Dunkelflaute analysis

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Introduction

A key condition to mitigate climate change within the energy context is to reduce the combustion of fossil fuels. In 2021, the world fossil fuel consumption represented 77.1% of the total energy consumption while wind represented 2.8% and solar represented 1.5% (Ritchie et al., 2022). In Belgium, the sole electricity generation was mainly provided by thermal combustion (30.6%) and nuclear power (49.7%) while 12.2% was from WIND and 5.8% from PV energy (FEBEG, 2021). The renewable total installed capacity was 7129 MW for PV and split between 2254 MW and 2764 MW for offshore and onshore WIND production, respectively. Belgium has agreed to reach carbon neutrality by 2050 following the Green deal (European Commission, 2020). Yet, with the projected increased share of WIND and PV production of electricity, dealing with the atmospheric conditions become more and more challenging. The ability to properly meet the demand of electricity over short and long terms, has been investigated to some extent in our work by considering only the onshore production though PV and WIND to balance the electric system. We did not explicitly incorporate other sources of power such as imports of foreign electricity, storage solutions, or other power plants.

The main focus of the work is on dunkelflautes and we have investigated several research questions regarding them. The first concerns the sensitivity of a hypothetical REN Belgian electric system to the particular weather conditions that amount to very low energy production during dunkelflaute periods. More specifically, we assessed what the REN capacity should be for the system to be resilient against dunkelflautes and what is the optimal fraction of PV and WIND generation to do so. Next, we investigated the possibility of sharing energy resources during dunkelflautes with the neighboring countries. Finally, the work included an analysis of the future climate conditions impacting the REN Belgian average production and dunkelflautes.

In the scientific literature, there is no consensus on a single definition regarding dunkelflautes characteristics. Commonly, it implies variables expressing a) the energy production, b) the duration, c) the spatial extent and d) a threshold defining the presence of an event based on estimates of one or several of the previously cited characteristics. In literature, each study focuses on one or several of the cited aspects. Here, to answer our aforementioned research questions, we propose a more general approach regarding dunkelflautes by including PV and WIND productions as well as the energy demand. More specifically, we consider extremes with varying return periods calculated based on extreme value theory and several event durations (from 12-h to 1-month).

Data

For evaluation studies, reanalyses are good candidates to provide surface wind, radiation and many other atmospheric variables. Reanalyses are gridded long-term datasets for past and present climate created with the assimilation of available observations from many sources and resolving atmospheric evolution equations. As such, they benefit from having several atmospheric variables that are coherent on a grid as compared to other sources which can be spatially or temporally limited (e.g. ground based measurements, balloons, masts, satellites...). Therefore, for the present study, the meteorological variables (2m temperature, solar radiation, 10m and 100m wind speed) are taken from the ERA5 reanalysis with hourly frequency covering the period 1979-2019 (41 years). ERA5 reanalysis is the newest global reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) and has a 0.25° horizontal resolution. Climate data sets are widely used in renewable energy analysis and ERA5 is starting to be frequently used.

For the future climate, the same meteorological variables are taken from the regional climate model ALARO (from the RMI) with an hourly frequency and covering the period 1976-2005 for the historical simulation and both 2021-2050 and 2051-2080 periods for the near and far future, respectively. The simulations were run at 4 km spatial resolution on a domain over Belgium from a dynamical downscaling of the General Circulation Model (GCM) CNRM-CM5 based on 3 possible future RCPs (RCP 2.5, RCP 4.5 and RCP 8.5). These scenarios allow us to evaluate the impact on the dunkelflautes in the near and far future following a low-emission scenario (RCP 2.6), an intermediate scenario (RCP 4.5) and an extreme scenario (RCP 8.5).

For the energy demand, we use the electricity demand from the European Network of Transmission System Operators for Electricity (ENTSO-e) dataset of 2010 in Belgium and its neighboring countries. Based on the ENTSO-e data for 2010, we generate a synthetic load profile for the period 1979-2019. For the future period, the 2005 year was used to create synthetic load profiles both for the historical (1976-2005) and future period (2021-2080). Our aim is to investigate only the impact of future climate changes. Therefore, we do not address the potential future changes in electric demand (no hypothesis is made concerning a possible increase of electric vehicles, heat pumps, cooling devices...). The year 2005 was used from Elia's historic database instead of the previously cited 2010 from ENTSO-e since the later historical database started in 2006. However, it does not affect our findings since ENTSO-e's database incorporates the country's high-voltage transmission system operator.

