REPORT

Description Methodology

BREGILAB WP3 RES Generation: Wind & PV deployment evolution and availability factor.

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Study accomplished under the authority of FOD economy (Energy Transition Fund)
2022/RMA/R/2757

08.2022

The work is supported by the energy transition funds project "BREGILAB'' organised by the FPS economy, S.M.E.s, Self-employed and Energy.

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SUMMARY

In WP3 of the Bregilab project, the renewable energy (RE) production and potential is calculated at high spatial and temporal resolution by means of the Dynamic Energy Atlas (DEA). First, current renewable energy production is modelled with the DEA based on hourly meteorological data to assess hourly energy production (i.e. electricity generation profiles within the BREGILAB project) based on the spatial location of a wind turbine and photovoltaic (PV) installation. Next, the technical potential[1] for PV and wind is modelled based on a bottom-up spatial modelling approach. This report describes our methodological approach and results relevant to the BREGILAB objective in detail. Therefore, the information contained within this report is based on the assumptions specific to the BREGILAB project mentioned in this report (Clymans et al., 2022; VITO) and information provided by third parties. The use of the results for other purposes then BREGILAB research should always be done with the necessary diligence with respect to its original purpose and by informing the authors of this report and official funding agency (FOD economy) of the BREGILAB project.

The first chapter frames WP3 within the general objective of the project. Chapter 2 describes the functionalities of the Dynamic Energy Atlas. Chapter 3 and 4 report on the results of energy production by respectively wind turbines and photovoltaic solar panels. Chapter 5 reports on the results of the spatial analysis required to assess the potential of renewable energy production in Belgium, and the potential energy production data as such. All three chapters describe the data sources and methodology used to calculate the renewable (current and potential) energy production, and report on the implementation within the Dynamic Energy Atlas.

Currently (12/04/2022), eight datasets have been created containing hourly modelled energy production (MWh), installed capacity (MW) and availability factor (i.e. Energy production/ Installed Capacity) for wind and PV aggregated per BREGILAB zone, region and Belgium.

The eight datasets differ in the technology (PV versus wind), energy production type (current versus potential) and the meteorological period covered (reference year 2017 versus a climatic series 2006-2019):

- S1: Current wind energy production for the reference year 2017
- S2: Current PV production for the reference year 2017
- S3: Potential wind production for the reference year 2017
- S4: Potential PV production for the reference year 2017
- S5: Current wind energy production for the weather years 2006-2019
- S6: Current PV production for the weather years 2006-2019
- S7: Potential wind production for the weather years 2006-2019
- S8: Potential PV production for the weather years 2006-2019

The reference year 2017 was selected at the start of the BREGILAB project to match existing energy demand profiles used in the energy system modelling.

Current energy production is optimized to match the statistical 2017 Elia data. As such the hourly installed capacity corresponds with those reported by Elia. In addition, simulations of current energy production were ran for multiple weather years (2006 – 2019) to capture inter-annual variability in energy production under fixed capacity conditions.

For wind, the results are produced for following categories of wind turbine installations:

[1] See text box.

- Onshore ≥5MW or <5MW
- Offshore ≥5MW or <5MW

For PV, the results are produced for following categories of PV installations (based on current model Trina Solar TSM-250-PC/PA05A with 152.7 Wp per m^2 capacity):

- PV installation < 10kW which are classified residential (res)
- PV installation ≥ 10kW which are classified commercial & industrial (com&ind)

To produce generation profiles, theoretic transfer functions are deployed in the DEA, using climatic data at hourly resolution. A validation with measured load data of 2017 provided by the Belgian DSO (distribution system operator) highlights the limitation of the modelling for wind and PV. Although temporal patterns are reproduced well, a consistent overestimation of generation for wind (> 15%) and PV (about 8%) is observed. Modelers need to be aware of the limitations when using the data for further analysis.

Potential energy production for 2017 was simulated by using the validated transfer functions but altering the expected technology to be installed in the future. Like for current energy production the simulations were repeated for multiple years (2006-2019) but keeping the technically available space for each technology fixed.

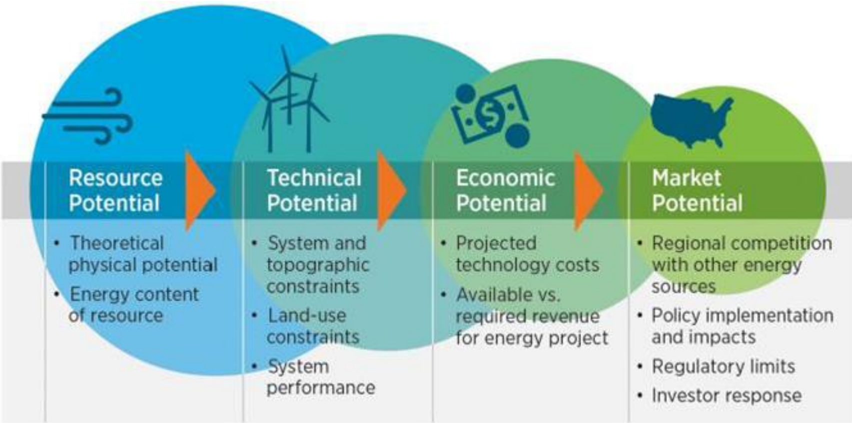
For wind, the results are produced for following categories of wind turbine installations:

- Onshore using standard market model (VESTAS V112; 3.3MW)
- Offshore using planned wind turbine technology (status 1.1.2018)

For PV, the results are produced for following categories of PV installations (based on market model Sunpower Maxeon 3 – with 226 Wp per m^2 capacity):

- PV installation on residential roofs (res)
- PV installation on commercial & industrial roofs (com&ind)
- Ground-mounted PV installation along transport infrastructure

The **technical potential** assessment is based on a detailed spatial analysis to identify the available space to install wind and PV technology. The potential placement of a certain technology depends on relevant spatial criteria where positive boundary conditions indicate high potential or desirable locations for the development of decentralized energy production (e.g. for wind near existing infrastructure, for PV on west, south and east facing roofs) and negative boundary conditions indicate low potential or no-go zones (e.g. for wind due to safety reasons at a minimum distance from residential housing, for residential PV limited to roofs). The (spatial) boundary conditions for each technology are determined by policy frameworks and regulations at the level of the regions in Belgium. Regional differences in legislation and ambitions are, where relevant and feasible, considered. To avoid the overestimation of the potential, a feasibility parameter (F_t) based on technological and performance constraints for a certain technology is used. Importantly, the optimization of the potential energy production is done from a spatial perspective and not an energetic or economic perspective. Specifically, for BREGILAB, this economic factor will be considered in the next step where the results are incorporated in an energy system model (e.g. TIMES).



Source: Brown et al. (2016) Models for quantifying and mapping energy potential from renewable energy sources

It is important in this context to differentiate between resource, technical, economic and market potential. **In this report the technical potential is calculated based on spatial and regulatory criteria.** All land-use, topographic and system performance constraints are detailed in CHAPTER 5. This does not automatically imply that a full exploitation of the potential for onshore wind or PV systems is from an economic point of view feasible or from a societal point of view desireable.

The report shows that:

- Belgium has a technical potential for renewable energy generation of 118 GW from PV on roofs and onshore wind installations, corresponding to a maximum *theoretical* electricity generation of approximately 134 TWh per year, exceeding the current demand of approximately 80 TWh per year of Belgium today.

- The national and regional renewable energy ambitions for 2030 as spelled out in the National Energy and Climate Plan (NECP) for PV and onshore wind can be covered by utilizing approximately 6% of the technical potential calculated for PV on roofs, and 17% of the technical potential for onshore wind turbines.

- The Dynamic Energy Atlas is a flexible software tool that combines high resolution spatial, technological and meteorological data with spatial modelling to assess potential renewable energy generation.

- A spatially explicit approach gives an objective picture of the potential role of renewable energy on the future electricity system in Belgium and is a stepping stone to investigate how to achieve a balanced system considered spatial limitations and opportunities.

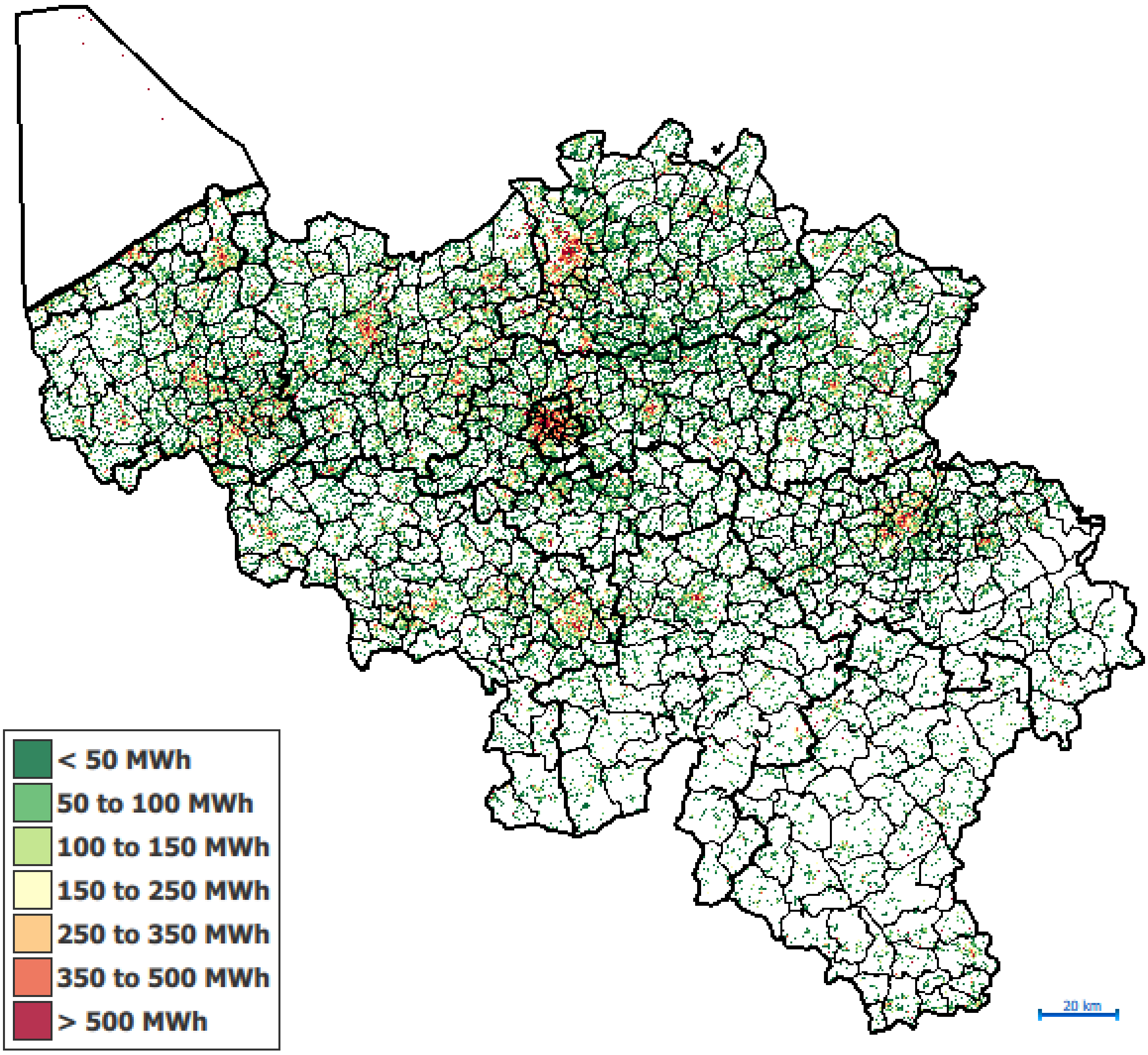


Figure 1 Additional potential energy production (MWh) for PV and wind per 100 by 100m pixel

Disclaimer

Information contained within this report, including tables and maps produced, is based on and subject to the assumptions specific to the BREGILAB project mentioned in this report (Clymans et al., 2022; VITO) and information provided by third parties at the time. The use of the results for other purposes then BREGILAB research should always be done with the necessary diligence with respect to its original purpose and by informing the authors of this report and official funding agency (FPS Economy) of the BREGILAB project.

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LIST OF ACRONYMS

BREGILAB	Balancing the Belgian electricity system for maximal use of Renewable Energy generation by a Grid Injection Limit Algorithm and optimal Battery deployment
DHI	Diffuse horizontal irradiance
DNI	Direct normal irradiance
DSO	Distribution System Operator
GHI	Global horizontal irradiance
PV	Photovoltaic
RCM	Regional Climate Model
RE	Renewable energy
RMI	Royal Meteorological Institute
WT	Wind turbine

CHAPTER 1 OBJECTIVE

The BREGILAB (Balancing the Belgian electricity system for maximal use of Renewable Energy generation by a Grid Injection Limit Algorithm and optimal Battery deployment) project investigates how a balanced electricity system can be established in Belgium at minimal cost (Figure 2). Reaching a balance between electricity generated by intermittent sources (wind and PV) and the variable consumption profiles is complex and needs in-depth analysis of the generation profiles, consumer profiles and especially an optimization of the electricity transmission and distribution system with or without potential for storage. Depending on the choices of electricity generation technologies and the new demand profiles, different optimization calculations result in lower or higher costs. The impact of potential future decisions and evolutions on the cost for the Belgian energy system balancing and security of supply will be tested using different energy-focused models including an hourly energy system model and electricity market model. An evaluation will be made within the 2017-2050 time frame.

A key challenge is to maximize immediate consumption of the generated renewable energy to keep grid investment costs low. Renewable Energy (RE) generation, electrical demand and current grid limitations are inherently spatially explicit factors. BREGILAB aims to improve the spatial representation of these components within the different energy models, and hereby investigating the optimal placement of wind and PV over Belgium. The solution needs to balance the optimal placement for maximum generation, optimal placement for immediate consumption and reduction of the need for non-intermittent generation.

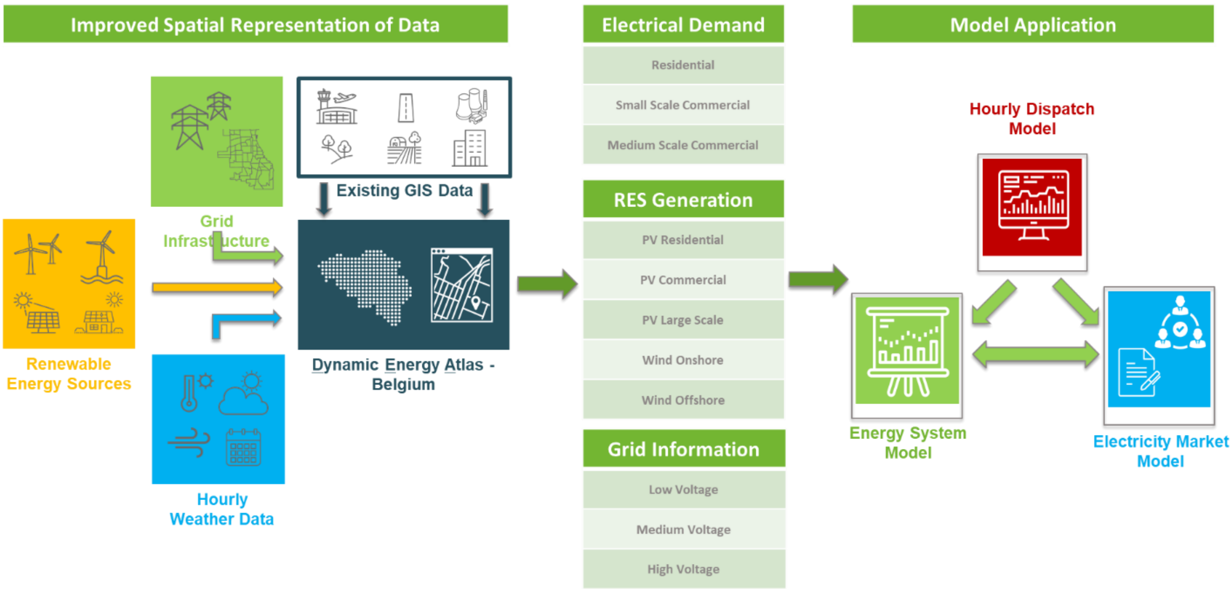


Figure 2 Schematic representation of the workflow within the BREGILAB project

In WP3, the renewable energy production and potential is calculated at high spatial and temporal resolution. The calculations are carried out within the Dynamic Energy Atlas (DEA), a spatial model developed as stand-alone software tool that allows to monitor and model renewable energy production and demand, at present and in the future according to alternative scenarios. To fulfill the needs of this research project, the temporal resolution of the DEA is increased from annual to hourly calculations. Instead of using annual full load hours as energy production factor, (potential) renewable energy production is calculated based on hourly meteorological data.

WP3 deploys the DEA for Belgium based on hourly meteorological data and spatially explicit data on the availability of space to install RE-installations at 1ha resolution. Results of WP3 are used in the energy system modelling work package (WP1) to (1) investigate the capacity of the Belgian grid to cope with the temporal and spatial variability of the RE present and potential production and to (2) confront the RE-potential with future and present energy demand of different sectors.

CHAPTER 2 DYNAMIC ENERGY ATLAS

The DEA uses a bottom-up approach to delineate for RE sources (including wind, PV, *biomass, geothermal and water*) the potential for (additional) energy production and combined with meteorological data to predict hourly production for representative years. Relevant spatial criteria (existing GIS data) are combined in scenarios (technical or policy), where the 'positive spatial criteria' indicate high potential or desirable locations for the development of decentralized energy production (like near existing energy infrastructure, along linear landscape elements like canals, railways) and the 'negative spatial criteria' indicate low potential or no-go zones (military zones, nature reserves, etc.). The output of these scenarios is aggregated within relevant energy and distribution zones (13 in total) and are used as input for energy models such as Times, models that deal with information on demand and grid. Flexibility in investments are ran as scenarios. Scenarios consider policy constraints on available space, and optimize the generation potential with the demand, and grid capacity and flexibility. A unique feature of our approach is that through spatial modelling expected shifts in the spatial criteria (further loss of open space, increased urbanization in specific locations) can be considered during long-term planning.

All calculations for the BREGILAB project are performed using the Dynamic Energy Atlas v2.2.8 (Figure 3) which includes the Wind Energy Module to simulate wind generation profiles using wind speed data. The system is programmed in C++ and uses OS libraries listed below for database management and geographical operations. The computational extent for BREGILAB is (Xll,Yll; 22000,21100) with (Rows, Columns; 2509, 2735) in Belgian Lambert 1972 (EPSG: 31370) with a cell size of 100m.

Open Source Libraries:

- Qt (GPL-3.0 License)
- fmt (BSD-2-Clause)
- date (MIT License)
- spdlog (MIT License)
- sqlite (Public domain)
- sqlpp11 (BSD-2-Clause)
- sqlpp11-connector-sqlite3 (BSD-2-Clause)
- eigen (MPL-2.0)
- GSL (MIT License)
- zlib (Zlib License)
- libpng (Zlib License)
- libjpeg-turbo (libjpeg-turbo License)
- expat (Expat License)
- xz (Public domain)
- GDAL (GDAL License)
- proj.4 (MIT License)

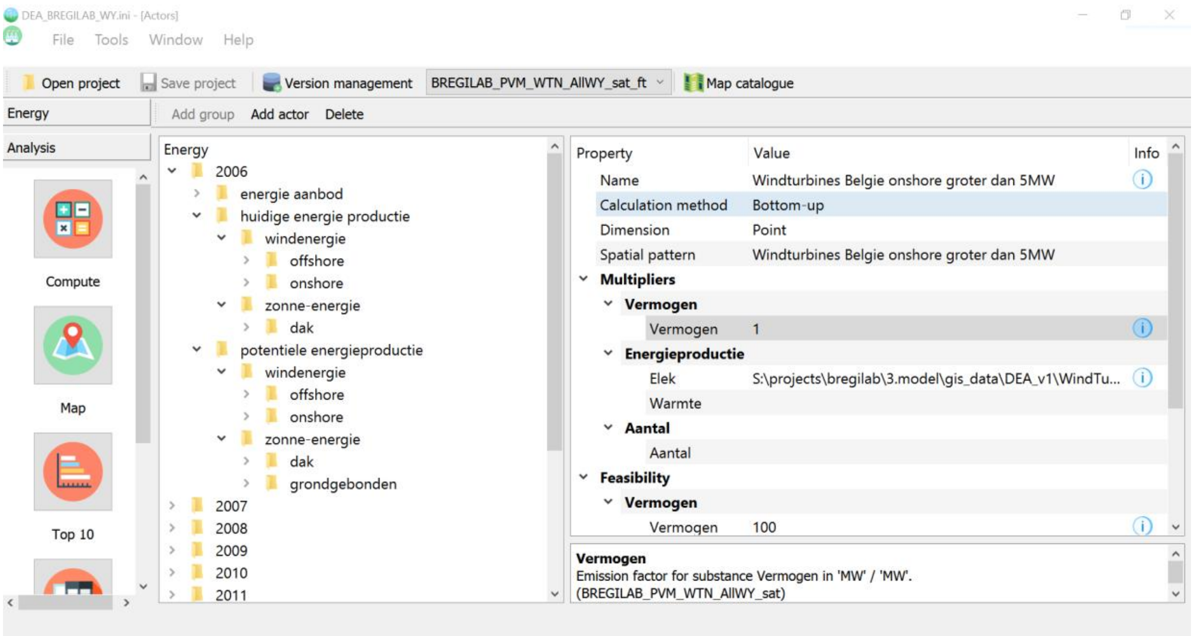


Figure 3 The Dynamic Energy Atlas user-interface providing an overview of all the energy sources included in the BREGILAB project. The analysis panel indicates the options to report the results as maps, tables etc.

CHAPTER 3 WIND ENERGY PRODUCTION

This chapter elaborates on the modelling of wind energy production. First, the data sources used are described, next the methodology to model wind energy with the Dynamic Energy Atlas is explained and finally a validation of the results is given.

3.1. Data Sources

To model wind energy production in a spatially explicit manner, we need to know where wind turbines are located, and what their generation potential is. The generation potential depends on the characteristics of the installed wind turbine (e.g. rated power and rotor diameter) and the wind speed distribution at this location. So we require both technological data (geolocation combined with technical characteristics) and meteorological data (wind speed at hub height) to model wind production using a bottom-up approach. The data sources used within the BREGILAB study are presented here.

3.1.1. Wind turbines

Both present and technical potential energy production depend on the technical characteristics of existing and presently developed wind turbines. Higher wind turbines with a larger rotor diameter (≥ 2MW) generate electricity more efficiently than small to mid-sized wind turbines (< 2MW). Planning the construction of wind turbines in the landscape is limited by a series of restrictions implemented to safeguard safety, to protect nature, landscapes and heritage sites etc. Therefore, an inventory of the existing and planned wind turbines, including on-and offshore sites, and their technical characteristics is made.

Following characteristics, if available, were included in the inventorisation of the existing wind turbines in Belgium:

- Geolocation (x, y; Lambert 72)
- Model producer and type (e.g. Enercon E82 2.3MW)
- Rated Power (MW)*
- Cut-in (V_{in}) & cut-out (V_{out}) wind speeds (in m s^{-1})*
- Rotor diameter (in m, D)
- Hub height (in m, H)*
- Power density (in kW m^{-2}, P_d)
- Max. rotor speed (in U min^{-1}, $V_{r,max}$)
- Max. blade tip speed (in m s^{-1}, $V_{b,max}$)
- Constructed: Yes or No
- Construction date (if available)
- Status building permit application: Granted, In review, Declined

*Characteristics that influence climatological input data or specific criteria.

The list is in function of the next phase in which current and potential wind production is simulated and evaluated. Good knowledge of technical parameters of the wind farm fleet (such as the hub height, power curve, rotor diameter, etc.) is key to reduce uncertainty in wind production estimates.

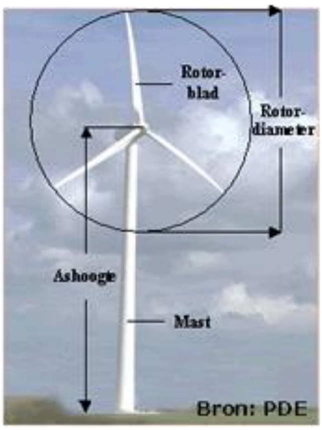


Figure 4 Representation of technical parameters that support wind production modelling. Source: Omzendbrief EME/2006/01 – RO/2006/02.

Table 1 Overview data sources of technical specifications for existing on- and offshore wind turbines in Flanders, Wallonia and Brussels*.

Data source	Characteristics extracted	Date
Geopunt Vlaanderen – Stedenbouwkundig aangevraagde windturbines (eng. Building permits).	Geolocation, Rated Power, Rotor diameter[1], Hub height, Constructed, Status application for Flanders	9/10/2018
APERe – Liste Éolienne www.apere.org/fr/observatoire-eolien	Geolocation, Rated Power, Brand and model wind turbine, Constructed, Status application for the Walloon region	16/07/2018
Wind-turbines-models.com - https://en.wind-turbine-models.com/turbines combined with model descriptions constructors	Per wind turbine model: Rated Power, Cut-in and out wind speeds, Rotor diameter, Hub Height, Power density, Max. rotor and blade tip speed for Walloon region and offshore models.	Extracted 31/01/2019
Belgian Offshore Platform - https://www.belgianoffshoreplatform.be/en/projects/	Per offshore wind park: Rated Power, Brand and model wind turbine, Constructed, Construction date	Extracted 31/01/2019
Vliz waterportaal	Geolocation (not complete) for offshore platforms (C-power, Northwind, Belwind, Nobelwind)	
CREG publicaties – result permit application.	Geolocation completion for offshore platforms (C-power, Northwind, Nobelwind and Rentel), **incomplete** update Belwind (25 out of 56)	Extracted 31/01/2019

[1] Rotor diameter (in m) is calculated: (max. height – hub height) *2.

Table 2 reports the technical characteristics of the installed and manufactured (licensed and in review) wind farm fleet in Belgium on 1/1/2018. A total of 1138 wind turbines are spread over

Belgium with 467 in Flanders, 426 in the Walloon region and 245 installed offshore. Averages for rated power, rotor diameter, hub height and wind range are reported per region. Both installed as manufactured offshore wind turbines outsizes those installed and planned on land. The average hub height varies between 86 (Walloon region) and 127m (offshore).

Table 2 Overview technical characteristics of current (1/1/2018) and manufactured wind farm fleet for the different regions*.

	Onshore Flanders		Onshore Walloon		Offshore	
	Installed 2018	Manufactured	Installed 2018	Manufactured	Installed 2018	Manufactured
Number	467		426		245	
Rated Power (MW)	2.7	3.5	2.4	3.5	4.1	8.8
Rotor diameter (m)	88	130	91	130	116	167
Hub height (m)	106	120	86	120	127	109
Wind range (m)	62-150	30-185	41 -131	30-185	69-185	30-190

*Brussels HG does not report on large-scale wind production (> 300kW)

3.1.2. WIND SPEED DATA

The Royal Meteorological Institute (RMI) provided wind speed data for the period 1980-2019 (Figure 5; Figure 6). A climate simulation is performed by the ALARO-0 regional climate model (RCM) on the European domain at 12.5 km, nested inside ECMWF's ERA-Interim global reanalysis. A second nesting procedure provides high resolution climate data at 4km for the Belgian domain. OUTPUT: Hourly wind speed data (m s^{-1}) at a height of 100m and at 4 by 4km scale for the period 1980-2019.

The meteorological data is used for validation by comparing model output with Elia production data for 2017/2018. The output forms an additional base for a sensitivity analysis to inter-annual meteorological variability.

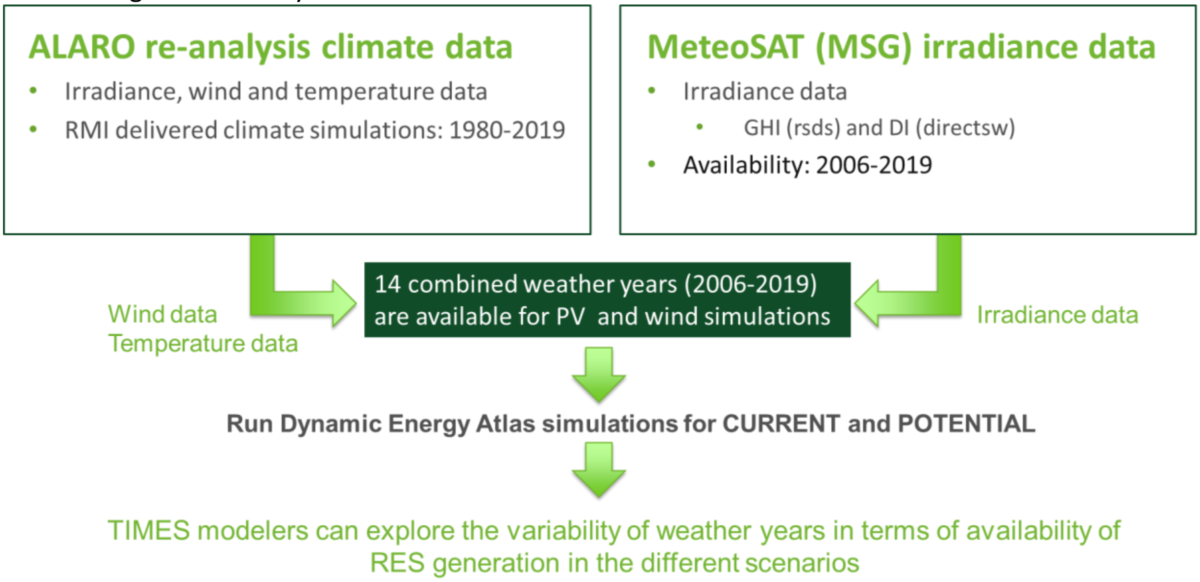
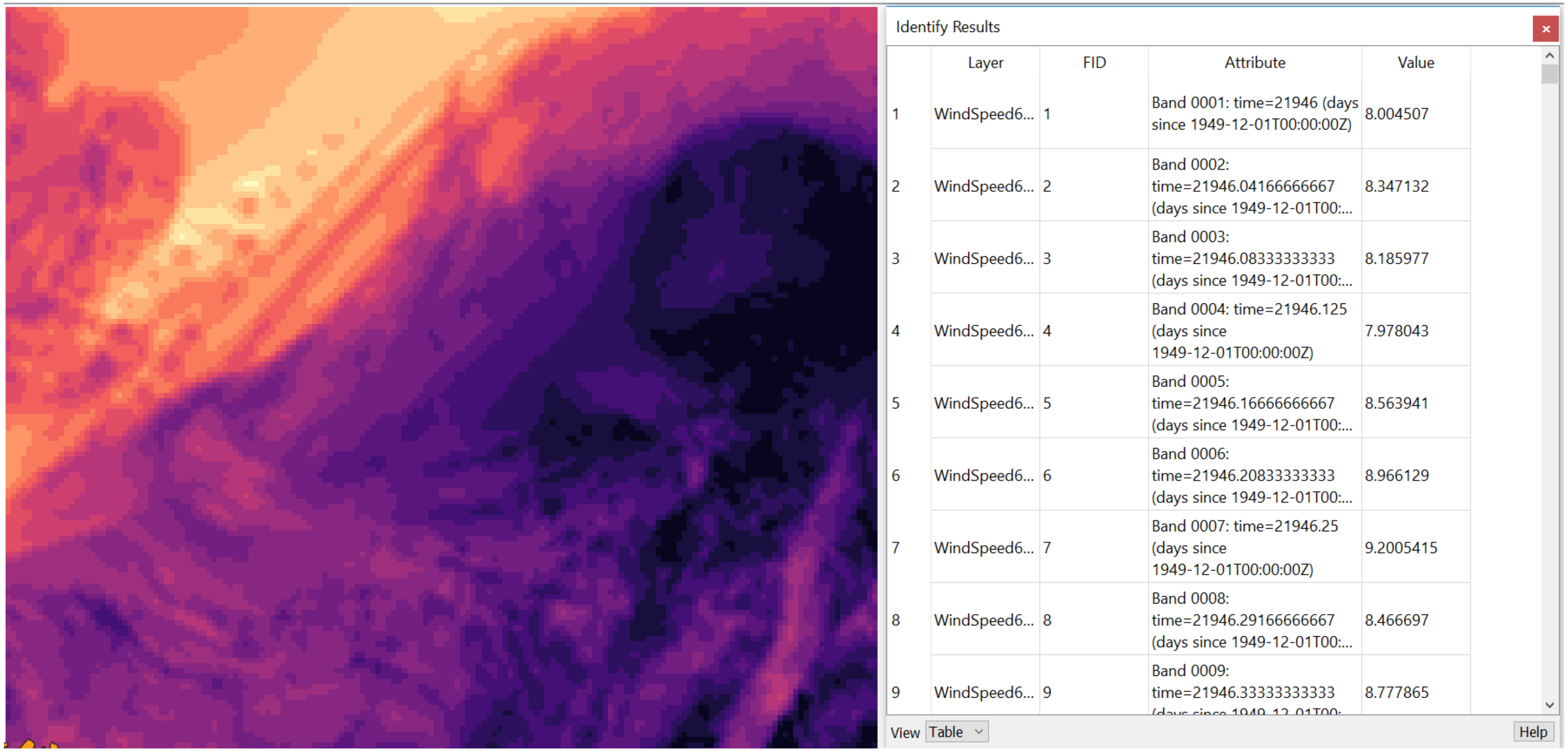


Figure 5 Schematic representation of the use of meteorological data (provided by the RMI) to simulate current and potential energy production for 2017 and the period 2006-2019.



	Layer	FID	Attribute	Value
1	WindSpeed6...	1	Band 0001: time=21946 (days since 1949-12-01T00:00:00Z)	8.004507
2	WindSpeed6...	2	Band 0002: time=21946.04166666667 (days since 1949-12-01T00:...	8.347132
3	WindSpeed6...	3	Band 0003: time=21946.08333333333 (days since 1949-12-01T00:...	8.185977
4	WindSpeed6...	4	Band 0004: time=21946.125 (days since 1949-12-01T00:00:00Z)	7.978043
5	WindSpeed6...	5	Band 0005: time=21946.16666666667 (days since 1949-12-01T00:...	8.563941
6	WindSpeed6...	6	Band 0006: time=21946.20833333333 (days since 1949-12-01T00:...	8.966129
7	WindSpeed6...	7	Band 0007: time=21946.25 (days since 1949-12-01T00:00:00Z)	9.2005415
8	WindSpeed6...	8	Band 0008: time=21946.29166666667 (days since 1949-12-01T00:...	8.466697
9	WindSpeed6...	9	Band 0009: time=21946.33333333333	8.777865

Figure 6 Overview wind speed data (m s^{-1}) at 100m altitude for Western-Europe with table representing the hourly results for 1 pixel of 4 by 4km (8760 layers)

3.2. Model wind power generation

3.2.1. Dynamic Energy Atlas: General Approach

The Dynamic Energy Atlas (DEA) uses a bottom-up approach to model wind power generation at a spatial resolution of 100 by 100m. A simple multiplication is used to estimate energy production per technology. The general formula is independent of the technology studied, and expressed as

Production (per pixel) =
energy production factor (technology and/or space specific) X
spatial pattern (where technology is/can be located) X
feasibility (technic, economic, public support/resistance, performance ratio…)

Formula: **$(P)Ep_{i,t}$ = $EpF_{j,t}$ * $EpEV_{i,t}$ * F_t**

$(P)Ep_{i,t}$= (Potential) Energy production by technology t at location i (in kWh)
$EpF_{j,t}$ = Energy production Factor for the existing technology t and expresses the energy production per unit of $EpEV_{i,t}$. EpF can vary between a single multiplicator for the study-area or be location dependent. The use of spatially explicit information (j), if available, is the preferred methodology when geographical differentiation is relevant.
$EpEV_{i,t}$ = Energy production Explanatory Variable for technology t at location i. EpEV is an as accurate as possible representation of the spatial distribution and size of technology t.
F_t= x% (technic) * x% (public) * x% (performance ratio)
i = each pixel
j = spatial unit (e.g. municipality), can be equal to i
t= technology

Previously, wind power generation was estimated at the annual level using average full load hours per year (ranged between 1400 – 3500 hours for Flanders) as energy production factor (Van Esch et al., 2016). Within BREGILAB, we improve our approach by using hourly meteorological data to obtain time-series. A wind transfer function that accounts for the non-linear behaviour of wind production was included as a module in the DEA.

