Photovoltaic and Wind Power Plants Production Profiles Generation from Scarce Data

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***Abstract*—To perform optimal parametrization and scheduling of renewable energy systems or systems connected to them, realistic yearly renewable energy production profiles are necessary. Such generation profiles are often unobtainable in public databases of existing renewable energy sources used for automated analysis of possibilities for the upgrade of green energy infrastructures via parametrization and scheduling tools. This paper presents a method for scaling of generic photovoltaic and wind farm production profiles to adapt them for a particular site. Annual energy production and installed power are the only necessary parameters to obtain the site-adapted time series of energy production. For the case of photovoltaic production, the approach is extended to also include the daylight duration linked to the provided geo-location.**

***Index Terms*—photovoltaic power plant, wind farm, production profile, yearly production, nominal power, daylight duration**

I. INTRODUCTION

Renewable energy sources have been gaining significant attention in recent years due to their potential to mitigate climate change and reduce dependence on fossil fuels. Solar and wind renewable sources are the key to building sustainable future energy systems. Their intermittency is posing an enormous burden on the power system's stability. Appropriate controls and strategies to enable photovoltaic (PV) and wind power systems grid integration are in that respect crucial [1].

As renewable energy is still expensive and engages a significant amount of public resources in the corresponding facilities' building and operation, these facilities must be very carefully planned in terms of investment sizing and operation scheduling. Thereby usually public databases of existing renewable energy sources are used for automated analysis of possibilities for the upgrade of green energy infrastructures via parametrization and scheduling tools from a territorial perspective, in terms of better integration in energy systems and improved economic performance. Such databases are usually scarce in data about specific renewable energy plants while the optimal parametrization and scheduling tools require generation profiles of these sources on a yearly time scale with fine time granulation.

There are many approaches to generating a full-year production profile when real-time measurements are not available. Deterministic calculations require many system parameters to conduct the calculations. For PV systems, the type and amount of panels, their orientation and tilt angles are all necessary inputs to get an approximation of the profile. Wind power systems use detailed data about wind speed, turbine model and hub height to generate energy production profiles that have a small offset from the actual production. Renewables.ninja online tool offers a service where a large database is used and previously mentioned parameters are the inputs for the creation of hourly sampled energy profiles [2]–[4]. Other approaches often include neural networks for which a large amount of historical data is needed [5], [6]. An overview of different approaches compared to the one presented in this paper is shown in the following table where different approaches are compared based on the needed quantity of parameters and historical data.

	Parameters	Historical Data
Deterministic approach	Many	None
Neural networks	Many	Many
This paper	Few	None

TABLE I
TABLE OVERVIEW OF DIFFERENT APPROACHES

Historical data is often non-existing or not available and other parameters, such as type and number of installed solar panels, are also not known. This paper introduces an approach of scaling generic PV and wind power plant production profiles into generation profiles of the corresponding power plants for which only the peak nominal power and the yearly amount of produced energy are given. The proposed method is based on an iterative scaling of a generic production profile. It also includes a PV production profile transformation based on a given location. This method preserves a characteristic dynamic shape of the production profile and it is a good option to provide needed inputs for operations of optimal sizing and scheduling of green energy systems.

The method is implemented as a part of the Optimization Tool for optimal sizing and operation scheduling of power-to-gas (P2G) hubs [7]. By coupling a P2G hub with a renewable energy plant, it is possible to use green electricity in P2G processes for energy storage and provision of flexibility to

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electricity and gas grid systems. Parameters describing the renewable energy plant selected can be obtained from the Atlas Tool [8] which is a GIS tool with a database of renewable energy plants in the Danube region. Atlas Tool contains the data about the yearly energy production and the nominal power of the plant while the Optimization Tool uses yearly production profiles to determine the optimal size and operation schedule of the prospective P2G hub.

The work is organized as follows. Section II describes the mathematical formulation of the iterative scaling method for the generation of the energy production profiles. Rescaling of the PV profiles for a given location, based on daylight duration, is presented in the same section. Section III shows the application of the introduced procedure for several different setups. Finally, Section IV concludes the paper.

II. PROBLEM FORMULATION

This section covers the mathematical background for scaling of generic PV and wind generation profiles to produce a profile with the expected yearly energy production and peak power. The first part covers the iterative approach of adapting the generic profiles with the multiplication formula. The second part covers the modification of a daily PV production profile to adapt the production profile to the given location.

