The impact of a Dunkelflaute event on the planning of a decarbonized energy system

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What are we doing in this paper?

- Energy systems, currently mostly depending on fossil fuels, will need to rely on an increasingly significant proportion of decarbonized energy sources.
  - In global climate mitigation scenarios, electricity is poised to become the main energy carrier by 2050 (PV/Windmills mainly in many countries)

→We analyse the following challenge for such future energy systems:

prolonged periods when **wind and photovoltaic** productions **decrease sharply and simultaneously** (the so-called ***Dunkelflaute periods***)

- It is **crucial to consider** the impacts of Dunkelflaute events **when planning the future energy system**. We must thus **add this consideration in energy system planning models**!
  - Energy system models are often used by national energy planners to design a least-cost long-term pathway to meet a policy target. These models have detailed representations of interconnected energy sectors and include the power sector.
  - However**, only very few studies include "such events"** in a planning model!

  →We aim to fill this gap

  →We do it for the **Belgium** case, analysing the impacts on the **transition towards 2050**

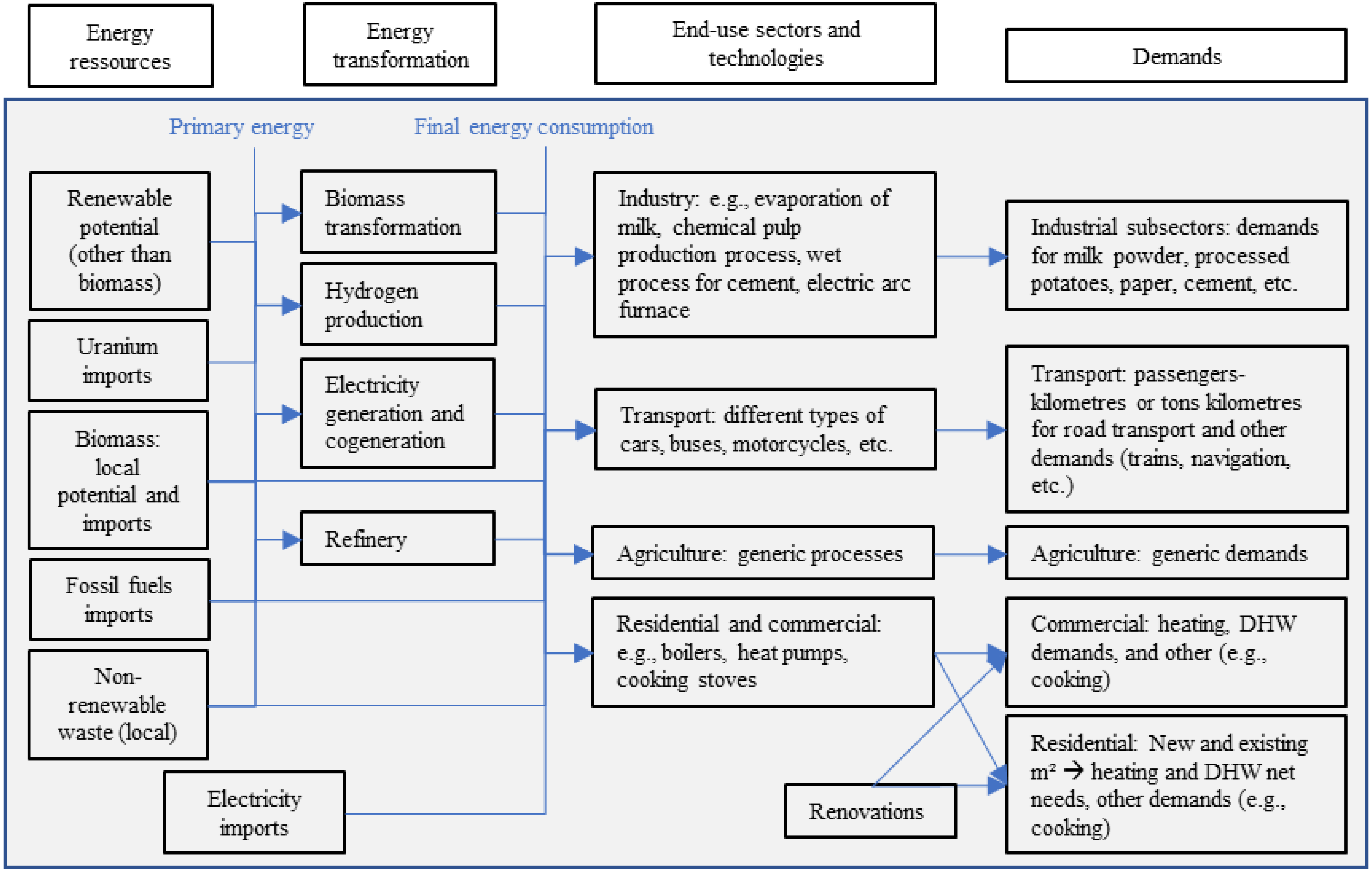
How we do it

First, we need an energy system model:

→ New energy system model with unprecedented spatial resolution over Belgium (**TIB3R**) based on the **TIMES modelling framework**

TIB3R

- Structure of the model :



Energy ressources

Energy transformation

End-use sectors and technologies

Demands

Primary energy

Final energy consumption

Renewable potential (other than biomass)

Uranium imports

Biomass: local potential and imports

Fossil fuels imports

Non-renewable waste (local)

Electricity imports

Biomass transformation

Hydrogen production

Electricity generation and cogeneration

Refinery

Industry: e.g., evaporation of milk, chemical pulp production process, wet process for cement, electric arc furnace

Transport: different types of cars, buses, motorcycles, etc.

Agriculture: generic processes

Residential and commercial: e.g., boilers, heat pumps, cooking stoves

Renovations

Industrial subsectors: demands for milk powder, processed potatoes, paper, cement, etc.

Transport: passengers-kilometres or tons kilometres for road transport and other demands (trains, navigation, etc.)

Agriculture: generic demands

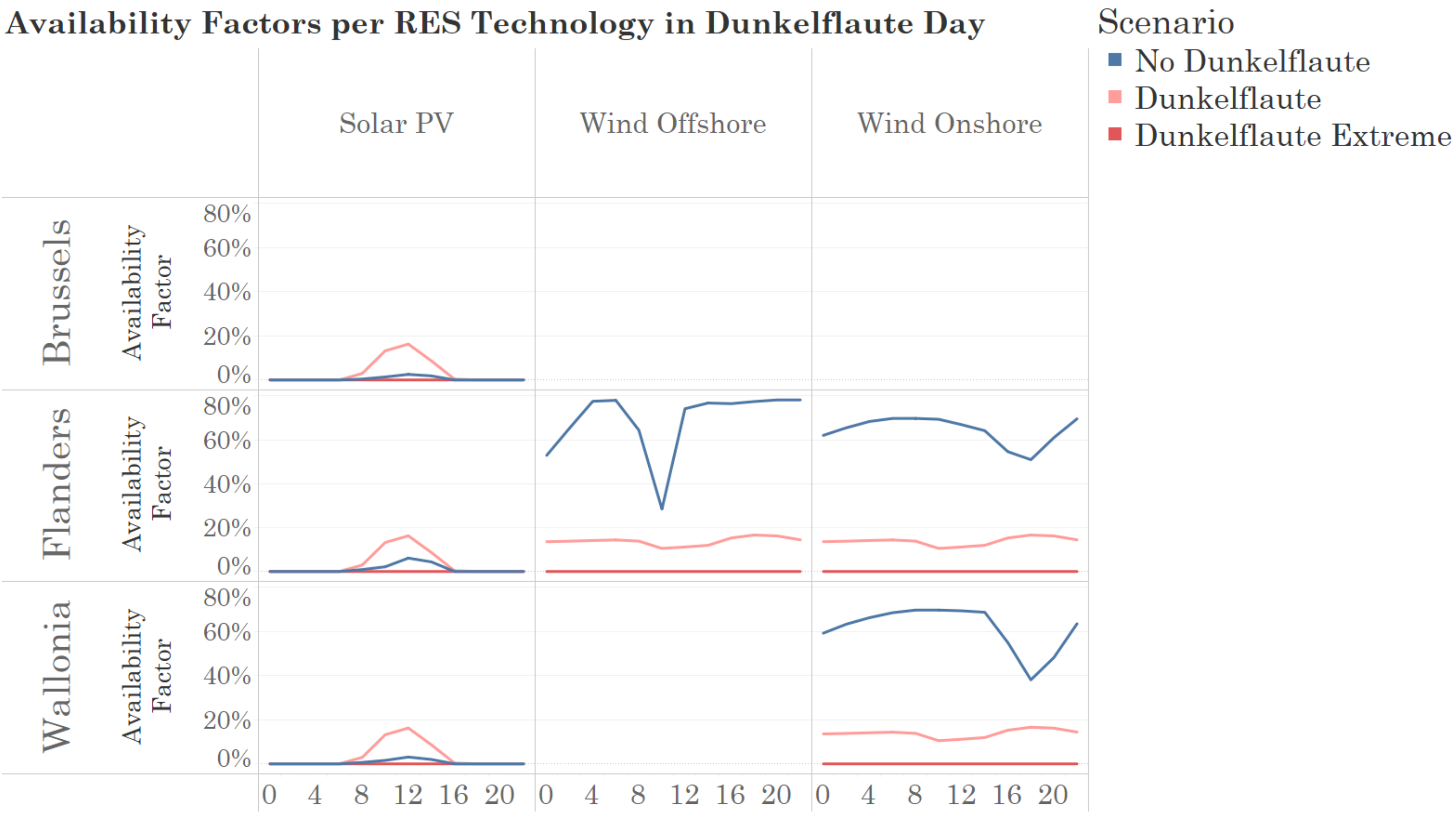
Commercial: heating, DHW demands, and other (e.g., cooking)