Methodology

The methodology employed in this work is limited to Belgium and its neighboring countries. It is based on ERA5 reanalysis and ALARO simulations. At every point of the domain and for every hour, we compute the PV and WIND power generations using the relations presented in Jerez et al. (2015) and Iratxe et al. (2016).

The physical parameters of the representative WIND are taken from the VESTAS V112-3.3MW (https://en.wind-turbine-models.com/turbines/693-vestas-v112-3.3). The VESTAS V112 has a rate power of 3.3MW, a rotor diameter of 112m, the cut-in and cut-out wind speeds are 3 and 25 m/s, respectively, and the rated wind speed is 13 m/s. Although one could expect future technological improvements, the focus here is on the influence of climate on a typical wind power curve rather than on the technology used. For simplicity, only onshore WIND production is (explicitly) taken into account. However, our analysis is general enough that for most results one could include offshore wind production by imaginary distributing it over the land area, as a first approximation. Especially for Belgium, where both the available offshore zone and land area are relatively small, we expect wind speeds and hourly capacity factors of offshore and onshore to be heavily correlated. Explicitly including the Belgian offshore zone in the meteorological analysis would therefore likely not change most of the conclusions much, but this could be interesting to check in a further study.

To increase the interpretability of the amount of REN production required to adequately balance the load, we assume that we have a maximum installed peak capacity of 1 MW per km^2. To compare the production with the demand, the PV and WIND power productions are merged depending on their respective contribution. Both have a respective installed peak capacity of 1MW/km^2 and, in order to fulfill the hypothesis of a total combined maximum capacity of $1 MW/km^2$, we define δ as the fraction of PV with respect to the fraction of WIND installed. This parameter allows us to examine all possible mixes of PV and WIND. The total power production is then given by:

$$P_{total}(t) = (1-\delta)P_{wt}(t) + \delta P_{PV}(t) \quad (1)$$

The power production thus obtained reflects the hourly country-wide production in case there is 1 MW of renewables available per km^2. Currently in Belgium (30688 km^2), there is an averaged installed capacity of renewable sources of 0.32 MW/km^2 (with almost 70% PV). Therefore, our hypothesis corresponds to a theoretical increase of 3.1 times the currently-installed capacity.

Commented [PV1]: Actually, this is still below the limit that TIMES uses. However it may be realistic, as TIMES uses the geospatial maximum potential. E.g. human resistance may cause less installed capacity

For the energy demand, we generate a synthetic hourly load profile of the demand of electricity for every year in Belgium and its neighboring countries. To do so, we fit a linear model on one year of real load (2010 for the reanalysis and 2005 for the climate change periods) as a function of the temperature of that year. Then, the fitted relations are used to calculate a synthetic load for all days of the entire period (1979-2019, 1976-2005 and 2021-2080) based on the average 24-hour temperature. Prior to the regression, the loads on weekend days were replaced with their adjacent week days' load in order to remove the effect of the diminished load during the weekend. During those reference years (2005 and 2010), there is not yet a lot of cooling devices in Belgium as compared to heating, so the load is much higher during colder periods.

The last definition we establish in order to characterize a dunkelflaute is the electric balance defined as the ratio of the synthetic load by the power production. Contrary to the definition of Heide et al. (2010), the power balance is defined as a ratio between the load and the energy production rather than a difference between them. The main advantage from our definition (in addition to our hypothesis of an installed peak capacity of 1 MW per km^2) is that we can immediately infer by how much the installed capacity production should be multiplied in order to match the demand of electricity whether it is for average time or during dunkelflautes. The balance is so defined as:

$$Balance(t) = \frac{Synthetic\ Load(t)}{Power(t)} \quad (2)$$

The lower the balance, the more energy is produced compared to the consumption. In case the balance is below 1, extra electricity is potentially produced. A balance above 1 indicates that the system will fail to produce enough energy. In this work, the balance will be analyzed for different time windows (from hourly to monthly) both for average times and dunkelflautes. These ranges are computed with a running mean on both the load and the power production with a window step of half the averaging time. Dunkelflautes are defined for each time window (i.e. the dunkelflaute's duration) as the events with value of balance corresponding to the lowest occurrences of events ranging from 1-event-per-year to 1-event-per-30-years. Compared to literature, we are selecting dunkelflautes based on their return level rather than on CF threshold. Finally, we define the term "optimal balance", the balance obtained by the PV/WIND fraction minimizing the most the balance for a given time window. Finding the most optimal balance both for average times and dunkelflautes is the main objective of this work.