3.2.2. Dynamic Energy Atlas: Implementation wind transfer function

→ Wind transfer function (i.e. Wind Energy Module)

The exact location of wind turbines is known. The actual energy production depends on the local wind speed and technical specifications of the wind turbine. The theoretical relationship for a specific wind turbine type in pixel i is expressed as:

$$Ep_{wind} = 0.5 \cdot \rho \cdot U^3 \cdot \frac{\pi \cdot D^2}{4} \cdot C_p(U). \boldsymbol{F_t}$$

Ep_{wind} =Estimated Energy Production by wind for wind turbine in pixel i (in W)
ρ = air density (kg m^{-3}) at 20°C and 101.325kPa it equals 1.2041
U = wind speed (m s^{-1}) at height (H, m) in pixel i
D = rotor diameter (m) of wind turbine in pixel i.

Cp = power coefficient that is based on the Betz limit. It expresses the efficiency of a wind turbine at varying wind speeds. The power coefficient is not a static value as it varies with the tip speed ratio (i.e. blade tip speed/wind speed) (λ) of the turbine).
F_t= x% (technic) * x% (public) * x% (performance ratio)

The theoretical cubic relationship is reflected by a quick increase with wind speed, which is tempered by taking into account the power coefficient (Figure 7; efficiency curve).

In reality, energy production by wind turbines is further constrained by technical, economic and safety issues. The maximum capacity of wind turbines expressed as the rated power (MW) provides an upper boundary for energy production. There are two wind speed boundaries called the cut in and cut out wind speeds. The lower boundary or cut in wind speed varies between 2 and 5 m s^{-1}, production below this wind speed energy is not deemed economic. For safety reasons, wind turbines are shut down gradually or abruptly once a certain wind speed is exceeded. At present, the upper boundary decreases gradually between 25 to 35 m s^{-1} depending on the type of wind turbine. We only consider cut out speed as fixed wind speed and do not take into gradually decreases between two wind speeds. These considerations are wind turbine dependent and considered when establishing wind power curves (Figure 7; practical curve).

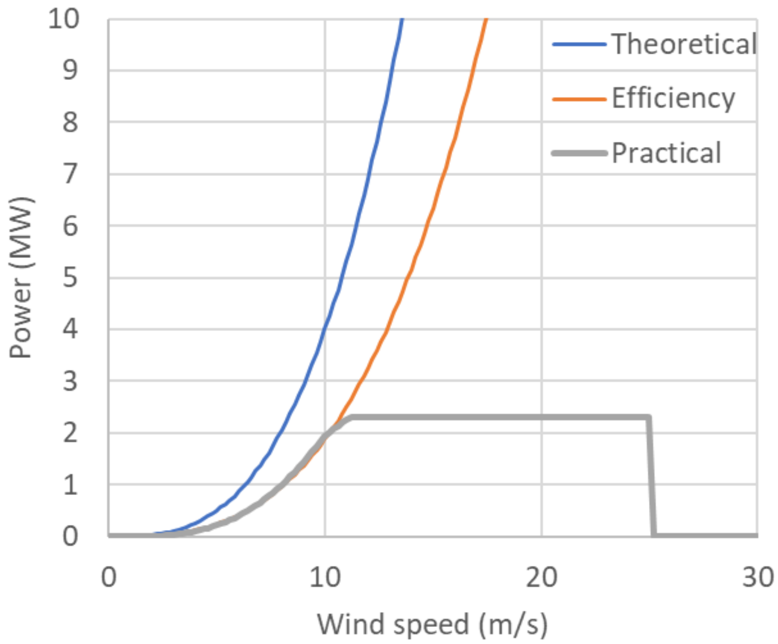


Figure 7 Typical power curve for a wind turbine with a rated power of 2.3MW, cut in 2 m s^{-1} and cut out 25 m s^{-1}. Theoretical curve does not consider a power coefficient (C_p), Efficiency curve takes into account power coefficient (C_p), Practical curve takes into account rated power and cut in / out wind speeds.

→ Stepwise calculation of wind energy production in the DEA

The information required to calculate energy production for a wind turbine (n) besides wind speed:

- ρ = air density (kg m^{-3}) at 20°C and 101.325kPa it equals 1.2041 kept CONSTANT
- D_n = rotor diameter (m) for wind turbine n
- $U_{in,n}$ = Cut in wind speed (m s^{-1}) as lower boundary for wind turbine n

- $U_{out,n}$ = Cut out wind speed (m s^{-1}) as upper boundary for wind turbine n
- $P_{r,n}$ = rated power (MW) for wind turbine n
- Cp = power coefficient in function of instantaneous U and categorized by rated power (MW).
- Type of wind turbine determines the Cp-U relationship (e.g. Enercon E82 2.3MW)
- F_t = Performance ratio (%)

Following steps need to be run through to calculate energy production for a time bin (b) of 1 hour:

$$Ep_{wind,n,b} = 0.5 \cdot \rho \cdot U_b^3 \cdot \frac{\pi \cdot {D_n}^2}{4} \cdot C_p(U_b).F_t$$

→ **STEP 1: Derive integrated wind speed at hub height**

In order to connect the wind speed data per pixel (NetCDF format) to specific wind turbines (point location; xy-coordinates), we identify per wind turbine the closest centroid of the 4 by 4km wind speed data. The corresponding times series of hourly wind data at 100m height will be used to calculate wind production at the 1ha scale.

However, the wind turbines have varying heights and rotor diameters. Hence, the observed wind speed for each wind turbine (e.g. hub height 80m) will differ from the wind speed modelled at 100m. Therefore we calculate corrected wind speeds ($U_{b,cor}$) integrated over the rotor diameter taken the hub height in account (in m). We assume neutral atmospheric stability and use a simplified formula to estimate the wind speed at hub height deriving it from the input dataset (e.g. wind speed at z_{ref} = 100m).

$$U_{b,cor} = U_b \cdot \left(\frac{H}{z_{ref}}\right)^{\frac{1}{7}}$$

Integrate over the rotor diameter (D, H ± D/2), it gives:

$$U_{b,cor} = 0.875 \cdot \frac{U_b}{D} \cdot \frac{1}{(z_{ref})^{\frac{1}{7}}} \left[\left(H + \frac{D}{2}\right)^{\frac{8}{7}} - \left(H - \frac{D}{2}\right)^{\frac{8}{7}}\right]$$

U_b: wind speed (m/s) at time bin b
D: rotor diameter wind turbine (in m)
Z_{ref}: reference height of the wind input dataset (e.g. 100m)
H: Hub height wind turbine (in m)

→ **STEP 2: Select Cp value**

The power coefficient depends on the instantaneous U. From literature, we obtained typical Cp vs. wind speed profiles for the existing generation of wind turbines.

For offshore, we obtained wind speed profiles for all offshore parks (i.e. Vestas, Senvion and Siemens) apart from Rentel. For onshore, we obtained wind speed profiles for eight common types of installed wind turbines. Onshore, we differentiate for wind turbines with $P_{r,n}$ above and below 5 MW.

So if $P_{r,n} \geq$ 5MW, we use value Cp_{high} and if $P_{r,n} <$ 5MW, we use value Cp_{low}.
The Cp-U profiles are given in Table 3.

The corrected wind speed ($U_{b,cor}$ Step 1) is used to match the correct power coefficient.

Table 3 Cp-U profiles for wind turbines types (offshore) and average (onshore).

$U_{b,cor}$	Cp_High	Cp_Low	Vestas MVOW V112 3.0	Vestas MVOW V112 3.3	Senvion 6.2M	Senvion 5M	Vestas V90 3M	Siemens D7
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.000	0.108	0.000	0.000	0.000	0.000	0.000	0.000
3	0.263	0.282	0.140	0.140	0.000	0.000	0.000	0.340
4	0.352	0.394	0.340	0.350	0.175	0.293	0.314	0.380
5	0.423	0.432	0.400	0.400	0.360	0.366	0.397	0.410
6	0.453	0.462	0.430	0.420	0.415	0.392	0.427	0.430
7	0.470	0.479	0.440	0.440	0.438	0.414	0.442	0.430
8	0.478	0.487	0.450	0.440	0.433	0.420	0.452	0.430
9	0.478	0.493	0.440	0.440	0.429	0.418	0.456	0.430
10	0.484	0.483	0.430	0.430	0.423	0.422	0.443	0.420
11	0.471	0.425	0.370	0.380	0.426	0.399	0.413	0.410
12	0.430	0.357	0.290	0.310	0.391	0.366	0.376	0.350
13	0.382	0.293	0.230	0.250	0.349	0.302	0.332	0.290
14	0.330	0.239	0.190	0.200	0.299	0.243	0.281	0.250
15	0.282	0.197	0.150	0.160	0.243	0.197	0.232	0.210
16	0.237	0.161	0.120	0.130	0.200	0.163	0.191	0.175
17	0.200	0.135	0.100	0.110	0.167	0.136	0.159	0.150
18	0.169	0.113	0.090	0.090	0.140	0.114	0.134	0.120
19	0.143	0.097	0.070	0.080	0.119	0.097	0.114	0.110
20	0.123	0.083	0.060	0.070	0.102	0.083	0.098	0.100
21	0.106	0.071	0.060	0.060	0.088	0.072	0.085	0.090
22	0.093	0.063	0.050	0.050	0.077	0.063	0.074	0.080
23	0.081	0.055	0.040	0.050	0.067	0.055	0.064	0.070
24	0.072	0.047	0.040	0.040	0.059	0.048	0.057	0.060
25	0.064	0.045	0.030	0.040	0.052	0.043	0.050	0.050
26	0.062	0.045			0.047	0.038		
27	0.060	0.044			0.042	0.034		
28	0.059	0.044			0.037	0.030		
29	0.057	0.043			0.034	0.027		
30	0.056	0.043			0.030	0.025		
31	0.054	0.041						
32	0.052	0.040						

$U_{b,cor}$	Cp_High	Cp_Low	Vestas MVOW V112 3.0	Vestas MVOW V112 3.3	Senvion 6.2M	Senvion 5M	Vestas V90 3M	Siemens D7
33	0.051	0.038						
34	0.049	0.037						
35	0.048	0.035						
36	0.046	0.033						
37	0.044	0.032						
38	0.043	0.030						
39	0.041	0.029						
40	0.040	0.027						

*Cp_High and Cp_Low are also applied for offshore wind parks for which no wind turbine specific profile was available

→ **STEP 3: Wind speed within production range**

Energy is only produced between the cut in and cut out wind speed defined for wind turbine n.
If $U_{b,cor} < U_{in,n}$ *OR* $U_{b,cor} > U_{out,n}$ then $Ep_{wind,n} = 0$
If $U_{in,n} \leq U_{b,cor} \leq U_{out,n}$ then Step 4.

→ **STEP 4: Maximum rated power constraint**

Energy production cannot exceed the maximum capacity of wind turbine n, defined as $P_{r,n}$.
If $P_{r,n} *10^{-6} \leq Ep_{wind,n}$ then $Ep_{wind,n} = P_{r,n}*10^{-6}$
If $P_{r,n} *10^{-6} > Ep_{wind,n}$ then $Ep_{wind,n} = Ep_{wind,n}$

→ **STEP 5: Applying performance ratio**

Theoretical models are known to lead to systematic biases when modeling onshore- and offshore wind production (Hankins et al., 2011; Staffel & Green, 2014; Ofgem, 2012; Schallenberg-Rodriguez, 2013). They do not account for factors like machine availability, operating efficiency, wake effects & turbine aging. Instead the effect of these mechanisms on wind power generation are typically captured by a performance ratio and is part of the feasibility factor in the Dynamic Energy Atlas. A detailed quantification of the effect of the different influencing factors is not within the scope of the BREGILAB study, we deduced the performance ratio directly from comparing the 2017 modelled and measured loads (see details in section 3.3.2; Table 6). An average PR was included as feasibility factor (F_t) to correct hourly wind production:

- Offshore: 0.78
- Onshore: 0.70

$$Ep_{wind,n,b} = 0.5 \cdot \rho \cdot U_{b,cor}^{3} \cdot \frac{\pi \cdot {D_n}^2}{4} \cdot C_p(U_{b,cor}). F_t$$

As we are working with 1hour bins (b) the result is expressed as Wh.

The procedure needs to be repeated for 8760 time bins (for b:1->8760). For each time bin a map (Geotiff) is created with wind production at time step t. The result is therefore 8760 snapshots

(Geotiff) of wind energy production in Belgium. The information can be aggregated spatially at the 100*100m pixel level, statistical sectors, communes, pre-defined zones, regions etc., and temporally for days, months, seasons, year etc.

Within the Bregilab project it was decided to aggregate the information at the level of 13 representative energy zones that largely overlap with the 10 provinces, Brussels and offshore area (Figure 8). West-Flanders is split in a coastal zone (i.e. communities with a coastline) and a continental zone.

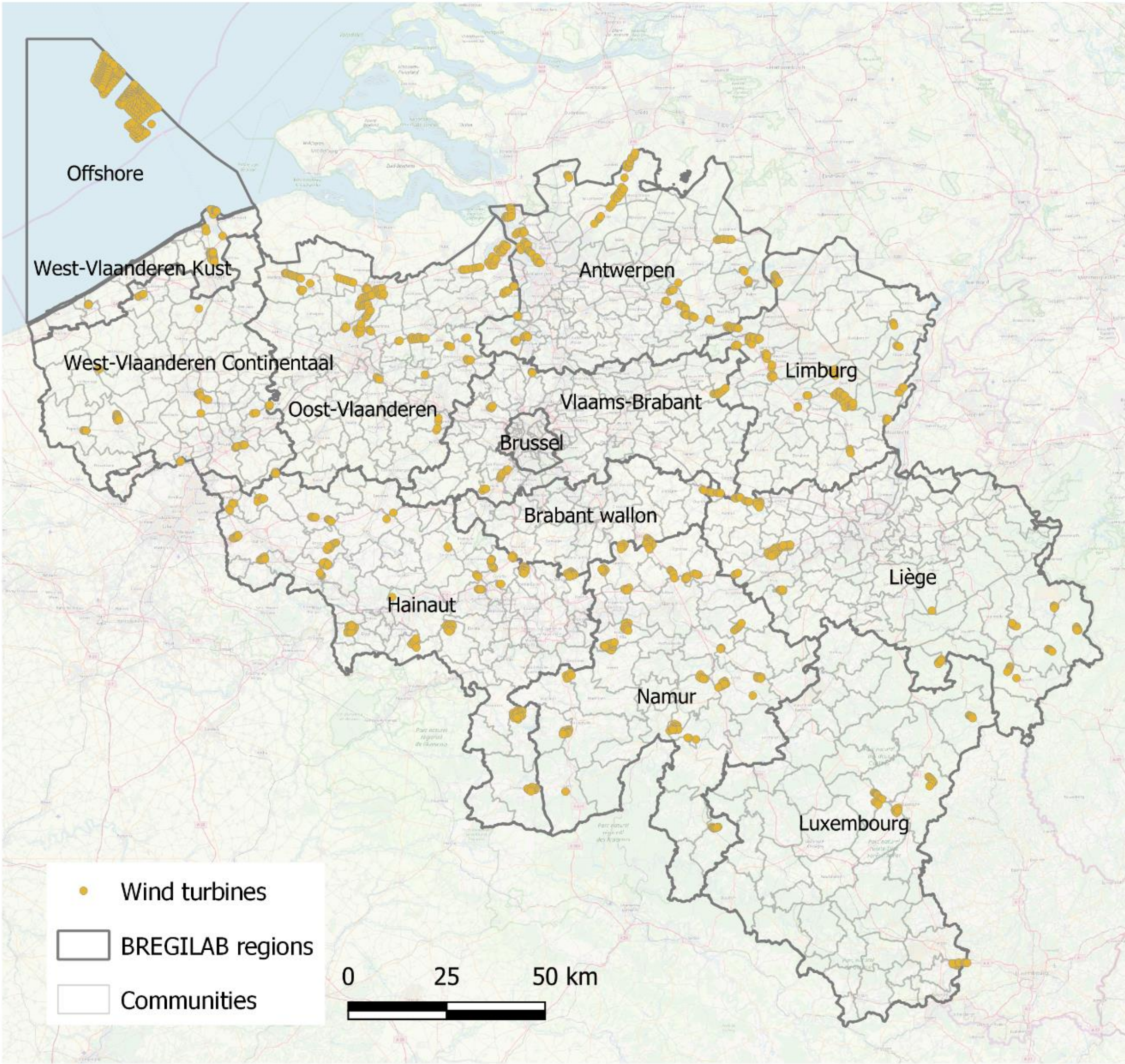


Figure 8 Distribution of installed wind turbines across the 13 BREGILAB zones

3.3. VALIDATION WITH STATISTICAL DATA

We applied the described methodology (section 3.2) for the years 2017 and 2018 using the wind turbine database (anno 1/1/2018) and re-analysis data for 2017 and 2018. The hourly wind production data (MWh) are aggregated at the level of 13 Bregilab zones (Figure 8) and regions. The results are compared at the level of regions (Flanders, Brussels, Walloon and Offshore) with hourly wind production data reported by the Belgian DSO (Elia). Elia provided us with wind production data

(MWh; every 15 minutes since 2003; *Measured & upscaled)*) and installed capacity (MW; every 15 minutes since 2003; *Monitored Wind capacity*). Elia aims to regularly update installed capacity based on available data however it is not an automated process, and therefore the reported capacity might not be entirely complete. The reported data exclude self-consumption.

3.3.1. MATCHING INSTALLED CAPACITY

The bottom-up approach uses information on installed wind turbines as described in section 3.1.1. Unfortunately, there is no information on the exact date at which wind turbines were taken in operation after installation. The installed capacity (MW) used to estimate wind generation therefore is a snapshot of the situation in 2018. Combining this information with hourly meteorological data of 2017 and 2018 will inevitably lead to overestimations as the actual operation capacity at the start of 2017 and 2018 was much lower. For example, the installed capacity at the start of 2017 (i.e. 712 MW) and start of 2018 (877MW) is 40% and 26% lower than the installed capacity at the end of 2018 as reported by Elia and used as input for the BREGILAB model. Furthermore there are some regional differences with those reported by the official authorities (Apère) and DSO (Elia) and used as input to BREGILAB (Table 4 and Table 5).

Table 4 Installed capacity of wind turbines per region according to different data sources (situation 31/12/2017)

Capacity	Totaal	Walloon Region	Flanders	Offshore	Data source
Apère	2827	835	1115	877	https://apere.org/fr/observatoire-eolien
Elia	2622	700	1045	877	https://www.elia.be/nl/grid-data/productie/windenergieproductie
Bregilab	3281	1008	1244	1029	see sectie 3.1.1

Table 5 Installed capacity of wind turbines per region according to different data sources (situation 31/12/2018)

Capacity	Totaal	Walloon Region	Flanders	Offshore	Data source
Apère	3190	872	1141	1178	https://apere.org/fr/observatoire-eolien
Elia	3157	806	1172	1178	https://www.elia.be/nl/grid-data/productie/windenergieproductie
Bregilab	3281	1008	1244	1029	see sectie 3.1.1

The hourly wind production (MWh) at time t has been corrected for the actual installed capacity at that moment in time. Elia provides at the level of regions the hourly installed capacity (CAP; MW).

We apply an hourly correction factor to the BREGILAB energy production (E_p) estimates:

$$E_{P,Wind,cor} = E_{P,Wind} \cdot \frac{CAP_{Wind,Elia}}{CAP_{Wind,BREGILAB}}$$

Figure 4 shows an example of the data output at the level of BREGILAB zones for the period 24/11/2018-7/12/2018. Offshore is responsible for the largest contribution to wind power production. There are clear temporal and spatial variations between the different regions.

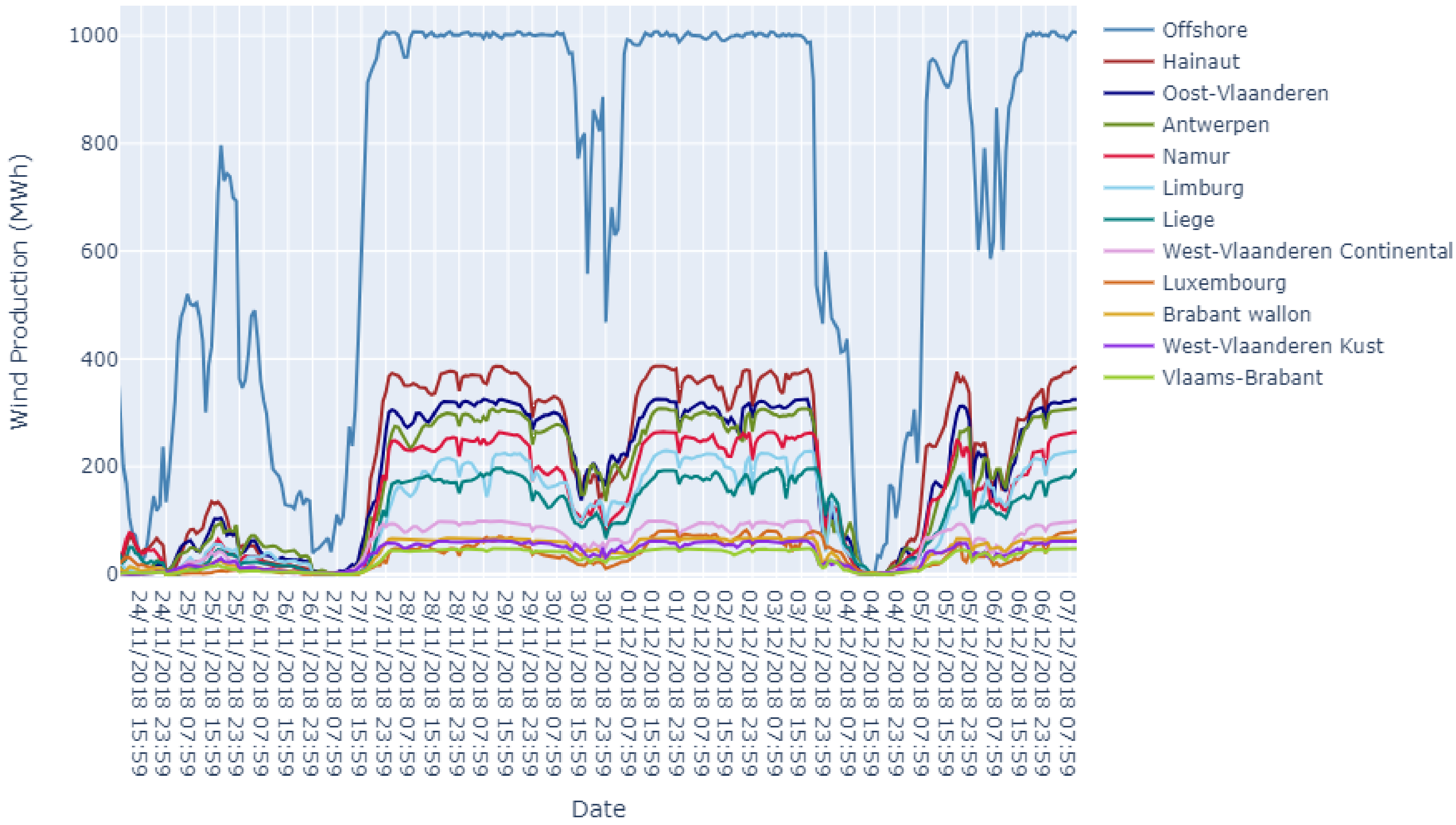


Figure 9 Modelled wind production (MWh) based on installed capacity in the 13 BREGILAB zones (period 24/11/2018-7/12/2018). The Brussels region has no wind capacity.

3.3.2. PERFORMANCE WIND TRANSFER FUNCTION

A theoretical function is used to translate hourly wind speed data into wind power production. The validation aims to investigate if the BREGILAB model/transfer functions reproduce:

- Total energy production for the different geographical regions
- Patterns in hourly and daily energy production throughout the year that are consistent between both databases

→ **Annual and monthly energy production per region**

The annual overestimation of measured wind production for 2017 is large, and ranges between 20 and 35% (Table 6). Elia reports a total production for Belgium of 5425 GWh, while our theoretical model estimates a total production of about 7222 GWh. The performance ratio for Belgium equals 0.75 meaning that the theoretical model does not capture the complete variability of wind generation in Belgium. There are important regional differences. The model achieves a better performance offshore (0.78) than onshore (0.70), and the lowest model performance is observed for the Walloon region. Besides a spatial difference in performance there is also a temporal variation in how well measured wind power has been approximated (Figure 10). Offshore the performance varies between 0.67 (May) and 0.85 (December). Lowest performance is observed during spring to early summer. In contrast, we observe best performance onshore during this period, while performing at its worst during the onset of winter. Onshore the performance varies between 0.54 (December) and >1.0 (May).

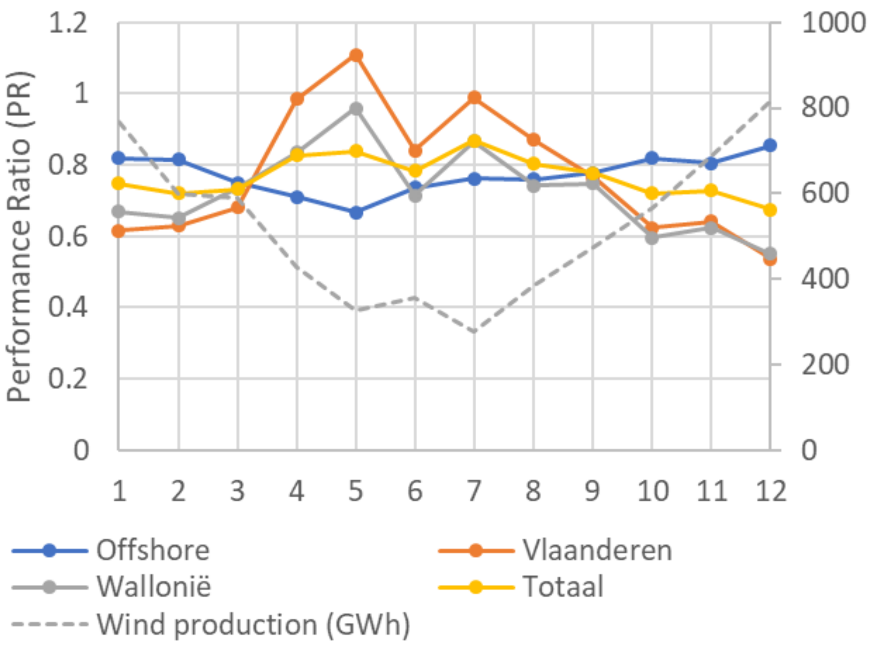


Figure 10 Monthly performance ratio comparing measured and modelled wind production in 2017. The measured wind production (GWh) is reported as comparison.

Table 6 Annual and monthly, modelled (Bregilab) and measured (Elia) wind production (GWh) per region in 2017. The performance ratio indicates a systematic over-or underestimation (Elia versus Bregilab) for the year 2017.

2017	BREGILAB Production				ELIA Production				Performance Ratio (PR)			
	Offshore	Vlaanderen	Wallonië	Totaal	Offshore	Vlaanderen	Wallonië	Totaal	Offshore	Vlaanderen	Wallonië	Totaal
Jan	241	126	142	495	197	78	95	370	0.82	0.62	0.67	0.75
Feb	294	207	185	681	240	131	121	491	0.82	0.63	0.65	0.72
March	356	230	199	779	267	157	146	570	0.75	0.68	0.73	0.73
April	184	91	67	334	131	89	56	276	0.71	0.98	0.83	0.83
May	248	79	60	370	166	88	57	310	0.67	1.11	0.96	0.84
June	285	146	110	523	210	122	79	410	0.74	0.84	0.71	0.78
July	261	120	88	454	199	118	77	394	0.76	0.99	0.87	0.87
Aug	210	111	71	384	159	97	53	309	0.76	0.87	0.74	0.80
Sept	237	152	107	491	185	116	80	381	0.78	0.77	0.75	0.78
Oct	458	304	202	951	375	189	120	685	0.82	0.62	0.60	0.72
Nov	361	222	153	726	291	142	95	529	0.81	0.64	0.62	0.73
Dec	431	353	257	1036	368	190	142	700	0.85	0.54	0.55	0.68
Annual	**3566**	**2141**	**1642**	**7222**	**2788**	**1517**	**1121**	**5425**	**0.78**	**0.71**	**0.68**	**0.75**

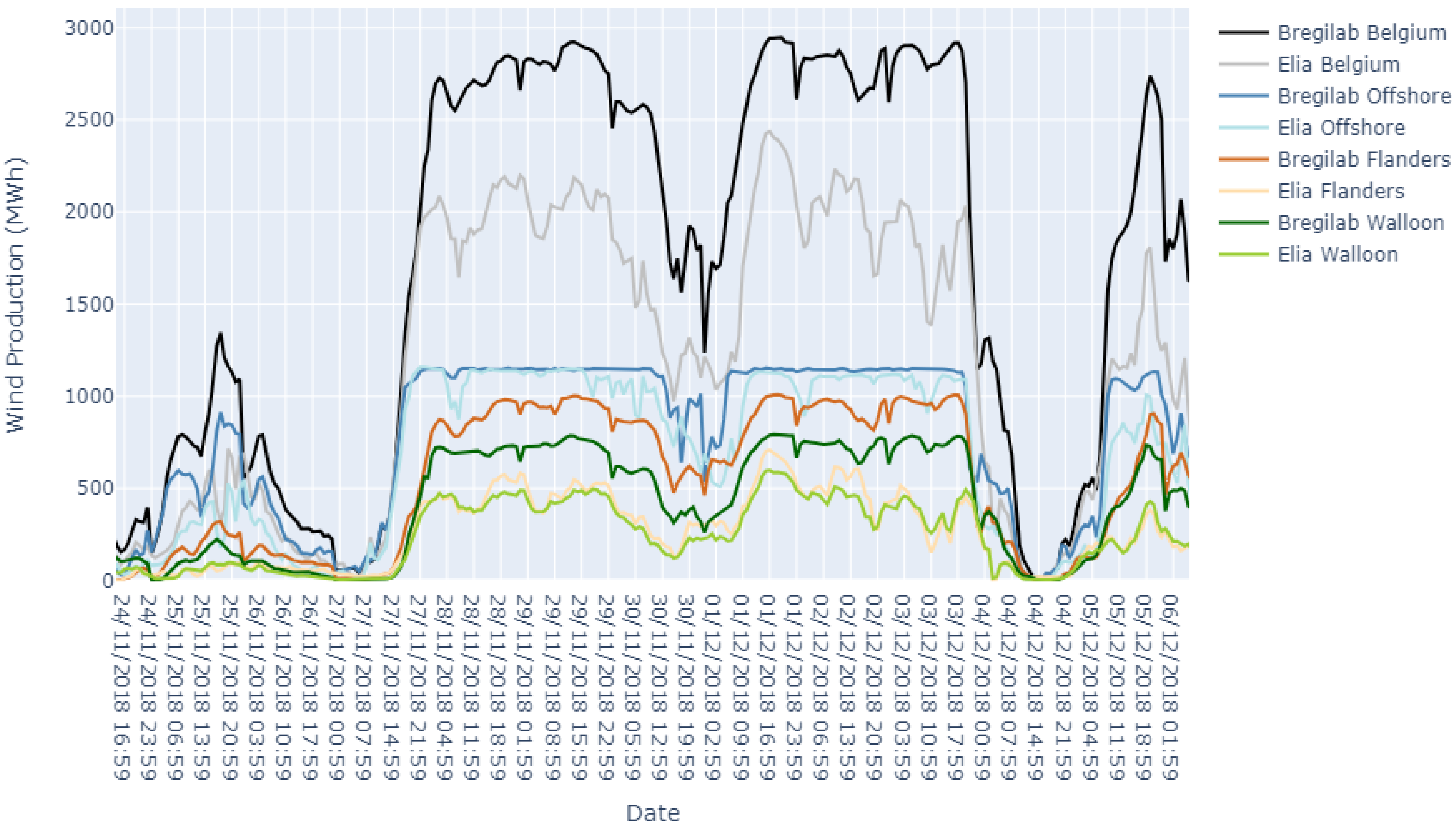


Figure 11 Modelled (BREGILAB, dark) and measured (Elia, light) wind production (MWh) in Belgium and its regions for the period 24/11/2018-7/12/2018.

→ **Daily and hourly energy production patterns per region**

Table 7 summarizes the daily measured and modelled wind production data per region for 2017 and 2018. For both years and each region, there is a consistent overestimation of the measured data by our model.

Table 7 Description of daily measured (Elia) and modelled (BREGILAB) PV production (MWh) for 2017 and 2018

Year	Region	mean	sd	median	min	max	skew	kurtosis	se
2017	Modelled Belgium	19786	15785	15743	66	58160	0.72	-0.59	826
	Measured Belgium	14864	10904	11707	1041	43855	0.83	-0.3	571
	Modelled Offshore	9770	6412	9715	0	20544	0.11	-1.33	336
	Measured Offshore	7637	5778	6507	29	20017	0.5	-0.96	302
	Modelled Flanders	5864	5621	3679	1	21275	1.1	0.11	294
	Measured Flanders	4157	2957	3249	443	14117	1.29	1.13	155
	Modelled Walloon	4497	4538	2774	6	16577	1.08	0.02	238
	Measured Walloon	3070	2673	2181	161	12417	1.27	0.97	140
2018	Modelled Belgium	24701	18239	19364	843	70619	0.66	-0.68	955
	Measured Belgium	17181	13033	13211	809	59675	0.87	-0.11	682
	Modelled Offshore	11848	7856	10994	59	27573	0.3	-1.02	411
	Measured Offshore	9072	7308	7539	-20	27452	0.66	-0.6	383
	Modelled Flanders	7647	6361	5203	162	24140	0.87	-0.4	333
	Measured Flanders	4595	3368	3440	343	17600	1.3	1.37	176
	Modelled Walloon	5607	4942	3941	29	19030	0.89	-0.32	259
	Measured Walloon	3514	2976	2446	200	14623	1.17	0.7	156

Table 8 Time-series analysis of daily measured and modelled PV production (MWh) for 2017 and 2018.