Residential: New and existing m² → heating and DHW net needs, other demands (e.g., cooking)

How we do it

Second, we need data on Dunkelflaute periods in Belgium:

- We use recent data on temperature, solar radiation and wind speed
- Dunkelflautes are then defined as the “**worst events of 3 weeks**” (1-event-per-30-years)



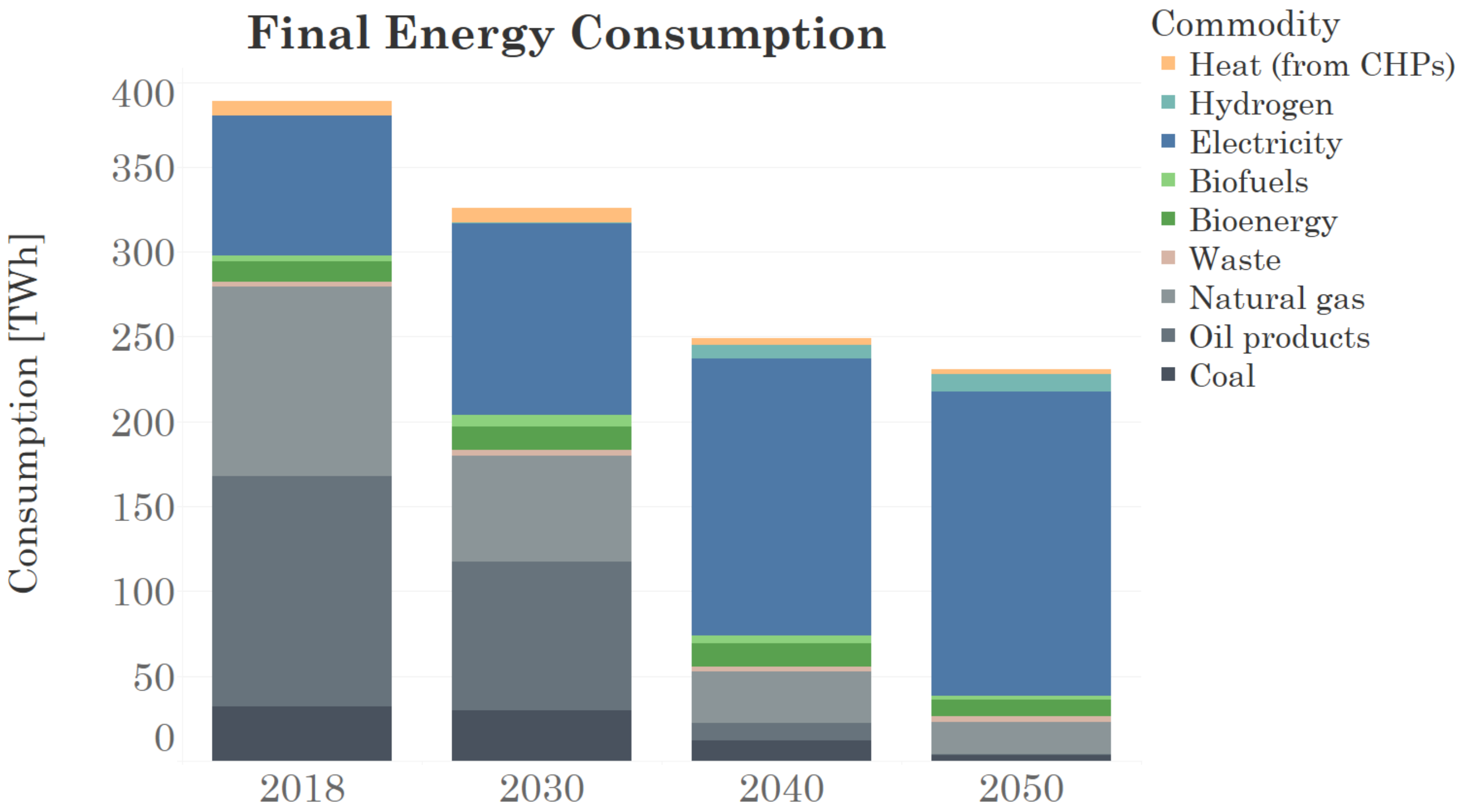
How we do it

- Third, we run 6 carbon-neutral scenarios (with the TIB3R model) to analyse possible pathways :