A. Iterative scaling of a production profile

As mentioned before, the starting inputs are the originally recorded profiles of a wind farm or a PV plant energy production f, and the values for the nominal power and yearly energy production for the target plant to which these profiles need to be rescaled, denoted with P and E, respectively. Production profile f consists of N samples. Each sample denoted with $f(k)$ represents energy generated in a time interval $[\,kT,(k+1)T\,\rangle$ where T is the production profile sampling time. For the location-based modifications of the PV profile, the geographic location for which the modification is done must be known. It is also assumed that the original PV profile is stemming from a PV plant that has the same or similar orientation setup of the panels as the targeted PV plant.

Before the original profile modification, P and E parameters are checked for consistency, i.e. that it is possible to achieve such a combination of peak power and yearly energy production. The original profile f is then normalized to take on values from 0 to 1, where 0 denotes no energy production and 1 denotes the production of energy with nominal power:

$$f^*(k) = \frac{1}{\max\limits_{k\in\{0,\dots,N-1\}} f(k)} \cdot f(k). \tag{1}$$

The initial step of the scaling method is the calculation of the coefficient for rescaling which is defined from the final peak power and energy production. For the given nominal power P, the rescaling coefficient to obtain actual production samples from a normalized profile is:

$$K = P \cdot T. \tag{2}$$

To achieve the final energy production E via the iterative scaling procedure introduced in the following, scaled energy production E_K is also introduced:

$$E_\mathrm{K} = \frac{E}{K}. \tag{3}$$

The following requirements are set on the scaling function $h(x)$ for a normalized production profile, where $x \in [0,1]$. Firstly, the scaling function needs to incorporate a tunable coefficient β which with its different values determines whether the normalized production profile samples are increased or decreased. Secondly, the scaling function must be a non-decreasing function on the interval [0,1]:

$$h'(x) \geq 0,\ \forall\, x \in [0,1]. \tag{4}$$

This will ensure that the relative relations between the samples in the profile in terms of smaller-bigger are kept through the iterative procedure until they reach the final values. The next important property of the proposed scaling function is keeping the edge values 0 and 1 of the normalized profile unchanged. That property makes sure that after rescaling, the periods of nominal production and of no production are retained.

The scaling function is assessed in the form:

$$h(x) = x \cdot s(x) \tag{5}$$

where the function $s(x)$ dictates the scaling. Values of the function $s(x) \leq 1$ will make the samples x of the normalized profile decrease or remain the same after scaling while the vice-versa holds for $s(x) \geq 1$. For the correct behaviour of scaling at the edges of the normalized profile, it is required that $s(0) = s(1) = 1$ in all scaling cases.

The following function is defined:

$$s(x) = 1 + \beta \cdot x \cdot (1 - x). \tag{6}$$

The function $s(x)$ satisfies the increasing function requirement described in Eq. (4) for the scaling function $h(x)$ when $\beta \in [-1,1]$.

$$\begin{aligned}
&h'(x) = s(x) + x \cdot s'(x),\\
&h'(0) = s(0) + 0 \cdot s'(0) = 1,\\
&h'(1) = s(1) + 1 \cdot s'(1) = 1 + s'(1) \geq 0,\\
&s'(1) = \beta \cdot ((1-1) - 1) = -\beta \geq -1. \rightarrow \beta \leq 1
\end{aligned} \tag{7}$$

Function $s(x)$ also satisfies the upscaling requirement when β is in range $[0,1]$ and downscaling requirement when β is in range $[-1,0]$:

$$\begin{aligned}
&s(x) \geq 1,\ \beta \in [0,1],\\
&s(x) \leq 1,\ \beta \in [-1,0].
\end{aligned} \tag{8}$$

Expanding the Eq. (5) with the expression in the Eq. (6) gives the proposed scaling function:

$$h(x) = x \cdot (1 + \beta \cdot x \cdot (1 - x)). \tag{9}$$

Figure 1 shows the graphical representation of the scaling function for different values of the β coefficient.

