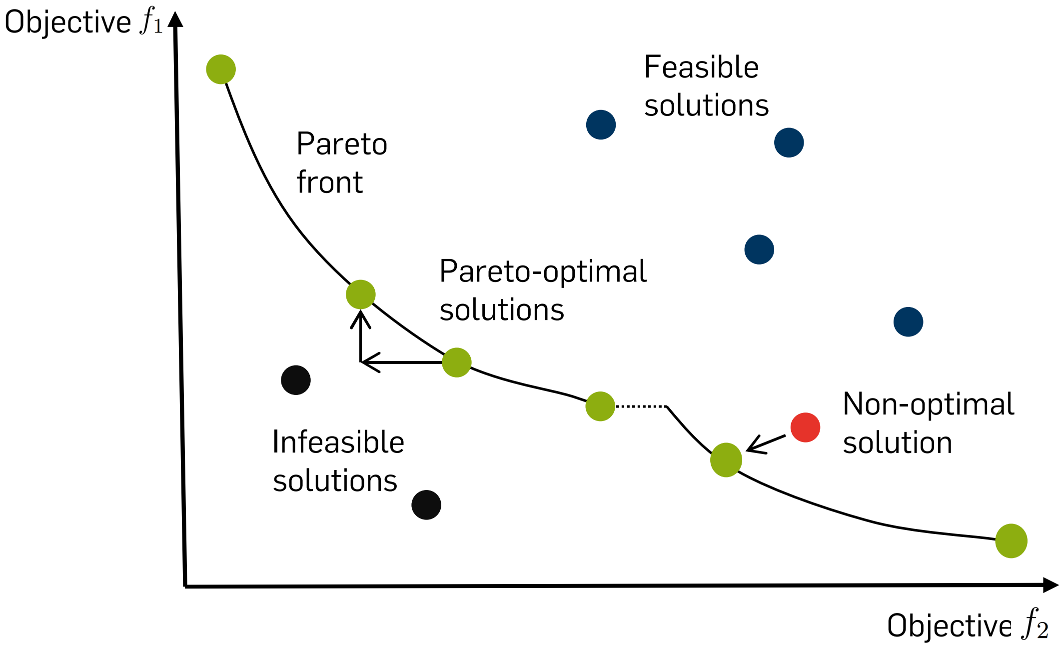
# Multi-objective optimisation method

# Multi-objective optimisation with AUGMECON

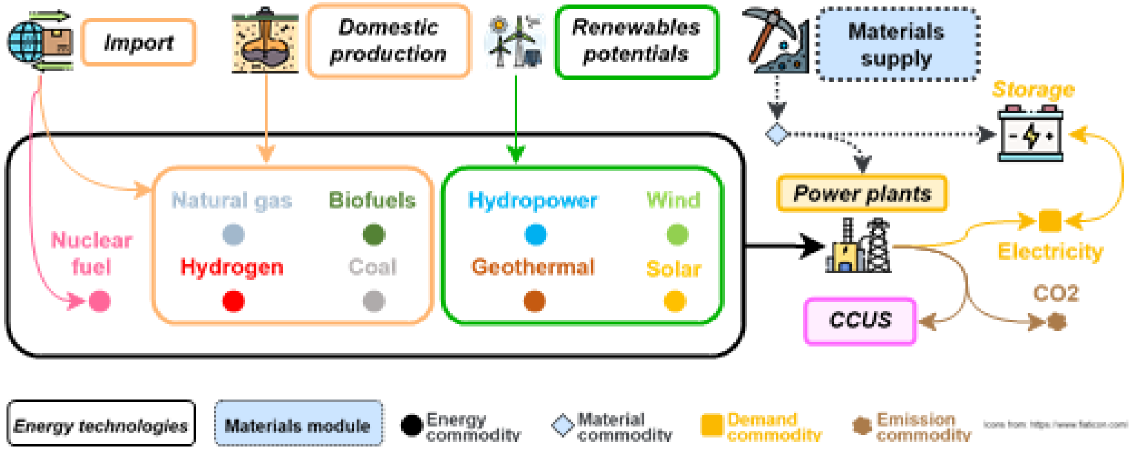





AUGMECON is developed by Mavrotas, *Effective implementation of the epsilon-constraint method in Multi-Objective Mathematical Programming problems*, Applied Mathematics and Computation 2009. https://doi.org/10.1016/j.amc.2009.03.037