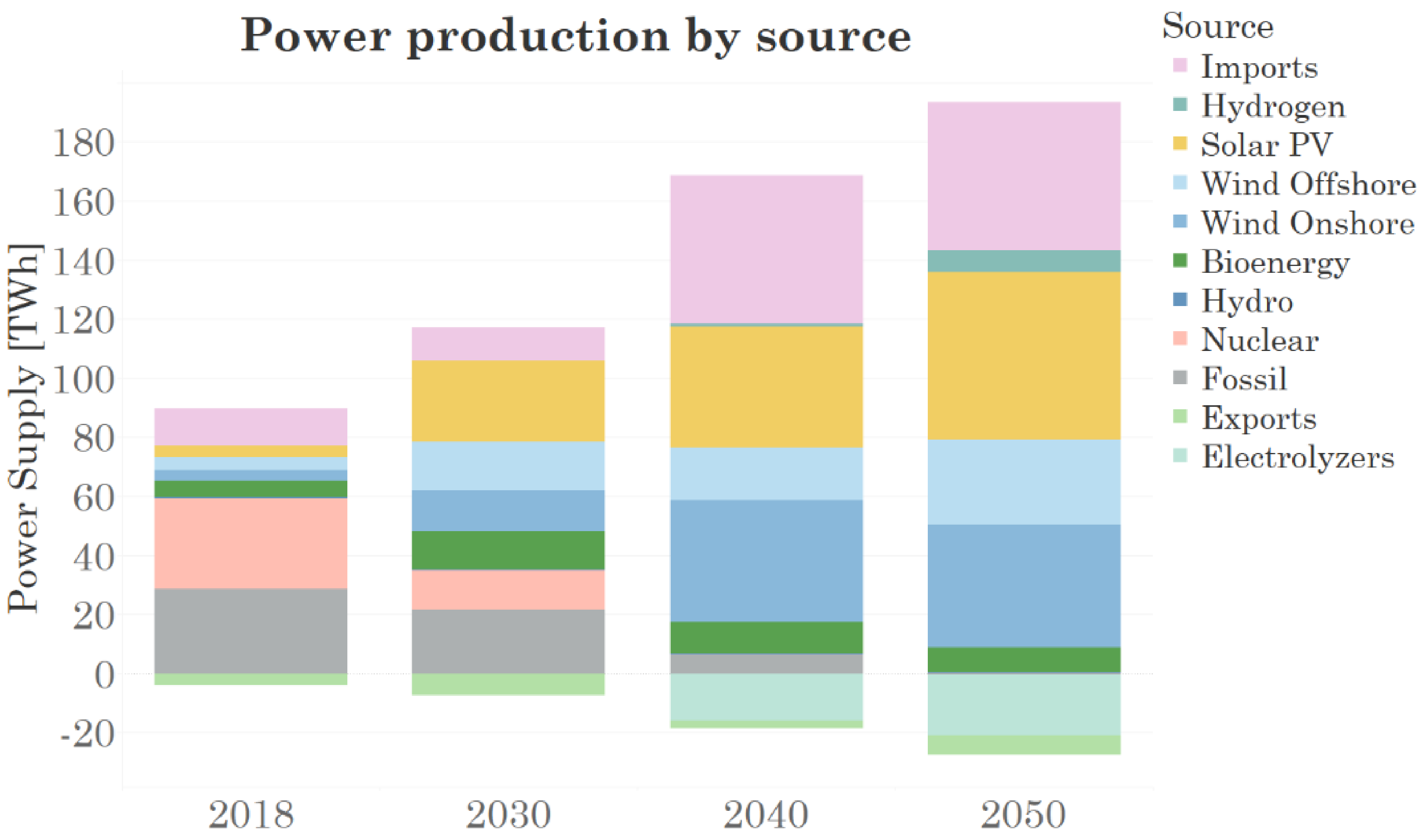
	Environmental Policy assumptions: carbon tax (up to 350€/t in 2050) and target of 2 Mt CO2 emissions in 2050	
	Nuclear SMR not available	Nuclear SMR available from 2045
No Dunkelflaute event	“Central” Scenario	“Nuclear” Scenario
Dunkelflaute event:	“Dunkelflaute” Scenario	“Nuclear Dunkelflaute” Scenario (or “Nucl. + DF”)
Extreme Dunkelflaute event:	“Dunkelflaute Extreme” Scenario (or “DF Extreme”)	“Nuclear Dunkelflaute Extreme” Scenario (or “Nucl. + DF Extr. ”)

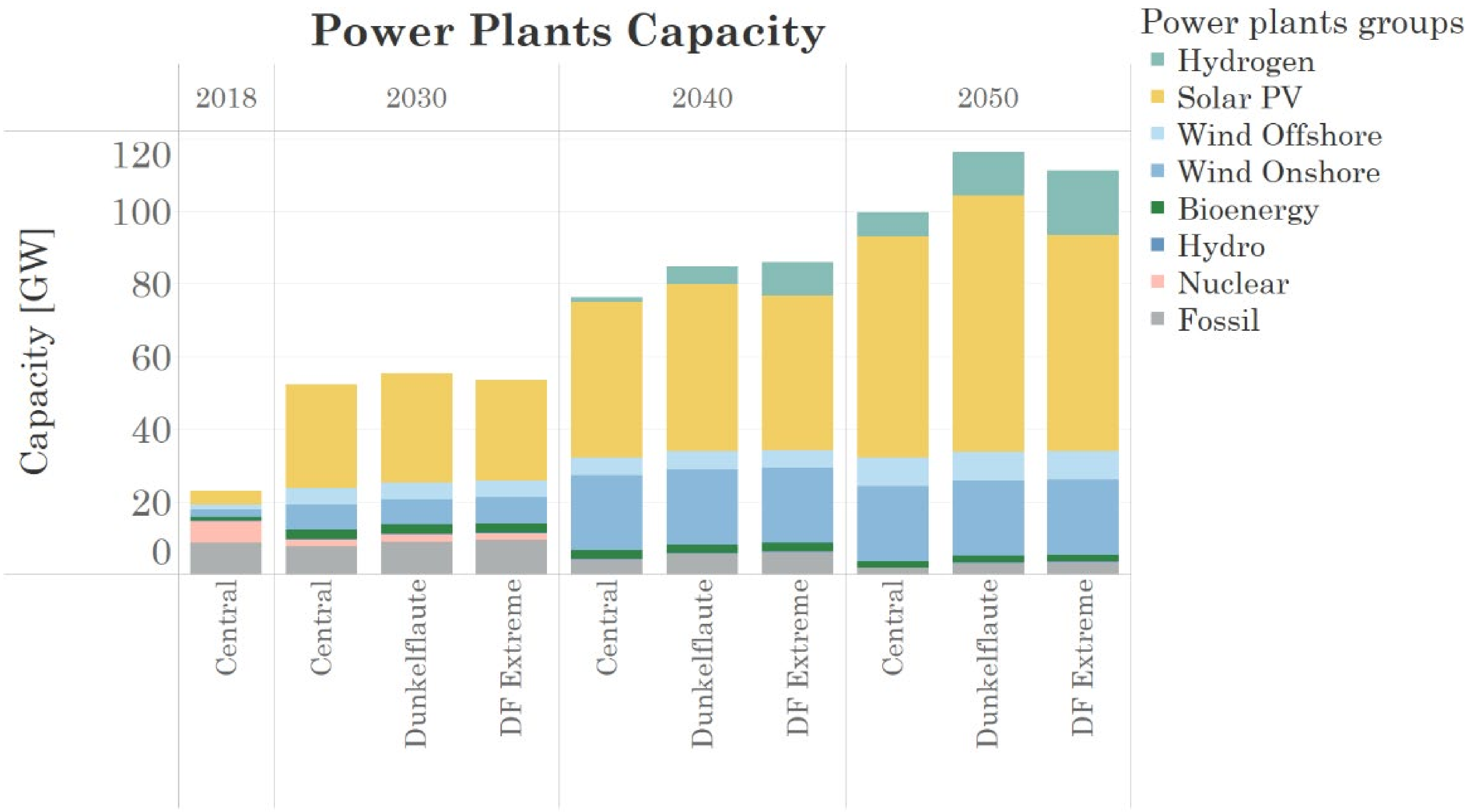
+ one BAU scenario without carbon neutrality

