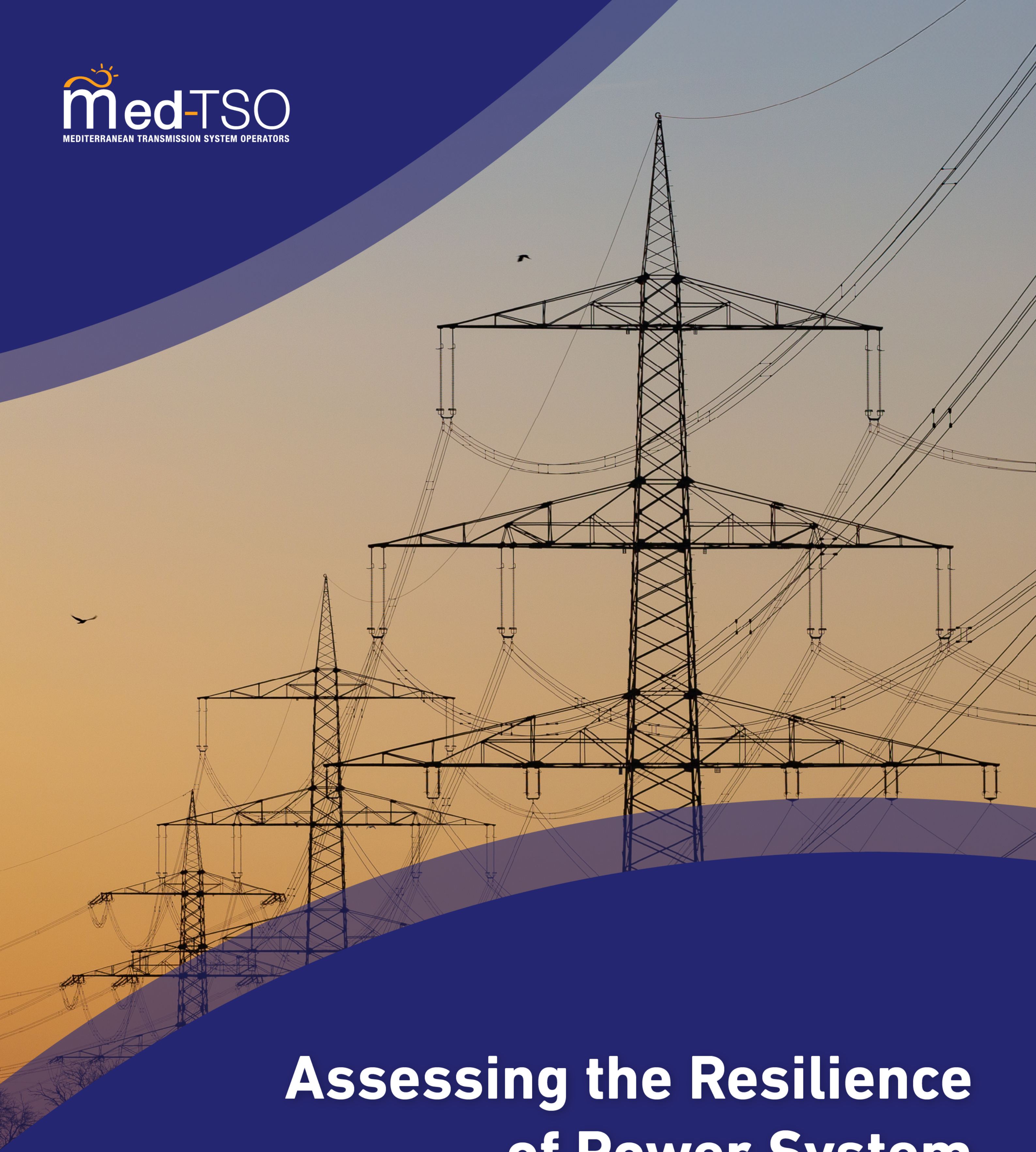
Med-TSO

MEDITERRANEAN TRANSMISSION SYSTEM OPERATORS



Assessing the Resilience of Power System

Flexibility needs assessment for selected Southern and Eastern Mediterranean countries TSOs

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Executive Summary

The decarbonisation of the electricity sector represents a cornerstone of global efforts to mitigate climate change. Achieving this transformation requires a decisive shift towards renewable energy, particularly solar and wind, and a corresponding reduction in reliance on conventional dispatchable generation.

This transition will fundamentally reshape power system operations. Transmission System Operators (TSOs) must therefore anticipate emerging challenges and implement proactive measures to safeguard system security and ensure adequacy in a future characterised by high shares of renewable energy.

The intermittent nature of solar and wind generation introduces new complexities. Their variability prevents a consistent alignment with daily, weekly, and seasonal demand profiles. As a result, power systems must increasingly depend on flexible resources capable of balancing fluctuations by supplying energy and reserves during peak demand and absorbing or curtailing excess generation during periods of low demand.

Furthermore, higher renewable penetration amplifies the volatility of the residual load (demand minus variable renewable generation), resulting in steeper ramping requirements. Addressing these dynamics demands a robust portfolio of flexible assets that can swiftly adjust output to maintain system balance and reliability.

This study quantifies the flexibility requirements necessary to support this evolving system landscape. It also explores how these needs are expected to evolve over time and evaluates the potential of enhanced interconnections with neighbouring countries to mitigate operational challenges and optimise resource use.

Six Med-TSO countries (Morocco, Tunisia, Libya[1], Egypt, Jordan and Lebanon) and three future scenarios covering 2025, 2027, and 2030, were assessed, each reflecting progressive increases in variable renewable capacity. Wind generation is projected to grow from 6 GW to 22 GW, and solar capacity from 8 GW to 23 GW. The analysis reveals a substantial rise in both flexibility and ramping needs over this period, underlining the scale of transformation required to maintain system resilience.

Finally, the comparison between an idealised “copper plate” scenario (where cross-border exchanges are unrestricted) and an “isolated operation” scenario (where no exchanges occur) underscores the strategic value of interconnections. Enhanced regional integration significantly reduces the system’s flexibility requirements by smoothing variability and optimising resource deployment across borders.

Investing in new interconnections and maximising the efficiency of their use through greater coordination among TSOs represents a crucial step towards building a resilient, secure, and fully decarbonised Mediterranean Power System.

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[1] Libya was missing from the mid-term data collection (2027 & 2030) due to limited engagement from the Libyan side.

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Introduction

Renewable energy sources, particularly solar and wind, are anticipated to play a significant role in the transition toward low-carbon power systems.

The generation from these energy sources is closely tied to their intermittent availability, which means they cannot consistently meet daily, weekly, or seasonal demand patterns. This situation requires resources capable of covering demand and providing reserve capacity during peak load hours, as well as storage solutions or curtailment strategies during periods of low demand ("overgeneration").

Furthermore, the integration of these energy sources may lead to more pronounced ramps in the "residual load" (demand minus variable renewable generation), necessitating flexible resources that can quickly adjust their output upwards or downwards as needed.

The objective of this study is to quantitatively assess the flexible resource requirements necessary to address the challenges outlined above. It will also provide insights into how these needs are expected to evolve over time and explore how interconnections with neighbouring countries could help mitigate these challenges.

It is important to note that power systems with a large share of renewables may also encounter stability and congestion issues, although these concerns fall outside the scope of this study.

The document is organised as follows:

- **Chapter 3:** Description of the methodology and key indicators
- **Chapter 4:** Overview of the case studies adopted in the assessment
- **Chapter 5:** Quantitative results of the assessment
- **Chapter 6:** Conclusions

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Methodology

In line with the approach adopted in the European Commission's study "Mainstreaming RES – Flexibility portfolios"[2], the first step in identifying appropriate flexible solutions to enable high levels of RES penetration in power systems is the evaluation of flexibility needs.

In this study, the methodological approach developed in the European Commission's studies "Mainstreaming RES – Flexibility portfolios"[2] and "Optimal flexibility portfolios for a high-RES 2050 scenario"[3] has been applied, integrating additional indicators to provide a more comprehensive assessment of flexibility needs.

In particular, the basic parameter of the analysis is the "residual load", which is the load that has to be supplied by dispatchable resources (thermal, hydro, storage, demand-response, interconnectors, etc.). It is computed by subtracting hourly wind and solar infeed from the hourly electricity demand.

The flexibility needs for power systems are assessed across different timeframes (hourly, daily, weekly, and yearly) using hourly residual load profiles (RL_h). Each indicator is computed for each country or for a set of countries by summing the residual load profiles of the countries belonging to the assessed set.

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[2] https://euneighbourseast.eu/wp-content/uploads/2021/07/mj0119583enn.en_.pd

[3] https://www.artelys.com/app/uploads/2019/04/S1-Optimal-flexibility-portfolios-for-a-high-RES-2050-scenario.pdf

Hourly Assessment

Residual Load ramp rates are assessed for each set of countries and for all the climate years' time series, considering 1 hour, 2-hour and 4-hour ramps:

$$RAMP1_h = RL_h - RL_{h-1}$$

$$RAMP2_h = RL_h - RL_{h-2}$$

$$RAMP4_h = RL_h - RL_{h-4}$$

Then, relevant statistics for each of the indicators are computed across their time series (including all the climate years together): 99th, 95th, 90th, 75th, 25th, 10th, 5th and 1st percentiles.

Daily Assessment

Assuming that a flat residual load profile would not require flexibility resources, the daily assessment quantifies how far the assessed residual load profile for each day deviates from a flat profile.

For this purpose, two indicators are adopted and computed.

ENERGY INDICATOR

For each climate year time series, the following procedure is applied:

1. For each day of the year, compute the daily average of the residual load:

$$AVG_d = \frac{\sum_{h\in d}\left(RL_h\right)}{24} \quad \forall d\in cy$$

2. For each day of the year, compute the sum, across all the hours of the day, of the difference (when positive) between the hourly residual load value and the daily average (computed at step 1):

$$FN_d = \sum_{h\in d}\left(MAX\left(0; RL_h - \left(AVG_d\right)\right)\right) \quad \forall d\in cy$$

3. Sum, across all the days of the year, the values obtained in the previous step: the result is expressed as a volume of energy per year (TWh per year):

$$FN_{daily,cy} = \sum_{d\in cy} FN_d$$

$$FNMAX_{daily,cy} = MAX(FN_d)$$

POWER INDICATOR

For each climate year time series, the following procedure is applied:

1. For each day of the year, compute the difference between the maximum and the minimum hourly residual load value:

$$FNP_{d,cy} = MAX\left(RL_{h\in d}\right) - MIN\left(RL_{h\in d}\right) \forall d \in cy$$

2. Compute relevant statistics across the daily values:

$$FNP_{daily,x,cy} = percentile(FN1_{d,cy}; x)$$

Then, for each of the indicators (ENERGY and POWER) relevant statistics are computed across all the assessed climate years.

Weekly Assessment

For each climate year time series, the following procedure is applied:

1. For each week of the year, compute the weekly average of the residual load:

$$AVG_{w} = \frac{\sum_{h\in w}\left(RL_{h}\right)}{168} \forall w \in cy$$

2. For each day of the week, compute the daily average of the residual load:

$$AVG_{d} = \frac{\sum_{h\in d}\left(RL_{h}\right)}{24} \forall d \in w,\ \forall w \in cy$$

3. For each week of the year, compute the sum, across all the days of the week, of the difference (when positive) between the average daily residual load value (computed at step 2) and the weekly average (computed at step 1):

$$FN_{w,cy} = \sum_{d\in w}\left(MAX\left(0; AVG_{d} - AVG_{w}\right)\right) \forall w \in cy$$

4. Sum, across all the weeks of the year, the values obtained in the previous step: the result is expressed as a volume of energy per year (TWh per year).

$$FN_{weekly,cy} = \sum_{w\in cy} FN_{w}$$

$$FNMAX_{weekly,cy} = MAX(FN_{w})$$

Then, relevant statistics are computed across all the assessed climate years.

Yearly Assessment

For each climate year time series, the following procedure is applied:

1. Compute the yearly average of the residual load:

$$AVG_y = \frac{\sum_{h \in y} \left(RL_h \right)}{8760}$$

2. For each month of the year, compute the monthly average of the residual load ($\#h_m$ is the number of hours in the given month):

$$AVG_m = \frac{\sum_{h \in m} \left(RL_h \right)}{\#h_m} \forall m \in cy$$

3. Compute the sum, across all the months of the year, of the difference (when positive) between the average monthly residual load value (computed at step 2) and the yearly average (computed at step 1):

$$FN_{yearly,cy} = \sum_{m \in cy} \left(MAX\left(0; AVG_m - AVG_y\right)\right)$$

$$FNMAX_{yearly,cy} = MAX(FN_m)$$

Then, relevant statistics are computed across all the assessed climate years.

4

Assessed Case Studies

For the case studies, we focus on the same six countries previously analysed in our adequacy assessment: Morocco, Tunisia, Libya[4], Egypt, Jordan, and Lebanon.

To support the analysis, we rely on the Pan-European Climate Database (PECD), for all the cases. The database is divided into two sections:

- Climate data, which includes city temperatures, population-weighted temperatures, solar irradiance, and relative humidity.
- Energy data, which provides wind and solar capacity factors.

PECD was developed by ENTSO-E in collaboration with the Copernicus Climate Change Service (C3S). It provides consistent, high-quality data adapted for energy modelling at national levels, making it highly valuable for coordinated assessments across the Mediterranean region.

Med-TSO heavily relies on PECD data for:

- Demand Forecasting: Using multiple climatic years to simulate all possible demand scenarios over short- and long-term horizons.

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[4] Libya was missing from the mid-term data collection (2027 & 2030) due to limited engagement from the Libyan side.

- Variable Renewable Energy Sources (vRES) Profiling: Depending on weather conditions and capacity factors of different technologies we can generate vRES profiles using multiple climatic years to simulate all possible vRES profiles over short- and long-term horizons.

In previous editions of our adequacy assessment (summer outlook 2025), we relied on PECD 3.5, which was based on adjusted historical weather and climate data. The hourly time series data, which cover 38 climate years (1982-2019) for PECD 3.5, are essential for our long-term market studies, as well as for seasonal adequacy assessments. These data are often used in Monte Carlo simulations to reflect different climate conditions and uncertainties.

Whilst useful, this approach was limited in its ability to capture renewable energy behaviour under evolving climate conditions, as the coverage of future climate projections was restricted.

Thanks to the cooperation agreement between Med-TSO and ENTSO-E, we gained early access to the newly released PECD v4.2 (2025 edition). This updated dataset includes both long-term historical records (from 1950 onwards) and forward-looking climate projections based on four Shared Socioeconomic Pathways (SSPs) and six CMIP6 climate models, covering the period 2015-2100. Developed by the Copernicus Climate Change Service (C3S), PECD v4.2 provides scientifically robust futures rather than relying solely on past data.

By integrating PECD v4.2, the Mid-term Adequacy Assessment 2027 and 2030 is now able to simulate electricity demand, renewable output, and cross-border flows with hourly resolution across multiple climate scenarios. This offers a much clearer picture of how extreme weather events, seasonal variability, and long-term climate shifts could impact adequacy risks. Overall, it represents a major methodological step forward and significantly strengthens the robustness

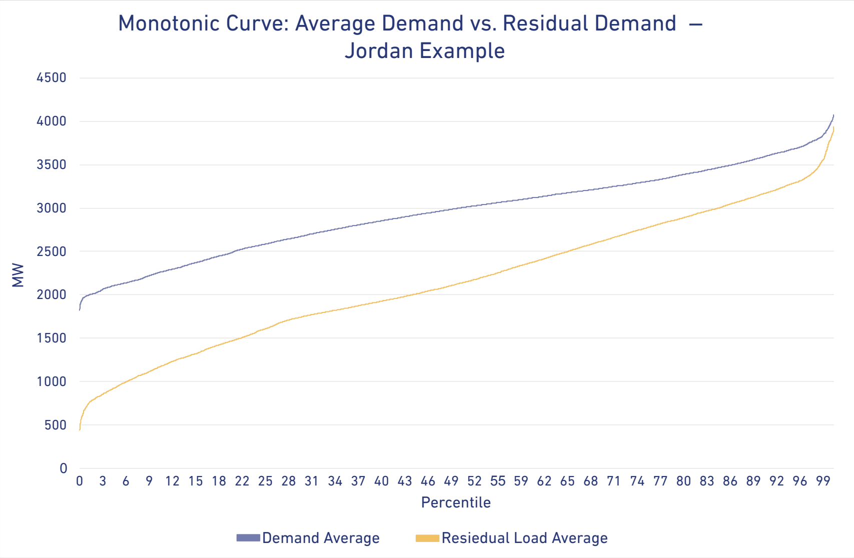
Key indicators

The chart below illustrates the duration curve of Jordan’s average hourly electricity demand and residual demand over a year, plotted against percentiles.

- Demand average: This represents the sorted hourly electricity demand from highest to lowest. It gives a view of how demand varies throughout the year.
- Residual load average: This is the demand remaining after accounting for renewable energy sources (vRES), i.e. residual load = demand - vRES generation.
- Percentiles are used to express how demand and residual load values are distributed across the year. In a monotonic (duration) curve, Each percentile (0–100%) represents a point in the sorted time series, with 0% being the minimum value and 100% the maximum.

Lower percentiles (e.g. 1st percentile) highlight the importance of identifying critical low-residual load conditions, which are relevant for assessing system minimum load coverage and the potential curtailment of renewables.

By comparing demand and residual load curves at various percentiles, we can assess how much load is offset by RES, not just on average, but across the full spectrum of operating



4.1 Short-term case study

The short-term case study is based on 2025 data collected by February 2025 and uses PECD3.5.

The table below summarises key electricity system indicators for the selected Southern and Eastern Mediterranean countries. It includes installed capacities for wind, solar PV, and solar thermal; average annual electricity demand; and two hourly load metrics: 1st percentile hourly demand and residual load, reflecting system behaviour during low-load periods and the impact of vRES generation.

Country	Installed Wind [GW]	Installed Solar PV [GW]	Installed Solar CSP [GW]	Avg Yearly Demand [TWh]	1st Percentile Hourly Demand [GW]	1st Percentile Hourly Residual Load [GW]	Reduction of Minimum Load Induced by vRES [5]	Extreme vRES Penetration [6]
Egypt	3.04	3.13	0.14	255.95	21.22	19.47	8%	17%
Jordan	0.62	2.20	0.00	25.83	1.99	0.73	64%	79%
Lebanon	0.00	1.30	0.00	23.73	1.71	1.66	3%	33%
Libya	0.00	0.05	0.00	43.80	3.24	3.24	0%	0.9%
Morocco	2.41	0.62	0.54	47.66	3.95	2.55	35%	47%
Tunisia	0.23	0.44	0.00	22.41	1.67	1.54	8%	21%

Table 1 Electricity vRES Installed Capacities and Demand Overview (2025)

A brief description of the key findings follows

Egypt has the highest average yearly electricity demand among the assessed countries (255.95 TWh), reflecting the largest grid size and load base. It also has the highest installed capacity of wind (3.04 GW) and solar PV (3.13 GW), along with 0.14 GW of solar thermal. Despite these sizeable capacities, the impact of renewables during low-demand hours remains limited. The 1st percentile hourly demand is 21.22 GW, and the corresponding residual load is 19.47 GW, meaning that wind and solar together reduce the load by only 1.75 GW or roughly 8% of the demand during those conditions. This shows that, although Egypt is making progress in vRES deployment, the penetration of wind and solar remains low relative to its large demand, and their contribution during low-load periods is still modest. Additionally, even under the most favourable conditions, the maximum observed vRES contribution ("extreme vRES penetration") reaches only 17% of demand.

Jordan shows strong solar PV development relative to its smaller electricity demand. With 2.20 GW of PV and only 0.62 GW of wind, Jordan's renewable mix is solar dominated. Average yearly demand is 25.83 TWh, much lower than Egypt's, but the impact of solar is more significant in relative terms. The 1st percentile hourly demand is 1.99 GW, while the residual load at that same percentile is just 0.73 GW. This indicates that solar PV is capable of covering a large portion of the demand even in the lowest load periods, reducing the net load by 1.26 GW or roughly 64% of the demand during those conditions. The system benefits from the alignment of solar generation with demand and from relatively high penetration levels,

[5] This metric provides an indicator of the system's vulnerability to overgeneration risks and flexibility needs during extreme low-demand periods characterised by high-RES infeed.

[6] This metric gives an indicator of high-stress periods (in terms of RES penetration) across all simulated scenarios considered. It helps assess the need for flexibility, storage, or curtailment mechanisms under extreme RES conditions.

making Jordan one of the most solar-active countries in the region during low-load hours. At its maximum, Jordan's vRES penetration can reach up to 79%, reflecting an extremely high renewable contribution during periods of maximum generation.

Lebanon has 1.30 GW of solar PV installed and no wind or solar thermal capacity. Average yearly demand stands at 23.73 TWh. During the 1st percentile demand hour, the system load is 1.71 GW, with a residual load of 1.66 GW. This indicates that solar PV makes a very limited contribution during the lowest demand periods, with only 0.05 GW of net load reduction or roughly 3% of the demand during those conditions. Overall, vRES in Lebanon does not significantly affect net load patterns during the most critical low-load moments. Even under the most resource-rich conditions, Lebanon's extreme vRES penetration reaches around 33%, indicating a moderate but limited renewable contribution.

Libya, with only 0.05 GW of solar PV and no wind or solar thermal, has an average yearly demand of 43.80 TWh. The 1st percentile hourly demand is 3.24 GW, and the residual load is exactly the same (3.24 GW), indicating zero contribution from renewables during these low-demand conditions. This reflects a fully conventional generation-based system with no flexibility from variable RES. Libya's system remains entirely reliant on fossil generation even during low-demand periods, with no mitigation of net load by renewable sources. Its extreme vRES penetration is only 0.9%, highlighting the minimal role of renewables even under ideal conditions.

Morocco presents a more balanced renewable mix, with 2.41 GW of wind, 0.62 GW of solar PV, and 0.54 GW of solar thermal. The yearly demand is 47.66 TWh. During the lowest 1% demand hours, the total system load is 3.95 GW, while the residual load drops to 2.55 GW. This 1.40 GW demand reduction or roughly 35% reflects a meaningful contribution of renewables, particularly from the combined effect of wind and solar thermal, which can support evening and night demand better than PV alone. Morocco's diversified vRES portfolio allows it to reduce its residual load during critical periods more effectively than countries relying solely on PV. Solar thermal in particular adds flexibility to the system and strengthens the role of renewables in balancing the load. Morocco's extreme vRES penetration can reach 47%, demonstrating strong renewable output potential during peak renewable generation periods.

Tunisia has a modest level of renewable capacity: 0.23 GW of wind and 0.44 GW of solar PV, with no solar thermal. The average yearly demand is 22.41 TWh. At the 1st percentile demand hour, the total load is 1.67 GW, and residual load is 1.54 GW, implying that renewables reduce the load by only 0.13 GW or roughly 8% of the demand during those conditions. The limited vRES penetration and small absolute capacities mean that the impact on the system's low-load conditions remains minor. While some progress has been made in integrating solar and wind, Tunisia still depends largely on conventional generation to meet demand, even during periods of low system stress. Tunisia's maximum vRES penetration reaches around 21%, offering only moderate renewable contribution at best.

4.2 Mid-term case study

The mid-term case study is based on data for the years 2027 and 2030, collected by May 2025 and based on PECD4.2.

The table below summarises key electricity system indicators for the selected Southern and Eastern Mediterranean countries. It includes installed capacities for wind, solar PV, and solar thermal; average annual electricity demand; and two hourly load metrics, 1st percentile hourly demand and residual load, reflecting system behaviour during low-load periods and the impact of vRES generation.

Country	Installed Wind [GW]	Installed Solar PV [GW]	Installed Solar Thermal [GW]	Avg Yearly Demand [TWh]	1st Percentile Hourly Demand [GW]	1st Percentile Hourly Residual Load [GW]	Minimum Load Reduction Induced by vRES	Extreme vRES Penetration
Egypt	4.34	6.49	0.14	258.14	20.82	16.91	19%	30%
Jordan	0.62	2.85	0.00	27.71	2.02	0.59	71%	86%
Lebanon	0.00	1.67	0.00	24.98	1.81	1.67	8%	42%
Morocco	4.87	3.52	0.54	58.30	4.82	1.81	63%	85%
Tunisia	0.32	1.88	0.00	24.20	1.81	0.89	51%	68%

Table 2 Electricity vRES Installed Capacities and Demand Overview (2027)

Country	Installed Wind [GW]	Installed Solar PV [GW]	Installed Solar Thermal [GW]	Avg Yearly Demand [TWh]	1st Percentile Hourly Demand [GW]	1st Percentile Hourly Residual Load [GW]	Minimum Load Reduction Induced by vRES	Extreme vRES Penetration
Egypt	13.24	8.04	0.14	292.66	23.48	14.46	38%	54%
Jordan	0.85	3.62	0.00	34.92	2.61	0.65	75%	88%
Lebanon	0.23	2.13	0.00	27.30	1.98	1.57	20%	50%
Morocco	5.87	5.07	0.54	70.43	5.82	1.79	69%	89%
Tunisia	1.64	3.29	0.00	27.30	2.04	-0.41	120%	127%

Table 3 Electricity vRES Installed Capacities and Demand Overview (2030)

Situation in 2027

In 2027, the five assessed Mediterranean countries show steady progress in renewable energy deployment, with visible impacts on system load patterns and residual demand.

Egypt has the highest average yearly electricity demand among the assessed countries (258.14 TWh), reflecting the largest system size and load base. Installed vRES capacities reach 4.34 GW of wind, 6.49 GW of solar PV, and 0.14 GW of solar thermal. During the 1st percentile hourly demand (20.82 GW), the residual load falls to 16.91 GW, a reduction of 19%. Despite large renewable capacities, the impact on low-load periods remains moderate due to Egypt's vast demand. The maximum ("extreme") vRES penetration reaches 30%, confirming a still limited but improving contribution of renewables during peak output conditions.

Jordan continues to demonstrate strong progress in solar PV, with 2.85 GW of installed PV and 0.62 GW of wind. With an average yearly demand of 27.71 TWh, the 1st percentile hourly demand is 2.02 GW, and the residual load decreases to 0.59 GW, a 71% reduction. Jordan's extreme vRES penetration reaches 86%, highlighting a highly solar-active system and an effective renewable contribution during low-demand hours.

Lebanon relies solely on solar PV, totalling 1.67 GW, with no wind or solar thermal capacity. The average yearly demand is 24.98 TWh. At the 1st percentile hourly demand (1.81 GW), the residual load is 1.67 GW, corresponding to an 8% reduction. Although the installed capacity has grown, the contribution of PV to the lowest load conditions remains modest. The extreme vRES penetration reaches 42%, reflecting moderate renewable integration.

Morocco presents a balanced renewable mix with 4.87 GW of wind, 3.52 GW of solar PV, and 0.54 GW of solar thermal. The average yearly demand is 58.30 TWh. The 1st percentile hourly demand is 4.82 GW, while the residual load decreases to 1.81 GW, a 63% reduction. The combination of wind, PV, and solar thermal enhances system flexibility, allowing extreme vRES penetration to reach 85% , which is one of the highest in the region.

Tunisia has a moderate renewable base with 0.32 GW of wind and 1.88 GW of PV. The average yearly demand is 24.20 TWh. The 1st percentile hourly demand is 1.81 GW, while the residual load decreases to 0.89 GW, a 51% reduction. The extreme vRES penetration reaches 68%, showing an improving renewable impact on low-load hours, although further integration efforts are still needed.

Situation in 2030

By 2030, renewable deployment accelerates significantly in all countries, resulting in deeper load reductions and much higher vRES penetration levels.

Egypt expands its renewable portfolio to 13.24 GW of wind, 8.04 GW of solar PV, and 0.14 GW of solar thermal. Average yearly demand increases to 292.66 TWh. The 1st percentile hourly demand is 23.48 GW, and the corresponding residual load decreases to 14.46 GW, a 38% reduction, which is double the 2027 value. The extreme vRES penetration climbs to 54%, showing a substantial strengthening of the role of renewables, although Egypt's large load base continues to limit the relative share.

Jordan further enhances its PV capacity to 3.62 GW and wind to 0.85 GW, with demand growing to 34.92 TWh. The 1st percentile hourly demand (2.61 GW) and residual load (0.65 GW) yield a 75% reduction. The extreme vRES penetration reaches 88%, confirming Jordan's leading regional position in solar integration and its near-complete renewable supply during certain daytime conditions.

Lebanon introduces 0.23 GW of wind and increases PV capacity to 2.13 GW. The average yearly demand is 27.30 TWh. The 1st percentile hourly demand is 1.98 GW, and the residual load is 1.57 GW, representing a 20% reduction. While vRES integration improves compared to 2027, renewables still play a limited role during the lowest-load hours. The extreme vRES penetration increases to 50%, marking gradual progress in solar utilization.

Morocco continues to diversify its mix, reaching 5.87 GW of wind, 5.07 GW of solar PV, and 0.54 GW of solar thermal. With an average yearly demand of 70.43 TWh, the 1st percentile hourly demand (5.82 GW) and residual load (1.79 GW) indicate a 69% reduction. The extreme vRES penetration reaches 89%, consolidating Morocco's leadership in renewable balancing and flexibility.

Tunisia undergoes the most striking transformation, expanding to 1.64 GW of wind and 3.29 GW of PV, while demand rises to 27.30 TWh. The 1st percentile hourly demand (2.04 GW) results in a negative residual load of –0.41 GW, meaning vRES generation exceeds system demand during certain hours, equivalent to a 120% reduction. The extreme vRES penetration reaches 127%, indicating surplus renewable generation that could support exports or require curtailment and storage solutions.

4.3 Comparison between case studies

Between 2025 and 2030, the Southern and Eastern Mediterranean countries show a clear acceleration in renewable energy deployment, particularly in wind and solar PV capacities, leading to notable impacts on minimum load levels and extreme vRES penetration.

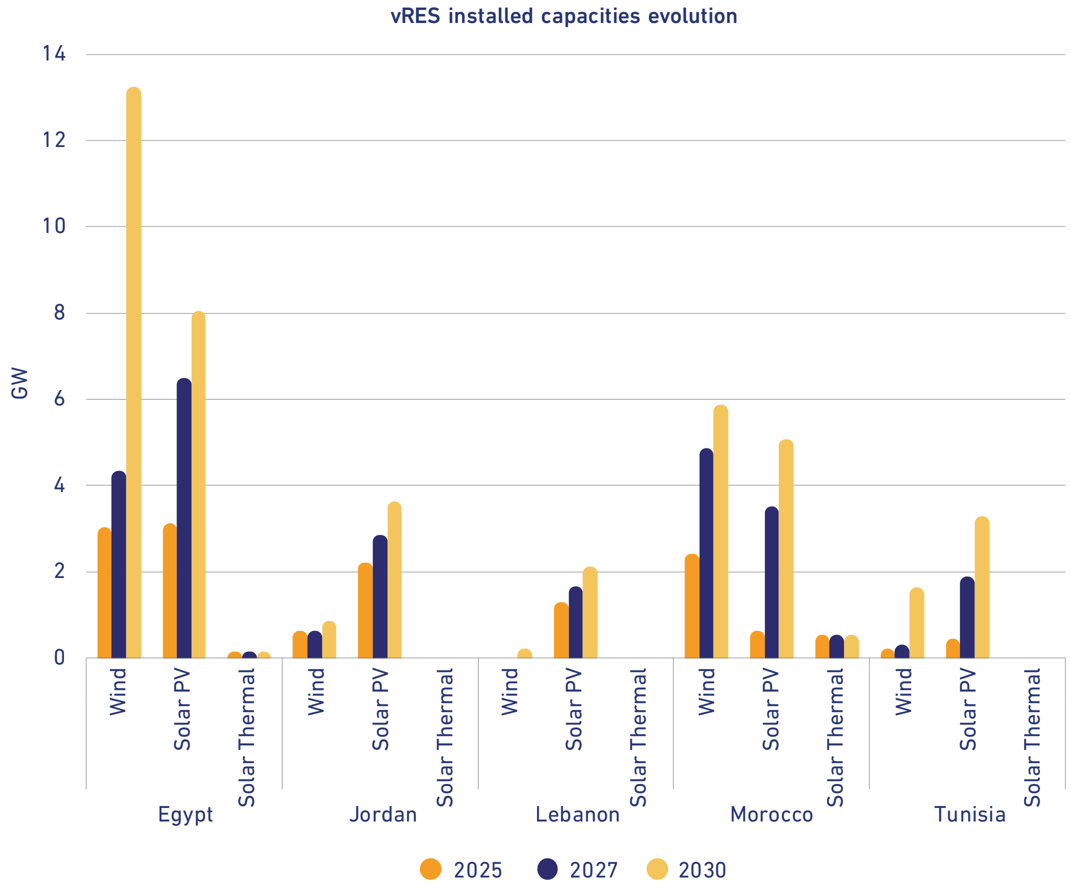


Figure 1 Comparative Overview of Renewable Energy Expansion (2025-2027-2030)

In 2025, renewable integration was still moderate. Egypt and Morocco presented the highest installed capacities, reaching 3.04 GW of wind and 3.13 GW of solar PV, and 2.41 GW of wind and 0.62 GW of solar PV, respectively. The reduction of minimum load induced by vRES remained limited: 8% in Egypt and 35% in Morocco, while other countries like Jordan (64%) and Tunisia (8%) showed localised but growing vRES impacts. Libya's system remained almost unchanged, with negligible renewable penetration (below 1%).

By 2027, significant capacity additions were realised, particularly in Egypt, where installed PV more than doubled to 6.49 GW, and wind increased to 4.34 GW. Morocco also saw a substantial jump to 4.87 GW of wind and 3.52 GW of solar PV, while Tunisia and Jordan reached 1.88 GW and 2.85 GW of PV, respectively.

These developments resulted in a marked rise in extreme vRES penetration, reaching 85% in Morocco, 86% in Jordan, and 68% in Tunisia. The minimum load reduction induced by vRES also intensified, reflecting higher variability and increasing system flexibility challenges.

In 2030, all countries, particularly Egypt and Morocco, continued this upward trend. Egypt's wind capacity tripled compared to 2025, reaching 13.24 GW, while solar PV reached 8.04 GW, resulting in an extreme vRES penetration of 54% and a minimum load reduction of 38%.

Tunisia showed a remarkable shift, with its minimum load reduction exceeding 100%, meaning that vRES generation can surpass the total system demand during certain hours. Morocco maintained its leading position, with 89% extreme vRES penetration and a 69% reduction in minimum load, indicating an increasingly renewable-dominant system.

Jordan and Lebanon continued to expand moderately, while Libya remained largely fossil-based with minimal vRES integration.

5

Flexibility needs

In the Hourly Assessment section, the figures report, for each assessed climate year separately, key percentiles (1st, 5th, 10th, 25th, 75th, 90th, 95th, 99th) and the average value of the:

- 1h residual load ramp rates indicator time series
- 2h residual load ramp rates indicator time series
- 4h residual load ramp rates indicator time series

At the top of the figure, the same percentiles (and the average value) across all the climate years are reported.

5.1 Short-term case study

The short-term case study, whose key data are described in Chapter 4.1, has been assessed by computing the key indicators described in Chapter 3 for each individual country and for the aggregated area. The main results are reported in the following tables and described in this chapter.

The aggregated area assessment is conducted by computing the residual load of the whole area (by summing, on an hourly basis, the load of all the countries and subtracting the sum of the RES infeed). This is a proxy for a power system covering all the countries in the case of no cross-border capacity constraints. The comparison between the indicators obtained for the aggregated area and the sum of the individual country indicators allows the benefits deriving from interconnections to be highlighted in terms of flexibility needs reduction.

Country	Ramp 1h [MW/h]			Ramp 2h [MW/h]			Ramp 4h [MW/h]		
	5th perc.	Avg.	95th perc.	5th perc.	Avg.	95th perc.	5th perc.	Avg.	95th perc.
Egypt	85	780	1847	175	1473	3393	469	2621	5609
Jordan	17	194	568	30	370	1046	70	670	1638
Lebanon	7	104	274	13	201	492	23	371	884
Libya	14	168	380	22	316	750	40	562	1279
Morocco	13	203	527	26	383	963	52	651	1564
Tunisia	7	95	239	14	178	448	21	303	740
Total	**143**	**1544**	**3835**	**280**	**2921**	**7092**	**675**	**5178**	**11714**
Aggregated	126	1226	3101	330	2389	5884	918	4519	9911

Country	FNdaily [TWh] (average)	FNMAXdaily [GW] (average)	FNP_50_daily [MW] (average)	FNweekly [TWh] (average)	FNMAXweekly [GW] (average)	FNyearly [GWh] (average)
Egypt	9.24	34.8	9217	0.13	6.4	17.91
Jordan	2.67	10.3	2121	0.03	1.2	1.05
Lebanon	1.48	5.6	1150	0.02	1.0	1.06
Libya	2.18	7.9	1818	0.04	2.4	3.2
Morocco	2.31	10.4	2043	0.05	1.8	1.38
Tunisia	1.06	4.4	988	0.03	1.4	2.14
Total	**18.94**	**73.4**	**17337**	**0.30**	**14.2**	**26.74**
Aggregated	17.14	60.7	14633	0.18	7.8	23.81

In the Daily Assessment section, the power indicator is shown for each climate year; while, in the Weekly Assessment section the focus is on the maximum weekly value of flexibility need. Finally, in the Yearly Assessment, the total long-term amount of flexibility needs, in terms of energy, is represented.

Aggregated area

Hourly Assessment

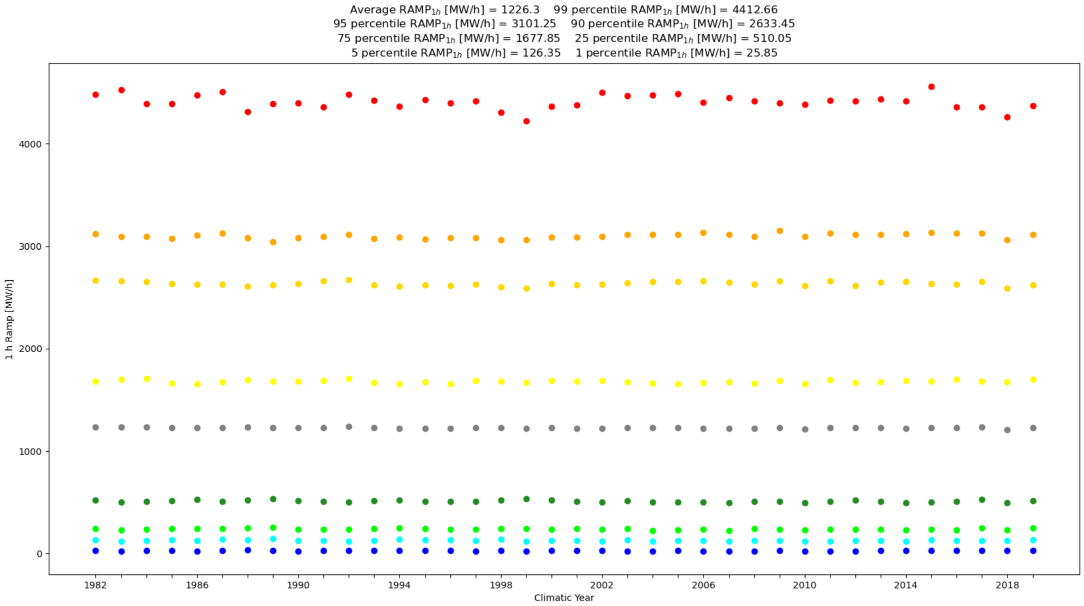
The following figures show substantial stability of the indicators across the different climate years and a greater stability than individual countries. Only the 99th percentile shows some variability. The ramps have a higher absolute value in winter months compared to the summer months due to the reduction in residual load. Within the same day, the ramps show a high evening peak on winter days and two smoother peaks (one in the morning and one in the evening) on summer days.

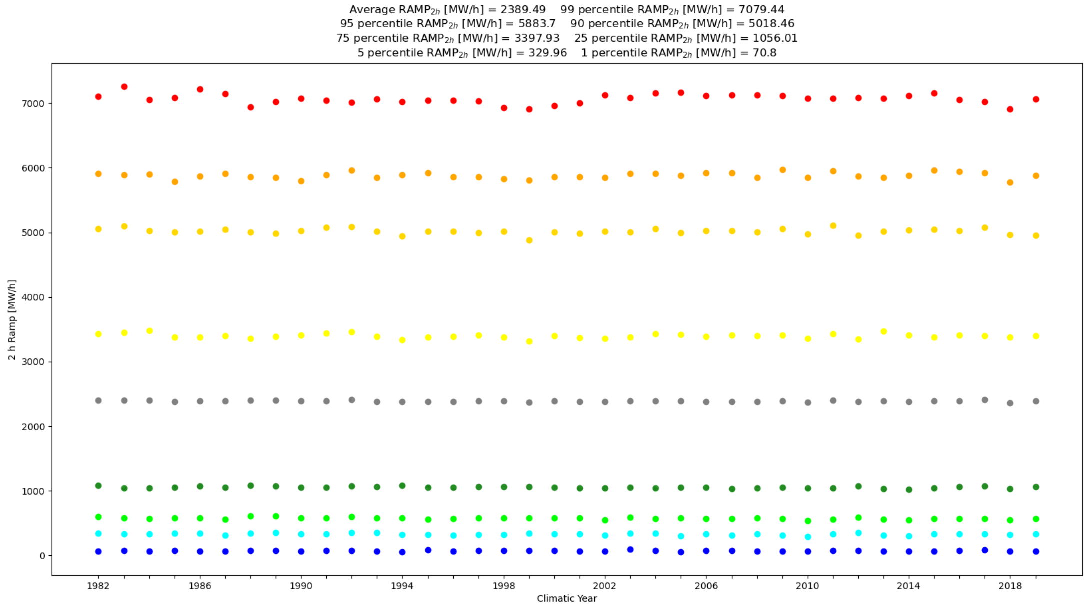
The 1h residual load ramp rate could reach values greater than 3.1 GW/h for 5% of the hours of the year (and greater than 4.4 GW/h for 1% of the hours of the year).

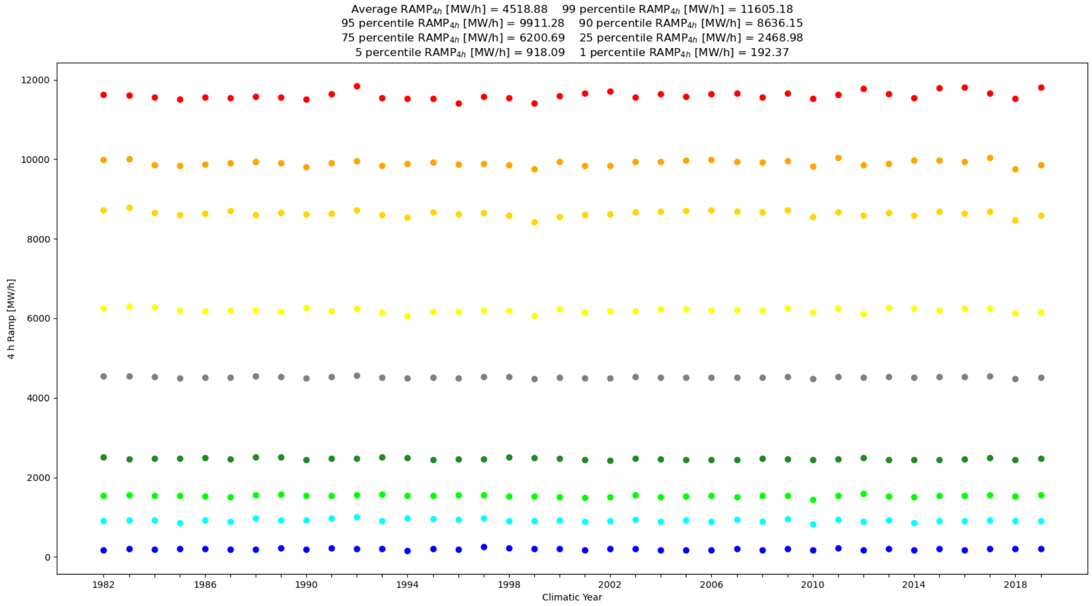
The 2h residual load ramp rate could reach values greater than 5.9 GW/2h for 5% of the hours of the year (and greater than 7.1 GW/2h for 1% of the hours of the year).

The 4h residual load ramp rate could reach values greater than 9.9 GW/4h for 5% of the hours of the year (and greater than 11.6 GW/4h for 1% of the hours of the year).

Even in this case, enlarging the time scale for assessing the ramp smooths the derivative but highlights the necessity of flexible resources to follow ramp rates of several GW over a few hours.