# Energy system model

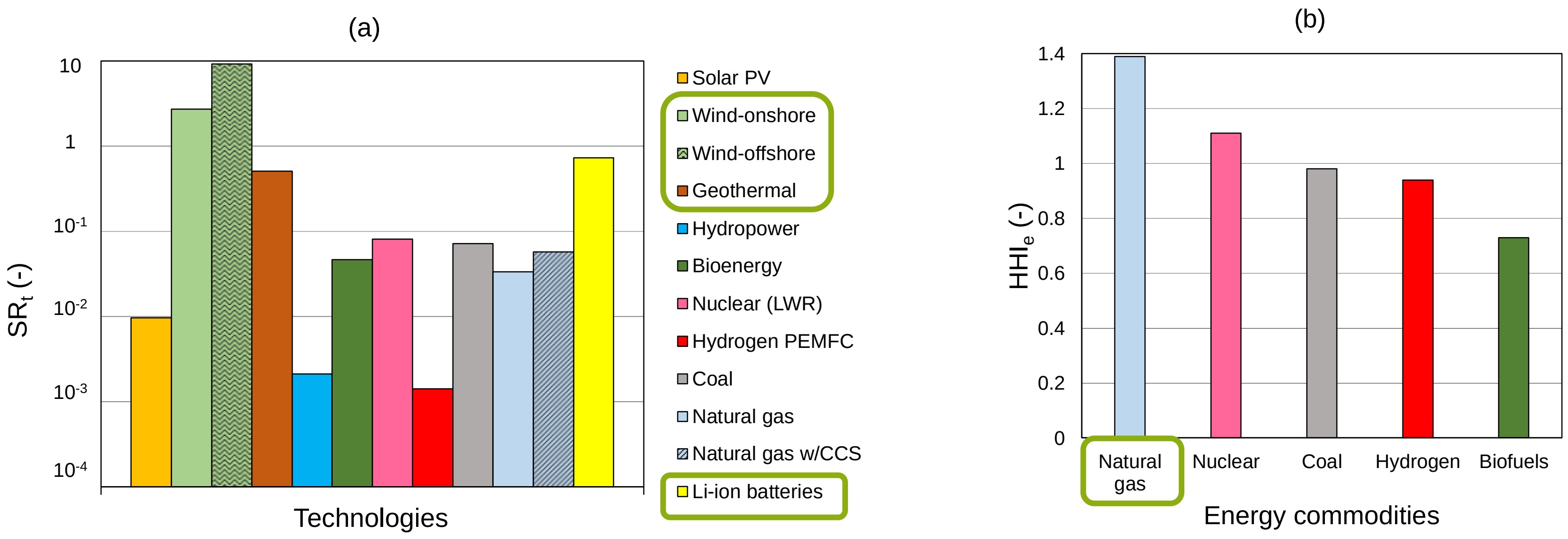
# TEMOA Italy power sector model




Openly available at
https://github.com/MAHTEP/TEMOA/tree/moo
https://github.com/MAHTEP/TEMOA-Italy/tree/materials


TEMOA Italy is developed by Nicoli et al. (2022) *Can We Rely on Open-Source Energy System Optimization Models? The TEMOA-Italy Case Study.* Energies 15(18). https://doi.org/10.3390/en15186505