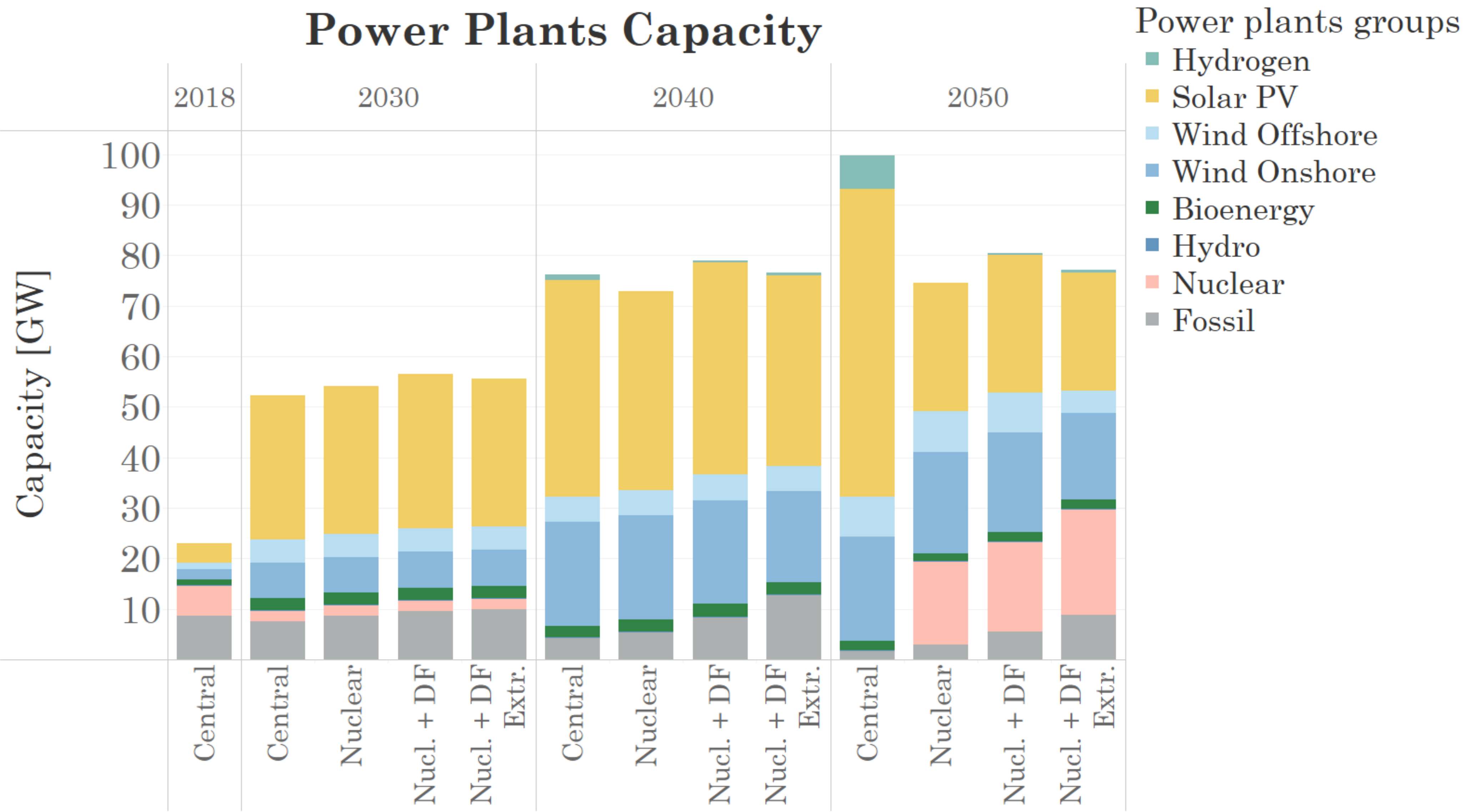
Results

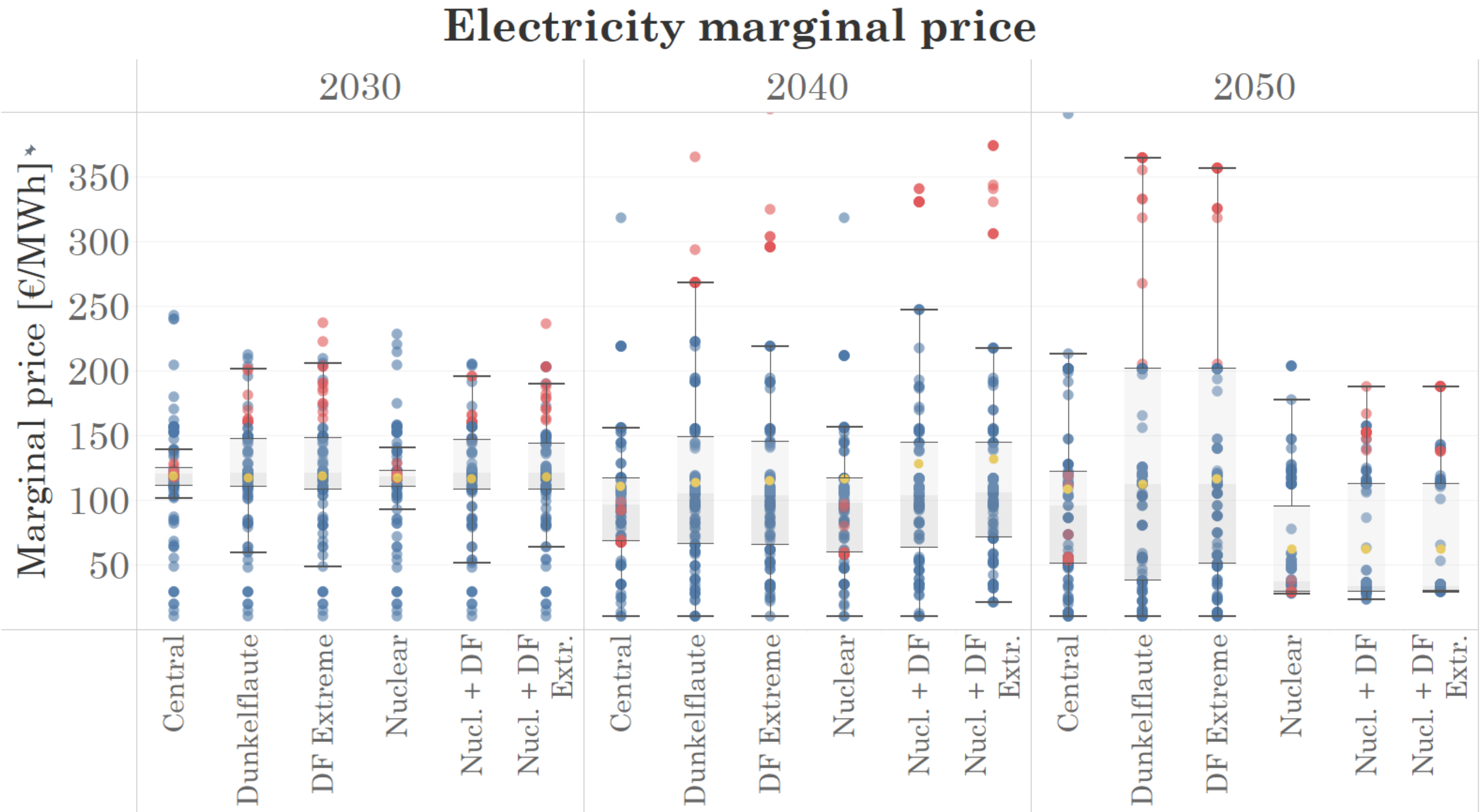


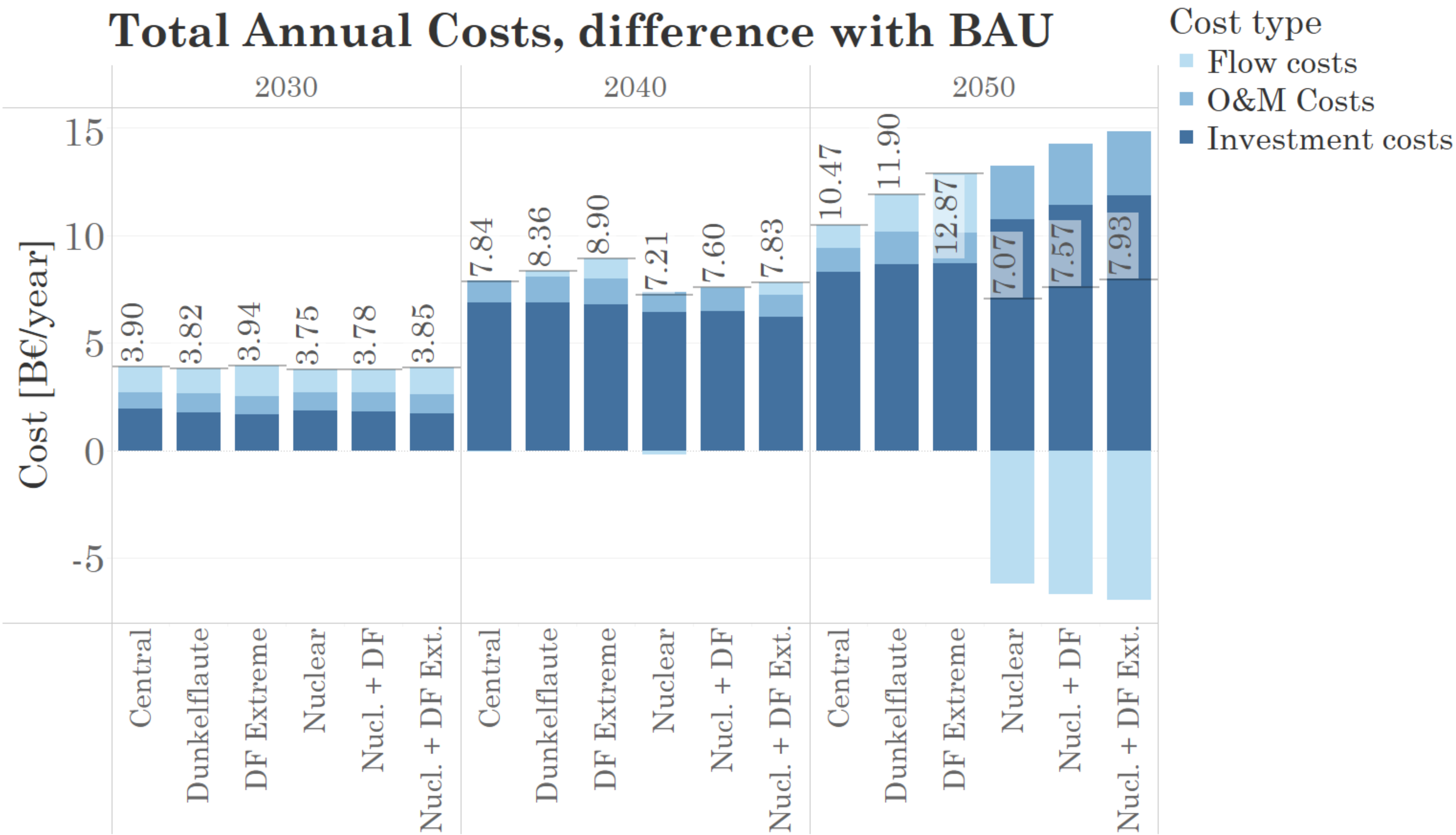
Final Energy Consumption
Consumption [TWh]
400
350
300
250
200
150
100
50
0
2018
2030
2040
2050
Commodity
Heat (from CHPs)
Hydrogen
Electricity
Biofuels
Bioenergy
Waste
Natural gas
Oil products
Coal