Results

An overview for the year 2005 of hourly production and demand in Belgium is represented on Fig. 1. The ratio between PV and Wind turbines is set here with a δ = 0.7 (i.e. which is equivalent to a fraction of 70% PV and 30% WIND) as the current installed capacities. It clearly shows that the power produced throughout the year (assuming a 1MW/km^2) is mostly too low as compared to the demand. Only 957 hours out of 8760 (i.e. 11% of the time) have a balance above 1. Currently, the electric production is balanced with thermal and nuclear power plants as well as with offshore WIND production (not included in this study).

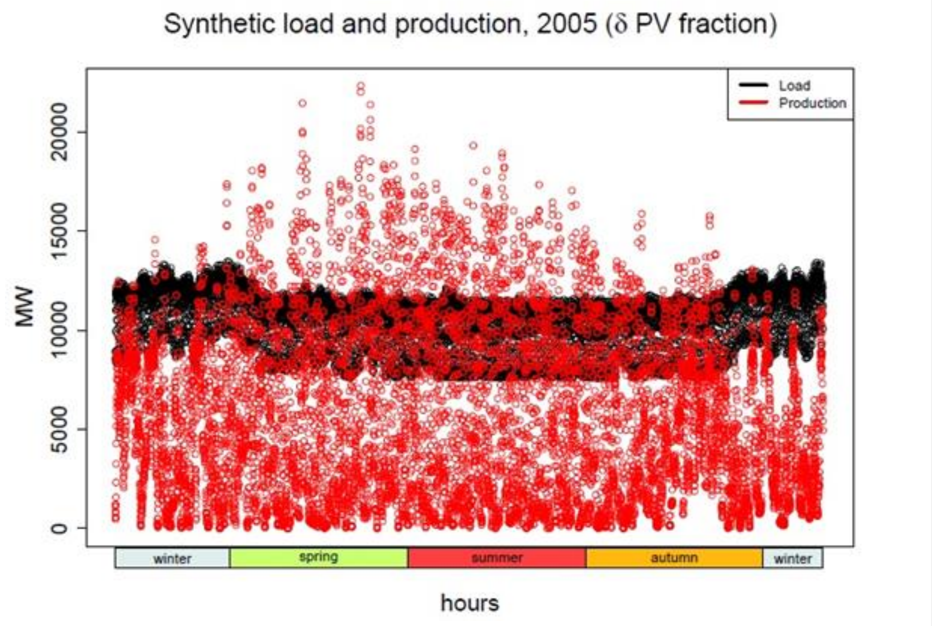

Figure 1: Hourly power production (red) and load (black) over Belgium in 2005 in the case of a δ = 0.7 (i.e. 70% PV and 30% WIND fraction)

We next focus on dunkelflautes, which are here defined as the low-probability events of high balance. Figure 2 shows the dunkelflaute events which correspond to the rarest 24-hour balances of Belgium against the different PV/Wind fractions for return periods ranging from once a year to once in 30 years. The left y-axis represents the balance value defined previously, the right y-axis represents the equivalent amount of magnification required from the current REN installed capacity. As such, the 1-event-per-year line can be interpreted as a 24-hour dunkelflaute occurring once per year with a magnitude requiring, in order to fulfill the load, an increased installed capacity equal to the amount indicated on the left y-axis in MW/km^2 (or equivalent to the number on the right y-axis times the current REN installed capacity). The main result from Fig. 2a is that, in contrast to the 24-hour averaged balance (Fig 2b), more emphasis on PV rather than wind turbines produces more energy during extreme events. This is because these 24-hour 'events' are mostly low WIND production events during day time, where there is still some small PV production. Note however, that the balance values are very high and would require a minimum increase of almost 56.4 times the current installed renewable capacity to deal with the most frequent dunkelflautes (1 event / year) and 100.1 times for the rarest (1 event in 30 years). The optimal range for the smaller balance during extremes (between 60-80%) is different than for averaged time (between 40-50%). Outside of that range, the balance quickly rises. This "u-shape" of the balance as a function of the δ, present for all countries and other time windows (not shown), suggests that it would be better to rely on a mix of both PV and WIND in order to minimize the 24-hour balance rather than solely depend on just one.

