WEATHER CONDITIONS AS CHALLENGE FOR GREEN ELECTRICITY SYSTEMS OF THE FUTURE

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1. INTRODUCTION & MOTIVATION (1)

- Due to vast deployment of renewable energy techologies and increasing occurence of climate change related weather events, the **European electricity market will be affected more intensively by weather conditions in the future**
- There is a broad literature showing the diverse challenges of electricity markets in light of changes to climatic parameters and extreme weather events
- In recent years, research in the field of **investigating the weather and climate impact on RES becomes more relevant**
- However, many studies are limited in assessing **only parts of the power system in isolation**
- On the other hand, complex energy and power system models can model an entire system and its interactions
- However, these models generally have **enormous computational requirements of running**
- Numerous approaches have been developed to mitigate computational demands, primarily focusing on information aggregation and **investigating only short time periods**
- Given the inter-annual variability of weather conditions, these approaches may be **limited in analyzing the true extent of e.g. supply security in future electricity systems dominated by renewables**

1. INTRODUCTION & MOTIVATION (2)

- Therefore, the use of simplified integrated models with large capacities in data processing can be beneficial in **considering longer-term weather variability**
- We use the **Electricity Market Model for Europe (EMME)** to analyze how the electricity market in European countries will be affected by weather conditions in 2030 using data from 40 historical weather years on hourly basis
- Key parameters to be investigated
  - **Security of electricity supply** and **resilience** (indicated by renewables coverage rate and import quota)
  - **Economic competitiveness** and **distribution effects** (indicated by wholesale market price and producer surplus)
- Deliverables of the model
  - **General forecasts** of electricity market figures in 2030 for average and specific weather years
  - Investigation of the **range of electricity market‘s outcome based on weather fluctuations**
  - **Identification of critical periods and situations** (and its frequency of occurrence) in terms of energy security etc.
  - **Scenario analysis**: Investigating the impact of extreme weather conditions

2. METHODOLOGICAL APPROACH: EMME (1)

Basis model assumption: Power plant operators aim to minimize running costs

- **Objective function**

$$\min Z = \sum_{h,i,d} [\Pr(h,i,d) * Cst(i,d)] + \sum_{h,d,k} Im(h,d,k) * T$$

- **Constraint 1:** Demand has to fulfilled at each point in time

$$\sum_{h,i,d} \Pr(h,i,d) + \sum_{h,d,k} Im(h,d,k) = Dm(h,d)$$

- **Constraint 2:** Only existing capacity can be used

$$\Pr(h,i,d) \leq Cp(h,i,d)$$

- **Constraint 3:** Import/export capacities are constrained by existing infrastructure (NTC)

$$Im(h,d,k) \leq NTC(d,k)$$

with:

i = generation technology type
h = specific hour of the year [-]
T = transport costs for imports and exports [€/MWh]
d and k = country indexes [-]
Cst = variable generation costs [€/MWh]

Pr = electricity production [MWh]
Cp = generation capacity [MW]
Im = electricity imports from country k to country d [MWh]
Dm = electricity demand [MWh]
NTC = net transfer capacity between two markets [MW]

2. METHODOLOGICAL APPROACH: EMME (2)

Input (data)

- **ENTSO-E database**
  - TYNDP 2018 scenarios for 2030
    - load data on hourly basis and at European country level
    - installed capacities per energy carrier
    - net transfer capacities (NTC)
    - fuel & CO2 prices
- **Renewables.ninja database:** Capacity factors PV & wind on hourly and national basis (1980-2019)

EMME modeling
(GAMS)