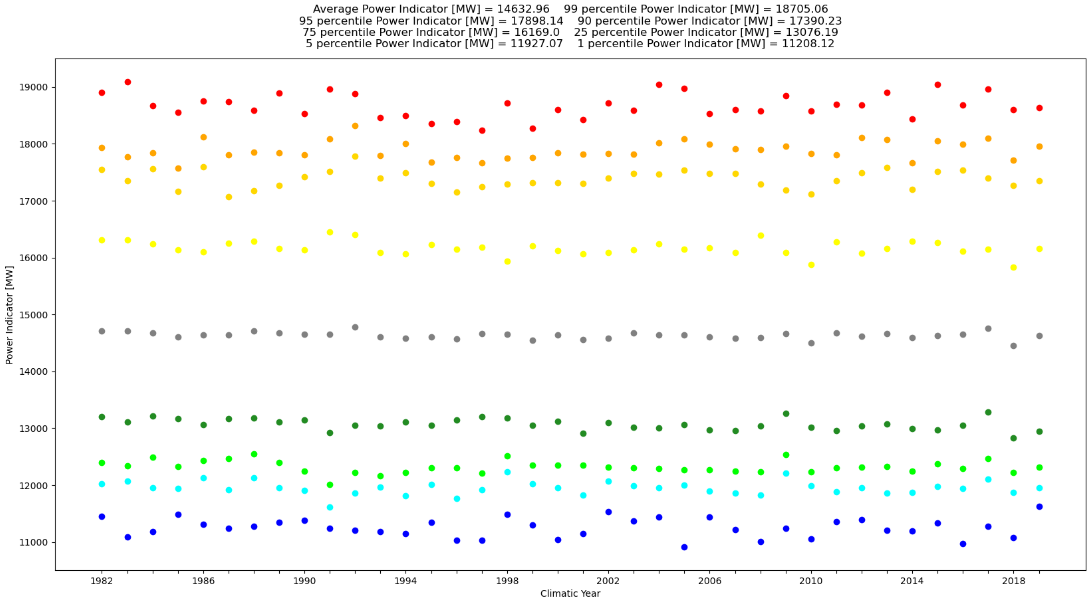
Daily Assessment

The daily energy indicator FN$_{daily}$ shows little variation within the whole time series (and across climate years): the 99th percentile is 17.32 TWh, the 1st percentile is 16.94 TWh and the average value is 17.14 TWh.

The daily energy indicator FNMAX$_{daily}$ shows little variation across climate years, remaining in the range between 58 GWh and 65 GWh for all the assessed climate years, with a mean value of about 60.7 GWh. This represents the maximum amount of flexibility needed on a daily basis.

The power indicator is reported in the figure below for each climate year and relevant percentile.

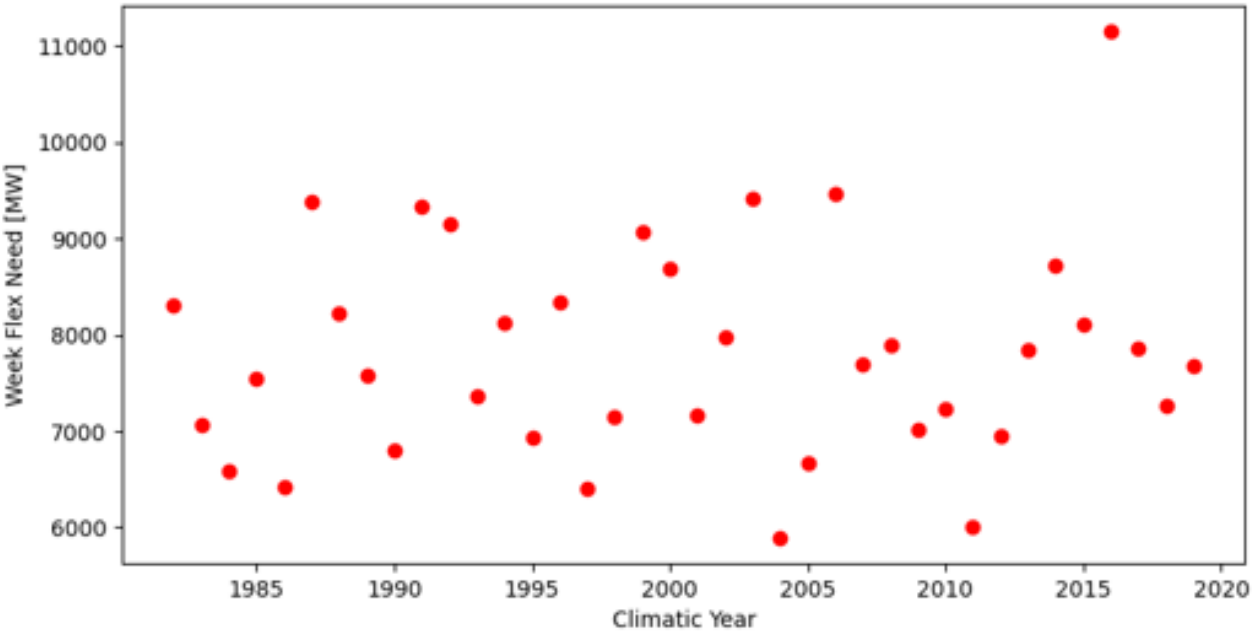
The average value across the whole time series (and climate years) is about 14.6GW, which represents the average difference between daily minimum and maximum residual load values. This difference can rise to 17.9 GW for 5% of the days and up to 18.7 GW for 1% of the days.



Weekly Assessment

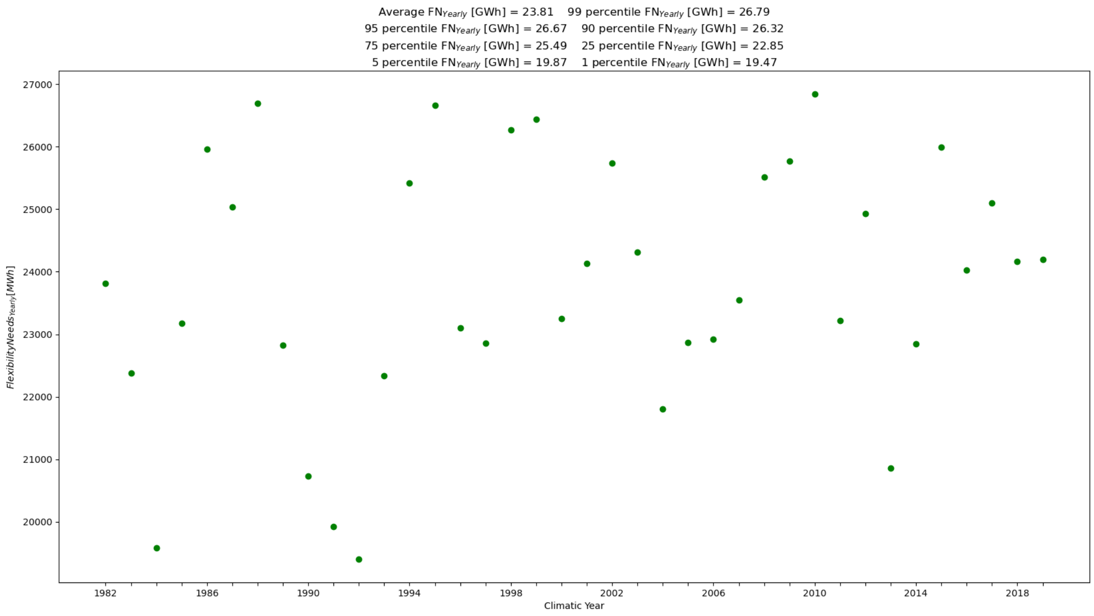
The weekly energy indicator FN_{weekly} shows very little variation across the whole time series (and across climate years) compared to the daily ones: the 99th percentile is 0.2TWh, the 1st percentile is 0.16TWh and the average value is 0.18TWh. This indicator assumes values that are one order of magnitude lower than the corresponding daily indicator. This means there are no significant variations in terms of residual load between days of the same week. This characteristic is consistent with what has been observed for each country individually.

The weekly energy indicator $FNMAX_{weekly}$ is on average (across all the climate years) about 7.8 GW. This represents the maximum amount of flexibility needed on a weekly basis. However, this indicator shows a peak for the 2016 climate year (of about 11.0 GW, see figure below).



Yearly Assessment

The yearly energy indicator FN$_{yearly}$ shows little variation across the whole time series (and across climate years): the 99th percentile is 26.8 GWh, the 1st percentile is 19.5 GWh and the average value is 23.8 GWh. This indicator assumes values that are very low compared to the weekly and, especially, the daily indicators. This means there is no significant variation in terms of residual load between months of the same year.



5.2 Mid-term case study

The mid-term case study for the 2027 and 2030 years has also been assessed, computing the same key indicators described in Chapter 3 for each individual country and for the aggregated area. The main results are reported in the following tables and described in this chapter. In the cases analysed, the average value increased in MT2027 and MT2030, while the extreme values showed greater dispersion.

Also in this case, the aggregated area assessment is carried out by computing the residual load of the whole area by summing, on an hourly basis, the load of all the countries and subtracting the sum of the RES infeed).

Country	Year	Ramp 1h [MW/h]			Ramp 2h [MW/h]			Ramp 4h [MW/h]		
		5th perc.	Avg.	95th perc.	5th perc.	Avg.	95th perc.	5th perc.	Avg.	95th perc.
Egypt	2027	120	850	1977	225	1596	3446	361	2857	5367
Egypt	2030	79	899	2153	144	1661	3757	296	2906	6090
Jordan	2027	18	205	638	38	392	1074	78	701	1619
Jordan	2030	23	273	873	49	523	1483	102	937	2213
Lebanon	2027	8	121	310	25	234	570	38	420	952
Lebanon	2030	10	147	382	29	285	697	43	511	1161
Morocco	2027	19	270	688	39	511	1245	72	867	2018
Morocco	2030	27	362	920	55	686	1674	98	1162	2682
Tunisia	2027	11	148	385	21	281	710	40	486	1196
Tunisia	2030	12	224	655	25	429	1224	51	764	2027
Total	**2027**	176	1594	3998	348	3014	7045	589	5331	11152
Total	**2030**	151	1905	4983	302	3584	8835	590	6280	14173
Aggregated	2027	123	1195	2879	270	2301	5364	522	4220	9086
Aggregated	2030	98	1327	3472	194	2537	6386	381	4625	10786

Country	Year	FNdaily [TWh] (average)	FNMAXdaily [GW] (average)	FNP_50_daily [MW] (average)	FNweekly [TWh] (average)	FNMAXweekly [GW] (average)	FNyearly [GWh] (average)
Egypt	2027	11.56	45.1	9791	0.16	8	19.49
Egypt	2030	11.69	63.5	10011	0.3	12.5	22.01
Jordan	2027	2.63	11.4	2244	0.03	1.5	1.28
Jordan	2030	3.54	15.2	2985	0.04	1.8	1.47
Lebanon	2027	1.51	6	1227	0.02	1	1.2
Lebanon	2030	1.81	7.2	1505	0.02	1.1	1.3
Morocco	2027	2.55	14.3	2426	0.08	3.3	2.11
Morocco	2030	3.35	17.6	3193	0.1	3.9	2.58
Tunisia	2027	1.55	7.1	1484	0.03	1.6	2.19
Tunisia	2030	2.75	13.3	2382	0.05	2.6	2.51
Total	**2027**	**19.8**	**83.9**	**17172**	**0.32**	**15.4**	**26.27**
Total	**2030**	**23.14**	**116.8**	**20076**	**0.51**	**21.9**	**29.87**
Aggregated	2027	17.53	66.5	14022	0.2	10.9	23.94
Aggregated	2030	19.41	87.1	15348	0.34	14.8	26.65

Aggregated area

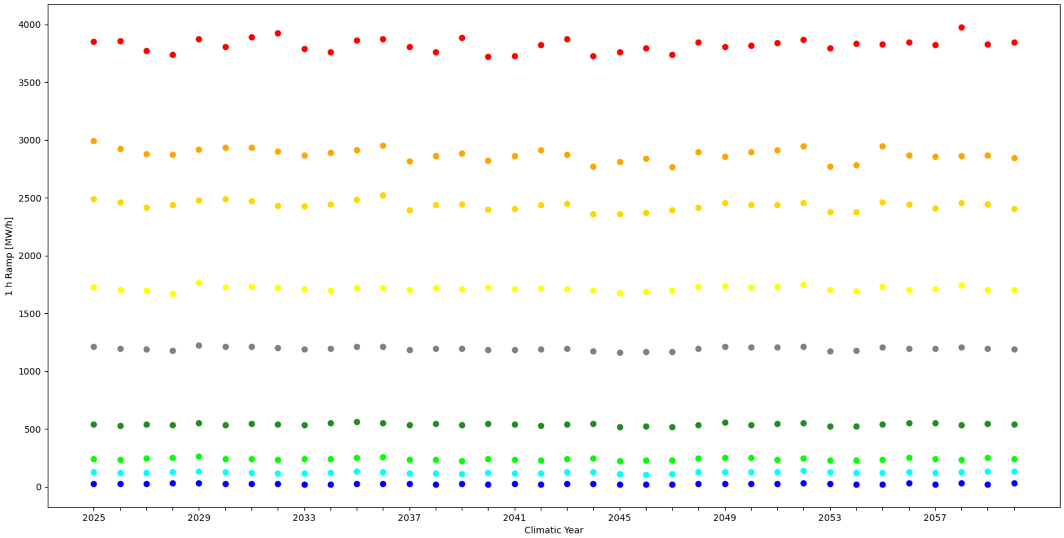
Hourly Assessment

The 1h residual load ramp rate could reach values greater than 2.9 GW/h and 3.5 GW/h for 5% of the hours of the year (and greater than 3.8 GW/h and 4.7 GW/h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

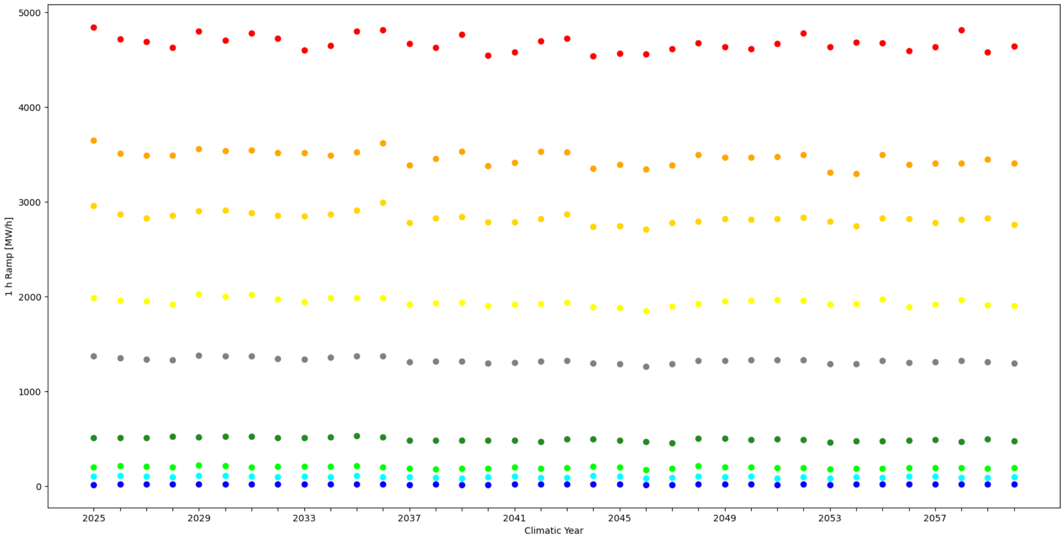
The 2h residual load ramp rate could reach values greater than 5.4 GW/2h and 6.4 GW/2h for 5% of the hours of the year (and greater than 6.5 GW/2h and 8.0 GW/2h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

The 4h residual load ramp rate could reach values greater than 9.1 GW/4h and 10.8 GW/4h for 5% of the hours of the year (and greater than 10.5 GW/4h and 12.9 GW/4h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

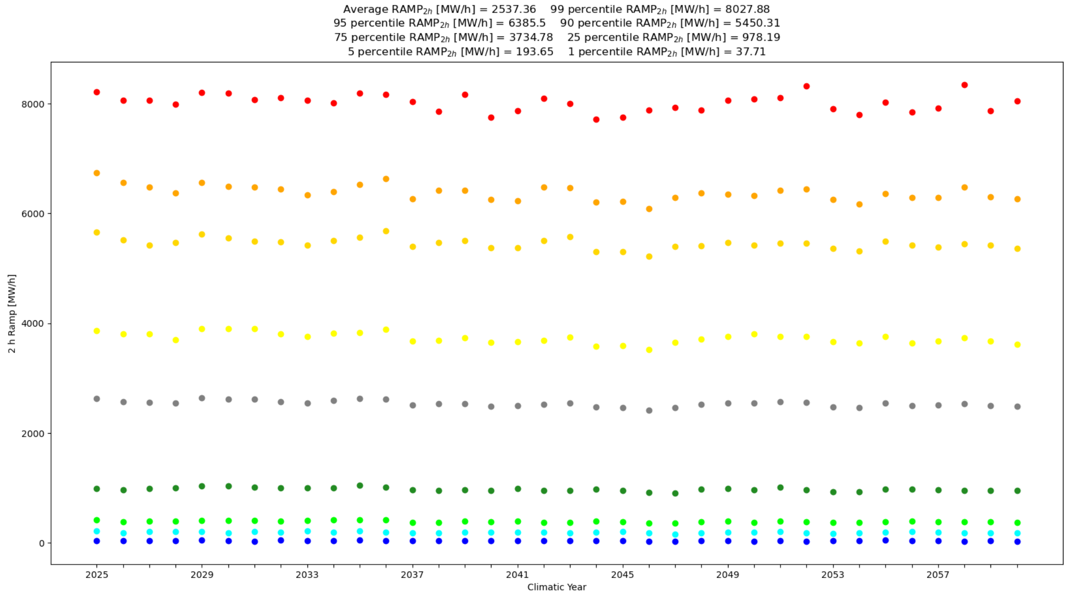
Enlarging the time scale for assessing the ramp smooths the derivative but highlights the necessity of flexible resources to follow the ramp rates of several GW over a few hours.

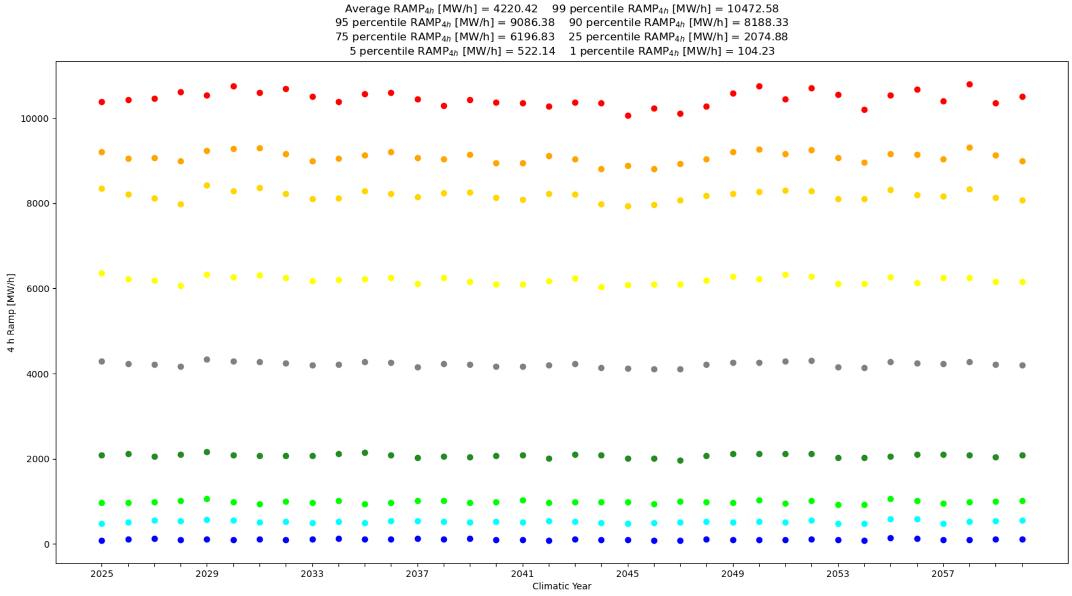


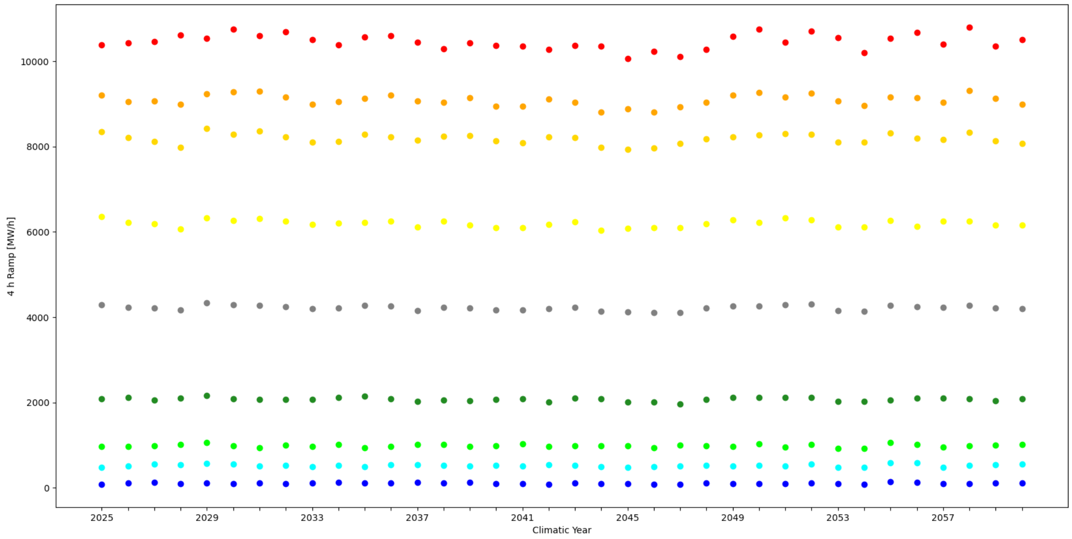
Average $RAMP_{1h}$ [MW/h] = 1194.53   99 percentile $RAMP_{1h}$ [MW/h] = 3823.8
95 percentile $RAMP_{1h}$ [MW/h] = 2878.6   90 percentile $RAMP_{1h}$ [MW/h] = 2433.37
75 percentile $RAMP_{1h}$ [MW/h] = 1714.67   25 percentile $RAMP_{1h}$ [MW/h] = 538.79
5 percentile $RAMP_{1h}$ [MW/h] = 122.75   1 percentile $RAMP_{1h}$ [MW/h] = 24.88



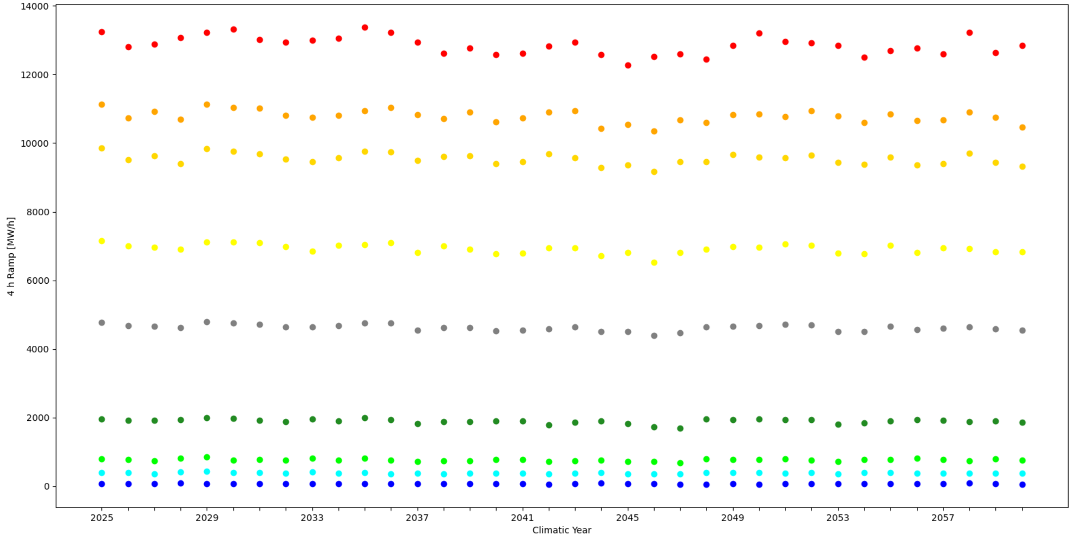
Average $RAMP_{1h}$ [MW/h] = 1326.81   99 percentile $RAMP_{1h}$ [MW/h] = 4679.52
95 percentile $RAMP_{1h}$ [MW/h] = 3472.09   90 percentile $RAMP_{1h}$ [MW/h] = 2830.32
75 percentile $RAMP_{1h}$ [MW/h] = 1942.94   25 percentile $RAMP_{1h}$ [MW/h] = 494.94
5 percentile $RAMP_{1h}$ [MW/h] = 97.96   1 percentile $RAMP_{1h}$ [MW/h] = 19.18


Average RAMP$_{2h}$ [MW/h] = 2537.36   99 percentile RAMP$_{2h}$ [MW/h] = 8027.88
95 percentile RAMP$_{2h}$ [MW/h] = 6385.5   90 percentile RAMP$_{2h}$ [MW/h] = 5450.31
75 percentile RAMP$_{2h}$ [MW/h] = 3734.78   25 percentile RAMP$_{2h}$ [MW/h] = 978.19
5 percentile RAMP$_{2h}$ [MW/h] = 193.65   1 percentile RAMP$_{2h}$ [MW/h] = 37.71
2 h Ramp [MW/h]
8000
6000
4000
2000
0
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year


Average RAMP$_{4h}$ [MW/h] = 4220.42   99 percentile RAMP$_{4h}$ [MW/h] = 10472.58
95 percentile RAMP$_{4h}$ [MW/h] = 9086.38   90 percentile RAMP$_{4h}$ [MW/h] = 8188.33
75 percentile RAMP$_{4h}$ [MW/h] = 6196.83   25 percentile RAMP$_{4h}$ [MW/h] = 2074.88
5 percentile RAMP$_{4h}$ [MW/h] = 522.14   1 percentile RAMP$_{4h}$ [MW/h] = 104.23
4 h Ramp [MW/h]
10000
8000
6000
4000
2000
0
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year



Average RAMP_{4h} [MW/h] = 4220.42   99 percentile RAMP_{4h} [MW/h] = 10472.58
95 percentile RAMP_{4h} [MW/h] = 9086.38   90 percentile RAMP_{4h} [MW/h] = 8188.33
75 percentile RAMP_{4h} [MW/h] = 6196.83   25 percentile RAMP_{4h} [MW/h] = 2074.88
5 percentile RAMP_{4h} [MW/h] = 522.14   1 percentile RAMP_{4h} [MW/h] = 104.23



Average RAMP_{4h} [MW/h] = 4624.75   99 percentile RAMP_{4h} [MW/h] = 12864.03
95 percentile RAMP_{4h} [MW/h] = 10785.82   90 percentile RAMP_{4h} [MW/h] = 9539.79
75 percentile RAMP_{4h} [MW/h] = 6925.18   25 percentile RAMP_{4h} [MW/h] = 1895.38
5 percentile RAMP_{4h} [MW/h] = 381.2   1 percentile RAMP_{4h} [MW/h] = 71.77

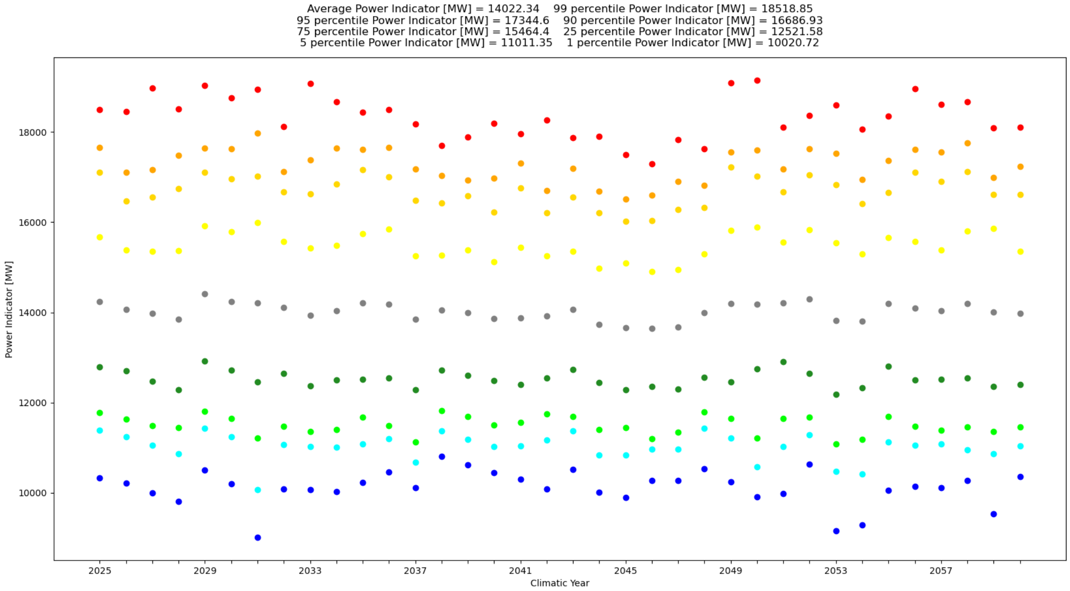
Daily Assessment

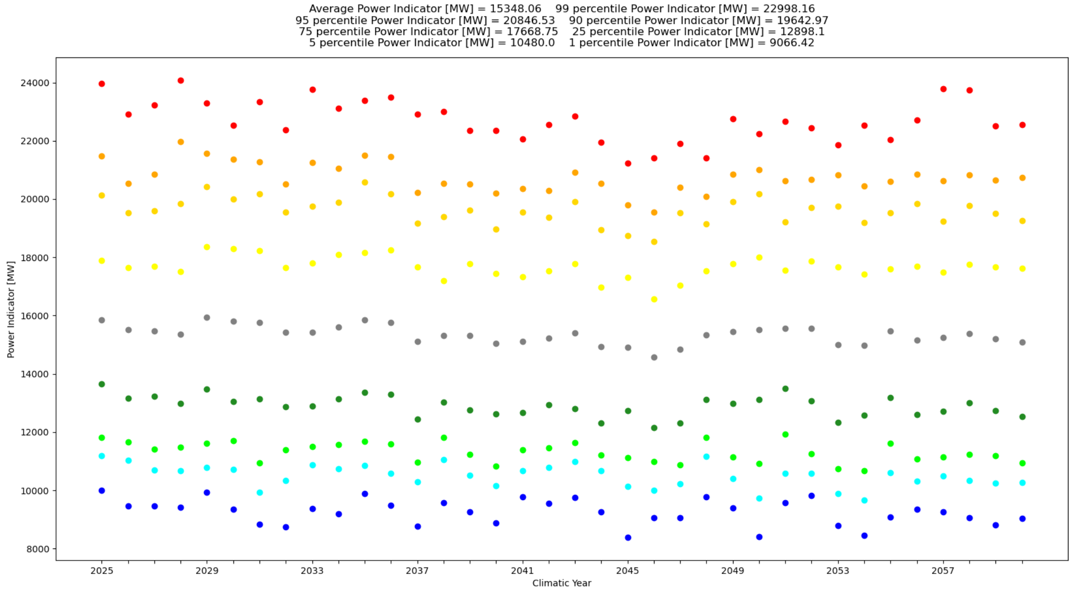
The daily energy indicator FN_{daily} shows little variation across the whole time series (and across climate years): the 99th percentile is 17.93 TWh and 19.98 TWh, the 1st percentile is 17.11 TWh and 18.65 TWh and the average value is 17.53 TWh and 19.41TWh in MT2027 and MT2030, respectively.

The daily energy indicator $FNMAX_{daily}$ shows little variation across climate years, resulting in the range between 63 GWh and 72 GWh and in the range between 80GWh and 96GWh for all the assessed climate years, with a mean value of about 66 GWh and 87 GWh in MT2027 and MT2030, respectively. This represents the maximum amount of flexibility needed on a daily basis.

The power indicator is reported in the figure below for each climate year and relevant percentile. The average value across the whole time series (and climate years) is about 14 GW and 15 GW in MT2027 and MT2030, respectively, which represents the average difference between daily minimum and maximum residual load value. This difference can rise to 17 GW and 21 GW for 5% of the days and up to 18 GW and 23 GW for 1% of the days in MT2027 and MT2030, respectively.

MT2030, respectively, which represents the average difference between daily minimum and maximum residual load value. This difference can rise to 17 GW and 21 GW for 5% of the days and up to 18 GW and 23 GW for 1% of the days in MT2027 and MT2030, respectively.

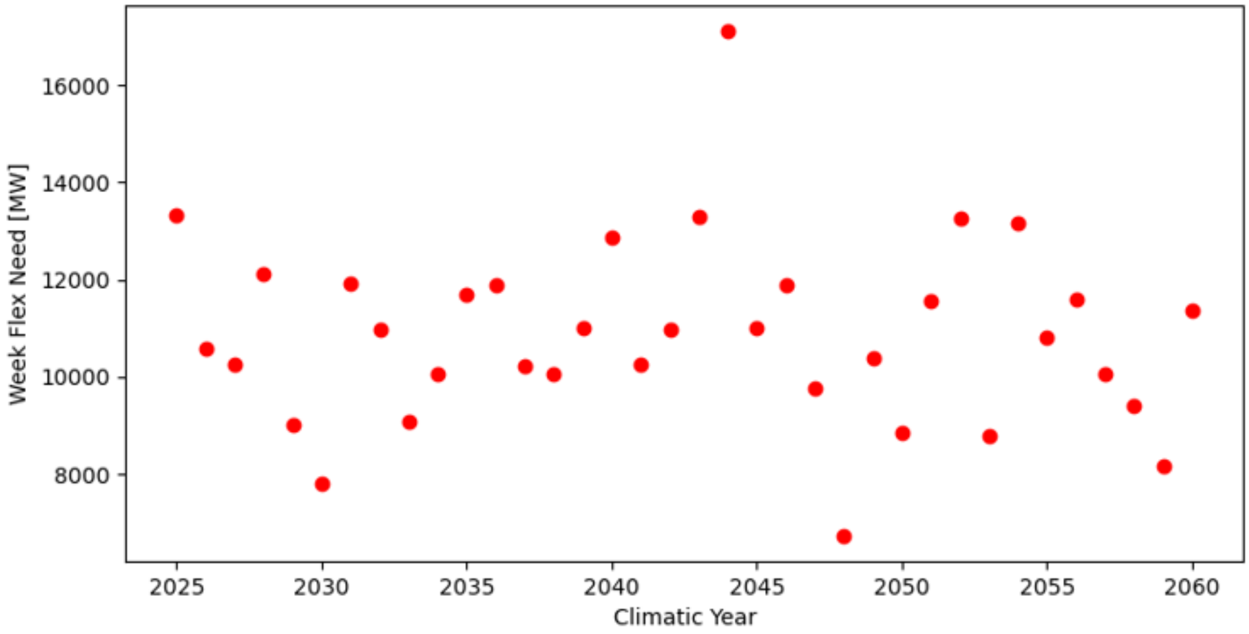


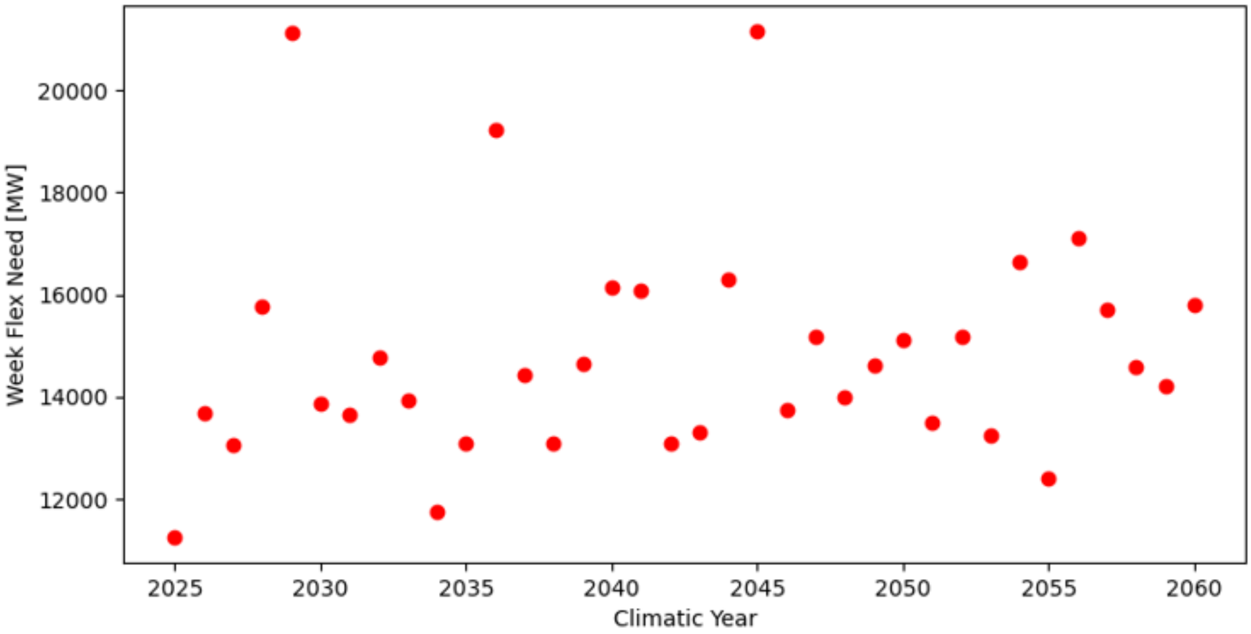


Weekly Assessment

The weekly energy indicator FN_{weekly} shows little variation across the whole time series (and across climate years): the 99th percentile is 0.24 TWh and 0.40 TWh, the 1st percentile is 0.18 TWh and 0.29 TWh and the average value is 0.20TWh and 0.34 TWh in MT2027 and in MT2030, respectively. This indicator assumes values that are one order of magnitude lower than the corresponding daily indicator. This means there are no significant variations in terms of residual load between days of the same week.

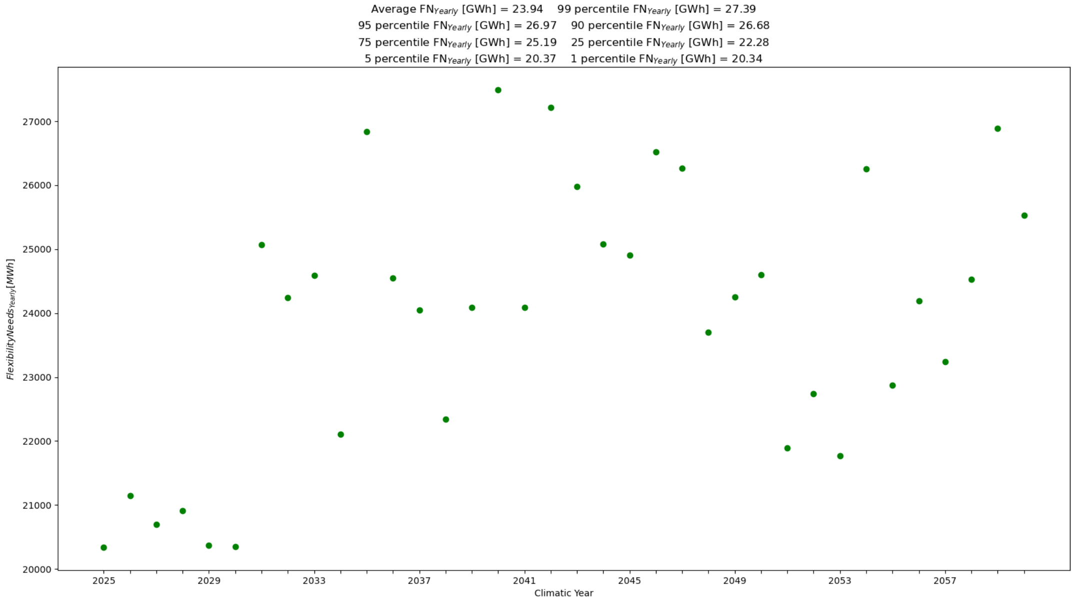
The weekly energy indicator $FNMAX_{weekly}$ is on average (across all the climate years) about 11GW and 15GW in MT2027 and MT2030, respectively. This represents the maximum amount of flexibility needed on a weekly basis. However, this indicator shows a peak for the 2044 climate year (of about 17 GW) in MT2027, and it shows a peak for the 2045 climate year (of about 22 GW) in MT2030.

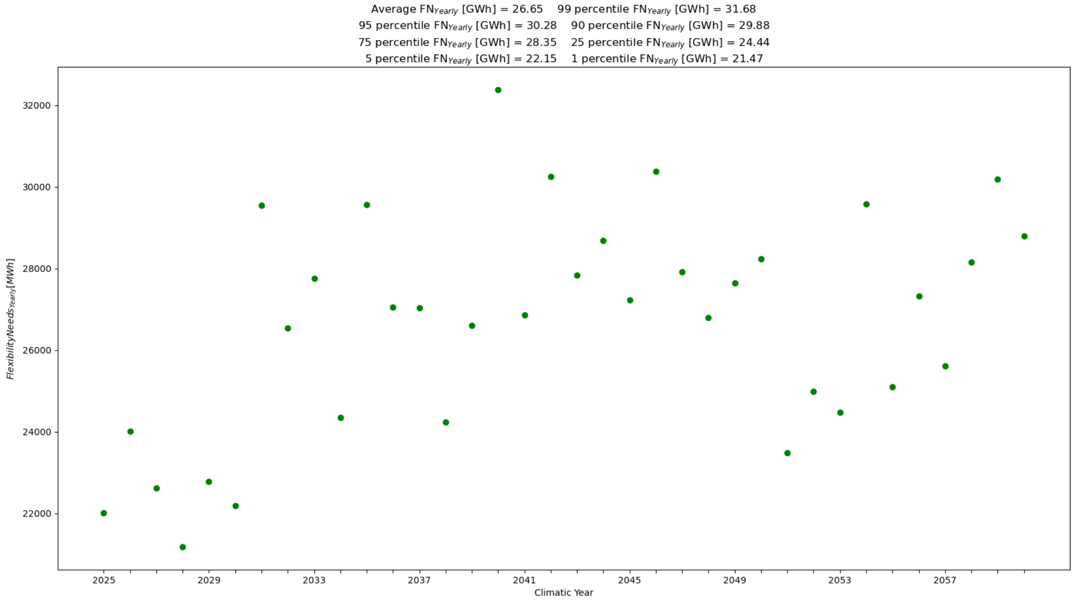




Yearly Assessment

The yearly energy indicator FN_{yearly} shows little variation across the whole time series (and across climate years): the 99th percentile is 27.39 GWh and 31.68 GWh, the 1st percentile is 20.34 GWh and 21.47 GWh and the average value is 23.94 GWh and 26.65 GWh in MT2027 and MT2030, respectively. This indicator assumes values that are very low compared to the weekly and, especially, the daily indicators. This means there is no significant variation in terms of residual load between months of the same year.


Average FN$_{Yearly}$ [GWh] = 23.94   99 percentile FN$_{Yearly}$ [GWh] = 27.39
95 percentile FN$_{Yearly}$ [GWh] = 26.97   90 percentile FN$_{Yearly}$ [GWh] = 26.68
75 percentile FN$_{Yearly}$ [GWh] = 25.19   25 percentile FN$_{Yearly}$ [GWh] = 22.28
5 percentile FN$_{Yearly}$ [GWh] = 20.37   1 percentile FN$_{Yearly}$ [GWh] = 20.34
$FlexibilityNeeds_{Yearly} [MWh]$
27000
26000
25000
24000
23000
22000
21000
20000
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year


Average FN$_{Yearly}$ [GWh] = 26.65   99 percentile FN$_{Yearly}$ [GWh] = 31.68
95 percentile FN$_{Yearly}$ [GWh] = 30.28   90 percentile FN$_{Yearly}$ [GWh] = 29.88
75 percentile FN$_{Yearly}$ [GWh] = 28.35   25 percentile FN$_{Yearly}$ [GWh] = 24.44
5 percentile FN$_{Yearly}$ [GWh] = 22.15   1 percentile FN$_{Yearly}$ [GWh] = 21.47
$FlexibilityNeeds_{Yearly} [MWh]$
32000
30000
28000
26000
24000
22000
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year

5.3 Expected evolution

The following table summarises the main ramp indicators for each time horizon.

Country	Year	Ramp 1h [MW/h]			Ramp 2h [MW/h]			Ramp 4h [MW/h]		
		5th perc.	Avg.	95th perc.	5th perc.	Avg.	95th perc.	5th perc.	Avg.	95th perc.
Egypt	2025	85	780	1847	175	1473	3393	469	2621	5609
Egypt	2027	120	850	1977	225	1596	3446	361	2857	5367
Egypt	2030	79	899	2153	144	1661	3757	296	2906	6090
Jordan	2025	17	194	568	30	370	1046	70	670	1638
Jordan	2027	18	205	638	38	392	1074	78	701	1619
Jordan	2030	23	273	873	49	523	1483	102	937	2213
Lebanon	2025	7	104	274	13	201	492	23	371	884
Lebanon	2027	8	121	310	25	234	570	38	420	952
Lebanon	2030	10	147	382	29	285	697	43	511	1161
Morocco	2025	13	203	527	26	383	963	52	651	1564
Morocco	2027	19	270	688	39	511	1245	72	867	2018
Morocco	2030	27	362	920	55	686	1674	98	1162	2682
Tunisia	2025	7	95	239	14	178	448	21	303	740
Tunisia	2027	11	148	385	21	281	710	40	486	1196
Tunisia	2030	12	224	655	25	429	1224	51	764	2027
Total	**2025**	**129**	**1376**	**3455**	**258**	**2605**	**6342**	**635**	**4616**	**10435**
Total	**2027**	**176**	**1594**	**3998**	**348**	**3014**	**7045**	**589**	**5331**	**11152**
Total	**2030**	**151**	**1905**	**4983**	**302**	**3584**	**8835**	**590**	**6280**	**14173**
Aggregated	2025	109	1106	2800	271	2133	5274	691	4004	8947
Aggregated	2027	123	1195	2879	270	2301	5364	522	4220	9086
Aggregated	2030	98	1327	3472	194	2537	6386	38 1	4625	10786

Across Egypt, Jordan, Lebanon, Morocco, and Tunisia, ramping requirements, especially over 2-hour and 4-hour intervals, are steadily increasing from 2025 to 2030. This reflects growing system flexibility needs, likely due to higher renewable energy integration.