Validation	Region	RMSE	Bias	Percentage bias	Correlation (Pearson)
2017	Belgium	7792	-4923	-0.25	0.96
	Offshore	3158	-2133	-0.54	0.93
	Flanders	3475	-1708	-0.21	0.94
	Walloon	2603	-1427	-0.27	0.95
2018	Belgium	9679	-7520	-0.45	0.98
	Offshore	3524	-2776	-0.9	0.96
	Flanders	4572	-3052	-0.53	0.94
	Walloon	3003	-2093	-0.49	0.97

The time-series analysis (Table 8) confirms the large uncertainty on the prediction with RMSE values for each region in the order of 50 to 90% of the mean value. The bias, which computes the average amount by which measured data is greater than model output, ranges between 25 to 60% of the mean value depending on the region or year. Lowest RMSE and bias values were observed offshore, and highest in Flanders

Figure 11 confirms that certainly onshore there is a significant difference at hourly level between the modelled and measured data. During periods of high wind intensity, the differences are largest for the onshore regions as the maximum capacity is never reached. The bias is smaller during periods of low wind intensity. There is however a good correlation at the daily level which suggest that despite an important consistent bias (overestimation) at least temporal patterns are reproduced in a satisfactory manner. So, patterns in wind production are reproduced but an overestimation remains.

→ **Sources of uncertainty and bias**

It implies that either there is an uncertainty related to the input data (wind speed data and technical characteristics reported per wind turbine) or several mechanisms are not modelled appropriately when using the theoretical approximation.

With respect to the input data, RMI performs regular validation procedures on their model output. These checks confirm limited uncertainty on modelled wind speed data at different heights. Technical specifications per wind turbine are typically gathered during the procedure to obtain a permit for construction (Dutch 'Omgevingsvergunning'). The information is entered by the applicant and collected in a central database. The accuracy depends on the diligence of the applicant to complete the information. For the Flemish database, it is known that inaccuracy is present, and they are working on a renewed and automatized system. Here, a pre-modeling sanity check was performed on the reported technical specifications per wind turbine, and false data was omitted and corrected for where possible (using wind turbine type information). Although the impact for individual wind turbines can be large, we expect only a limited impact on aggregated wind production data.

Nevertheless, we observe an important bias compared to measured loads both on-and offshore. This is in line with studies performed for onshore- and offshore wind parks across Europe (Hankins et al., 2011; Staffel & Green, 2014; Ofgem, 2012; Schallenberg-Rodriguez, 2013). All observe a systematic bias, dominantly overestimating the loads measured by DSOs, and attributed to a series of explaining variables. Due to their erratic nature or need for detailed information on wind turbine characteristics and implementation in the landscape, they are difficult to account when modelling wind power generation at the level of regions. Following factors contribute to the uncertainty of the model output, and are typically captured as a performance ratio (PR) to downscale the ideal load factor:

- **Machine availability:** typical downtime (UK) of 4-7% which translates to 11% reduction in energy output
- **Operating efficiency:** sub-optimal control systems, misaligned component, electrical losses leads to a reduction of 2% in energy output
- **Wake effects:** power loss due to interactions between neighboring turbines increase turbulence and reduce wind speeds (5-15%, but offshore sometimes up to 20-30% during crosswinds)
- **Turbine aging:** loss in efficiency with each extra year of age – with a 7.5% reduction for a wind park with an average age of 5 years to a fleet of same new-turbines.
- **Site conditions:** imperfections in the turbine surrounding (windvang) are not considered, and lower observed wind speeds at hub height. Difficult to monitor or provide a general estimation of reduction in energy output for.

It is therefore suggested to correct for the observed bias using a performance ratio that captures the uncertainty of the different factors in one number:

$$F_t = \mu(t) \cdot \omega(t) \cdot \theta(u) \cdot \tau(u) \cdot \varepsilon$$

- μ(t) = machine availability = 0.89
- ω(t)= operating efficiency = 0.98
- Θ(u)= wake effects = 0.90
- τ(u)=turbine aging = 0.925
- ε = site conditions = ?

The PR based on literature data from the UK equals 0.725, and when including site conditions is further lowered to 0.6972.

As a detailed quantification of the effect of the different influencing factors is not within the scope of the BREGILAB study, we deduce the PR directly from comparing the 2017 modelled and measured loads (Table 6). An average PR was used to correct hourly wind production:

- Offshore: 0.78
- Onshore: 0.70

Applying the performance ratio copes with the observed bias at the annual and partially monthly scale. It however does lead to an improved reproduction of the temporal patterns at the hourly and daily level.

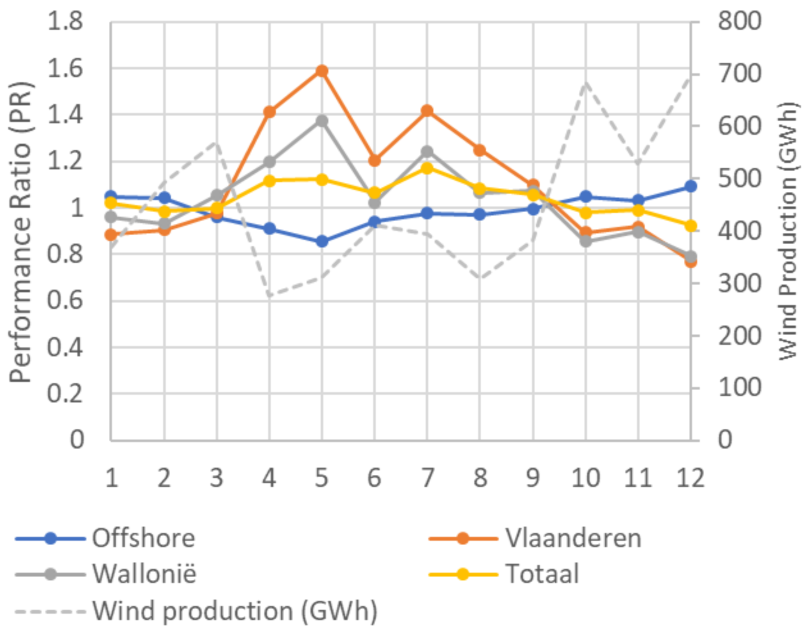


Figure 12 Monthly performance ratio comparing measured and modelled wind production in 2017. The measured wind production (GWh) is reported as comparison.

Table 9 Annual and monthly, modelled including the performance ratio (Bregilab) and measured (Elia) wind production (GWh) per region in 2017. The performance ratio indicates a systematic over-or underestimation (Elia versus Bregilab) for the year 2017.

2017	BREGILAB Production				ELIA Production				Performance Ratio (PR)			
	Offshore	Vlaanderen	Wallonië	Totaal	Offshore	Vlaanderen	Wallonië	Totaal	Offshore	Vlaanderen	Wallonië	Totaal
Jan	189	88	99	363	197	78	95	370	1.05	0.88	0.96	1.02
Feb	230	145	129	498	240	131	121	491	1.04	0.90	0.93	0.98
March	278	161	139	572	267	157	146	570	0.96	0.98	1.05	1.00
April	144	63	47	247	131	89	56	276	0.91	1.41	1.20	1.12
May	194	55	42	277	166	88	57	310	0.85	1.59	1.38	1.12
June	222	102	77	386	210	122	79	410	0.94	1.20	1.02	1.06
July	204	84	62	336	199	118	77	394	0.98	1.42	1.24	1.17
Aug	164	77	50	284	159	97	53	309	0.97	1.25	1.06	1.09
Sept	186	106	75	361	185	116	80	381	0.99	1.10	1.07	1.06
Oct	358	212	141	699	375	189	120	685	1.05	0.89	0.85	0.98
Nov	282	155	107	535	291	142	95	529	1.03	0.92	0.90	0.99
Dec	337	246	180	757	368	190	142	700	1.09	0.77	0.79	0.92
Annual	**2788**	**1493**	**1145**	**5315**	**2788**	**1517**	**1121**	**5425**	**1.00**	**1.02**	**0.98**	**1.02**

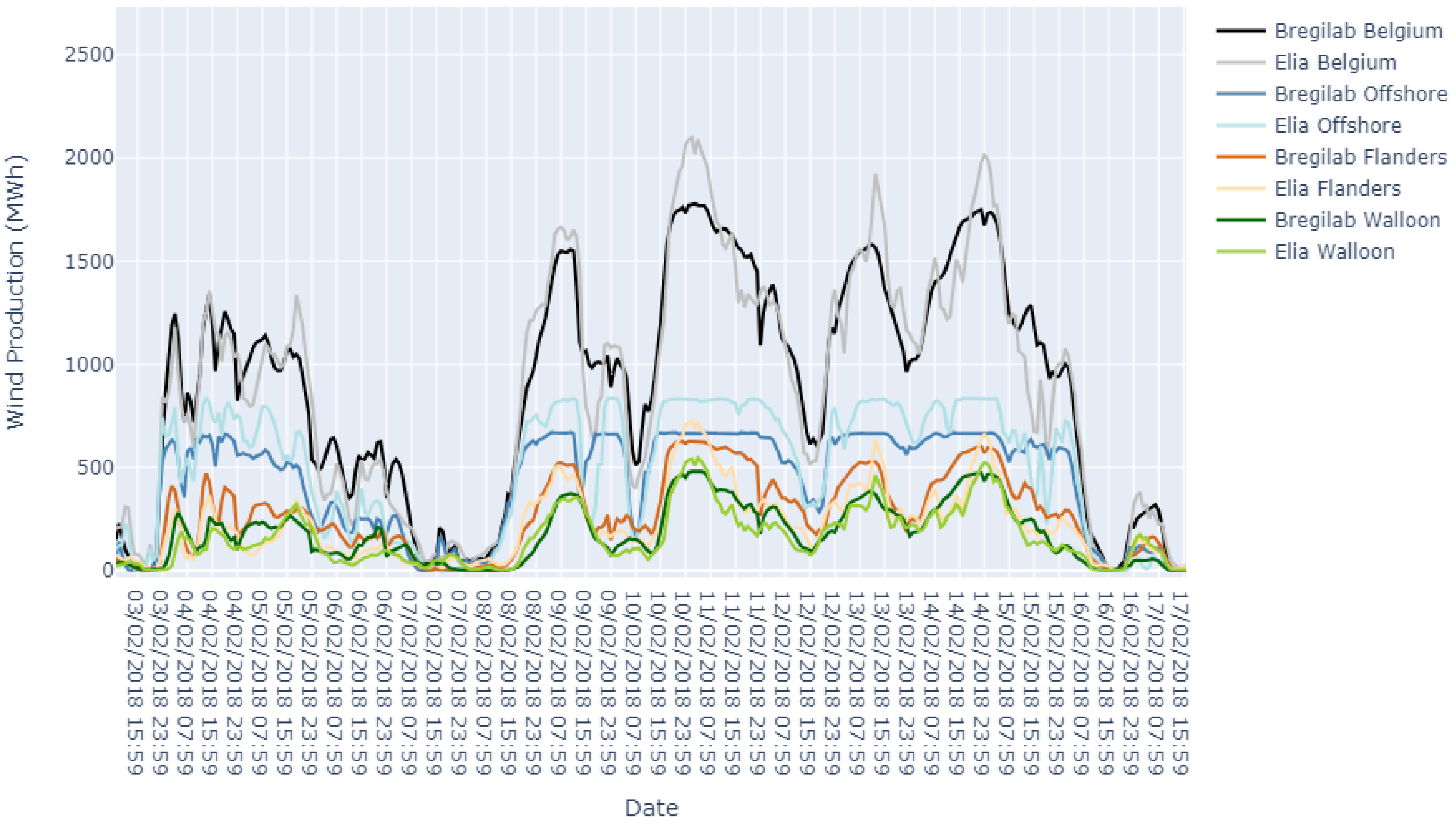


Figure 13 Modelled including the performance ratio (BREGILAB, dark) and measured (Elia, light) wind production (MWh) in Belgium and its regions for the period 3/02/2018-17/02/2018, and taken into account performance ratio (F_t).

Table 10 summarizes the daily measured and modelled wind production data per region for 2017 and 2018 after a performance ratio was taken into account. For both years and each region, the consistent overestimation has been eliminated or reduced.

Table 10 Description of daily measured (Elia) and modelled (BREGILAB) PV production (MWh) for 2017 and 2018, and taken into account performance ratio (F_t)

Year	Region	mean	sd	median	min	max	skew	kurtosis	se
2017	Modelled Belgium	14904	11573	12143	59	42110	0.65	-0.71	606
	Measured Belgium	14864	10904	11707	1041	43855	0.83	-0.3	571
	Modelled Offshore	7675	5034	7594	0	16059	0.11	-1.34	263
	Measured Offshore	7637	5778	6507	29	20017	0.5	-0.96	302
	Modelled Flanders	4093	3923	2566	1	14838	1.1	0.11	205
	Measured Flanders	4157	2957	3249	443	14117	1.29	1.13	155
	Modelled Walloon	3137	3165	1935	4	11561	1.08	0.02	166
	Measured Walloon	3070	2673	2181	161	12417	1.27	0.97	140
2018	Modelled Belgium	18398	13379	15033	602	51552	0.62	-0.72	700
	Measured Belgium	17181	13033	13211	809	59675	0.87	-0.11	682
	Modelled Offshore	9262	6141	8594	46	21554	0.3	-1.02	321
	Measured Offshore	9072	7308	7539	-20	27452	0.66	-0.6	383
	Modelled Flanders	5410	4455	3707	115	16839	0.85	-0.45	233
	Measured Flanders	4595	3368	3440	343	17600	1.3	1.37	176
	Modelled Walloon	3727	3371	2557	17	13242	0.96	-0.14	176
	Measured Walloon	3514	2976	2446	200	14623	1.17	0.7	156

Table 11 Time-series analysis of daily measured and modelled PV production (MWh) for 2017 and 2018, and taken into account performance ratio (F_t)

Validation	Region	RMSE	Bias	Percentage bias	Correlation (Pearson)
2017	Belgium	3167	-40	0.05	0.96
	Offshore	2119	-38	-0.21	0.93
	Flanders	1545	64	0.15	0.94
	Walloon	1063	-66	0.11	0.95
2018	Belgium	3015	-1218	-0.08	0.98
	Offshore	2201	-190	-0.48	0.96
	Flanders	1933	-815	-0.09	0.94
	Walloon	830	-213	0.02	0.97

The time-series analysis (Table 11) confirms the significant reduction of the bias. Although almost halved, the RMSE remains high which suggest that extremes are not reproduced well within the BREGILAB model. A higher bias for 2018 suggests that applying the PR based on 2017 data to other years will inevitably lead to inter-annual uncertainty.

Figure 13 confirms that certainly onshore there is a significant improvement in reproducing the observed loads at hourly level by applying the PR. Offshore the maximum capacity is consistently underestimated during periods of high wind intensity, while the bias is reduced during periods of low wind intensity. There is however a good correlation at the daily level which suggest that despite an important consistent bias (overestimation) at least temporal patterns are reproduced in a satisfactory manner. So, patterns in wind production are reproduced, and there is an important improvement in reducing the daily and annual overestimation.

The present set-up can be used to estimate potential wind production using any given wind speed input dataset (i.e. re-analysis data 2006-2019). There are some obvious limitations. The performance ratio is based on the validation year 2017 and is deemed representative for all other years. From literature, we know that the performance ratio is off course dependent on the annual wind conditions and will vary with several percentages between years. Further, it is an annual average while Figure 12 clearly shows monthly variability.

CHAPTER 4 PHOTOVOLTAÏC ENERGY PRODUCTION

This chapter elaborates on the modelling of photovoltaic electricity generation. First, the data sources used are described, next the methodology to model photovoltaic energy with the Dynamic Energy Atlas is explained and finally a validation of the results is given. There is an important link with the PV module framework developed by Imec/Energyville.

4.1. DATA SOURCES

To model PV production in a spatially explicit manner, we need to know how much PV is installed and where they are located, and what their generation potential is. The generation potential depends on the characteristics of the installed PV (e.g. tilt and orientation) and climatic conditions at this location (irradiation, wind speed and temperature). So, we require both technological data (geolocation combined with technical characteristics) and meteorological data to model wind production using a bottom-up approach. The data-sources used within the BREGILAB study are presented here.

4.1.1. PHOTOVOLTAIC INSTALLATIONS

All regional authorities report on the installed photovoltaic capacity (kW) at the community level. Flanders and the Walloon region report annually, while for Brussels the last publicly available data dates from 1/1/2018. The Walloon region only reports publicly about the <10kW installations at the community level. Installed PV capacity, including <10kW and ≥10kW installations, at the regional level (as reported by Apère) are used to attribute a certain amount of ≥10kW installation to each community in the Walloon region. The known distribution of <10kW installations over the different communities is used as a distribution key.

In absence of a detailed geolocation for large PV installations, it is assumed that all PV panels are installed on roofs. Those with a capacity≥10kW are assumed to be installed on roofs of commercial and industrial buildings while those with <10kW capacity are typical residential.

In Belgium on 1/1/2018, a total of 3621MW of PV is installed with 2561MW in Flanders, 1003MW in the Walloon region, and 57MW in Brussels.

4.1.2. CLIMATIC DATA

To model PV production a series of climatic data are required:

- Ambient temperature at the surface (K)
- Wind speed at 10 m (m s^{-1})
- Wind direction
- Global horizontal irradiance (GHI), direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) (W m^{-2})

Two datasets are combined (Figure 5):

- The Royal Meteorological Institute (RMI) provided irradiance, wind speed and temperature data for the period 1980-2019. A climate simulation is performed by the ALARO-0 regional climate model (RCM) on the European domain at 12.5 km, nested inside ECMWF's ERA5 global reanalysis. A second nesting procedure provides high resolution climate data at 4km for the Belgian domain.
- The MeteoSAT (MSG) irradiance data which are processed taking into account a cloud index calculation and in-situ observations for the period 2006-2019.

Irradiance data is derived from the MeteoSAT dataset and combined with wind and temperature data from the ERA5 re-analysis data to model PV availability in Belgium.

The 2017-2018 data is used for validation by comparing model output with Elia production data. The output forms an additional base for a sensitivity analysis to climate change.

Table 12 Overview data sources of technical specifications for existing PV installations in Flanders, Wallonia and Brussels.

Data source	Characteristics extracted	Date
Energiesparen.be - https://www.energiesparen.be/zonnekaart/FAQ/cijfers	Installed PV capacity (4 klasses: <10kW, 10-250kW, 250-750kW en >750kW) for each Flemish community. Updated monthly by Flemish energy providers – no information on exact geolocation	1/1/2018
Commission wallone pour l'Energie (CWAPE) - https://www.cwape.be/?dir=6.4	Installed PV capacity <10kW for each Walloon community. Updated annually – no information on exact geolocation	1/1/2018
Observatoire photovoltaïque (Apère) - https://apere.org/fr/observatoire-photovoltaique	Total installed PV capacity per region	Extracted 31/12/2019
Le regulateur Bruxellous pour l'energie (brugel) – studie in eigen initiatief (p70-72): https://www.brugel.brussels/publication/document/studies/2018/nl/Etude-initiative-27-NL-ParcPV2016-Projet-rapport-final.pdf	Installed PV capacity according to owner (particulier, commercial or governmental) for each community in Brussels. Updated annually – no information on exact geolocation	Last update: 1/1/2018

4.2. Model photovoltaic power generation

4.2.1. Dynamic Energy Atlas: General Approach

The Dynamic Energy Atlas (DEA) uses a bottom-up approach to model photovoltaic power generation at a spatial resolution of 100 by 100m. A simple multiplication is used to estimate energy production per technology. The general formula is independent of the technology studied, and expressed as

Production (per pixel) =
energy production factor (technology and/or space specific) X spatial pattern (where technology is/can be located) X feasibility (technic, economic, public support/resistance, …)

Formula: **$(P)Ep_{i,t} = EpF_{j,t} * EpEV_{i,t} * F_t$**

$(P)Ep_{i,t}$= (Potential) Energy Production by technology t at location i (in kWh)
$EpF_{j,t}$ = Energy production Factor for the existing technology t and expresses the energy production per unit of $EpEV_{i,t}$. EpF can vary between a single multiplicator for the study-area or be location dependent. The use of spatially explicit information (j), if available, is the preferred methodology when geographical differentiation is relevant.
$EpEV_{i,t}$ = Energy production Explanatory Variable for technology t at location i. EpEV is an as accurate as possible representation of the spatial distribution of technology t.
F_t= x% (technic) * x% (public) * x% (performance ratio)
i = each pixel
j = spatial unit (e.g. municipality)
t= technology

Previously, PV generation was estimated at the annual level using an average energy production factor (Van Esch et al., 2016). Within BREGILAB, we improve our approach by using hourly meteorological data to obtain time-series.

4.2.2. Dynamic Energy Atlas: Implementation BREGILAB

→ Spatial pattern

Installed PV capacities are known at the community level (Table 12). They are a diffuse source of information and can be further detailed by applying a dasymetric mapping procedure. Dasymetric mapping is a technique which allows to distribute data available at large spatial units (like administrative regions) over smaller homogenic units by using an additional spatial indicator.

In case of PV, we combine the building layer contained in the CADGIS dataset (https://financien.belgium.be/nl/experten_partners/open-patrimoniumdata/datasets/kadastraal-plan/download) and information on permitted purpose of each building to categorize roofs by activity type into residential versus commercial & industrial roofs (FOD economy, VITO-AADP protocol: https://vito.be/sites/vito.be/files/tt_vz-protocol-_vito_1.pdf). It allows to estimate for each 100 by 100m pixel the roof surface area (m²) per activity type.

Subsequently, the total amount of installed PV capacity will be distributed proportionally within the community over the available roof surface per pixel. The PV installations <10kW are distributed over residential roofs while ≥10kW are distributed over commercial&industrial roofs.

Finally, the installed PV capacity per pixel is translated into installed area of PV panels within a pixel. A module with peak capacity of 152.7 Wp per m² and dimensions 1.64x0.992m² (Trina Solar TSM-250-PC/PA05A) was selected to represent the current (average) installed technology in Belgium. The Energy production Explanatory Variable ($EpVV_{i,PV}$) for PV at location i equals the installed PV capacity per pixel expressed as m² PV panel.

→ **Energy production**

The Energy production Factor ($EpF_{j,PV}$, kWh per m²h) for the current technology (i.e. module 152.7 Wp per m²) per pixel is determined by the spatial and temporal variations in climatic conditions on location j. Imec developed a spatially explicit transfer function that translates the climatic data (irradiation, temperature, wind speed & direction) into an hourly energy production factor. A complete overview of the applied methodology can be found in the functional description (Annex A). Importantly, the transfer function allows to calculate the energy production factor for any given PV installation type and year of interest.

Currently, four types of PV installation are combined with 2017 climatic data:

- Residential roofs: 35° tilt angle with a south, west and east orientation
- Commercial and industrial roofs: 10° tilt angle with south orientation

South orientation is the energetically optimal solution to maximize daily production. However, it is not always technically feasible (e.g. not enough roof area oriented south) or economically desirable (e.g. optimize self-consumption by spreading) to install PV panels southwards on residential roofs. There is no information available about the exact distribution of PV capacity according to east, west or south orientation in Belgium or the different regions. Using measured PV data for 2017 (Elia), we derived an optimal distribution of PV panels over the three orientations to match the observed loads (Annex A):

- South: 0.71
- West: 0.05
- East: 0.24

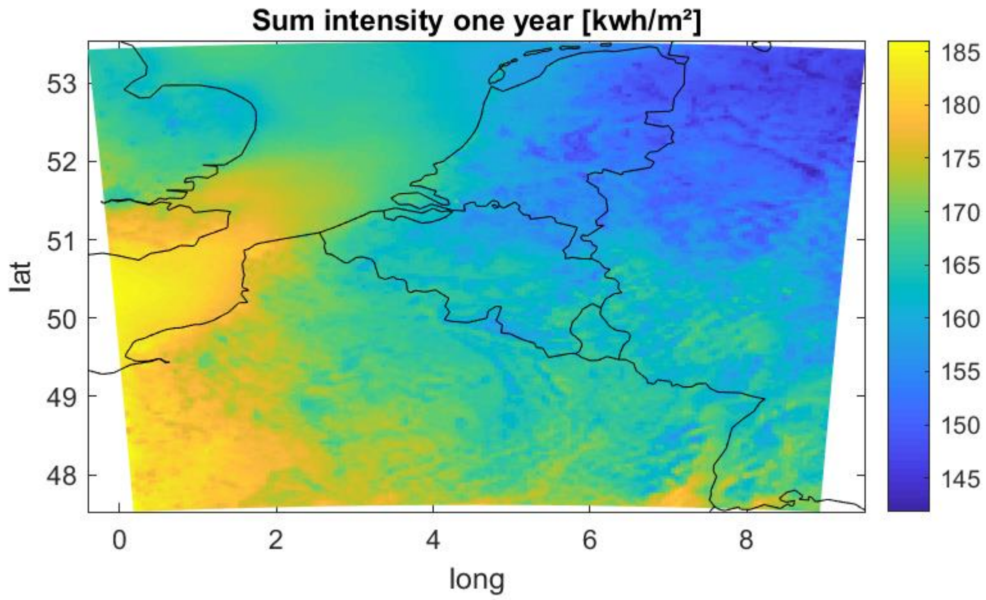


Figure 14 Modelled energy production factor (kWh/m²) for PV module (Trina Solar TSM-250-PC/PA05A) with 35° tilt and west orientation (270°) using the PV framework (Imec) and 2017 climatic data (provided by RMI).

→ **Feasibility factor**

Some mechanisms decreasing the energy produced by photovoltaic installations have not been considered in the computation of the provided energy production. Instead the feasibility factor corrects for the known mechanisms:

- **Effects of shading**: Decreased energy production due to shading by surrounding buildings, trees, structures or even other modules accounts for a reduction in energy production of about 1.5%
- **Aging of PV panels**: The installed PV panels in Belgium are on average 5 years old while there efficiency drops annualy with roughly 1%. This results in a reduction of energy production with about 5%.
- **Operational losses:** Loss of electrical power due to resistance of the cables between modules and inverter. This is a rather small loss factor and contributes for less than 1%

Combined the applied feasibility factor equals 0.9259.

4.3. VALIDATION WITH STATISTICAL DATA

We applied the described methodology (section 4.2) for the year 2017 using the photovoltaic (PV) installation database (anno 1/1/2018) and climatic forecast data for 2017. The hourly PV production data (MWh) are aggregated at the level of 13 Bregilab zones (Figure 8) and regions. The results are compared at the level of regions (Flanders, Brussels and Walloon) with hourly PV production data reported by the Belgian DSO (Elia). Elia provided us with PV production data (MWh; every 15 minutes since 2003; *Measured & upscaled)*) and installed capacity (MW; every 15 minutes since 2003; *Monitored solar PV capacity*). Elia aims to regularly update installed capacity based on available data however it is not automated process, and therefore the reported capacity might not be entirely complete. The reported data is free of self-consumption.

4.3.1. MATCHING INSTALLED CAPACITY

The bottom-up approach uses information on PV installed as described in section 4.1.1. The installed capacity (MW) used to estimate PV generation is a snapshot of the situation at the onset of 2018. Combining this information with hourly meteorological data of 2017 will inevitably lead to overestimations as the actual operation capacity at the start of 2017 was much lower. Furthermore, the installed capacity at the start of 2018 (3621MW) is 25% higher than as reported by Elia (Table 13).

The hourly PV production (MWh) at time t has been corrected for the actual installed capacity at that moment in time. Elia provides at the level of provinces the hourly installed capacity (CAP; MW).

We apply an hourly correction factor to the BREGILAB energy production (PE) estimates:

$$PE_{PV,cor} = PE_{PV} \cdot \frac{CAP_{PV,Elia}}{CAP_{PV,BREGILAB}}$$

Table 13 Installed capacity of PV (MW) per region according to different data sources (situation 31/12/2017)

Capacity	Totaal	Walloon Region	Flanders	Brussels	Data source
Apère	3887	1003	2817	67	https://apere.org/fr/observatoire-photovoltaique
Elia	2953	736	2168	49	https://www.elia.be/nl/grid-data/productie/zonne-energieproductie
Bregilab	3621	1003	2561	*57*	see below

*Walloon region (1/1/2018):Combined <10kV from https://www.cwape.be/?dir=6.4 with assumption that APERe reports correct tot including >10kV

*Flanders:(1/1/2018) https://www.energiesparen.be/stroomvoorspeller/faq

*Brussels: see attachment (1/1/2017)

4.3.2. PERFORMANCE PV TRANSFER FUNCTION

The imec framework is used to translate hourly climatic data into an energy production factor (kWh per m^2h). In combination with the installed capacity and feasibility factor PV generation is calculated at the level of 100 by 100m pixels and aggregated at the level of BREGILAB zones. The validation aims to investigate if the BREGILAB model reproduces:

- Total energy production for the different geographical regions
- Patterns in hourly and daily energy production throughout the year that are consistent between both databases

→ Annual energy production per region

Table 14 reports the annual modelled and measured PV generation per region. The modelled values take into account optimization for orientation of residential PV and account for the effect of aging and shading.

Table 14 Annual modelled and measured PV generation per region in 2017 with radiation data based on measured METEOSAT data. The performance ratio (Elia/Bregilab) is a measure of validation.

Energy production	BREGILAB			Elia	Elia/ BREGILAB
	Residential (MWh)	Commercial & Industrial (MWh)	Total (MWh)	Total (MWh)	[-]
Antwerpen	264551	191066	455617	478859	1.05
Brabant wallon	47878	21307	69185	70369	1.02
Brussel	7680	43523	51203	47083	0.92
Hainaut	126860	56484	183344	189452	1.03
Liège	170870	75930	246800	257801	1.04
Limburg	248348	174785	423133	438482	1.04
Luxembourg	56221	24969	81190	80680	0.99
Namur	75920	33865	109784	113485	1.03
Oost-Vlaanderen	264519	189905	454424	476412	1.05
Vlaams-Brabant	173878	66801	240679	245871	1.02
West-Vlaanderen	247115	215952	463066	489685	1.06
Belgium	**1683841**	**1094585**	**2778426**	**2888178**	**1.04**

The current model underestimates the annual energy production for 2017. Elia loads are at a 1.04 level for 2017. The largest underestimations by the model are made in the northern provinces, while the model performs better in the southern provinces. In Brussels, the production is overestimated. The differences between provinces are limited.

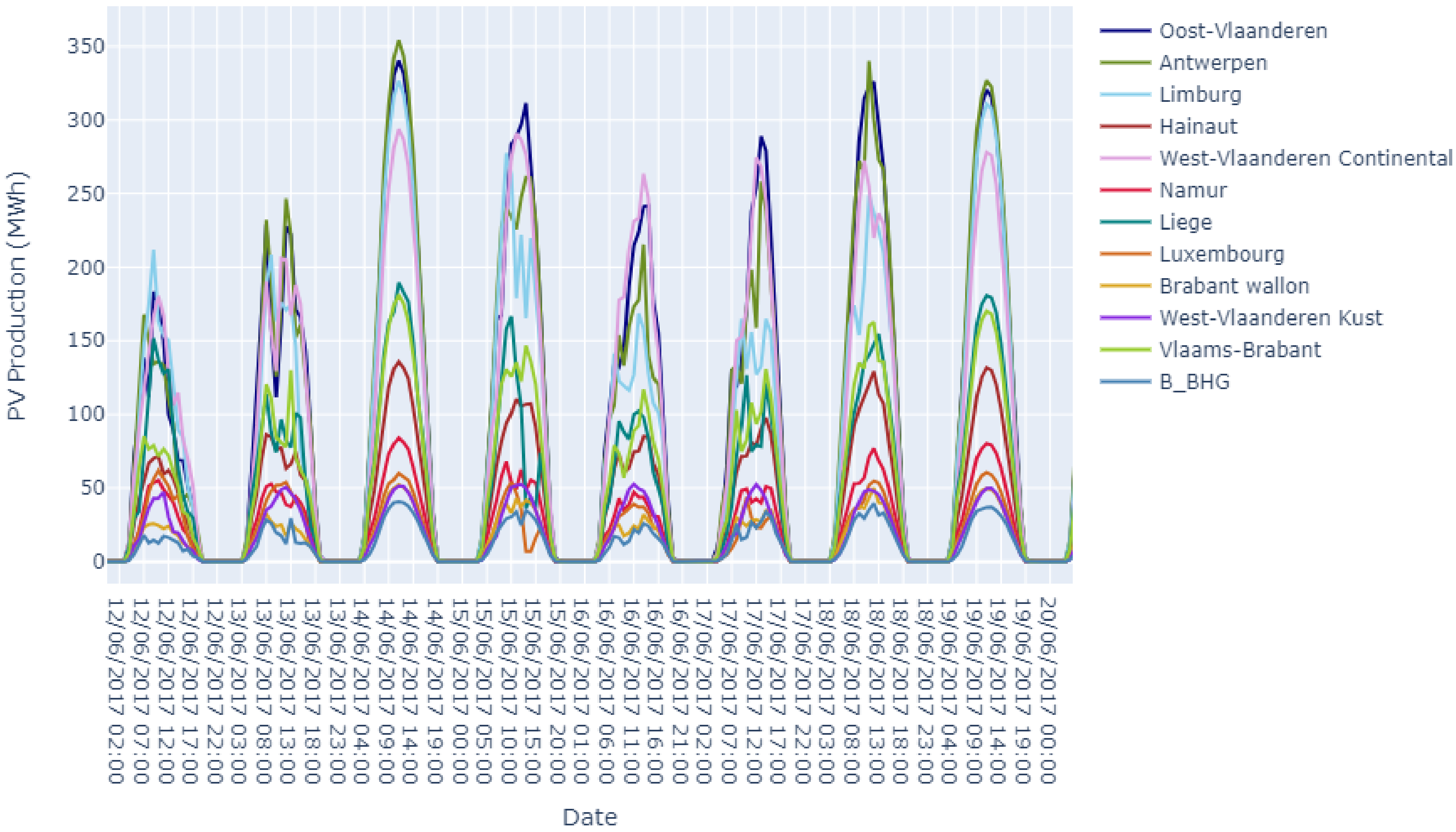


Figure 15 Modelled (BREGILAB) PV production (MWh) in the 13 BREGILAB zones for the period 12/06/2017-20/06/2017. The offshore region has no PV capacity.