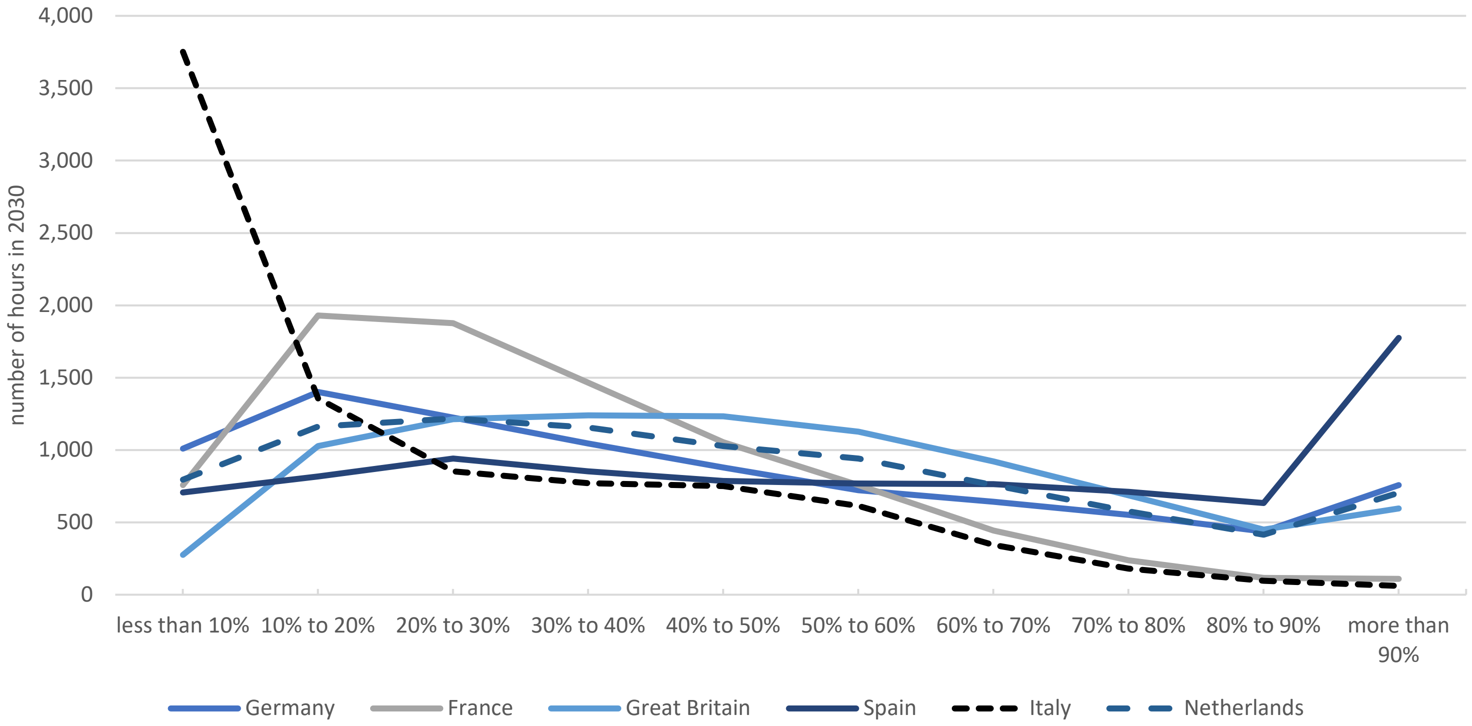
→

Output

- Calculation of the following key figures for 2030 (given the weather conditions and renewables‘ capacity factors in 1980-2019)
  - Domestic electricity supply (e.g. in relation to domestic demand)
  - Wholesale market prices for electricity
  - Cross-border electricity transfer
  - Producer surplus of power plant operators
- Key figures available on hourly basis, for all European countries and different power plant types

3. RESULTS FOR MEAN WEATHER CONDITIONS – RENEWABLES COVERAGE

Frequency distribution of median electricity demand coverage by domestic solar and wind power in selected European countries in 2030 (given the weather conditions in 1980-2019)



- On average, solar and wind power plants in Germany can only meet max. 20% of domestic electricity demand in about 28% of total hours in 2030.
- Italy faces the most challenges with low wind and solar coverage rates, whereas Spain is expected to satisfy domestic demand almost completely by wind and solar in one quarter of total time in 2030

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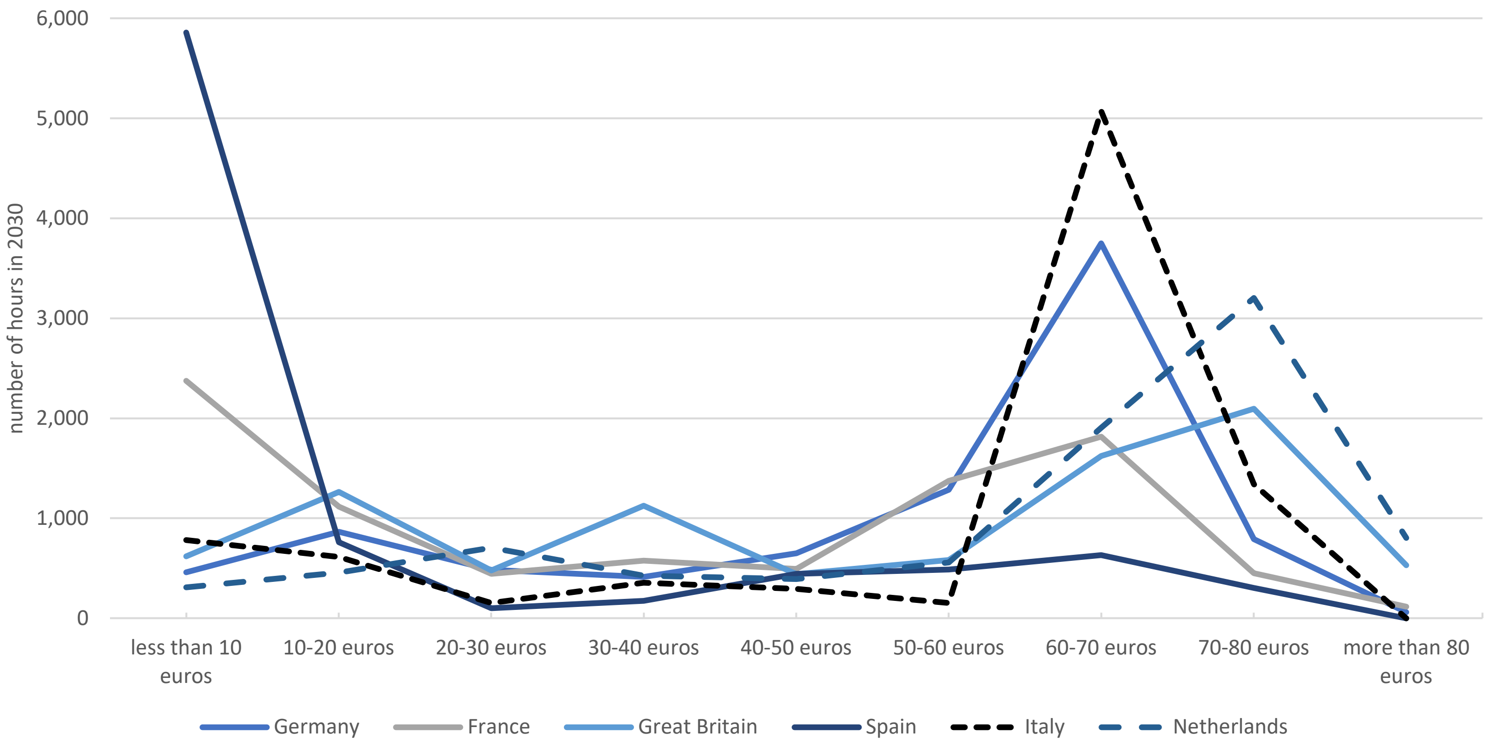
3. RESULTS FOR MEAN WEATHER CONDITIONS – ELECTRICITY MARKET PRICE