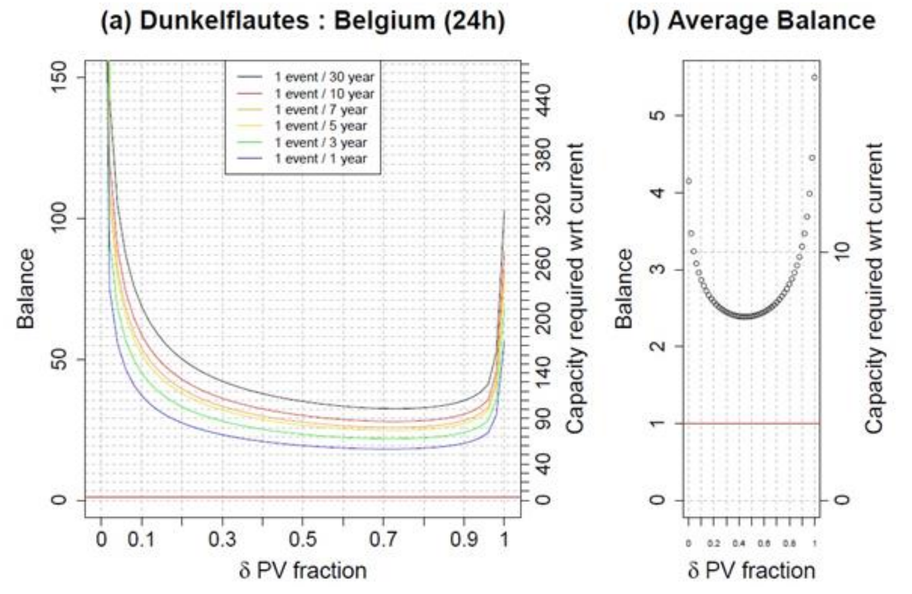

Figure 2: 48 hours' average balance of Belgium over the different PV/Wind fraction δ. Dunkelflaute events of varying return levels are represented by the different colors (a). The circles correspond to the 48h average (b). For clarity of representation, the y-axis was truncated to remove the highest balance values. The horizontal red line represents the balance value of 1

Instead of the full range of δ for a selected time scale, Fig. 3b shows the optimal balance against the dunkelflaute duration in Belgium while Fig. 3a shows the associated δ per return level also against dunkelflaute duration. The best proportion of installed PV with respect to WIND to cope with dunkelflautes changes from 12% to 74%, depending mostly on the dunkelflaute duration (1-month to 12-hourly). The dependence on the dunkelflaute's return periods, on the other hand, is very weak. The corresponding optimal balances scale exponentially with the inverse of the duration as shown in Fig. 5b. It ranges from 2.3 to 406.8 for monthly to 12-hourly windows respectively for the rarest events. As stated before, both the 24-hours and 48-hours average optimal mix contains predominantly PV but this is reduced as the averaging time window diminishes or grows. There are two reasons for this. First, at sub-daily time scales the highest balance values may be expected to occur at night when PV production is zero and the total balance will rely more on the wind. At weekly to monthly timescales, extreme balance values are close to the average balance and the optimal PV/Wind fraction δ is therefore close to the one of the average balance.