Egypt consistently exhibits the highest ramping values across all timeframes (1h, 2h, 4h), with average 4-hour ramping increasing from 2,621 MW/h in 2025 to 2,906 MW/h in 2030, and 95th percentile values reaching 6,090 MW/h. This suggests a growing need for dispatchable capacity and grid flexibility.

Jordan shows moderate increases, with average 4-hour ramping growing from 670 MW/h in 2025 to 937 MW/h in 2030. The 95th percentile values nearly double over the period, indicating more frequent high-ramping events.

Lebanon's ramping needs remain the lowest among the countries analysed but still show a steady increase. The average 4-hour ramping increases from 371 MW/h in 2025 to 511 MW/h in 2030, with the 95th percentile reaching 1,161 MW/h.

Morocco demonstrates significant growth in ramping requirements, especially in the 4-hour window, where the average increases from 651 MW/h in 2025 to 1,162 MW/h in 2030, and the 95th percentile more than doubles to 2682 MW/h.

Tunisia also shows a marked increase, with average 4-hour ramping increasing from 303 MW/h in 2025 to 764 MW/h in 2030, and the 95th percentile reaching 2027 MW/h. The residual load analysis for Tunisia reveals several periods throughout the year where residual load values become negative, primarily due to the high penetration of variable renewable energy sources (vRES), such as solar PV and wind. These negative values occur predominantly during winter months, when system demand is relatively low and renewable generation remains significant. Solar and wind production exhibit an almost periodic daily pattern across the year and among different climatic years, whereas the load profile shows a pronounced seasonal variation, with an average increase of approximately 30% during summer months. This structural mismatch between generation and demand leads to frequent oversupply conditions (more details are provided in the Appendix section).

Aggregated and total regional values confirm a significant rise in both average and extreme ramping events, indicating increasing operational challenges. The aggregated value is lower than the sum of the individual countries' flexibility needs, indicating that increasing interconnection capacity and sharing flexible resources across nations can reduce the overall flexibility requirement. The aggregated case represents the ideal copper plate condition. These trends highlight the importance of enhancing grid flexibility, forecasting capabilities, and integrating fast-responding resources.

The following table presents the evolution of the ratio between the total system ramp (sum of all national ramps) and the simulated ramp of a fully aggregated system capabilities across 1-hour, 2-hour, and 4-hour intervals for the years 2025, 2027, and 2030.

Country	Year	Ramp 1h Ratio			Ramp 2h Ratio			Ramp 4h Ratio		
		5th perc.	Avg.	95th perc.	5th perc.	Avg.	95th perc.	5th perc.	Avg.	95th perc.
Total/Aggregated	2025	1.18	1.24	1.23	0.95	1.22	1.2	0.92	1.15	1.17
Total/Aggregated	2027	1.43	1.33	1.39	1.29	1.31	1.31	1.13	1.26	1.23
Total/Aggregated	2030	1.54	1.44	1.44	1.56	1.41	1.38	1.55	1.36	1.31

Across all time intervals, the ramp ratios show a consistent increase from 2025 to 2030. This trend suggests a growing difference between the total and aggregated ramping behaviour, likely driven by enhanced system integration and coordination across countries.

- 1-Hour ramp: The average ramp ratio increases from 1.24 in 2025 to 1.44 in 2030, with both the 5th and 95th percentiles following a similar upward trend.
- 2-Hour ramp: The average ratio remains relatively stable between 2025 and 2027 (1.22 to 1.31) but rises to 1.41 by 2030. The 5th percentile shows a notable increase from 0.95 to 1.56, suggesting that even the lowest ramping conditions are becoming less aligned with the aggregated behaviour.
- 4-Hour ramp: The average ratio grows from 1.15 in 2025 to 1.36 in 2030, with the 5th percentile increasing significantly from 0.92 to 1.55. This reflects a stronger smoothing effect over longer time horizons, likely due to improved balancing and forecasting capabilities.

The increasing ramp ratios across all percentiles and time intervals imply that the aggregated system is becoming more representative of the sum of its parts. This could be attributed to better cross-border coordination, enhanced grid flexibility, and the deployment of advanced forecasting and balancing tools. The narrowing gap between the 5th and 95th percentiles also suggests reduced variability and improved reliability in system response.

Country	Year	FNdaily [TWh] (average)	FNMAXdaily [GW] (average)	FNP_50_daily [MW] (average)	FNweekly [TWh] (average)	FNMAXweekly [GW] (average)	FNyearly [GWh] (average)
Egypt	2025	9.24	34.8	9217	0.13	6.4	17.91
Egypt	2027	11.56	45.1	9791	0.16	8	19.49
Egypt	2030	11.69	63.5	10011	0.3	12.5	22.01
Jordan	2025	2.67	10.3	2121	0.03	1.2	1.05
Jordan	2027	2.63	11.4	2244	0.03	1.5	1.28
Jordan	2030	3.54	15.2	2985	0.04	1.8	1.47
Lebanon	2025	1.48	5.6	1150	0.02	1	1.06
Lebanon	2027	1.51	6	1227	0.02	1	1.2
Lebanon	2030	1.81	7.2	1505	0.02	1.1	1.3
Morocco	2025	2.31	10.4	2043	0.05	1.8	1.38
Morocco	2027	2.55	14.3	2426	0.08	3.3	2.11
Morocco	2030	3.35	17.6	3193	0.1	3.9	2.58
Tunisia	2025	1.06	4.4	988	0.03	1.4	2.14
Tunisia	2027	1.55	7.1	1484	0.03	1.6	2.19
Tunisia	2030	2.75	13.3	2382	0.05	2.6	2.51
Total	2025	16.76	65.5	15519	0.26	11.8	23.54
Total	2027	19.8	83.9	17172	0.32	15.4	26.27
Total	2030	23.14	116.8	20076	0.51	21.9	29.87
Aggregated	2025	15.45	55.6	13096	0.17	7.62	21.65
Aggregated	2027	17.53	66.5	14022	0.2	10.9	23.94
Aggregated	2030	19.41	87.1	15348	0.34	14.8	26.65

The data show a consistent increase in flexibility requirements across Egypt, Jordan, Lebanon, Morocco and Tunisia, reflecting the growing need for system adaptability due to higher renewable energy integration.

Egypt has the highest flexibility needs, with daily averages increasing from 9.24 TWh in 2025 to 11.69 TWh in 2030, and daily peaks reaching 63.5 GW. Jordan, Lebanon, Morocco and Tunisia show moderate but steady growth. Annual flexibility needs increase from 23.54 GWh (2025) to 29.87 GWh (2030) in total.

Also in this case, aggregated values, which represent an idealised interconnected system (copper plate scenario), are consistently lower than the sum of individual country needs. The fact that aggregated flexibility needs are lower than the total of individual countries indicates that enhancing cross-border exchange capacity and sharing flexible resources can reduce overall system flexibility requirements. The aggregated scenario reflects the benefits of increasing cross-border capacity, regional integration and coordinated operation.

The following table presents the evolution of the ratio between the total system flexibility needs and the simulated FN of a fully aggregated system across all time horizons.

Country	Year	FNdaily Ratio (average)	FNMAXdaily Ratio (average)	FNP_50_daily Ratio (average)	FNweekly Ratio (average)	FNMAXweekly Ratio (average)	FNyearly Ratio (average)
Total/Aggregated	2025	1.08	1.18	1.19	1.53	1.55	1.09
Total/Aggregated	2027	1.13	1.26	1.22	1.6	1.41	1.1
Total/Aggregated	2030	1.19	1.34	1.31	1.5	1.48	1.12

The ratio of individual daily flexibility energy needs to aggregated needs (FNdaily) increases from 1.08 in 2025 to 1.19 in 2030, while the maximum daily requirement ratio (FNMAXdaily) increases from 1.18 to 1.34. This widening gap reflects the compounding benefits of regional integration, as uncoordinated renewable variability drives up standalone flexibility requirements. Similarly, the typical daily peak flexibility power ratio (FNP) shows a consistent increase from 1.19 in 2025 to 1.31 in 2030. This upward trend underscores that isolated operations will increasingly penalize individual TSOs with significantly higher localized balancing power demands compared to a coordinated system.

The ratio for weekly flexibility energy needs (FNweekly) remains relatively stable, peaking at 1.60 in 2027 before slightly decreasing to 1.50 in 2030. Meanwhile, the weekly maximum requirement ratio (FNMAXweekly) fluctuates across the timeline, indicating that the relative grid-pooling benefit varies depending on specific seasonal weather and load profiles. Finally, the ratio for yearly long-term flexibility energy needs (FNyearly) shows a modest but steady increase from 1.09 in 2025 to 1.12 in 2030. This steady upward crawl indicates that as renewable penetration grows toward the end of the decade, the long-term structural variance between isolated national operations and an optimized regional network expands incrementally.

The upward trend across most metrics highlights the increasing importance of system-wide flexibility to accommodate evolving generation profiles, particularly with higher shares of variable renewable energy. The relatively stable yearly values suggest that, while total energy needs remain manageable, the system must be prepared for more frequent and intense short-term fluctuations. This underscores the need for enhanced forecasting, storage solutions and cross-border coordination to ensure system reliability.

The observed increase in flexibility requirements across all time horizons is closely tied to the projected growth in installed renewable capacity over the coming years. As variable renewable energy sources, particularly wind and solar, continue to expand, the power system faces greater fluctuations in generation patterns. These fluctuations necessitate more dynamic and responsive balancing mechanisms to maintain system stability. The rising values in daily, weekly and yearly flexibility metrics reflect this trend, underscoring the importance of investing in grid flexibility solutions such as storage, demand response, and enhanced interconnection capacity. The data confirm that flexibility will be a cornerstone of future system resilience in a decarbonised energy landscape.

6

Conclusion

This study quantifies the flexibility requirements necessary to support the ongoing evolution of the power system toward higher shares of renewable energy. It also examines how these needs are expected to develop over time and assesses the role of enhanced interconnections with neighbouring countries in mitigating operational challenges and optimizing resource utilisation.

Six Med-TSO countries (Morocco, Tunisia[7], Libya , Egypt, Jordan and Lebanon) were analysed under three future scenarios, 2025, 2027 and 2030, each reflecting progressive increases in variable renewable capacity. Wind generation is projected to expand from 6 GW to 22 GW, while solar capacity is expected to grow from 8 GW to 23 GW. The analysis reveals a substantial rise in both flexibility and ramping requirements over this period, underlining the magnitude of the transformation needed to preserve system stability and reliability.

The country with the highest number of occurrences of residual load below zero is Tunisia, particularly during winter months when demand is lower and renewable generation remains significant. Solar and wind output follow an almost periodic daily pattern throughout the year and across climatic variations, while the load exhibits strong seasonality, with an average increase of about 30% during summer. This mismatch between generation and demand highlights structural oversupply conditions and reinforces the need for flexibility solutions and

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[7] Libya was missing from the mid-term data collection (2027 & 2030) due to limited engagement from the Libyan side.

improved operational planning.

A comparison between an idealised “copper plate” scenario (where cross-border exchanges are unrestricted) and an “isolated operation” (where exchanges are not permitted) further highlights the strategic value of interconnections. Enhanced regional integration significantly reduces system flexibility requirements by smoothing variability and enabling more efficient use of generation resources across borders.

In particular, average 1-hour, 2-hour, and 4-hour ramp rates are observed to be 30 to 40% lower in the “copper plate” scenario. Flexibility indicators also show marked improvements, with the benefits of interconnection becoming even more pronounced as variable renewable capacity increases.

The findings of this study reaffirm the critical importance of regional collaboration and system integration in advancing the energy transition. Investing in new interconnections and maximising their efficiency through enhanced coordination among TSOs represents a pivotal step toward developing a resilient, flexible and fully decarbonised Mediterranean Power System.

Such investments will not only strengthen operational security and market efficiency but also enable the region to unlock the full potential of renewable energy, supporting the broader objectives of sustainability, competitiveness, and energy independence.

7

Appendix A: Country-Level Detailed Results (2025)

Egypt

Hourly Assessment

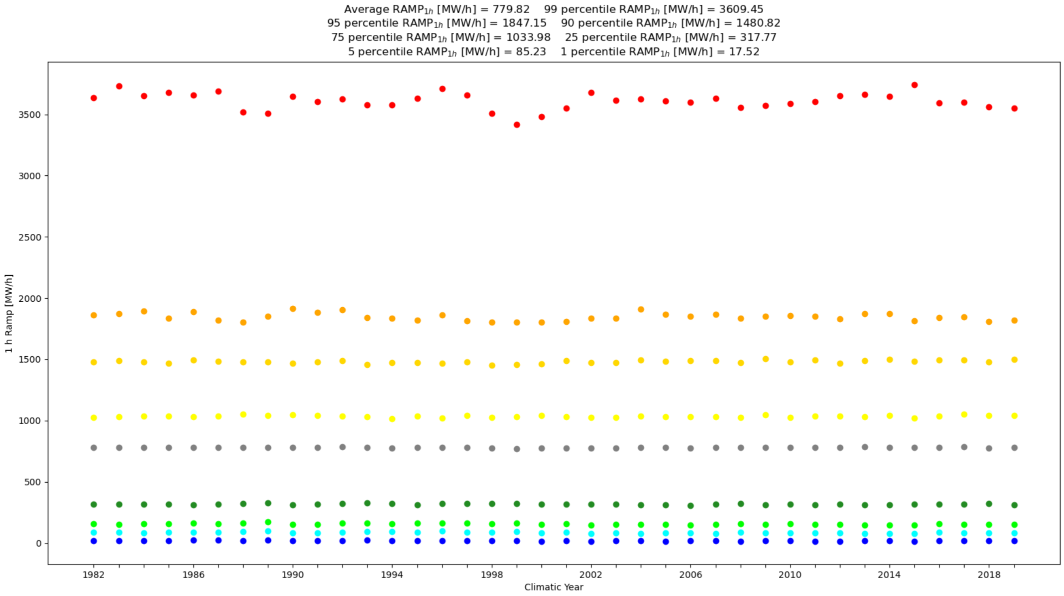
The following figures clearly show substantial stability of the indicators across the different climate years: only the 99th percentile shows some variability.

The 1h residual load ramp rate could reach values greater than 1.8 GW/h for 5% of the hours of the year (and greater than 3.6 GW/h for 1% of the hours of the year).

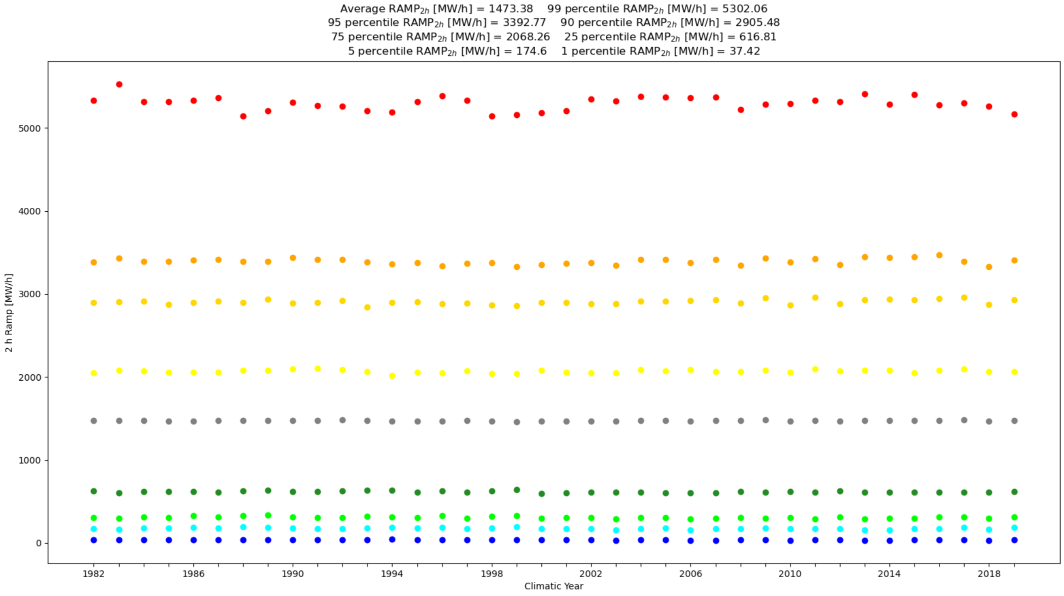
The 2h residual load ramp rate could reach values greater than 3.4 GW/2h for 5% of the hours of the year (and greater than 5.3 GW/2h for 1% of the hours of the year).

The 4h residual load ramp rate could reach values greater than 5.6 GW/4h for 5% of the hours of the year (and greater than 6.5 GW/4h for 1% of the hours of the year).

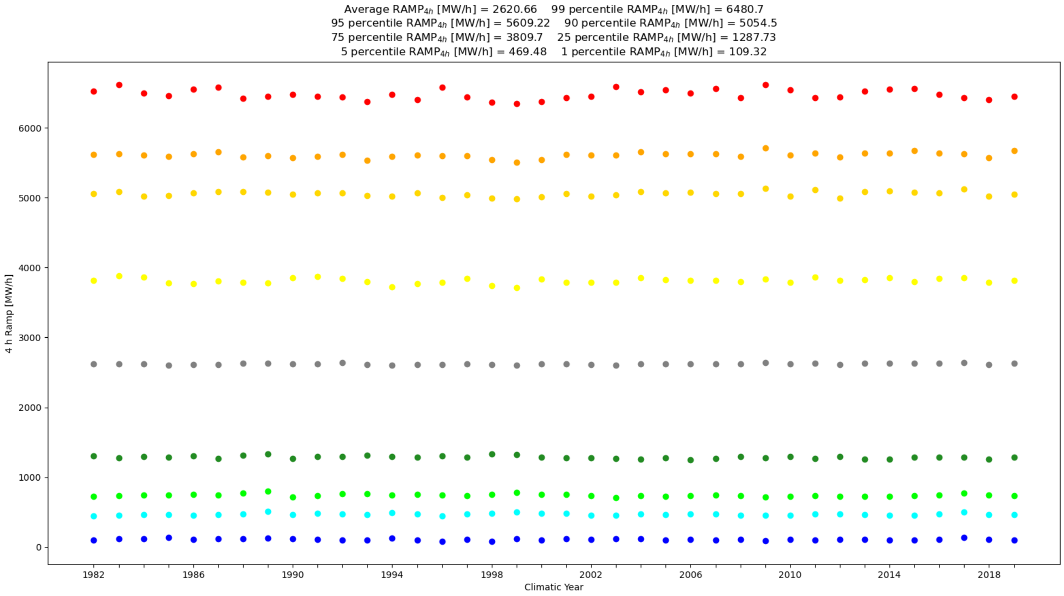
Enlarging the time scale for assessing the ramp smooths the derivative but highlights the need for flexible resources to follow the ramp rates of several GW over a few hours.



Average RAMP$_{1h}$ [MW/h] = 779.82   99 percentile RAMP$_{1h}$ [MW/h] = 3609.45
95 percentile RAMP$_{1h}$ [MW/h] = 1847.15   90 percentile RAMP$_{1h}$ [MW/h] = 1480.82
75 percentile RAMP$_{1h}$ [MW/h] = 1033.98   25 percentile RAMP$_{1h}$ [MW/h] = 317.77
5 percentile RAMP$_{1h}$ [MW/h] = 85.23   1 percentile RAMP$_{1h}$ [MW/h] = 17.52



Average RAMP$_{2h}$ [MW/h] = 1473.38   99 percentile RAMP$_{2h}$ [MW/h] = 5302.06
95 percentile RAMP$_{2h}$ [MW/h] = 3392.77   90 percentile RAMP$_{2h}$ [MW/h] = 2905.48
75 percentile RAMP$_{2h}$ [MW/h] = 2068.26   25 percentile RAMP$_{2h}$ [MW/h] = 616.81
5 percentile RAMP$_{2h}$ [MW/h] = 174.6   1 percentile RAMP$_{2h}$ [MW/h] = 37.42

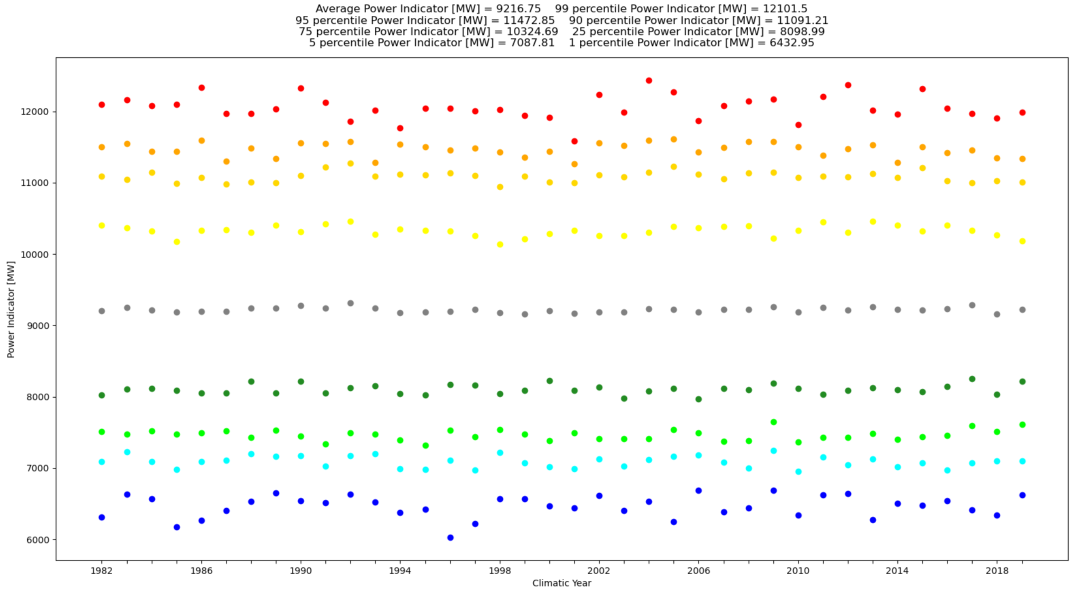


Daily Assessment

The daily energy indicator FN$_{daily}$ shows little variation across the whole time series (and across climate years): the 99th percentile is 9.31 TWh, the 1st percentile is 9.17 TWh and the average value is 9.24 TWh.

The daily energy indicator FNMAX$_{daily}$ shows little variation across climate years, resulting in a range between 32 GWh and 38 GWh for all the assessed climate years, with a mean value of about 35 GWh. This represents the maximum amount of flexibility needed on a daily basis.

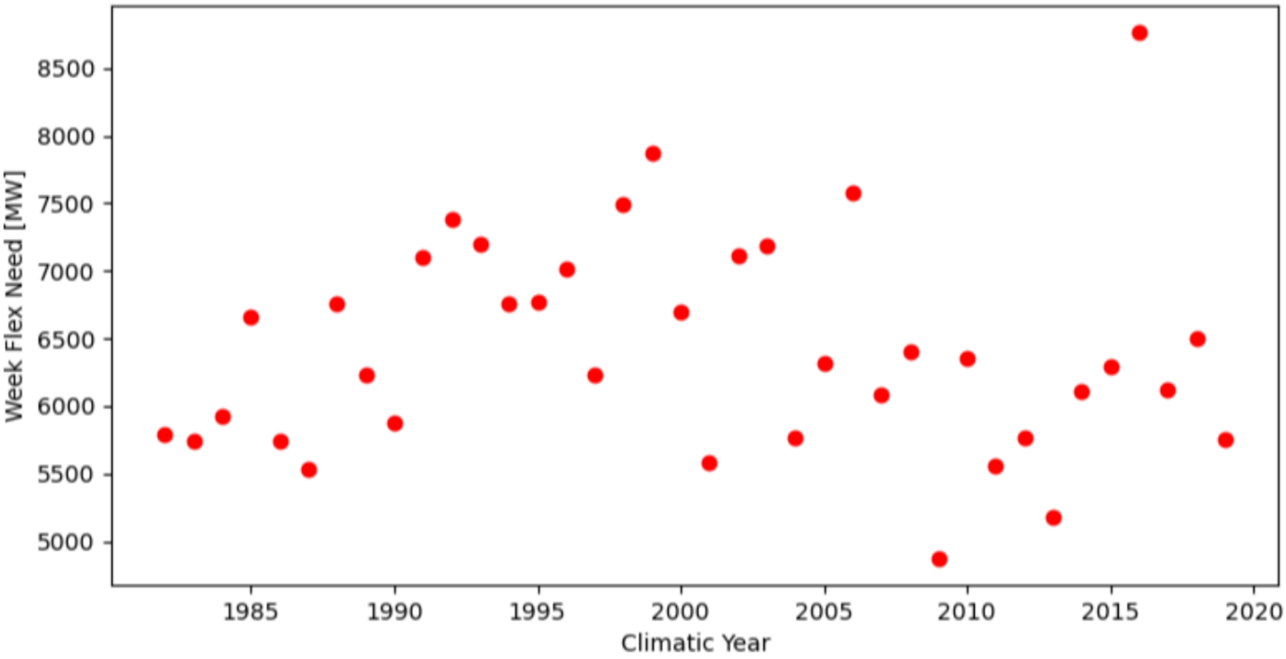
The power indicator is reported in the figure below for each climate year and relevant percentile. The average value across the whole time series (and climate years) is about 9.2GW, which represents the average difference between daily minimum and maximum residual load values. This difference can rise up to 11.5 GW for 5% of the days and up to 12.1 GW for 1% of the days.



Weekly Assessment

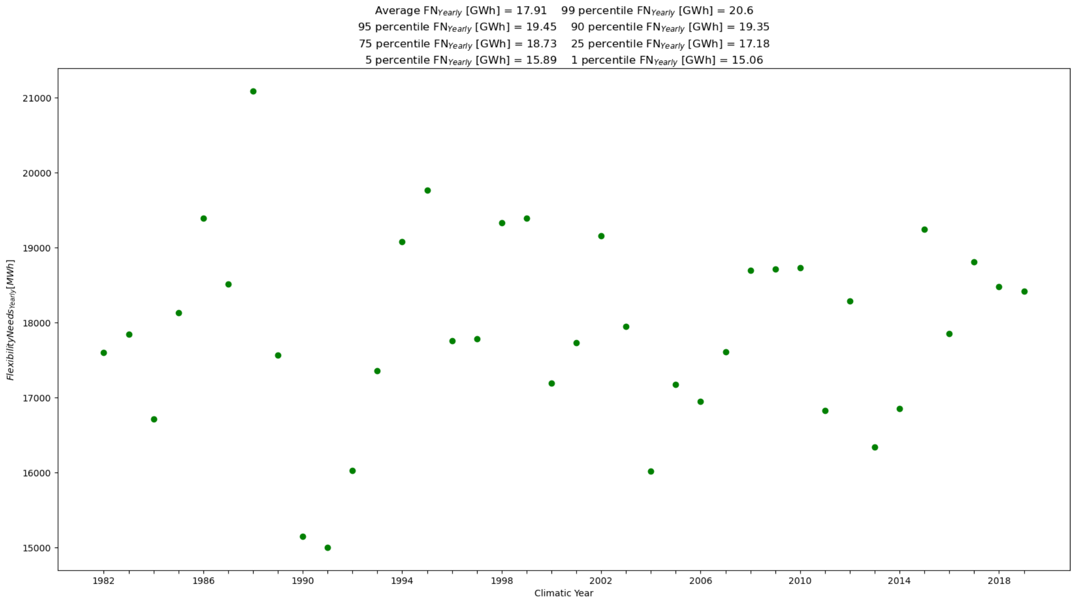
The weekly energy indicator FN_{weekly} shows little variation across the whole time series (and across climate years): the 99th percentile is 0.16 TWh, the 1st percentile is 0.13 TWh and the average value is 0.14 TWh. This indicator assumes values that are one order of magnitude lower than the similar daily indicator. This means there is no significant variation in terms of residual load between days of the same week.

The weekly energy indicator $FNMAX_{weekly}$ is on average (across all the climate years) about 6.4 GW. This represents the maximum amount of flexibility needed on a weekly basis. However, this indicator shows a peak for the 2016 climate year (of about 8.7 GW, see figure below).



Yearly Assessment

The yearly energy indicator FN_{yearly} shows little variation across the whole time series (and across climate years): the 99th percentile is 20.6 GWh, the 1st percentile is 15.06 GWh and the average value is 17.91 GWh. This indicator assumes values that are very low compared to the weekly and, especially, the daily indicators. This means there is no significant variation in terms of residual load between months of the same year.



Jordan

Hourly Assessment

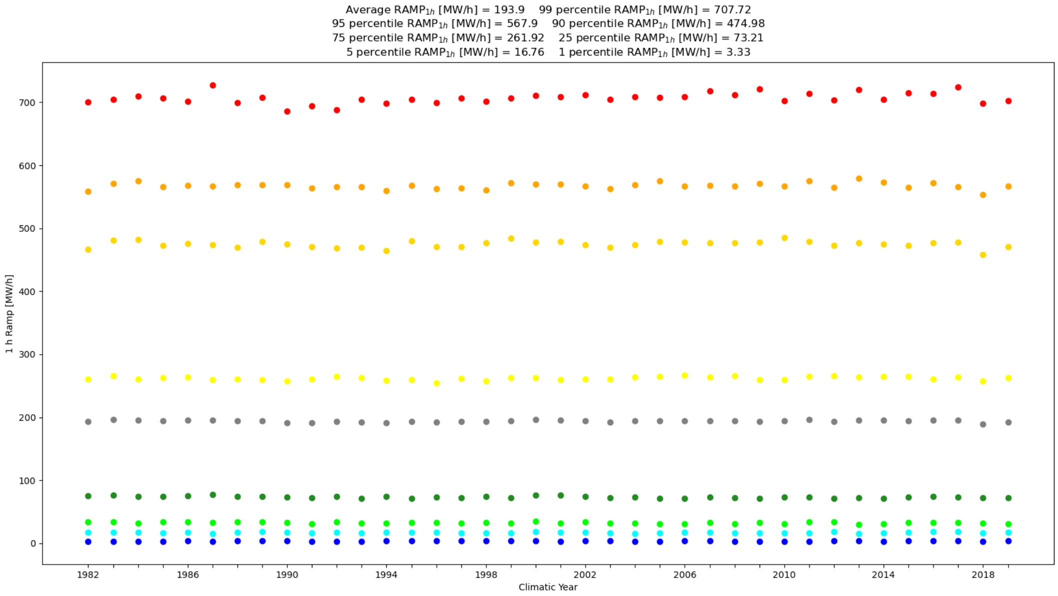
The following figures show substantial stability of the indicators across the different climate years: only the 99th percentile show some variability.

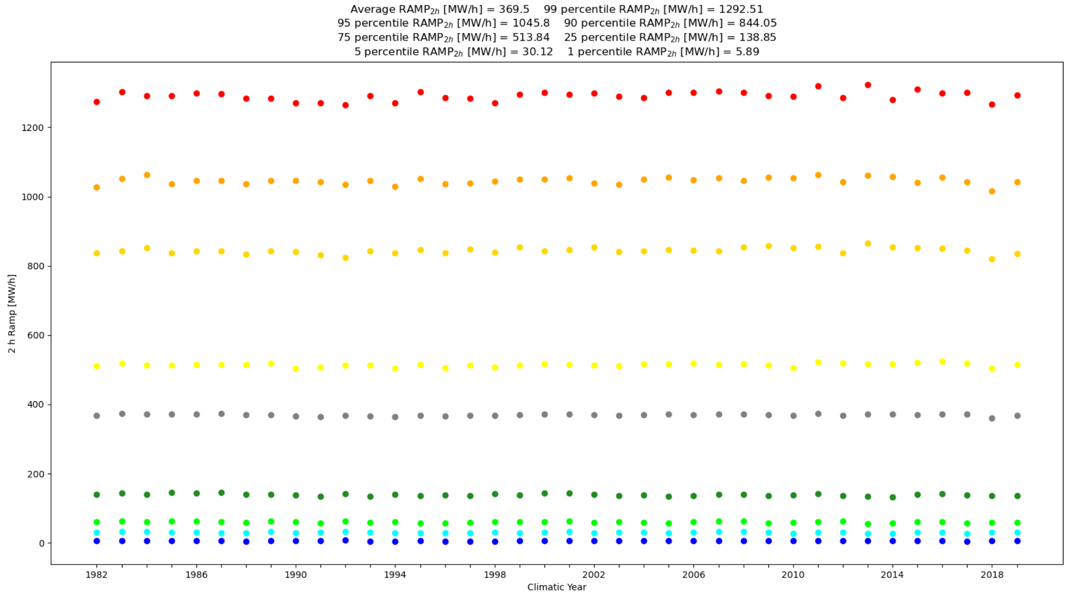
The 1h residual load ramp rate could reach values greater than 0.6 GW/h for 5% of the hours of the year (and greater than 0.8 GW/h for 1% of the hours of the year).

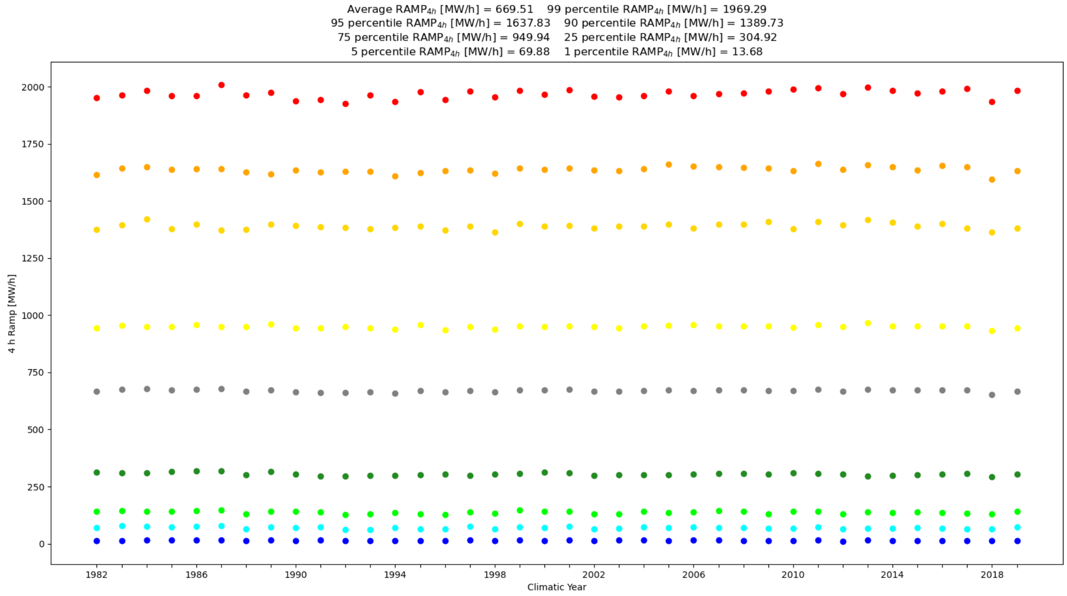
The 2h residual load ramp rate could reach values greater than 1.0 GW/2h for 5% of the hours of the year (and greater than 1.3 GW/2h for 1% of the hours of the year).

The 4h residual load ramp rate could reach values greater than 1.6 GW/4h for 5% of the hours of the year (and greater than 2.0 GW/4h for 1% of the hours of the year).

Also in this case, enlarging the time scale for assessing the ramp smooths the derivative but highlights the need for flexible resources to follow the ramp rates of several GW over a few hours.





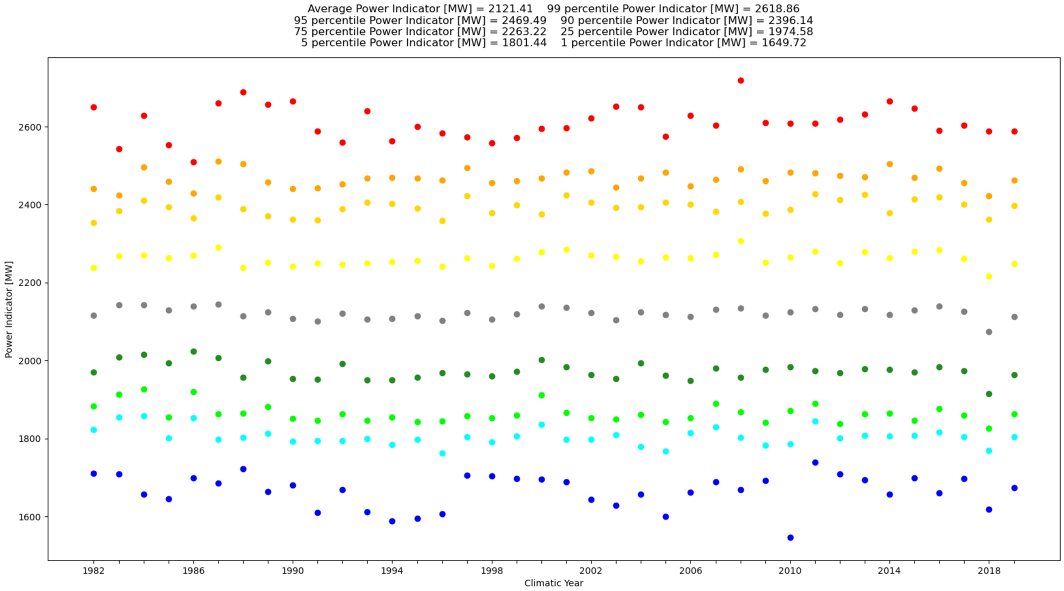


Daily Assessment

The daily energy indicator FN$_{daily}$ shows little variation across the whole time series (and across climate years): the 99th percentile is 2.7 TWh, the 1st percentile is 2.62 TWh and the average value is 2.67 TWh.

The daily energy indicator FNMAX$_{daily}$ shows little variation across climate years, resulting in a range between 9.5 GWh and 11.5 GWh for all the assessed climate years, with a mean value of about 10.4 GWh. This represents the maximum amount of flexibility needed on a daily basis.

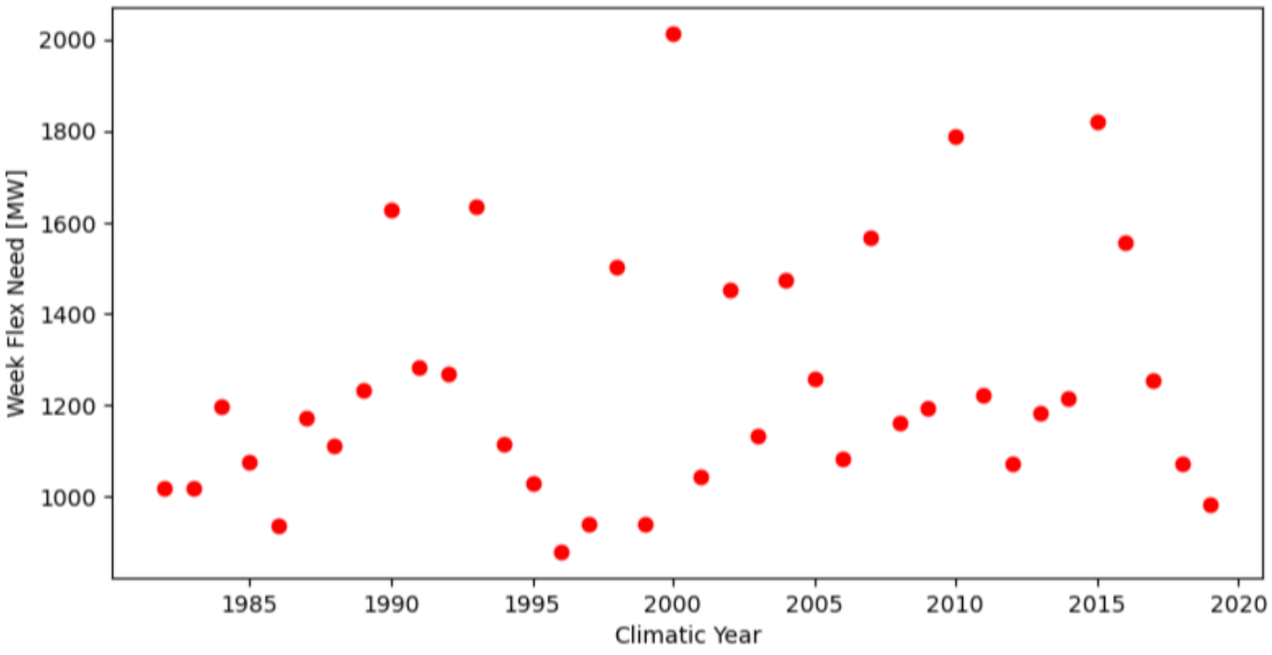
The power indicator is reported in the figure below for each climate year and relevant percentile. The average value across the whole time series (and climate years) is about 2.1 GW, which represents the average difference between daily minimum and maximum residual load values. This difference can rise (a little) up to 2.5 GW for 5% of the days and up to 2.6 GW for 1% of the days.



Weekly Assessment

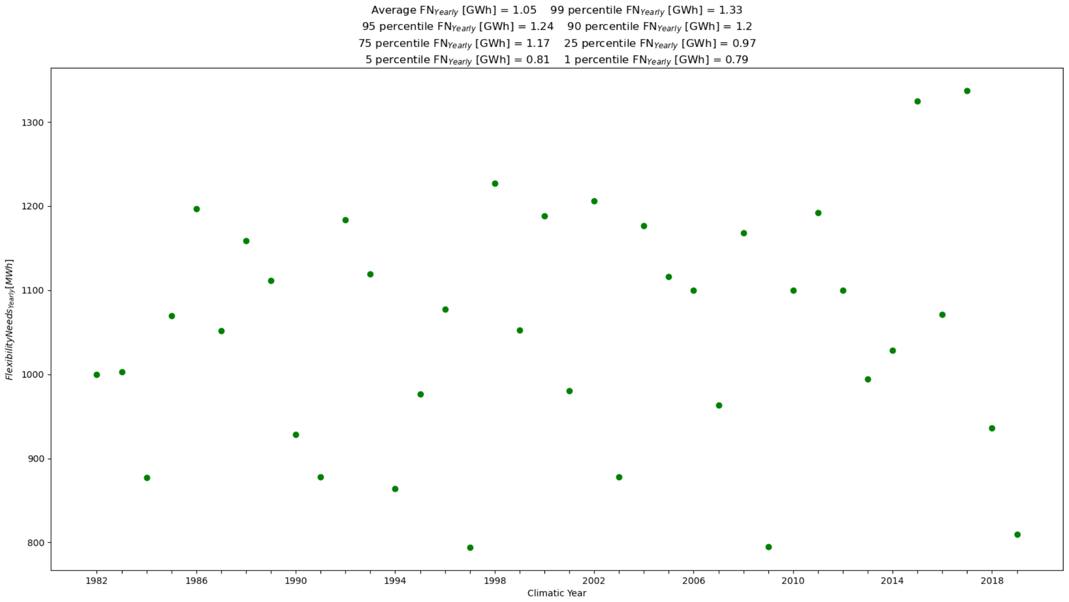
The weekly energy indicatorFN$_{weekly}$ shows no relevant variations across the whole time series (and across climate years): the 99th percentile is 0.03 TWh, the 1st percentile is 0.03 TWh and the average value is 0.03 TWh. This indicator assumes values that are one order of magnitude lower than the corresponding daily indicator. This means there is no significant variation in terms of residual load between days of the same week.

The weekly energy indicatorFNMAX$_{weekly}$ is on average (across all the climate years) of about 1.2 GW. This represents the maximum amount of flexibility needed on a weekly basis. However, this indicator shows a peak for the 2000 climate year (of about 2.1 GW, see figure below).



Yearly Assessment

The yearly energy indicator FN$_{yearly}$ shows little variation across the whole time series (and across climate years): the 99th percentile is 1.33GWh, the 1st percentile is 0.79GWh and the average value is 1.05GWh. This indicator assumes values that are very low compared to the weekly and, especially, the daily indicators. This means there is no significant variation in terms of residual load between months of the same year.



Lebanon

Hourly Assessment

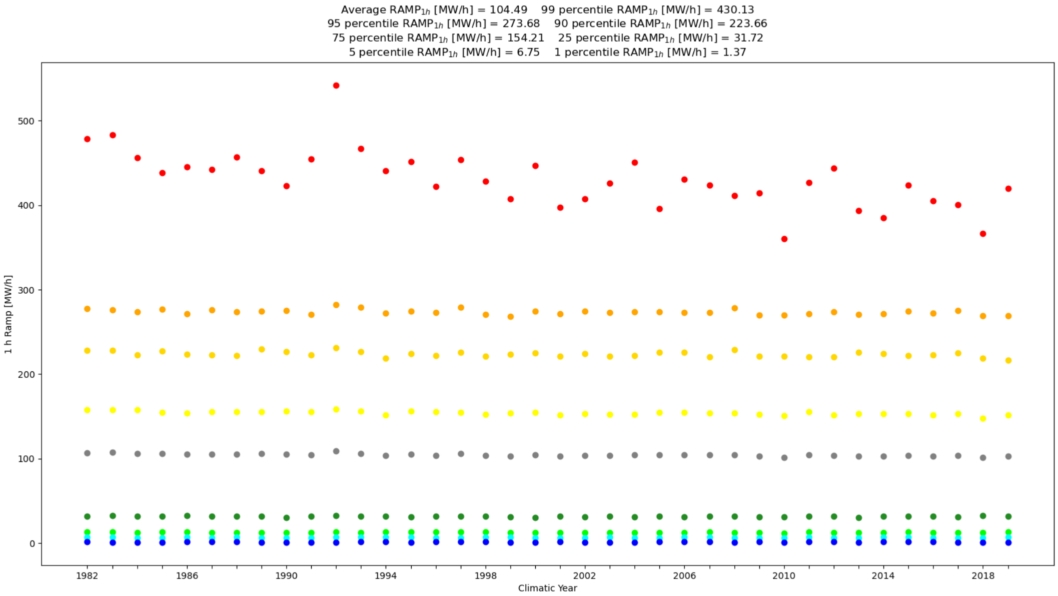
The following figures show substantial stability of the indicators across the different climate years: only the 99th percentile shows some variability.