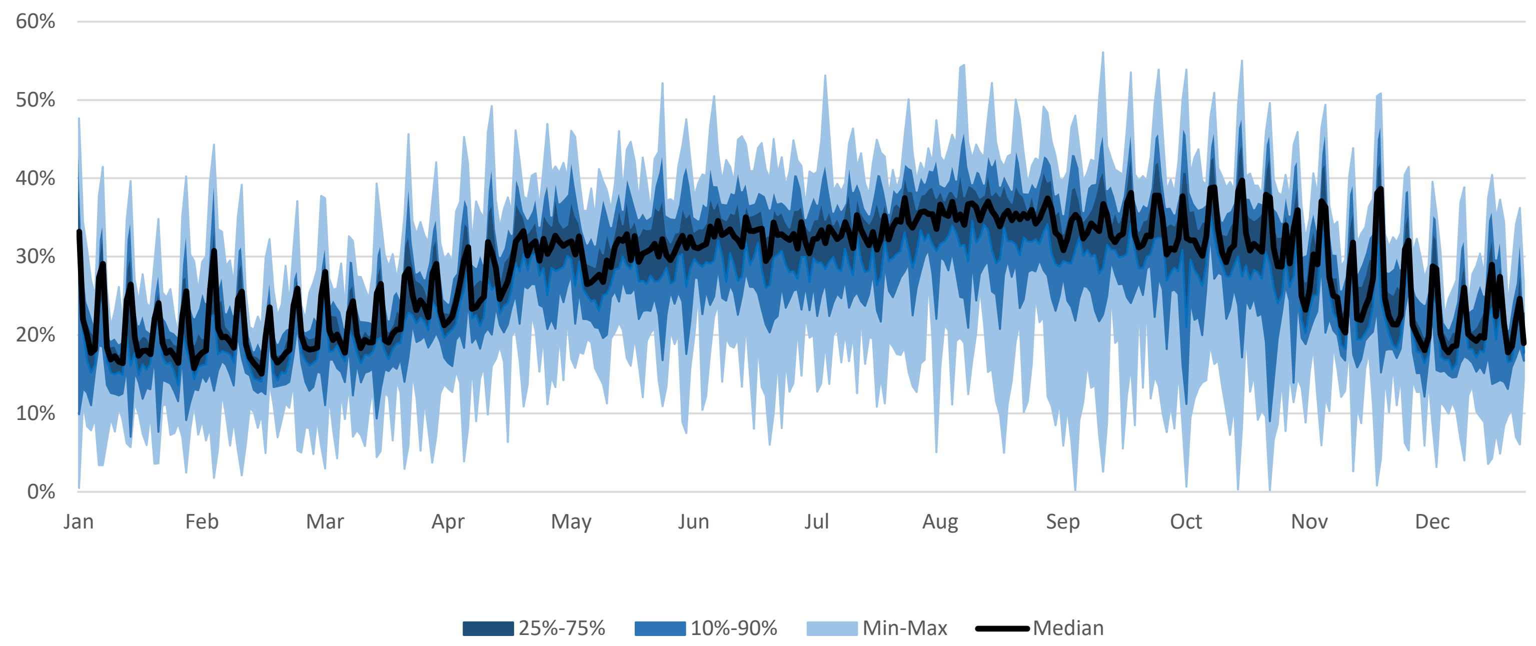
Frequency distribution of median wholesale market electricity prices (in euros/MWh) in selected European countries in 2030 (given the weather conditions in 1980-2019)



- According to the merit-order principle, Spain is expected to experience most hours in 2030 with electricity market prices less than 20 euros/MWh
- In contrast, companies operating in Italy, Netherlands and Germany may experience competitive disadvantages due to higher electricity prices arising from low renewables shares and phases of insufficient wind speed and solar irradiation, among others

4. OCCURRENCE OF EXTREME SITUATIONS – EXAMPLE IMPORT QUOTA

Daily average electricity import quota in Germany in 2030 (given the weather conditions in 1980-2019)

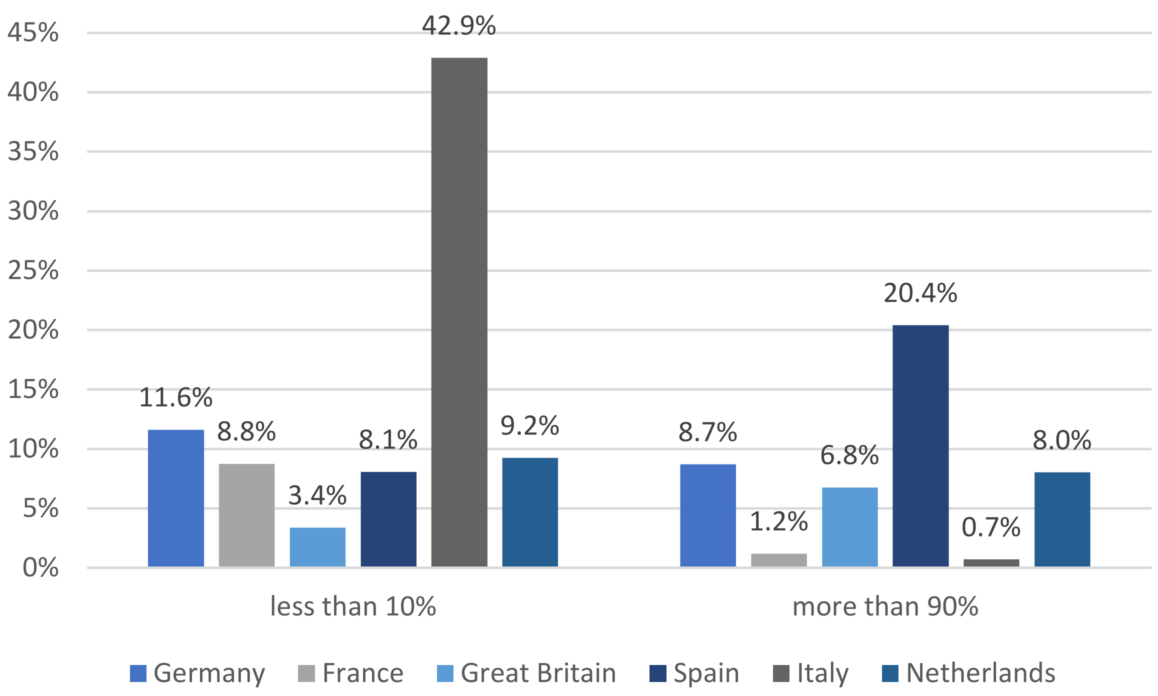


- In Germany, the mean import quota is expected to continuously reach its maximum values in the summer and autumn months in 2030 (up to 35%).
- The largest fluctuations in mean import quota from day to day are expected in the winter months, whereas the largest outliers and thus greatest uncertainties regarding dependence on foreign countries are to expected in autumn