To show how the production profile is changing in an iterative procedure, $f_k^* \equiv f^*(k)$ is introduced to simplify the

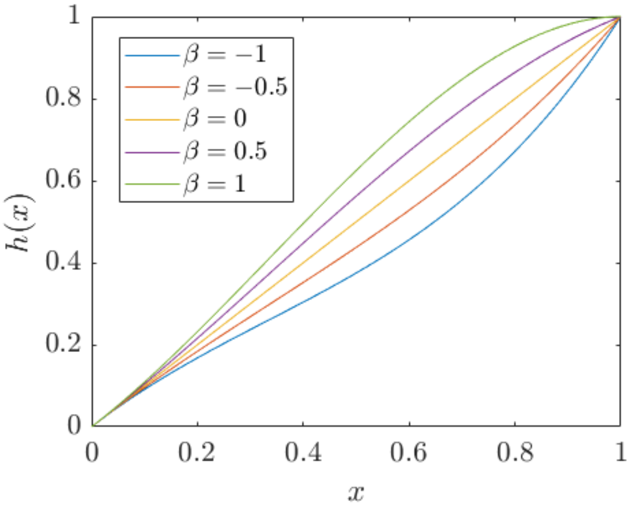

Fig. 1. Graphical representation of the scaling function $h(x)$ for different values of the β coefficient.

representation where $f_k^*(i)$ represents the k-th element of the production profile after the i-th iteration and $f_k^*(0)$ represents the k-th element of the starting profile. In every iteration i, the production profile is modified using the scaling function from Eq. (9):

$$f_k^*(i+1) = f_k^*(i)\cdot(1+\beta(i)\cdot f_k^*(i)\cdot(1-f_k^*(i))). \tag{10}$$

New values of the profile are changing with the β coefficient which is directing if the profile values will rise or fall in the next iteration. For $\beta \in (0, 1]$ the values of the profile will be non-decreasing in the next iteration while they will be non-increasing for $\beta \in [-1, 0)$. For $\beta = 0$ the values of the profile will stay the same and such value of β means that no more iterations are needed.

The iterative process must continue until the sum of the production profile is equal to E_K which occurs at iteration $j+1$.

$$\sum_{k=0}^{N-1} f_k^*(j+1) = E_\text{K}. \tag{11}$$

From the previous equation, expression how the β coefficient is reevaluated in every iteration is given:

$$\sum_{k=0}^{N-1} f_k^*(j{+}1) = \sum_{k=0}^{N-1} \left(f_k^*(j)\cdot(1+\beta(j)\cdot f_k^*(j)\cdot(1-f_k^*(j))\right),$$

$$E_\text{K} = \sum_{k=0}^{N-1} f_k^*(j) + \beta(j)\cdot\sum_{k=0}^{N-1} \cdot f_k^*(j)^2\cdot(1-f_k^*(j))), \tag{12}$$

$$\beta(j) = \frac{E_\text{K} - \sum\limits_{k=0}^{N-1} f_k^*(j)}{\sum\limits_{k=0}^{N-1}\left[\left(f_k^*(j)\right)^2\cdot(1-f_k^*(j))\right]}.$$

To make sure that values in a profile remain within the limits $[0, 1]$, and that all the previously introduced conditions on the scaling function are respected, saturation function f_sat is added to limit the β coefficient value. In every iteration i, β coefficient is reevaluated by the following expression:

$$\beta(i) = f_\text{sat}\left(\frac{E_\text{K} - \sum\limits_{k=0}^{N-1} f_k^*(i)}{\sum\limits_{k=0}^{N-1}\left[\left(f_k^*(i)\right)^2\cdot(1-f_k^*(i))\right]}\right), \tag{13}$$

$$f_\text{sat}(\beta) = \min(\max(\beta, -1), 1). \tag{14}$$

Figure 2 is showing the graphical representation of the saturation function from Eq. (14).

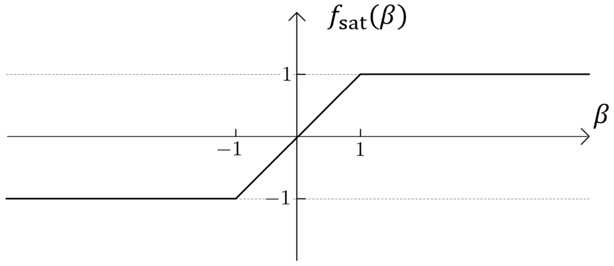

Fig. 2. Graphical representation of the saturation function.

At the beginning of the scaling procedure (iterations $i < j$) the β coefficient might be saturated to -1 or 1, but the first time it becomes greater than -1 and less than 1 (iteration $i = j$) the procedure will be concluded with final iteration ($i = j+1$). After the iteration $j+1$ the sum of the production profile is equal to E_K.