Power production by source
Source
Imports
Hydrogen
Solar PV
Wind Offshore
Wind Onshore
Bioenergy
Hydro
Nuclear
Fossil
Exports
Electrolyzers
Power Supply [TWh]
180
160
140
120
100
80
60
40
20
0
-20
2018
2030
2040
2050


Power Plants Capacity
Power plants groups
Hydrogen
Solar PV
Wind Offshore
Wind Onshore
Bioenergy
Hydro
Nuclear
Fossil
Capacity [GW]
120
100
80
60
40
20
0
2018
2030
2040
2050
Central
Central
Dunkelflaute
DF Extreme
Central
Dunkelflaute
DF Extreme
Central
Dunkelflaute
DF Extreme


Power Plants Capacity
Power plants groups
Hydrogen
Solar PV
Wind Offshore
Wind Onshore
Bioenergy
Hydro
Nuclear
Fossil
2018
2030
2040
2050
Capacity [GW]
100
90
80
70
60
50
40
30
20
10
Central
Central
Nuclear
Nucl. + DF
Nucl. + DF Extr.
Central
Nuclear
Nucl. + DF
Nucl. + DF Extr.
Central
Nuclear
Nucl. + DF
Nucl. + DF Extr.


Electricity marginal price
2030
2040
2050
Marginal price [€/MWh]*
350
300
250
200
150
100
50
Central
Dunkelflaute
DF Extreme
Nuclear
Nucl. + DF
Nucl. + DF Extr.
Central
Dunkelflaute
DF Extreme
Nuclear
Nucl. + DF
Nucl. + DF Extr.
Central
Dunkelflaute
DF Extreme
Nuclear
Nucl. + DF
Nucl. + DF Extr.



Total Annual Costs, difference with BAU

Scenario	**Total cost increase [%]**
Central	11.8
Dunkelflaute	12.9
Dunkelflaute Extreme	13.9
Nuclear	10.1
Nuclear + DF	10.8
Nuclear + DF Ext.	11.4

Conclusions

Electrification results to be one key driver for the decarbonization of the Belgian energy system, with the power demand being more than **doubled** by 2050 → large-scale installations of both **solar photovoltaic and wind energy**

→ The **impact of considering a Dunkelflaute** on a country's energy planning is far from negligible.

→ Dunkelfaute **should be accounted for in scenarios** as it notably leads to:

1. A **substantially different electricity mix**, including e.g., **increased capacity** of low-carbon backup technology
2. substantial **supplementary costs**

In the long term (by 2050), depending on the scenarios considered, two solutions are proposed:

1. One approach relies on the import of electricity and the deployment of **peaking plants**, namely **hydrogen turbines** (~13 GW), to cover demand during periods of low renewable availability and high import prices.
2. The other approach involves substantial investments in **flexible baseload capacity**, namely **nuclear SMRs** (~18 GW) (and becoming net exporters, significantly reducing both electricity and hydrogen imports).

Thank you for your attention!

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Supplementary slides

TIB3R

Basic features of TIMES models:

- TIMES is a widely used energy system modelling framework for long-term energy system planning developed by the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (IEA).
- TIMES-based models **minimize the total system cost** or maximize the total surplus over the planning horizon while meeting various constraints.
- Taking the **inputs** of present stock of technologies, future demands, descriptions of new technologies, resource potentials, and any user-defined constraints, it identifies the cost-optimal pathway to meet the system demands.
- It calculates commodity shadow prices, technology activity, capacity, costs of new investments etc., for each reporting year over the planning horizon.
- TIMES has widely been used to study long-term evolution of interconnected or an individual energy sector at city, country or global level

A bit more details on TIB3R…

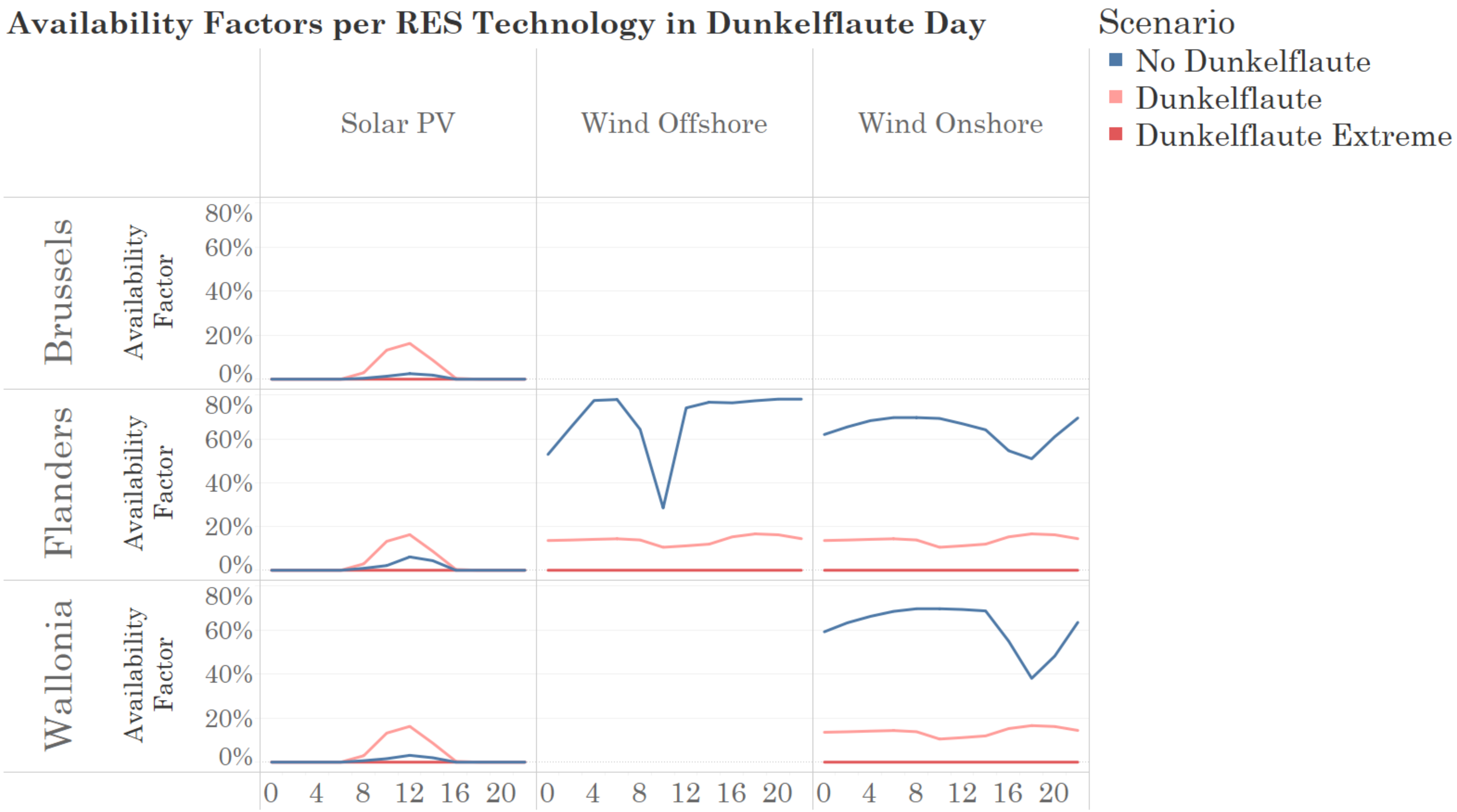
- each year is represented through **ten representative days** with bi-hourly resolution, for a total of **120 time slices**, to reflect the impact of both seasonal and intra-day fluctuations on demand and supply sides.
  - The 10 representative days are chosen through an optimization algorithm using multiple relevant time-series
- annual system-wide discount rate of 3%.
- **import/export power curves** are included (coming from an European-level dispatch model, developed by Ghent University), where the electricity trading price is contingent not only on time but also on the quantity exchanged.
  - These outcomes are integrated into the TIB3R framework, representing the availability and pricing of imported electricity during each time period
- Energy consumptions of the reference year is calibrated to the data within the regional energy balances, for each sector (industry, buildings,…)