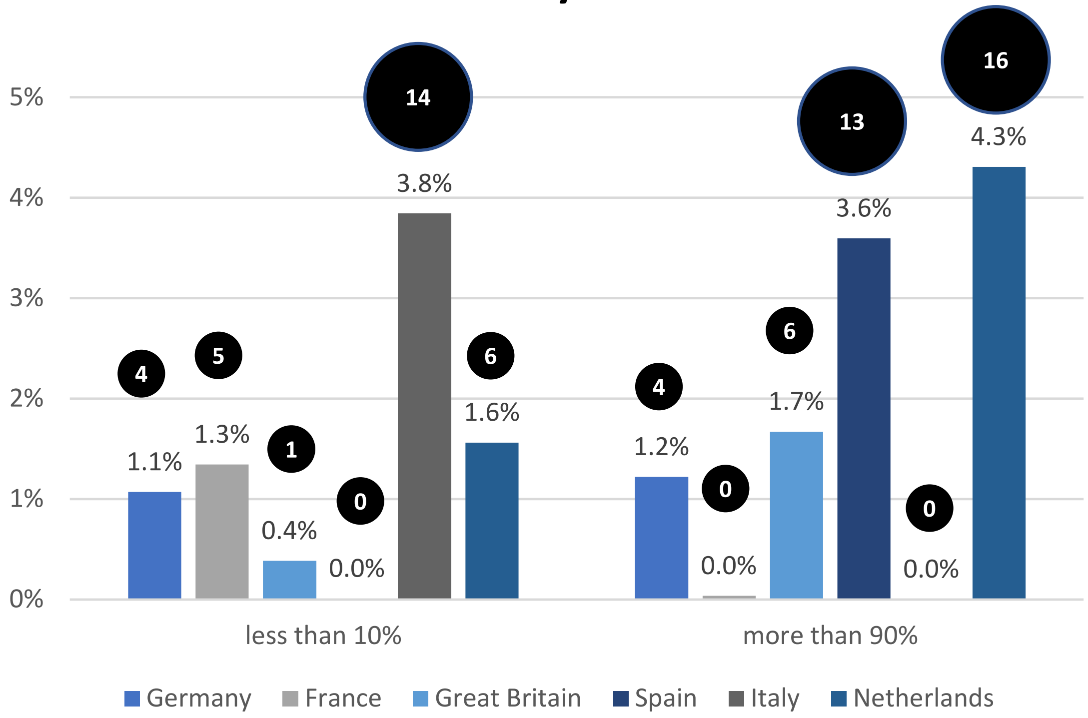
4. OCCURRENCE OF EXTREME SITUATIONS – LOW/HIGH RENEWABLE SHARES

Expected frequency of occurence of wind & solar coverage rates less than 10% and more than 90%, respectively, in selected European countries in 2030 (given the weather conditions in 1980-2019)