The 1h residual load ramp rate could reach values greater than 0.2 GW/h for 5% of the hours of the year (and greater than 0.4 GW/h for 1% of the hours of the year).

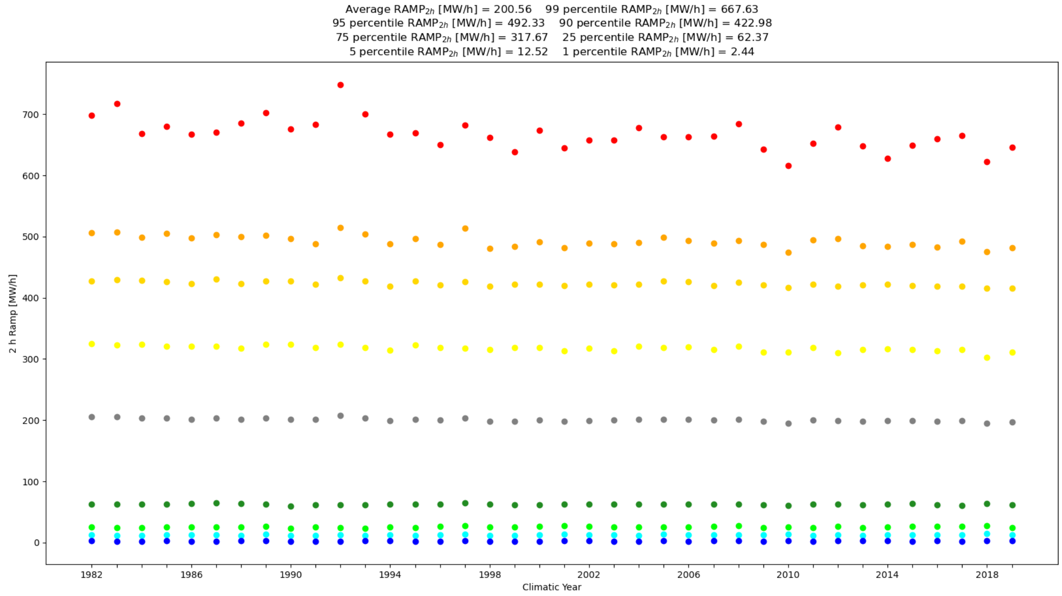
The 2h residual load ramp rate could reach values greater than 0.5 GW/2h for 5% of the hours of the year (and greater than 0.7 GW/2h for 1% of the hours of the year).

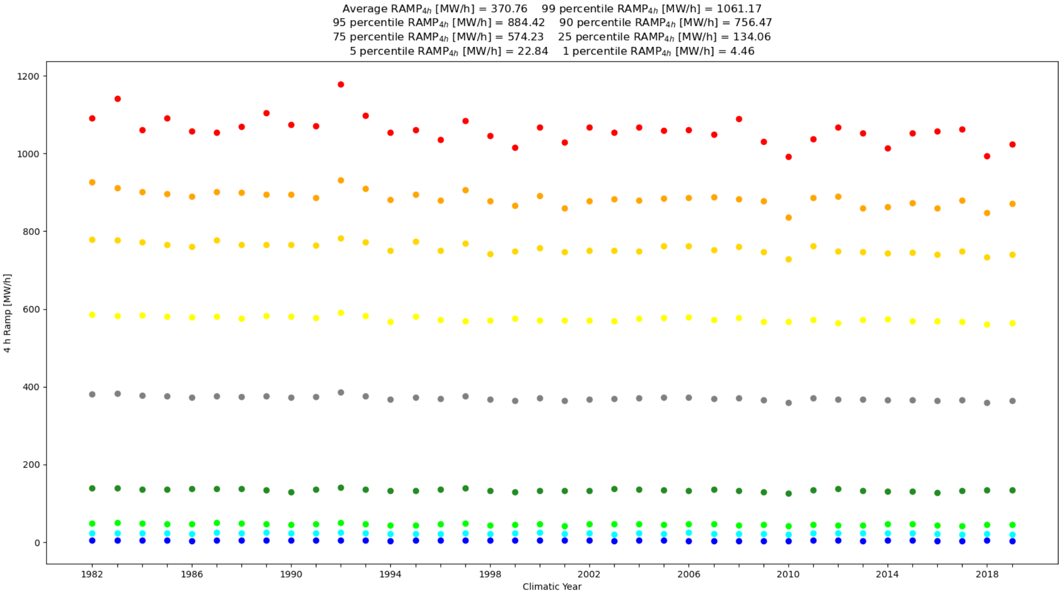
The 4h residual load ramp rate could reach values greater than 0.9 GW/4h for 5% of the hours of the year (and greater than 1.0 GW/4h for 1% of the hours of the year).

Also in this case, enlarging the time scale for assessing the ramp smooths the derivative but highlights the need for flexible resources to follow the ramp rates of several GW over a few hours.



Average $RAMP_{1h}$ [MW/h] = 104.49   99 percentile $RAMP_{1h}$ [MW/h] = 430.13
95 percentile $RAMP_{1h}$ [MW/h] = 273.68   90 percentile $RAMP_{1h}$ [MW/h] = 223.66
75 percentile $RAMP_{1h}$ [MW/h] = 154.21   25 percentile $RAMP_{1h}$ [MW/h] = 31.72
5 percentile $RAMP_{1h}$ [MW/h] = 6.75   1 percentile $RAMP_{1h}$ [MW/h] = 1.37



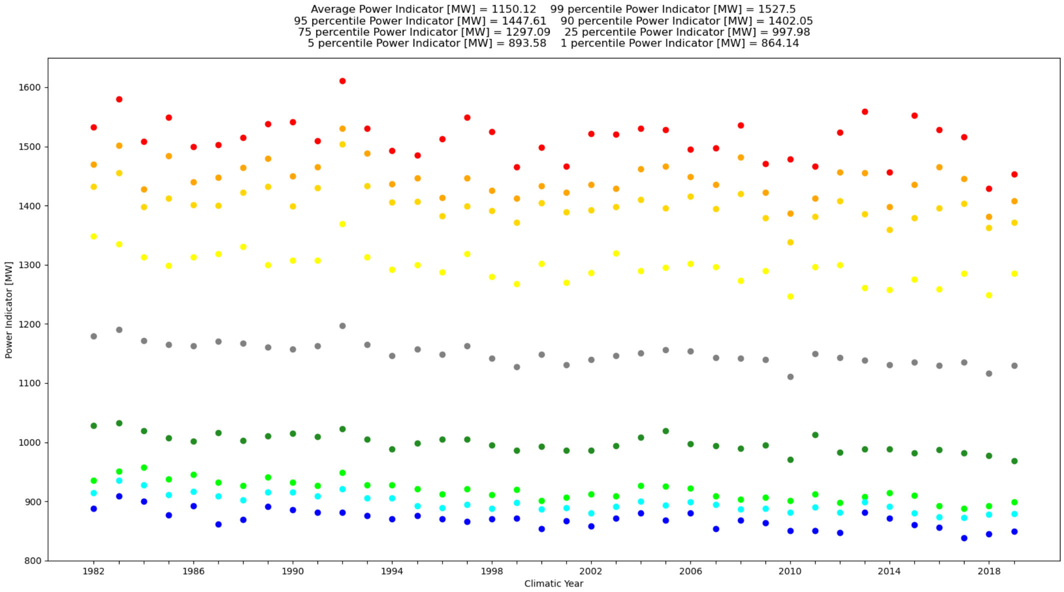


Daily Assessment

The daily energy indicator FN_{daily} shows little variation across the whole time series (and across climate years): the 99th percentile is 1.55TWh, the 1st percentile is 1.43TWh and the average value is 1.48TWh.

The daily energy indicator FNMAX$_{daily}$ shows little variation across climate years, resulting in a range between 5.2 GWh and 6.3 GWh for all the assessed climate years, with a mean value of about 5.6 GWh. This represents the maximum amount of flexibility needed on a daily basis.

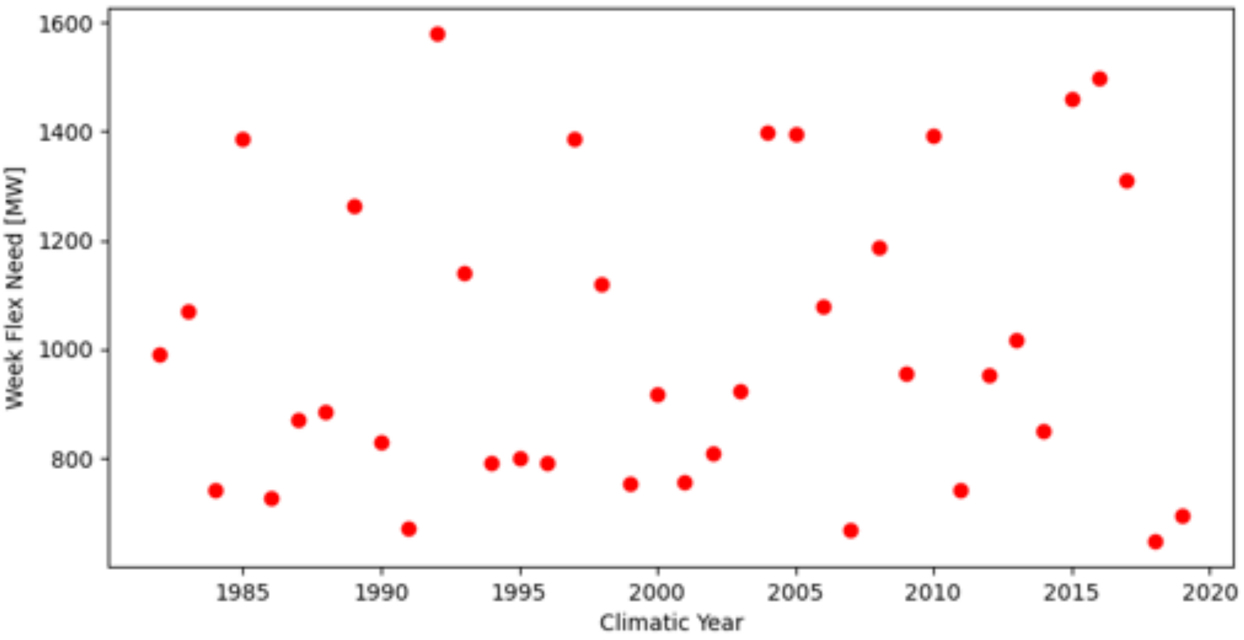
The power indicator is reported in the figure below for each climate year and relevant percentile. The average value across the whole time series (and climate years) is about 1.15 GW, which represents the average difference between the daily minimum and maximum residual load values. This difference can rise up to 1.4 GW for 5% of the days and up to 1.5 GW for 1% of the days.



Weekly Assessment

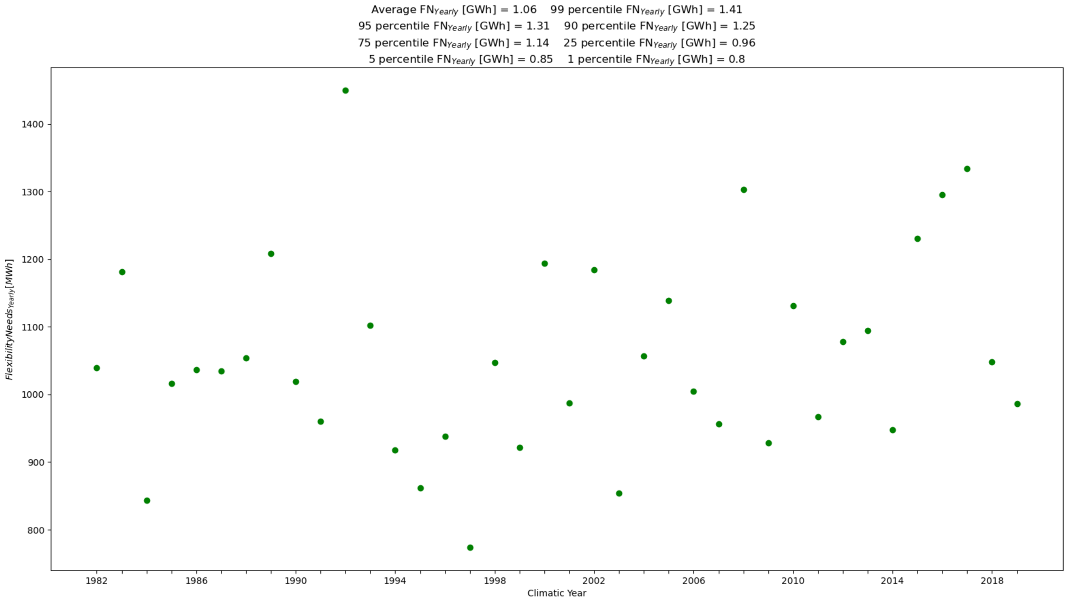
The weekly energy indicator FN$_{weekly}$ shows a variation across the whole time series (and across climate years) smaller than the sensitivity of the last decimal place of the displayed results: therefore, the 99th percentile, the 1st percentile and the average value are 0.02 TWh. This indicator assumes values that are one order of magnitude lower than the corresponding daily indicator. This means there is no significant variation in terms of residual load between days of the same week.

The weekly energy indicator FNMAX$_{weekly}$ is on average (across all the climate years) of about 1.0 GW. This represents the maximum amount of flexibility needed on a weekly basis. However, this indicator shows a peak for the 1992 climate year (of about 1.6 GW, see figure below).



Yearly Assessment

The yearly energy indicator FN$_{yearlyyealy}$ shows little variation across the whole time series (and across climate years): the 99th percentile is 1.4 GWh, the 1st percentile is 0.8 GWh and the average value is 1.06 GWh. This indicator assumes values that are very low compared to the weekly and, especially, the daily indicators. This means there is no significant variation in terms of residual load between months of the same year.



Libya

Hourly Assessment

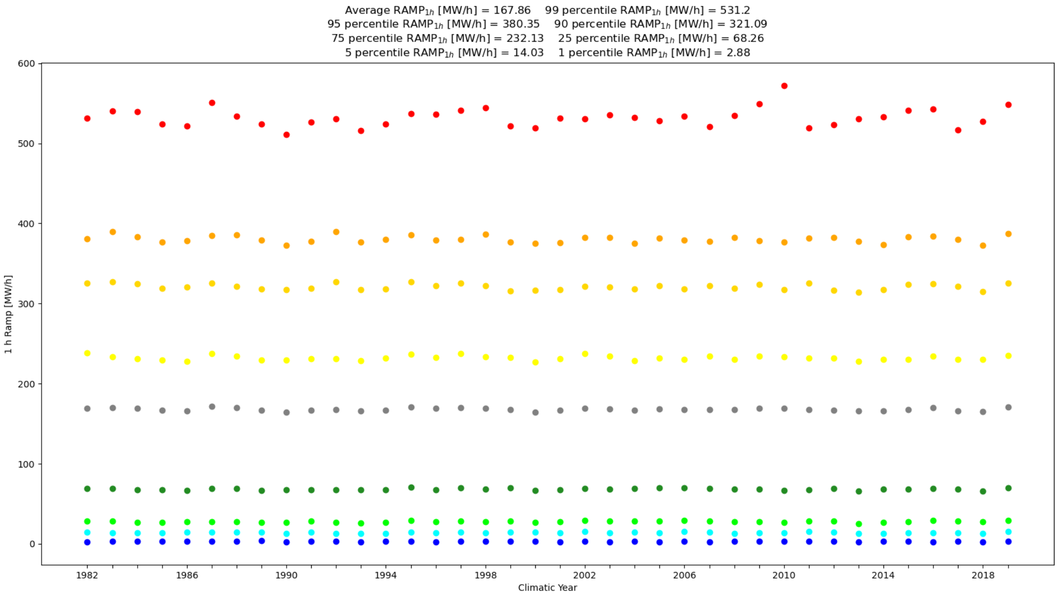
The following figures show substantial stability of the indicators across the different climate years: however, there is a significant gap between the 99th and the 95th percentiles. Some variations in the indicator across different climatic years are already present from the 90th percentile and become particularly evident at the 99th percentile.

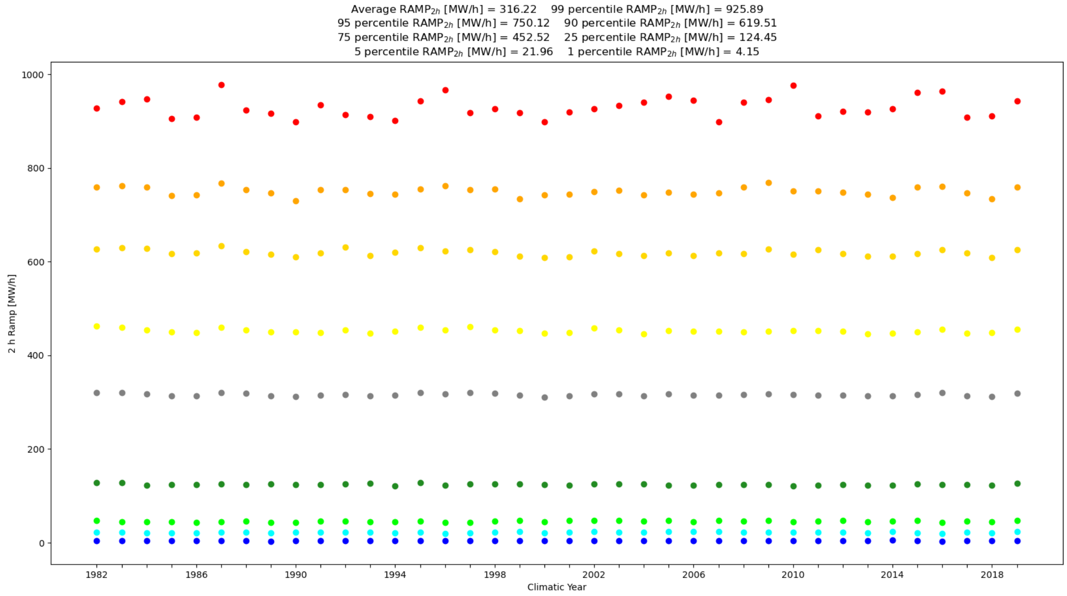
The 1h residual load ramp rate could reach values greater than 0.4 GW/h for 5% of the hours of the year (and greater than 0.5 GW/h for 1% of the hours of the year).

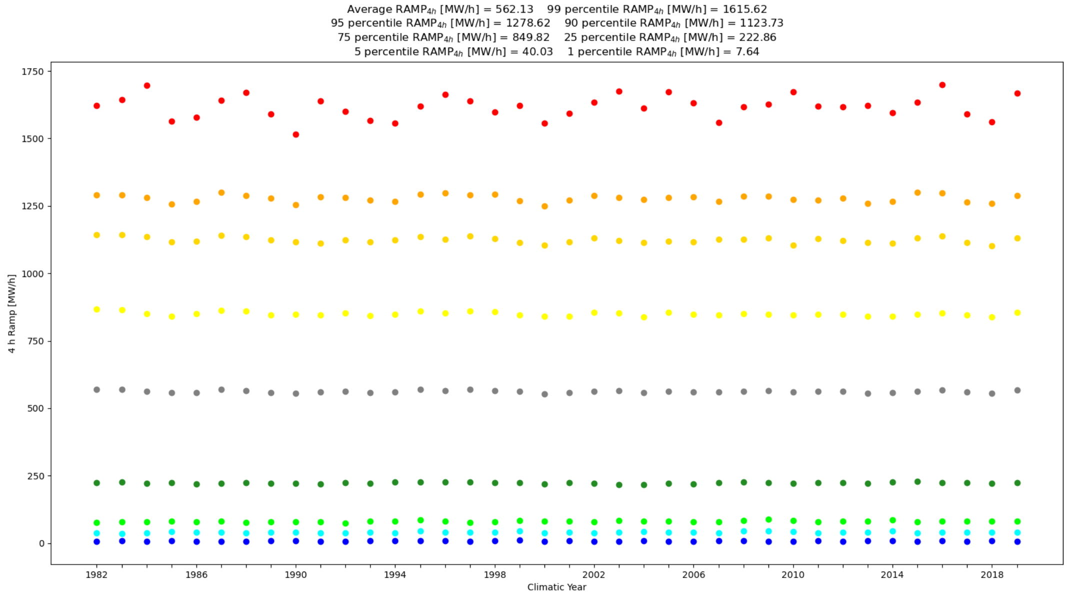
Proportionally, the 2h residual load ramp rate could reach values greater than 0.8GW/2h for 5% of the hours of the year (and greater than 1.0GW/2h for 1% of the hours of the year).

The 4h residual load ramp rate could reach values greater than 1.3 GW/4h for 5% of the hours of the year (and greater than 1.6 GW/4h for 1% of the hours of the year).

Also in this case, enlarging the time scale for assessing the ramp smooths the derivative but highlight the need for flexible resources to follow the ramp rates of several GW over a few hours.





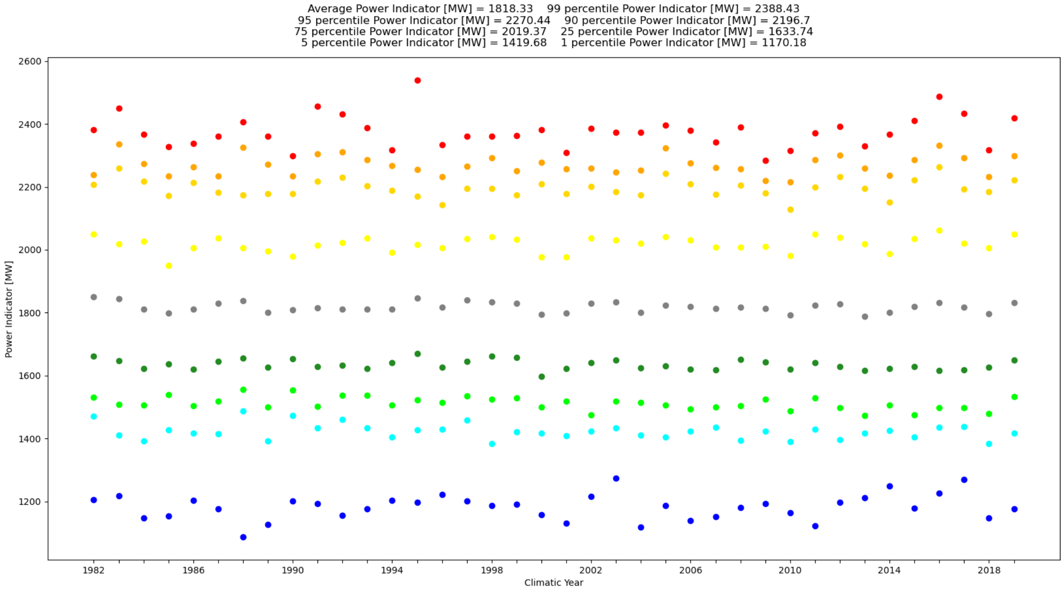


Daily Assessment

The daily energy indicator FN$_{daily}$ shows little variation across the whole time series (and across climate years): the 99th percentile is 2.22 TWh, the 1st percentile is 2.15 TWh and the average value is 2.18 TWh.

The daily energy indicator $FNMAX_{daily}$ shows little variation across climate years, resulting in a range between 7.4 GWh and 9.0 GWh for all the assessed climate years, with a mean value of about 8.0G Wh. This represents the maximum amount of flexibility needed on a daily basis.

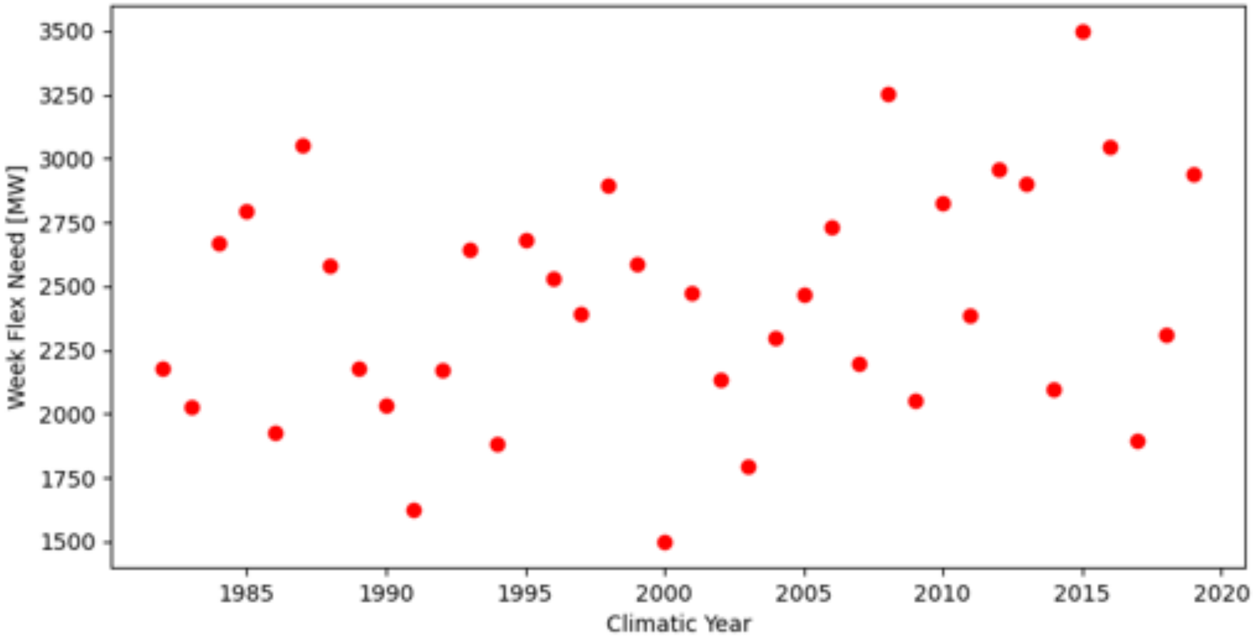
The power indicator is reported in the figure below for each climate year and relevant percentile. The average value across the whole time series (and climate years) is about 1.8 GW, which represents the average difference between daily minimum and maximum residual load values. This difference can rise up to 2.3 GW for 5% of the days and up to 2.4 GW for 1% of the days.



Weekly Assessment

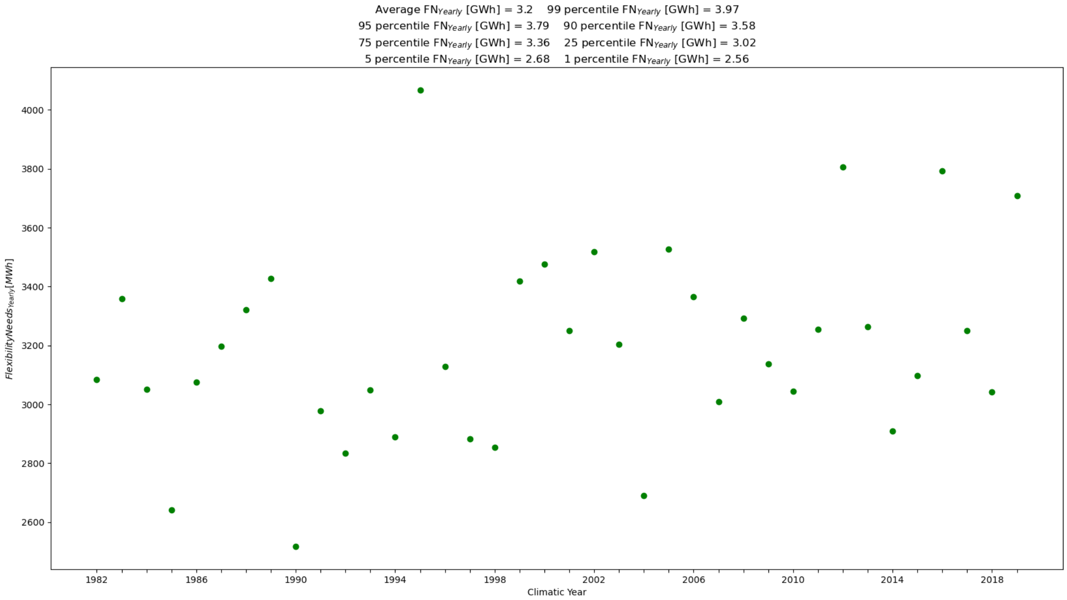
The weekly energy indicator FN_{weekly} shows little variation across the whole time series (and across climate years): the 99th percentile is 0.05 TWh, the 1st percentile is 0.04 TWh and the average value is 0.04 TWh. This indicator assumes values that are one order of magnitude lower than the corresponding daily indicator. This means there is no significant variation in terms of residual load between days of the same week.

The weekly energy indicator $FNMAX_{weekly}$ is on average (across all the climate years) about 2.4 GW. This represents the maximum amount of flexibility needed on a weekly basis. However, this indicator shows a peak for the 2015 climate year (of about 3.5 GW, see figure below).



Yearly Assessment

The yearly energy indicator FN$_{yearly}$ shows little variation across the whole time series (and across climate years): the 99th percentile is 4.0 GWh, the 1st percentile is 2.6 GWh and the average value is 3.2 GWh. This indicator assumes values that are very low compared to the weekly and, especially, the daily indicators. This means there is no significant variation in terms of residual load between months of the same year.



Morocco

Hourly Assessment

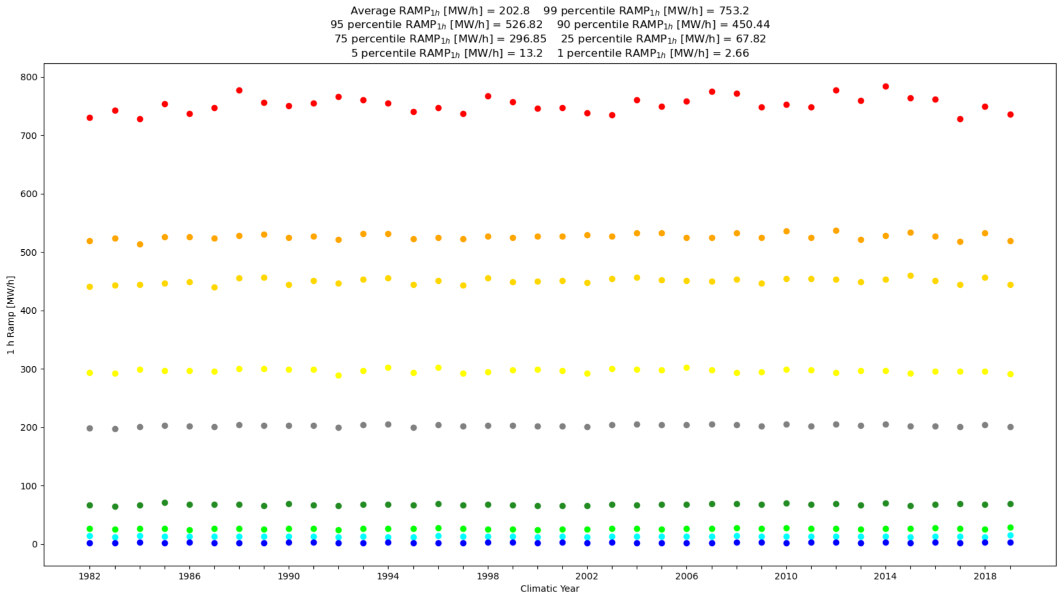
The following figures show substantial stability of the indicators across the different climate years: only the 99th percentile shows some variability.

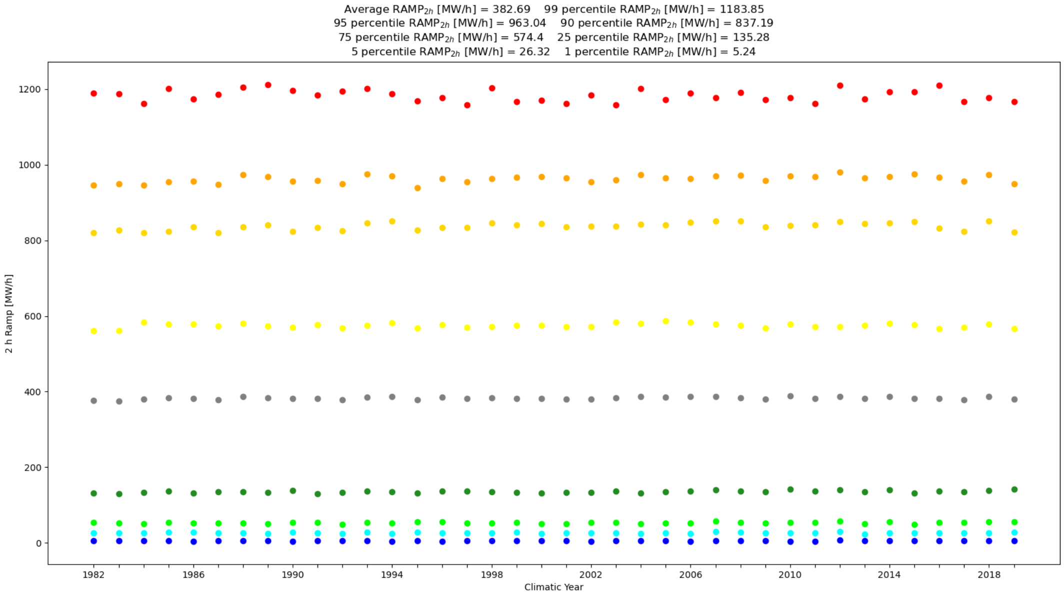
The 1h residual load ramp rate could reach values greater than 0.5 GW/h for 5% of the hours of the year (and greater than 0.8 GW/h for 1% of the hours of the year).

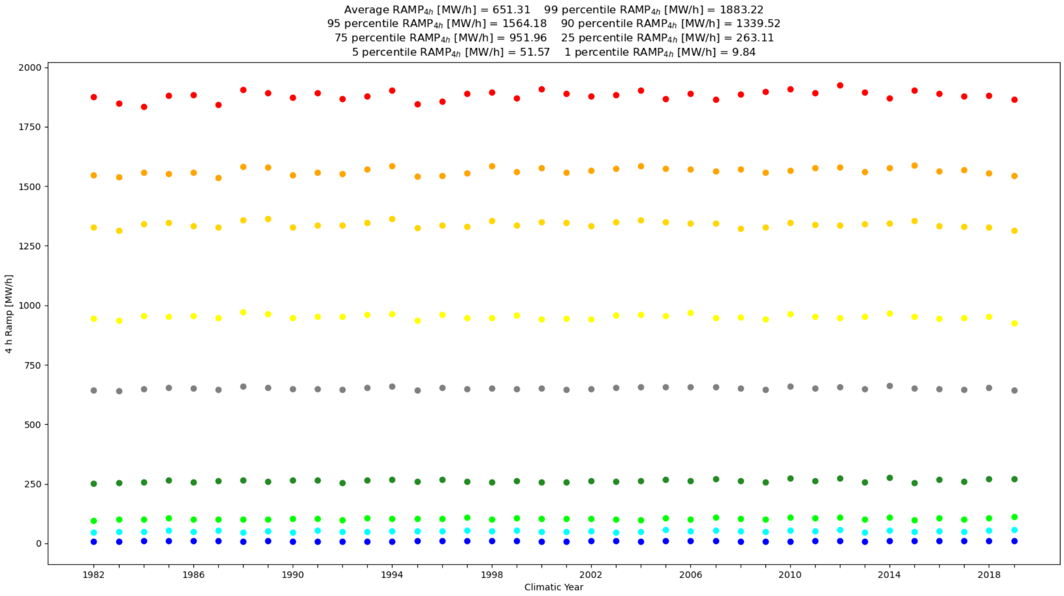
The 2h residual load ramp rate could reach values greater than 1.0 GW/2h for 5% of the hours of the year (and greater than 1.2 GW/2h for 1% of the hours of the year).

The 4h residual load ramp rate could reach values greater than 1.6 GW/4h for 5% of the hours of the year (and greater than 1.9 GW/4h for 1% of the hours of the year).

Also in this case, enlarging the time scale for assessing the ramp smooths the derivative but highlights the need for flexible resources to follow the ramp rates of several GW over a few hours.




Average RAMP$_{2h}$ [MW/h] = 382.69   99 percentile RAMP$_{2h}$ [MW/h] = 1183.85
95 percentile RAMP$_{2h}$ [MW/h] = 963.04   90 percentile RAMP$_{2h}$ [MW/h] = 837.19
75 percentile RAMP$_{2h}$ [MW/h] = 574.4   25 percentile RAMP$_{2h}$ [MW/h] = 135.28
5 percentile RAMP$_{2h}$ [MW/h] = 26.32   1 percentile RAMP$_{2h}$ [MW/h] = 5.24
2 h Ramp [MW/h]
1200
1000
800
600
400
200
0
1982
1986
1990
1994
1998
2002
2006
2010
2014
2018
Climatic Year

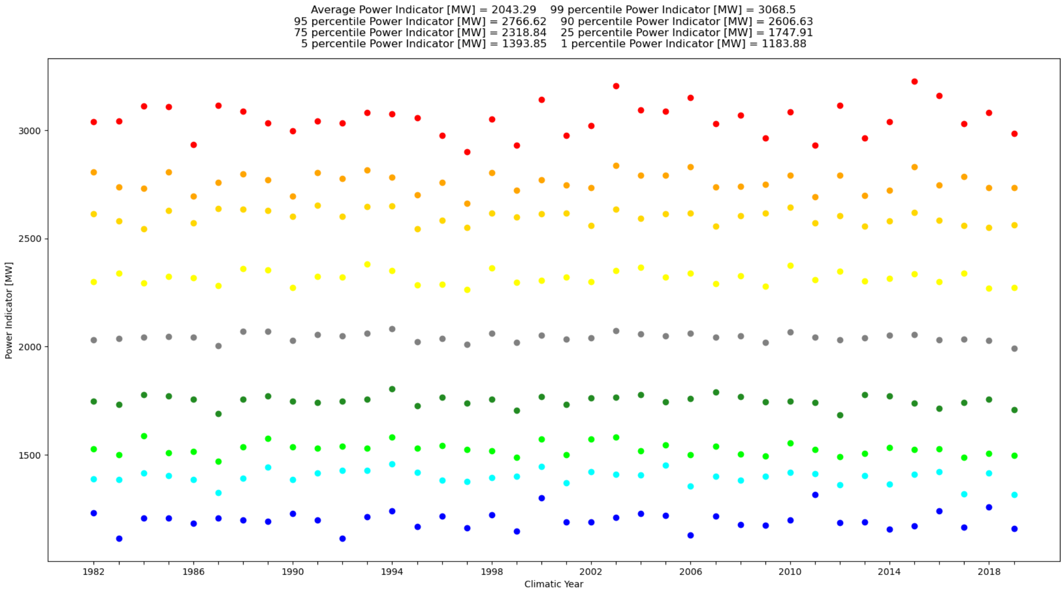

Average RAMP$_{4h}$ [MW/h] = 651.31   99 percentile RAMP$_{4h}$ [MW/h] = 1883.22
95 percentile RAMP$_{4h}$ [MW/h] = 1564.18   90 percentile RAMP$_{4h}$ [MW/h] = 1339.52
75 percentile RAMP$_{4h}$ [MW/h] = 951.96   25 percentile RAMP$_{4h}$ [MW/h] = 263.11
5 percentile RAMP$_{4h}$ [MW/h] = 51.57   1 percentile RAMP$_{4h}$ [MW/h] = 9.84
4 h Ramp [MW/h]
2000
1750
1500
1250
1000
750
500
250
0
1982
1986
1990
1994
1998
2002
2006
2010
2014
2018
Climatic Year

Daily Assessment

The daily energy indicator FN_{daily} shows little variation across the whole time series (and across climate years): the 99th percentile is 2.35 TWh, the 1st percentile is 2.26 TWh and the average value is 2.31 TWh.

The daily energy indicator $FNMAX_{daily}$ shows little variation across climate years, resulting in a range between 9.8 GWh and 11.2 GWh for all the assessed climate years, with a mean value of about 10.4 GWh. This represents the maximum amount of flexibility needed on a daily basis.

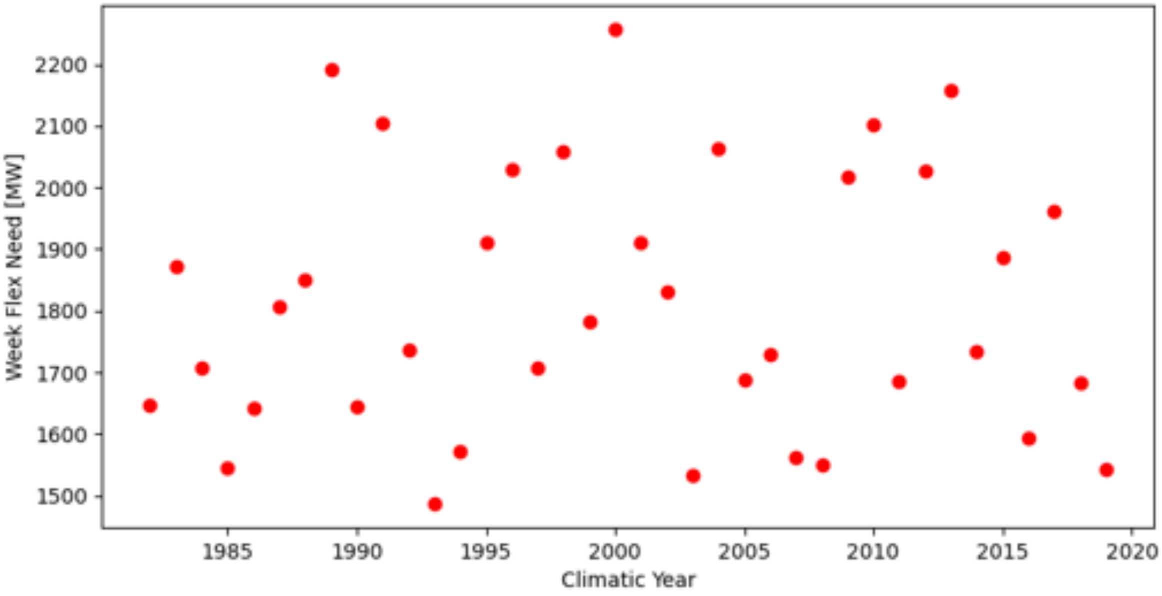
The power indicator is reported in the figure below for each climate year and relevant percentile. The average value across the whole time series (and climate years) is about 2.4 GW, which represents the average difference between daily minimum and maximum residual load values. This difference can rise up to 2.8 GW for 5% of the days and up to 3.1 GW for 1% of the days.



Weekly Assessment

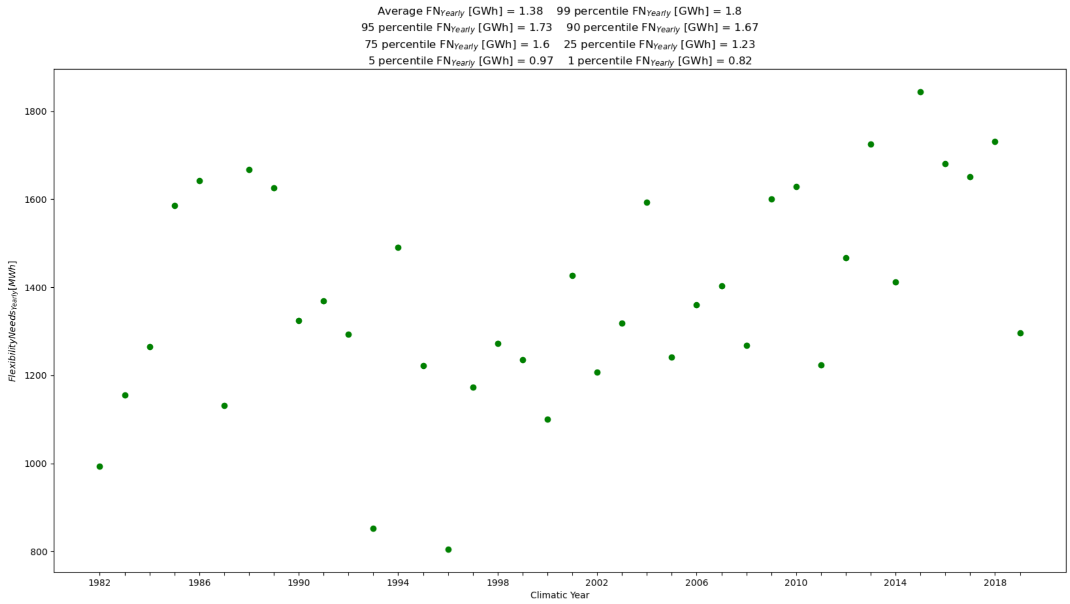
The weekly energy indicator FN_{weekly} shows little variation across the whole time series (and across climate years): the 99th percentile is 0.05 TWh, the 1st percentile is 0.04 TWh and the average value is 0.05 TWh. This indicator assumes values that are one order of magnitude lower than the corresponding daily indicator. This means there is no significant variation in terms of residual load between days of the same week.

The weekly energy indicator $FNMAX_{weekly}$ is on average (across all the climate years) about 1.8 GW. This represents the maximum amount of flexibility needed on a weekly basis. However, this indicator shows a peak for the 2000 climate year (of about 2.3 GW, see figure below).



Yearly Assessment

The yearly energy indicator FN_{yearly} shows little variation across the whole time series (and across climate years): the 99th percentile is 1.8 GWh, the 1st percentile is 0.8 GWh and the average value is 1.4 GWh. This indicator assumes values that are very low compared to the weekly and, especially, the daily indicators. This means there is no significant variation in terms of residual load between months of the same year.



Tunisia

Hourly Assessment

The following figures show substantial stability of the indicators across the different climate years: only the 99th percentile shows some variability.