How we do it

Second, we need data on Dunkelflaute periods in Belgium:

- We use recent data on temperature, solar radiation and wind speed
- We convert this into power generation: (parameter δ is defined as the fraction of PV with respect to the fraction of wind turbines)

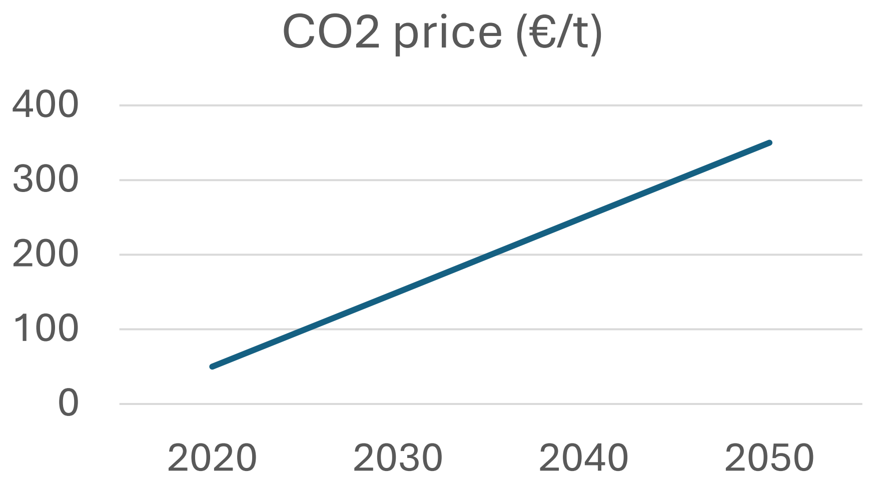
  $$Power\ (t) = (1 - \delta) P_{wind}\ (t)\ +\ \delta_{PV}\ (t)$$
- Then compute the electric balance : $Balance\ (t)\ =\ \dfrac{Synthetic\ Load\ (t)}{Power\ (t)}$
- Dunkelflautes are then defined as the events with the balance which have the lowest occurrences (**1-event-per-30-years**)
  - We consider **a Dunkelfaute duration of 3 weeks.**


Availability Factors per RES Technology in Dunkelflaute Day
Scenario
No Dunkelflaute
Dunkelflaute
Dunkelflaute Extreme
Solar PV
Wind Offshore
Wind Onshore
Brussels
Flanders
Wallonia
Availability Factor
80%
60%
40%
20%
0%
0
4
8
12
16
20

Assumptions

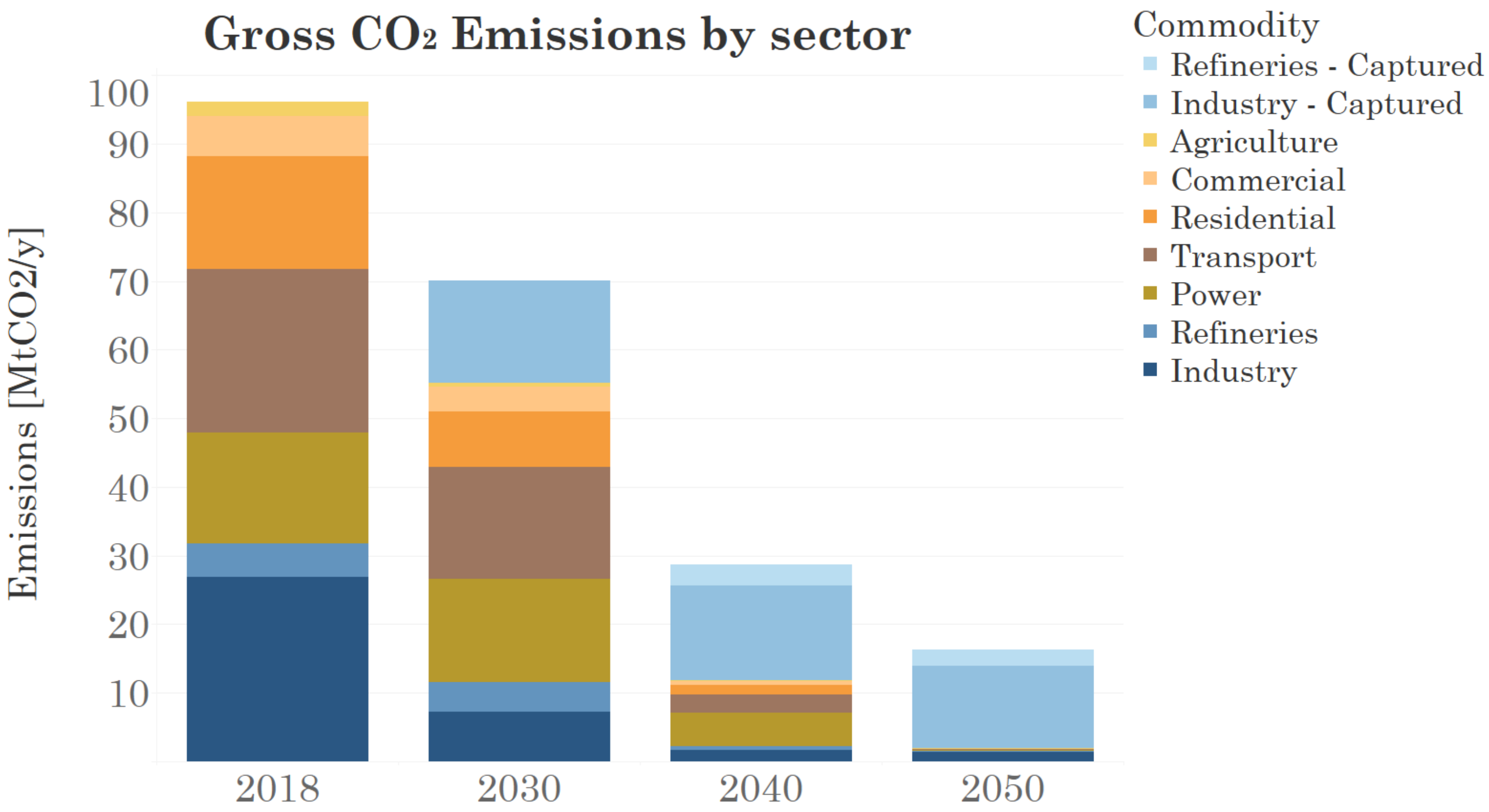
- Industrial demand
  - Constant, not relocated
- Renewable potential: (Bregilab project)
  - Wind onshore: 20.6 GW
  - Wind offshore: 8 GW
  - PV: 104 GW
- Biomass local potential and imports are limited