# Supply risks for individual power sector technologies and energy carriers in Italy

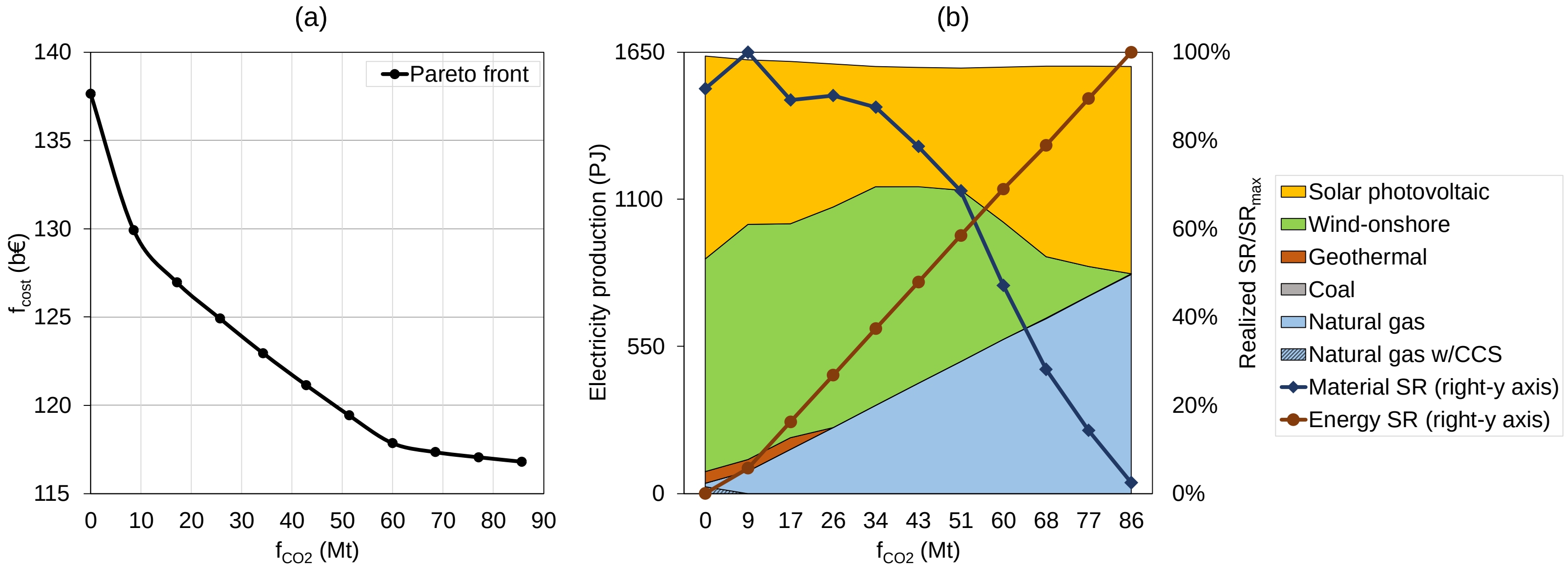





This case study is based on Colucci, G., Finke, J., Di Cosmo, V., Bertsch, V., Savoldi, L. *Combined assessment of material and energy supply risks in the energy transition: a multi-objective energy system optimization approach* (Under review)