The modified production profile still needs to be rescaled to the initially given parameters P and E with the previously defined coefficient K to obtain the scaled production profile g:

$$g(k) = K\cdot f_k^*(j+1). \tag{15}$$

After rescaling, the modified profile will have the specified peak power and the sum of energy production:

$$\begin{gathered}\max\left(g(k)\right) = P\cdot T,\\ \sum_{k=0}^{N-1} g(k) = E.\end{gathered} \tag{16}$$

This method can be used on all energy profiles where there is a need for adjusting the profile to the given maximum value and the sum.

B. PV profile adaptation to a specific location

When the production profile is modified for a different location compared to the original production profile, a change in location latitude will alter the duration of the days throughout the year period considered in the production profile. That affects the limits of the PV plant's energy production. It has to be ensured that the PV production is zero outside the daylight hours. This modification is done before the adjustment of the produced energy and the peak power.

The duration of the daylight on each day is determined from the average solar elevation angle α which is calculated for each time interval of the profile. The solar elevation angle measures the Sun's height relative to the horizon line and it can range from -90° to 90° [9]. The positive values mean the Sun is above the horizon which represents the day, while negative ones represent night when there is no PV production. The solar elevation angle is calculated by using:

$$\alpha = \sin^{-1}[\sin\delta\sin\theta + \cos\delta\cos\theta\cos\gamma] \tag{17}$$

where δ is the declination angle, θ is the geographic latitude and γ is the local hour angle [10].

Using Eq. (17), the average solar elevation angle for each time interval of the generation profile is obtained. Positive angle defines the daytime and after the limits of each day are established for the original and new location, resampling of the original profile f is done. Resampling adapts the original PV production profile for each day to the limits of that same day in a different location. It is done day by day because by changing the latitude some days become longer and some shorter.

Resampling is done by applying the Fourier method to interpolate the signal of production on the original day. If the duration of the day for which the signal is resampled is longer than the original (roughly said, mid-day power production shape must be widened), the production signal will be upsampled. If the duration of the day is shorter (mid-day production must be narrowed), the production signal will be downsampled [11].

To resample the production profile of each day, only the daylight part of the profile is taken which behaves like a discrete signal with non-zero samples of length A. To resample it to a new length B which is the length of the daytime samples on a specified location, first a discrete Fourier transform (DFT) is applied to create its frequency-domain representation. Part of the production profile that is taken for resampling $f(l)$ is obtained from the solar elevation angle α of the original location where $l \in \{L, ..., L + A\}$ and L is the first daylight sample in the production profile for a single day. Frequency-domain representation $F(n)$ is then obtained by applying DFT:

$$F(n) = \sum_{l=0}^{A-1} f(l) \cdot e^{-i\frac{2\pi}{A}ln}. \tag{18}$$

After that, mapping the original frequencies to the new frequencies is done. For the downsampling ($B \leq A$), the original frequency-domain representation is cut-off to fit the new number of samples.

$$G(n) = F(n)\ , n < B. \tag{19}$$

In the case of upsampling ($B \geq A$), frequency-domain representation is extended with zero-padding:

$$G(n) = \begin{cases} F(n), & n \leq A, \\ 0, & \text{otherwise.} \end{cases} \tag{20}$$

After the length of the samples is set, it is converted back to the time domain to length B using the inverse Fourier transform:

$$g^*(l) = \frac{1}{B}\sum_{n=0}^{B-1} G(n) \cdot e^{i\frac{2\pi}{B}ln}. \tag{21}$$

Finally, the resulting time samples need to be multiplied with the coefficient A/B:

$$g(l) = \frac{A}{B} \cdot g^*(l). \tag{22}$$

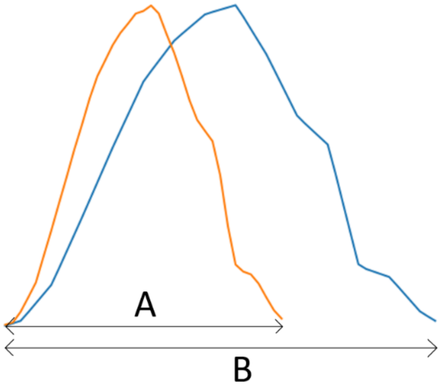

Fig. 3. Graphical representation of the resampling method.

Figure 3 shows how the original production curve is upsampled from the length A to the new length B.

Resampled PV production profile of a single day g is then placed inside the previously defined limits of a single day. After all days in a year are resampled, the full-year profile is scaled using the method mentioned in the first part.