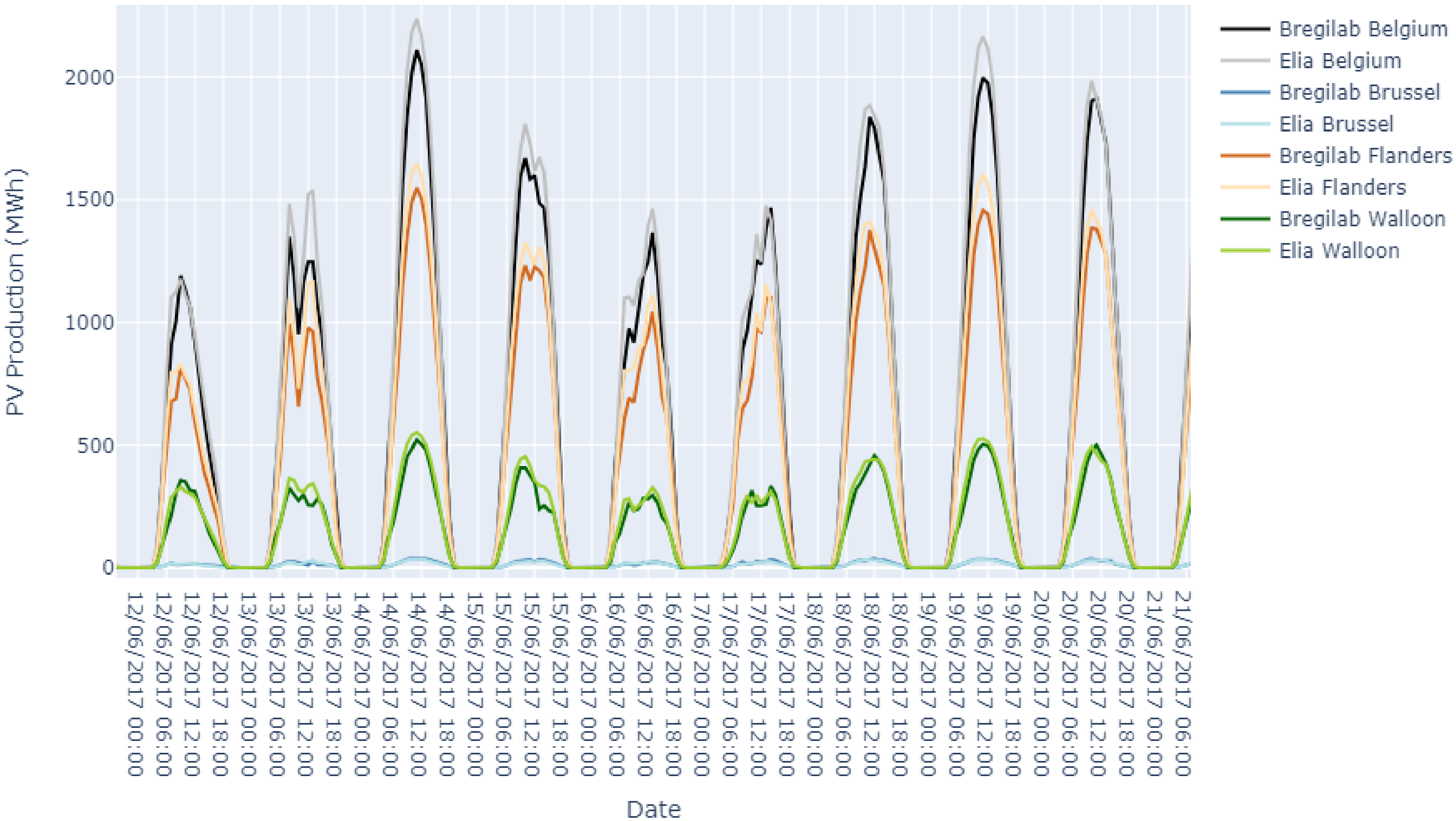


Figure 16 Modelled (BREGILAB, dark) and measured (Elia, light) PV production (MWh) in Belgium and its regions for a ***summer period*** *(12/06/2017-21/06/2017) showing a good reproduction of daily PV load but limited hourly detail.*

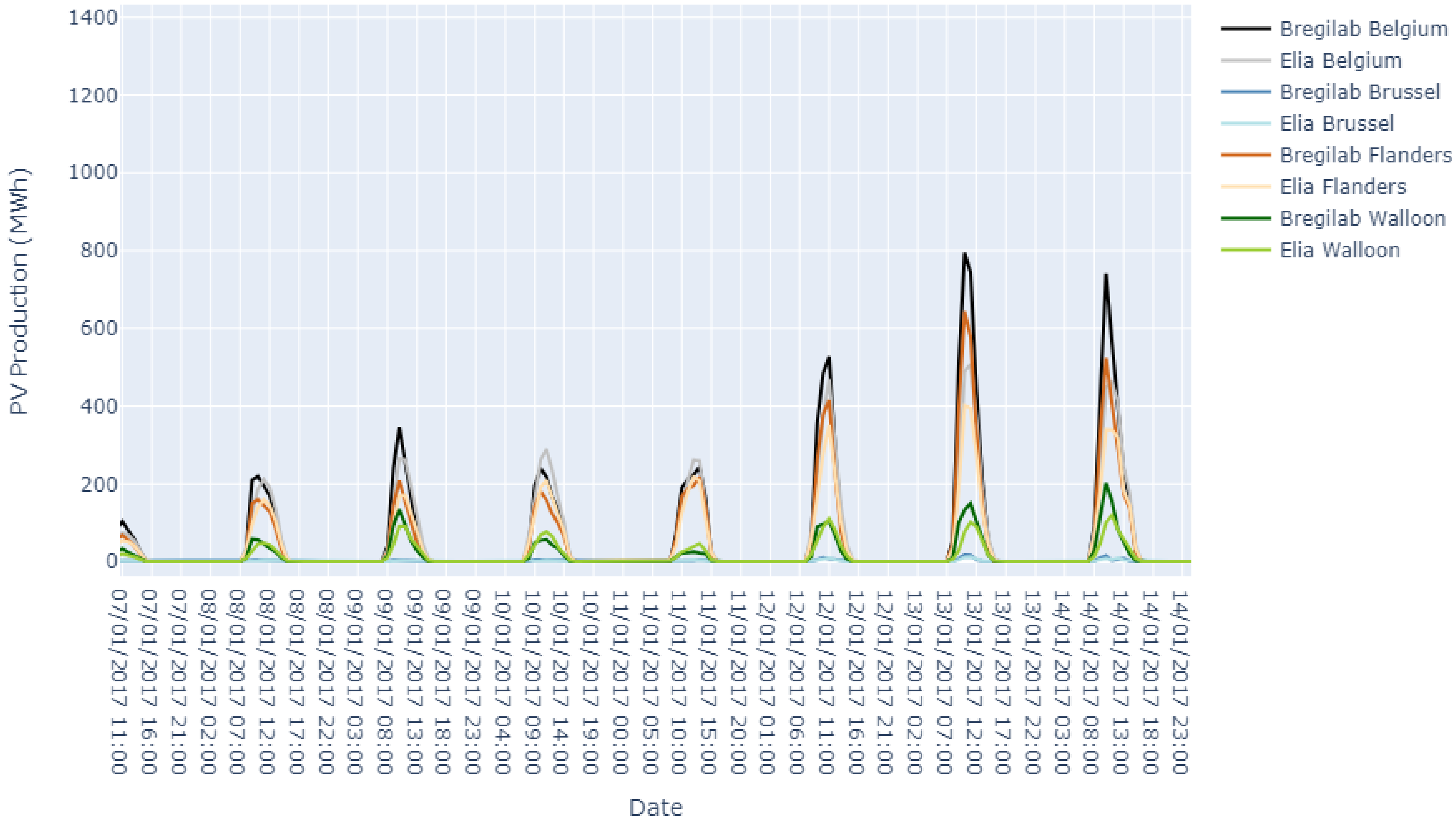


Figure 17 Modelled (BREGILAB, dark) and measured (Elia, light) PV production (MWh) in Belgium and its regions for a **winter period** (7/01/2017-14/01/2017) showing a large overestimation of the measured PV production.

In terms of full load hours, i.e. the amount of hours that PV is produced at full capacity (i.e. Energy production in MWh/Installed capacity MW), Elia reported for Belgium 978 hours. Based on the BREGILAB data it adds up to 1000 for 2017.

The PV distribution optimization and performance correction for aging and shading resulted in an improved reproduction of the annual PV loads with about 13%; and is now limited depending on the province from 1 till 8%.

→ **Monthly energy production per region**

Figure 18 shows how well the model performs in simulating monthly production throughout the year.

There are intra-annual differences in the performance of the BREGILAB model as compared to the measurements. During the winter periods the performance drops to a factor 0.8 (i.e. overestimation by the model) while during the late summer months there is an underestimation (i.e. factor 1.1) with 10%.

The model performs worst in central and southern Belgium and performs better towards the coastline. The overestimation during winter months is balanced out on an annual basis due to typical shorter days, and therefore lower energy production.

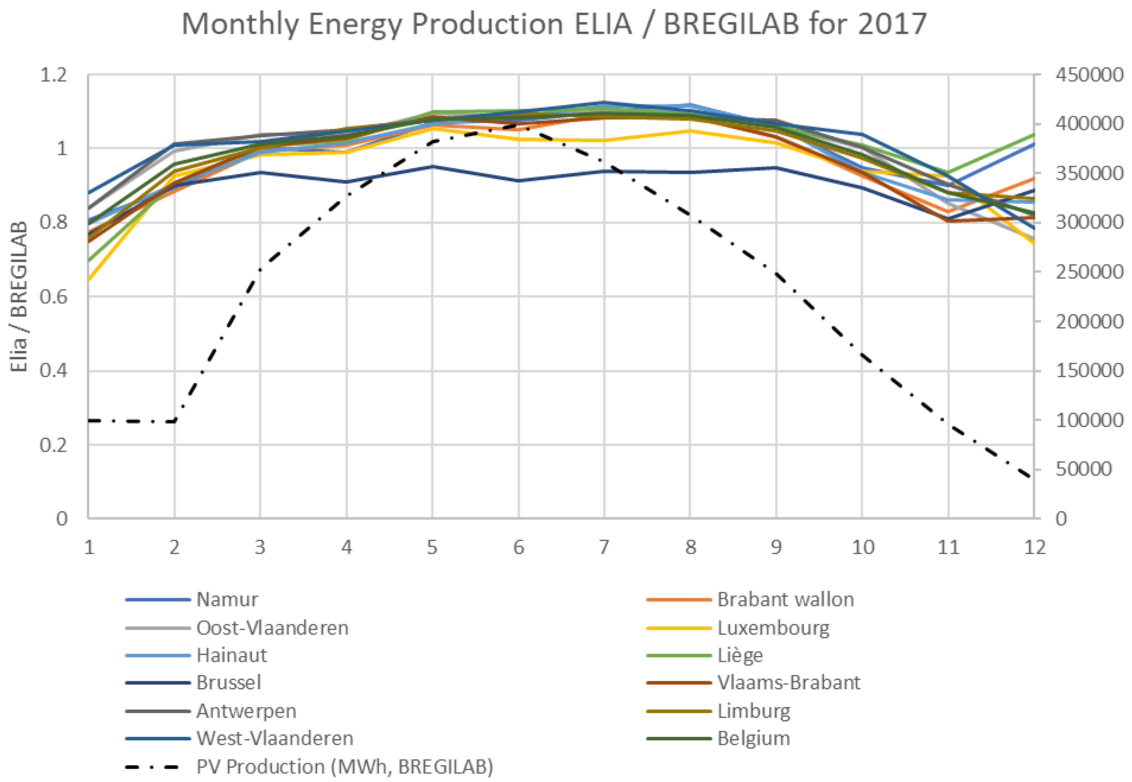


Figure 18 Monthly performance ratio for PV production per region in.

→ **Daily energy production pattern per region**

Compared with Elia data of 2017, the model calculations result in a final overestimation of 2% (RMSE: 758 and Bias: 262) for daily energy production (MWh) which is on average 7913 MWh (Elia) in 2017 (Table 15). The overestimation is larger during winter periods and in the southern provinces. *Figure 16* and Table 16 show on an hourly and daily basis the difference in performance of the model during summer and winter periods.

Table 15 Description of daily measured and modelled PV production (MWh) for 2017

Year	Source	mean	sd	median	min	max	skew	kurtosis	se
2017	Actual (Elia)	7913	5429	7228	98	19938	0.34	-1.03	284
	Predicted (BREGILAB)	7651	5015	6976	271	18896	0.28	-1.03	263

Table 16 Time-series analysis of daily measured and modelled PV production (MWh) for 2017

Validation	RMSE	Bias	Percentage bias	Correlation (Pearson)
2017 (BREGILAB)	758	262	-0.01	0.99

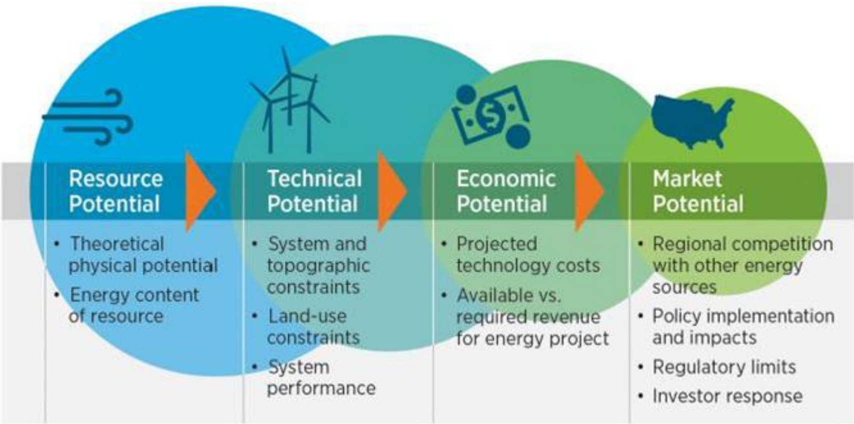
Summarized:

- There is a good agreement between the BREGILAB estimates and Elia measured at the daily level.
- During winter months an overestimation of the PV production by the model exists but does not exceed 20% for most days. The METEOSAT data can predict cloud cover in a reliable manner.
- The hourly pattern (i.e. timing of the peaks) is reproduced well. Best performance is reached during the summer months. In winter periods it appears that the BREGILAB model predicts the PV peak before the actual measured peak by ELIA.

The present set-up can be used to estimate potential PV production using any given climatic input dataset (i.e. re-analysis data 2006-2019).

CHAPTER 5 SPATIAL ANALYSIS AND POTENTIAL OF RENEWABLE ENERGY PRODUCTION IN BELGIUM

Chapter 5 provides an as accurate as possible assessment and cartographic visualization of the technical potential for additional wind and solar production in Belgium. The first section focuses on the rationale and general methodology applied to estimate potential energy production. Section 5.2 and 5.3 describe for Wind and PV the relevant data sources, delineation of the available space (i.e. spatial pattern), applied energy production factor and feasibility factor. Section 5.4 highlights the most important results of the modelling work at the level of the Belgian regions.



Source: Brown et al. (2016) Models for quantifying and mapping energy potential from renewable energy sources

It is important in this context to differentiate between resource, technical, economic and market potential. **In this report the technical potential is calculated based on spatial and regulatory criteria.** All land-use, topographic and system performance constraints are detailed in CHAPTER 5. This does not automatically imply that a full exploitation of the potential for onshore wind or PV systems is from an economic point of view feasible or from a societal point of view desireable.

5.1. DYNAMIC ENERGY ATLAS: SPATIAL ANALYSIS TO ESTIMATE POTENTIAL ENERGY PRODUCTION

The Dynamic Energy Atlas supports besides the inventarisation and mapping of current renewable energy production (Chapter 3 & 4) also, and mainly, the assessment of additional production potential for the different renewable energy technologies. Here, we investigate the potential hourly production at a 100 by 100m scale for Belgium taking into account the available space at which a present market technology can be optimally used to generate renewable energy. The actual construction of a certain technology depends on relevant spatial criteria where positive boundary conditions indicate high potential or desirable locations for the development of decentralized energy production (e.g. for wind near existing infrastructure, for PV on west, south and east facing roofs) and negative boundary conditions indicate low potential or no-go zones (e.g. for wind due to safety reasons at a minimum distance from residential housing, for residential PV limited to roofs). The (spatial) boundary conditions for each technology are determined by policy frameworks and regulations at the level of regions in Belgium. Regional differences in legislation and ambitions are, where relevant and feasible, taken into account. To avoid the overestimation of the potential, a feasibility parameter (F_t) based on technological and performance constraints for a certain technology is used (see for example section 3.2.2 and 4.3.2).

The general formula is independent of the technology studied, and remains expressed as:

Production (per pixel) =
energy production factor (technology and/or space specific) X
spatial pattern (where technology is/can be located) X
feasibility (technic, economic, public support/resistance, performance ratio…)

Formula: $\mathbf{PEp_{i,t} = EpF_{j,t} * EpEV_{i,t} * F_t}$

$PEp_{i,t}$= **Potential** Energy Production by technology t at location i (in kWh)
$EpF_{j,t}$ = Energy production Factor for the existing technology t and expresses the energy production per unit of $EpEV_{i,t}$. EpF can vary between a single multiplicator for the study-area or be location dependent. The use of spatially explicit information (j), if available, is the preferred methodology when geographical differentiation is relevant.
$EpEV_{i,t}$ = Energy production Explanatory Variable for technology t at location i. EpEV is an as accurate as possible representation of the spatial distribution of technology t.
F_t= x% (technic) * x% (public) * x% (performance ratio)
i = each pixel
j = spatial unit (e.g. municipality)
t= technology

The spatial pattern where a technology can be located, or the Energy production Explanatory Variable ($EpEV_{i,t}$), is the result of combining spatial boundary conditions to delineate the available space for a certain technology. In what follows, we describe for each technology in detail which boundary conditions and assumptions are taken into account to assess their generation potential.

5.2. POTENTIAL WIND ENERGY PRODUCTION

A large variety of wind turbine types exist. This study focusses on large-scale wind turbines of more than 300kW to ensure optimal energetic use of the remaining space in Belgium. A distinction is made between the offshore and onshore potential for wind production. A bottom-up approach is used in both instances to estimate energy production. The main difference is that for offshore, only the planned wind turbines are taken into account while onshore, the energy production results from a spatial modelling exercise. Offshore, the locations and technical characteristics of planned constructions in the eastern part of the North Sea are taken into account (see https://www.belgianoffshoreplatform.be/nl/projecten/), while onshore the available space is delineated using spatially explicit boundary conditions for Belgium or at the level of a region. An allocation algorithm is then used to fill the available space with representative wind turbine technology with known technical characteristics. Like current energy production calculations (see 3.2), the actual and allocated locations are combined with hourly wind speed data for 2017 to estimate wind production at a resolution of 100 by 100m for the whole of Belgium.

5.2.1. OFFSHORE POTENTIAL WIND ENERGY PRODUCTION

→ **Data source**

In 2020, six of the nine wind farms (i.e. Rentel, Norther, Belwind, C-Power, Nobelwind, Northwind) are completely operational. The Belgian offshore platform and Royal Belgian Institute of Natural Science track the progress of the various wind farms and log the technical characteristics of the installed and planned wind turbines.

Table 17 Source of geolocation and technical characteristics of installed and licensed wind turbines in Belgium (offshore).

Data source	Characteristics extracted	Date
Belgian Offshore Platform - https://www.belgianoffshoreplatform.be/en/projects/	For each offshore wind park: Rated Power, Brand and model wind turbine, Constructed, Construction date	Extracted 31/01/2019
Vliz waterportaal	Geolocation (not complete) for offshore platforms (C-power, Northwind, Belwind, Nobelwind)	
CREG publications- based on result building permit requests.	Geolocation completion for offshore platforms (C-power, Northwind, Nobelwind and Rentel), **incomplete** update Belwind (25 out of 56)	Extracted 31/01/2019
Royal Belgian Institute of Natural Science – MUMM scientific service (https://odnature.naturalsciences.be/mumm/en/windfarms/)	Geolocations for Rentel, Norther, Belwind, C-Power, Nobelwind, Northwind	Extracted 4/4/2020

To match potential calculations with the results of current offshore production reported in Chapter 3, it is decided to account for all turbines built after 1/1/2018 (see Table 18 within the offshore potential. A capacity of 1.01GW was operational at the start of 2018, and since then an additional 1.24GW has been partly made operational (i.e. C-power phase 2 and Northwind) and is planned to be completed over the course of 2020 (Mermaid, Northwester 2 and Seastar).

Currently, there is a tender out to construct additional wind parks in the western area of the North Sea. However, permissions have not been granted as environmental impact studies are being conducted. The ambition is to build an additional 3.5GW by 2030, increasing the total installed offshore capacity in the Belgian North Sea to 5.8 GW (https://news.belgium.be/nl/energie-productiecapaciteit-van-de-prinses-elisabeth-zone-de-noordzee). As no details are available on the expected number of wind turbines, and their technical specifications we have not included them in the potential offshore estimates.

→ Spatial pattern

Exact geolocations of wind turbines were used for the currently (2020) operational wind parks being C-power phase 2 and Northwind. Unfortunately, exact locations for the wind turbines under construction at Mermaid, Northwester 2 and Seastar were not available. Instead, we generate random points within the boundaries of the wind park (*QGis > Random Points Inside Polygons*). The number of random points matched the number of planned wind turbines per wind park (see Table 17), and the minimum distance between these points exceeded at least five times the rotor diameter (D, see Table 18). The latter agrees with typical spacing advice to construct wind turbines within a wind park (3 to 10 times its rotor diameter).

→ Potential energy production

The methodology developed within Chapter 3 to calculate current wind energy generation has been applied to calculate the offshore potential:

$$PEp_{wind,n,b} = 0.5 \cdot \rho \cdot U_{b,cor}^{3} \cdot \frac{\pi \cdot {D_n}^2}{4} \cdot C_p\left(U_{b,cor}\right). F_t$$

Wind speed integrated over the rotor diameter ($U_{b,cor}$) were derived from the modelled (re-analysis) wind speed data at 100m for the year 2017, and at a spatial resolution of 4 by 4km (see 3.1.2). Table 18 provides per wind turbine the technical characteristics (e.g. rated power, hub height, rotor diameter, cut in and out wind speed etc.) required to calculate wind energy production. The power coefficient (C_p) depends on the instantaneous wind speed ($U_{b,cor}$). For offshore, we obtained wind speed profiles for all currently installed offshore parks (i.e. Vestas, Senvion and Siemens) apart from Rentel and Northwind. No power coefficients were available for those under constructions. Therefore, average C_p values (Cp_high in Table 3) were used to estimate the offshore potential.

→ Feasability factor

An average performance ratio of 0.78 was included as feasibility factor (F_t) to correct hourly wind production. The performance ratio takes into account machine availability, operating efficiency, wake effects and turbine aging. Hourly wind production data is produced per 100 by 100m pixel and aggregated spatially for the offshore zone.

Currently 2017 wind speed data has been used to match current wind production data. However, these can easily be replaced by relevant reference years to be more representative for average and extreme climatic conditions.

Table 18 Technical characteristics licensed wind turbines per wind park including the number of planned wind turbines, their rated power, rotor diameter.

Wind Park	Status	Total Capacity Wind Park (MW)	Type Wind Turbine	Number of installed/planned Wind Turbines	Rated Power per Wind Tubrine (MW)	Rotor Diameter (m, D)	Cut in wind speed ($m\ s^{-1}$)	Cut out wind speed ($m\ s^{-1}$)	Hub height (m, H)
*C-Power (phase 2)**	*operational*	*179*	*Senvion 6.15MW V126m*	*29*	*6.15*	*126*	*4*	*30*	*95*
Norther/North Sea Power	operational	370	MHI VESTAS 8MW V164	44	8	164	4	25	140
Northwester 2	construction planned 2020	219	MHI VESTAS 9.5MW V164	23	9.5	164	4	25	140
Mermaid	construction planned 2020	235	MHI VESTAS 8.4MW V167	28	8.4	164	4	25	140
Seastar	construction planned 2020	252	MHI VESTAS 8.4MW V167	30	8.4	164	4	25	140

*C-power was partly operational on the 1/1/2018. The reported data is for the second phase of C-power construction.

5.2.2. Onshore potential wind energy production

The construction of large-scale wind turbines on land requires space. Space which is already sparse and fragmented in Belgium due to high demand to support housing, economic activities, transport infrastructure, agriculture and nature areas. Besides competing for space, the construction of wind turbines needs to have a limited impact on its environment and the safety for humans and economic activities need to be safeguarded. The delineation of the remaining areas suitable to construct wind turbines depends therefore on the combination of relevant spatial criteria where positive boundary conditions indicate high potential or desirable locations for the development of decentralized energy production (e.g. for wind near existing infrastructure and near areas of demand) and negative boundary conditions indicate low potential or no-go zones (e.g. for wind due to safety reasons at a minimum distance from residential housing, or protected heritage and nature conservation sites). These spatial criteria are captured in official policy documents and frameworks at the level of regions.

We follow the methodology developed and implemented in the Dynamic Energy Atlas by VITO (Van Esch et al., 2016) to delineate zones for wind turbine construction. An allocation algorithm is used to optimally distribute wind turbines within the available space. The optimization is done from a spatial perspective and not an energetic perspective. This means that as many as possible wind turbines are built within the available space taken into account a minimal distance between constructed wind turbines. The spacing depends on the technical characteristics of the wind turbine used to fill up the available space. The rule of thumb currently used is a distance of five times the rotor diameter of the representative market model under investigation. From an energetic perspective a lower density might be useful a) as specific configurations could lower energy losses due to reduced wake effects, and b) because an economically acceptable energy efficiency is not reached in parts of the available space under current wind regimes. Our study focuses on the spatial requirements to safely and with minimal impact on its environment construct wind turbines in the Belgian landscape.

Anno 2020, the representative wind turbine is the VESTAS V112 with a capacity of 3.3MW, a rotor diameter of 112m and a hub height of 94m. VESTAS V112 is only one of the many types of wind turbines currently manufactured, and for which construction permits are requested and granted across Belgium (see Table 2 for more details). The VESTAS V112 is withheld as the current market model for following reasons:

- It recurs often in granted permit applications (*Dataset: Geopunt Vlaanderen – Stedenbouwkundig aangevraagde windturbines*);
- its dimensions are in line with typical dimensions of other recurring models (capacity > 3MW and rotor diameter > 100m; Table 2);
- it is used in a European study for similar purposes (Ruiz et al., 2019);
- and the power curve and coefficient data are readily available allowing more accurate wind generation calculations.

Obviously, the selected wind turbine model is not limitative, and can easily be replaced by other model types. It is however important that the reader is aware that only one wind turbine type is used to model the potential wind turbine generation across Belgium, and that we are not working with location dependent wind turbine types (e.g. difference between regions with high and low wind regimes).

→ **Spatial boundary conditions**

In a first step, the potential zones to construct wind turbines are delineated by combining positive and negative boundary conditions. Relevant spatial criteria are identified by reviewing policy documents concerning the construction of wind turbines. For Flanders, we updated the list of criteria captured in the study "Hernieuwbare EnergieAtlas Vlaamse gemeenten" (Van Esch et al., 2016, VITO study for Flemish government). For the Walloon region, we updated the list of criteria captured in the study "Estimation du potentiel de developpement d'unites de production decentralizes d'electricit (renouvelable et cogeneration) en Wallonie" (ICEDD report, 2009). For Brussels, a reference framework for large scale wind turbines does not exist, and permission request are evaluated on a case by case basis.

Table 19 provides an overview of the policy documents, briefs, plans and studies which were reviewed to establish an updated list of spatial criteria:

Table 19 Policy documents, briefs, plans and studies reviewed to establish an updated list of spatial criteria

Region	Policy documents, briefs and relevant studies
Flanders	▪ Omzendbrief RO/2014/02 ▪ Windgids 2019 (VEA) ▪ Conceptnota Windkracht 2020 ▪ VLAREM 5.20.6.1 regulations ▪ Handboek Windturbines 2019 (veiligheidsrichtlijnen + rekenblad) ▪ Hernieuwbare EnergieAtlas Vlaamse gemeenten (Van Esch et al., 2016) ▪ Onderzoek naar de GIS-modellering van diverse aspecten van windturbines (Vermeiren et al., 2017)
Walloon region	▪ Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013) ▪ Code du developpement territoriel (CODT_FR; 2019). Estimation du potentiel de developpement d'unites de production decentralizes d'electricit (renouvelable et cogeneration) en Wallonie (ICEDD report, 2009)
Brussels	No official documents are publicly available for large scale wind turbines. A draft was made by Prof. Marc Runacres and colleagues (awaiting permission to review). The principles from the Flemish framework were adopted to Brussels.

Table 20 and Table 21 describe all the positive and negative boundary conditions used in the Dynamic Energy Atlas, and include references to the relevant policy texts and documents that warrant their inclusion in this study.

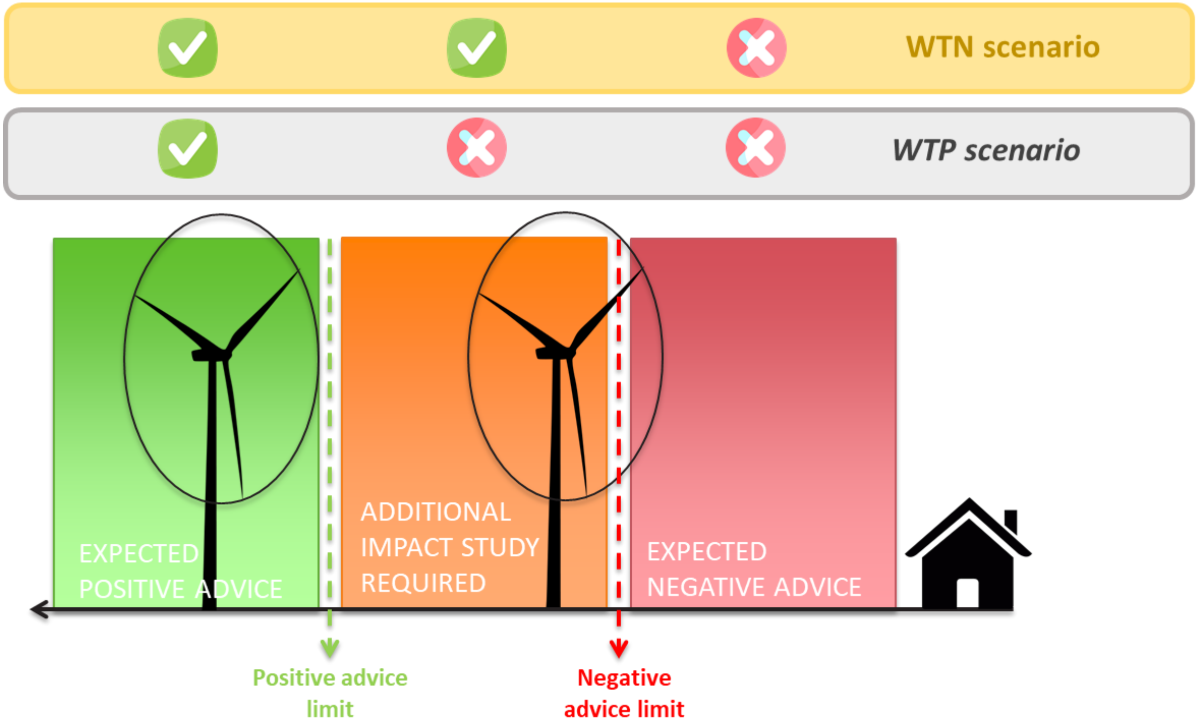
For BREGILAB, we developed two scenario's combining the information captured in the study by Van Esch and colleagues with the 'REV2030' and 'REV2030+' policy scenarios and the ICEDD study with 'the haute and moyenne policy scenarios' with the outcomes of the study "Onderzoek naar de GIS-modellering van diverse aspecten van windturbines" (Vermeiren et al. 2017) with respect to safety distances and norms.

The Vermeiren et al. (2017) study specifically focuses on taking into account safety and nuisance to households and economic activities when modelling the available space for wind turbines as a set of distance rules. Distance rules refer to minimum distance between a wind turbine and existing infrastructure, buildings or designated areas where either no turbine can be built(negative advice limit) or where it is expected that the construction of wind turbines is permitted without additional research and checks (positive advice limit) (Figure 19). Often the negative and positive advice limit are not identical, the zone in between is where wind turbines can be built if additional research or checks confirm certain criteria are fulfilled. For Flanders actual distance rules are described in Vermeiren et al., 2017, and where needed updated with the most recent version of the computation rules embedded in the "Handboek Windturbines 2019". For the Walloon region distance rules are described in the Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013).

Additionally, distance rules are also defined for positive boundaries. Here, the emphasis lies on areas where wind turbines are preferentially located. For example, all regional governments prefer, or allow, the construction of wind turbines within a certain distance of existing roads, railways, waterways and energy infrastructure. Also for positive boundaries, the distance rules are based on policy documents, briefs and relevant studies (Table 19).

The adopted distance rules for positive and negative boundary conditions are described in Table 20 and Table 21.

There are also several negative and positive boundary conditions without distance rules, but overlap with the spatial extent of a criteria is the limiting factor (e.g. nature conservation areas, protected air traffic control zones etc.). In such case the rule of thumb is that minimal overlap leads to exclusion in the case of a negative boundary condition or inclusion in case of a positive boundary condition. However, there are some criteria that form an exception as they are not limitative (inclusive) as such but only in combination with another negative or positive boundary condition. To allow this differentiation, we work with a weight between 0 and 1 per criteria, and a threshold 0.5 to exclude (or include) a pixel (100 by 100m) based on all criteria limitative (or inclusive) at this location. We use the principle of marginal utility to evaluate a pixel (see Van Esch et al., 2016; p69). For example, air traffic control orange zones, military protection orange zones, open space > 1000ha in Flanders and Brussels and the protected views around urban settlements in the Walloon region receive a weight of 0.4 (i.e. 2/5 in Table 20 and Table 21) while all others receive a weight of 1 (i.e. x in Table 20 and Table 21). A location that falls only within an air traffic orange control zone is not excluded as potential location to install a wind turbine (0.4< threshold), if the location falls within a nature protection zone (weight 1) as well it would have been excluded as the total weight (1) exceeded the threshold (0.5). Likewise, if the location falls within a contiguous open space >1000ha (0.4< threshold), the combined weight based on the principle of marginal utilities equals 0.64 and the pixel is excluded. Weights that differ from one are described in Table 20 and Table 21.



	Positive advice limit	Negative advice limit	
Example:	150m	56m	Buildings
	392m	168m	Power lines
	Orange zones	Red zones	Air traffic
	560m	560m	Wind turbines
	√	√	Natura2000 (contour)

Figure 19 Schematic overview representing the distance rules to construct wind turbines, where within the negative advice limit no wind turbines are allowed, outside the positive advice limit wind turbines are usually licensed, and in between (orange zone) additional impact studies are required before licensing.

The two BREGILAB scenarios are:

- The **WTN scenario** where the negative advice limit is used as the minimal distance between wind turbines and other infrastructure, buildings and designated areas. In addition, all relevant negative boundary conditions without distance rules are taken into account to their full extent with the exception of the air traffic control orange zones, military protection orange zones, open space > 1000ha in Flanders and Brussels and the protected views around urban settlements in the Walloon region. Here at least one other negative boundary condition needs to be limitative at the location to be considered limiting. Positive boundary conditions indicate where wind turbines can be built. An important criterion is that they need to be within a certain distance of existing roads, railways, waterways and energy infrastructure. In the WTN scenario, this distance is at its maximum for Flanders. The maximum distance implies that multiple rows of wind turbines can be constructed at both sides of existing infrastructure.
- The **WTP scenario** where the positive advice limit is used as the minimal distance between wind turbines and other infrastructure, buildings and designated areas. In addition, all relevant negative boundary conditions without distance rules are taken into account to their full extent apart from the protected views around urban settlements in the Walloon region

who only play a role when at least one other negative boundary condition is limitative. Further, protected landscapes (PIP) and areas with moderate risks for karst in the Walloon region are added to the list of negative boundary conditions. Positive boundary conditions indicate where wind turbines can be built. An important criterion is that they need to be within a certain distance of existing roads, railways, waterways and energy infrastructure. In the WTP scenario, this distance is at its minimum for Flanders, and unchanged for the Walloon region. The minimum distance only allows the construction of one row of wind turbines at both sides of the existing infrastructure.