# Results

# Cost-efficient decarbonisation leads to uncontrolled rise of material supply risk



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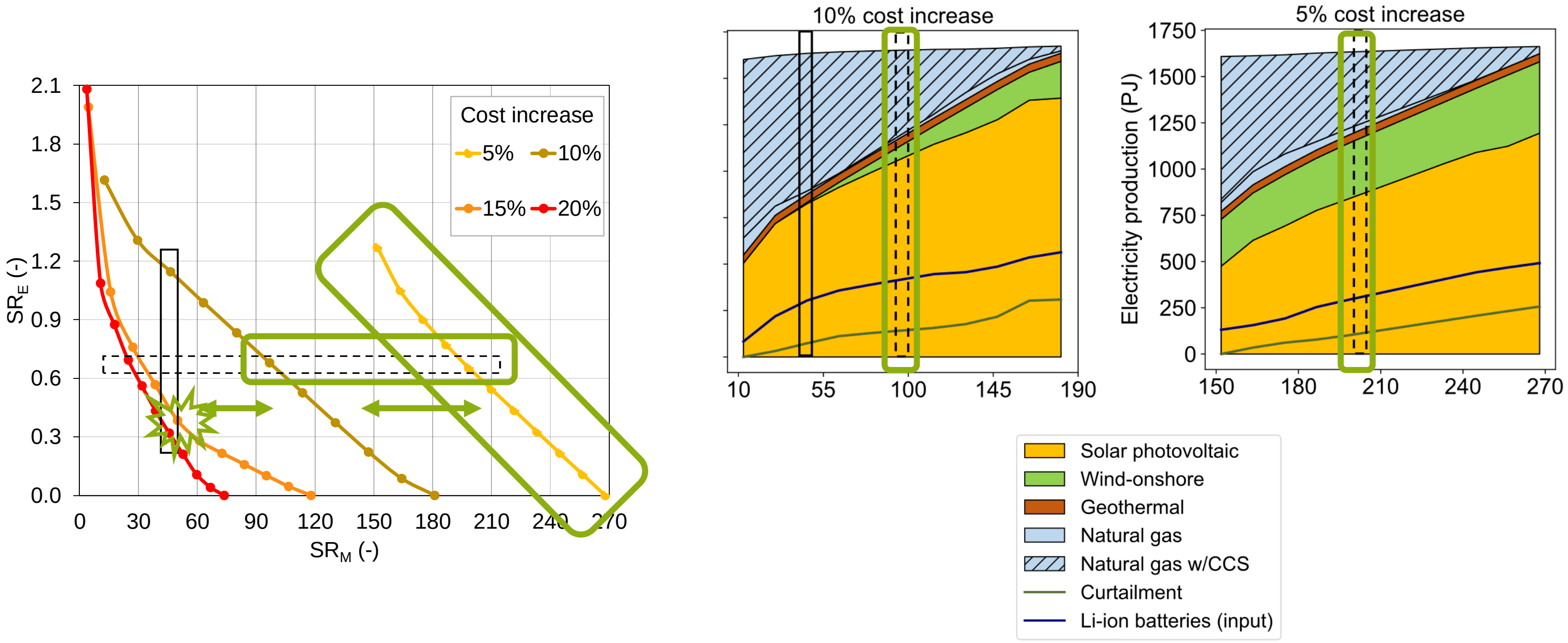
# Multi-objective optimisation of energy and material supply risk under cost and emission constraints






This case study is based on Colucci, G., Finke, J., Di Cosmo, V., Bertsch, V., Savoldi, L. *Combined assessment of material and energy supply risks in the energy transition: a multi-objective energy system optimization approach* (Under review)

# Discussion

# Limitations

- Power sector only, but extension would be big effort in terms of data
- Static material and energy supply, but demand may affect supply for larger systems
- Supply risks only at material and energy level, but import of manufactured appliances / technologies may also induce supply risks
- No constraints on CCS availability, which may be limited technically or politically
- Usual model limitations (temporal, geographical and technical details)

# Conclusions

- Developed a first-of-a-kind energy system optimisation framework based on TEMOA
  - Endogenous material and energy supply risk metrics
  - Multi-objective optimisation with AUGMECON
  - Open-source: https://github.com/MAHTEP/

- Italian power sector case study
  - Decarbonisation and energy supply risk reduction coincide (both driven by natural gas)
  - Material supply risk rises sharply with cost-efficient decarbonisation due to wind and LIBs
  - Under decarbonisation, reducing material supply risk shifts wind to PV to gas w/CCS
  - Diminishing marginal utility of extra cost (supply risk reductions until 15%)

- May need supply risk reductions by new / diversified supply chains, domestic production or new energy technologies