III. APPLICATION OF THE PROPOSED METHOD

The procedure for rescaling is tested by using full-year energy production profiles sampled on a 15-minute basis. Profiles used as a starting point for scaling are existing measurements of production for a wind farm in Neusiedel am See in Austria and a small PV system at Laboratory for Renewable Energy Systems in Zagreb, Croatia. The wind farm production profile has 32.4 MW nominal power [12], while the peak power of the PV system production profile is 6.25 kW. All the solar panels of the PV system have a south orientation (azimuth is 0°) and a 50° tilt angle. As mentioned before, it is assumed that the target PV plant also has the south orientation of panels.

All the computations are done using Python. Scaling is done according to the procedure mentioned in Section II. To calculate the solar elevation angle, `pysolar` library is used, while to resample the PV production based on the location with the Fourier transform, `scipy.signal` library is used.

The following figures show how the proposed method changes the wind and PV energy production profile. Figure 4 shows the modification of the wind production profile. Scaling is done to modify the original profile so that the peak power of 32.4 MW remains the same while the energy production is reduced by 40% from 57.9 GWh to 34.7 GWh. To have a better graphical representation, the graph is showing a three-day profile from the 1st of November to the 3rd of November.

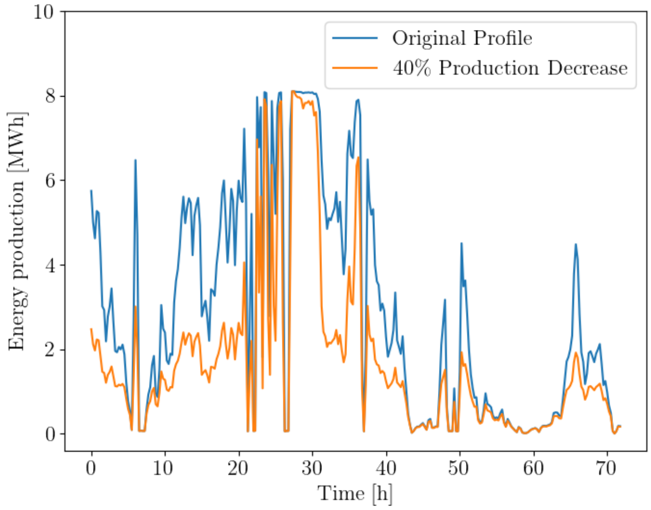

Fig. 4. 40% production decrease while maintaining the same peak power on wind production profile, shown profile detail for three days in a year.

The next two figures show how the scaling function changes the PV production profile. In this case, energy production is increased by 20% and the peak power remained the same. Yearly production changed from 8.42 MWh to 10.1 MWh.

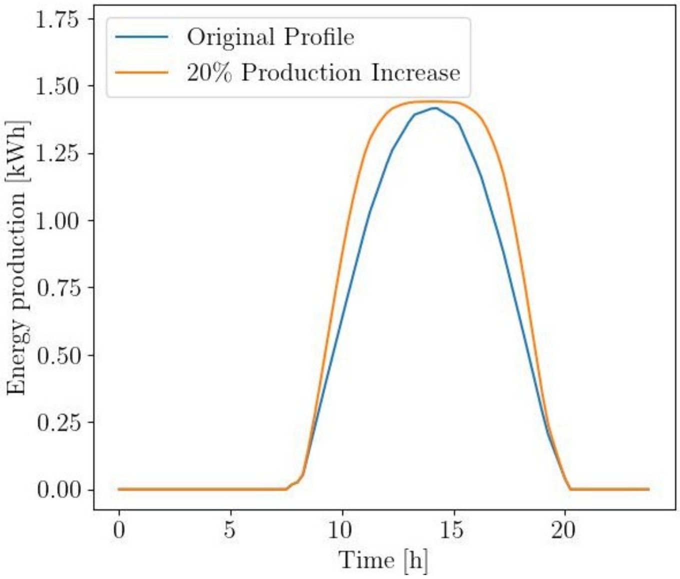

Fig. 5. 20% production increase while maintaining the same peak power on a PV system, generation profile detail for a single day in a year (March 28th).

Figure 5 shows the production increase for a single day in a year and Figure 6 shows the production increase for a full year. The new profile computation was done after 2 iterations.