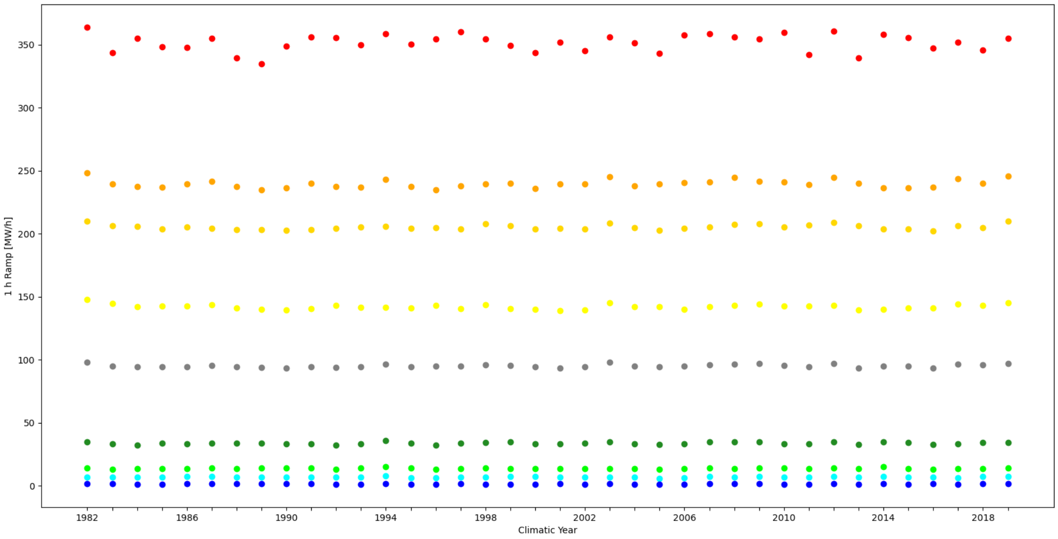
The 1h residual load ramp rate could reach values greater than 0.2 GW/h for 5% of the hours of the year (and greater than 0.4 GW/h for 1% of the hours of the year).

The 2h residual load ramp rate could reach values greater than 0.4 GW/2h for 5% of the hours of the year (and greater than 0.5 GW/2h for 1% of the hours of the year).

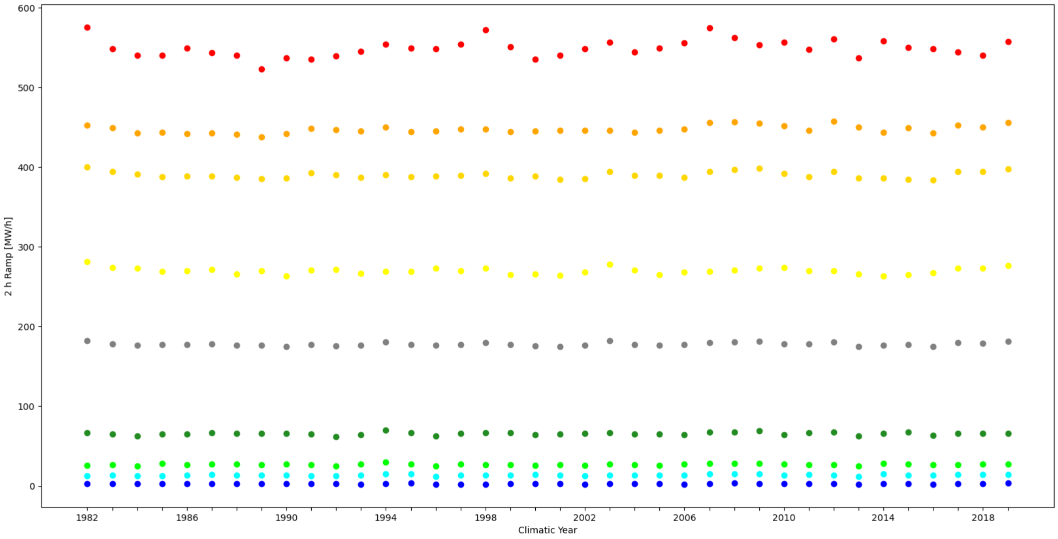
The 4h residual load ramp rate could reach values greater than 0.7 GW/4h for 5% of the hours of the year (and greater than 0.9 GW/4h for 1% of the hours of the year).

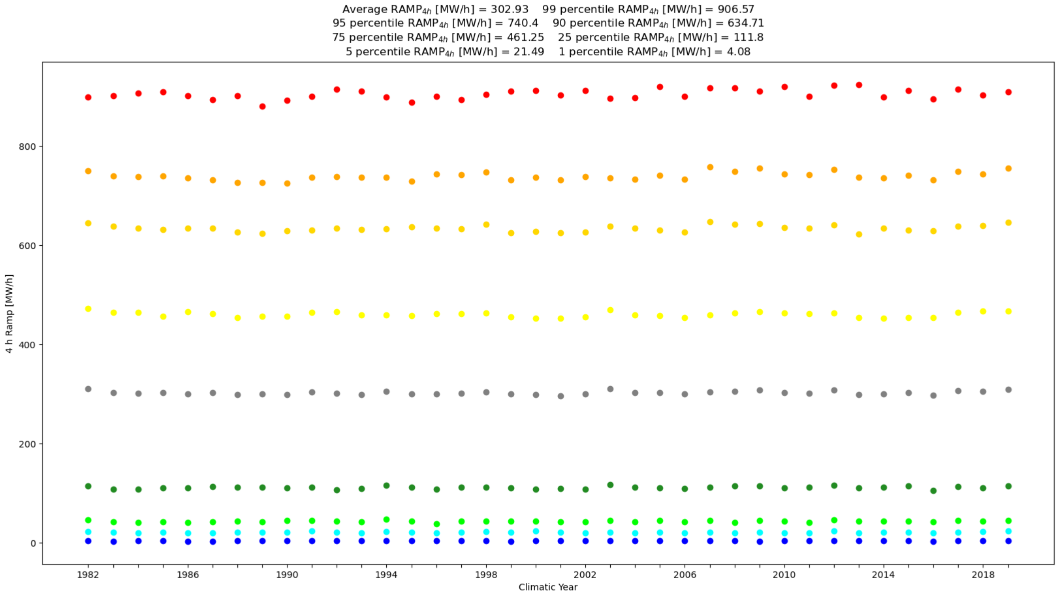
Also in this case, enlarging the time scale for assessing the ramp smooths the derivative but highlights the need for flexible resources to follow the ramp rates of several GW over a few hours.

Average RAMP$_{1h}$ [MW/h] = 95.11   99 percentile RAMP$_{1h}$ [MW/h] = 353.12
95 percentile RAMP$_{1h}$ [MW/h] = 239.41   90 percentile RAMP$_{1h}$ [MW/h] = 205.34
75 percentile RAMP$_{1h}$ [MW/h] = 142.06   25 percentile RAMP$_{1h}$ [MW/h] = 33.68
5 percentile RAMP$_{1h}$ [MW/h] = 6.83   1 percentile RAMP$_{1h}$ [MW/h] = 1.35



Average RAMP$_{2h}$ [MW/h] = 177.93   99 percentile RAMP$_{2h}$ [MW/h] = 549.94
95 percentile RAMP$_{2h}$ [MW/h] = 447.61   90 percentile RAMP$_{2h}$ [MW/h] = 390.37
75 percentile RAMP$_{2h}$ [MW/h] = 270.21   25 percentile RAMP$_{2h}$ [MW/h] = 65.67
5 percentile RAMP$_{2h}$ [MW/h] = 13.67   1 percentile RAMP$_{2h}$ [MW/h] = 2.72



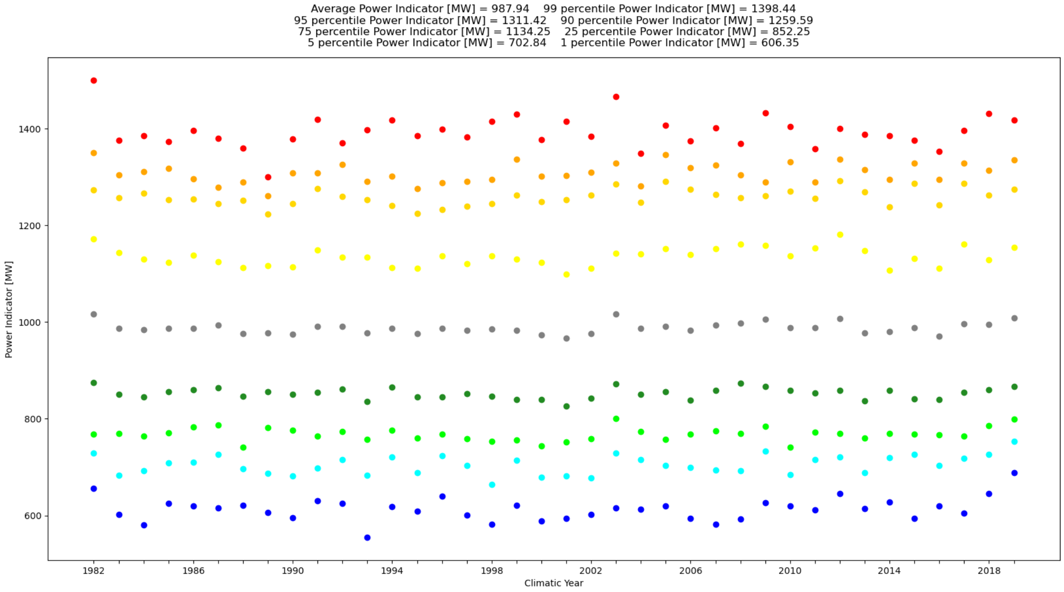


Daily Assessment

The daily energy indicator FN$_{daily}$ shows little variation across the whole time series (and across climate years): the 99th percentile is 1.09 TWh, the 1st percentile is 1.04 TWh and the average value is 1.06 TWh.

The daily energy indicator FNMAX$_{daily}$ shows little variation across climate years, resulting in a range between 4GWh and 4.8GWh for all the assessed climate years, with a mean value of about 4.4 GWh. This represents the maximum amount of flexibility needed on a daily basis.

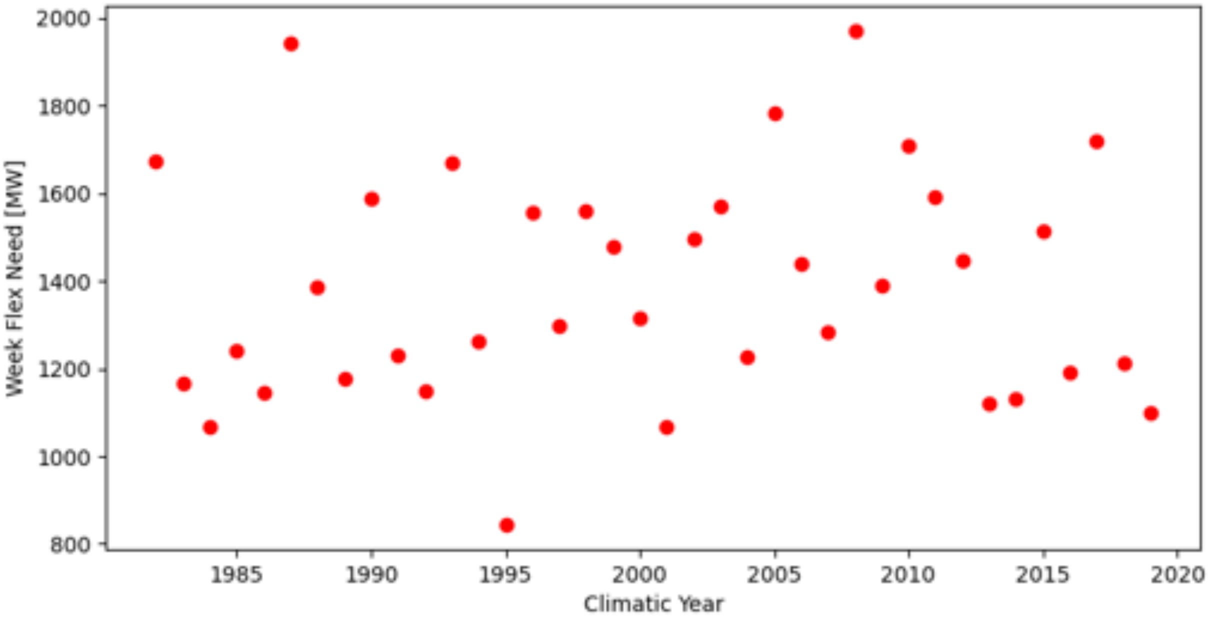
The power indicator is reported in the figure below for each climate year and relevant percentile. The average value across the whole time series (and climate years) is about 1.0 GW, which represents the average difference between daily minimum and maximum residual load values. This difference can rise up to 1.3 GW for 5% of the days and up to 1.4 GW for 1% of the days.



Weekly Assessment

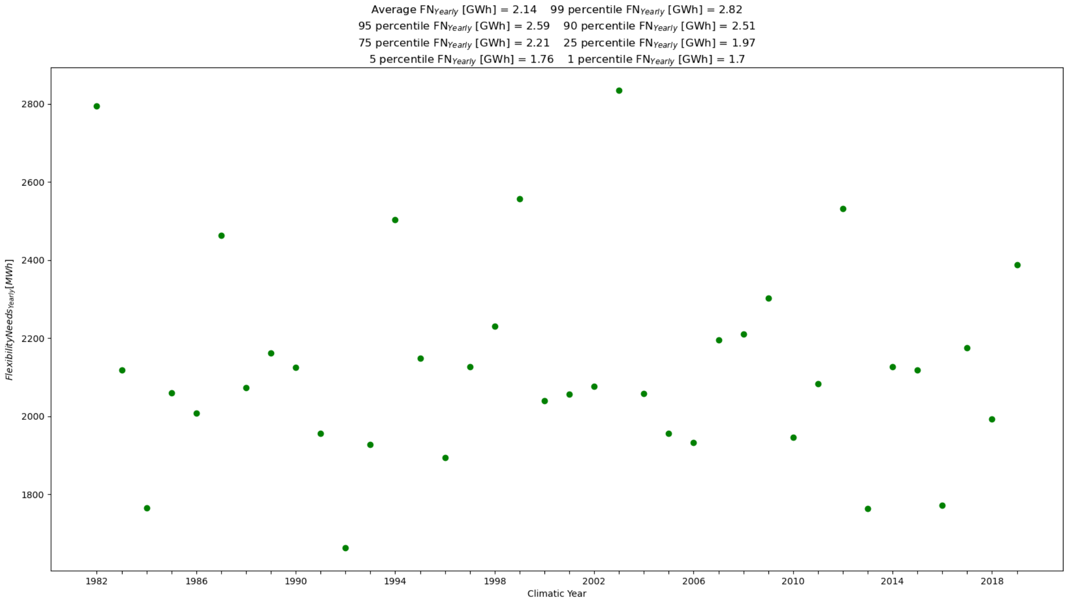
The weekly energy indicator FN_{weekly} shows little variation across the whole time series (and across climate years): the 99th percentile is 0.03 TWh, the 1st percentile is 0.02 TWh and the average value is 0.03 TWh. This indicator assumes values that are one order of magnitude lower than the corresponding daily indicator. This means there is no significant variation in terms of residual load between days of the same week.

The weekly energy indicator $FNMAX_{weekly}$ is on average (across all the climate years) about 1.4 GW. This represents the maximum amount of flexibility needed on a weekly basis. However, this indicator shows a peak for the 2008 climate year (of about 2.0 GW, see figure below).



Yearly Assessment

The yearly energy indicator FN*yearly* shows little variation across the whole time series (and across climate years): the 99th percentile is 2.8 GWh, the 1st percentile is 1.7 GWh and the average value is 2.1 GWh. This indicator assumes values that are very low compared to the weekly and, especially, the daily indicators. This means there is no significant variation in terms of residual load between months of the same year.



8

Appendix B: Country-Level Detailed Results (2027, 2030)

Egypt

Hourly Assessment

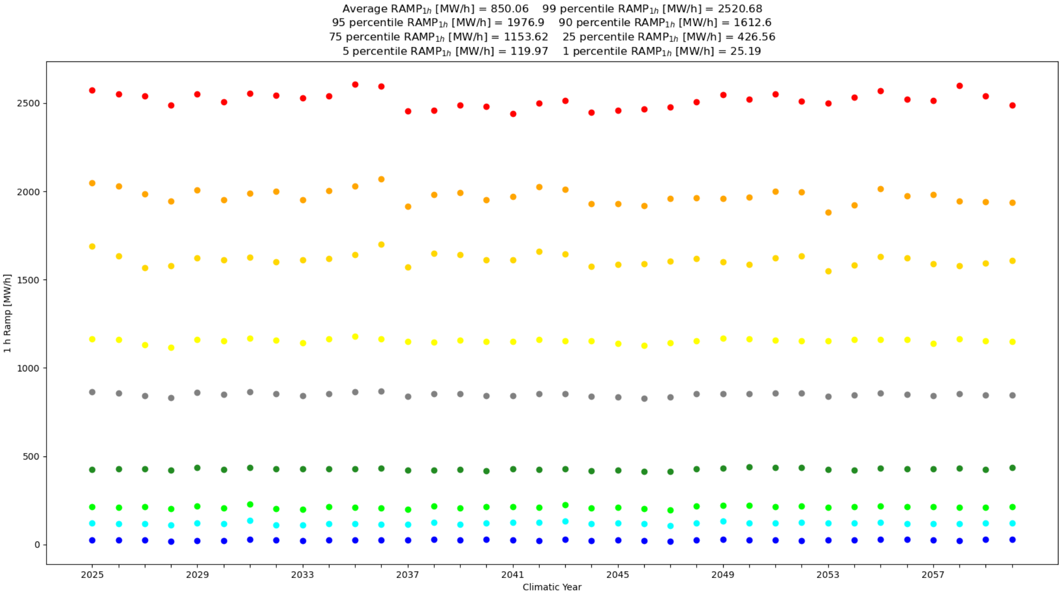
The following figures show substantial stability of the indicators across the different climate years: only the 99th percentile show little variability, which becomes wider in the MT2030.

The 1h residual load ramp rate could reach values greater than 1.9 GW/h and 2.1 GW/h for 5% of the hours of the year (and greater than 2.5 GW/h and 2.8 GW/h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

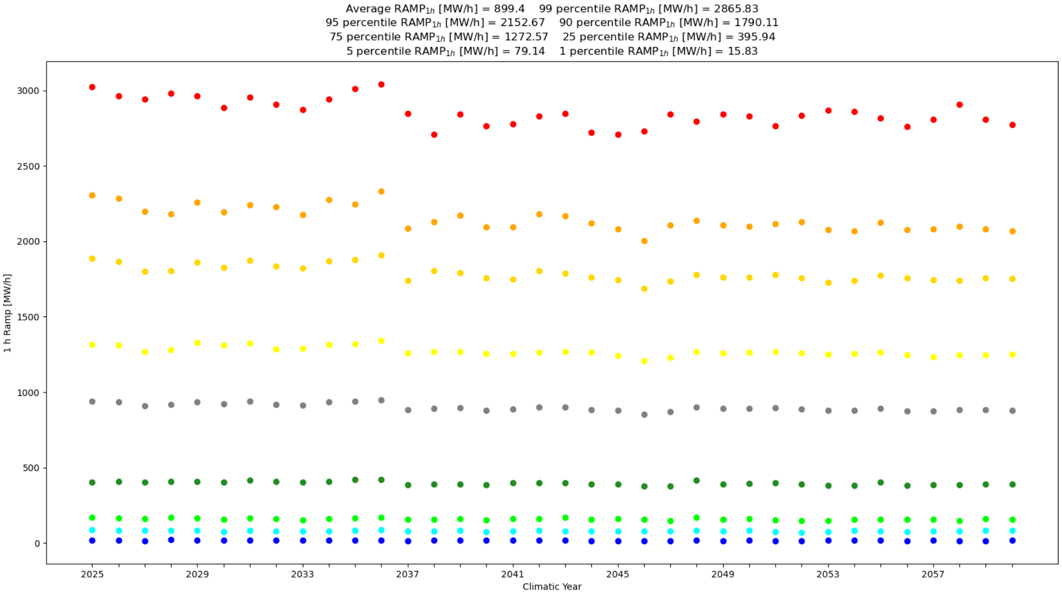
The 2h residual load ramp rate could reach values greater than 3.4 GW/2h and 3.7 GW/2h for 5% of the hours of the year (and greater than 4.0 GW/2h and 4.6 GW/2h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

The 4h residual load ramp rate could reach values greater than 5.3 GW/4h and 6.0 GW/4h for 5% of the hours of the year (and greater than 6.2 GW/4h and 7.3 GW/4h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

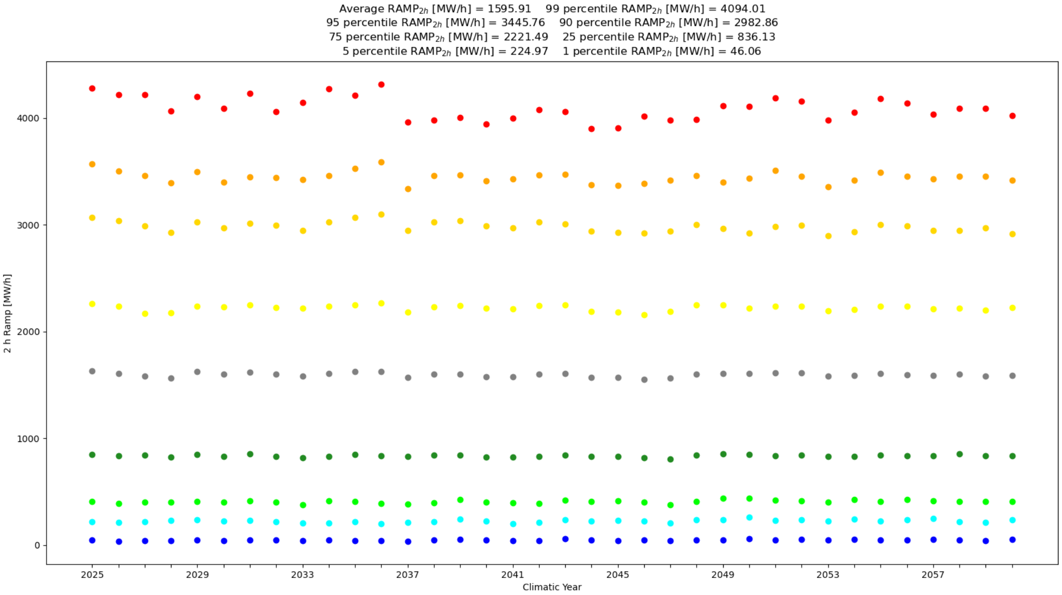
Enlarging the time scale for assessing the ramp smooths the derivative but highlights the need for flexible resources to follow ramp rates of several GW over a few hours.

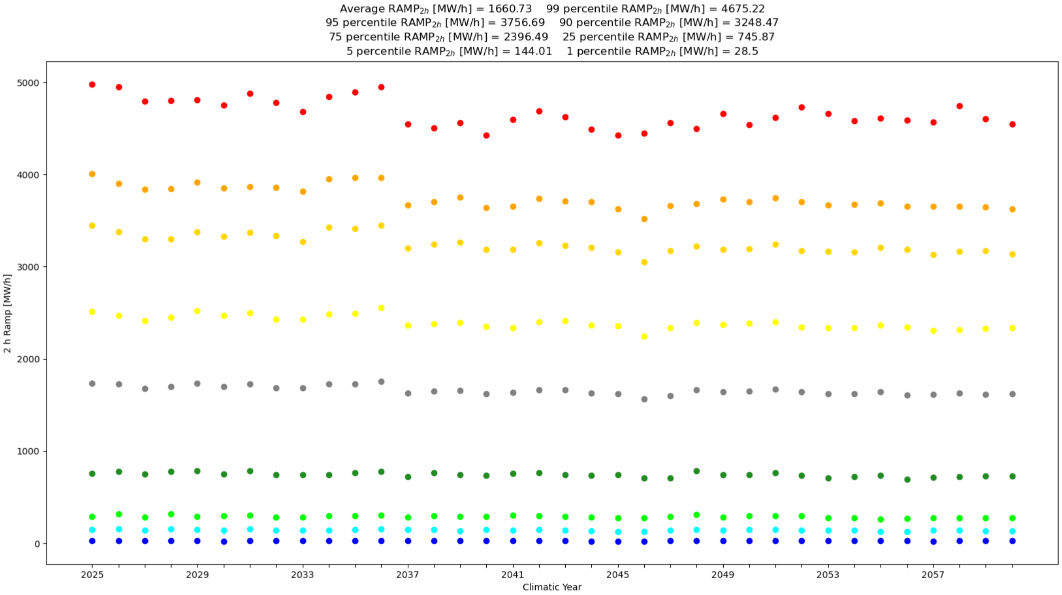


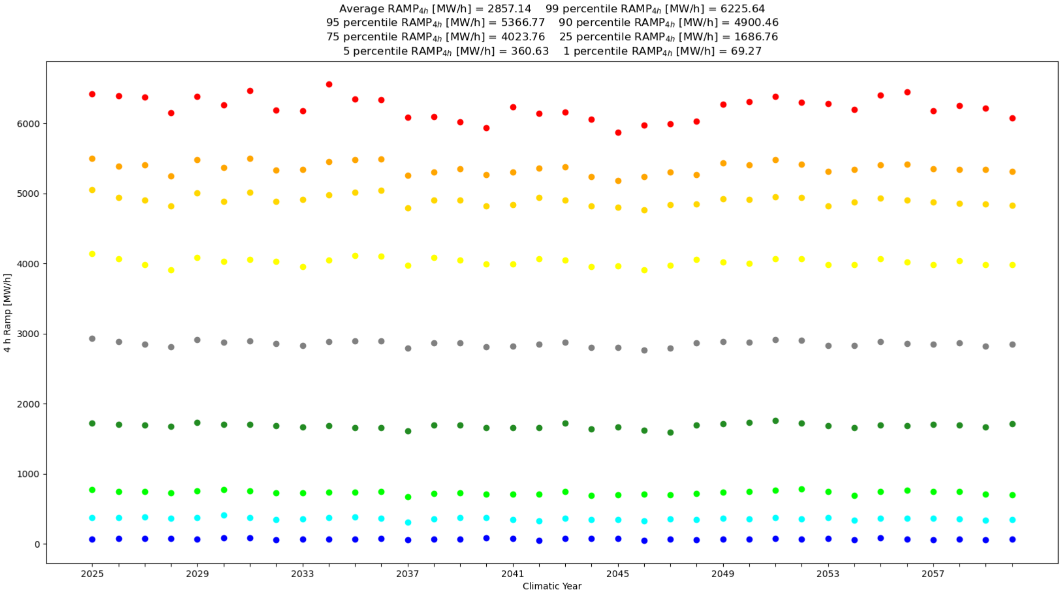
Average RAMP$_{1h}$ [MW/h] = 850.06   99 percentile RAMP$_{1h}$ [MW/h] = 2520.68
95 percentile RAMP$_{1h}$ [MW/h] = 1976.9   90 percentile RAMP$_{1h}$ [MW/h] = 1612.6
75 percentile RAMP$_{1h}$ [MW/h] = 1153.62   25 percentile RAMP$_{1h}$ [MW/h] = 426.56
5 percentile RAMP$_{1h}$ [MW/h] = 119.97   1 percentile RAMP$_{1h}$ [MW/h] = 25.19

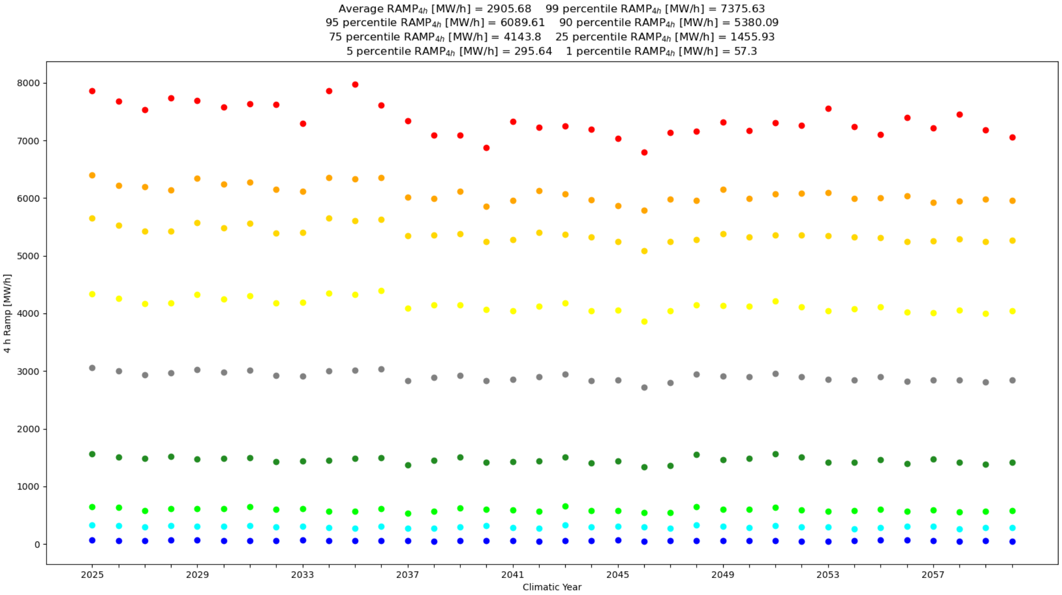


Average RAMP$_{1h}$ [MW/h] = 899.4   99 percentile RAMP$_{1h}$ [MW/h] = 2865.83
95 percentile RAMP$_{1h}$ [MW/h] = 2152.67   90 percentile RAMP$_{1h}$ [MW/h] = 1790.11
75 percentile RAMP$_{1h}$ [MW/h] = 1272.57   25 percentile RAMP$_{1h}$ [MW/h] = 395.94
5 percentile RAMP$_{1h}$ [MW/h] = 79.14   1 percentile RAMP$_{1h}$ [MW/h] = 15.83


Average RAMP$_{2h}$ [MW/h] = 1595.91   99 percentile RAMP$_{2h}$ [MW/h] = 4094.01
95 percentile RAMP$_{2h}$ [MW/h] = 3445.76   90 percentile RAMP$_{2h}$ [MW/h] = 2982.86
75 percentile RAMP$_{2h}$ [MW/h] = 2221.49   25 percentile RAMP$_{2h}$ [MW/h] = 836.13
5 percentile RAMP$_{2h}$ [MW/h] = 224.97   1 percentile RAMP$_{2h}$ [MW/h] = 46.06
2 h Ramp [MW/h]
4000
3000
2000
1000
0
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year


Average RAMP$_{2h}$ [MW/h] = 1660.73   99 percentile RAMP$_{2h}$ [MW/h] = 4675.22
95 percentile RAMP$_{2h}$ [MW/h] = 3756.69   90 percentile RAMP$_{2h}$ [MW/h] = 3248.47
75 percentile RAMP$_{2h}$ [MW/h] = 2396.49   25 percentile RAMP$_{2h}$ [MW/h] = 745.87
5 percentile RAMP$_{2h}$ [MW/h] = 144.01   1 percentile RAMP$_{2h}$ [MW/h] = 28.5
2 h Ramp [MW/h]
5000
4000
3000
2000
1000
0
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year


Average RAMP$_{4h}$ [MW/h] = 2857.14 99 percentile RAMP$_{4h}$ [MW/h] = 6225.64
95 percentile RAMP$_{4h}$ [MW/h] = 5366.77 90 percentile RAMP$_{4h}$ [MW/h] = 4900.46
75 percentile RAMP$_{4h}$ [MW/h] = 4023.76 25 percentile RAMP$_{4h}$ [MW/h] = 1686.76
5 percentile RAMP$_{4h}$ [MW/h] = 360.63 1 percentile RAMP$_{4h}$ [MW/h] = 69.27

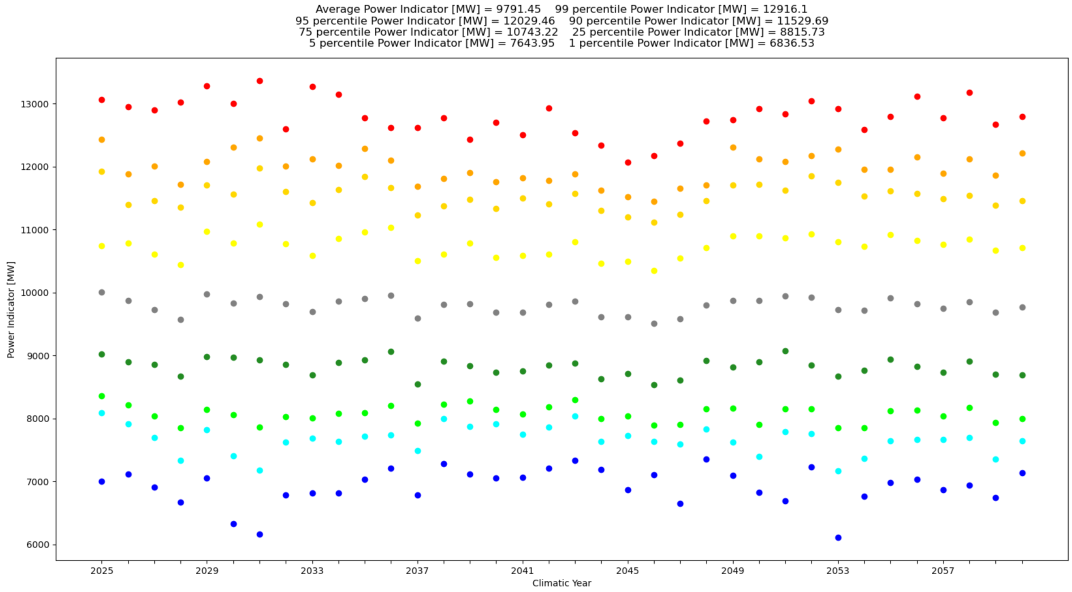

Average RAMP$_{4h}$ [MW/h] = 2905.68 99 percentile RAMP$_{4h}$ [MW/h] = 7375.63
95 percentile RAMP$_{4h}$ [MW/h] = 6089.61 90 percentile RAMP$_{4h}$ [MW/h] = 5380.09
75 percentile RAMP$_{4h}$ [MW/h] = 4143.8 25 percentile RAMP$_{4h}$ [MW/h] = 1455.93
5 percentile RAMP$_{4h}$ [MW/h] = 295.64 1 percentile RAMP$_{4h}$ [MW/h] = 57.3

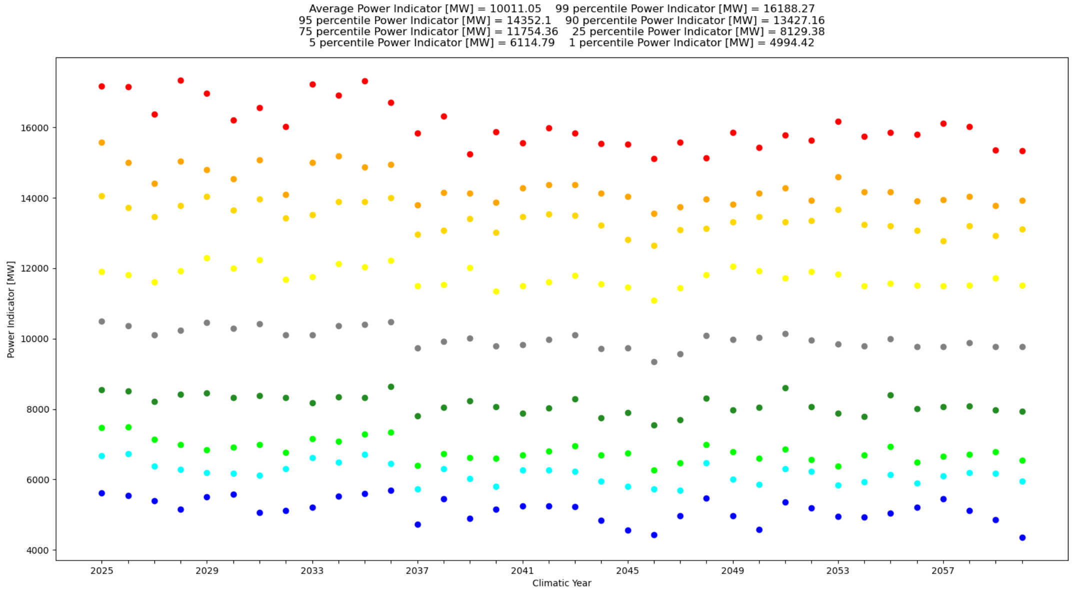
Daily Assessment

The daily energy indicator FN_{daily} shows little variation across the whole time series (and across climate years): the 99th percentile is 11.85 TWh and 12.1 TWh, the 1st percentile is 11.24 TWh and 11.08 TWh and the average value is 11.56 TWh and 11.69 TWh in MT2027 and MT2030, respectively.

The daily energy indicator $FNMAX_{daily}$ shows little variation across climate years, resulting in a range between 41 GWh and 50 GWh and in a range between 55 GWh and 75 GWh for all the assessed climate years, with a mean value of about 45 GWh and 63 GWh in MT2027 and MT2030, respectively. This represents the maximum amount of flexibility needed on a daily basis.

The power indicator is reported in the figure below for each climate year and relevant percentile. The average value across the whole time series (and climate years) is about 9.8 GW and 10.0 GW in MT2027 and MT2030, respectively, which represents the average difference between daily minimum and maximum residual load values. This difference can rise up to 12.0 GW and 14.4 GW for 5% of the days and up to 12.9 GW and 16.2 GW for 1% of the days in MT2027 and MT2030, respectively.

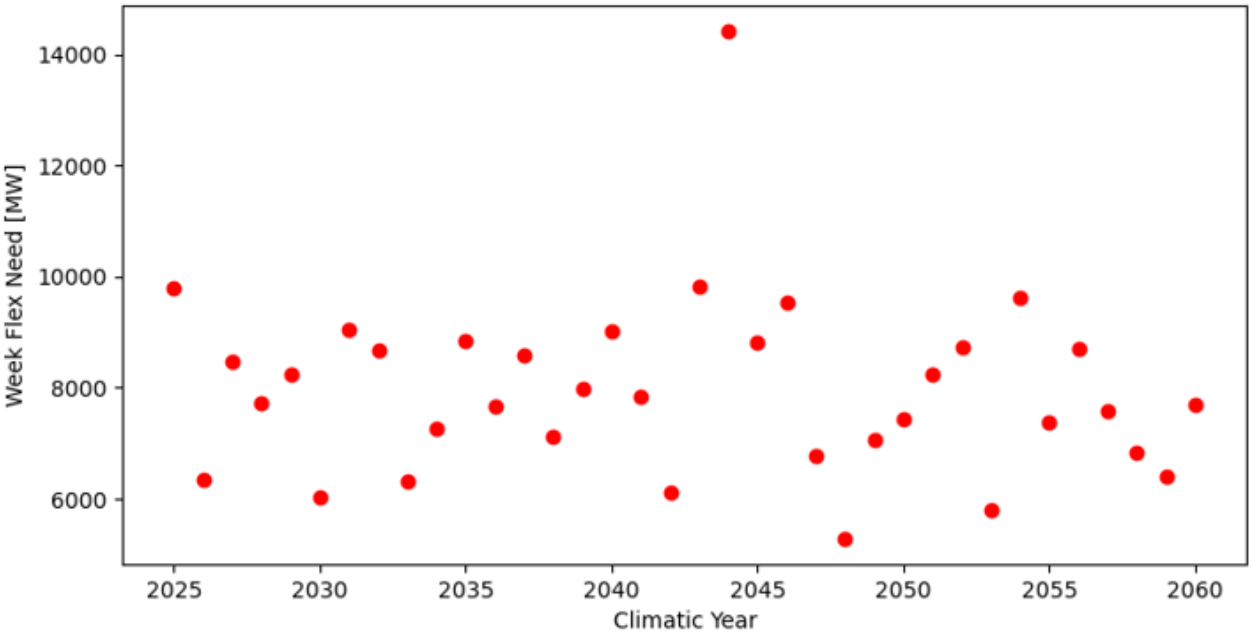


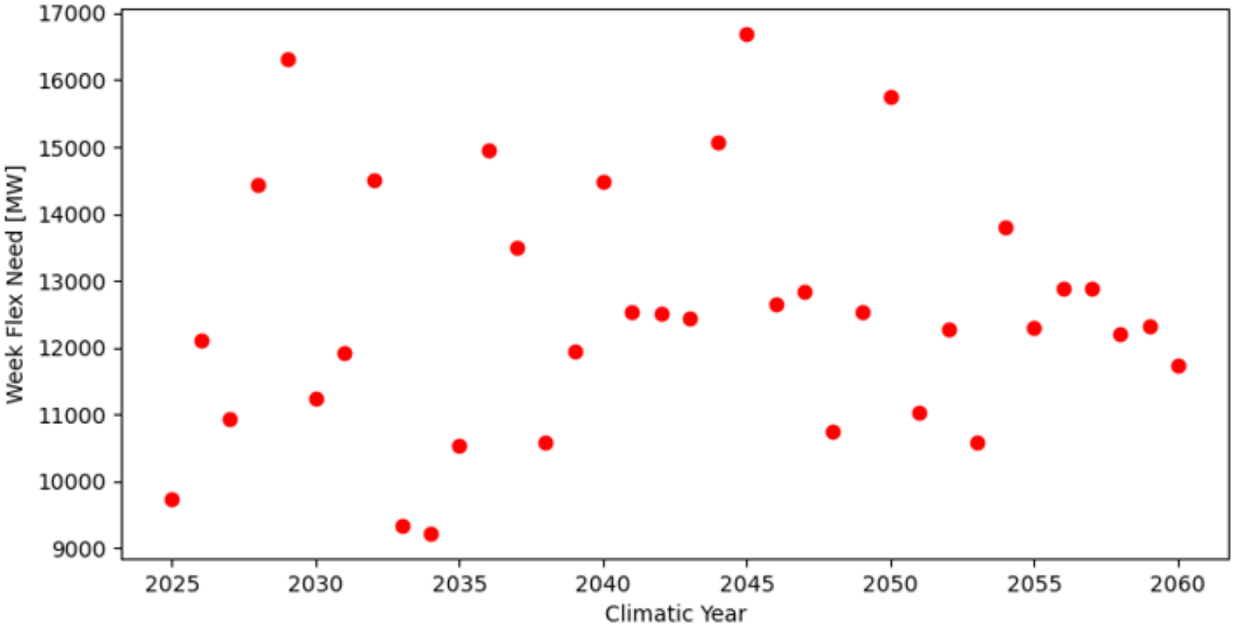


Weekly Assessment

The weekly energy indicator FN_{weekly} shows little variation across the whole time series (and across climate years): the 99th percentile is 0.18 TWh and 0.35 TWh, the 1st percentile is 0.14 TWh and 0.26 TWh and the average value is 0.16 TWh and 0.30 TWh in MT2027 and MT2030, respectively. This indicator assumes values that are one order of magnitude lower than the corresponding daily indicator. This means there is no significant variation in terms of residual load between days of the same week.

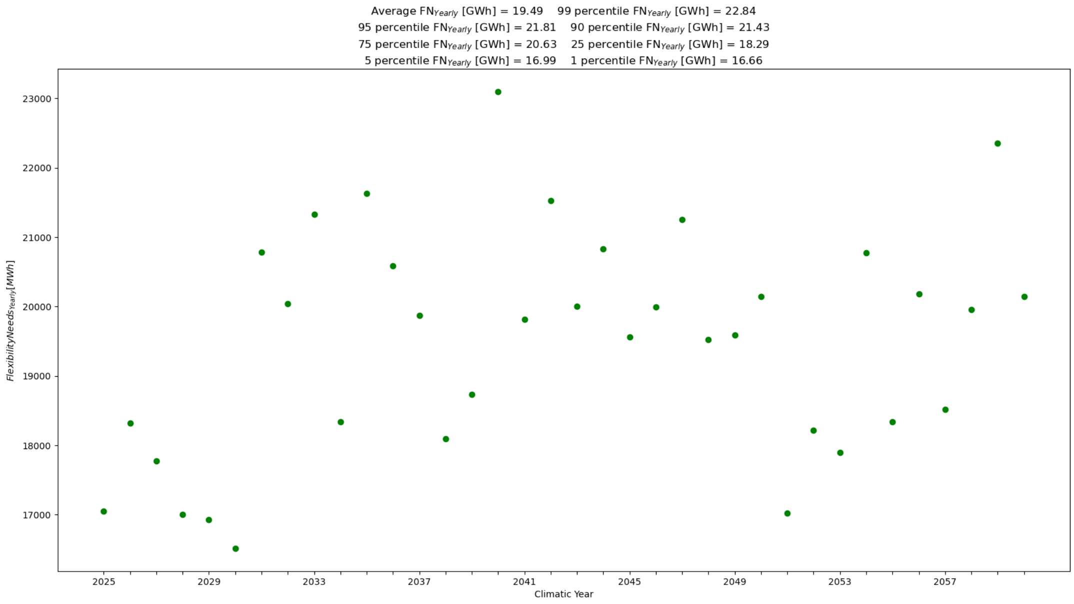
The weekly energy indicator $FNMAX_{weekly}$ is on average (across all the climate years) about 8.0 GW and 12.5 GW in MT2027 and MT2030, respectively. This represents the maximum amount of flexibility needed on a weekly basis. However, this indicator shows a peak for the 2044 climate year (of about 14 GW) in MT2027, and a peak for the 2045 climate year (of about 17GW) in MT2030.