# Thank you!

**Jonas Finke**
Chair of Energy Systems and Energy Economics | Ruhr-Universität Bochum
jonas.finke@rub.de

# Backup

Table 1. Data and sources of the parameters needed to define the material SR metric. Concerning $SR_m$, two values for each material are reported. The one adopted in the manuscript is reported in the column "Equation (1)". It was derived from the EU CRMs list [10], the value of which is reported in the column "EU", by omitting the recycling and substitution factors. Indeed, they were neglected for consistency reasons with the energy SR metric.

| **Material** | $SR_m(-)$ [10] | | $cons_m^{yref}$ $(Mt)$ [75] | $f_{m,t}$ $(\frac{t}{GW})$ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | EU | Equation (1) | | *Solar PV* [39], [6] | *Wind* [39], [6] Onshore | Offshore | *Geothermal* [6], [76] | *Hydropower* [6], [56] | *Bioenergy* [6], [56] | *Nuclear (LWR)* [6], [76] | *Hydrogen PEMFC* [34], [77], [78], [79], [80], [81] | *Coal* [6], [76] | *Natural gas* [76], [81] w/o CCS | w/ CCS | *Li-ion batteries* [76] |
| *Aluminum* | 1.2 | 2.1 | $1.6 \cdot 10^{1}$ | 6750.0 | 901.4 | 478.8 | | 3400.0 | 3900.0 | | | | 4.8 | 4.8 | 5796.0 |
| *Boron* | 3.6 | 3.7 | $1.9 \cdot 10^{-2}$ | | 0.1 | 0.5 | | | | | | | | | |
| *Cobalt* | 2.8 | 3.7 | $1.1 \cdot 10^{-2}$ | | | | | | 2.0 | | | 201.5 | 71.1 | 78.6 | 720.0 |
| *Copper* | 0.1 | 0.3 | 2.1 | 4150.1 | 1292.4 | 1938.6 | 3605.0 | 1050.0 | 2270.0 | 764.8 | 14.3 | 1150.0 | 355.4 | 1047.4 | 2616.0 |
| *Dysprosium (HREE)* | 5.6 | 5.7 | $1.1 \cdot 10^{-6}$ | | 0.5 | 1.6 | | | | | | | | | |
| *Gallium* | 3.9 | 4.0 | $3.3 \cdot 10^{-5}$ | $1.5 \cdot 10^{-2}$ | | | | | | | | | | | |
| *Hafnium* | 1.5 | 1.6 | $1.1 \cdot 10^{-5}$ | | | | | | | 0.5 | | | | | |
| *Lithium* | 1.9 | 2.0 | $1.8 \cdot 10^{-3}$ | | | | | | | | | | | | 438.0 |
| *Manganese* | 1.2 | 1.3 | $2.7 \cdot 10^{-1}$ | | 564.5 | 569.9 | 4325.0 | 200.0 | | | | 4.6 | 24.1 | 3785.1 | 660.0 |
| *Neodymium (LREE)* | 4.5 | 4.6 | $1.2 \cdot 10^{-4}$ | | 4.1 | 16.3 | | | | | | | | | |
| *Nickel* | 0.5 | 0.6 | $2.6 \cdot 10^{-1}$ | | 287.3 | 194.4 | 120155.0 | 215.0 | 20.0 | 778.0 | | 721.5 | 29.2 | 1174.2 | 2160.0 |
| *Niobium* | 4.4 | 4.6 | $2.8 \cdot 10^{-3}$ | | | | | | | | | | 5.3 | 5.3 | |
| *Phosphorus* | 3.3 | 3.4 | $7.4 \cdot 10^{-2}$ | | | | | | | | | | 0.9 | 0.9 | |
| *Platinum* | 2.1 | 2.5 | $7.2 \cdot 10^{-5}$ | | | | | | | | $4.0 \cdot 10^{-2}$ | | | | |
| *Praseodymium (LREE)* | 3.2 | 3.3 | $1.1 \cdot 10^{-4}$ | | 0.6 | 3.1 | | | | | | | | | |
| *Silicon* | 1.4 | 1.4 | $4.2 \cdot 10^{-1}$ | 1900.0 | | | | | | | | | 17.3 | 17.3 | |
| *Terbium (HREE)* | 4.9 | 5.4 | $5.9 \cdot 10^{-6}$ | | 0.1 | 0.6 | | | | | | | | | |
| *Titanium* | 1.6 | 1.6 | $1.4 \cdot 10^{-2}$ | | | | 1634.0 | | 400.0 | 1.5 | | 23.0 | 4.8 | 4.8 | |
| *Vanadium* | 2.3 | 2.7 | $4.4 \cdot 10^{-3}$ | | | | | | | 0.6 | | | 8.2 | 8.2 | |
| *Yttrium (HREE)* | 3.5 | 3.9 | $2.2 \cdot 10^{-4}$ | | | | | | | 0.5 | | | | | |