In other words, the WTN scenario is from both the negative and positive boundary condition side the most flexible scenario as it does not automatically exclude the zone which requires additional studies (orange), and positive boundary conditions are less restrictive (i.e. multiple rows of wind turbines can be built on both sides of infrastructure). The output of this scenario will in first instance be used to run the energy system model (e.g. TIMES).

Table 20 Negative boundary conditions used to model the available space to construct onshore wind turbines in Belgium according the WTN and WTP scenarios.

For each boundary condition it is indicated which policy text and documents forms warrants inclusion as relevant criteria, and the WT dependent distance rule (expressed in m) for negative and positive advice limit (if relevant). An x indicates in the WTN and WTP column those boundary conditions where minimal overlap is limitative (i.e. weight = 1), while a weight between 0 and 1 indicates boundary conditions which are only important in case of other limitative conditions present at that location. Most recent available data are used for each boundary conditions (2013-2020). Source data and version information is available upon request for each criterion.

Negative boundary conditions	**Flemish region**	**Walloon region**	**Brussels Capital**	**WTN**	**WTP**	**Policy Framework (*original text)***	**Policy Document**	**Distance rule (depends on WT characteristics)**
Buildings	x	x	x	56m	150m	Bijzondere zorg moet worden gedragen ten aanzien van bewoonde vergunde of vergund geachte gebouwen in de omgeving die vreemd aan de inrichting zijn; Als een slagschaduwgevoelig object zich bevindt binnen de contour van vier uur verwachte slagschaduw per jaar van de windturbine, wordt de windturbine uitgerust met een automatische stilstand module; Voor relevante slagschaduwgevoelige objecten in industriegebied, met uitzondering van woningen, geldt een maximum van dertig uur effectieve slagschaduw per jaar, met een maximum van dertig minuten effectieve slagschaduw per dag; Exclure d'emblée de certains périmètres bien délimités par différents classements ou status de protection en vigueur - zones d'habitats et d'habitat à caractère rural au plan de secteur.	**Omzendbrief RO/2014/02** - Windgids 2019 (VEA) - VLAREM 5.20.6.1 - Handboek Windturbines 2019 (veiligheidsrichtlijnen + rekenblad) - Onderzoek naar de GIS-modellering van diverse aspecten van windturbines (Vermeiren et al. 2017) Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013)	Negative advice limit: rotor diameter/2 Positive advice limit: rotor diameter/2+Hub height

Negative boundary conditions	Flemish region	Walloon region	Brussels Capital	WTN	WTP	Policy Framework (*original text*)	Policy Document	Distance rule (depends on WT characteristics)
Residential parcels (Fl and Br)	x		x	250m	250m	Wanneer de dichtstbijzijnde vreemde woning of het dichtstbijzijnde woongebied zich bevinden op een afstand van meer dan 250 m van de windturbinemast, mag ervan uitgegaan worden dat de hinder veroorzaakt door de windturbine/het windturbinepark tot een aanvaardbaar niveau beperkt kan worden; Als een slagschaduwgevoelig object zich bevindt binnen de contour van vier uur verwachte slagschaduw per jaar van de windturbine, wordt de windturbine uitgerust met een automatische stilstand module; De windturbines die in de indelingslijst van titel I van het VLAREM als hinderlijke inrichtingen zijn aangeduid, moeten voldoen aan de algemene en sectorale voorwaarden op het vlak van geluid opgenomen in titel II van het VLAREM (geluidsimpact, slagschaduw en veiligheid); Voor relevante slagschaduwgevoelige objecten in alle andere gebieden, en voor woningen in industriegebied, geldt een maximum van acht uur effectieve slagschaduw per jaar, met een maximum van dertig minuten effectieve slagschaduw per dag.	**Omzendbrief RO/2014/02** - Windgids 2019 (VEA) - VLAREM 5.20.6.1 - - Handboek Windturbines 2019 (veiligheidsrichtlijnen + rekenblad) - Onderzoek naar de GIS-modellering van diverse aspecten van windturbines (Vermeiren et al. 2017) - Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013)	Negative and positive advice limit: *Werpafstand bladbreuk (nominaal vermogen) indien > tiphoogte*
Residential parcels within residential area (Wal)		x		600m	600m	Exclure d'emblée de certains périmètres bien délimités par différents classements ou status de protection en vigueur - zones d'habitats et d'habitat à caractère rural au plan de secteur; Pour le grand éolien, la norme de bruit à l'immission est conforme aux conditions sectorielles et - la distance à la zone d'habitat s'élève à minimum 4 fois la hauteur totale des éoliennes pour le moyen eolien <1MW la distance minimale à l'habitat est fixée à 350m - la distance aux habitations hors zone d'habitat pourra être inférieure à 4 fois la hauteur totale des éoliennes (et sans descendre en-dessous de 400 mètres) pour autant L'effet stroboscopique ne doit pas être supérieur à 30 heures par an et 30 min par jour.	Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013)	Negative and positive advice limit: 4x (rotor diameter/2+Hub height) AND >400m for wind turbines with rated power > 1MW else 350m
Residential parcels outside residential area (Wal)		x		400m	400m			Negative and positive advice limit: 400m
Planned residential area (Fl)	x			250m	250m	See residential parcels (Fl and Br)	See residential parcels (Fl and Br)	Negative and positive advice limit: *Werpafstand bladbreuk (nominaal vermogen) indien > tiphoogte*

Negative boundary conditions	Flemish region	Walloon region	Brussels Capital	WTN	WTP	Policy Framework (*original text*)	Policy Document	Distance rule (depends on WT characteristics)
Planned residential area (Wal)		x		600m	600m	See residential parcels with residential area (Wal)	See residential parcels with residential area (Wal)	Negative and positive advice limit: 4x (rotor diameter/2+Hub height) AND >400m for wind turbines with rated power > 1MW else 350m
Undeveloped parcels in industrial areas (ZAE; Wal)		x		0m	200m	Périmètres dont l'affectation projetée selon l'avant-projet de révision de plan de secteur adoptée par le Gouvernement correspond à l'une des 5 zones visées ci-dessus - zones d'activité économique, à l'exception des parcelles déjà mise en oeuvre et pour autant que les activités présentes dans la ZAE ne soient pas mises en péril. Les éoliennes ne seront autorisées qu'à l'issue d'une évaluation spécifique du risque pour les personnes et les biens. En cas d'implamantation d'eoliennes dans un périmètre de 200m autour des ZAE, l'intercommunale de développement économique concernéee sera interrogée sur ses intentions d'extension.	Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013)	Positive advice limit: 200m
Vulnerable institutions (schools, retirement and nursing homes, etc)	x		x	250m	250m	See residential parcels (Fl and Br)	See residential parcels (Fl and Br)	Negative and positive advice limit: *Werpafstand bladbreuk (nominaal vermogen) indien > tiphoogte*
Navigable waterway network	x	x	x	56m	56m	Safety guidelines	Onderzoek naar de GIS-modellering van diverse aspecten van windturbines (Vermeiren et al. 2017)	Negative and positive advice limit are identical (rotor diameter/2 AND > 50m)
Railway network	x	x	x	56m	150m	Distance d'exclusion: zone tampon de 50 m autour du réseau ferroviaire & zone tampon de 190 m autour du réseau ferroviaire à grande vitesse (TGV) (info Infrabel) Distance conditionelle: Si la distance est inférieure à 50m (= la longueur de la pâle) : acceptation éventuelle dans certains cas (lignes à basse vitesse dans les zones industrielles, transport de marchandises, non électrifiées et avec peu de personnel) et sous la condition de mener une analyse de risque probante.	Onderzoek naar de GIS-modellering van diverse aspecten van windturbines (Vermeiren et al. 2017) - Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013)	Negative advice limit: rotor diameter/2 AND >30m Positive advice limit: rotor diameter/2+Hub height
High Speed Train infrastructure	x	x	x	190m	190m			Negative and positive advice limit: 190m

Negative boundary conditions	Flemish region	Walloon region	Brussels Capital	WTN	WTP	Policy Framework (*original text*)	Policy Document	Distance rule (depends on WT characteristics)
Road network (highway and primary roads) (Fl and Br)	x		x	56m	66m	Safety guidelines	Handboek Windturbines 2019 (veiligheidsrichtlijnen + rekenblad) - Onderzoek naar de GIS-modellering van diverse aspecten van windturbines (Vermeiren et al. 2017)	Negative advice limit: rotor diameter/2 AND > 50m Positive advice limit: rotor diameter/2+10 AND > 50m
Road network (highway and primary roads) (Wal)		x		84m	150m	Distance d'exclusion: Zone tampon de 1,5 fois la longueur des pales des éoliennes Distance conditionelle: Zone tampon allant du bord de la structure à la hauteur de l'éolienne autour du réseau autoroutier et des routes à 4 voies avec berme centrale	Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013)	Negative advice limit: 1.5*(rotor diameter/2) Positive advice limit: rotor diameter/2+hub height
Planned infrastructure works (Wal)		x		x	x	see Road network (Wal)	see Road network (Wal)	
Power lines (Elia)	x	x	x	168m	392m	De impact op veiligheid (afstand tot gebouwen, ondergrondse leidingen en Seveso-bedrijven); Distance d'exclusion: La distance minimale entre l'éolienne par rapport à l'axe de la ligne électrique HT doit être égale à au moins 1,5 fois le diamètre du rotor. Distance conditionelle: Si l'éolienne est située à une distance comprise entre 1,5 et 3,5 fois le diamètre du rotor, le promoteur du projet avertira les gestionnaires du réseau.	Windgids 2019 (VEA) + Handboek Windturbines 2019 (veiligheidsrichtlijnen + rekenblad) - Onderzoek naar de GIS-modellering van diverse aspecten van windturbines (Vermeiren et al. 2017) - Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013)	Negative advice limit: 1.5*rotor diameter Positive advice limit: 3.5*rotor diameter
Pipe lines (Fetrapi)	x	x	x	25m	131m	De impact op veiligheid (afstand tot gebouwen, ondergrondse leidingen en Seveso-bedrijven)	Windgids 2019 (VEA) + Handboek Windturbines 2019 (veiligheidsrichtlijnen + rekenblad) - Onderzoek naar de GIS-modellering van diverse aspecten van windturbines (Vermeiren et al. 2017)	Negative advice limit: 25m Positive advice limit: Hub height + 1/3*rotor diameter
SEVESO buildings	x	x	x	250m	477m	De windturbines die in de indelingslijst van titel I van het VLAREM als hinderlijke inrichtingen zijn aangeduid, moeten voldoen aan de algemene en sectorale voorwaarden op het vlak van geluid opgenomen in titel II van het VLAREM (veiligheid);	**Omzendbrief RO/2014/02** HANDBOEK WINDTURBINES Richtlijnen voor de risicoberekeningen van windturbines (01/10/2019 v1.1) - Windgids 2019 (VEA) - Onderzoek naar	Negative advice limit: *Werpafstand bladbreuk (rated power) AND > total height* Positive advice limit:

Negative boundary conditions	Flemish region	Walloon region	Brussels Capital	WTN	WTP	Policy Framework (*original text*)	Policy Document	Distance rule (depends on WT characteristics)
						De impact op veiligheid (afstand tot gebouwen, ondergrondse leidingen en Seveso-bedrijven)	de GIS-modellering van diverse aspecten van windturbines (Vermeiren et al. 2017)	*Werpafstand bladbreuk (overdrive) AND >total height*
Nuclear facilities	x	x	x	2000m	2000m	Guideline Federal Agency for Nuclear Control (FANC)	Handboek Windturbines 2019 (veiligheidsrichtlijnen + rekenblad)	Negative and positive advice limit: 2000m
Air traffic and radar control - red zones (Skeyes)	x	x	x	x	x	De mogelijke impact op militaire en burgerluchtvaart moet worden nagegaan, niet alleen in de nabijheid van luchthavens maar ook ten aanzien van bijvoorbeeld radarinstallaties. Oprichten van thematische werkgroep burgerluchtvaart met afstemming tussen windsector en veiligheid luchtvaartactiviteiten.	**Conceptnota Windkracht 2020** - Windgids 2019 (VEA) - Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013)	
Air traffic and radar control - orange zones (Skeyes)	x	x	x	2/5	x	See Air traffic and radar control - red zones (Skeyes)	See Air traffic and radar control - red zones (Skeyes)	Negative advice limit: Only relevant if one other criteria is fulfilled
Miltary air and radar protection zone - red zones (GCFOE)	x	x	x	x	x	De mogelijke impact op militaire en burgerluchtvaart moet worden nagegaan, niet alleen in de nabijheid van luchthavens maar ook ten aanzien van bijvoorbeeld radarinstallaties. Oprichten van een thematische werkgroep defensie met afstemming tussen windsector en veilige luchtvaart en andere activiteiten.	**Conceptnota Windkracht 2020** - Windgids 2019 (VEA) - Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013)	
Miltary air and radar protection zone - orange zones (GCFOE)	x	x	x	2/5	x			Negative advice limit: Only relevant if one other criteria is fulfilled
Constructed wind turbines	x	x	x	560m	560m	Avoid wake effects		Negative and positive advice limit: 5*rotor diameter
Licensed windturbines (Fl)	x			560m	560m			

Negative boundary conditions	**Flemish region**	**Walloon region**	**Brussels Capital**	**WTN**	**WTP**	**Policy Framework (*original text)***	**Policy Document**	**Distance rule (depends on WT characteristics)**
Natura2000	x	x	x	x	x	Inplanting windturbines vermijden in gebieden met een belang voor het functioneren van de agrarische, natuurlijke en bosstructuur; Voor de belangrijke natuurgebieden, waaronder Vlaams Ecologisch Netwerk, speciale beschermingszonehabitatrichtlijn en speciale beschermingszone-vogelrichtlijn, andere gebieden met belangrijke ecologische waarden (bijvoorbeeld leefplaatsen van beschermde soorten of beschermde vegetaties) en natuurreservaten dient een omgevingsanalyse uit te maken welke afstand als buffer aangewezen is. Concreet betekent dat laatste afwegingselement dat de oprichting van windturbines of een windturbinepark in het buitengebied wel kan in of nabij een bos en nabij een natuurgebied met eerder beperkte natuurwaarde, maar in principe moet worden vermeden in gebieden met een (potentieel) belang voor speciale beschermingszones. Artikel 36ter, §3, stelt dat als een activiteit (of een plan of een programma) een betekenisvolle aantasting van de natuurlijke kenmerken van een speciale beschermingszone (Vogel- of Habitatrichtlijngebied) kan veroorzaken, die activiteit aan een passende beoordeling moet worden onderworpen (= de habitattoets); Exclure d'emblée de certains périmètres bien délimités par différents classements ou status de protection en vigueur - zones de parc, naturelles au plan de secteur; Les sites permettant d'implanter des projets sans impacts pour la biodiversité sont privilégiés. En cas d'impact probable d'un projet sur les espèces et habitats protégés au sens des directives européennes, celui-ci intègrera des mesures d'atténuation des impacts; Geen richtlijnen op niveau Brussel voor grote windturbines (>250kWh) - daarom zie Vlaanderen	**Omzendbrief RO/2014/02** - Windgids 2019 (VEA) Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013)	
Nature conservation areas	x	x	x	x	x	see Natura2000	see Natura2000	
Reserved zones for nature reserves (i.e. Visiegebieden) (Fl)	x			x	x	see Natura2000	see Natura2000	

Negative boundary conditions	**Flemish region**	**Walloon region**	**Brussels Capital**	**WTN**	**WTP**	**Policy Framework (*original text*)**	**Policy Document**	**Distance rule (depends on WT characteristics)**
Designated silent zones (i.e. Stiltegebieden)	x			250m	250m	see Natura2000	see Natura2000	Negative and positive advice limit: *Werpafstand bladbreuk (nominaal vermogen) indien > tiphoogte*
Flemisch Ecological Network (Fl)	x			x	x	see Natura2000	see Natura2000	
Risks for birds and bats (Fl)	x			x	x	see Natura2000	see Natura2000	
Nature, green and park areas (Wal)		x		x	x	see Natura2000	see Natura2000	
Agroforestry zones (Wal)		x		x	x	Exclure d'emblée de certains périmètres bien délimités par différents classements ou status de protection en vigueur - zones forestières au plan de secteur (l'exception des zones pauvres en biodiversité et constituées de plantations de résineux à faible valeur biologique) -- Le mât des éoliennes visées à l'article D.II.37, § 1er, alinéa 6, est situé : 1° en dehors du périmètre d'un site reconnu en vertu de la loi du 12 juillet 1973 sur la conservation de la nature ; 2° à une distance maximale de sept cent cinquante mètres de l'axe des principales infrastructures de communication au sens de l'article R.II.21-1 ; 3° en dehors d'un peuplement de feuillus au sens du Code forestier.	Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013) - CODT_Fr v20.1 (2019)	
Contiguous open space >1000ha (Fl)	x			2/5	x	Inplanting windturbines vermijden in gebieden zonder of met een beperkte verstoring van het ruimtelijk functioneren van landbouw, natuur en bos door andere functies	Omzendbrief RO/2014/02	Negative advice limit: Only relevant if one other criteria is fulfilled
Inundation risk (Fl)	x			x	x	Technical and maintanance limitation	Study "Hernieuwbare EnergieAtlas Vlaamse gemeenten" (Van Esch et al., 2016).	
Waterbodies (Fl)	x	x	x	x	x			

Negative boundary conditions	Flemish region	Walloon region	Brussels Capital	WTN	WTP	Policy Framework (*original text*)	Policy Document	Distance rule (depends on WT characteristics)
Protected monuments	x	x		x	x	Inplanting windturbines vermijden in gebieden met een statuut als ankerplaats volgens de landschapsatlas Altijd evaluatie van nterferentie met de cultuurhistorische kenmerken van het gebied (lijnrelicten, puntrelicten, relictzones, ankerplaatsen, ...) zoals aangegeven in de landschapsatlas; Périmètres dont l'affectation projetée selon l'avant-projet de révision de plan de secteur adoptée par le Gouvernement correspond à l'une des 5 zones visées ci-dessus - sites classés ou inscrits sur la liste de sauvegyarde au sens de l'article 185 du CWATUPE	**Omzendbrief RO/2014/02** - Windgids 2019 (VEA) Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013)	
UNESCO protected zones (Fl)	x			x	x			
Protected cityscapes	x	x		x	x			
Protected landscapes	x	x		x	x			
Catalogued landscapes and sites	x	x		x	x			
Protected archeological sites	x	x		x	x			
Heritage landscapes	x	x		x	x			
Protected views (4km) around urban settlement (Wal)		x		2/5	2/5	Sauf lorsque les éoliennes sont implantées le long des autoroutes, une référence indicative à une inter-distance minimale de 4 km à 6 km, en fonction des résultats de l'étude d'incidence sera prise en considération. Un azimut (ou un angle horizontal) minimal sans éoliennes doit être préservé pour chaque village ; celui-ci sera d'au moins 130°, sur une distance de 4 km. Un examen de l'encerclement sera réalisé sur une distance de 9 km dans le cadre de l'EIE, afin de veiller à la meilleure intégration paysagère possible vis-à-vis des villages concernés et à limiter, le cas échéant, les effets de l'encerclement sur cette distance ;	Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013)	Negative and positive advice limit: Only relevant if one other criteria is fulfilled

Negative boundary conditions	**Flemish region**	**Walloon region**	**Brussels Capital**	**WTN**	**WTP**	**Policy Framework (*original text)***	**Policy Document**	**Distance rule (depends on WT characteristics)**
High risk zones karst (Wal)		x		x	x	Technical and maintanance limitation	The study “Estimation du potentiel de de developpement d’unites de production decentralizes d’electricit (renouvelable et cogeneration) en Wallonie” (ICEDD report, 2009)	
Medium risk zones karst (Wal)		x			x			

Table 21 Postive boundary conditions used to model the available space to construct onshore wind turbines in Belgium according the WTN and WTP scenario's.

For each boundary condition it is indicated which policy text and documents forms warrants inclusion as relevant criteria, and the WT dependent distance rule (expressed in m) for negative and positive advice limit (if relevant). An x indicates in the WTN and WTP column those boundary conditions where minimal overlap is limitative (i.e. weight = 1), while a weight between 0 and 1 indicates boundary conditions which are only important in case of other limitative conditions present at that location. Most recent available data is used for each boundary conditions (2013-2020). Source data and version information is available upon request for each criteria.

Positive boundary conditions	Flemish region	Walloon region	Brussels Capital	WTN	WTP	Policy Framework (*original text*)	Policy Document	Distance rule (depends on WT characteristics)
Industrial areas > 5ha	x		x	250m	250m	Gedeconcentreerde bundeling - een bundeling van windturbines met grootschalige bedrijventerreinen of in het bijzonder in de economische poorten (e.g. (zee)havengebied) en netwerken, gemeenschapsvoorzieningen; Maximaliseren van wind op grootschalige industriegebieden. Input van provincies; Le mât des éoliennes visées à l'article D.II.36, §2, alinéa 2 est situé à une distance maximale de mille cinq cent mètre de l'axe des principales infrastructures de communication au sens de l'article R.II.21-1, ou de la limite d'une zone d'activité économique.	**Omzendbrief RO/2014/02.** Conceptnota windkracht 2020 (Vlaams regering) - Windgids 2019 (VEA) - CODT-Fr v20.1 (2019) fs	Negative and positive advice limit: 250m
Planned industrial area > 5ha	x		x	250m	250m			
Industrial areas		x		1500m	1500m			Negative and positive advice limit: 1500m
Proximity to constructed wind turbines	x	x	x	840m	840m	Gedeconcentreerde bundeling - in clusters zo verspreide inplanting van verschillende individuele turbines vermeden wordt - vanaf 3 windturbines wordt van een cluster gesproken; Principe de regroupement: la priorité va au groupement des unités de production, plutôt qu'à la dispersion d'éoliennes individuelles / Les parcs se composant d'un minimum de 5 éoliennes seront prioritaires	Omzendbrief RO/2014/02 - Windgids 2019 (VEA)	Negative and positive advice limit: 1.5*(5*rotor diameter)
Proximity to licensed wind turbines	x			840m	840m			

<table>
<tr><th>Positive boundary conditions</th><th>Flemish region</th><th>Walloon region</th><th>Brussels Capital</th><th>WTN</th><th>WTP</th><th>Policy Framework (original text)</th><th>Policy Document</th><th>Distance rule (depends on WT characteristics)</th></tr>
<tr><td>Proximity to elongated infrastructre (road, rail and waterway netwok; power lines) (Fl&Br)</td><td>x</td><td></td><td>x</td><td>750m</td><td>500m</td><td rowspan="3">Een technisch haalbare locatie in de open ruimte kan worden onderzocht indien er naar een zo groot mogelijke ruimtelijke bundeling wordt gestreefd met andere infrastructuur, bij voorkeur grotere lijninfrastructuur (bv. wegen, spoorwegen, rivieren, hoogspanningslijnen,...). Resulteert in een beperkte bijkomende markering van het ruimtelijk-landschappelijke.
om landschappelijke redenen: aansluiting bij bestaande grootschalige infrastructuren zoals (zee-)haventerreinen, sluizencomplexen, bundeling met lijninfrastructuren;
Principe de regroupement: les grandes infrastructures de transport (autoroutes, voies navigables,…) et les éoliennes peuvent présenter une cohérence de perception donnant lieu à un renforcement de l’image créée;
Le mât des éoliennes visées à l’article D.II.36, §2, alinéa 2 est situé à une distance maximale de mille cinq cent mètre de l’axe des principales infrastructures de communication au sens de l’article R.II.21-1, ou de la limite d’une zone d’activité économique.</td><td rowspan="3">Omzendbrief RO/2014/02 - Windgids 2019 (VEA) - Cadre de référence pour l'implantation d'éoliennes en région wallone (11/07/2013) - CODT-Fr v20.1 (2019)</td><td>Negative advice limit: 750m
Positive advice limit: 500m</td></tr>
<tr><td>Proximity to elongated infrastructre (road, rail and waterway netwok WITHOUT power lines) (Wal)</td><td></td><td>x</td><td></td><td>1500m</td><td>1500m</td><td rowspan="2">Negative and positive advice limit: 1500m</td></tr>
<tr><td>Planned infrastructure (Wal)</td><td></td><td>x</td><td></td><td>1500m</td><td>1500m</td></tr>
</table>

We follow the methodology developed and implemented in the Dynamic Energy Atlas by VITO (Van Esch et al., 2016) to delineate zones for wind turbine construction. A weighted overlay algorithm is used to map criteria, if the summed (weighted) value of a pixels exceeds 0.5 then the area is excluded (in case of negative boundary conditions) and included (in case of positive boundary conditions) as being available to build wind turbines.

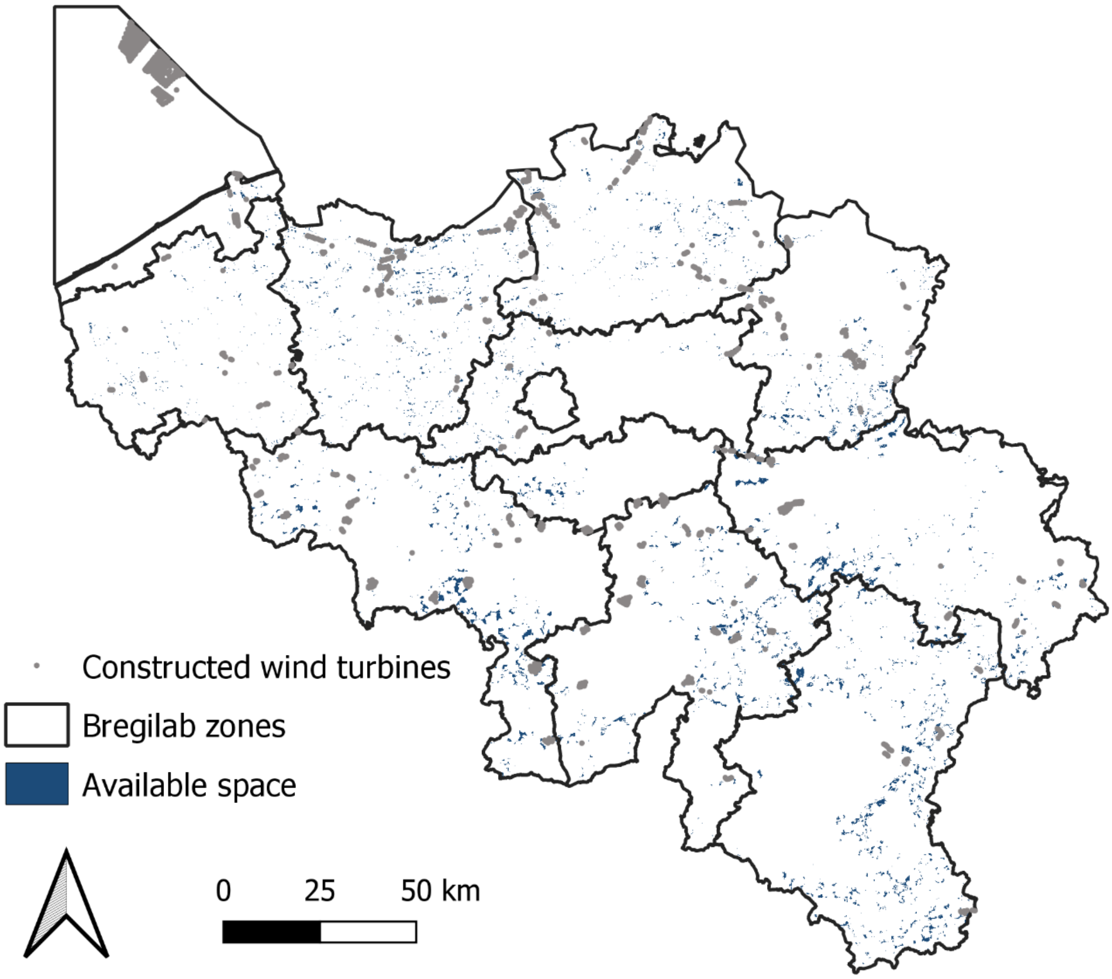


Figure 20 Available space for the construction of wind turbines modelled for Belgium using the WTN scenario, i.e. negative advice limits as boundary conditions (see Table 20 and Table 21).

Subsequently, an allocation algorithm is used to optimally distribute wind turbines (type VESTAS V112 with rated power 3.3MW) within the available space. The optimisation is done from a spatial perspective and not an energetic perspective. The result is the spatial pattern of allocated onshore wind turbines with rated power 3.3MW.

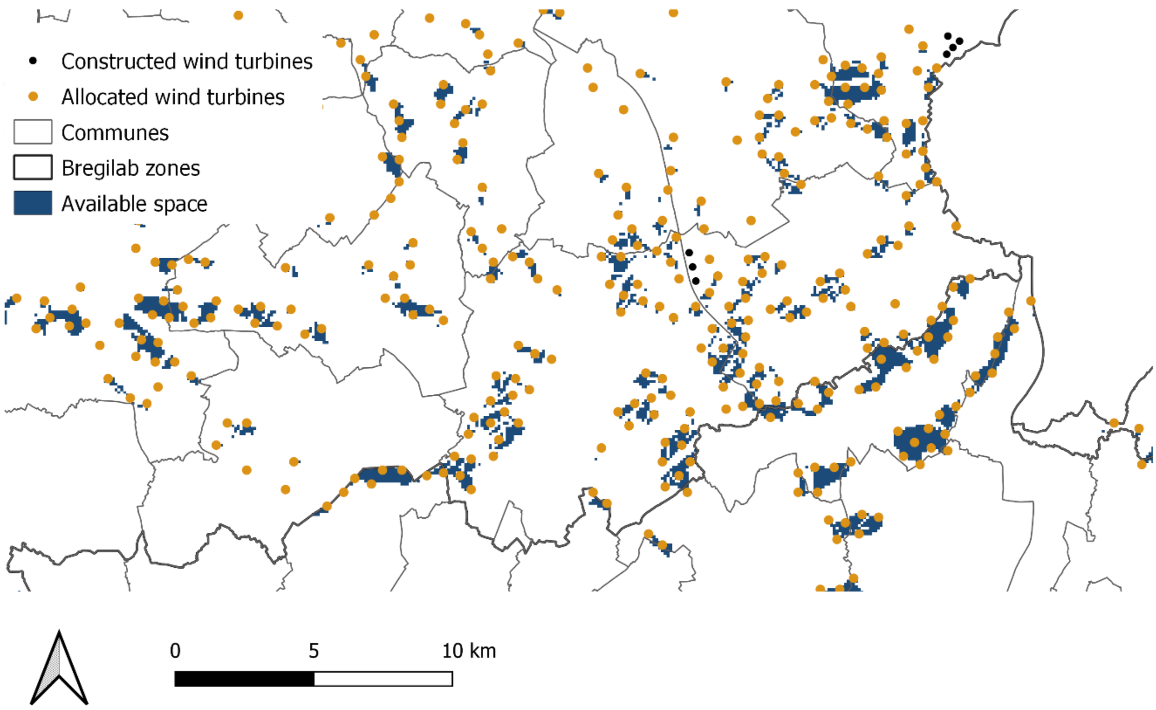


Figure 21 Allocated wind turbines (orange; spacing: 560m) and the available space modelled with the 2017 WTN scenario in South Limburg region.

Annex 2 provides an overview to which extent the selected negative boundary conditions applied in the WTN and WTP scenario overlap with the currently constructed wind turbines. This exercise allows a first evaluation on the limitation of the methodology. It shows that mainly in Flanders an important portion (>5%) of wind turbines are build within the no-go zone around buildings and residential areas. All other criteria overlap minimally with existing wind turbines. This also provides a first insight in the likeliness of existing wind turbines to be replaced by a larger more efficient wind turbine.

→ **Energy production factor**

The energy production factor expresses the amount of energy production per wind turbine. Within the Dynamic Energy Atlas, we calculate the hourly energy production factor (MWh/MW) for the whole of Belgium (on- and offshore) at 100x100m scale using the Wind Energy module. The 2017 hourly wind speed data and technical characteristics VESTAS V112 are combined to create an hourly and annual full load hours (Dutch *Vollast*) map for Belgium (Figure 22).

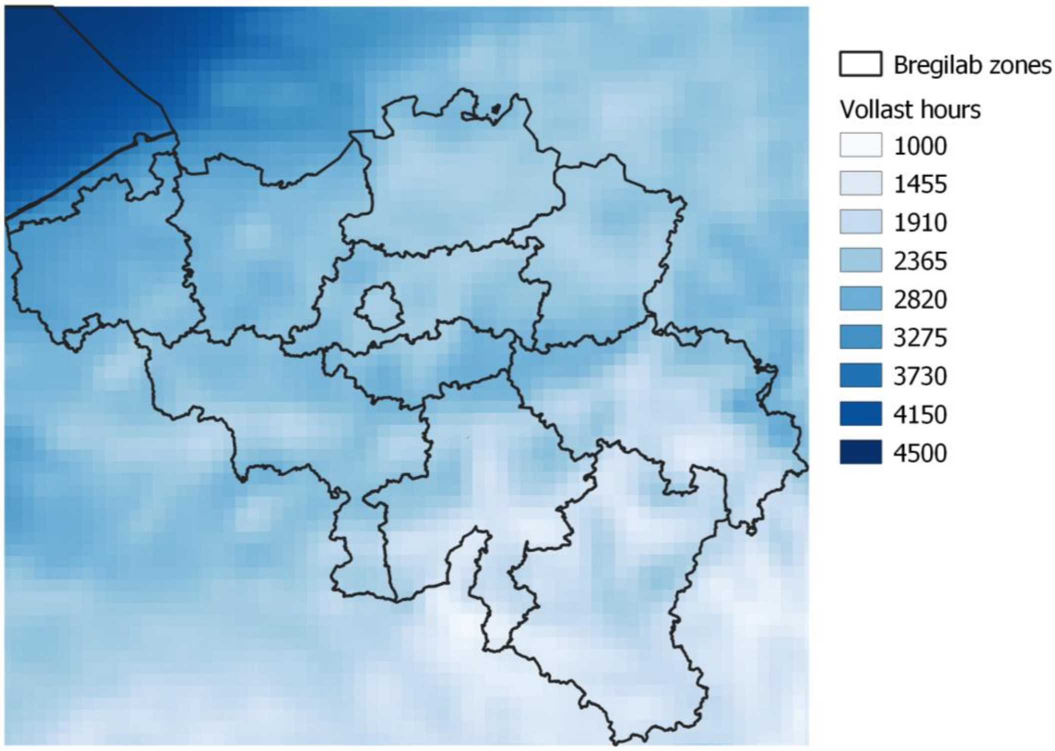


Figure 22 Potential full load hours (1 year is 8760) for 2017 using a VESTAS V112 wind turbine at 1ha level Belgium.

→ **Feasability factor**

An average performance ratio of 0.69 was included as feasibility factor (F_t) to correct hourly wind production. The performance ratio takes into account machine availability, operating efficiency, wake effects and turbine aging.

Hourly wind production data (MWh) is produced at a 100 by 100m resolution by multiplying all three factors (spatial pattern, energy production factor and feasibility factor). Installed capacity is equally derived by multiplying relevant layers (spatial pattern, capacity technology and feasibility factor). The results can be aggregated:

- spatially at each relevant aggregation level, e.g. in this project at the level of statistical sectors, communes, provinces, bregilab zones, regions and Belgium.
- temporally at each relevant aggregation level, e.g. in this project per month, season and year.