- CO_2 constraint to reach net-zero
- CO_2 carbon price (all sectors)
  - 350 €/t in 2050

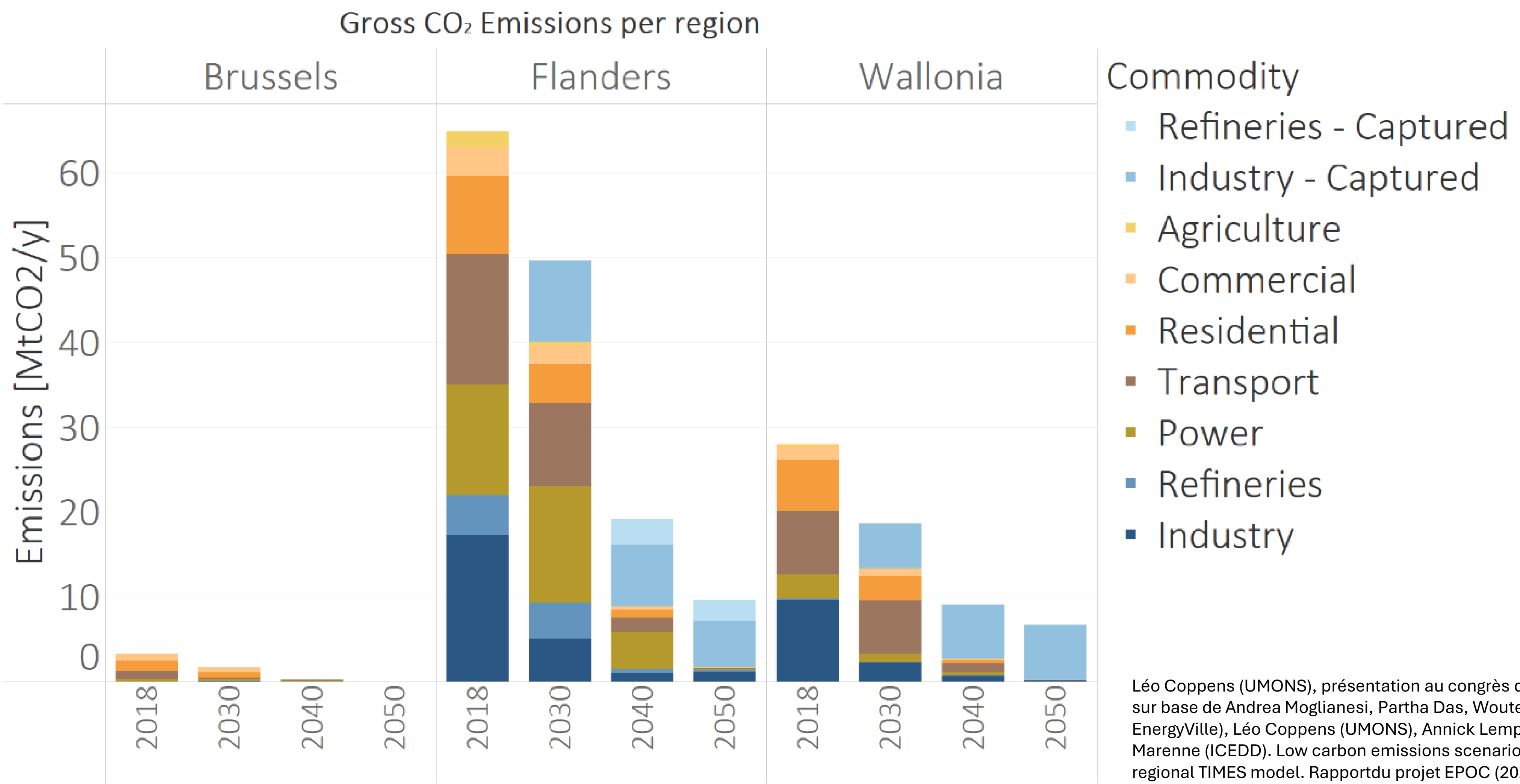


Léo Coppens (UMONS), présentation au congrès des économistes belges (2023) sur base de Andrea Moglianesi, Partha Das, Wouter Nijs, Pieter Vingerhoets (VITO-EnergyVille), Léo Coppens (UMONS), Annick Lempereur, Raphael Capart, Yves Marenne (ICEDD). Low carbon emissions scenarios for Belgium. Insights from a tri-regional TIMES model. Rapportdu projet EPOC (2023). The EPOC project was funded by the Energy Transition Fund.

Results


Gross CO₂ Emissions by sector
Emissions [MtCO2/y]
100
90
80
70
60
50
40
30
20
10
2018
2030
2040
2050
Commodity
Refineries - Captured
Industry - Captured
Agriculture
Commercial
Residential
Transport
Power
Refineries
Industry