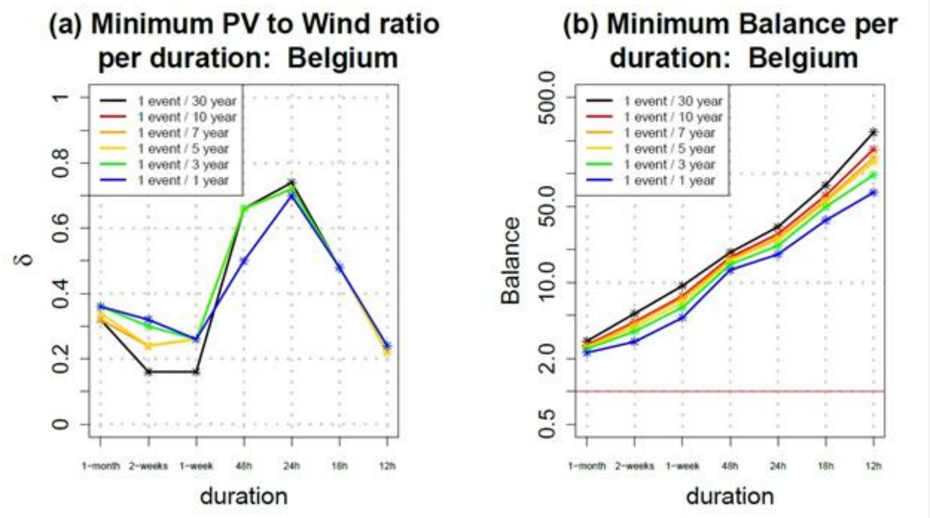

Figure 3: a) The optimal PV/Wind fraction δ as a function of duration and its associated balance (b). The horizontal red line in b represents the balance value of 1.

We also investigate whether dunkelflautes only happen during winter time or periods of low temperatures and if there is a dependence on dunkelflaute duration. As expected, most events occur during the cold seasons (winter and autumn) for any combinations of δ. However, even though they are rare, dunkelflautes do occur during summer especially when almost all renewables are from WINDs, i.e. for δ close to zero (as a result of the reduced average wind speed during summer). Overall, a total of 7072, 1042, 31 and 36 events happen in Winter, Autumn, Spring and Summer respectively indicating that 72% of the events occur in winter.

Fig. 4 shows the percentile of the 24-hours average balance in the neighboring countries of Belgium for a fixed 50% fraction δ. This middle δ fraction scenario was chosen arbitrarily to present an intermediate situation. The events selected correspond only to the 24-hours when a dunkelflaute is occurring in Belgium. For the comparison, we adapted the definition of dunkelflautes (for simplicity) to consider events with a balance above the 95th percentile. From the figure, the majority of dunkelflaute events in the neighboring countries coincide with those over Belgium.

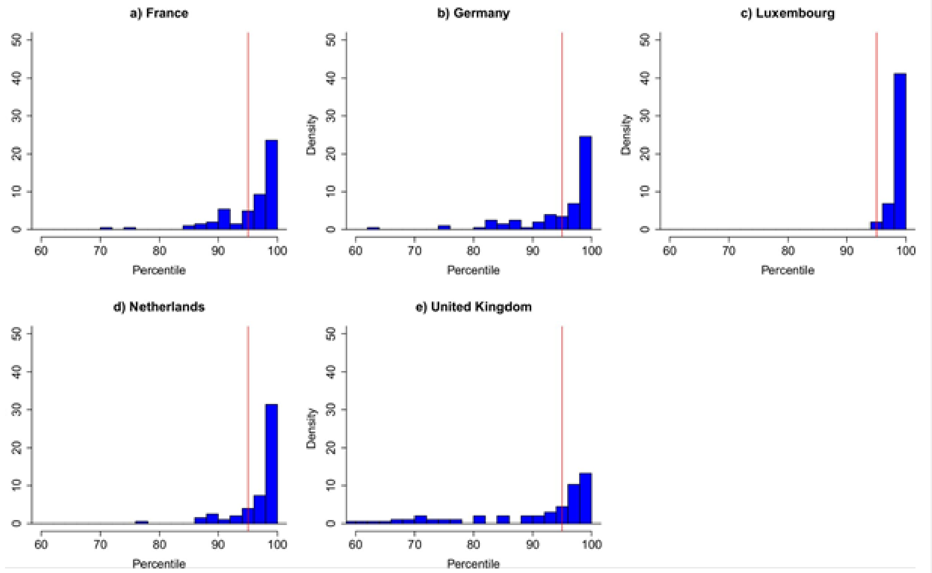

Figure 4: Percentile distribution of the 24-hours average balance of the neighboring countries of Belgium during Belgian dunkelflaute events (i.e. with the definition adapted to events exceeding the 95th percentile of the average balance in Belgium) with a 50% PV/Wind fraction δ. The red line corresponds to the 95th percentile

We estimate now how climate change may impact the balance during dunkelflaute events, based on high-resolution climate simulations of the ALARO model. The main purpose of this approach is to look solely at the climate impact on dunkelflautes assuming that the demand of electricity is kept constant. In other words, the statistical properties of the load do not take into account any increased electrification of the system (such as the inclusion of electric vehicles, heat pumps, cooling devices...). Only the differences of temperature in each scenario affect the load. In addition, the PV/Wind fraction δ is kept the same in the future in order to monitor the climate change impact only affecting a system designed to be optimal nowadays (i.e. by minimizing the historical balance with respect to δ). As our previous results indicated that, during dunkelflautes, the PV/Wind fraction δ of the optimal balance did not strongly depend on the return time, we focus here on dunkelflautes with a return level of 1 event per year for varying durations.