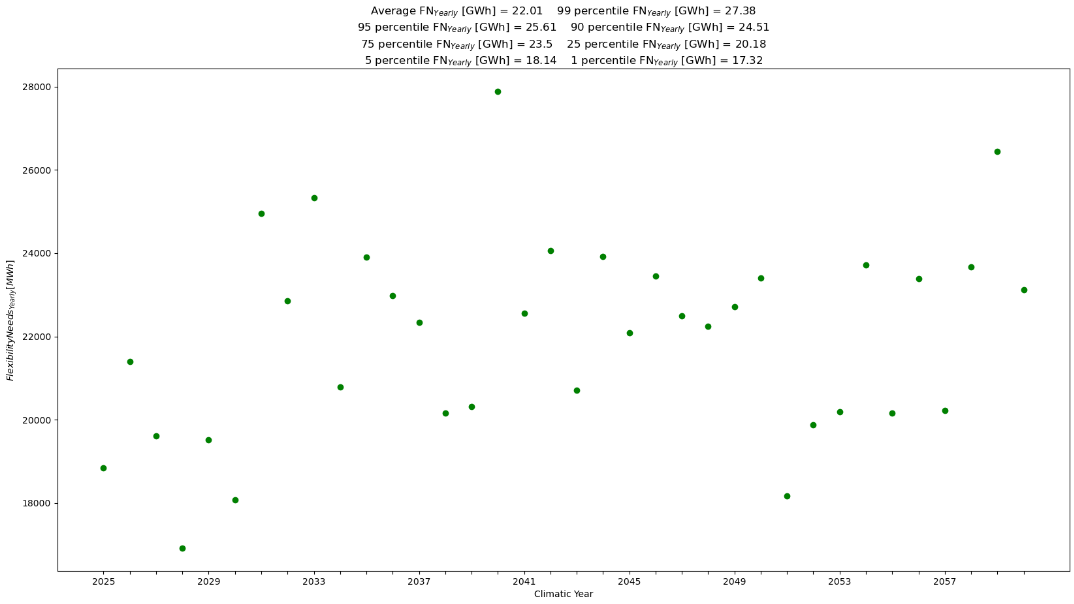

Week Flex Need [MW]
14000
12000
10000
8000
6000
2025
2030
2035
2040
2045
2050
2055
2060
Climatic Year


Week Flex Need [MW]
17000
16000
15000
14000
13000
12000
11000
10000
9000
2025
2030
2035
2040
2045
2050
2055
2060
Climatic Year

Yearly Assessment

The yearly energy indicator FN_{yearly} shows little variation across the whole time series (and across climate years): the 99th percentile is 22.84 GWh and 27.38 GWh, the 1st percentile is 16.66 GWh and 17.32 GWh and the average value is 19.49 GWh and 22.01 GWh in MT2027 and MT2030, respectively. This indicator assumes values that are very low compared to the weekly and, especially, the daily indicators. This means there is no significant variation in terms of residual load between months of the same year.





Jordan

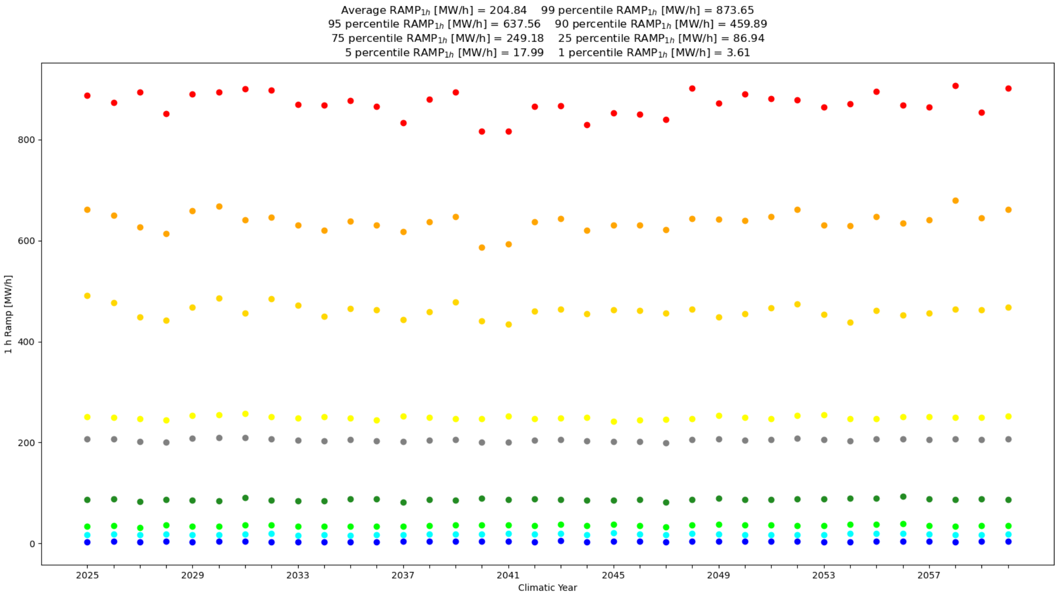
Hourly Assessment

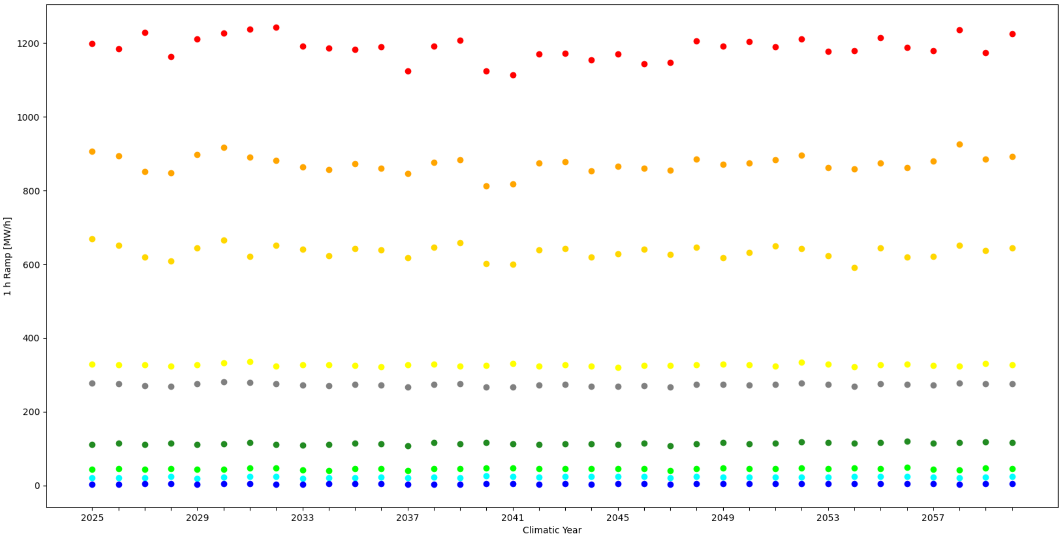
The 1h residual load ramp rate could reach values greater than 0.6 GW/h and 0.8 GW/h for 5% of the hours of the year (and greater than 0.8 GW/h and 1.1 GW/h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

The 2h residual load ramp rate could reach values greater than 1.0 GW/2h and 1.4 GW/2h for 5% of the hours of the year (and greater than 1.4 GW/2h and 2.0 GW/2h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

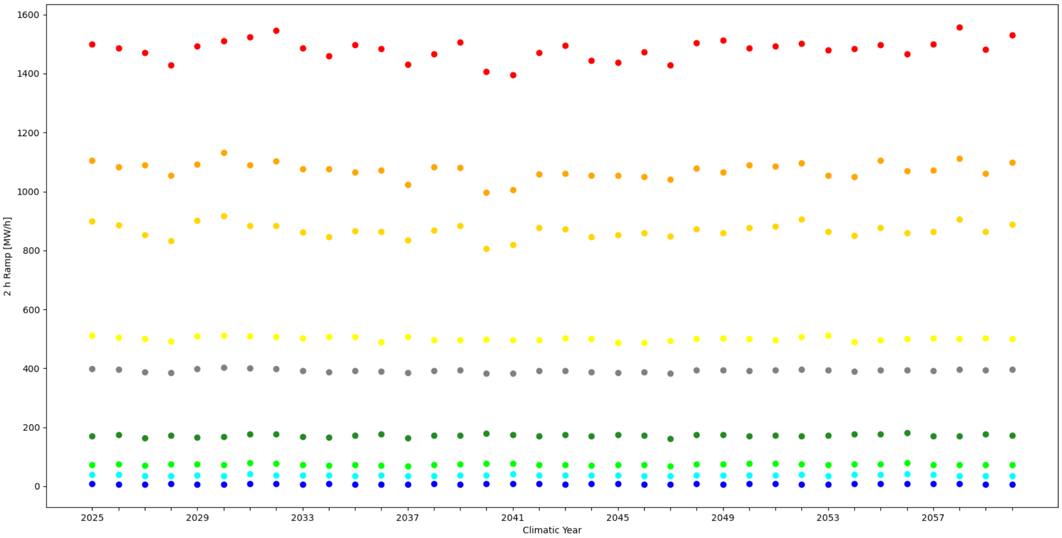
The 4h residual load ramp rate could reach values greater than 1.6 GW/4h and 2.2 GW/4h for 5% of the hours of the year (and greater than 2.0 GW/4h and 2.7 GW/4h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

Enlarging the time scale for assessing the ramp smooths the derivative but highlights the need for flexible resources to follow the ramp rates of several GW over a few hours.

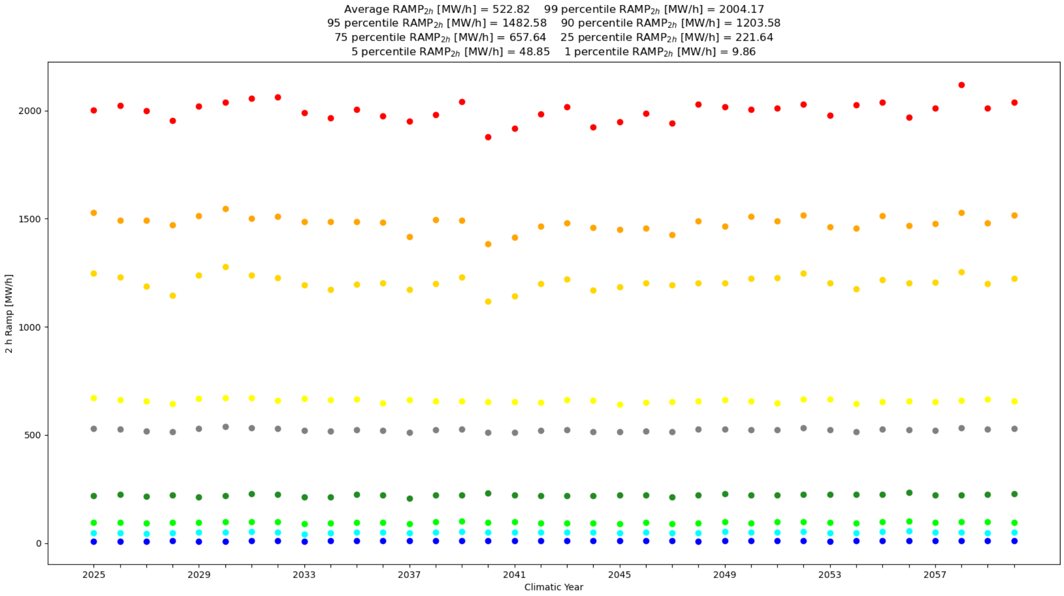




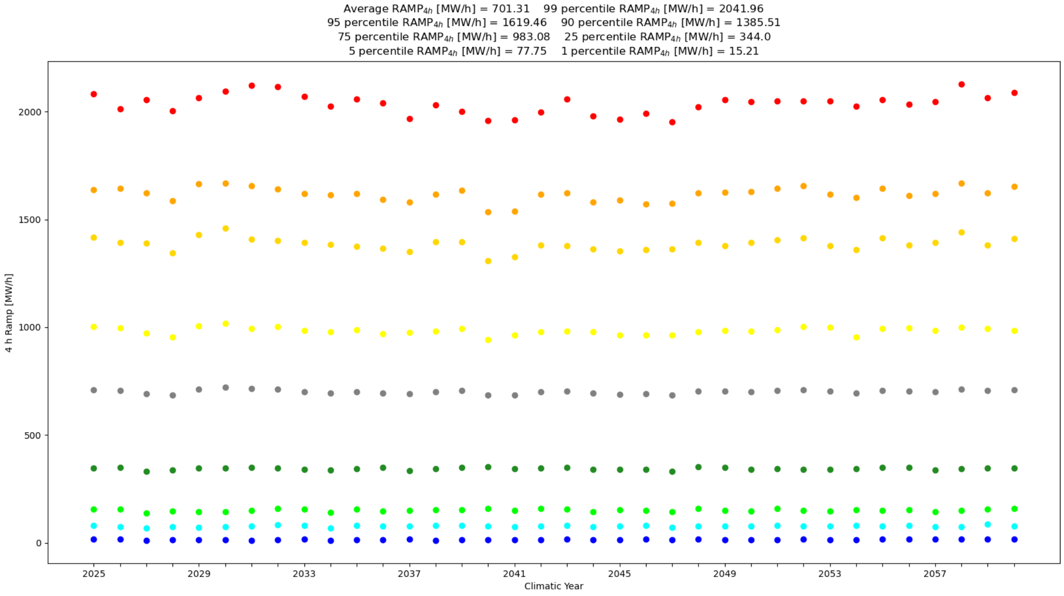
Average RAMP$_{1h}$ [MW/h] = 273.26   99 percentile RAMP$_{1h}$ [MW/h] = 1188.85
95 percentile RAMP$_{1h}$ [MW/h] = 872.99   90 percentile RAMP$_{1h}$ [MW/h] = 633.03
75 percentile RAMP$_{1h}$ [MW/h] = 326.9   25 percentile RAMP$_{1h}$ [MW/h] = 113.94
5 percentile RAMP$_{1h}$ [MW/h] = 22.79   1 percentile RAMP$_{1h}$ [MW/h] = 4.58



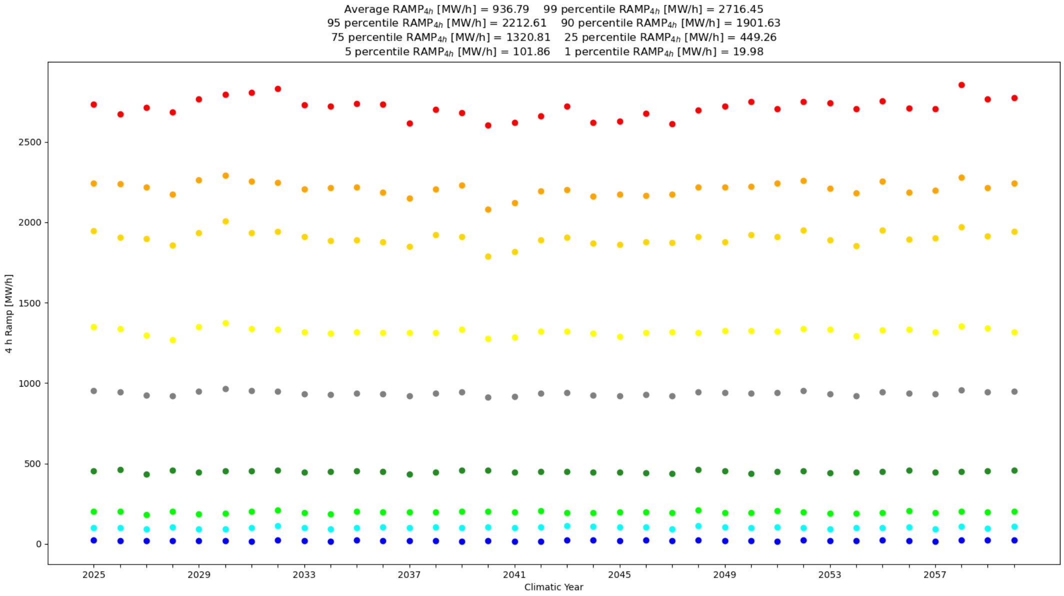
Average RAMP$_{2h}$ [MW/h] = 392.01   99 percentile RAMP$_{2h}$ [MW/h] = 1483.65
95 percentile RAMP$_{2h}$ [MW/h] = 1073.86   90 percentile RAMP$_{2h}$ [MW/h] = 867.66
75 percentile RAMP$_{2h}$ [MW/h] = 500.6   25 percentile RAMP$_{2h}$ [MW/h] = 172.35
5 percentile RAMP$_{2h}$ [MW/h] = 37.51   1 percentile RAMP$_{2h}$ [MW/h] = 7.57



Average RAMP$_{2h}$ [MW/h] = 522.82   99 percentile RAMP$_{2h}$ [MW/h] = 2004.17
95 percentile RAMP$_{2h}$ [MW/h] = 1482.58   90 percentile RAMP$_{2h}$ [MW/h] = 1203.58
75 percentile RAMP$_{2h}$ [MW/h] = 657.64   25 percentile RAMP$_{2h}$ [MW/h] = 221.64
5 percentile RAMP$_{2h}$ [MW/h] = 48.85   1 percentile RAMP$_{2h}$ [MW/h] = 9.86



Average RAMP$_{4h}$ [MW/h] = 701.31   99 percentile RAMP$_{4h}$ [MW/h] = 2041.96
95 percentile RAMP$_{4h}$ [MW/h] = 1619.46   90 percentile RAMP$_{4h}$ [MW/h] = 1385.51
75 percentile RAMP$_{4h}$ [MW/h] = 983.08   25 percentile RAMP$_{4h}$ [MW/h] = 344.0
5 percentile RAMP$_{4h}$ [MW/h] = 77.75   1 percentile RAMP$_{4h}$ [MW/h] = 15.21

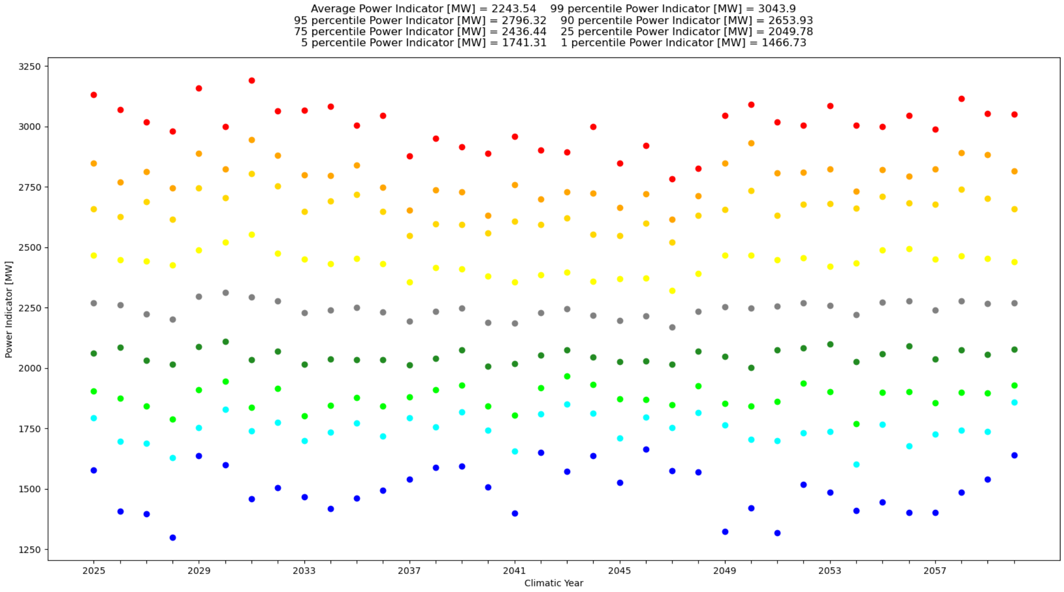


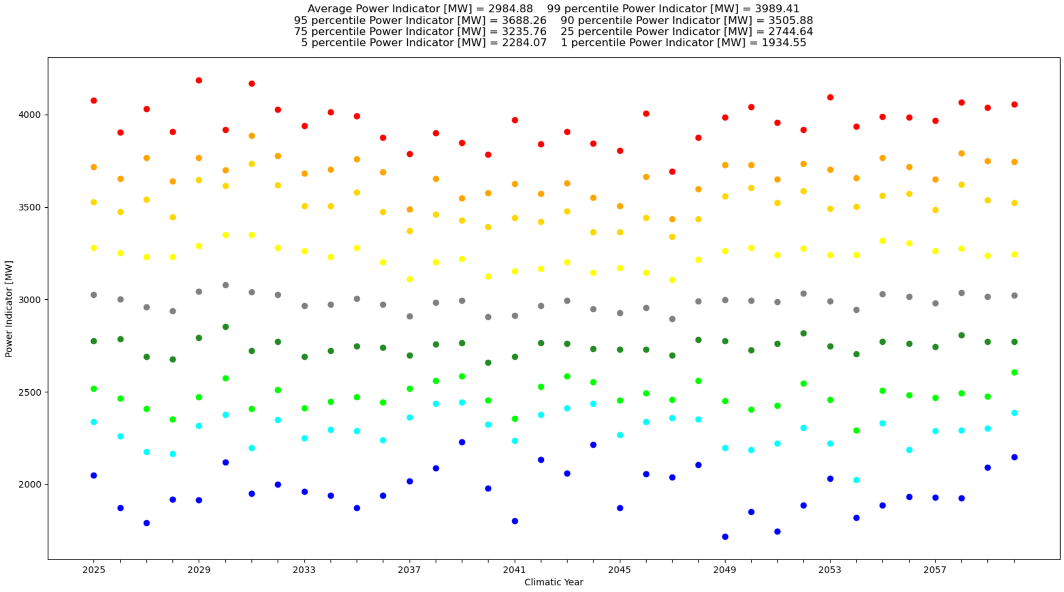
Daily Assessment

The daily energy indicator FN_{daily} shows little variation across the whole time series (and across climate years): the 99th percentile is 2.72 TWh and 3.68 TWh, the 1st percentile is 2.53 TWh and 3.40 TWh and the average value is 2.63 TWh and 3.54 TWh in MT2027 and MT2030, respectively.

The daily energy indicator $FNMAX_{daily}$ shows little variation across climate years, resulting in a range between 9 GWh and 14 GWh and in a range between 13 GWh and 18 GWh for all the assessed climate years, with a mean value of about 11 GWh and 15 GWh in MT2027 and MT2030, respectively. This represents the maximum amount of flexibility needed on a daily basis.

The power indicator is reported in the figure below for each climate year and relevant percentile. The average value across the whole time series (and climate years) is about 2.2 GW and 3.0 GW in MT2027 and MT2030, respectively, which represents the average difference between daily minimum and maximum residual load values. This difference can rise up to 2.8 GW and 3.7 GW for 5% of the days and up to 3.0 GW and 4.0 GW for 1% of the days in MT2027 and MT2030, respectively.

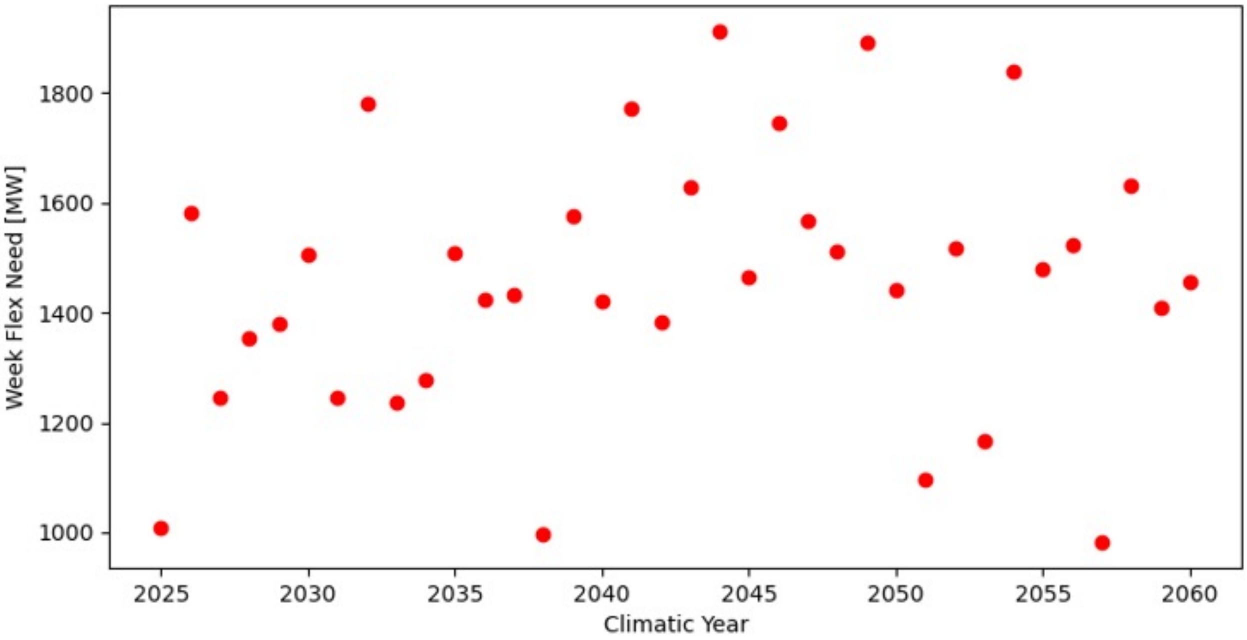

Average Power Indicator [MW] = 2243.54   99 percentile Power Indicator [MW] = 3043.9
95 percentile Power Indicator [MW] = 2796.32   90 percentile Power Indicator [MW] = 2653.93
75 percentile Power Indicator [MW] = 2436.44   25 percentile Power Indicator [MW] = 2049.78
5 percentile Power Indicator [MW] = 1741.31   1 percentile Power Indicator [MW] = 1466.73
Power Indicator [MW]
3250
3000
2750
2500
2250
2000
1750
1500
1250
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year

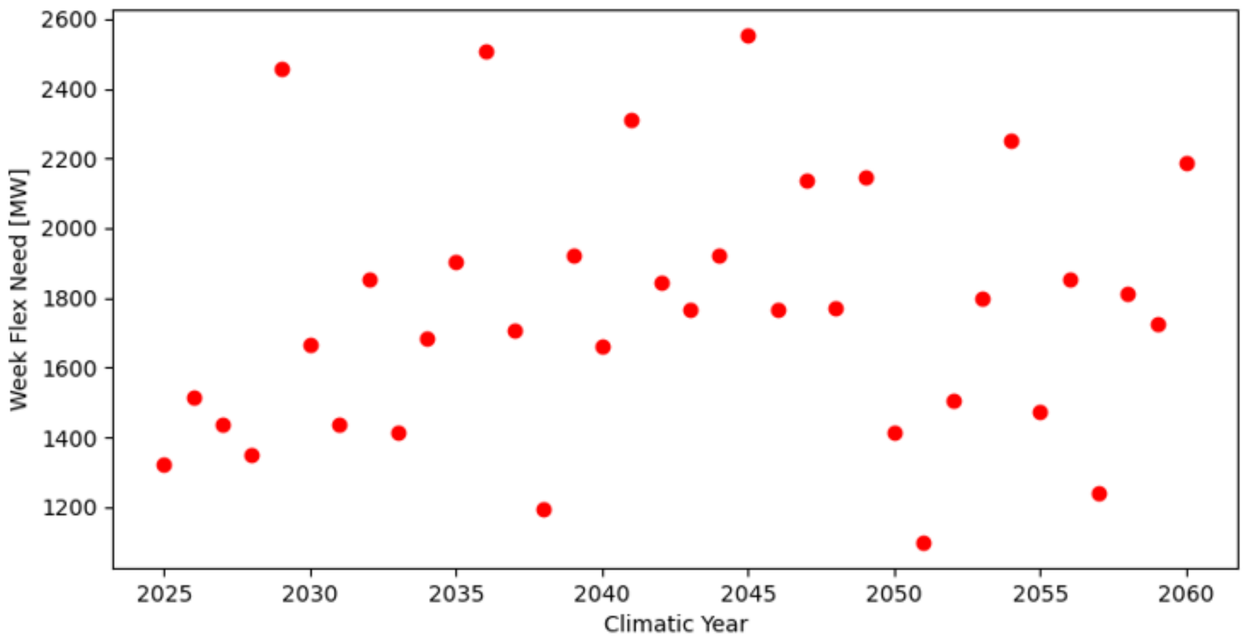

Average Power Indicator [MW] = 2984.88   99 percentile Power Indicator [MW] = 3989.41
95 percentile Power Indicator [MW] = 3688.26   90 percentile Power Indicator [MW] = 3505.88
75 percentile Power Indicator [MW] = 3235.76   25 percentile Power Indicator [MW] = 2744.64
5 percentile Power Indicator [MW] = 2284.07   1 percentile Power Indicator [MW] = 1934.55
Power Indicator [MW]
4000
3500
3000
2500
2000
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year

Weekly Assessment

The weekly energy indicatorFN$_{weekly}$ shows little variation across the whole time series (and across climate years): the 99th percentile is 0.04 TWh and 0.04 TWh, the 1st percentile is 0.03 TWh and 0.03 TWh and the average value is 0.03 TWh and 0.04 TWh in MT2027 and MT2030, respectively. This indicator assumes values that are one order of magnitude lower than the corresponding daily indicator. This means there is no significant variation in terms of residual load between days of the same week.

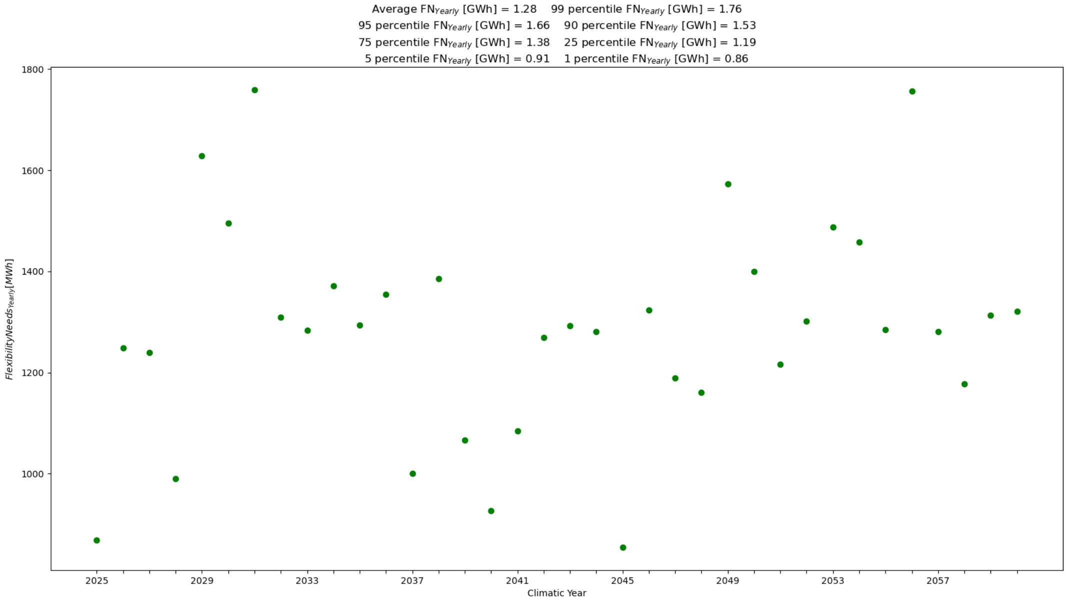
The weekly energy indicator FNMAX$_{weekly}$ is on average (across all the climate years) about 1.5 GW and 1.8 GW in MT2027 and MT2030, respectively. This represents the maximum amount of flexibility needed on a weekly basis. However, this indicator shows a peak for the 2044 climate year (of about 2GW) in MT2027, and a peak for the 2045 climate year (of about 2.6 GW) in MT2030.

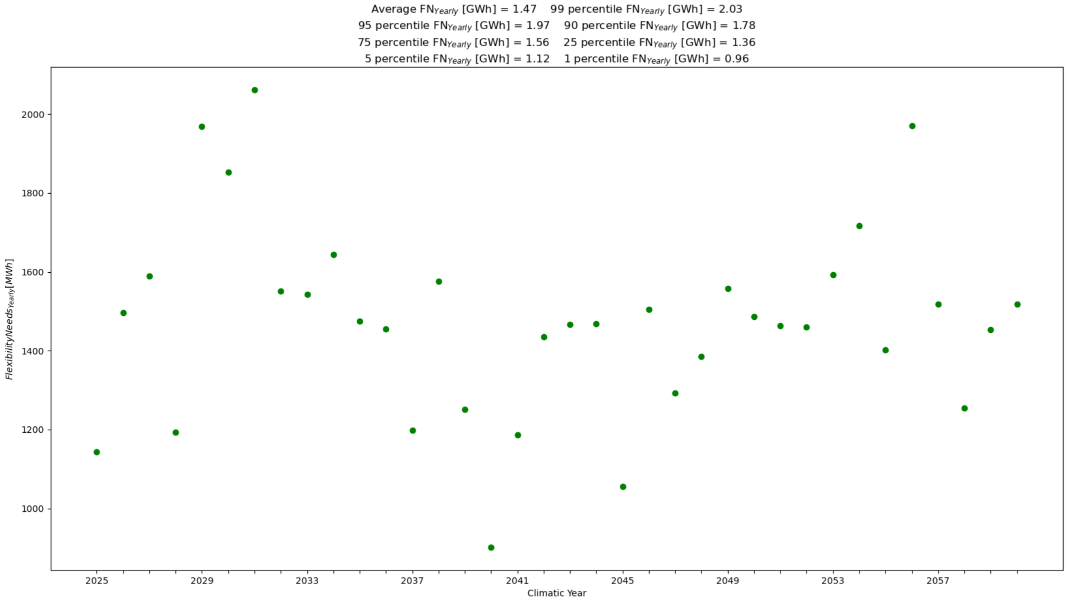




Yearly Assessment

The yearly energy indicator FN$_{yearlyyealy}$ shows little variation inside the whole time series (and across climate years): the 99th percentile is 1.76 GWh and 2.03 GWh, the 1st percentile is 0.86 GWh and 0.96 GWh and the average value is 1.28 GWh and 1.47 GWh in MT2027 and MT2030, respectively. This indicator assumes values that are very low if compared to the weekly and, especially, the daily indicators. This means there is no significant variation in terms of residual load between months of the same year.





Lebanon

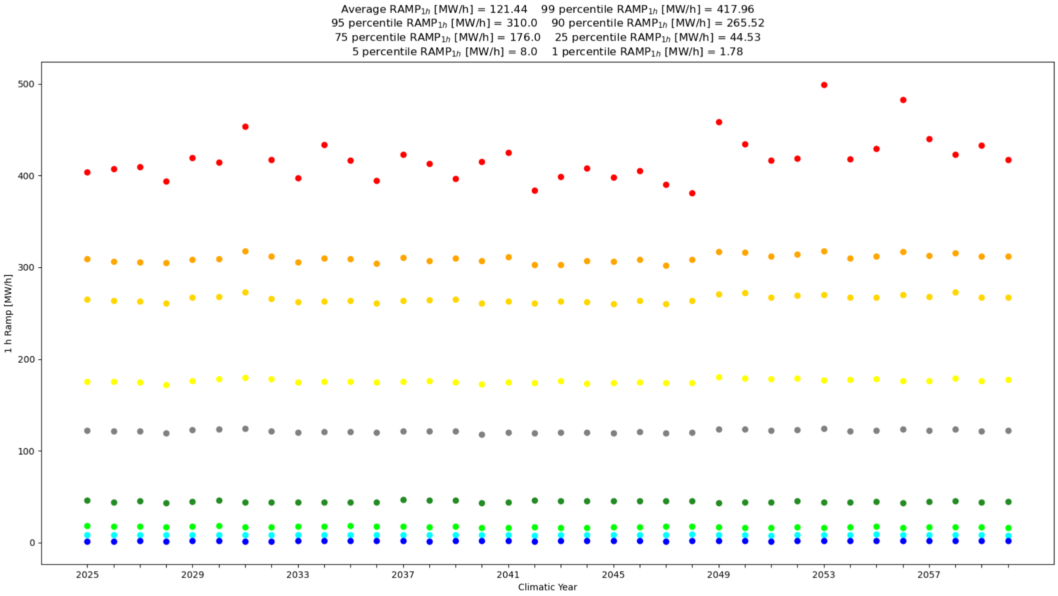
Hourly Assessment

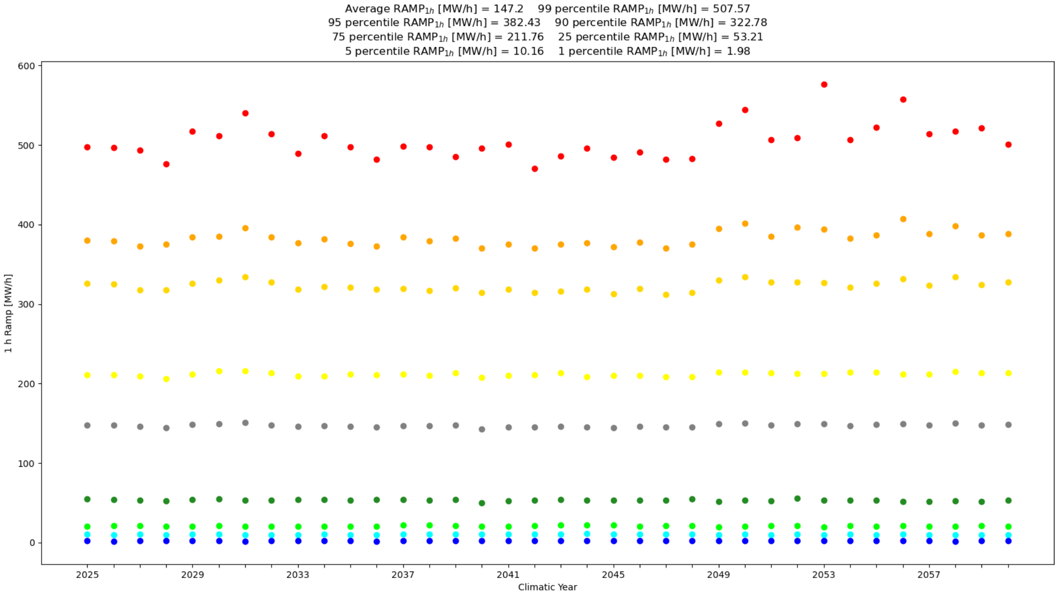
The 1h residual load ramp rate could reach values greater than 0.3 GW/h and 0.4 GW/h for 5% of the hours of the year (and greater than 0.4 GW/h and 0.5 GW/h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

The 2h residual load ramp rate could reach values greater than 0.5 GW/2h and 0.7 GW/2h for 5% of the hours of the year (and greater than 0.7 GW/2h and 0.9 GW/2h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

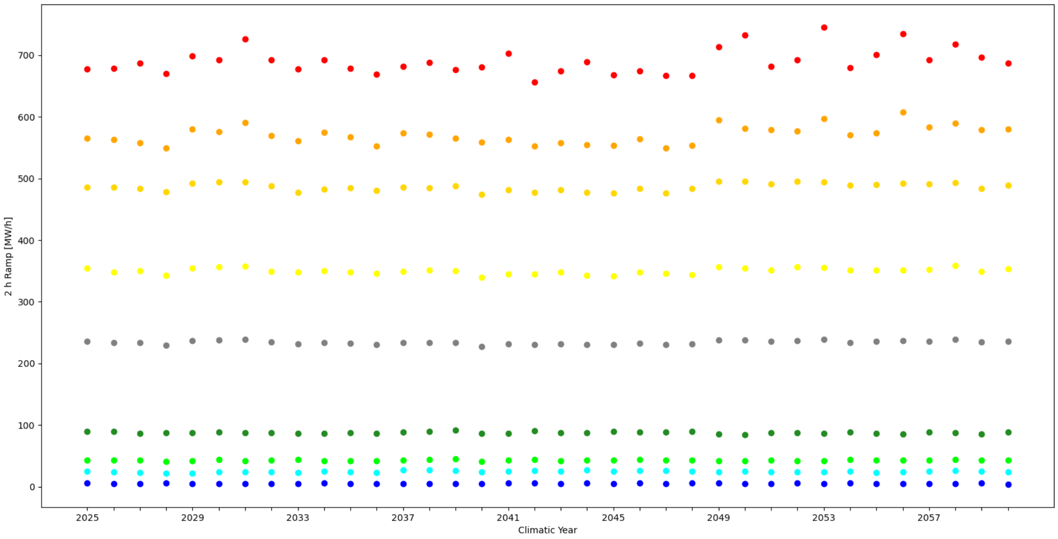
The 4h residual load ramp rate could reach values greater than 0.9 GW/4h and 1.1 GW/4h for 5% of the hours of the year (and greater than 1.1 GW/4h and 1.4 GW/4h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

Enlarging the time scale for assessing the ramp smooths the derivative but highlights the need for flexible resources to follow the ramp rates of several GW over a few hours.