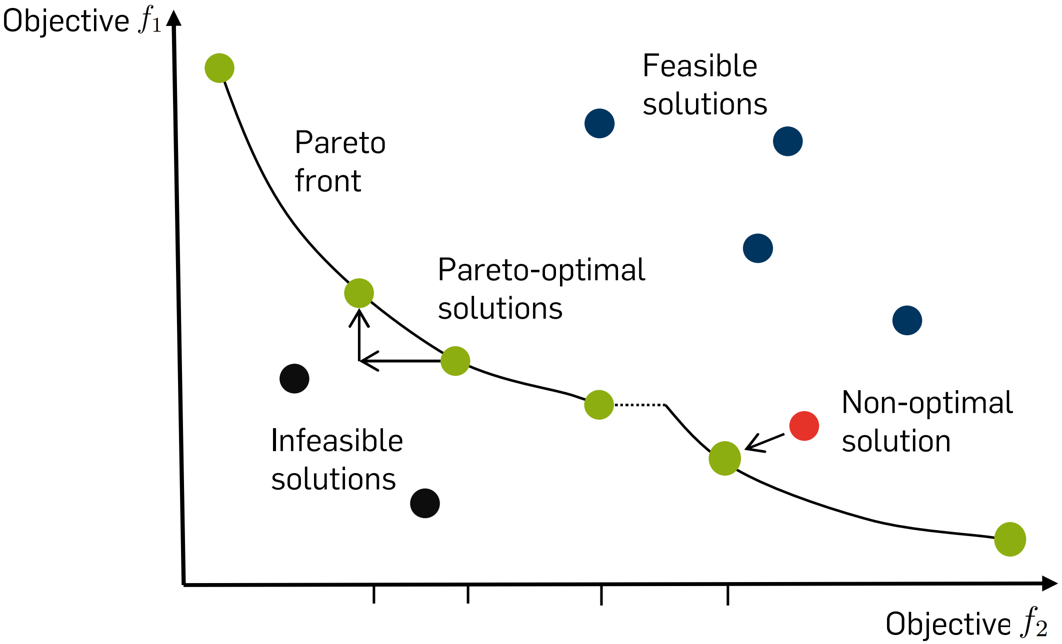
Table 2. Sub-technological shares adopted to derive a generic $SR_t^{st}$ for solar PV and onshore and offshore wind (the latter shares are in parenthesis).

| **Technology** | **Sub-technology** | **2050 share** [6] |
|---|---|---|
| **Solar PV** | *c-Si* | 95% |
| | *CdTe* | 4% |
| | *CIGS* | 1% |
| **Wind-onshore (offshore)** | *GB-PMSG* | 10% (15%) |
| | *GB-DFIG* | 70% (15%) |
| | *DD-EESG* | 6% (0%) |
| | *DD-PMSG* | 14% (85%) |

Table 3. Data and sources of the parameters needed to define the energy SR metric. Although only the top three supplier countries are shown, all supplier countries are used to derive the $HHI_e$. Moreover, note that a high value for $g_c$ refers to a low stability while a low $g_c$ value refers to a high stability.