5.2.3. CARTOGRAPHIC RESULTS POTENTIAL WIND ENERGY GENERATION

Following maps give a spatial representation of the addition potential for wind production at the level of statistical sectors (onshore only) and Bregilab zones (onshore and offshore). The 100 by 100m data are aggregated at the respective levels.

Onshore the VESTAS V112 with a rated power of 3.3MW is used as representative wind turbine technology.

Figure 23 to Figure 26 indicate that following regions have a high potential for additional onshore wind generation:

- South Province Luxembourg (Lotharingen)
- South Province Limburg
- East and centre Province Antwerpen and the Antwerp harbour
- South-West Province Hainaut
- Province of Oost-Vlaanderen, and especially the north

Following region have a low potential for additional onshore wind generation:

- Brussels Capital region and the surrounding Provinces of Vlaams-Brabant and Brabant Wallon
- The coastal region with exception of Zeebrugge
- Northern parts of the Province Limburg, Hainaut and Liège
- Province Namur

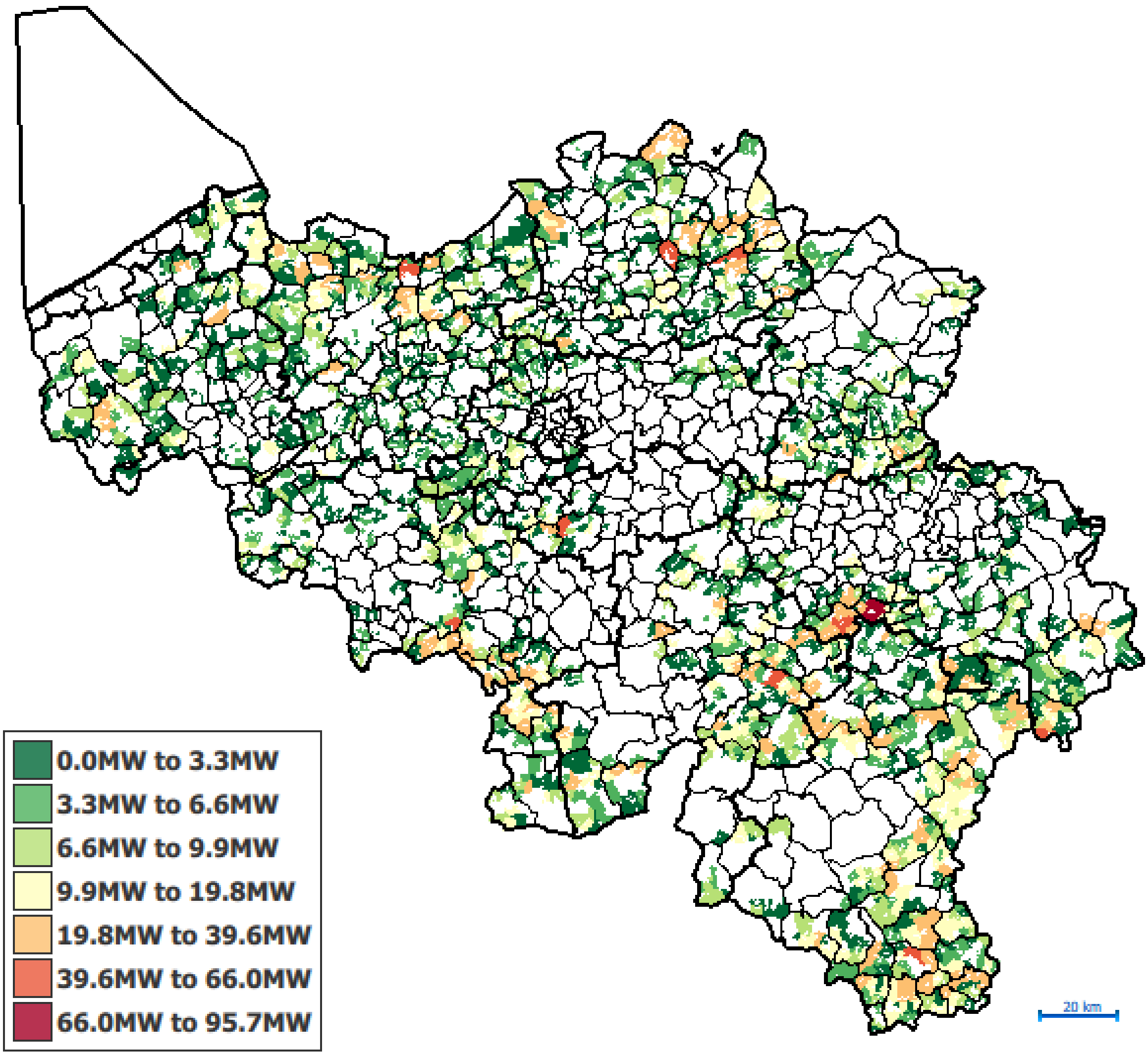


Figure 23 Additional potential WTN scenario for onshore wind capacity (MW) per statistical sector. The rated power of 1 Vestas V112 wind turbine is 3.3MW.

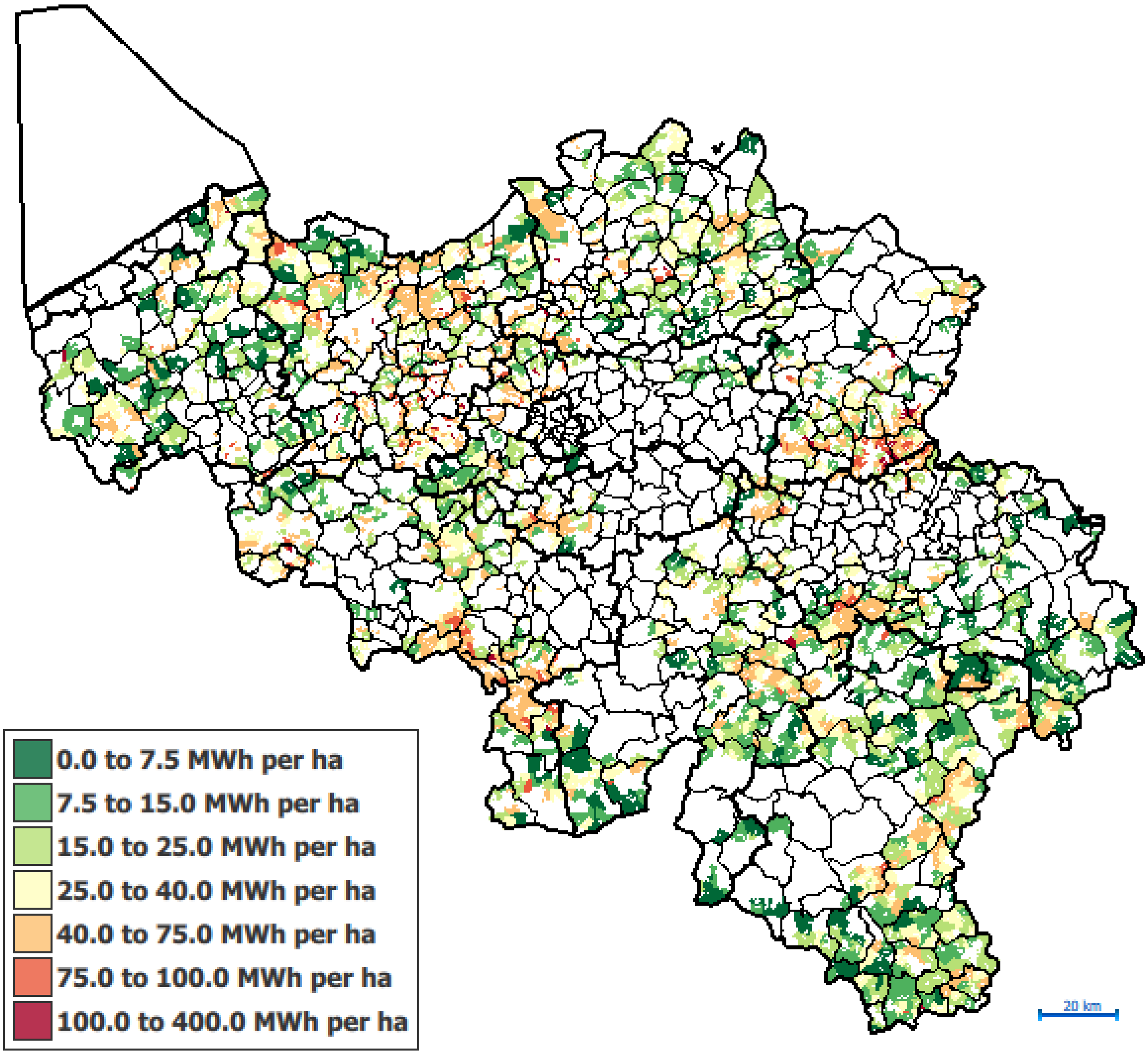


Figure 24 Additional potential WTN scenario for onshore wind energy production (MWh per ha) at the level of statistical sector. The surface area of the statistical sector is taken into account.

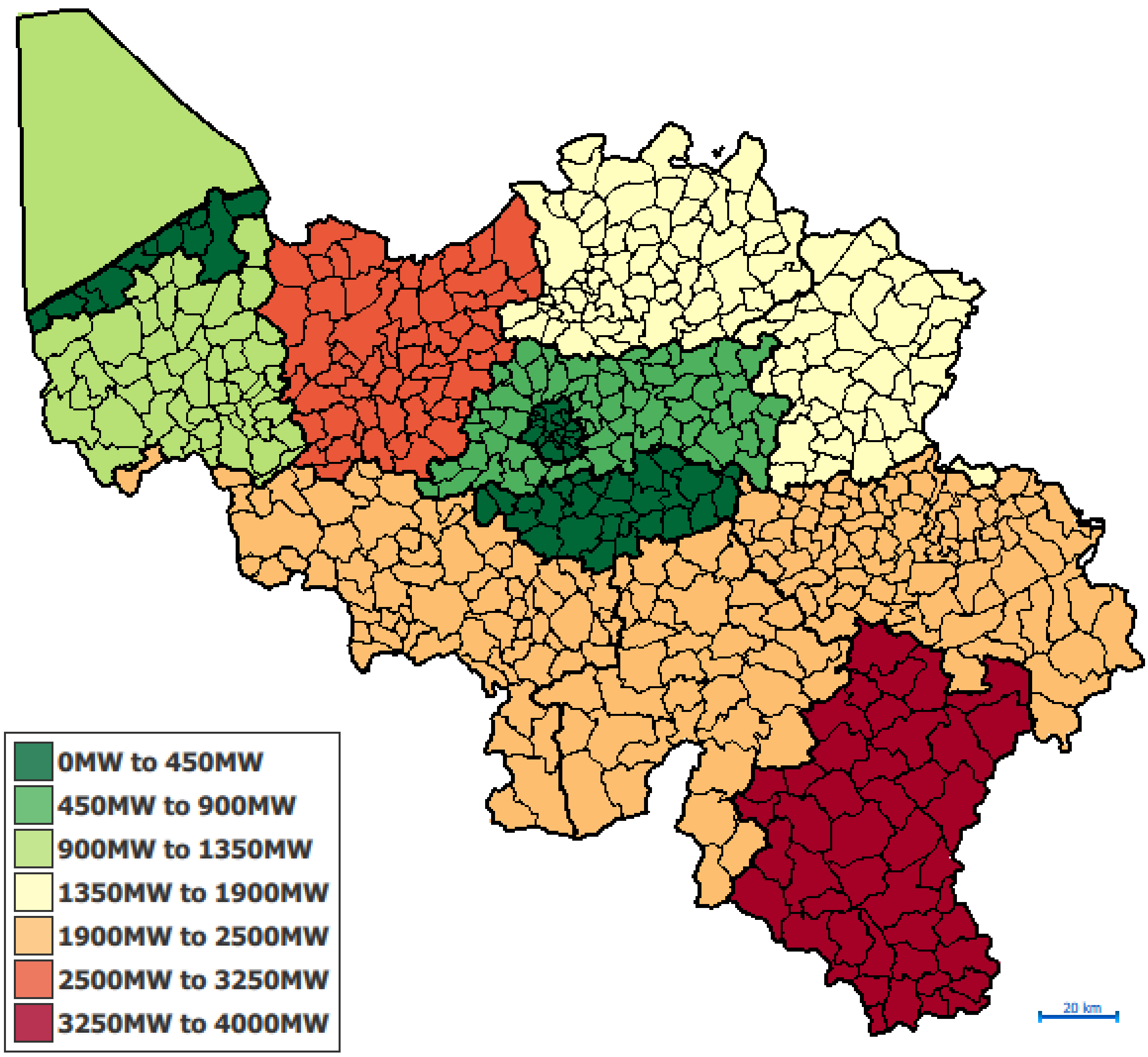


Figure 25 Additional potential WTN scenario for onshore and offshore wind capacity (MW) at the level of Bregilab zone. The rated power of 1 Vestas V112 wind turbine is 3.3MW.

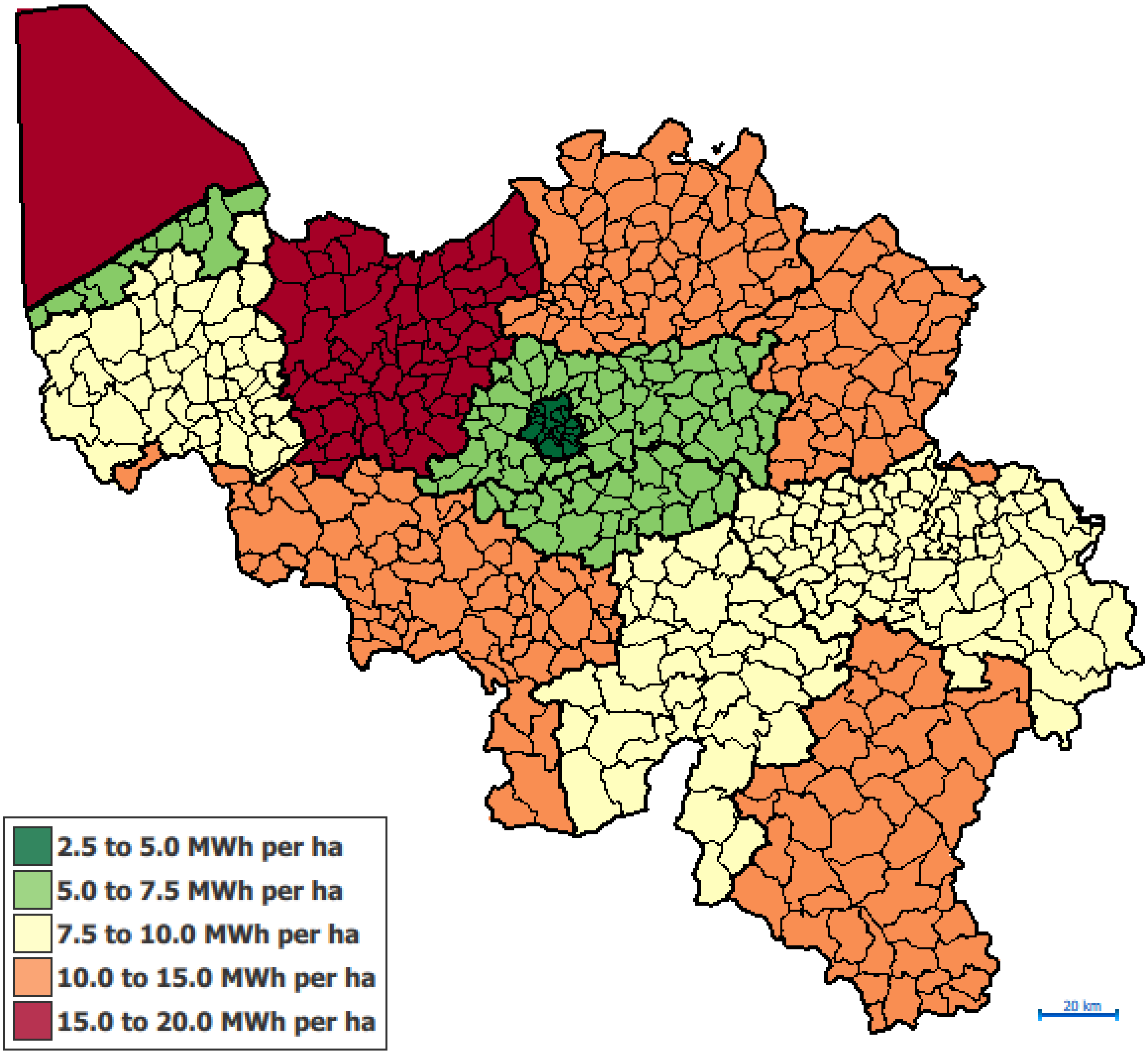


Figure 26 Additional potential WTN scenario for onshore and offshore wind energy production (MWh per ha) at the level of Bregilab zone. The surface area of the Bregilab zone is taken into account.

5.2.4. Variability between weather years (2006-2019) for potential wind production

Besides results for 2017, we extended the potential wind production dataset with 2006-2019 climatic data (see Figure 5). Be aware that spatial conditions did not alter and that 2017 boundary conditions to assess the available space, and therefore installed capacity, were kept fixed. The resulting dataset allows to assess the inter-annual variability in total production at the annual, daily or hourly scale. As such, it supports a sensitivity analysis to changing variability in climate and extreme periods of low wind and/or solar regimes.

Figure 27 exemplifies differences in annual availability factor (AF, MWh production/MW installed) for on- and offshore wind availability at the level of regions. Using 2006 as a reference year we observe that 2006 was a windy year as only 2015 exceeds its availability factor for all regions, and 2008 for offshore availability only. In 2010, the availability of wind was in all regions at its lowest. The variability is highest for onshore wind. Furthermore, a more detailed analysis on periods of low wind and solar is being conducted to allow for a more detailed assessment of the required flexibility of the energy system with a high penetration of wind and solar. The data presented serves as an input to a sensitivity analysis that is ongoing within the BREGILAB project and will be reported separately.

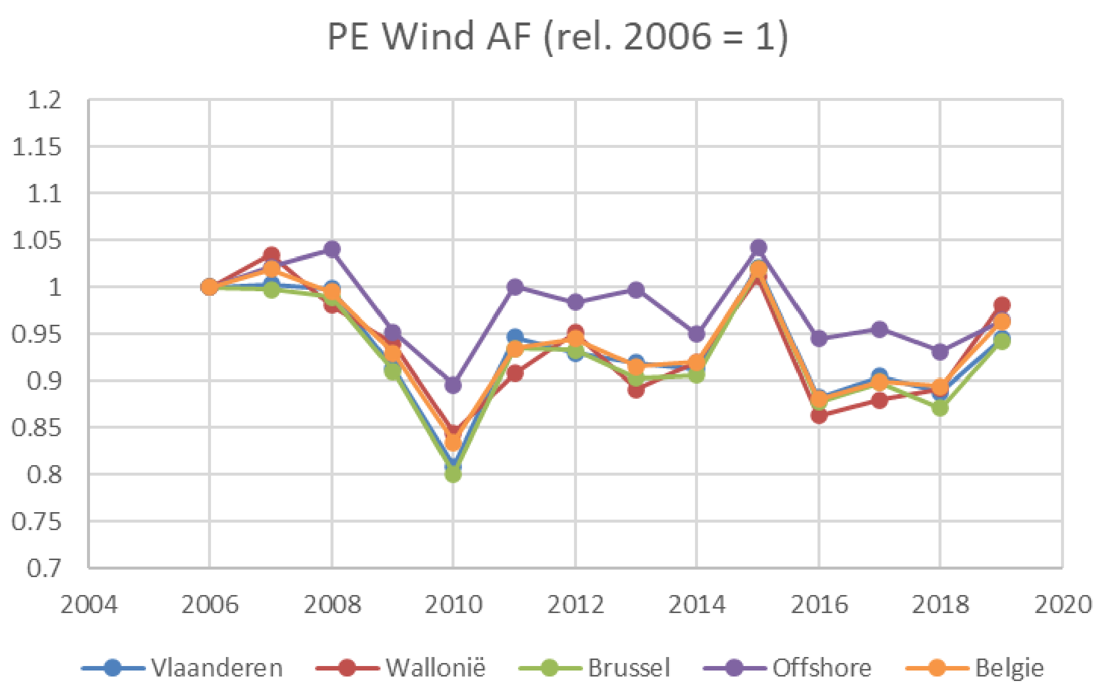


Figure 27 Variability in annual availability factor (MWh/MW) for potential energy production by onshore and offshore wind in the period 2006-2019 with 2006 as reference year.

5.3. POTENTIAL PV ENERGY PRODUCTION

A bottom-up approach is used to assess the potential for PV on roofs and ground-mounted PV. The potential PV production is estimated by mapping the available space in Belgian and combining it with a spatially explicit energy production factor. For roofs, the available roof surface (m²) and hourly energy production factor (kWh m^{-2}) are multiplied to estimate hourly energy production within the Dynamic Energy Atlas. For ground-mounted PV, the focus lays on non-built-up area along transportation infrastructure. Likewise, estimates are made for the corresponding installed capacity.

As for the current PV energy production on roofs (section 4.2), a distinction is made between PV production on residential versus commercial & industrial roofs. The distinction is required as traditionally residential roofs are typically tilted roofs while commercial and certainly industrial roofs are commonly flat. Consequently, installed PV panels will differ in typical orientation and tilt between building types. As the hourly energy production factor is controlled by the tilt and orientation of the PV module installed, different energy production factors will be used to estimate PV production per building type. The distinction is also warranted as different technical feasibility factors are applied with 80% on a commercial & industrial roof versus 40% on residential roofs. Similarly, ground-mounted PV is coupled with a specific tilt and orientation to derive energy production factors and is combined with a technical feasibility of 55% of the available area.

5.3.1. PV PRODUCTION ON RESIDENTIAL ROOFS

→ Spatial boundary conditions

The available space for PV is mapped within the Dynamic Energy Atlas. The positive boundary condition is the (remaining) roof surface on residential buildings. The building layer contained in the CADGIS dataset (FOD economy) is combined with the activity type information contained in the patrimonial data of the “Kadastraal plan België” to attribute a corresponding land use to the building and consequently calculate for each 100 by 100m pixel the residential roof area (m²). To estimate the remaining roof surface, we deduct the roof area occupied by current PV installations (see 4.2.2) and installed solar water heating. Information on the installed capacity and spatial distribution of solar water heating is lacking for Belgium. Instead, we corrected the available roof surface based on 2016 data for Flanders (Van Esch et al., 2016) showing a combined installed and potential of 326 GWh which is translated in a correction factor of 0.13% of available roof area per pixel (i.e. 88 ha / 67,400 ha). As a result, we obtained a map with remaining roof area (in m²) on residential buildings.

→ Energy production

A module with peak capacity of 226 Wp per m² (SPR-MAX3-400) was selected as market model likely to be installed in Belgium in the coming decade. This is aligned to the projected trends in module efficiencies for mass production of c-Si based cell technologies according to the International Technology Roadmap for Photovoltaic (VDMA, 2021; Figure 28). It reflects the continuously development of PV technology and differs with the module (152.7 Wp per m²) used to calculate current PV production which represented PV modules currently installed on Belgian roofs considering an average age of about 5 years.

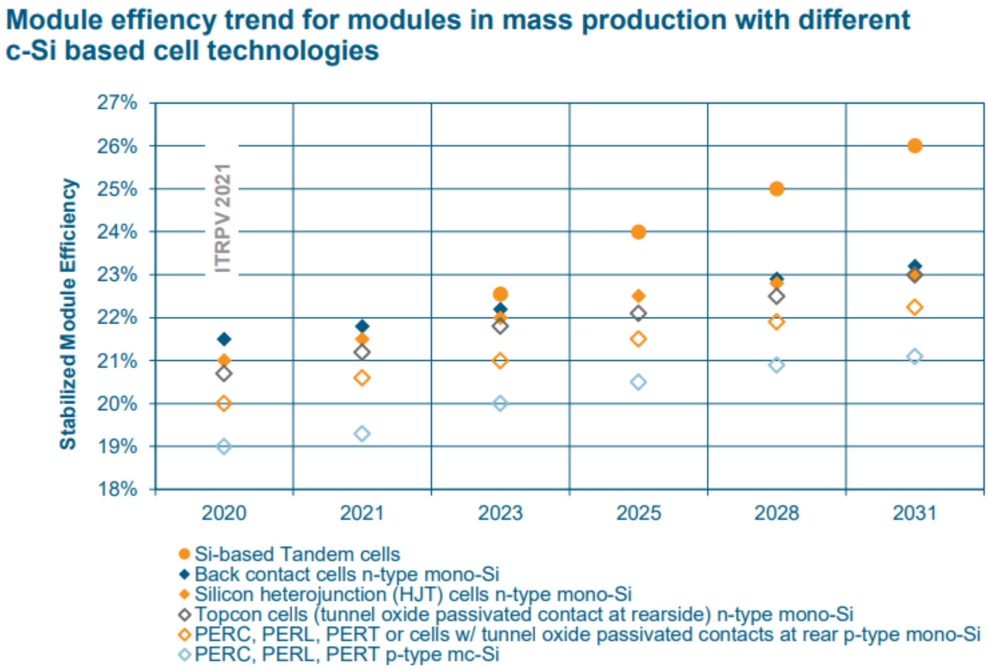


Figure 28 Average module efficiency in mass production in different c-Si solar cell technologies as reported in figure 54 in the ITRPV 2021 (VDMA, 2021).

The energy production factor ($EpF_{j,PV}$, kWh per m²h) for the market technology (i.e. module 226 Wp per m²) per pixel is determined by the spatial and temporal variations in climatic conditions on location j. Imec developed a spatially explicit transfer function that translates the climatic data (irradiation, temperature, wind speed & direction) into an hourly energy production factor. A complete overview of the applied methodology can be found in the functional description (Annex A). Importantly, the transfer function allows to calculate the energy production factor for any given PV installation type and year of interest (e.g. Figure 14).

Currently, three PV energy production factors are calculated for residential roofs (35° tilt angle) using 2006-2019 climatic data, one for south (180°), west (270°) and east (90°) orientation. South orientation is the energetically optimal solution to maximize daily production. However, it is not always technically feasible (e.g. not enough roof area oriented south) or economically desirable (e.g. optimize self-consumption by spreading) to install PV panels southwards on residential roofs. We assumed business-as-usual to distribute the potential PV capacity per orientation type. The optimal distribution was derived previously by comparing modelled with measured loads for 2017 (Annex A):

- South: 0.71
- West: 0.05
- East: 0.24

The same coefficients were used to calculate PV potential on residential roofs.

→ **Feasibility factor**

The remaining area (m²) takes into account the complete roof while the installation of PV is limited by the configuration of the roof, orientation (e.g. excluding north faced areas), spacing of PV panels to avoid shading and windows etc. We apply the rule of thumb produced by the International Energy Agency (International Energy Agency, 2002. Potential for Building Integrated Photovoltaics. IEA Report: PVPS T7-4, Paris) that 40% of the total residential roof area is typically available to install PV panels. For roofs with a tilt > 5°, the Zonnekaart (https://www.energiesparen.be/zonnekaart) reports that 35% is useable (typically east-west) and 36% ideal (typically south) for PV production (case-study Herentals). Unfortunately, it does not include an estimate of how much of these 71% can technically be used to construct PV panels (i.e. fitting rectangular PV panels on dominantly triangle window filled roofs). The 40% is included as a technical feasibility factor for residential roofs.

In addition, some mechanisms decreasing the energy produced by photovoltaic power cells have not been considered in the computation of the provided energy production. Instead the feasibility factor corrects for the known mechanisms like shading effects of neighboring buildings, aging of PV panels and operational losses. Combined these factors reduce the performance with a factor of 0.9259.

Taken into account limited available roof area for technical reasons (0.4) and mechanisms that reduce the performance of installed PV modules (0.9259), we apply a feasibility factor of 0.37 per pixel to correct the potential PV generation. The feasibility factor is independent of location and orientation.

5.3.2. PV PRODUCTION ON COMMERCIAL AND INDUSTRIAL ROOFS

→ Spatial boundary conditions

The available space for PV on commercial and industrial roofs is mapped within the Dynamic Energy Atlas. The positive boundary condition is the (remaining) roof surface on commercial and industrial buildings. The building layer contained in CADGIS dataset (FOD economy) is combined with the activity type information contained in the patrimonial data of the "Kadastraal plan België" to attribute a corresponding land use to the building and consequently calculate for each 100 by 100m pixel the commercial and industrial roof area (m²). To estimate the remaining roof surface, we deduced the roof area occupied by current PV installations (see 4.2.2). As a result, we obtained a map with remaining area (in m²) on commercial and industrial buildings.

→ Energy production

A module with peak capacity of 226 Wp per m² (SPR-MAX3-400) was selected as market model likely to be installed in Belgium in the coming decade. This is aligned to the projected trends in module efficiencies for mass production of c-Si based cell technologies according to the International Technology Roadmap for Photovoltaic (VDMA, 2021; Figure 28). As technology continuously develops this differs with the module (152.7 Wp per m²) used to calculate current PV production.

The energy production factor ($EpF_{j,PV}$, kWh per m²h) for the market technology (i.e. module 226 Wp per m²) per pixel is determined by the spatial and temporal variations in climatic conditions on location j. Imec developed a spatially explicit transfer function that translates the climatic data (irradiation, temperature, wind speed & direction) into an hourly energy production factor. A complete overview of the applied methodology can be found in the functional description (Annex A). Importantly, the transfer function allows to calculate the energy production factor for any given PV installation type and year of interest (e.g. Figure 14).

Currently, two PV energy production factors are calculated for commercial and industrial roofs (10° tilt angle) using 2017 climatic data, one for west (270°) and one for east (90°) orientation. Imec indicates that for flat roofs an equal separation between east and west oriented PV panels is the ideal configuration (e.g. Energyville 2 building) to maximize the available surface area and reduce operational losses due to shading. To simulate the optimal distribution a 50/50 distribution (personal communication Imec) of PV potential was used for west and east facing panels, i.e. applying a 0.5 coefficient to each pixel.

→ **Feasibility factor**

The remaining area (m²) takes into account the complete roof while the installation of PV is limited by the configuration of the roof, orientation (e.g. excluding north faced areas), spacing of PV panels to avoid shading and windows etc. Imec indicates that with an east-west orientation about 80% of the shared roof area (for cooling and other systems) can be occupied by PV panels. For roofs without tilt < 5°, the Zonnekaart (https://www.energiesparen.be/zonnekaart) reports that 25% is useable (typically east-west) and 71% ideal (typically south) for PV production (case-study Herentals). Unfortunately, it does not include an estimate of how much of these 96% can actually technically be used to construct PV panels (i.e. fitting rectangular PV panels on typically rectangular roofs but with shared space for other facilities like air conditioning, skylights, carrying capacity roofs etc.). Therefore, 80% is used as a technical feasibility factor for commercial and industrial roofs.

In addition, some mechanisms decreasing the energy produced by photovoltaic installations have not been considered in the computation of the provided energy production. Instead the feasibility factor corrects for the known mechanisms like shading effects of neighboring buildings, aging of PV panels and operational losses. Combined these factors reduce the performance with a factor of 0.9259.

Taken into account limited available roof area for technical reasons (0.8) and mechanisms that reduce the performance of installed PV modules (0.9259), we apply a feasibility factor of 0.74 per pixel to correct the potential PV generation on commercial and industrial roofs. The feasibility factor is independent of location and orientation.

5.3.3. GROUND MOUNTED PV PRODUCTION ALONG TRANSPORT INFRASTRUCTURE

→ **Spatial boundary conditions**

Besides PV on roofs, the potential for ground-mounted PV, floating PV and building integrated PV (BIPV) offer an important additional opportunity to increase the use of PV in Belgium. Unfortunately, no clear policy guidelines exist to prioritize ground-mounted PV over other land uses (waterbodies, agriculture or industrial complexes) nor to evaluate in a spatially explicit manner the technical potential for BIPV in a reliable way. We therefore limited our assessment to ground-mounted PV along transport infrastructure which is a conservative estimate of ground-mounted PV.

The positive boundary conditions considered are the first 50m along both sides of highways (OSM) and railways (Infrabel) in Belgium. Within this region only areas covered in low vegetation are considered feasible to install PV. For Flanders and Brussels, this corresponds with Class 2 'Laag groen' from the *Groenkaart* (AGIV; 10 by 10m resolution). For the Walloon region, this is derived from the COSW structural plan (2018), and includes the level 5 classes 2311, 2312, 232, 233, 25, 321, 322, 3242 and 325. In Flanders, large open space areas (> 1000ha) are excluded as a negative boundary condition.

→ **Energy production and feasibility factor**

Like for roof PV, a module with peak capacity of 226 Wp per m² (SPR-MAX3-400) was selected as market model likely to be installed in Belgium in the coming decade. Similarly, as for flat roofs, a tilt of 10° is considered and an optimal east-west orientation. A feasibility factor of 55% is lower than for flat roofs as proportionally the area within this 50m is also used for other utilities, hence being shaded and therefore the exclusion from the technical potential will be larger. The 55% is based on feedback from experts previously collected (Van Esch et al., 2016).

5.3.4. CARTOGRAPHIC RESULTS POTENTIAL PV PRODUCTION

Following maps give a spatial representation of the addition potential for PV production at the level of statistical sectors and Bregilab zones. For residential PV the examples refer to south facing roofs, for commercial and industrial PV the examples refer to west facing roofs. The combined residential and commercial&industrial roof potential is provided at 100 by 100m pixel level and Bregilab zones.

In all cases, the SPR-MAX3-400 module with 226 Wp per m² capacity was used as representative market model for PV technology.

Figure 29 to Figure 39 indicate that following regions have a high potential for additional PV on residential, commercial and industrial roofs. For residential roofs it clearly follows the urbanization degree of the different regions in Belgium, and the highest potential is therefore centered around the Brussels Capital region, within the Flemish diamond between Gent, Antwerp, Leuven, Brussels, and large cities across the other regions. The potential on commercial and industrial roofs is highest in the Flemish regions but geographically concentrated around large industrial complexes situated along highways, navigable waterways rather than in urban centres. In Flanders the most important zones are southern West-Flanders and the harbor regions. In the Walloon region forms the Meuse-Sambre an important axis.

Summarized, the potential is highest in Antwerp, Oost-Vlaanderen and Brussels Capital region, and decreases towards the southern and eastern provinces in Belgium. The controlling factor is of course the available roof area.

Figure 39 shows for western Limburg the potential for ground-mounted PV along transport infrastructure. The exits and crossroads are typically ideal locations with sufficient low green area.