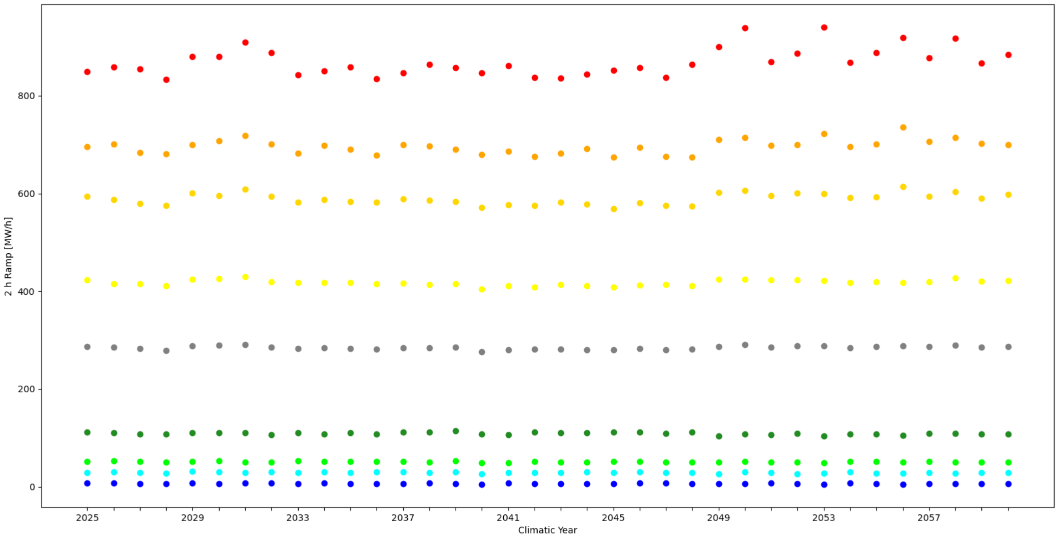

Average RAMP$_{1h}$ [MW/h] = 121.44   99 percentile RAMP$_{1h}$ [MW/h] = 417.96
95 percentile RAMP$_{1h}$ [MW/h] = 310.0   90 percentile RAMP$_{1h}$ [MW/h] = 265.52
75 percentile RAMP$_{1h}$ [MW/h] = 176.0   25 percentile RAMP$_{1h}$ [MW/h] = 44.53
5 percentile RAMP$_{1h}$ [MW/h] = 8.0   1 percentile RAMP$_{1h}$ [MW/h] = 1.78
1 h Ramp [MW/h]
500
400
300
200
100
0
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year

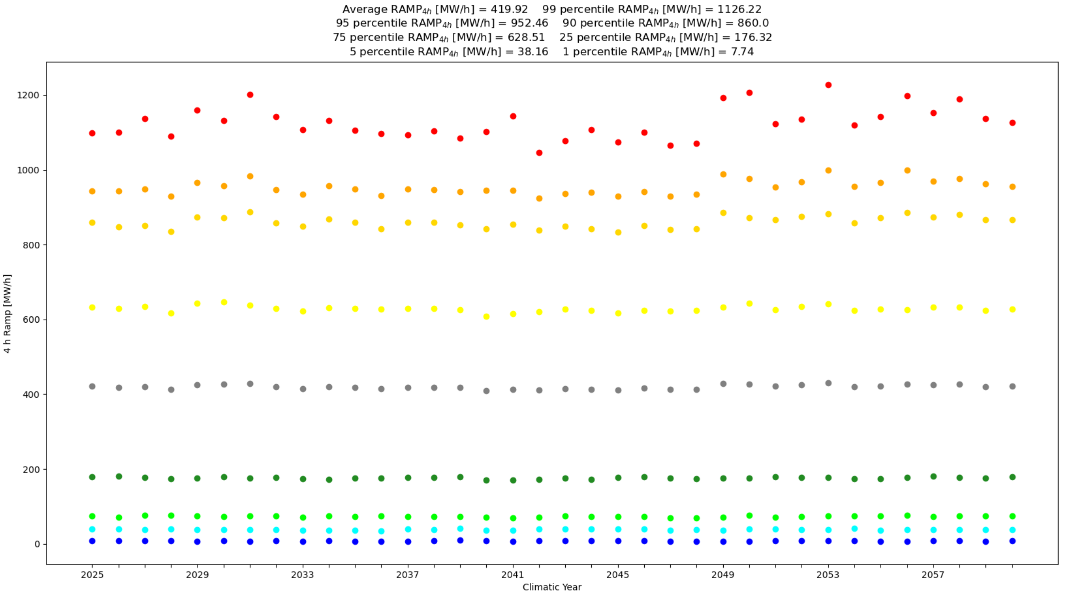

Average RAMP$_{1h}$ [MW/h] = 147.2   99 percentile RAMP$_{1h}$ [MW/h] = 507.57
95 percentile RAMP$_{1h}$ [MW/h] = 382.43   90 percentile RAMP$_{1h}$ [MW/h] = 322.78
75 percentile RAMP$_{1h}$ [MW/h] = 211.76   25 percentile RAMP$_{1h}$ [MW/h] = 53.21
5 percentile RAMP$_{1h}$ [MW/h] = 10.16   1 percentile RAMP$_{1h}$ [MW/h] = 1.98
1 h Ramp [MW/h]
600
500
400
300
200
100
0
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year

Average $RAMP_{2h}$ [MW/h] = 234.25   99 percentile $RAMP_{2h}$ [MW/h] = 690.94
95 percentile $RAMP_{2h}$ [MW/h] = 570.0   90 percentile $RAMP_{2h}$ [MW/h] = 486.0
75 percentile $RAMP_{2h}$ [MW/h] = 350.0   25 percentile $RAMP_{2h}$ [MW/h] = 88.0
5 percentile $RAMP_{2h}$ [MW/h] = 24.82   1 percentile $RAMP_{2h}$ [MW/h] = 5.27

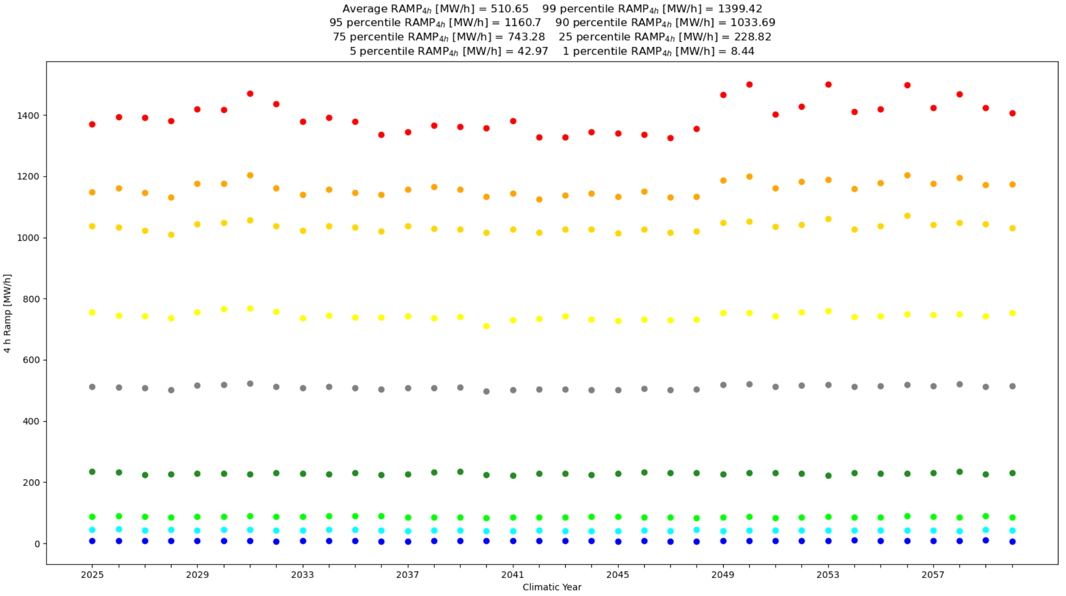


Average $RAMP_{2h}$ [MW/h] = 284.56   99 percentile $RAMP_{2h}$ [MW/h] = 868.76
95 percentile $RAMP_{2h}$ [MW/h] = 696.66   90 percentile $RAMP_{2h}$ [MW/h] = 588.74
75 percentile $RAMP_{2h}$ [MW/h] = 417.49   25 percentile $RAMP_{2h}$ [MW/h] = 108.95
5 percentile $RAMP_{2h}$ [MW/h] = 28.9   1 percentile $RAMP_{2h}$ [MW/h] = 6.3





Average RAMP$_{4h}$ [MW/h] = 419.92   99 percentile RAMP$_{4h}$ [MW/h] = 1126.22
95 percentile RAMP$_{4h}$ [MW/h] = 952.46   90 percentile RAMP$_{4h}$ [MW/h] = 860.0
75 percentile RAMP$_{4h}$ [MW/h] = 628.51   25 percentile RAMP$_{4h}$ [MW/h] = 176.32
5 percentile RAMP$_{4h}$ [MW/h] = 38.16   1 percentile RAMP$_{4h}$ [MW/h] = 7.74



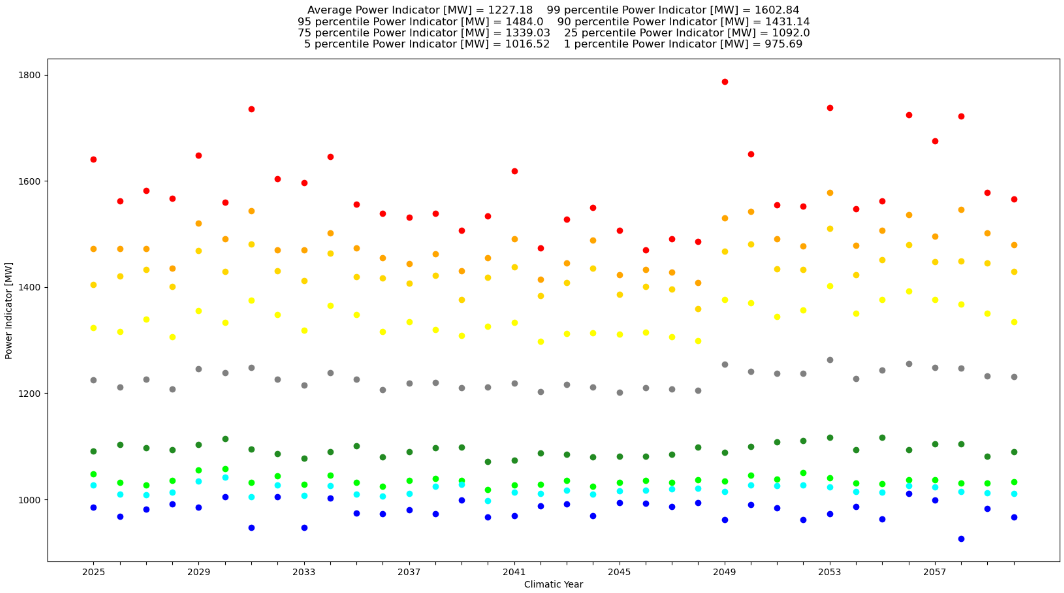
Average RAMP$_{4h}$ [MW/h] = 510.65   99 percentile RAMP$_{4h}$ [MW/h] = 1399.42
95 percentile RAMP$_{4h}$ [MW/h] = 1160.7   90 percentile RAMP$_{4h}$ [MW/h] = 1033.69
75 percentile RAMP$_{4h}$ [MW/h] = 743.28   25 percentile RAMP$_{4h}$ [MW/h] = 228.82
5 percentile RAMP$_{4h}$ [MW/h] = 42.97   1 percentile RAMP$_{4h}$ [MW/h] = 8.44

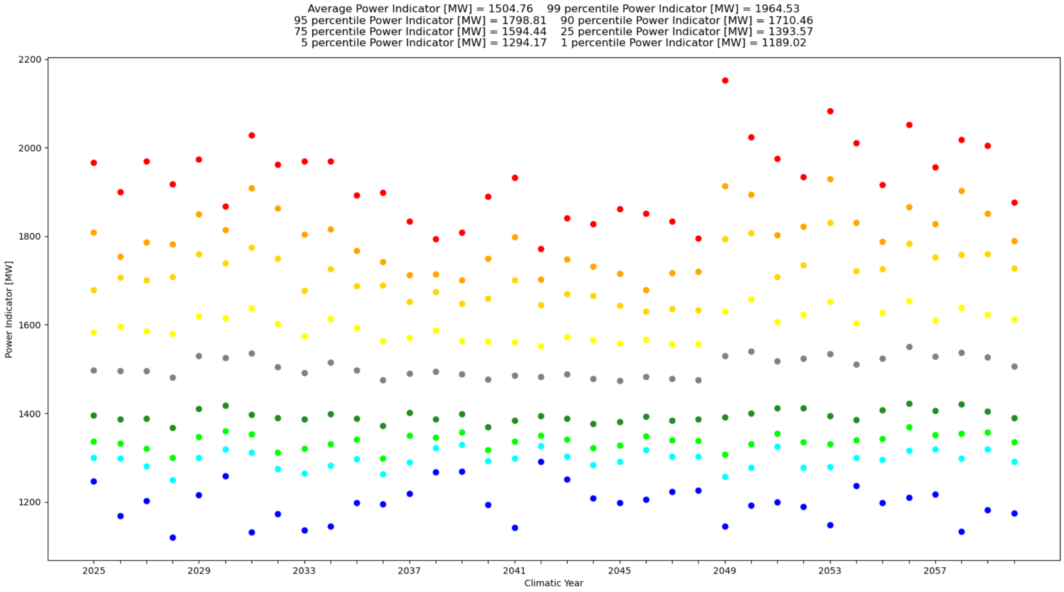
Daily Assessment

The daily energy indicator FN_{daily} shows little variation across the whole time series (and across climate years): the 99th percentile is 1.57 TWh and 1.86 TWh, the 1st percentile is 1.47 TWh and 1.76 TWh and the average value is 1.51 TWh and 1.81 TWh in MT2027 and MT2030, respectively.

The daily energy indicator $FNMAX_{daily}$ shows little variation across climate years, resulting in a range between 5 GWh and 7 GWh and in a range between 6GWh and 9 GWh for all the assessed climate years, with a mean value of about 6 GWh and 7 GWh in the MT2027 and MT2030, respectively. This represents the maximum amount of flexibility needed on a daily basis.

The power indicator is reported in the figure below for each climate year and relevant percentile. The average value across the whole time series (and climate years) is about 1.2 GW and 1.5 GW in MT2027 and MT2030, respectively, which represents the average difference between daily minimum and maximum residual load values. This difference can rise up to 1. 5GW and 1.8 GW for 5% of the days and up to 1.6 GW and 2.0 GW for 1% of the days in MT2027 and MT2030, respectively.

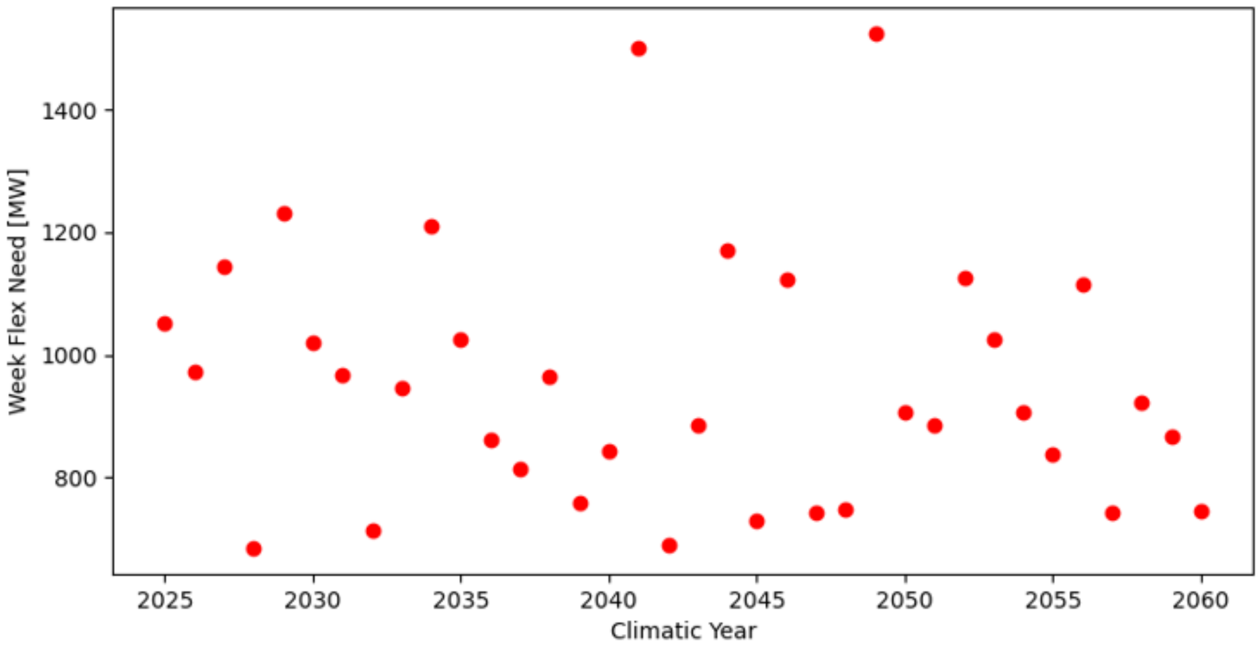


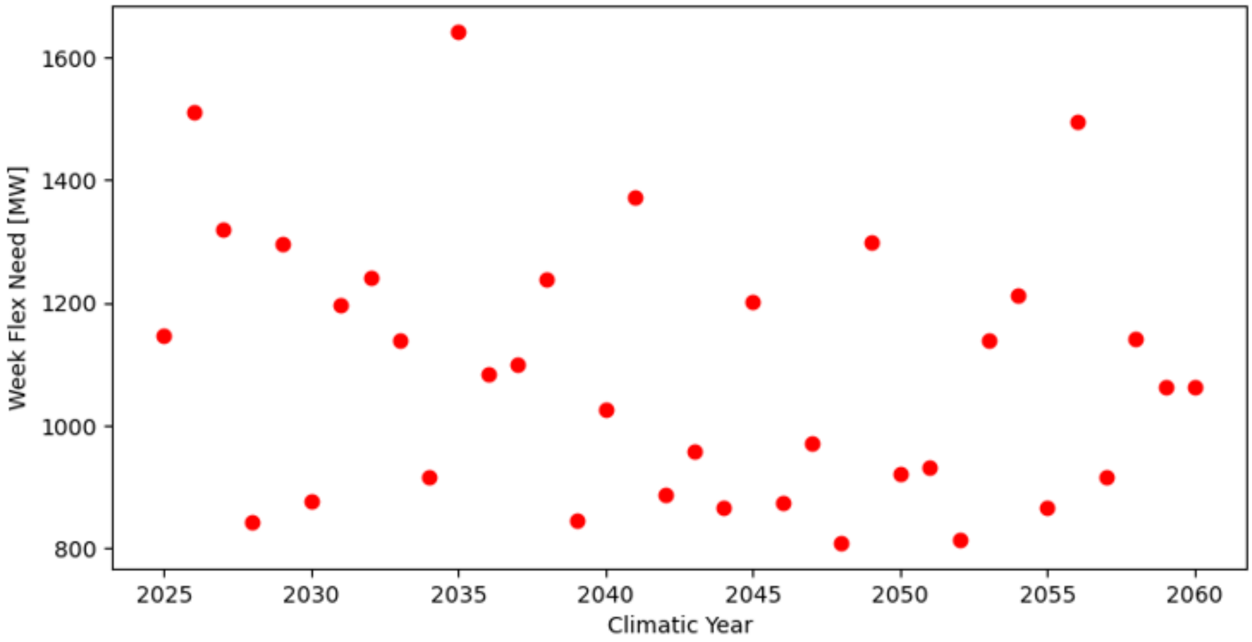


Weekly Assessment

The weekly energy indicator FN_{weekly} shows little variation across the whole time series (and across climate years): the 99th percentile is 0.03 TWh and 0.03 TWh, the 1st percentile is 0.02 TWh and 0.02 TWh and the average value is 0.02 TWh and 0.02 TWh in MT2027 and MT2030, respectively. This indicator assumes values that are one order of magnitude lower than the corresponding daily indicator. This means there is no significant variation in terms of residual load between days of the same week.

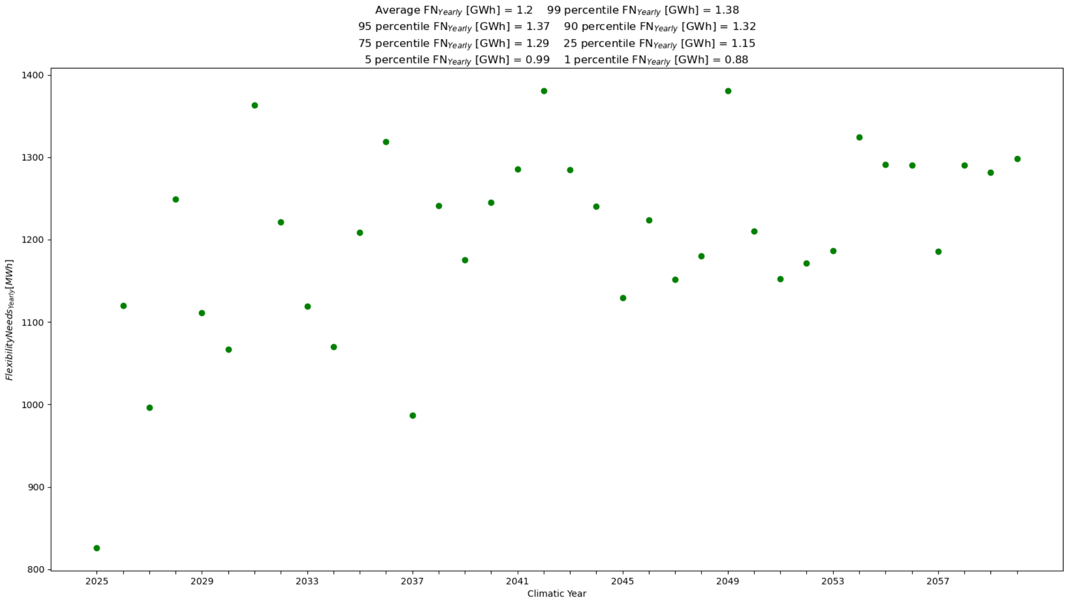
The weekly energy indicator $FNMAX_{weekly}$ is on average (across all the climate years) about 1.0 GW and 1.1 GW in MT2027 and MT2030, respectively. This represents the maximum amount of flexibility needed on a weekly basis. However, this indicator shows a peak for the 2049 climate year (of about 1.5 GW) in MT2027 and a peak for the 2035 climate year (of about 1.6GW) in MT2030.

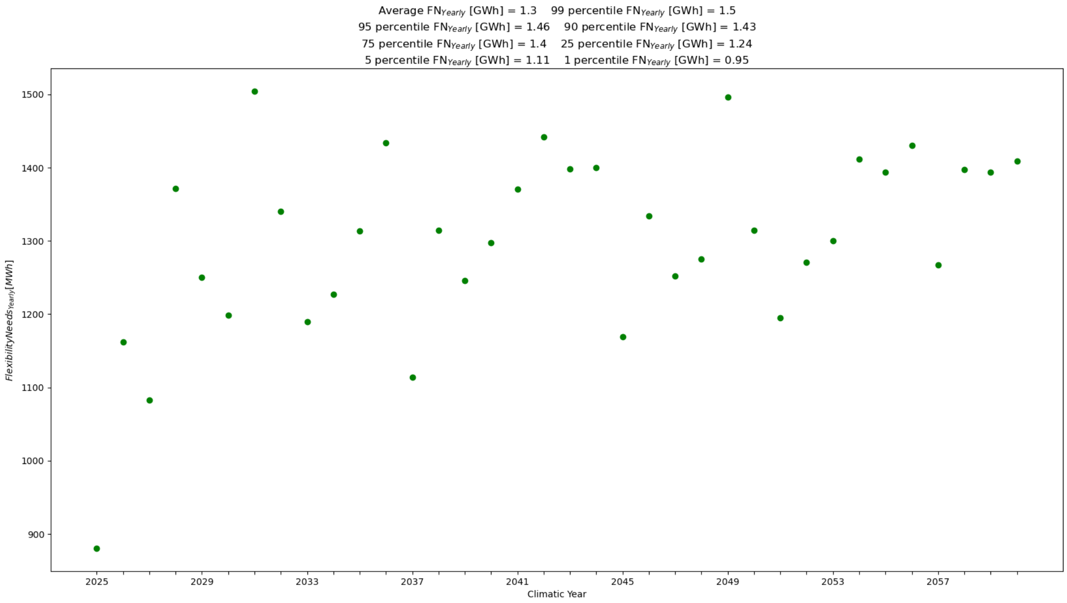

Week Flex Need [MW]
1400
1200
1000
800
2025
2030
2035
2040
2045
2050
2055
2060
Climatic Year


Week Flex Need [MW]
1600
1400
1200
1000
800
2025
2030
2035
2040
2045
2050
2055
2060
Climatic Year

Yearly Assessment

The yearly energy indicator FN$_{yearly}$ shows little variation across the whole time series (and across climate years): the 99th percentile is 1.38 GWh and 1.50 GWh, the 1st percentile is 0.88 GWh and 0.95 GWh and the average value is 1.20 GWh and 1.30 GWh in MT2027 and MT2030, respectively. This indicator assumes values that are very low compared to the weekly and, especially, the daily indicators. This means there is no significant variation in terms of residual load between months of the same year.





Morocco

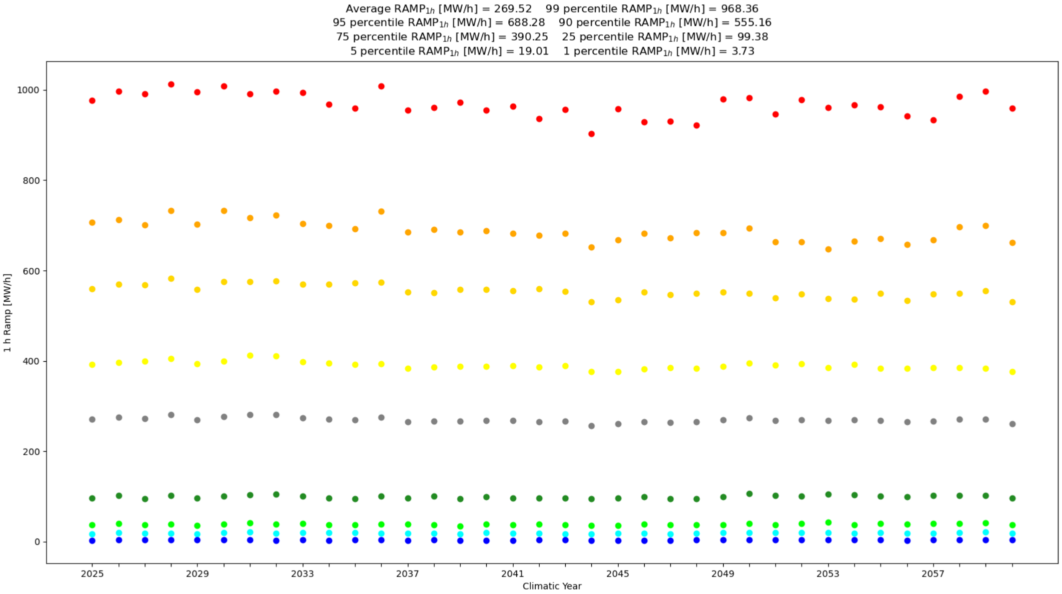
Hourly Assessment

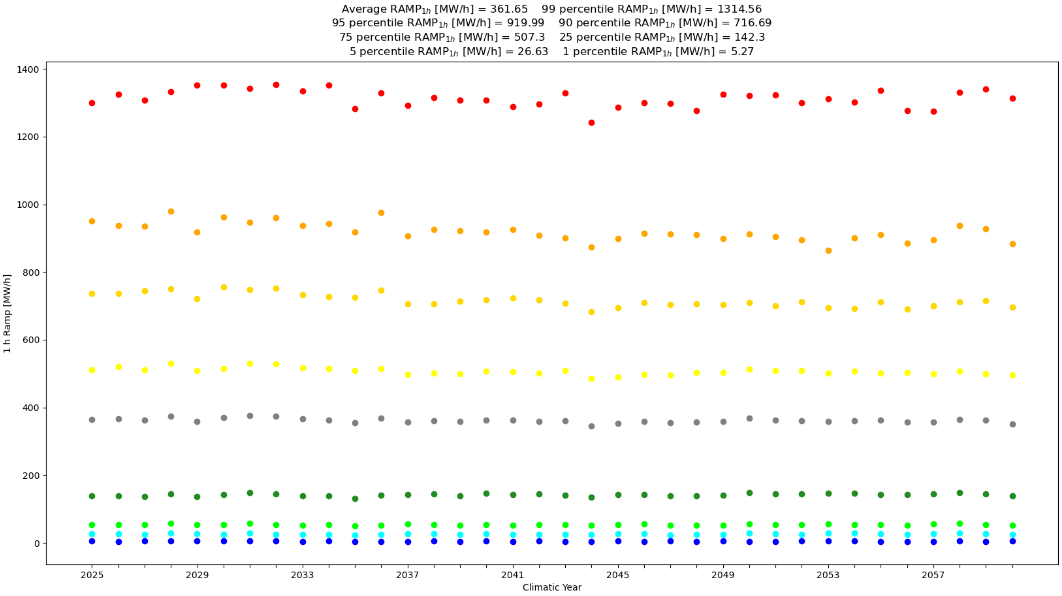
The 1h residual load ramp rate could reach values greater than 0.7 GW/h and 0.9 GW/h for 5% of the hours of the year (and greater than 1.0 GW/h and 1.3 GW/h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

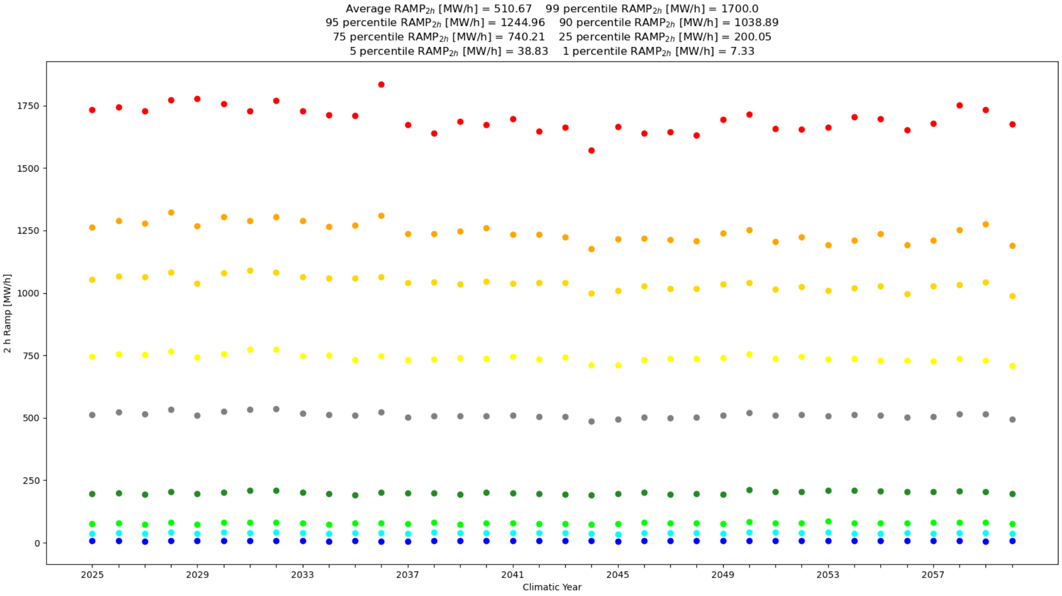
The 2h residual load ramp rate could reach values greater than 1.2 GW/2h and 1.7 GW/2h for 5% of the hours of the year (and greater than 1.7 GW/2h and 2.3 GW/2h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

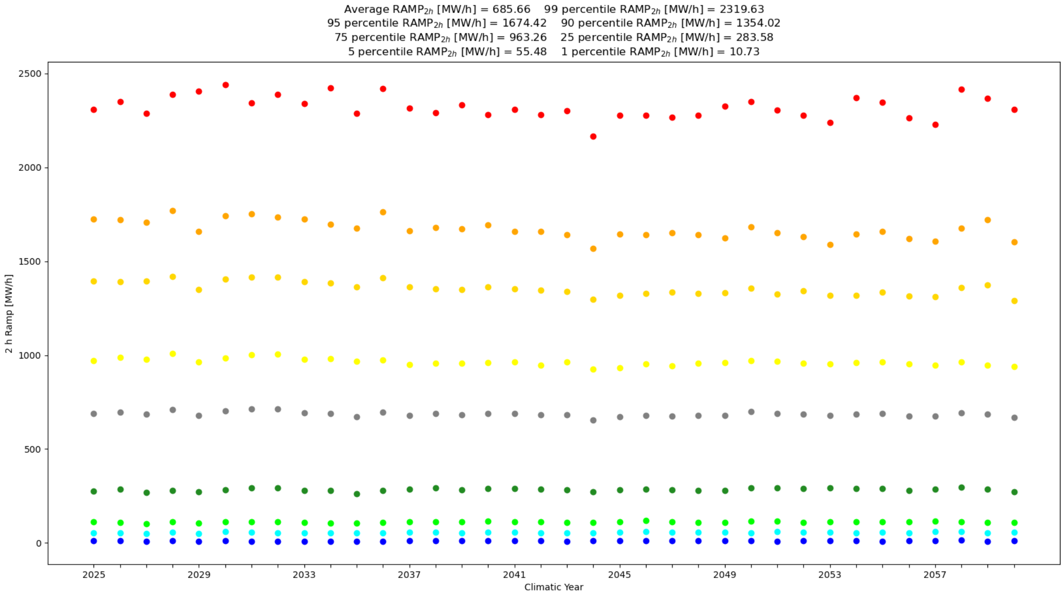
The 4h residual load ramp rate could reach values greater than 2.0 GW/4h and 2.7 GW/4h for 5% of the hours of the year (and greater than 2.6 GW/4h and 3.5 GW/4h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

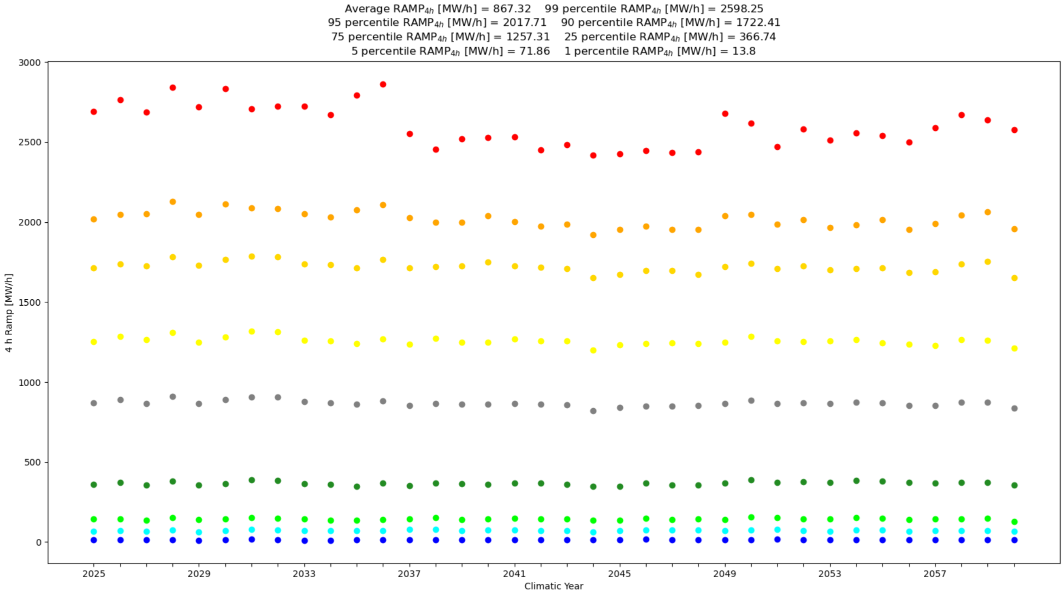
Enlarging the time scale for assessing the ramp smooths the derivative but highlights the need for flexible resources to follow the ramp rates of several GW over a few hours.

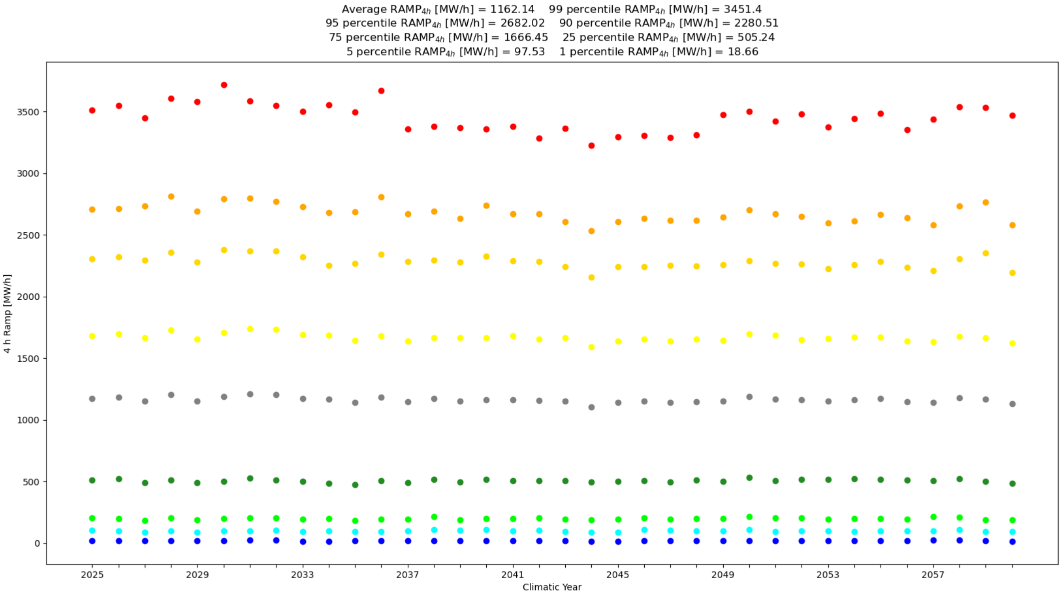



Average RAMP$_{1h}$ [MW/h] = 361.65   99 percentile RAMP$_{1h}$ [MW/h] = 1314.56
95 percentile RAMP$_{1h}$ [MW/h] = 919.99   90 percentile RAMP$_{1h}$ [MW/h] = 716.69
75 percentile RAMP$_{1h}$ [MW/h] = 507.3   25 percentile RAMP$_{1h}$ [MW/h] = 142.3
5 percentile RAMP$_{1h}$ [MW/h] = 26.63   1 percentile RAMP$_{1h}$ [MW/h] = 5.27
1 h Ramp [MW/h]
1400
1200
1000
800
600
400
200
0
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year


Average RAMP$_{2h}$ [MW/h] = 510.67   99 percentile RAMP$_{2h}$ [MW/h] = 1700.0
95 percentile RAMP$_{2h}$ [MW/h] = 1244.96   90 percentile RAMP$_{2h}$ [MW/h] = 1038.89
75 percentile RAMP$_{2h}$ [MW/h] = 740.21   25 percentile RAMP$_{2h}$ [MW/h] = 200.05
5 percentile RAMP$_{2h}$ [MW/h] = 38.83   1 percentile RAMP$_{2h}$ [MW/h] = 7.33
2 h Ramp [MW/h]
1750
1500
1250
1000
750
500
250
0
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year


Average RAMP_{2h} [MW/h] = 685.66   99 percentile RAMP_{2h} [MW/h] = 2319.63
95 percentile RAMP_{2h} [MW/h] = 1674.42   90 percentile RAMP_{2h} [MW/h] = 1354.02
75 percentile RAMP_{2h} [MW/h] = 963.26   25 percentile RAMP_{2h} [MW/h] = 283.58
5 percentile RAMP_{2h} [MW/h] = 55.48   1 percentile RAMP_{2h} [MW/h] = 10.73
2 h Ramp [MW/h]
2500
2000
1500
1000
500
0
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year


Average RAMP_{4h} [MW/h] = 867.32   99 percentile RAMP_{4h} [MW/h] = 2598.25
95 percentile RAMP_{4h} [MW/h] = 2017.71   90 percentile RAMP_{4h} [MW/h] = 1722.41
75 percentile RAMP_{4h} [MW/h] = 1257.31   25 percentile RAMP_{4h} [MW/h] = 366.74
5 percentile RAMP_{4h} [MW/h] = 71.86   1 percentile RAMP_{4h} [MW/h] = 13.8
4 h Ramp [MW/h]
3000
2500
2000
1500
1000
500
0
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year

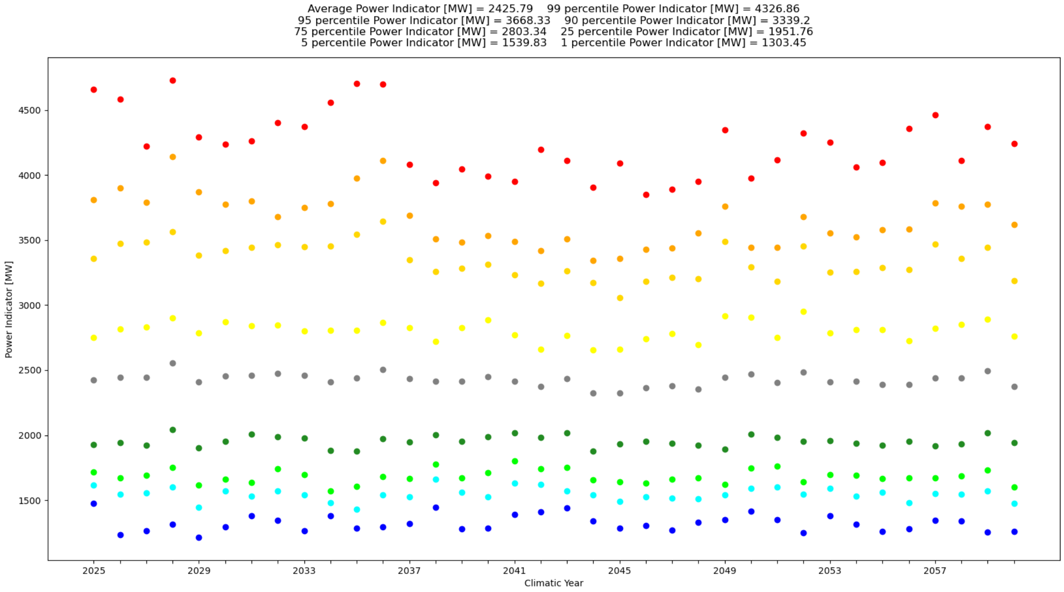


Daily Assessment

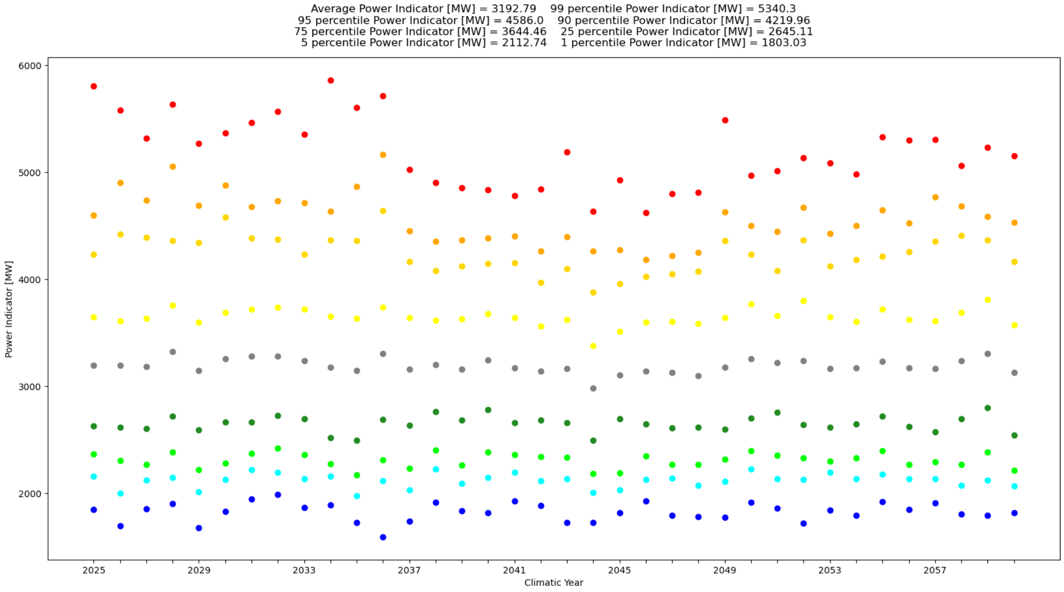
The daily energy indicator FN_{daily} shows little variation inside the whole time series (and across climate years): the 99th percentile is 2.69 TWh and 3.48 TWh, the 1st percentile is 2.41 TWh and 3.17 TWh and the average value is 2.45 TWh and 3.35 TWh in MT2027 and MT2030, respectively.

The daily energy indicator $FNMAX_{daily}$ shows little variation across climate years, resulting in a range between 12 GWh and 18 GWh and in the range between 14 GWh and 21 GWh for all the assessed climate years, with a mean value of about 14 GWh and 17 GWh in MT2027 and MT2030, respectively. This represents the maximum amount of flexibility needed on a daily basis.

The power indicator is reported in the figure below for each climate year and relevant percentile. The average value across the whole time series (and climate years) is about 2.4 GW and 3.2 GW in MT2027 and MT2030, respectively, which represents the average difference between daily minimum and maximum residual load value. This difference can rise up to 3.7 GW and 4.6 GW for 5% of the days and up to 4.3 GW and 5.3 GW for 1% of the days in MT2027 and MT2030, respectively.



Average Power Indicator [MW] = 2425.79   99 percentile Power Indicator [MW] = 4326.86
95 percentile Power Indicator [MW] = 3668.33   90 percentile Power Indicator [MW] = 3339.2
75 percentile Power Indicator [MW] = 2803.34   25 percentile Power Indicator [MW] = 1951.76
5 percentile Power Indicator [MW] = 1539.83   1 percentile Power Indicator [MW] = 1303.45

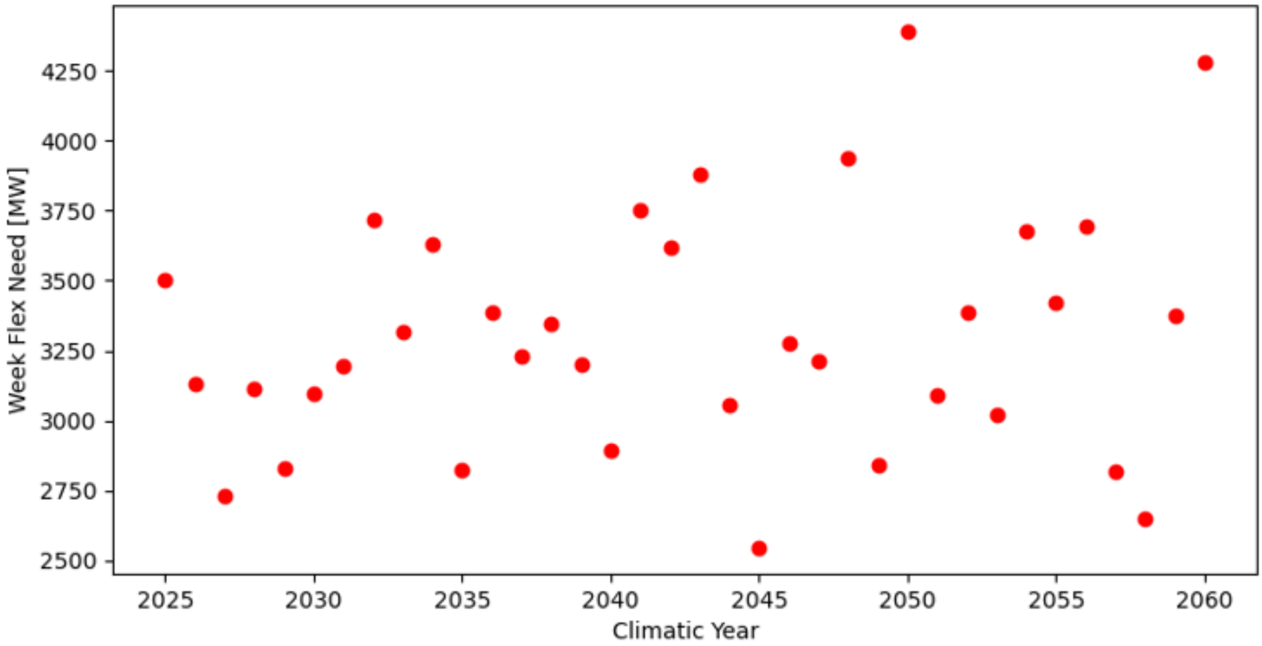


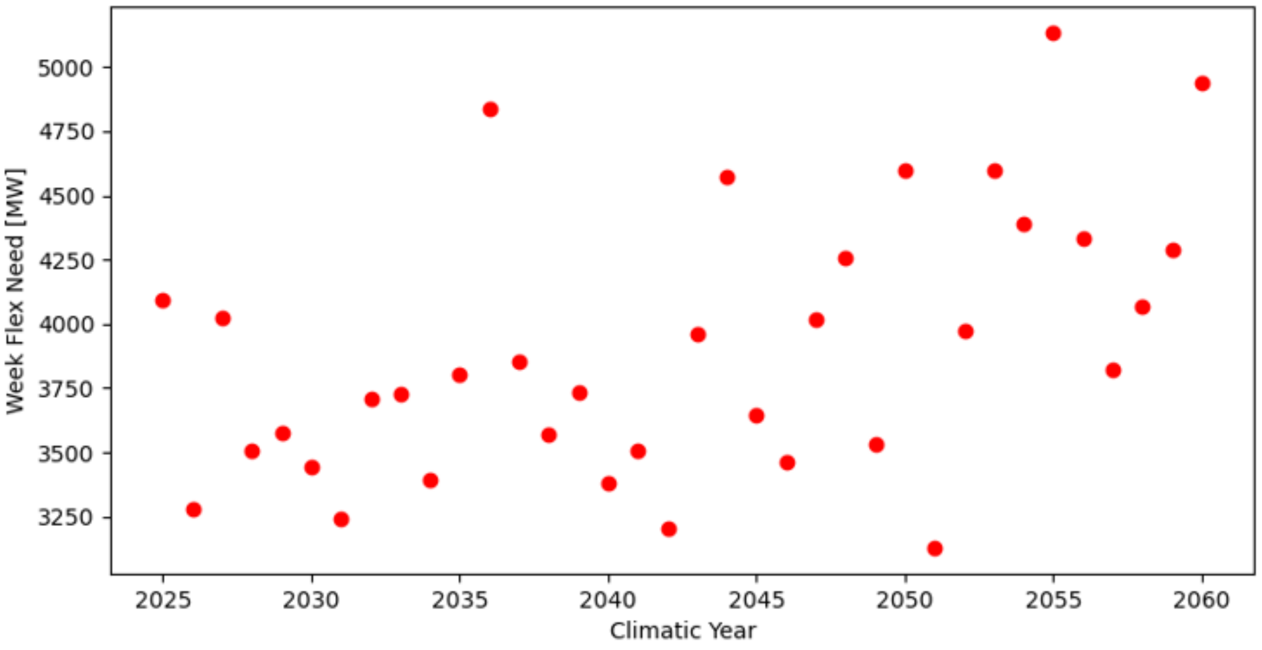
Average Power Indicator [MW] = 3192.79   99 percentile Power Indicator [MW] = 5340.3
95 percentile Power Indicator [MW] = 4586.0   90 percentile Power Indicator [MW] = 4219.96
75 percentile Power Indicator [MW] = 3644.46   25 percentile Power Indicator [MW] = 2645.11
5 percentile Power Indicator [MW] = 2112.74   1 percentile Power Indicator [MW] = 1803.03

Weekly Assessment

The weekly energy indicator FN_{weekly} shows little variation across the whole time series (and across climate years): the 99th percentile is 0.09 TWh and 0.10 TWh, the 1st percentile is 0.07 TWh and 0.09 TWh and the average value is 0.08 TWh and 0.10 TWh in MT2027 and MT2030, respectively. This indicator assumes values that are one order of magnitude lower than the similar daily indicator. This means there is no significant variation in terms of residual load between days of the same week.