| **Energy commodities** | **Geographical scope** | **Top three supplier countries** | $S_{c,e}$ | $g_c(-)$ [74] | $HHI_e$ (−) |
|---|---|---|---|---|---|
| *Natural gas* | Italy [85] | Algeria | 37.0% | 6.72 | 1.39 |
| | | Russia | 20.2% | 6.29 | |
| | | Azerbaijan | 14.6% | 6.39 | |
| *Coal* | Italy [86] | Russia | 32.8% | 6.29 | 0.98 |
| | | South Africa | 18.2% | 4.69 | |
| | | United States | 13.0% | 2.68 | |
| *Nuclear* | EU [87] | Kazakhstan | 27.0% | 5.72 | 1.11 |
| | | Niger | 25.4% | 6.50 | |
| | | Canada | 22.0% | 1.79 | |
| *Hydrogen* | EU [89] | Australia | 59.7% | 1.92 | 0.94 |
| | | Brazil | 15.0% | 5.40 | |
| | | Chile | 15.0% | 3.08 | |
| *Biofuels* | Global [91] | United States | 38.1% | 2.68 | 0.73 |
| | | Brazil | 21.8% | 5.40 | |
| | | Indonesia | 10.5% | 5.32 | |

# Multi-objective optimisation with AUGMECON




Slack variable

$$\min\,(f_1 - s) \quad \text{s.t.} \quad f_2 + s = \epsilon$$

Objective 1

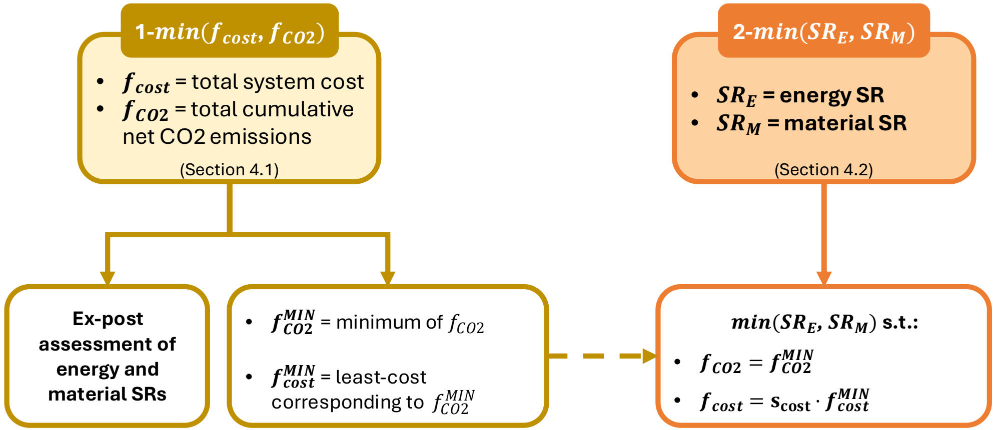
Objective 2

Caps

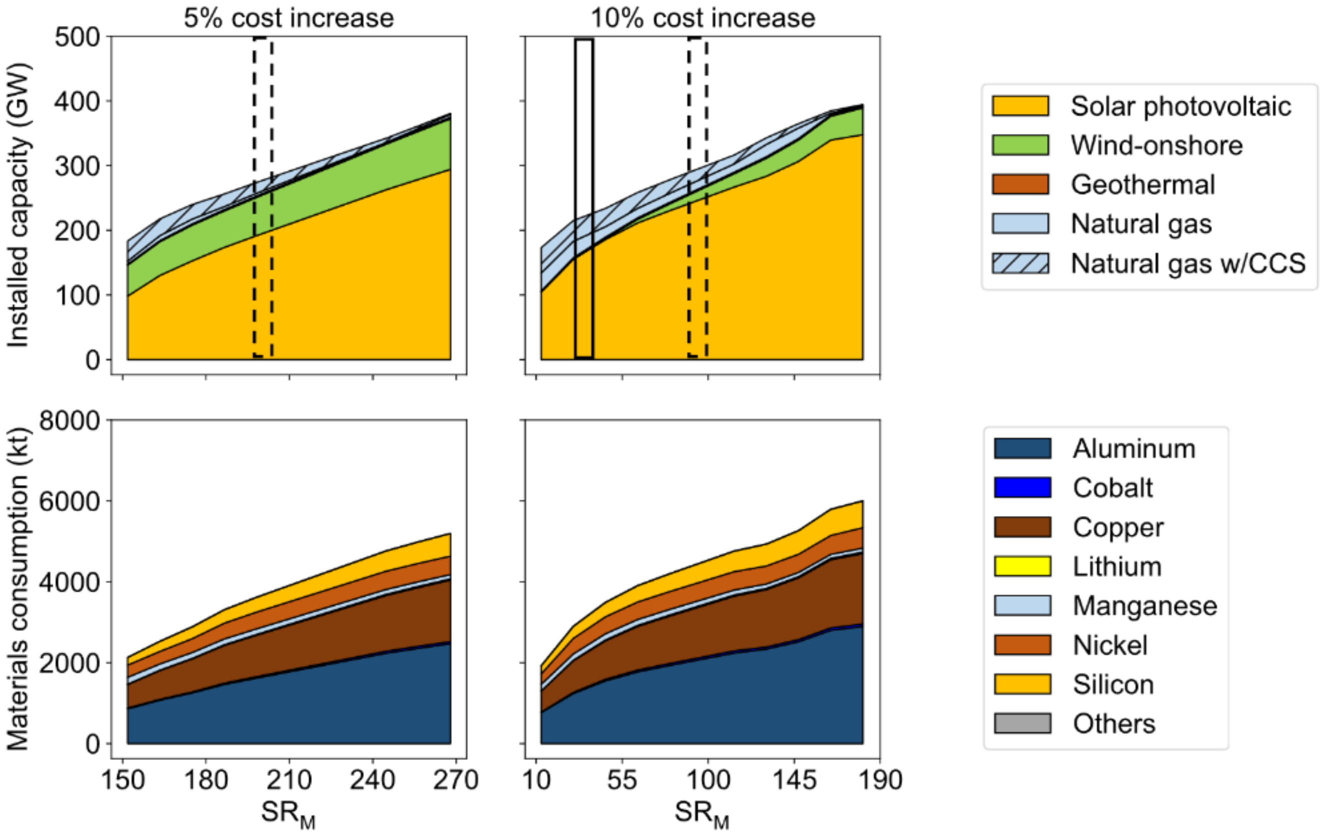
1. Determine boundaries