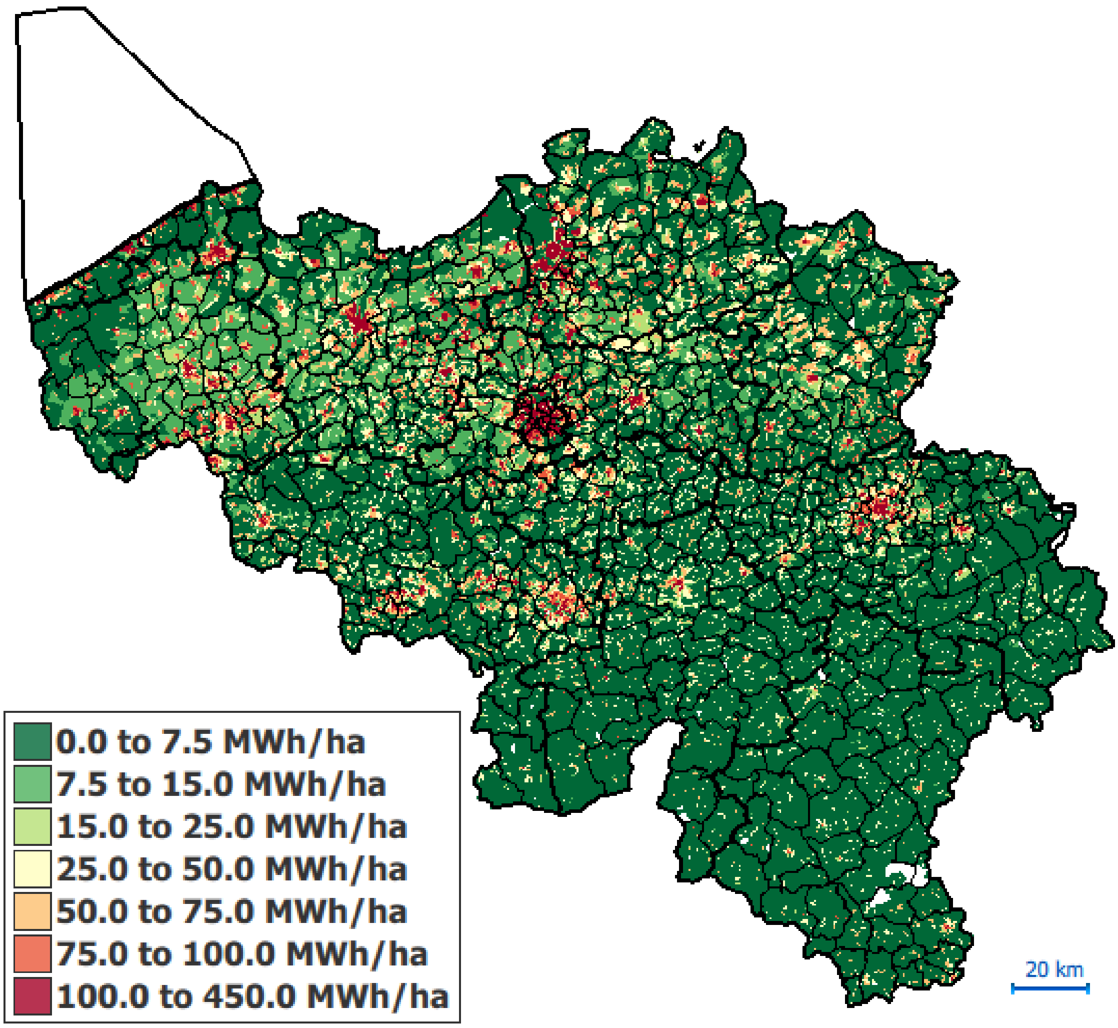


Figure 29 Additional potential energy production (MWh per ha) for south-facing PV on residential roofs at the level of statistical sector. The surface area of the statistical sector is taken into account.

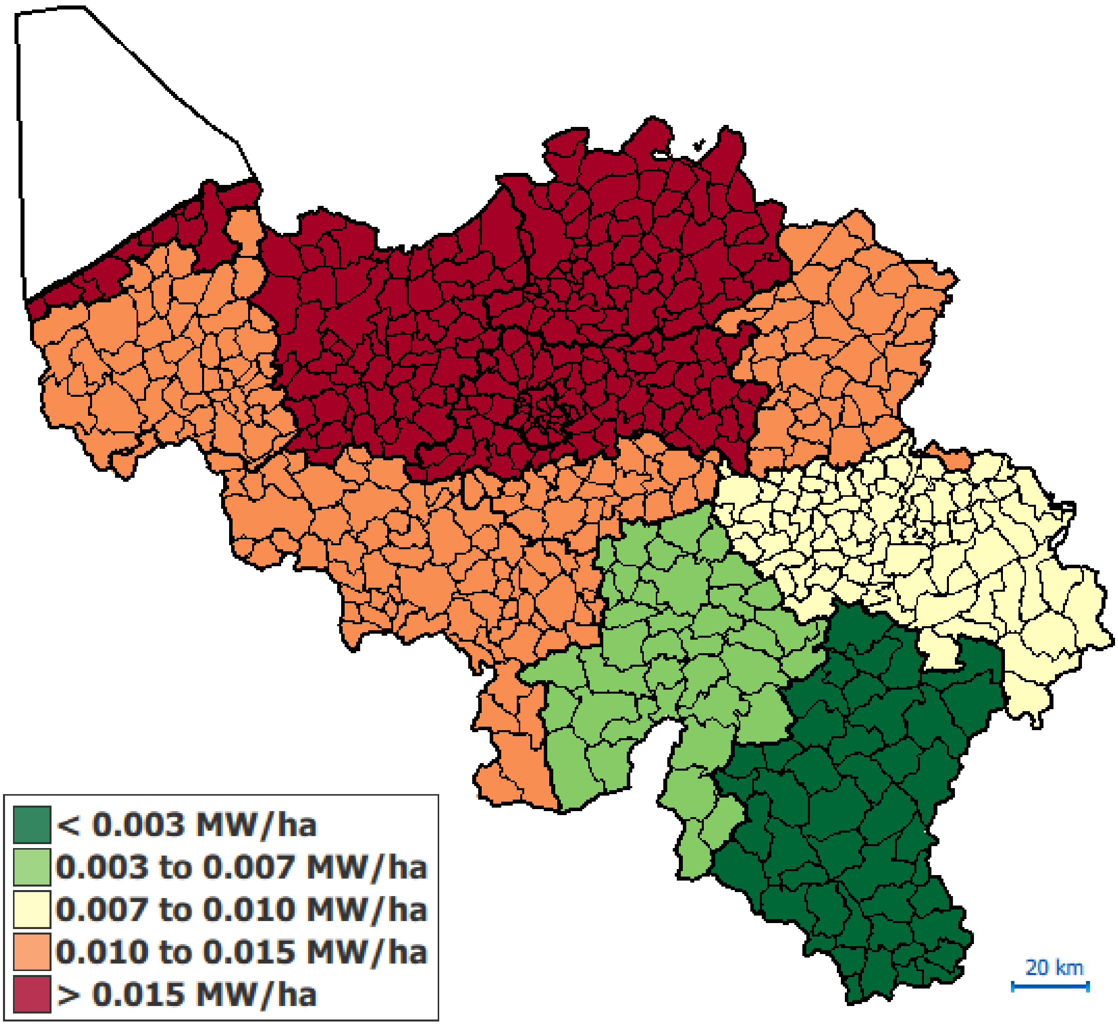


Figure 30 Additional potential capacity (MW per ha) for south-facing PV on residential roofs at the level of Bregilab zone. The surface area of the Bregilab zone is taken into account.

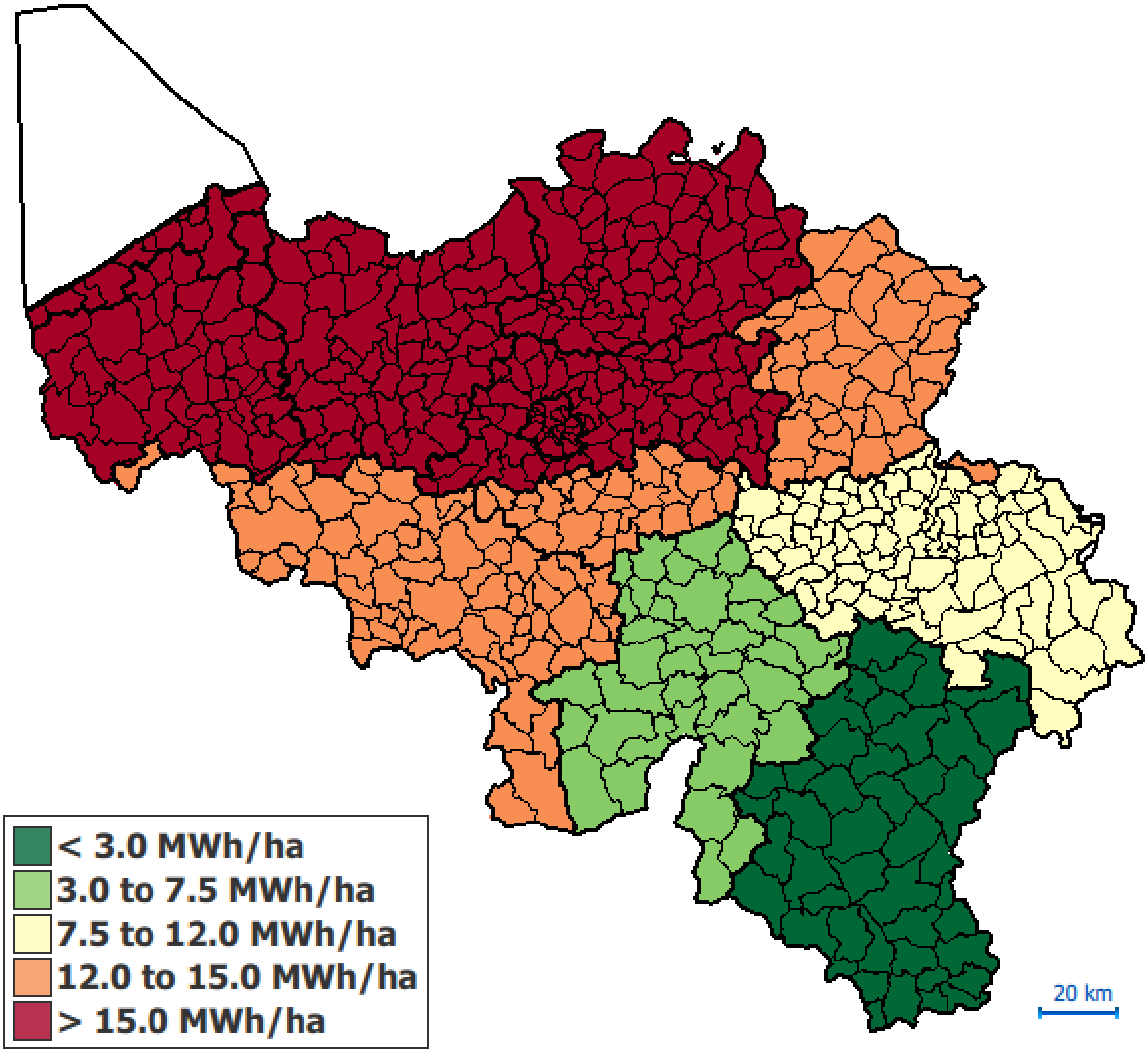


Figure 31 Additional potential energy production (MWh per ha) for south-facing PV on residential roofs at the level of Bregilab zone. The surface area of the Bregilab zone is taken into account.

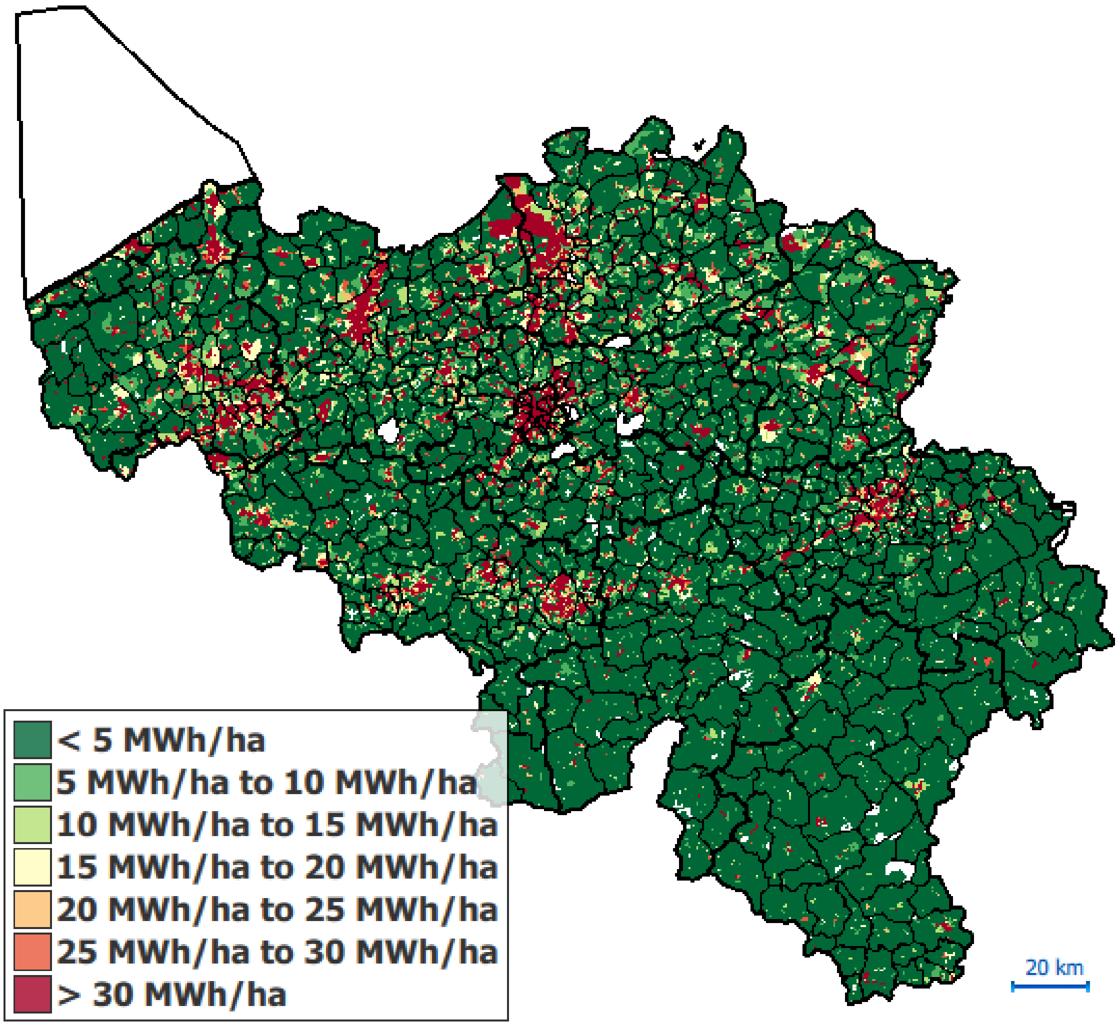


Figure 32 Additional potential energy production (MWh per ha) for west-facing PV on commercial and industrial roof at the level of statistical sector. The surface area of the statistical sector is taken into account.

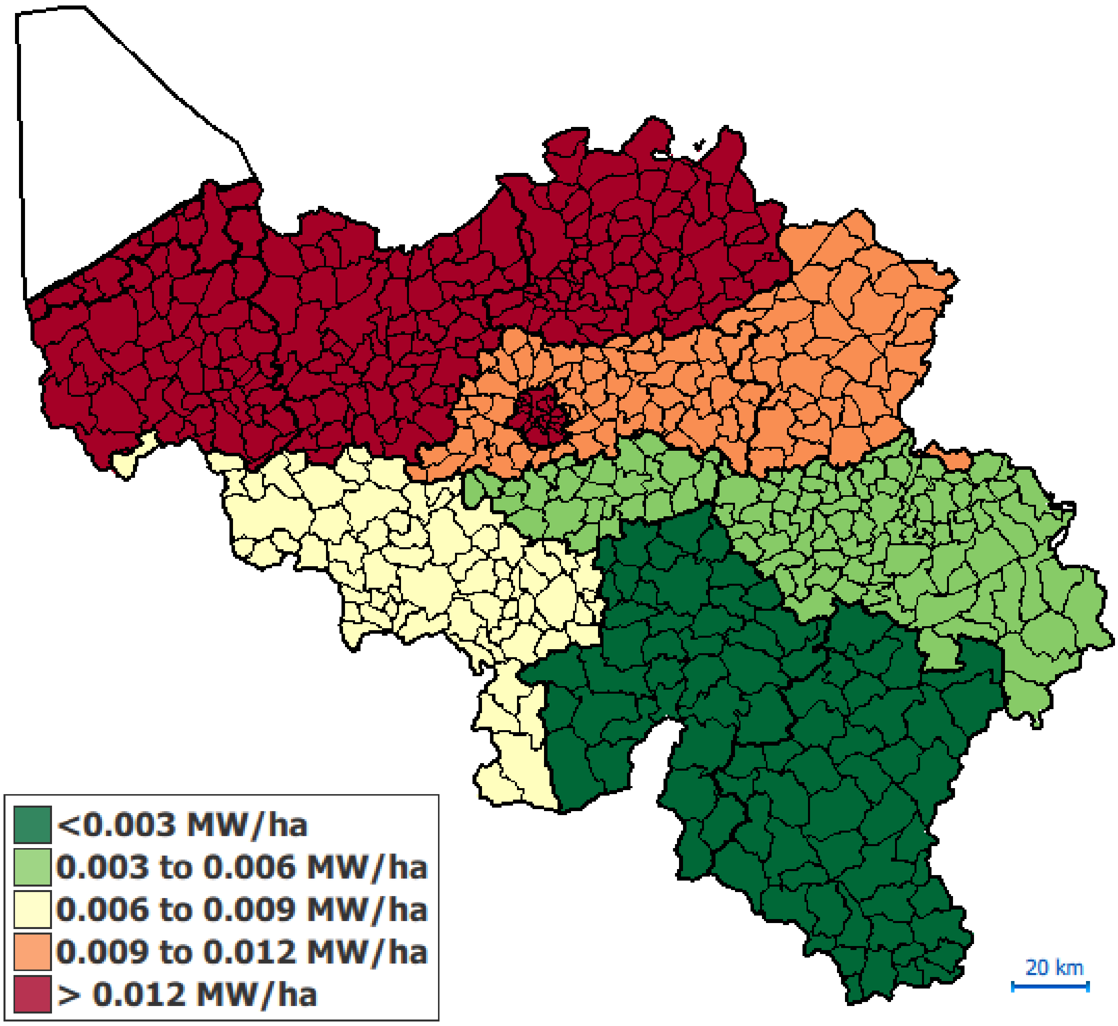


Figure 33 Additional potential capacity (MW per ha) for west-facing PV on commercial and industrial roofs at the level of Bregilab zone. The surface area of the Bregilab zone is taken into account.

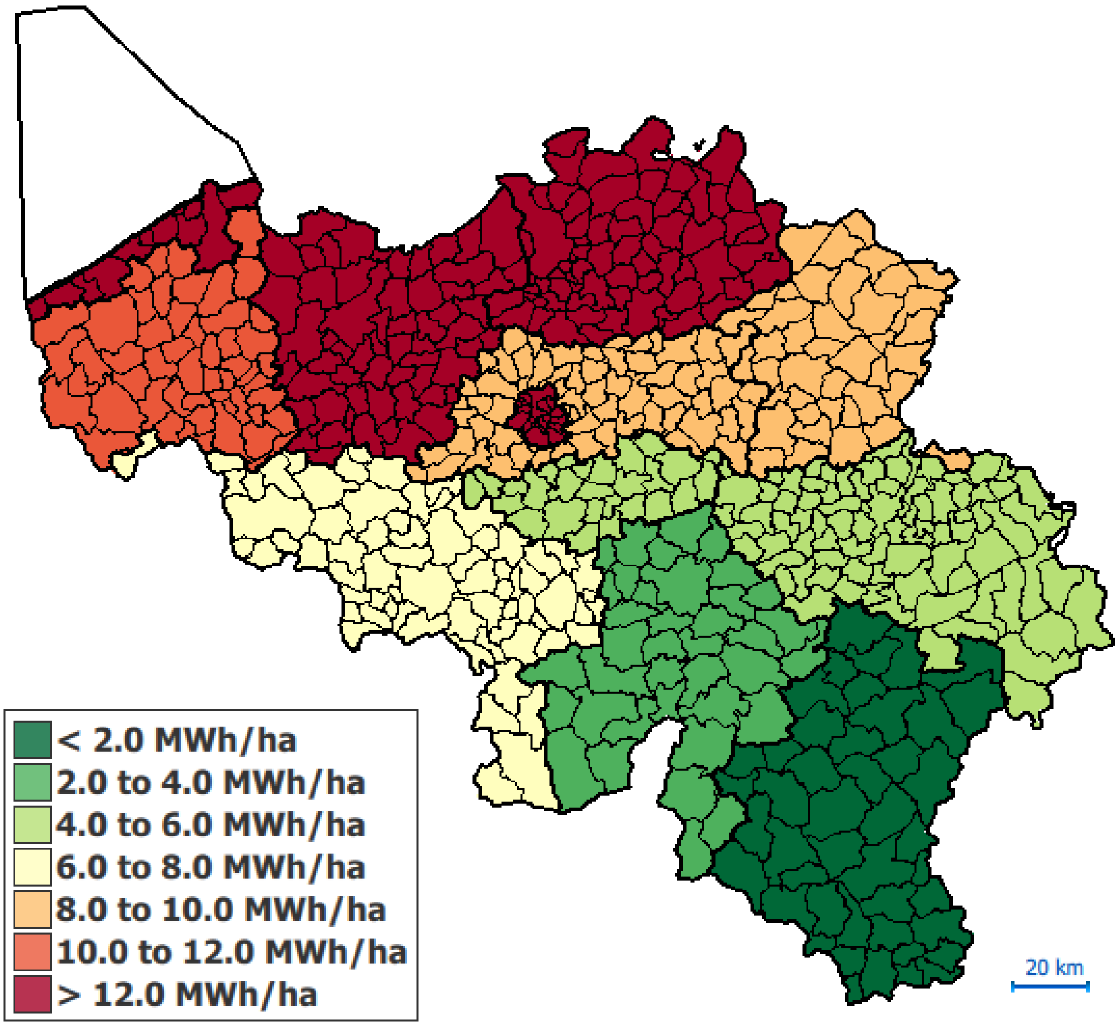


Figure 34 Additional potential energy production (MWh per ha) for west-facing PV on commercial and industrial roofs at the level of Bregilab zone. The surface area of the Bregilab zone is taken into account.

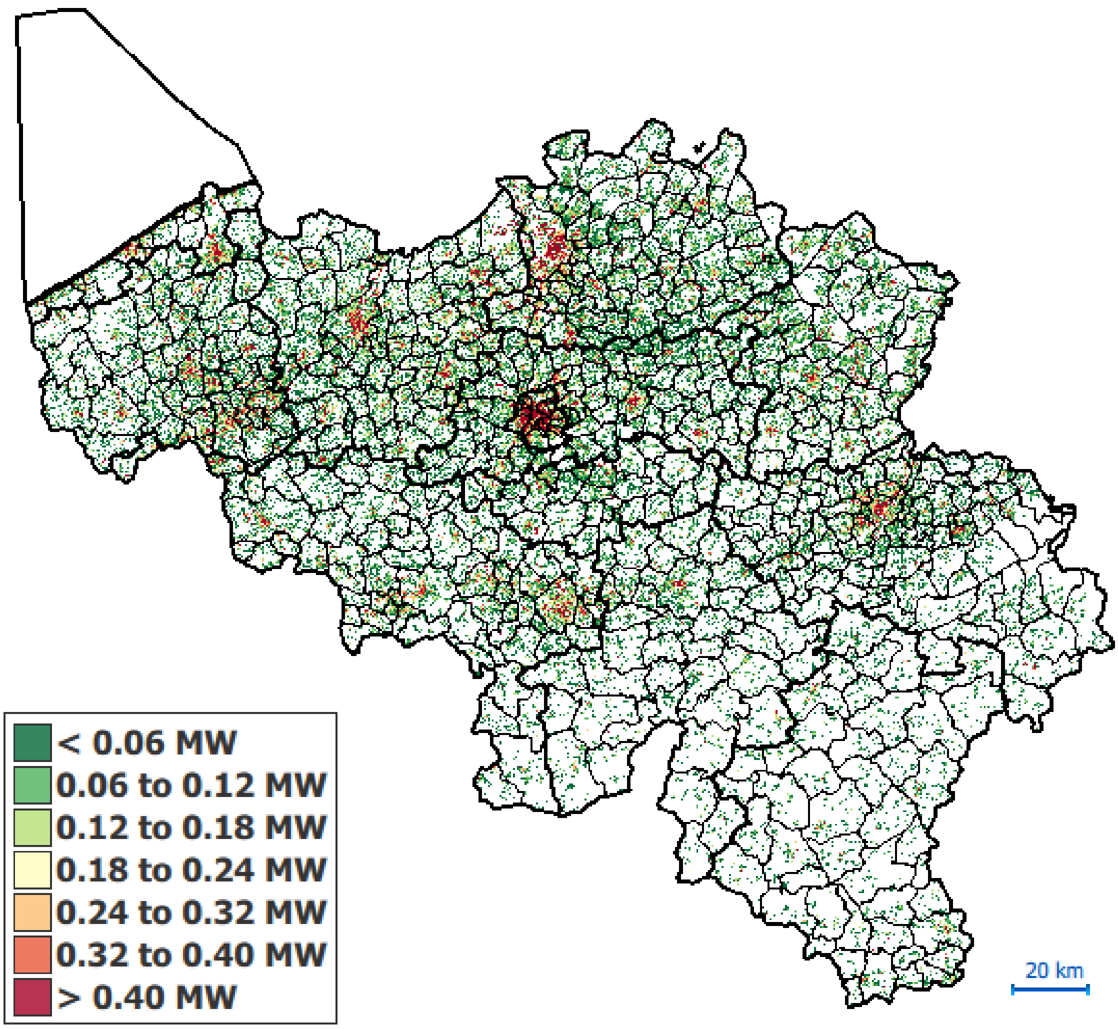


Figure 35 Additional potential capacity (MW) for residential, commercial and industrial PV per 100 by 100m pixel.

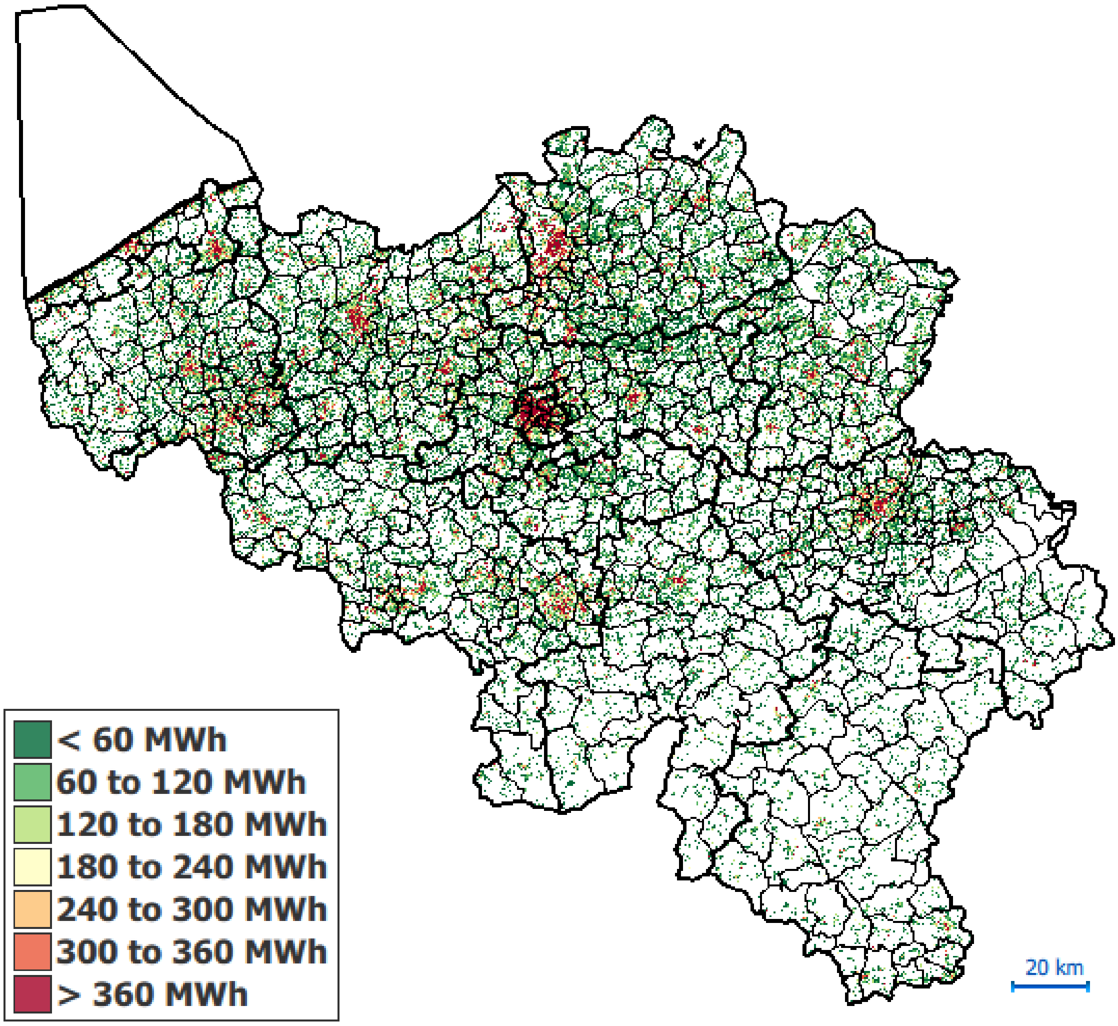


Figure 36 Additional potential energy production (MWh) for residential, commercial and industrial PV per 100 by 100m pixel.

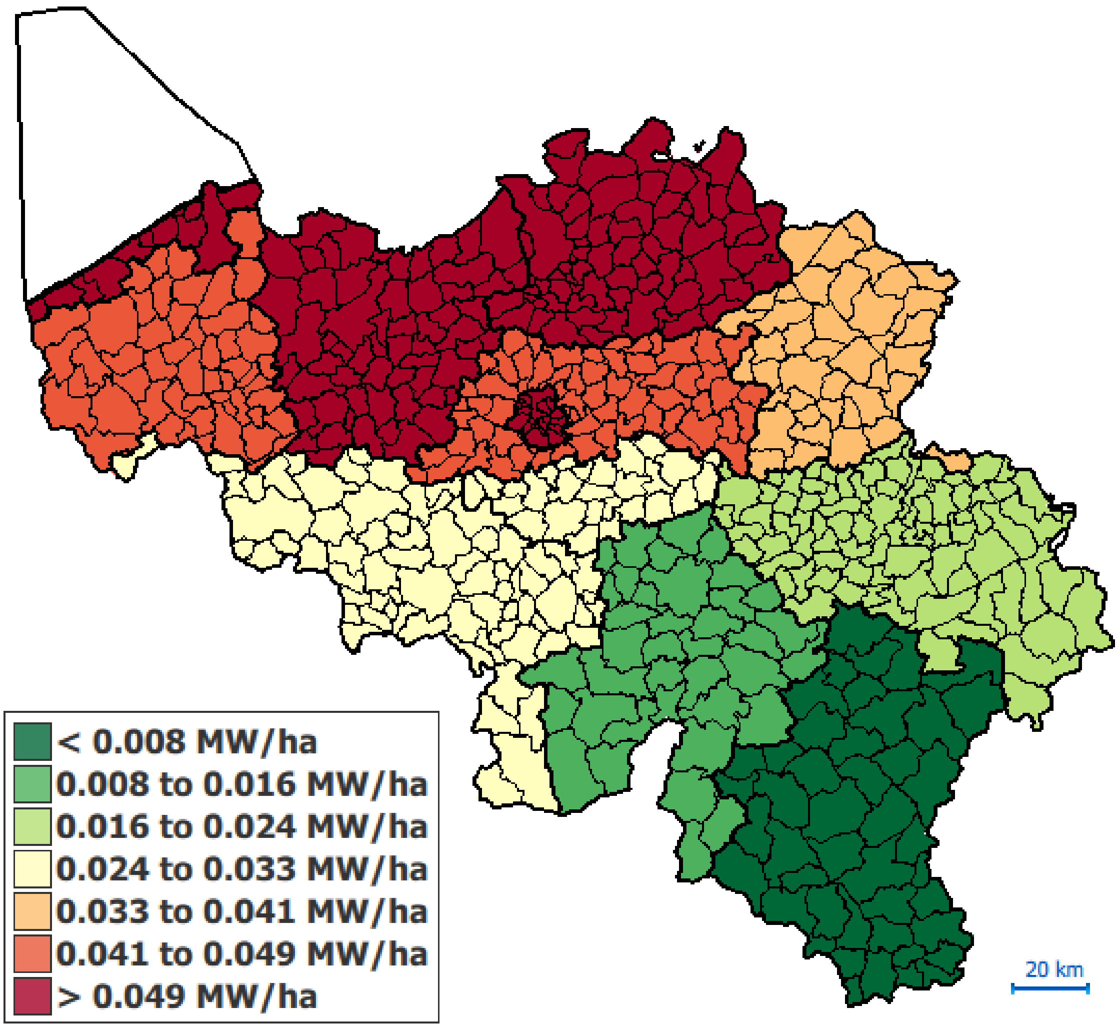


Figure 37 Additional potential capacity (MW per ha) for residential, commercial and industrial PV at the level of Bregilab zone. The surface area of the Bregilab zone is taken into account

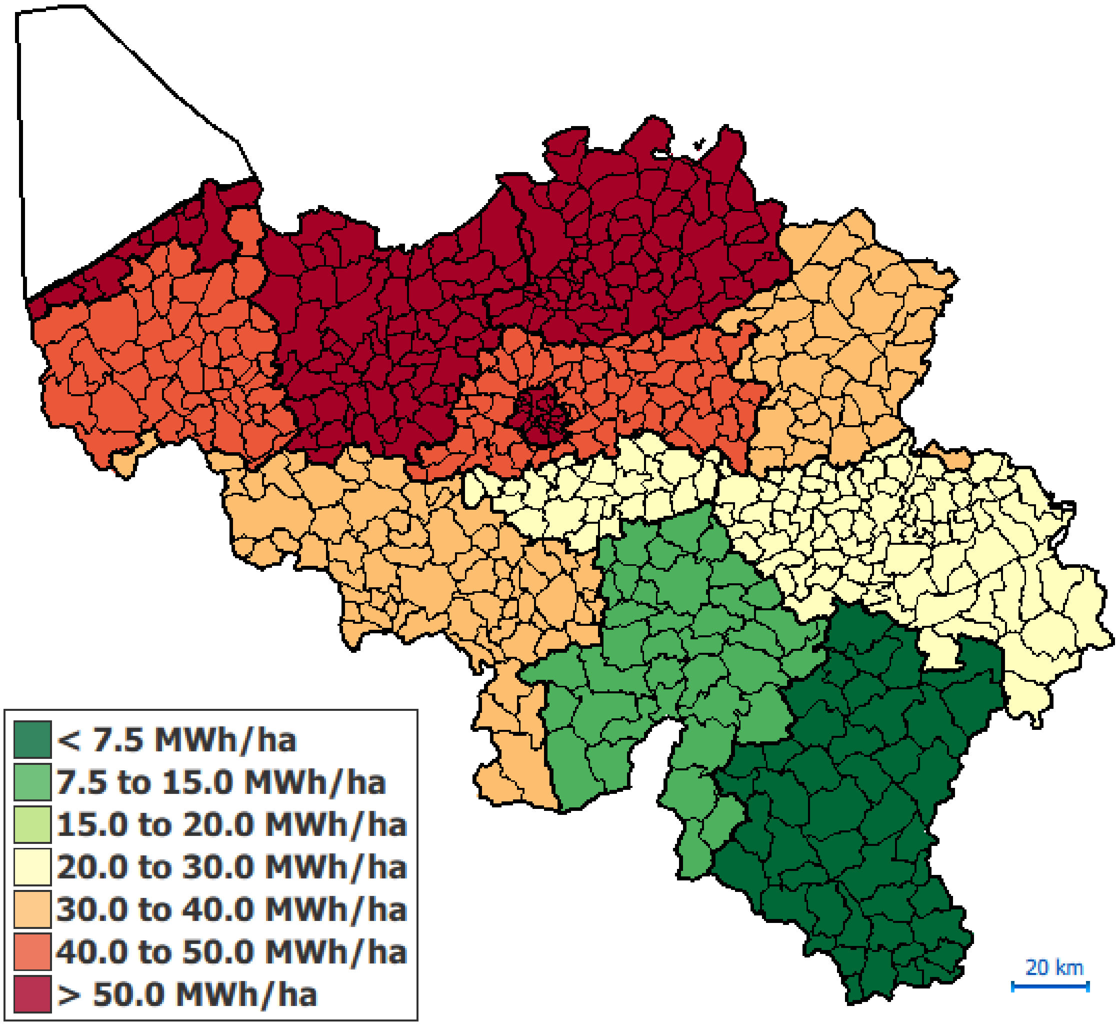


Figure 38 Additional potential energy production (MWh per ha) for residential, commercial and industrial PV at the level of Bregilab zone. The surface area of the Bregilab zone is taken into account.