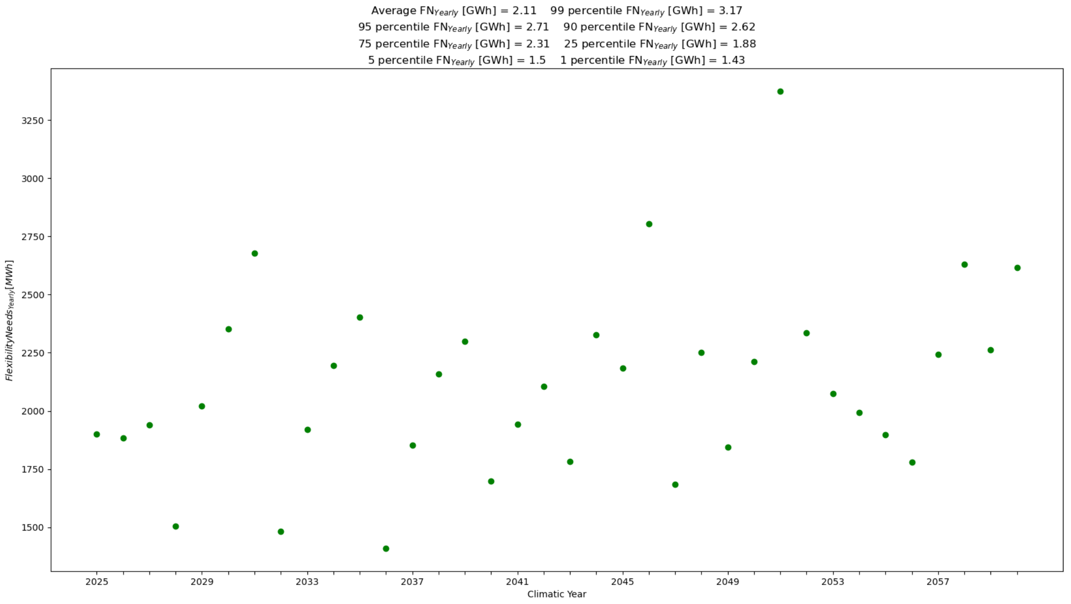
The weekly energy indicator $FNMAX_{weekly}$ is on average (across all the climate years) about 3.3 GW and 3.9 GW in MT2027 and MT2030, respectively. This represents the maximum amount of flexibility needed on a weekly basis. However, this indicator shows a peak for the 2050 climate year (of about 4.3 GW) in MT2027 and a peak for the 2055 climate year (of about 5.2 GW) in MT2030.

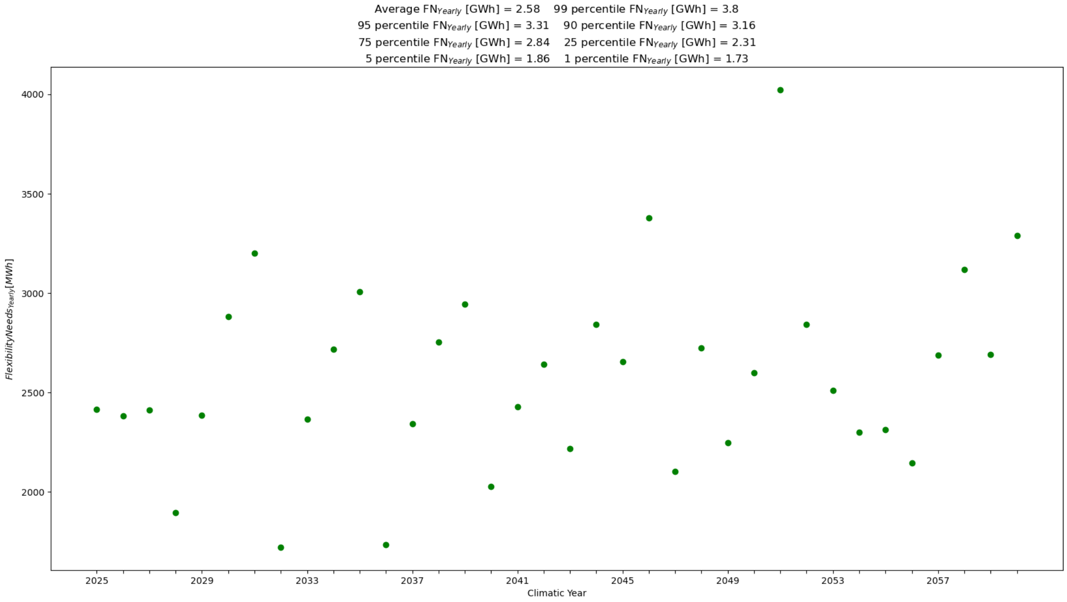




Yearly Assessment

The yearly energy indicator FN*yearly* shows little variation across the whole time series (and across climate years): the 99th percentile is 3.17 GWh and 3.80 GWh, the 1st percentile is 1.43 GWh and 1.73 GWh and the average value is 2.11 GWh and 2.58 GWh in t MT2027 and MT2030, respectively. This indicator assumes values that are very low compared to the weekly and, especially, the daily indicators. This means there is no significant variation in terms of residual load between months of the same year.

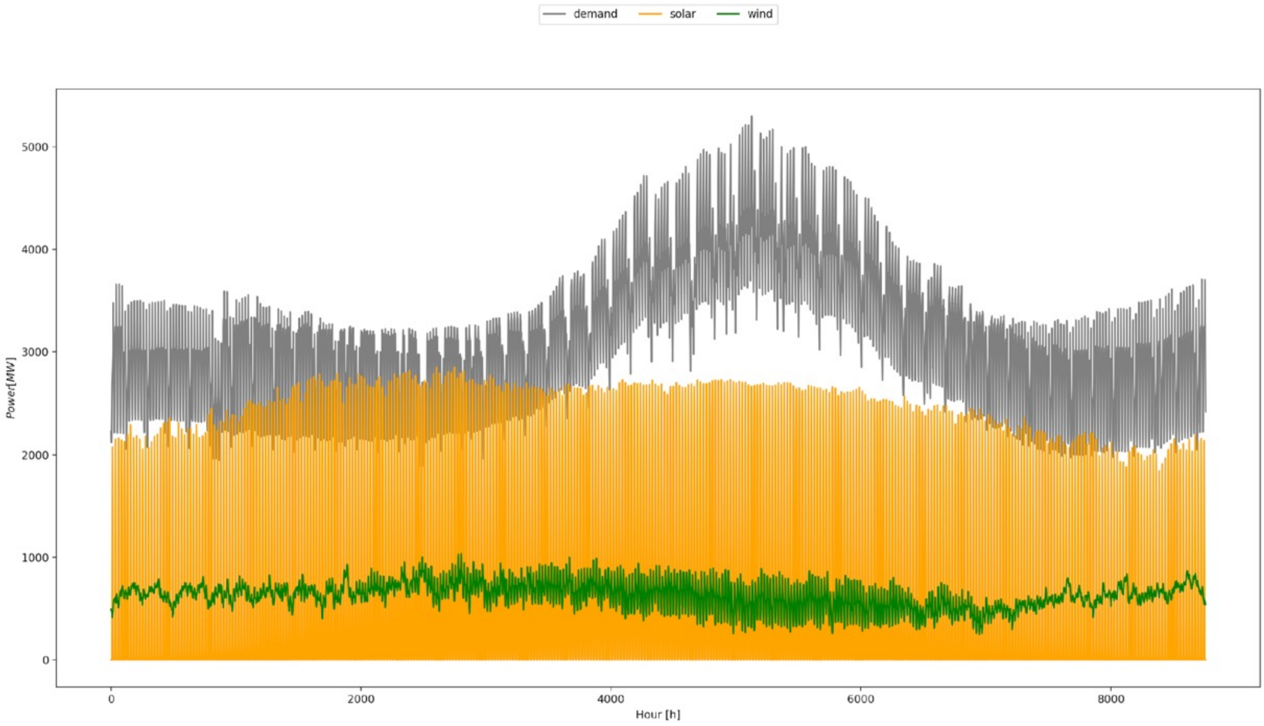




Tunisia

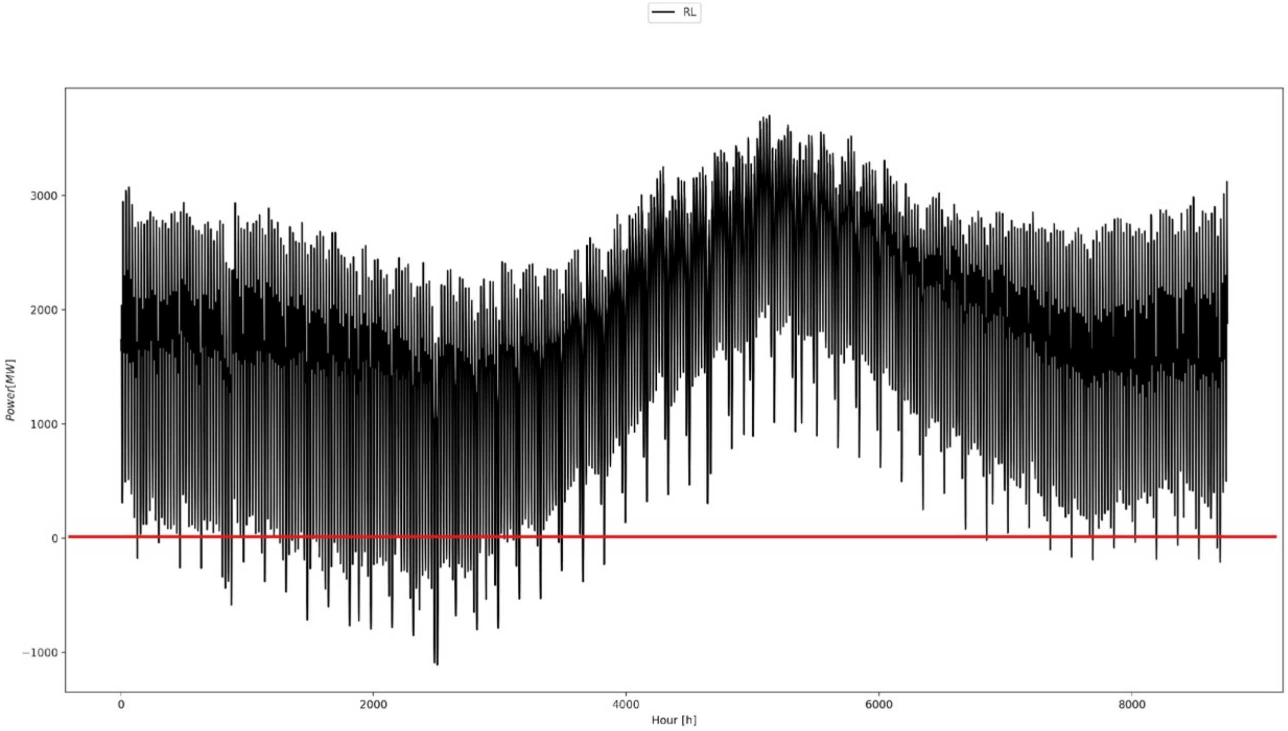
Hourly Assessment

The following figure shows the average hourly values across all climatic years for load, solar, and wind. During the winter months, the load is lower than in the summer months, while solar and wind generation follow an almost constant daily periodic pattern.



The figure presents the average values of load, solar, and wind generation; therefore, occurrences of negative residual load are partially smoothed by the use of averaged data. In the other countries, the demand remains higher than the forecast installed renewable capacity for most hours of the year, confirming the values reported in Table 3.

The following figure instead shows the average hourly residual load across all climatic years is represented, allowing the observation of negative residual load values.



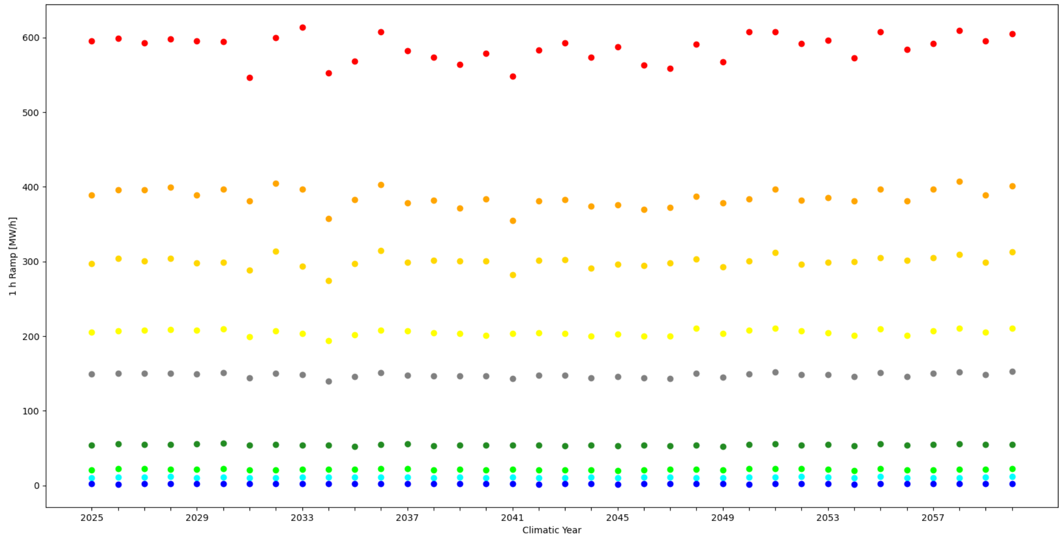
The 1h residual load ramp rate could reach values greater than 0.4 GW/h and 0.7 GW/h for 5% of the hours of the year (and greater than 0.6 GW/h and 0.9 GW/h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

The 2h residual load ramp rate could reach values greater than 0.7 GW/2h and 1.2 GW/2h for 5% of the hours of the year (and greater than 1.0 GW/2h and 1.7 GW/2h for 1% of the hours of the year) in MT2027 and MT2030, respectively.

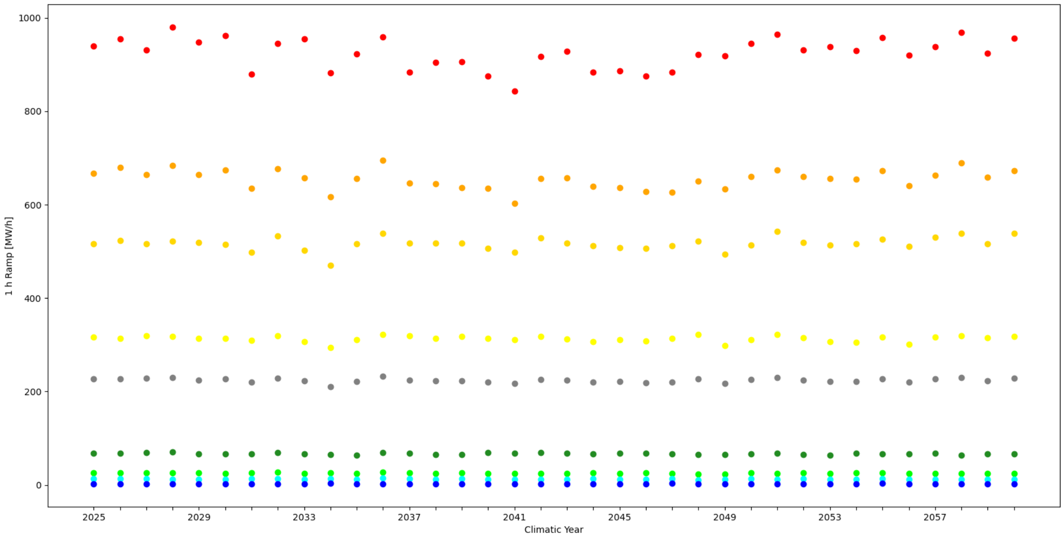
The 4h residual load ramp rate could reach values greater than 1.2 GW/4h and 2.0 GW/4h for 5% of the hours of the year (and greater than 1.6 GW/4h and 2.7 GW/4h for 1% of the hours of the year in MT2027 and MT2030, respectively.

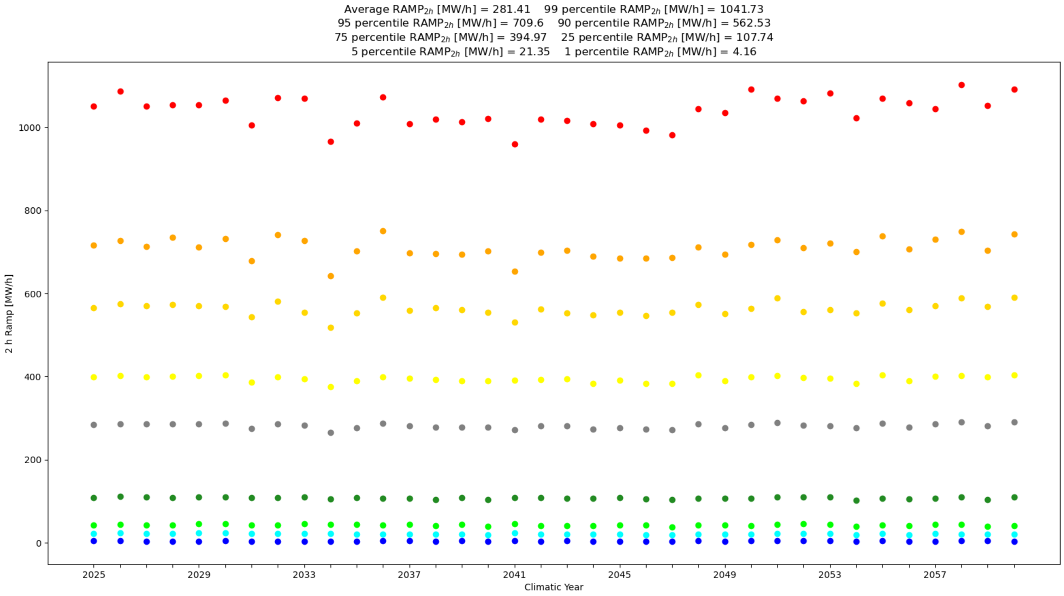
Enlarging the time scale for assessing the ramp smooths the derivative but highlights the necessity of flexible resources to follow the ramp rates of several GW over a few hours.

Average $RAMP_{1h}$ [MW/h] = 147.97   99 percentile $RAMP_{1h}$ [MW/h] = 586.68
95 percentile $RAMP_{1h}$ [MW/h] = 385.33   90 percentile $RAMP_{1h}$ [MW/h] = 299.86
75 percentile $RAMP_{1h}$ [MW/h] = 205.06   25 percentile $RAMP_{1h}$ [MW/h] = 54.44
5 percentile $RAMP_{1h}$ [MW/h] = 10.97   1 percentile $RAMP_{1h}$ [MW/h] = 2.21

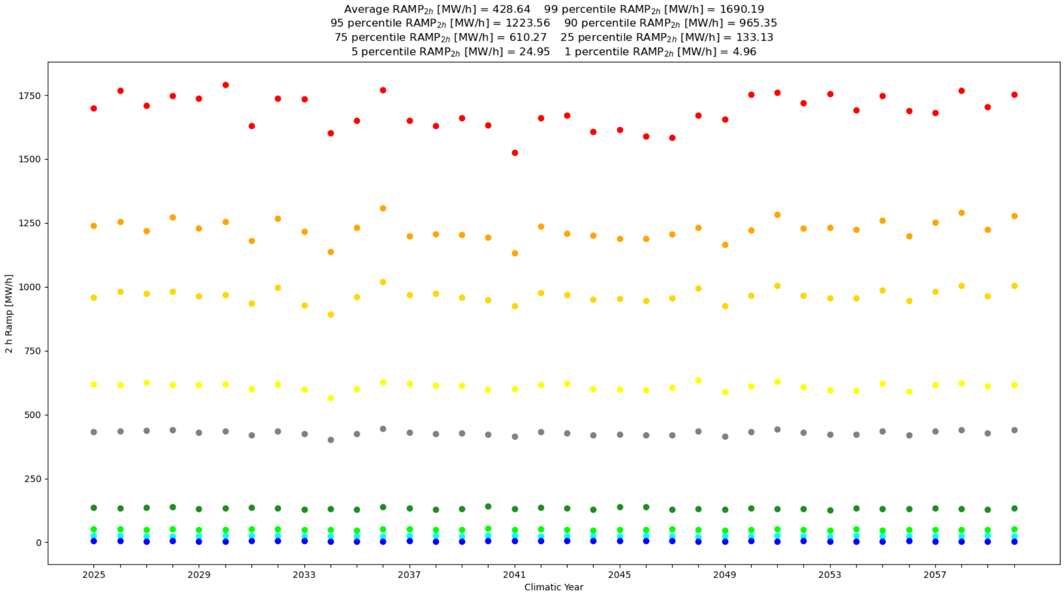


Average $RAMP_{1h}$ [MW/h] = 223.84   99 percentile $RAMP_{1h}$ [MW/h] = 927.04
95 percentile $RAMP_{1h}$ [MW/h] = 654.5   90 percentile $RAMP_{1h}$ [MW/h] = 516.46
75 percentile $RAMP_{1h}$ [MW/h] = 312.72   25 percentile $RAMP_{1h}$ [MW/h] = 66.83
5 percentile $RAMP_{1h}$ [MW/h] = 12.45   1 percentile $RAMP_{1h}$ [MW/h] = 2.51

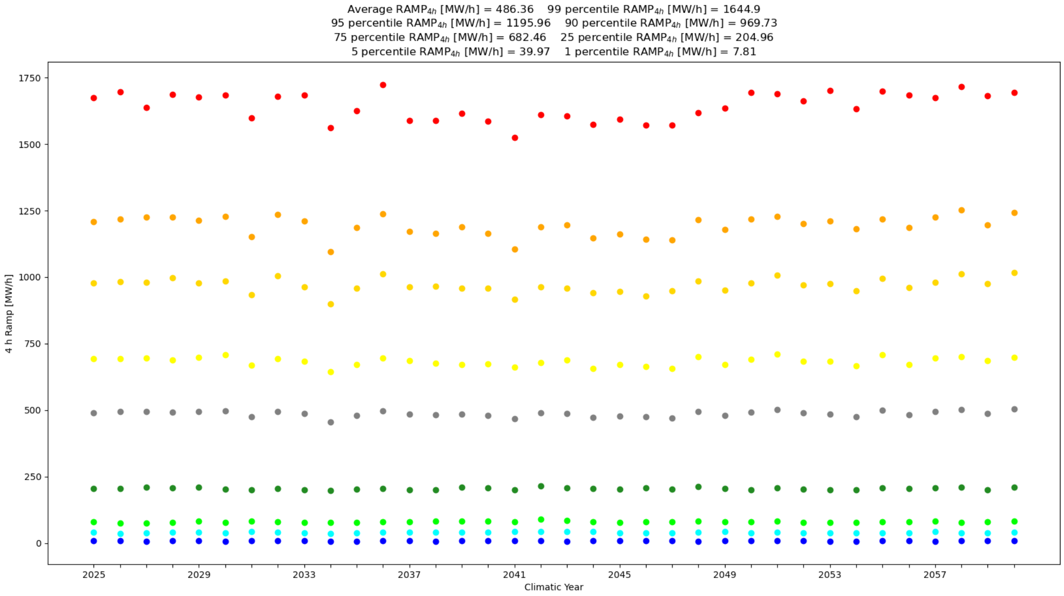


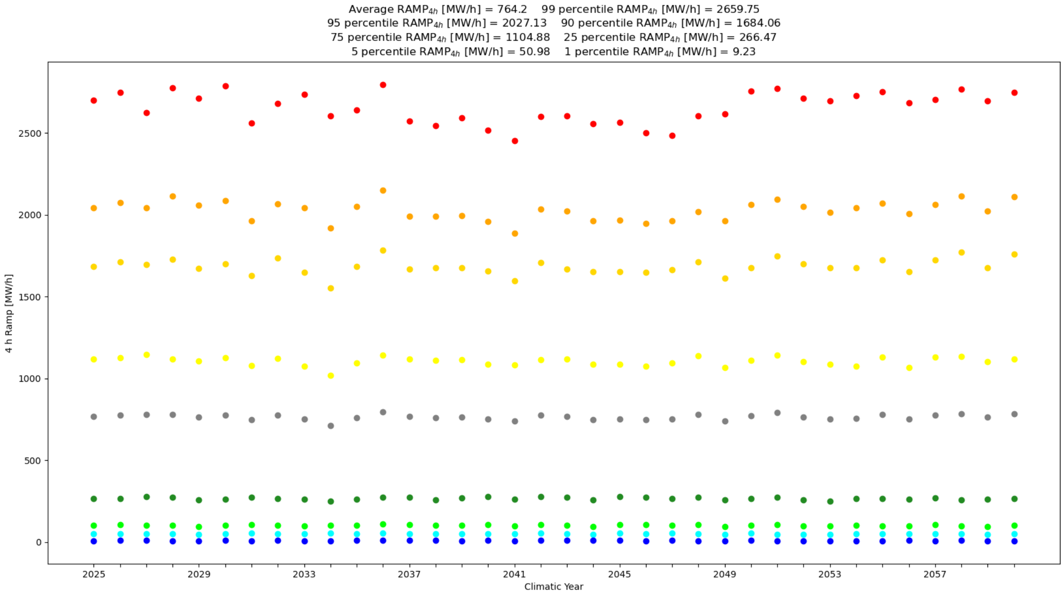


Average RAMP$_{2h}$ [MW/h] = 281.41   99 percentile RAMP$_{2h}$ [MW/h] = 1041.73
95 percentile RAMP$_{2h}$ [MW/h] = 709.6   90 percentile RAMP$_{2h}$ [MW/h] = 562.53
75 percentile RAMP$_{2h}$ [MW/h] = 394.97   25 percentile RAMP$_{2h}$ [MW/h] = 107.74
5 percentile RAMP$_{2h}$ [MW/h] = 21.35   1 percentile RAMP$_{2h}$ [MW/h] = 4.16



Average RAMP$_{2h}$ [MW/h] = 428.64   99 percentile RAMP$_{2h}$ [MW/h] = 1690.19
95 percentile RAMP$_{2h}$ [MW/h] = 1223.56   90 percentile RAMP$_{2h}$ [MW/h] = 965.35
75 percentile RAMP$_{2h}$ [MW/h] = 610.27   25 percentile RAMP$_{2h}$ [MW/h] = 133.13
5 percentile RAMP$_{2h}$ [MW/h] = 24.95   1 percentile RAMP$_{2h}$ [MW/h] = 4.96


Average RAMP$_{4h}$ [MW/h] = 486.36   99 percentile RAMP$_{4h}$ [MW/h] = 1644.9
95 percentile RAMP$_{4h}$ [MW/h] = 1195.96   90 percentile RAMP$_{4h}$ [MW/h] = 969.73
75 percentile RAMP$_{4h}$ [MW/h] = 682.46   25 percentile RAMP$_{4h}$ [MW/h] = 204.96
5 percentile RAMP$_{4h}$ [MW/h] = 39.97   1 percentile RAMP$_{4h}$ [MW/h] = 7.81
4 h Ramp [MW/h]
1750
1500
1250
1000
750
500
250
0
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year

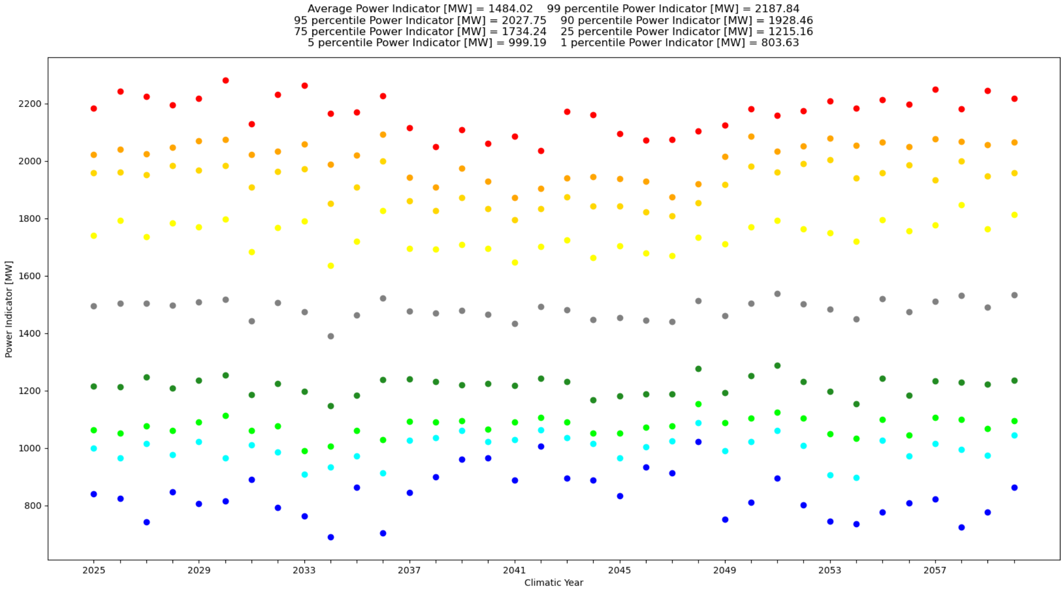

Average RAMP$_{4h}$ [MW/h] = 764.2   99 percentile RAMP$_{4h}$ [MW/h] = 2659.75
95 percentile RAMP$_{4h}$ [MW/h] = 2027.13   90 percentile RAMP$_{4h}$ [MW/h] = 1684.06
75 percentile RAMP$_{4h}$ [MW/h] = 1104.88   25 percentile RAMP$_{4h}$ [MW/h] = 266.47
5 percentile RAMP$_{4h}$ [MW/h] = 50.98   1 percentile RAMP$_{4h}$ [MW/h] = 9.23
4 h Ramp [MW/h]
2500
2000
1500
1000
500
0
2025
2029
2033
2037
2041
2045
2049
2053
2057
Climatic Year

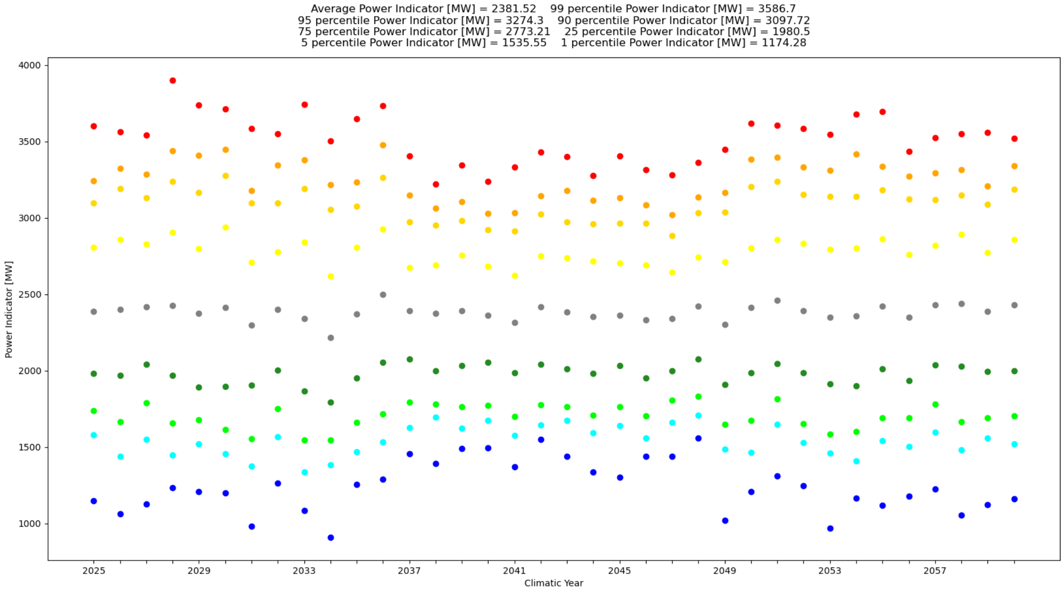
Daily Assessment

The daily energy indicator FN_{daily} shows little variation across the whole time series (and across climate years): the 99th percentile is 1.60 TWh and 2.87 TWh, the 1st percentile is 1.46 TWh and 2.56 TWh and the average value is 1.55 TWh and 2.75 TWh in MT2027 and MT2030, respectively.

The daily energy indicator $FNMAX_{daily}$ shows little variation across climate years, resulting in a range between 6GWh and 8GWh and in a range between 11 GWh and 16 GWh for all the assessed climate years, with a mean value of about 7 GWh and 13 GWh in MT2027 and MT2030, respectively. This represents the maximum amount of flexibility needed on a daily basis.

The power indicator is reported in the figure below for each climate year and relevant percentile. The average value across the whole time series (and climate years) is about 1.5 GW and 2.4 GW in MT2027 and MT2030, respectively, which represents the average difference between daily minimum and maximum residual load values. This difference can rise up to 2.0 GW and 3.3 GW for 5% of the days and up to 2.2 GW and 3.6 GW for 1% of the days in MT2027 and MT2030, respectively.

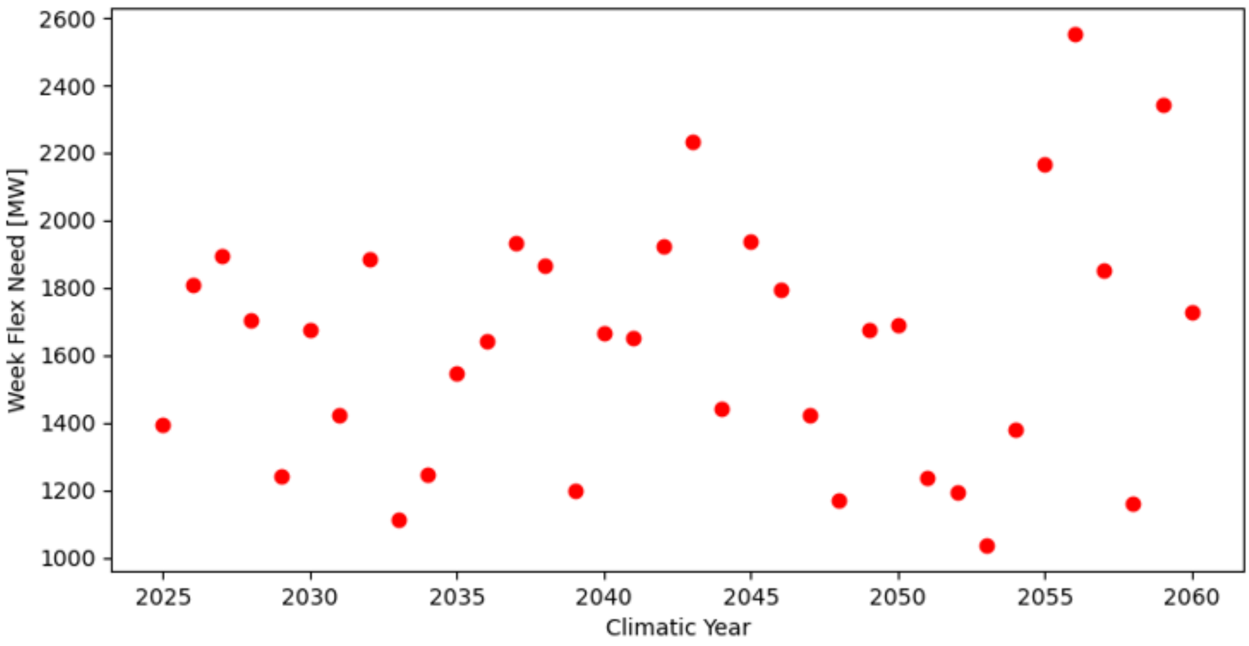


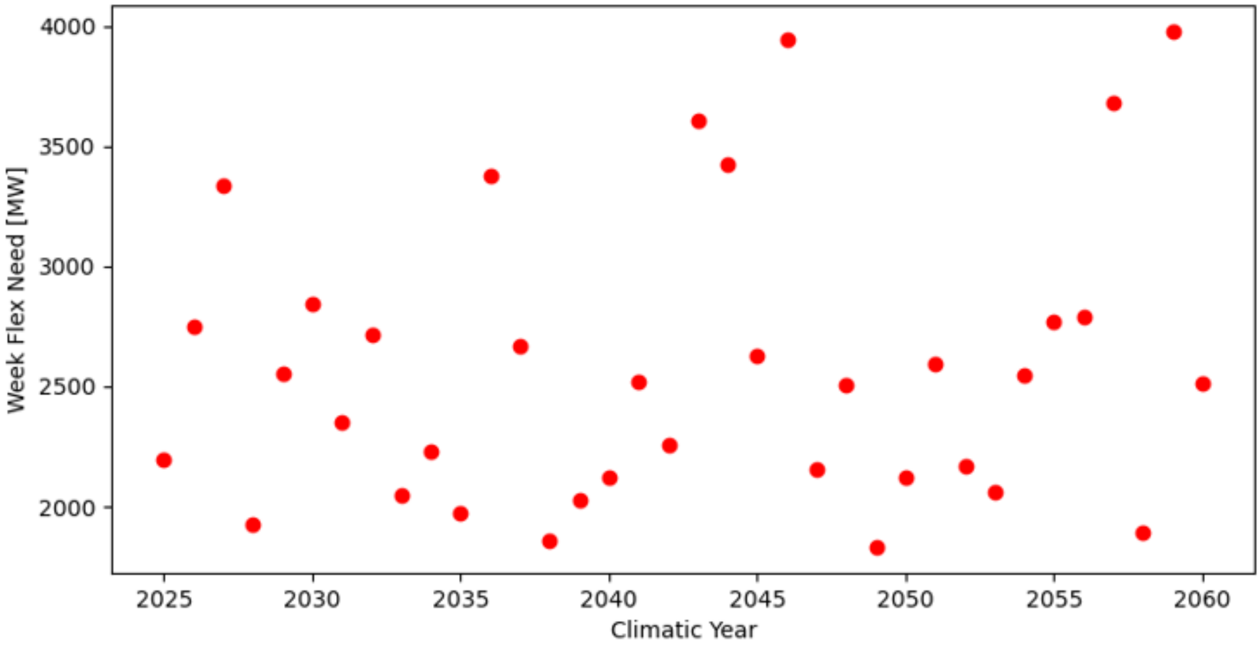


Weekly Assessment

The weekly energy indicator FN_{weekly} shows little variation across the whole time series (and across climate years): the 99th percentile is 0.03 TWh and 0.06 TWh, the 1st percentile is 0.03 TWh and 0.05 TWh and the average value is 0.03 TWh and 0.05 TWh in MT2027 and MT2030, respectively. This indicator assumes values that are one order of magnitude lower than the corresponding daily indicator. This means there is no significant variation in terms of residual load between days of the same week.

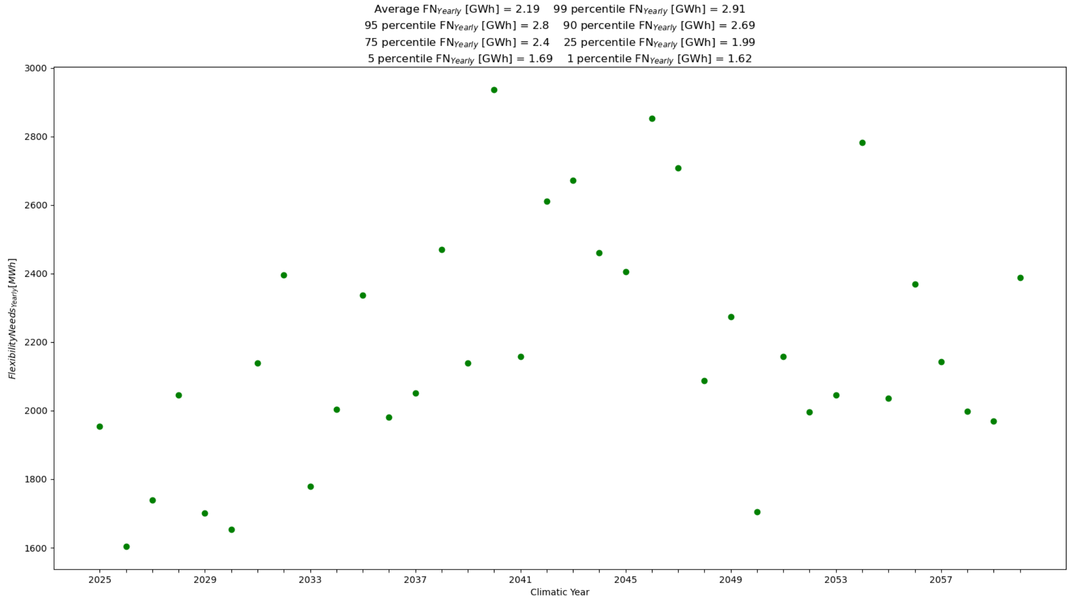
The weekly energy indicator $FNMAX_{weekly}$ is on average (across all the climate years) about 1.6 GW and 2.6 GW in MT2027 and in MT2030, respectively. This represents the maximum amount of flexibility needed on a weekly basis. However, this indicator shows a peak for the 2056 climate year (of about 2.6 GW) in MT2027 and a peak for the 2059 climate year (of about 4.0GW) in MT2030.

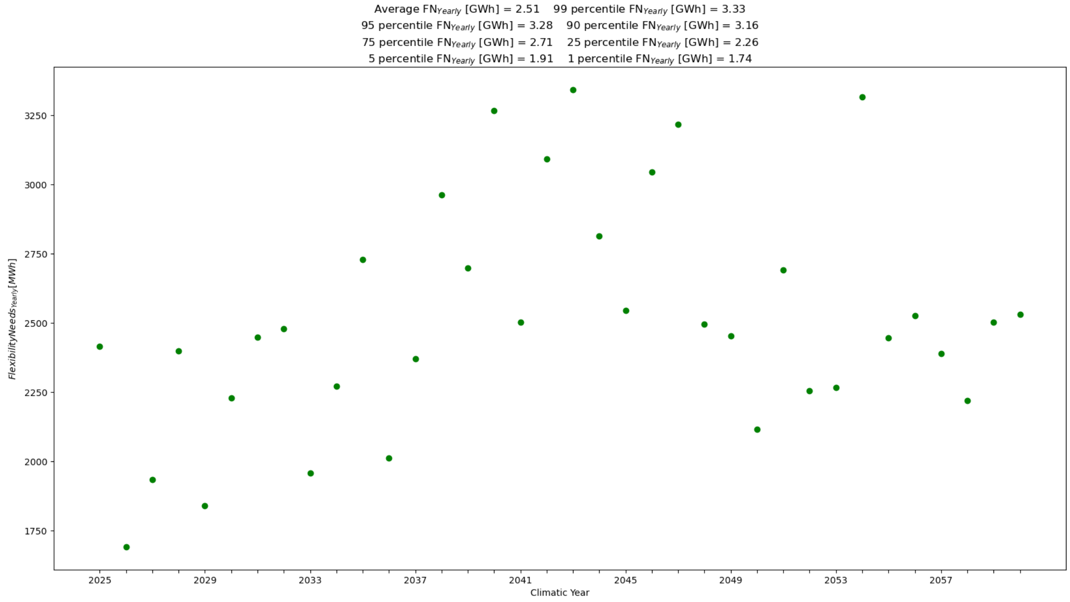

Week Flex Need [MW]
2600
2400
2200
2000
1800
1600
1400
1200
1000
2025
2030
2035
2040
2045
2050
2055
2060
Climatic Year


Week Flex Need [MW]
4000
3500
3000
2500
2000
2025
2030
2035
2040
2045
2050
2055
2060
Climatic Year

Yearly Assessment

The yearly energy indicator FN_{yearly} shows little variation across the whole time series (and across climate years): the 99th percentile is 2.91 GWh and 3.33 GWh, the 1st percentile is 1.62 GWh and 1.74 GWh and the average value is 2.19 GWh and 2.51 GWh in MT2027 and MT2030, respectively. This indicator assumes values that are very low compared to the weekly and, especially, the daily indicators. This means there is no significant variation in terms of residual load between months of the same year.





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