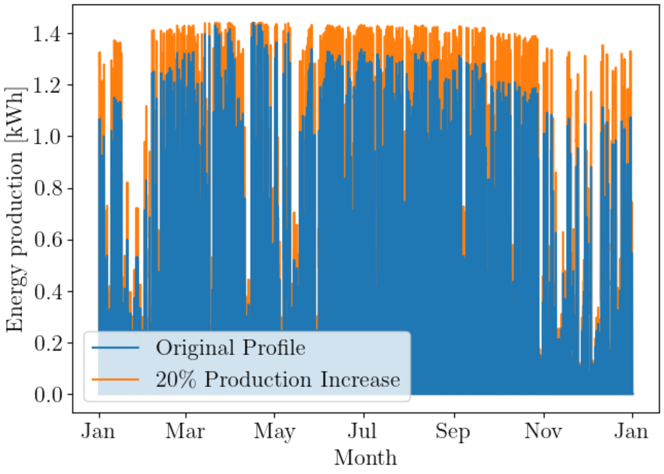

Fig. 6. 20% production increase while maintaining the same peak power on a PV system for a full year.

In the first iteration coefficient β was equal to 1 while in the second iteration, it was equal to 0.093.

To show how the production profile changes shape with the location change, the original PV production profile is scaled from the original profile in Zagreb, Croatia to Brussels, Belgium where the duration of the day during winter is shorter while the duration of the day is longer during summer. Also, due to a different geographic longitude, solar noon occurs at different times which is reflected as a shift of the profile. Using the calculation of the solar elevation angle, the daytime duration graph is shown for a day in the summer (July 6th) in Figure 7.

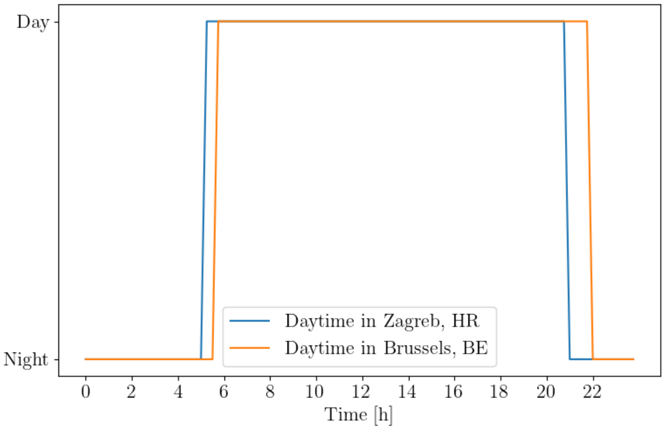

Fig. 7. Graphical representation of the daytime duration in Zagreb, Croatia and Brussels, Belgium for a day in the summer (July 6th).

Figure 8 is showing how the day is resampled to a different location. For a winter day shown (January 15th), the day in Zagreb, Croatia starts earlier and ends earlier. Downsampling is done from the length of 9 hours (36 15-minute samples) to the length of 8.5 hours (34 15-minute samples) to adapt to a shorter day in Brussels, Belgium. There is a visible shift of the solar noon.

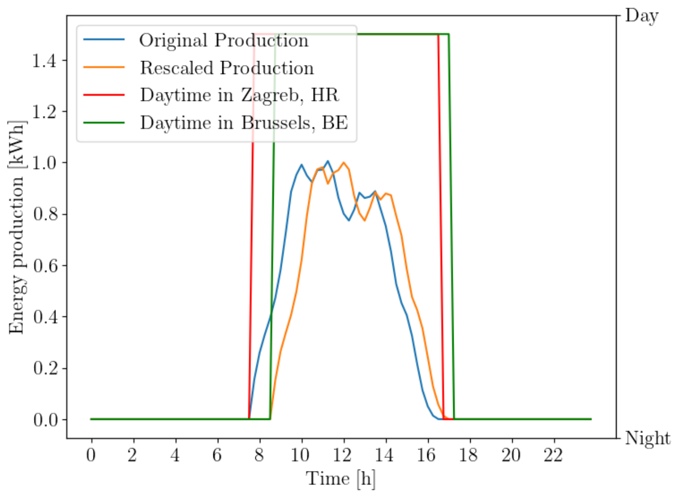

Fig. 8. Downsampling of the PV production profile for a single day in a year (January 15th) from the original location in Zagreb, Croatia to Brussels, Belgium with the representation of the daytime duration for both locations.