on hourly basis



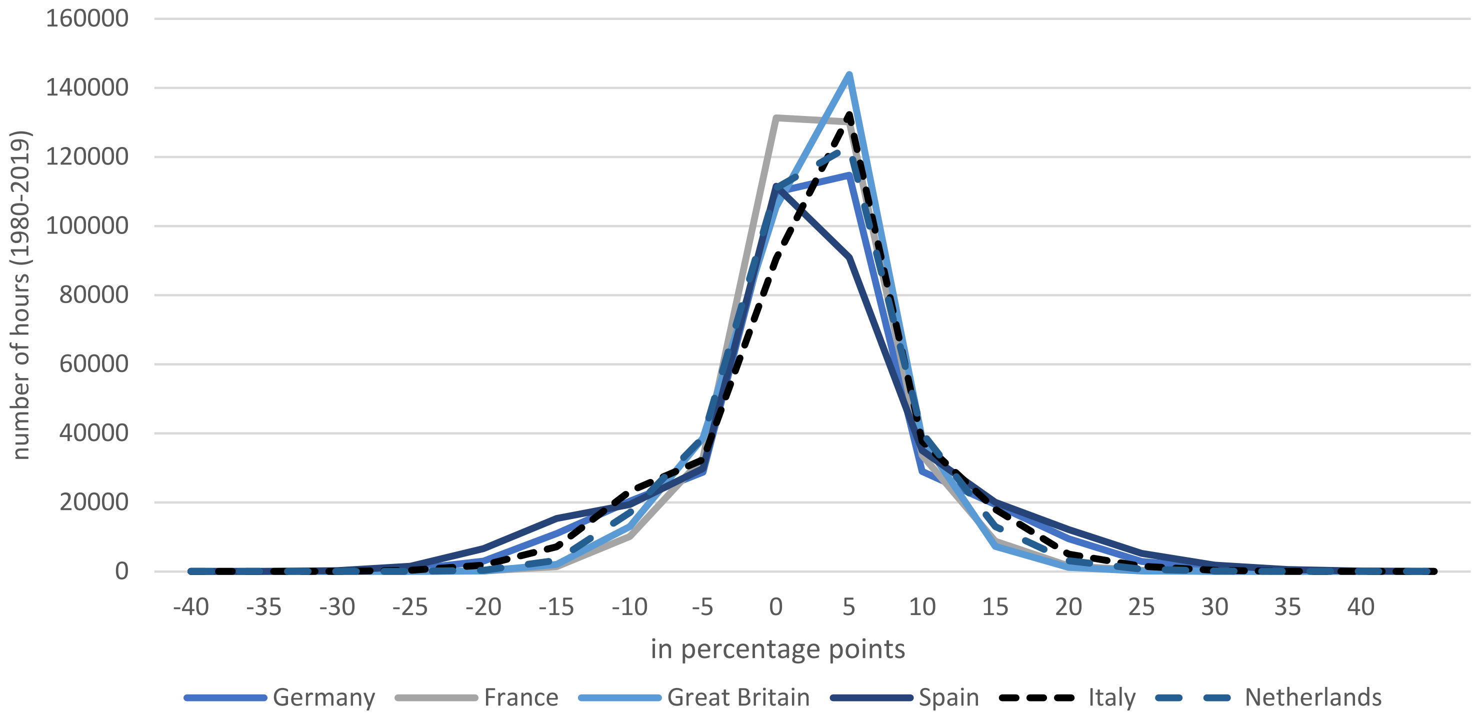
on daily basis



Note: black circles indicate the corresponding number of days per year.

4. OCCURRENCE OF EXTREME SITUATIONS – HOURLY RENEWABLES RAMPS

Frequency distribution of hourly changes in solar and wind coverage rate (in percentage points) in selected European countries in 2030 (given the weather conditions in 1980-2019)



- Ramping of solar and wind coverage rate at hourly scales is an issue for the stable operation of the European‘s future power system implying the need for backup and storage capacities
- By 2030, hourly ramps on the order of +/- 20 pp. are most likely for Spain (followed by Germany), whereas ramps of lower magnitudes are more frequent for Great Britain, Italy and France

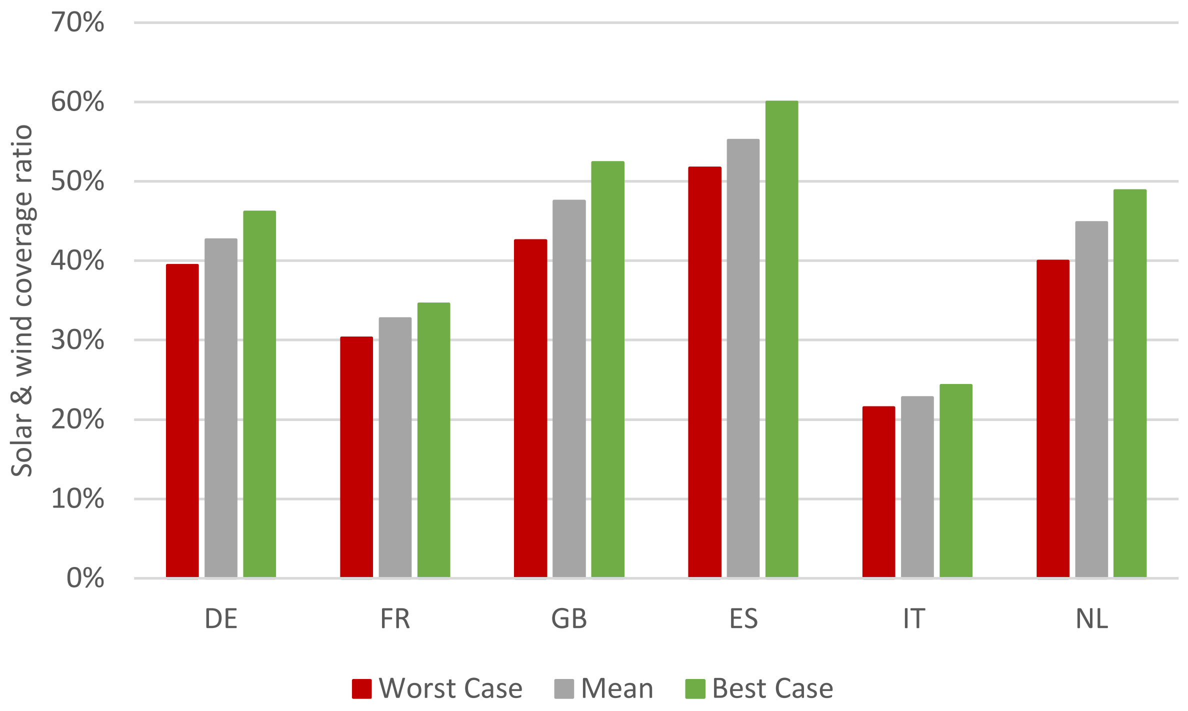
5. SCENARIO ANALYSIS – OVERVIEW

Weather condition scenarios for 2030

<table>
<tr><th>Scenario</th><th>Definition</th><th>Description/Modelling</th></tr>
<tr><td>Reference</td><td>Year with average weather conditions based on historical data of 40 weather years (on European country level)</td><td rowspan="3">• Most ideal/suboptimal weather conditions defined as hours with highest/lowest share of domestic demand covered by solar/wind
• For each weather year as well as for all weather years in total (Reference), distribution of solar and wind coverage rate is computed using 100 probability intervals
• The years with the maximum (Best Case) and minimum (Worst Case) cumulative deviation from the distribution function of the reference year are selected as the years representing the overall ideal/suboptimal weather conditions on yearly basis
• Approach according to Nik (2016)</td></tr>
<tr><td>Best Case</td><td>Year with most ideal weather conditions based on historical data of 40 weather years (on European country level)</td></tr>
<tr><td>Worst Case</td><td>Year with most suboptimal wind and solar conditions based on historical data of 40 weather years (on European country level)</td></tr>
</table>