Results



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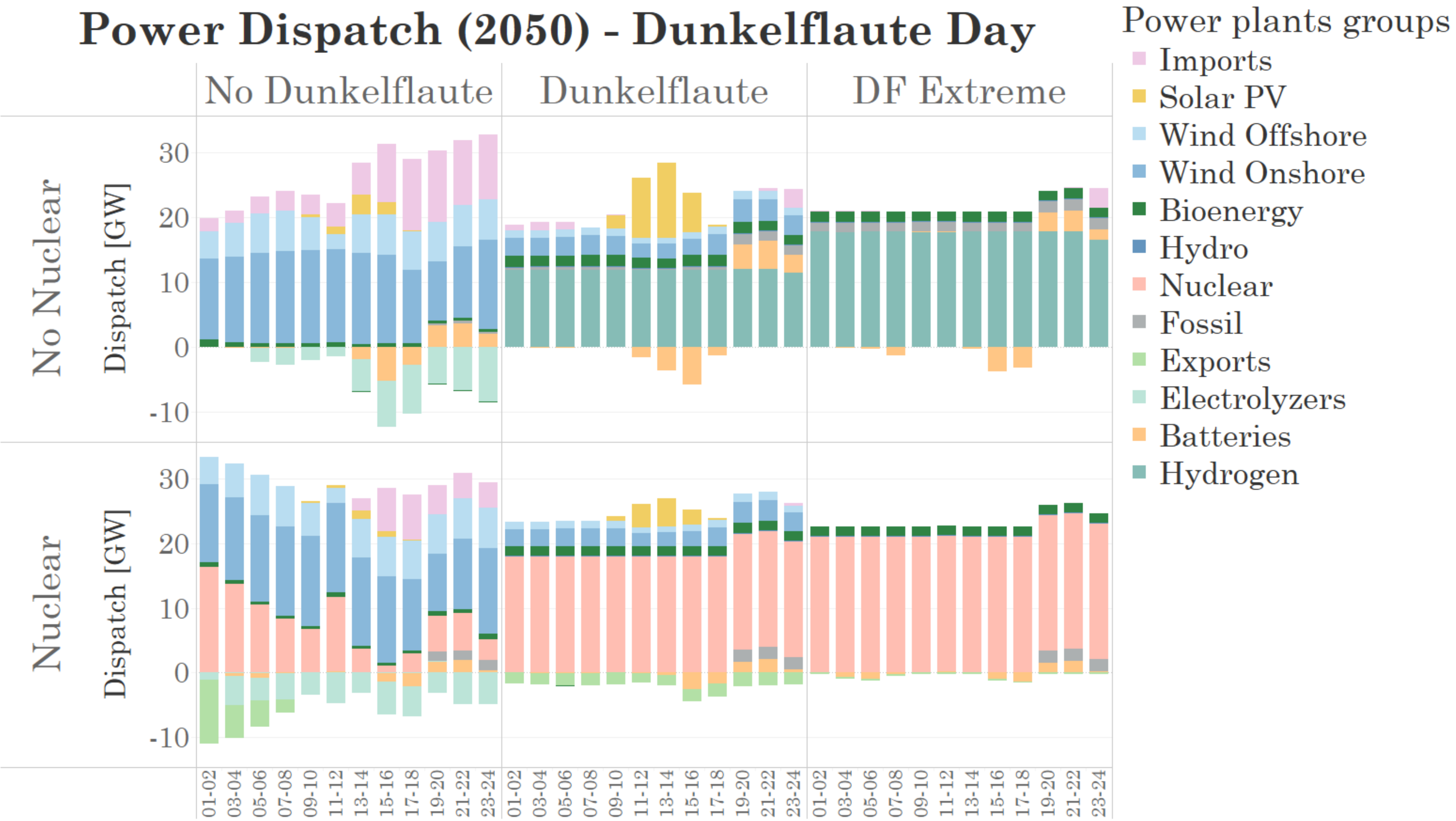
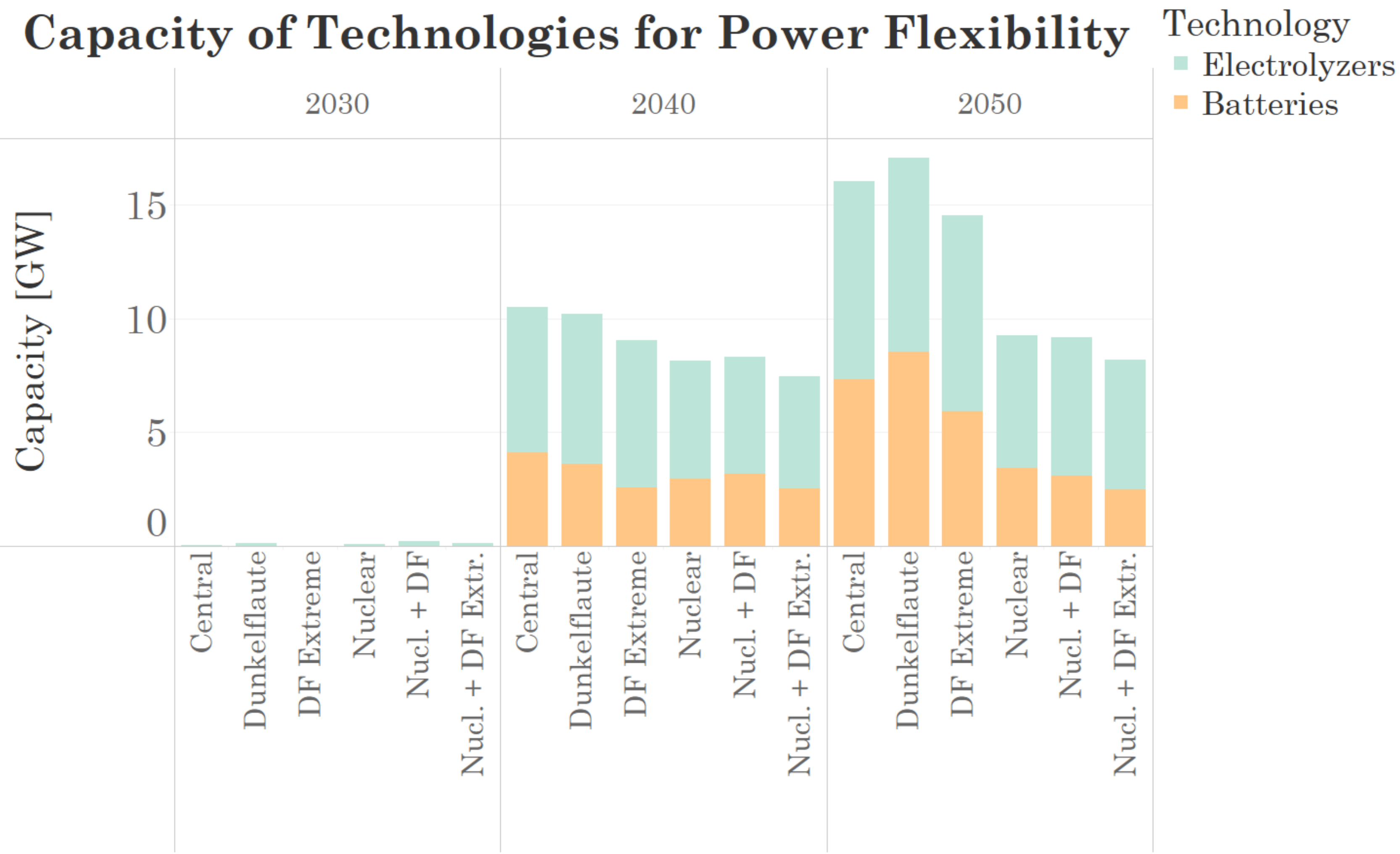

Power Dispatch (2050) - Dunkelflaute Day
No Dunkelflaute
Dunkelflaute
DF Extreme
No Nuclear
Nuclear
Dispatch [GW]
30
20
10
0
-10
01-02
03-04
05-06
07-08
09-10
11-12
13-14
15-16
17-18
19-20
21-22
23-24
Power plants groups
Imports
Solar PV
Wind Offshore
Wind Onshore
Bioenergy
Hydro
Nuclear
Fossil
Exports
Electrolyzers
Batteries
Hydrogen


Capacity of Technologies for Power Flexibility
Technology
Electrolyzers
Batteries
2030
2040
2050
Capacity [GW]
15
10
5
0
Central
Dunkelflaute
DF Extreme
Nuclear
Nucl. + DF
Nucl. + DF Extr.

Results

- In 2030: emissions are already down to 54 Mt/y (in the Central scenario), compared to 99 Mt/y (in the BAU scenario).

- The analysis of final energy consumption reveals that the primary driver for decarbonization is a **profound electrification** of end-use sectors.

→ The total electricity consumption **doubles** in just over twenty years

  - increasing from 83 TWh in 2018 to 165 TWh in 2040.

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Results

- In the industrial sector, electrification + carbon capture (+ hydrogen).
- In the transport sector, electricity consumption for road traffic is projected to reach 8.6 TWh in 2030 and 26 TWh in 2050.
  - Focusing on passenger cars,
    - the numbers projected for 2030 are highly challenging, with approximately 2.7 million electric vehicles (EVs).
    - The replacement of almost the entire current fleet with EVs would occur around 2040.
- In the building sector, electrification is key once again (for space heating)
  - heat pumps and energy efficiency measures.

→ Thus, the decarbonization of the energy system heavily relies on the strengthening of the power sector.

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Results

- Significant upfront investment in **PV and windmills**.
  - Specifically, solar photovoltaic capacity expands from the current level of just over 5 GW to 29 GW by 2030, with a further leap to 60 GW by 2050.
  - Similarly, both onshore and offshore wind power prove to be "no regret" options as investments are made up to their maximum installable potential.

- Starting from 2040, **hydrogen** turbines emerge as a viable option, with a peak capacity of over 7 GW installed by 2050.
- It is also important to highlight the significance of **electricity imports**, which quadruple by 2050 compared to the numbers in 2018 and 2030, reaching nearly 50 TWh/year.
- New biomass plants, particularly combined heat and power (CHP) are installed (around 1.5 GW), along with 0.5 GW of waste incinerators.

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Results

What if there is a remarkably long Dunkelflaute period?

- an overinvestment of around 10 GW in PV is considered cost-optimal, along with 12 GW of hydrogen turbines (or nearly 18 GW in the extreme Sc.) instead of 7 GW in the central scenario in 2050)

Would Nuclear SMR availability change the picture in 2050?

- 16 GW of nuclear capacity is installed, completely replacing the hydrogen turbines and reducing the need for additional PV installations + reducing the need for imports (16.3 TWh instead of 50 TWh) and increasing the export of low-carbon electricity.

Would nuclear SMR availability help in case of a Dunkelflaute period?

- the impact of Nuclear SMRs becomes even more significant.

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