In the near future (2021-2050), the optimal balance during dunkelflautes increases for the high-emission scenario by 5.81 and 3.4% for the RCP4.5 and RCP8.5, respectively, and slightly decreases by -2.64% for the low-emission scenario (RCP2.6). The separate factors causing the change of balance during dunkelflautes are: i) a decrease of the WIND production which tends to be stronger for the scenario of high emission (i.e. -17.4, -23.06 and -36.3% for the RCP2.6, RCP4.5 and RCP8.5, respectively); ii) an increase of the PV production; iii) a load that is increased by 1.43% for RCP2.6 scenario but decreased in by -0.83% and -0.97% for RCP4.5 and RCP8.5, respectively. The decreased load in the future for the two high emission scenarios is due to dependence of the load on temperature that is rising. A high load is currently associated with low temperature in the cold seasons which increases the demand for heating. Therefore, a rise in temperature during the cold seasons will decrease the need for heating which implies in turn a decrease of the load. The increased load for the lowest scenario is due to the warming being so little, that slightly more dunkelflautes occur in winter when the load is high (and less in the other seasons) compared to the historical period.

Commented [PV2]: I remember that the projections for future wind energy were different from model to model, correct? Which climate model is behind the numbers you quote here? Maybe include a paragraph which climate models are out there and what the results are?

In the far-future period (2051-2080), the trends are similar to the ones of the near future but, as expected, amplified in magnitude. The balance during dunkelflautes is projected to increase by 5.23%, 5.92% and 2.75% for RCP2.6, RCP4.5 and RCP8.5, respectively. The contributing factors for this increased balance are similar to the ones for the near future period: i) a decrease of WIND production (-25.08%, -45.43% and -44.55% for RCP2.6, RCP4.5 and RCP8.5, respectively); ii) an increase of PV production; iii) and a decreased load. As in the near future case, the decrease in load is due to the dependence of the load on temperature that has an even more pronounced rise in all three scenarios. In both future periods, the dominant cause of the increased balance is a reduction in WIND production during dunkelflaute events since it is the prevailing source of power production for the optimal balance for most of the dunkelflaute durations (i.e. all of them except 24-hours and 48-hours duration where the PV fraction is higher).

Finally, we studied the average changes. For those, PV and WIND productions were averaged here independently of the δ fraction, both fulfilling the 1MW/km^2 hypothesis. In the near future, PV production change is projected to be limited to less than one percent decrease in all three RCP scenarios. In the far future, PV production change is limited to just above -1% in two scenarios (RCP2.6 and RCP8.5) and half a percent decrease in RPC4.5. The WIND production change is not equal between the scenarios in the near future: +2.06%, -5.6% and 0.5% for the RCP2.6, RCP4.5 and RCP8.5, respectively. This unclear signal change in the coming decades could be caused by the natural variability of the climate that is still projected to be prevailing. In the far future, WIND production decrease is more aligned among the scenarios: -1.95%, -1.63% and -2.66% for the RCP2.6, RCP4.5 and RCP8.5, respectively. Finally, the load change is aligned with temperature changes in the future. In the near future, as temperature increase is relatively similar in all three scenarios, the load decrease is also comparable between the scenarios at around -0.7%. After 2050, as temperature differences between the RCPs are gradually stronger, the load follows those differences and decreases by -0.87%, -1.45% and -2.12% for the RCP2.6, RCP4.5 and RCP8.5, respectively.

- Temperature Change

To assess the possibility of the future need for heating or cooling in habitat, we investigate the future change of temperature in Belgium. More specifically, we look at the change of cold days/cold nights and warm days/warm nights as defined by the IPCC:

Cold days/cold nights: Days where maximum temperature, or nights where minimum temperature, falls below the 10th percentile, where the respective temperature distributions are generally defined with respect to the 1961-1990 reference period.

Warm days/warm nights: Days where maximum temperature, or nights where minimum temperature, falls above the 90th percentile, where the respective temperature distributions are generally defined with respect to the 1961-1990 reference period.