5. SCENARIO ANALYSIS – BEST VS. WORST WEATHER CONDITIONS IN 2030 (1)

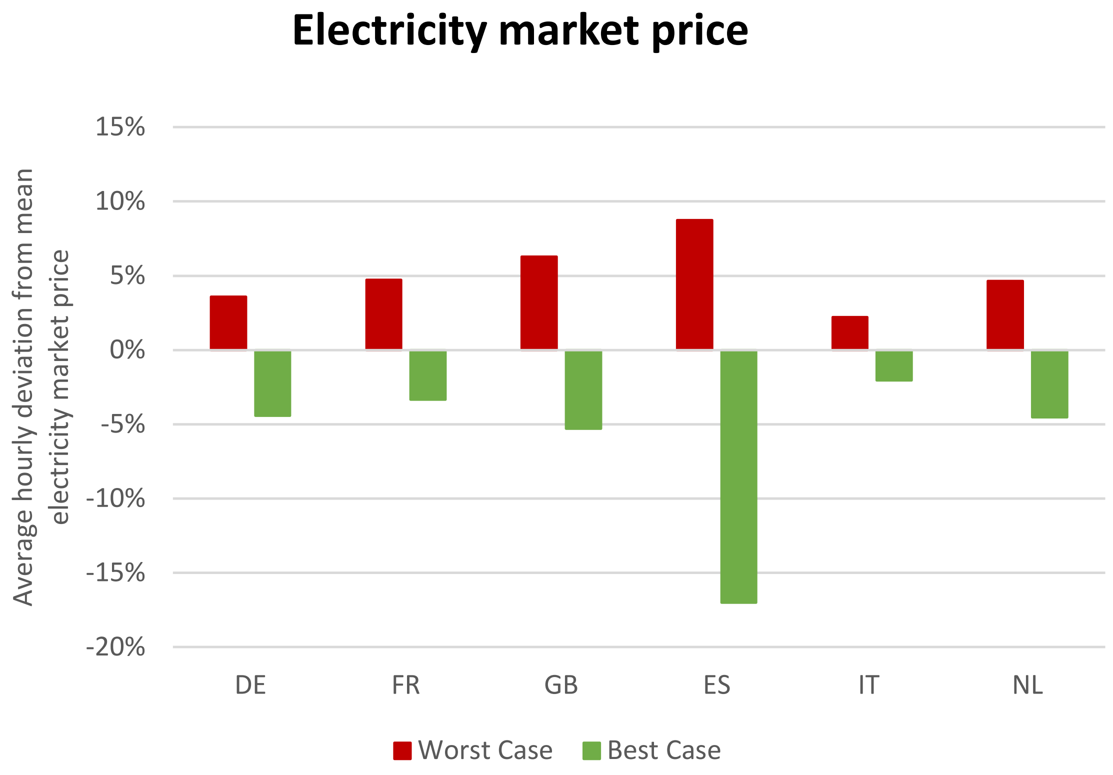
Hourly average solar and wind coverage rate (in percent of domestic demand) for selected European countries in 2030 (given the year with the mean, optimal and suboptimal weather conditions, respectively, in 1980-2019)

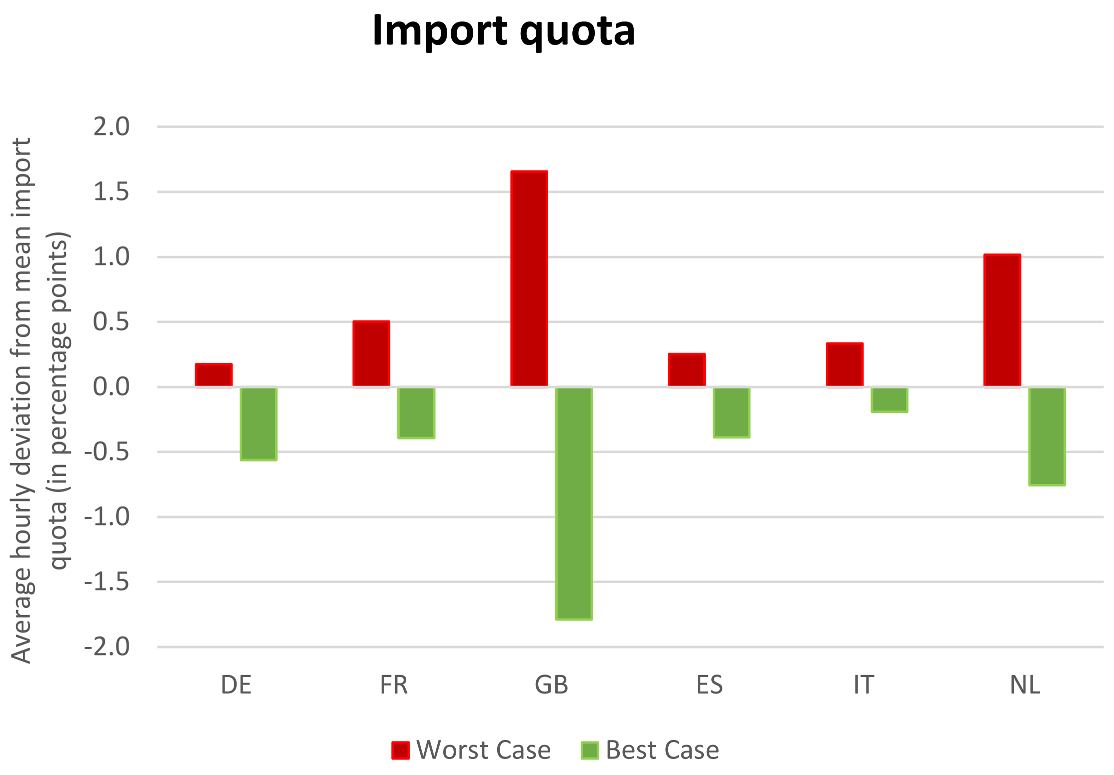


- Assuming that weather conditions in Germany in 2030 are the same as in 1987 (*Worst Case* year), hourly average demand coverage rate by wind and solar is about 39%, which is circa 7 percentage points less than in the *Best Case* scenario based on weather conditions in 1990
- Great-Britain (Italy) shows the largest (smallest) difference between the best and worst weather condition case