2. Decide on desired number and distribution of solutions (→ caps)
3. Solve above problem for each cap



AUGMECON is developed by Mavrotas, *Effective implementation of the epsilon-constraint method in Multi-Objective Mathematical Programming problems*, Applied Mathematics and Computation 2009. https://doi.org/10.1016/j.amc.2009.03.037



1-$min(f_{cost}, f_{CO2})$
$f_{cost}$ = total system cost
$f_{CO2}$ = total cumulative net CO2 emissions
(Section 4.1)
2-$min(SR_E, SR_M)$
$SR_E$ = energy SR
$SR_M$ = material SR
(Section 4.2)
Ex-post assessment of energy and material SRs
$f_{CO2}^{MIN}$ = minimum of $f_{CO2}$
$f_{cost}^{MIN}$ = least-cost corresponding to $f_{CO2}^{MIN}$
$min(SR_E, SR_M)$ s.t.:
$f_{CO2} = f_{CO2}^{MIN}$
$f_{cost} = s_{cost} \cdot f_{cost}^{MIN}$



5% cost increase
10% cost increase
Installed capacity (GW)
500
400
300
200
100
0
Solar photovoltaic
Wind-onshore
Geothermal
Natural gas
Natural gas w/CCS
Materials consumption (kt)
8000
6000
4000
2000
0
150
180
210
240
270
SR$_M$
10
55
100
145
190
SR$_M$
Aluminum
Cobalt
Copper
Lithium
Manganese
Nickel
Silicon
Others