Three RCPs scenario (RCP2.6, 4.5, 8.5) were used to assess the uncertainty related to future emission pathways for the near future (2006-2050) compared to the past (1961-2005). The IPCC's definitions were used to define cold days and nights in winter and warm days and nights during the summer.

The frequency and magnitude of extreme events in the sense of cold days and nights are summarized in table 1. The total number of cold days in the historical period was of 380 and it decreases by 8% on average in the future. The average temperature during those past days was of -4.27°C but will only increase by 4.3%. The number cold nights will slightly decrease by 4% (from 1102 total events in the past) while their magnitude will barely change. For the warm days and nights summarized in table 2, the change in frequency is stronger. Indeed, the number of warm days and nights will increase by 72 and 29% respectively. However, the change in magnitude of the of the average temperature during those events will only increase by 3 and 2% respectively.

Winter	Historical	Future change
Number cold days	380	-30.33 (±23.01)
Temperature cold days	-4.27	0.18 (±0.17)
Number cold nights	1102	-42 (±37.99)
Temperature cold nights	-6.28	0 (±0.02)

Table 1 : number of winter extreme events during historical period and average near future change.

Summer	Historical	Future change
Number warm days	516	373 (±75.39)
Temperature warm days	17.37	0.43 (±0.16)
Number warm nights	1608	472 (±88.83)
Temperature warm nights	9.6	0.18 (±0.15)

Table 2 : number of summer extreme events during historical period and average near future change.

- Publications?

Title : Current-day and future dunkelflaute risks for Belgium.
Submitted in January to Renewable Energy, under review.

- Perspectives

The current research was based on a statistical analysis on the output of climate simulations. Such research about future high penetration of wind turbines and solar power plants would greatly benefit from climate simulations performed with parameterized REN production explicitly included inside the climate model. It would enable taking into account effects such as the removal of kinetic energy from the wind by the turbines or the albedo change on the soil from solar panels. The inclusion of wind turbine parameterizations inside ALARO is precisely one of the goals of the recently started BeFORECAST project.

Commented [PV3]: I would like also some information on this: how will this work be followed up beyond the EPOC project? Will there be other PhD students working on the topic? Thanks

1.1.1. Import – export of electricity in the Belgian system

UGent describing the fit and solutions
Publications?

1.1.2. TIMES 3-regional model results

- Most important results of TIMES net-zero scenario
- Sensitivity with generation adequacy
- Sensitivity with and without biofuels
- Publications planned?

1.2. Adequacy task

- Work on operating reserves and generation expansion planning
- Work on long term storage
- To be done
    - Note on data used in TIMES
    - Results: TIMES models with adequacy check
- What are the lessons for Elia/ENTSO-E?

[1] S. Gonzato, K. Bruninx, and E. Delarue, “An improved treatment of operating reserves in generation expansion planning models”, in PMAPS, Liège, Belgium, 2020.
[2] S. Gonzato, K. Bruninx, and E. Delarue, “Long term storage in generation expansion planning models with a reduced temporal scope,” Appl. Energy, vol. 298, no. May, p. 117168, 2021.

1.3. Security of supply task

- More extensive description of data used, and framework, as not every aspect is backed up by scientific papers
- How does this work compare to the adequacy work?
- What are the lessons for Elia/ENTSO-E?

[1] Dumas, J., Lanaspeze, D., Wehenkel, A., Cornélusse, B., & Sutera, A. (2021). Diepe generatieve modellering voor probabilistische voorspellingen in energiesystemen. Geaccepteerd in Toegepaste Energie.
[2] Dumas, J., Cointe, C., Wehenkel, A., Sutera, A., Fettweis, X., & Cornélusse, B. (2021). Een op probabilistische voorspellingen gebaseerde strategie voor een risicobewuste deelname aan de markt voor capaciteitsversterking. arXiv preprint arXiv:2105.13801. Ingediend bij IEEE Transactions on Sustainable Energy

1.4. Market & Consumer models

1.4.1. Scarcity pricing models

- Executive summary of papers
- Describe interactions with CREG

1.4.2. Imbalance actor model

- Executive summary of papers and thesis
- Link with other EPOC task?
- Conclusions for market players?

1.4.3. Market design task

- Executive summary of papers and thesis
- Link with other EPOC task?
- Conclusions for market players?

Note on communication and workshops (Imec)

ANNEXES