5. SCENARIO ANALYSIS – BEST VS. WORST WEATHER CONDITIONS IN 2030 (2)

Hourly average deviation of country‘s optimal and suboptimal weather year 2030, respectively, from its mean value (given the weather years 1980-2019)





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6. NEXT STEPS – VERIFICATION OF EMME RESULTS

Collaboration with Karlsruhe Institute of Technology (KIT)

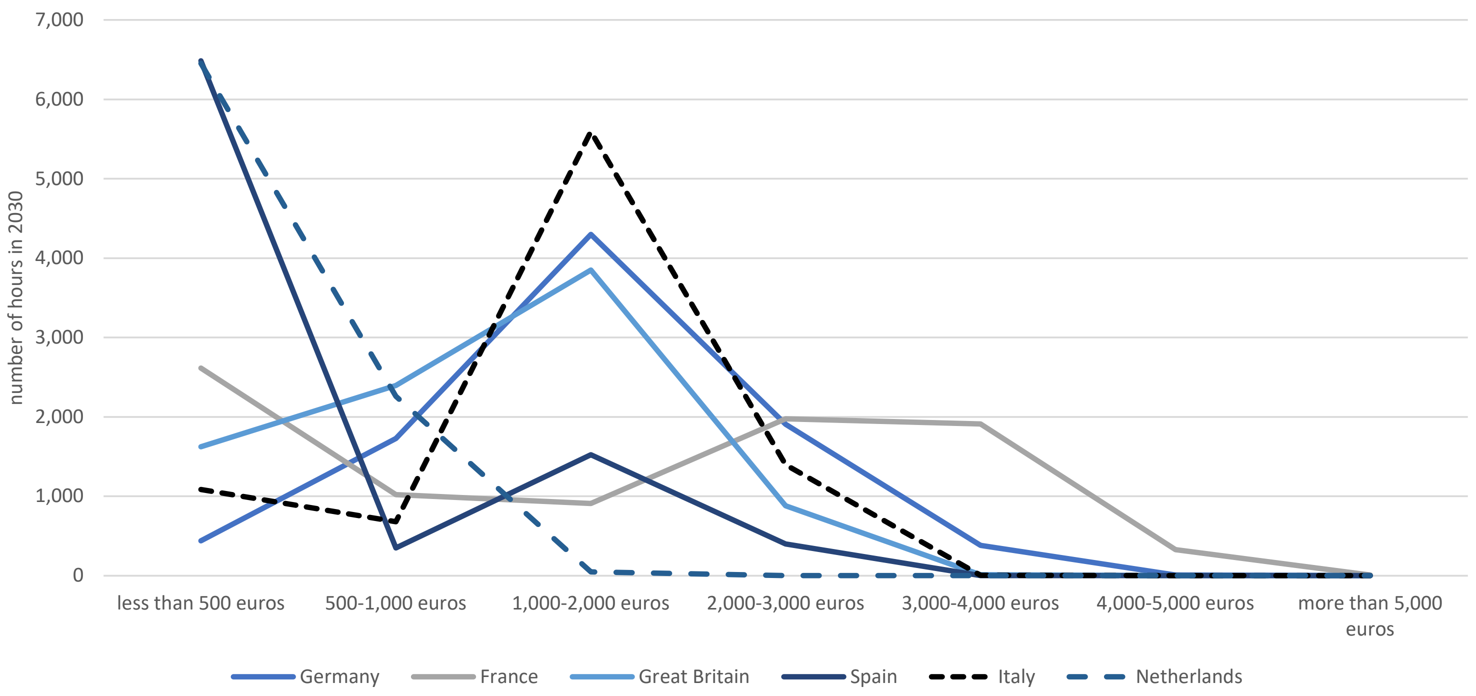
- Recap: simplified models such as EMME are able to process large data sets, while **requiring less computation time** than more complex power system models
- However, the latter incorporates a **more detailed and comprehensive representation of the electricity market system**
- Further research questions
  - Can EMME serves as a **reliable and effective preliminary tool** for an initial assessment of the weather impact?
  - Does it help to **preselect specific weather events** to be studied in greater detail with a more complex model?
- We will conduct a **sensitivity analysis of the EMME results using the advanced *PowerACE* model developed by KIT**
- *PowerACE* is an agent-based simulation tool for the electricity market system and integrates a wide range of representatives acting as key market players (utility companies, regulators and electricity consumers)
- First step: **harmonization of input data** for PowerAce & EMME (capacities, load etc. in 2030) using latest ENTSO-E data

7. CONCLUSION & OUTLOOK

- EMME approach convinces with its ability to **quickly and intuitively model future electricity market systems**, even when using large datasets such as 40 weather years on hourly basis and at European country level
- EMME represents a **comprehensive framework of the electricity market system** including interactions between demand and supply side, various power plant operators as well as across countries
- EMME results show that **uncertainties and fluctuations in weather conditions significantly matter** for the performance of future European electricity system
- This indicates the **need for flexibility options to balance the power system** (i.e. backup & storage capacities etc.)
- Next step is to **verify the EMME findings** such as the identified critical periods of extremely low electricity generation by renewables **using a more complex completed model**
- It is possible to **optimize and extend the EMME framework** including additional model assumptions and variables (e.g. storage capacities) as well as more specific scenarios (e.g. temporary extreme events)
- In addition, **linking EMME with macroeconomic models is possible**: How large should be capital expenditures in renewables to mitigate the risk of coverage gaps due to weather fluctuations? Which employment effects comes along with the corresponding economic activities? etc.