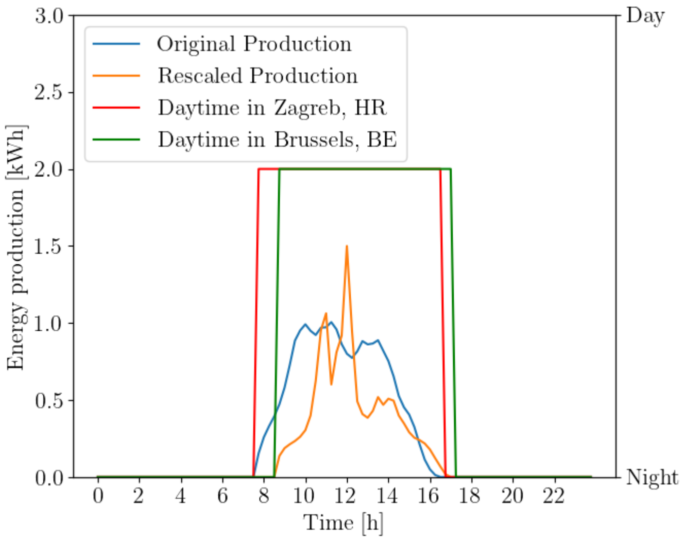

Fig. 9. 20% production increase of the PV production profile for a single day in a year (January 15th) from the original location in Zagreb, Croatia to Brussels, Belgium with the representation of the daytime duration for both locations.

Finally, Figure 9 is showing both changes in location and in energy production where the new production curve is adapted to limits of the day duration from Zagreb, Croatia to Brussels, Belgium. Energy production of the specified day is decreased from 22.6 kWh to 15 kWh and the peak power is increased from 4 kW to 6 kW.

IV. CONCLUSION

This paper introduces a procedure for obtaining energy production profiles of PV plants and wind farms from generic profiles that stem from real plant measurements, under conditions of known nominal power and yearly energy production for the target site.

In addition, for the PV plant production, the duration of daylight at a specific location is taken into account in the generation of the production profile. The original production profile is resampled to the daytime in a specified location. Resampling is done using Fourier transformation. The constraint of the method for PV plants is that the configuration of the orientation of panels in the starting and the target plant must be similar.

This method can be used to obtain a representation of the yearly production profile of a wind or solar power plant with small sampling periods in case detailed data is not available.

REFERENCES

[1] E. F. Camacho, T. Samad, M. Garcia-Sanz, and I. A. Hiskens, “Control for Renewable Energy and Smart Grids,” in *The Impact of Control Technology*, 2011.

[2] S. Pfenninger and I. Staffell, “Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data,” *Energy*, vol. 114, pp. 1251–1265, 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544216311744

[3] I. Staffell and S. Pfenninger, “Using bias-corrected reanalysis to simulate current and future wind power output,” *Energy*, vol. 114, pp. 1224–1239, 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544216311811

[4] I. S. Stefan Pfenninger. Renewables.ninja. [Online]. Available: renewables.ninja

[5] Y. He, Q. Gao, Y. Jin, and F. Liu, “Short-term photovoltaic power forecasting method based on convolutional neural network,” *Energy Reports*, vol. 8, pp. 54–62, 2022, 2022 International Conference on the Energy Internet and Energy Interactive Technology. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352484722020066

[6] S. M. J. Jalali, S. Ahmadian, M. Khodayar, A. Khosravi, M. Shafie-khah, S. Nahavandi, and J. P. Catalão, “An advanced short-term wind power forecasting framework based on the optimized deep neural network models,” *International Journal of Electrical Power & Energy Systems*, vol. 141, p. 108143, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0142061522001818

[7] F. Rukavina, M. Šundrica, A. Karneluti, and M. Vašak. DanuP-2-Gas: Optimization tool. [Online]. Available: https://danup2gas.eu/optimizationtool

[8] R. Paudyal, L. Fiegler, W. Dorner, and B. Kiss. DanuP-2-Gas: Renewable Energy Atlas. [Online]. Available: https://www.danup2gas.eu/atlas

[9] W. Sas. Sun Angle Calculator. [Online]. Available: https://www.omnicalculator.com/physics/sun-angle

[10] J. Twidell, *Renewable Energy Resources*. Routledge, 2015.

[11] F. Harris, *Multirate signal processing for communication systems*. Prentice Hall PTR, 2004.

[12] M. Pierrot. The Wind Power. [Online]. Available: https://www.thewindpower.net/windfarm_en_140_neusiedl-am-see.php