3. RESULTS FOR MEAN WEATHER CONDITIONS – PRODUCER SURPLUS

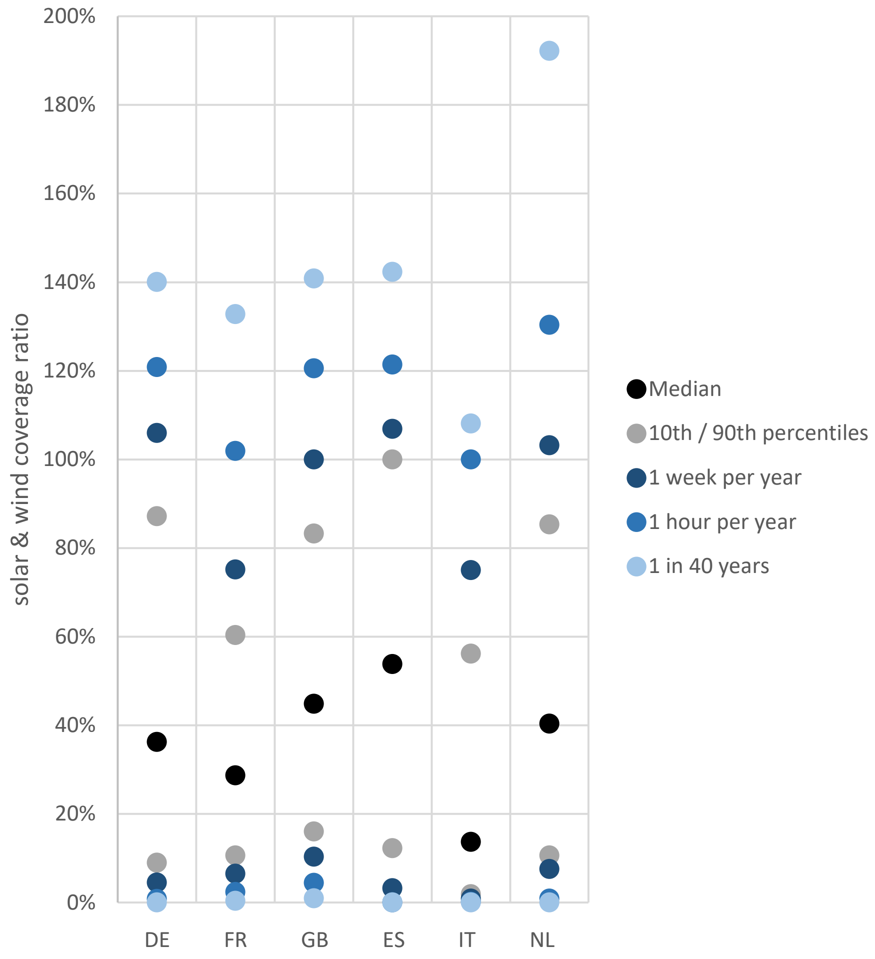
Frequency distribution of median producer surplus (in 1,000 euros per hour) of selected European power plant operators in 2030 (given the weather conditions in 1980-2019)



- Power plant operators in France are expected to gain producer surplus in the amount of more than 3 million euros on average in 26% of total hours in 2023
- In addition, Italian and German power plant operators benefit through relatively high wholesale market prices compared to Spanish producers
- This, in turn, implies that households in France, Italy and Germany tend to receive the smallest consumer surplus

4. OCCURENCE OF EXTREME SITUATIONS – FREQUENCIES

Distribution and negative extremes of hourly wind and solar coverage rate in selected European countries in 2030 (given the weather conditions in 1980-2019)



- It is expected for all the selected European countries, that at least one time in 40 years, wind and solar are not able to contribute to domestic electricity generation
- For Spain and Italy, the coverage rate is expected to remain at zero even one hour per year
- At the other extreme, peak values for the wind and solar generation in relation to demand are achieved in Netherlands, at least one time in 40 years

ANALYSE DER EFFEKTE VON WETTER AUF EE-DECKUNGSRATE, STROMMARKTPREISE, PRODUZENTENRENTE UND STROMIMPORTE – DARSTELLUNGSWEISE DER ERGEBNISSE

- **Ermittlung von absoluten Werten auf Stundenbasis**
  - MEDIAN-Häufigkeitsverteilung der stündlichen EE-Deckungsrate etc. über alle Wetterjahre
  - Häufigkeitsverteilung der stündlichen Abweichungen vom Tagesmedian (?) über ALLE Wetterjahre
- **Ermittlung von stündlichen Veränderungsraten**
  - MEDIAN-Häufigkeitsverteilung der stündlichen Schwankungen über alle Wetterjahre
  - Häufigkeitsverteilung der stündlichen Schwankungen über ALLE Wetterjahre (s. 1-hourly ramp; Staffell & Pfenninger 2018)
- **Ermittlung von Tagesdurchschnittswerten**
  - Variation innerhalb eines Jahres (z.B. Winter vs. Sommer) → Diagramm mit Monate auf der X-Achse / Variationskoeffizient
  - Variation eines Tages versch. Wetterjahre → Diagramm mit Monate auf der X-Achse / Variationskoeffizient
  - (evtl. Unterscheidung Wochentag vs. Wochenende)
- **Ermittlung von Tagesprofilen**
  - Schwankung von EE-Deckungsrate etc. an einem Durchschnittstag z.B. im Winter vs. Sommer
  - Variation innerhalb einer Stunde → Diagramm mit Stunden eines Tages auf der X-Achse / Variationskoeffizient
  - Variation innerhalb eines Tages → Diagramm mit Stunden eines Tages auf der X-Achse / Variationskoeffizient
- **Ermittlung der Anzahl Tage/Stunden pro Jahr (2030) mit „Extremsituation" für Stromsystem (?)**
  - S. „frequency of occurence" (Staffell & Pfenninger 2018)
  - In Excel mit „Zählenwenn"-Funktion → Wie viele Tage/Stunden unter einem bestimmten Wert (z.B. EE-Deckungsrate)
  - Evtl. Unterscheidung Wochentag-/ende bzw. Tag/Nacht notwendig