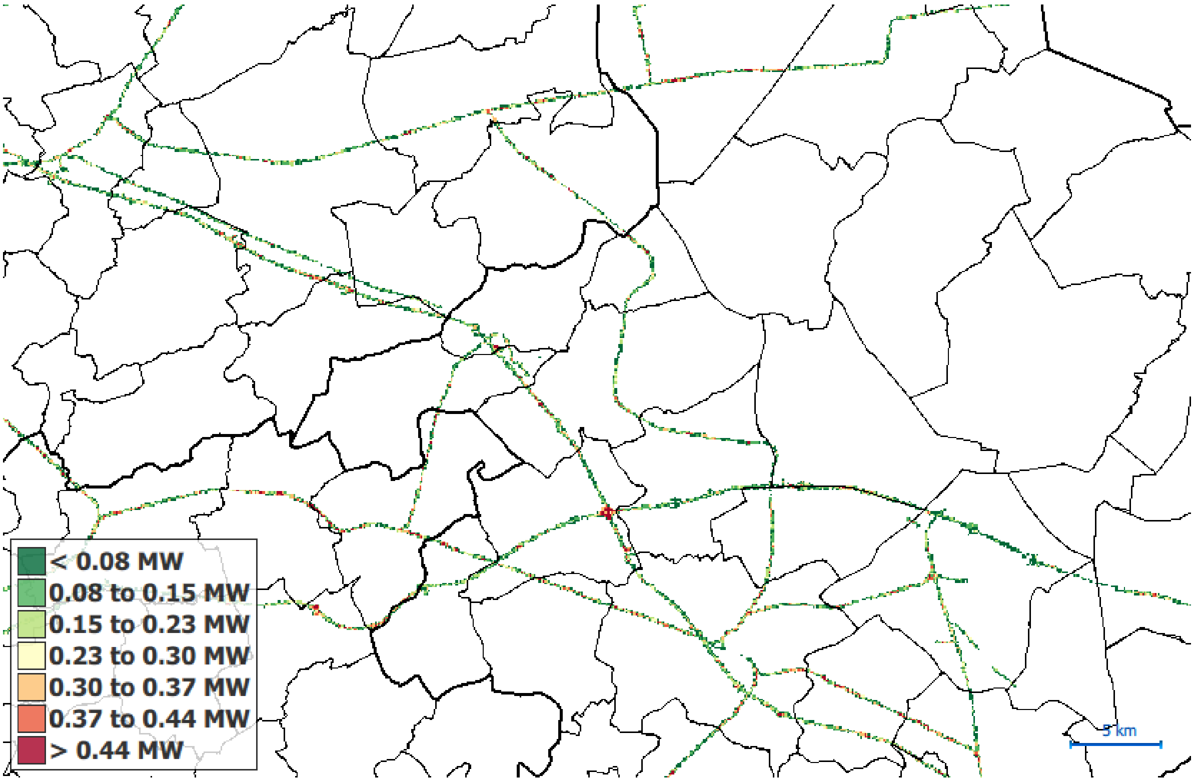


Figure 39 Additional potential capacity (MW) for ground-mounted PV along transport infrastructure per 100 by 100m pixel. Zoomed in on western Limburg.

5.3.5. VARIABILITY BETWEEN WEATHER YEARS (2006-2019) FOR POTENTIAL PV PRODUCTION

Besides results for 2017, we extended the potential PV production dataset with 2006-2019 climatic data (see Figure 5). Be aware that spatial conditions did not alter and that 2017 boundary conditions to assess the available space, and therefore installed capacity, were kept fixed. The resulting dataset allows to assess the inter-annual variability in total production at the annual, daily or hourly scale. As such, it supports a sensitivity analysis to changing variability in climate and extreme periods of low wind and/or solar regimes.

Figure 40, Figure 41 and Figure 42 exemplify differences in annual availability (AF, MWh production/MW installed) for PV on roofs and ground-mounted PV at the level of regions. Using 2006 as a reference year we observe that 2009, 2011, 2015, 2018 en 2019 had relatively higher radiation levels. For some years, there are also clear regional difference in solar availability, e.g. 2007, 2012 and 2013. A year with relatively high solar availability like 2018 does not necessary align with a windy year (Figure 27). Furthermore, a more detailed analysis on periods of low wind and solar is being conducted to allow for a more detailed assessment of the required flexibility of the energy system with a high penetration of wind and solar. The data presented serves as an input to a sensitivity analysis that is ongoing within the BREGILAB project and will be reported separately.

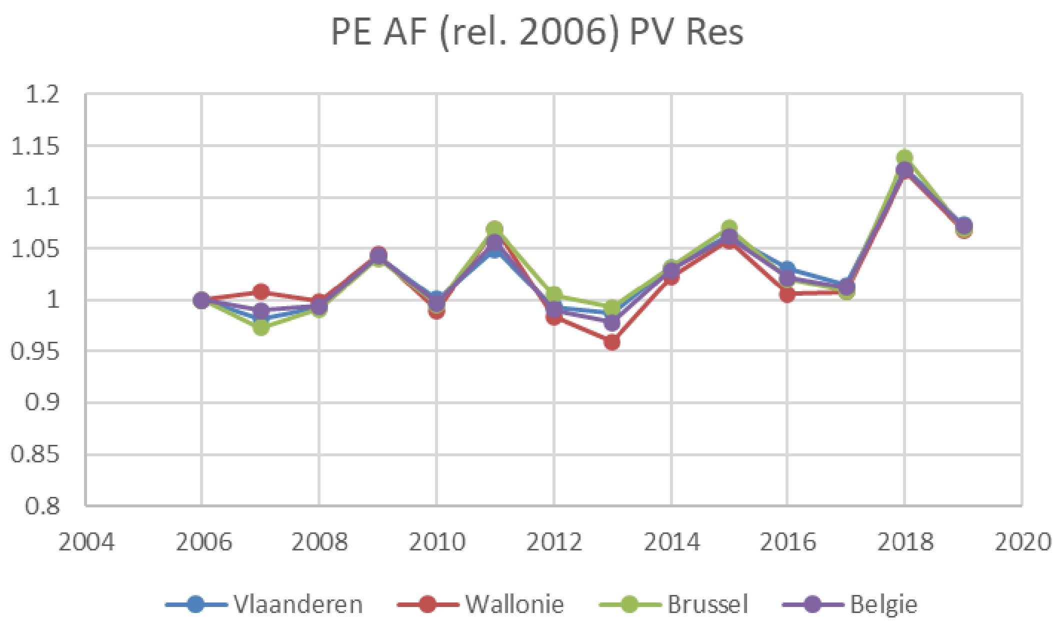


Figure 40 Variability in annual availability factor (MWh/MW) for potential energy production on residential roofs in the period 2006-2019 with 2006 as reference year.

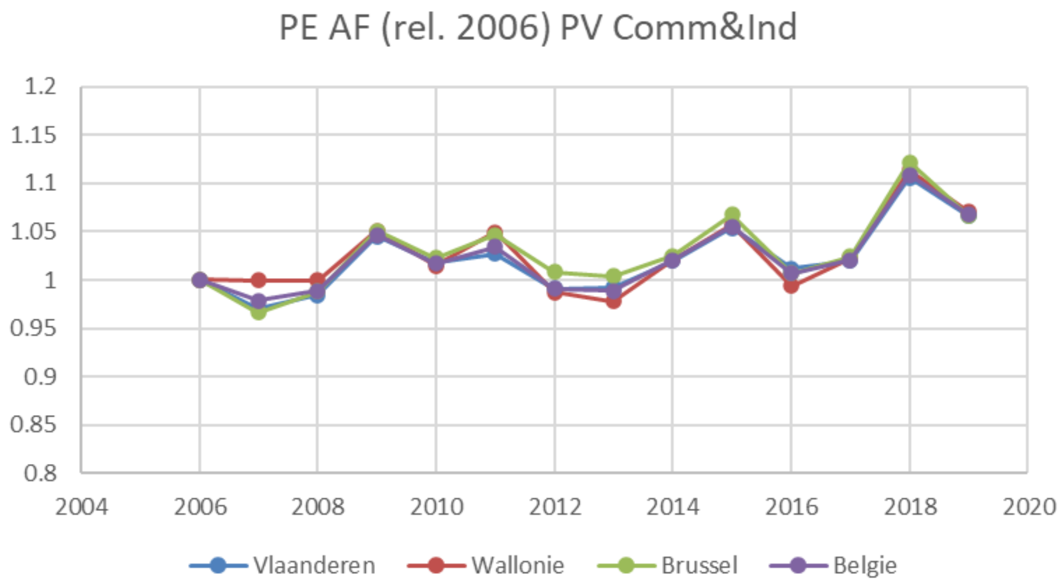


Figure 41 Variability in annual availability factor (MWh/MW) for potential energy production on commercial and industrial roofs in the period 2006-2019 with 2006 as reference year.

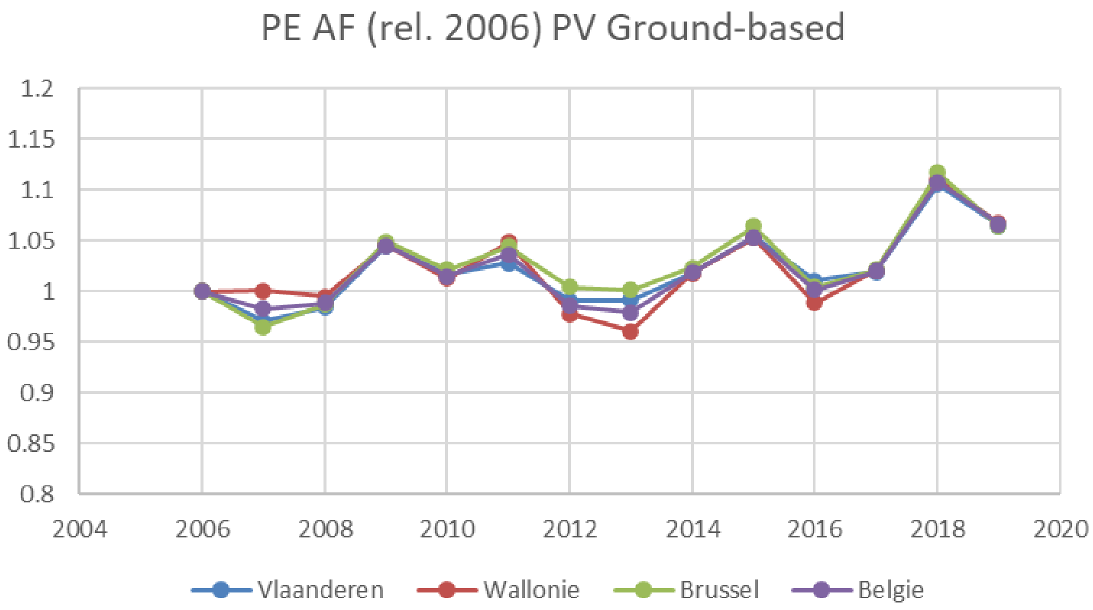


Figure 42 Variability in annual availability factor (MWh/MW) for potential energy production for ground-based PV in the period 2006-2019 with 2006 as reference year.

5.4. RESULTS CURRENT AND POTENTIAL PV AND WIND ENERGY GENERATION

5.4.1. SUMMARY TABLES, GRAPHS AND MAPS

We report on the reference year 2017.

Table 22 Overview of current and potential wind (i.e. scenario WTN) and PV production (GWh), installed capacity (GW) and availability factor (production (GWh)/(capacity(GW)*8760)) at the level of regions and Belgium using 2017 climatic data.

Technology	**Source**	**Flemish region**	**Brussels Capital Region**	**Walloon region**	**Belgium Offshore**	**Belgium**
Energy production (GWh)						
Wind Current	Offshore	0	0	0	3,390	3,390
	Onshore	2,149	0	1,744	0	3,894
	Subtotaal	*2,149*	*0*	*1,744*	*3,390*	*7,284*
PV Current[1]	Commercial&Industry	1,097	57	366	0	1,520
	Residential	1,512	10	791	0	2,312
	Subtotaal	*2,609*	*67*	*1,157*	*0*	*3,833*
Wind & PV Current Total		**4,758**	**67**	**2,901**	**3,390**	**11,116**
Wind Potential	Offshore[2]	0	0	0	4,248	4,248
	Onshore[3]	16,417	47	16,456	0	32,920
	Subtotaal	*16,417*	*47*	*16,456*	*4,248*	*37,168*
PV Potential[4]	Commercial&Industry	30,946	2,046	13,117	0	46,108
	Residential	32,649	1,997	16,690	0	51,335
	Subtotaal (roof)	*63,595*	*4,043*	*29,806*	*0*	*97,444*
	Ground-mounted	6,659	30	4,631	0	11,320
	Subtotaal (roof+GB)	*70,253*	*4,073*	*34,438*	*0*	*108,764*
Wind & PV Potential Total		**86,670**	**4,119**	**50,894**	**4,248**	**145,932**
Total Current and Potential		**91,428**	**4,186**	**53,795**	**7,639**	**157,049**

Technolog y	Source	Flemish region	Brussels Capital Region	Walloon region	Belgium Offshore	Belgium
Capacity (GW)						
Wind Current	Offshore	0.00	0.00	0.00	1.01	1.01
	Onshore	1.24	0.00	1.01	0.00	2.25
	Subtotaal	*1.24*	*0.00*	*1.01*	*1.01*	*3.26*
PV Current[1]	Commercial&Industry	1.09	0.06	0.37	0.00	1.51
	Residential	1.47	0.01	0.77	0.00	2.24
	Subtotaal	*2.55*	*0.07*	*1.14*	*0.00*	*3.76*
Wind & PV Current Total		**3.79**	**0.07**	**2.14**	**1.01**	**7.01**
Wind Potential	Offshore[2]	0.00	0.00	0.00	1.24	1.24
	Onshore[3]	7.86	0.02	10.39	0.00	18.28
	Subtotaal	*7.86*	*0.02*	*10.39*	*1.24*	*19.51*
PV Potential[4]	Commercial&Industry	33.33	2.21	14.19	0.00	49.73
	Residential	31.60	1.95	16.17	0.00	49.71
	Subtotaal (roof)	*64.93*	*4.16*	*30.36*	*0.00*	*99.44*
	Ground-based	7.17	0.03	5.01	0.00	12.21
	Subtotaal (roof+GB)	*72.10*	*4.19*	*35.37*	*0.00*	*111.66*
Wind & PV Potential Total		**79.96**	**4.21**	**45.76**	**1.24**	**131.17**
Total Current and Potential		**83.76**	**4.28**	**47.91**	**6.00**	**138.19**

[1]Trina Solar TSM-250-PC/PA05A PV module with 152.7 Wp per m² capacity was used as representative for currently installed PV technology for both residential as commercial and industrial roofs.
[2]Only approved wind parks were included in the potential calculations.
[3]Vestas V112 was used as representative wind turbine for the whole of (onshore) Belgium
[4] Sunpower SPR-MAX3-400 module with 226 Wp per m² capacity was used as representative market model for PV technology for both residential as commercial and industrial roofs.
Attention: The information contained within this table is based on the assumptions specific to the BREGILAB project mentioned in this report (Clymans et al., 2020; VITO) and information provided by third parties.

Table 23 Overview of current and potential (i.e. scenario WTN) wind and PV availability factor at the level of regions and Belgium using 2017 climatic data.

Technology	**Source**	**Flemish region**	**Brussels Capital Region**	**Walloon region**	**Belgium Offshore**	**Belgium**
Availability factor (GWh/GW)						
Wind Current	Offshore	0.000	0.000	0.000	0.384	0.384
	Onshore	0.198	0.000	0.197	0.000	0.198
	Subtotaal	*0.198*	*0.000*	*0.197*	*0.384*	*0.255*
PV Current[1]	Commercial&Industry	0.115	0.115	0.114	0.000	0.115
	Residential	0.118	0.117	0.117	0.000	0.118
	Subtotaal	*0.117*	*0.115*	*0.116*	*0.000*	*0.116*
Wind & PV Current Total						
Wind Potential	Offshore[2]	0.000	0.000	0.000	0.392	0.392
	Onshore[3]	0.238	0.230	0.181	0.000	0.206
	Subtotaal	*0.238*	*0.230*	*0.181*	*0.392*	*0.217*
PV Potential[4]	Commercial&Industry	0.106	0.106	0.106	0.000	0.106
	Residential	0.118	0.117	0.118	0.000	0.118
	Subtotaal (roof)	*0.112*	*0.111*	*0.112*	*0.000*	*0.112*
	Ground-mounted	0.108	0.108	0.108	0.000	0.108
	Subtotaal (roof+GB)	*0.113*	*0.113*	*0.113*	*0.000*	*0.113*
Wind & PV Potential Total						
Total Current and Potential						

[1]Trina Solar TSM-250-PC/PA05A PV module with 152.7 Wp per m² capacity was used as representative for currently installed PV technology for both residential as commercial and industrial roofs.
[2]Only approved wind parks were included in the potential calculations.
[3]Vestas V112 was used as representative wind turbine for the whole of (onshore) Belgium
[4] Sunpower SPR-MAX3-400 module with 226 Wp per m² capacity was used as representative market model for PV technology for both residential as commercial and industrial roofs.
Attention: The information contained within this table is based on the assumptions specific to the BREGILAB project mentioned in this report (Clymans et al., 2020; VITO) and information provided by third parties.

Figure 43 report for the regions the installed capacity and technical potential for only onshore wind and roof PV considering future technology options for the different regions in Belgium.

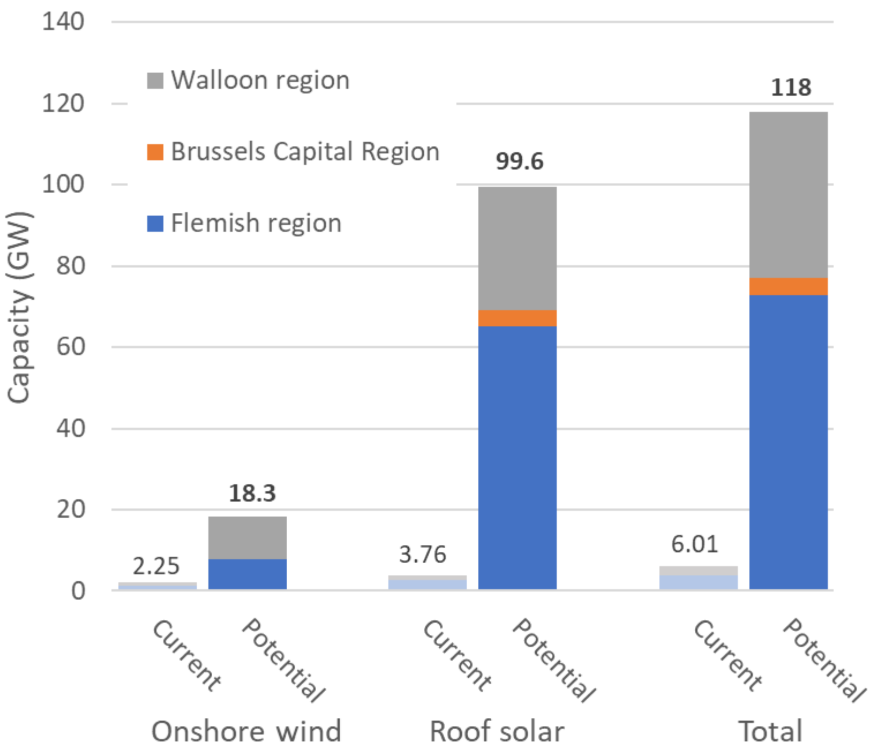


Figure 43 Installed capacity (1/1/2018) and technical potential per technology and regions in Belgium.

Onshore wind

Belgium has an additional technical capacity of 18.3 GW for onshore wind distributed over Flanders with 9.1 GW, Brussels with 0.02 GW and the Walloon region with 11.4 GW (Table 22). Compared to the installation's anno 1/2018, wind production capacity can increase 8-fold from 2.3 GW and is currently (1/1/2021) at 2.5 GW. Reported capacities assume the installation of 3.3 MW wind turbines (VESTAS V112) within the remaining available space. Depending on its geographical location the availability varies between 1000 and 3500 full load hours or a potential additional energy production of approximately 33 TWh per year for Belgium.

The resulting map (Figure 44) indicate that the Antwerp harbor region, northern part of East-Flanders and the southern parts of Luxembourg, Limburg and Hainaut have a high potential for additional onshore wind generation. Brussels, both Brabant provinces, the coastal region and the northern parts of Liège, Limburg and Hainaut have a low technical potential.

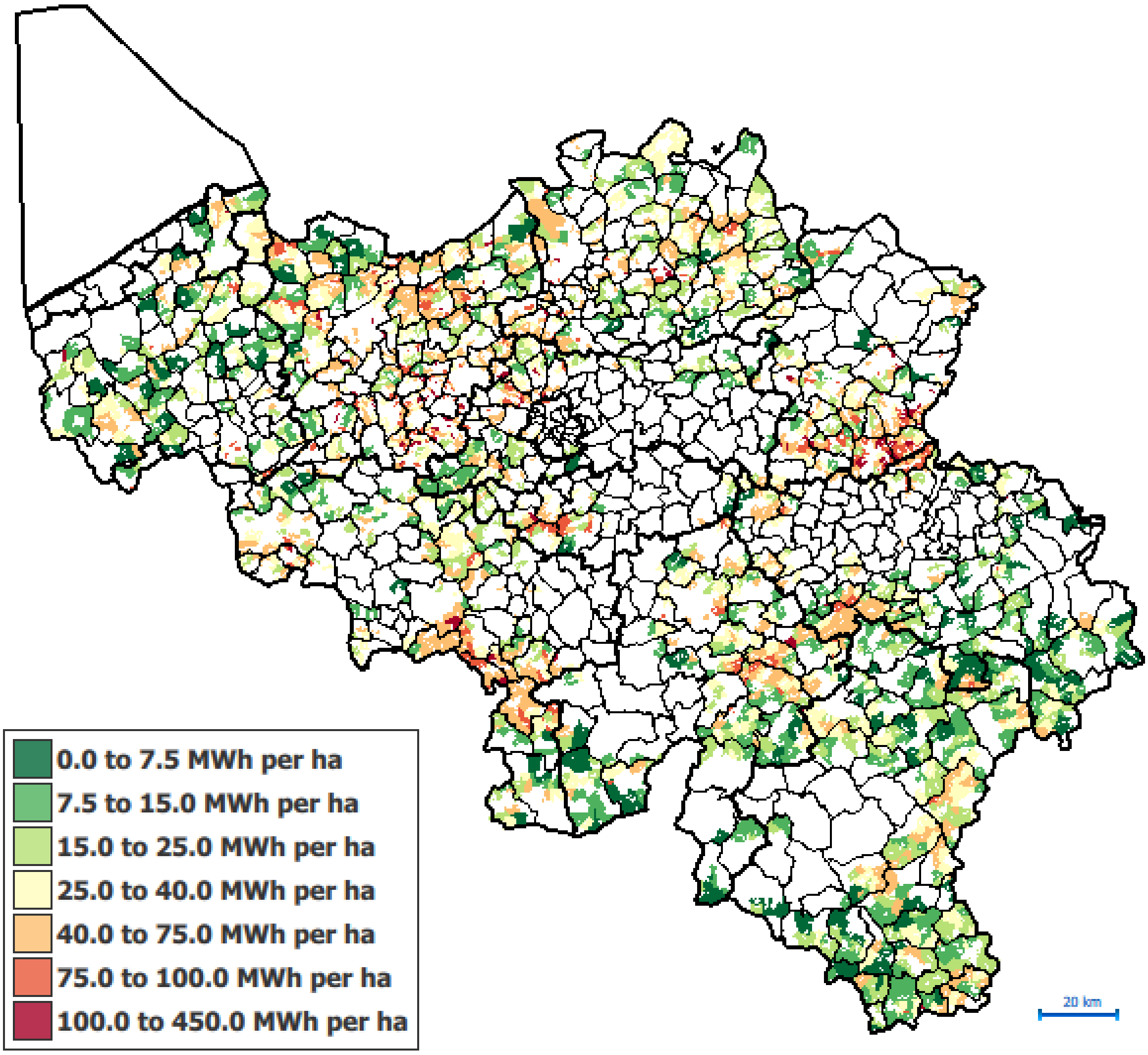


Figure 44 Additional potential for onshore wind energy production (MWh per ha, based on VESTAS V112 3.3MW) at the level of statistical sector. The surface area of the statistical sector is taken into account.

Offshore wind

The Bregilab project limited its offshore scope to the existing concessions that were permitted and already constructed (1.01 GW) or planned (1.24 GW) on 1/1/2018 (Table 22). Belgium has the ambition to increase the existing capacity to 5.8 GW with a maximal additional 3.5 GW by 2030 in the western part of the North Sea[2]. In combination with the 2017 meteorological data, the existing and planned offshore wind parks will have an availability that exceeds 3500 full load hours per year or a potential energy production of approximately 20.3 TWh.

Solar

Belgium has an additional technical capacity of 99.6 GW on roofs with a 50/50 split between residential versus commercial and industrial roofs. The Flemish region has the highest additional potential with 65 GW followed by the Walloon region with 30 GW and Brussels with 4.2 GW (Table

[2] Based on Ministerraad van 15 oktober 2021 - Energie: productiecapaciteit van de Prinses Elisabeth-zone in de Noordzee published by FOD Kanselarij van de Eerste Minister - algemene directie Externe Communicatie

22). Compared to the installations anno 1/2018 PV capacity can increase on roofs alone 26-fold from 3.8 GW and is currently at 4.8 GW. Reported new capacities in the study assume covering the available roof space with a 226 Wp per m² PV module (SPR-MAX3-400) at specified tilt and orientation per building type. The availability of PV varies between 930 till 1060 full load hours in Belgium or a potential additional energy production of approximately 99.3 TWh per year.

For residential roofs the spatial potential clearly follows the urbanization degree of the different regions in Belgium (Figure 45). The potential on commercial and industrial roofs is highest in the Flemish regions, but geographical concentrated around large industrial complexes situated along highways, navigable waterways like southern West-Flanders and the Meuse-Sambre axis rather than in urban centres.

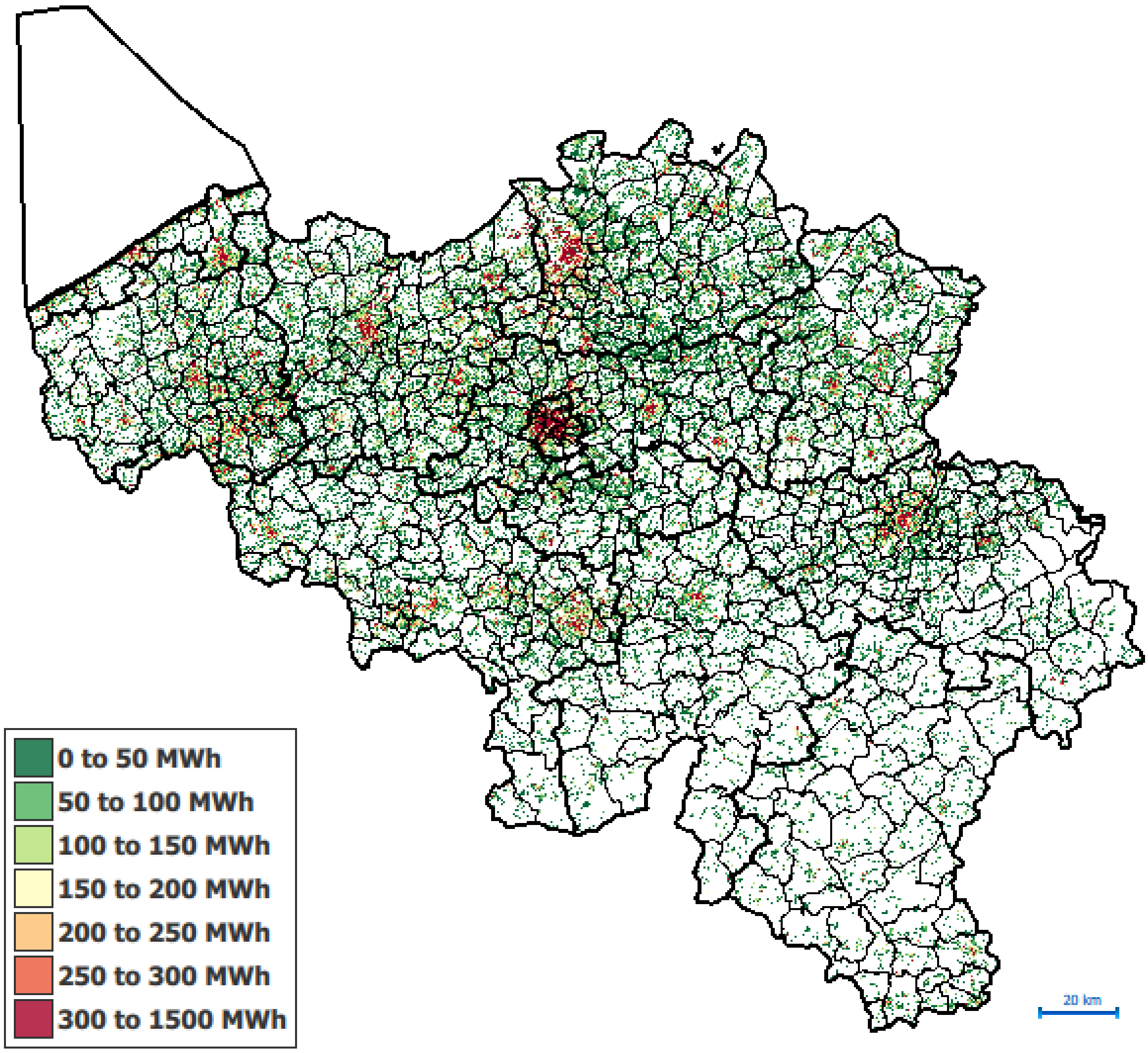


Figure 45 Additional potential energy production (MWh) for residential, commercial and industrial rooftop PV per 100 by 100m pixel.

5.4.2. ACHIEVING THE ENERGY AND CLIMATE ACTION GOALS

At the start of 2020 Belgium released its integrated *national energy and climate action plan* (NECP), which inter alia reports on renewable energy ambitions for 2030. The 2030 'with additional measures' (WAM) scenario aims at 9600 GWh electricity generation from onshore wind, and 9750 GWh from PV. This 2030 NECP ambition can be covered by utilizing approximately 6% of the technical potential calculated by this study for PV on roofs, and 17% of the available total potential for onshore wind turbines. An energy system model with a spatially explicit technology representation will allow to provide additional insights into the most cost-efficient utilization of available roofs and wind turbines by taking regional differences in availability factors into account. In such way, we aim to progress in subsequent steps from a technical potential analysis towards an estimate of the economic and energetic potential of renewable energy sources in Belgium.

5.4.3. TOWARDS A SPATIAL EXPLICIT APPROACH FOR ENERGY SYSTEM MODELLING

Decentralized energy provision requires space which is already sparse and fragmented in Belgium and therefore can compete, depending on technology choice, with high spatial demand to support housing, economic activities, transport infrastructure, agriculture and nature areas. The energy system modelling approach within BREGILAB takes into account current policy constraints on available space, and optimizes the generation potential with the demand, and grid capacity and flexibility. A unique feature of our approach is that through spatial modelling expected shifts in the spatial criteria (further loss of open space, increased urbanization in specific locations) can also be taken into account during long-term planning. For example, the Flemish land-use change scenario that assumes a continuation of current growth trends of build-up land shows a decrease in open space of 9% by 2050 compared to 2013. Assuming a realization of the Flemish policy target of 'no more net land take' by 2040, on the other hand, results in a loss of open space of only 2.5% by 2050. Similarly, land use change dynamics will impact the expected de- and recommission potential of aged onshore wind parks. The decisions made today will impact how much of the technical potential will be available in 30 years from now.

Our spatial assessment attempts to give an objective picture of the potential role of renewable energy on the future electricity system in Belgium and is a stepping stone to investigate how to achieve a balanced system taken into account spatial limitations and opportunities. With this quantitative analysis, VITO/EnergyVille aims to support industry and our governments and provide the latest objective data.

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ANNEX A

See attached document: Schils and Horvath, 2019. Photvoltaic energy yield simulation. Imec is part of the BREGILAB project, Genk and is working on an updated version.

Bregilab WP3: photovoltaic energy yield simulation

IMEC

December 5, 2019

1 Introduction

In the frame of the Bregilab project, the mission of the IMEC photovoltaic energy yield simulation team is to provide partners with photovoltaic availability factor I over whole Belgium and for any year of interest. The availability factor I of a given photovoltaic power plant is defined as:

$$I(t)\left[\frac{kWh}{hm^2}\right] = \frac{P(t)}{A}, \tag{1}$$

where P is the AC power generated by the power plant and A the sum of the area of each module in the power plant.

This area A is larger than the roof area occupied by the modules when the modules are more tilted than the roof itself. It is important to keep this difference in mind to properly map the installed photovoltaic peak capacity to the occupied roof area.

This availability factor can be used to easily compute the power produced by a typical area A photovoltaic installation in Belgium as well as the total energy produced over a period of interest $[t_1; t_2]$:

$$P(t)\left[\frac{kWh}{h}\right] = AI(t), \tag{2}$$

$$E\,[kWh] = A\int_{t_1}^{t_2} I(t)dt. \tag{3}$$

ANNEX B

Overview of overlap per negative boundary conditions included in WTN and WTP scenario and location of constructed wind turbines (status 1.1.2018).

Summarized, for following boundary conditions we observed an overlap for more than 5% of the constructed wind turbines in the WTN scenario:

- Buildings with 27%
- Residential parcels in Flanders with 24% (less of an issue in the Walloon region with 0%)
- Air traffic and radar control in orange zones with 19% (but has a lower weight)
- Military air and protection zone with 19% (but has a lower weight)
- Inundation risk 7%
- Protect views of urban settlement in the Walloon region 29% (but has a lower weight)

For 15 out of the 45 criteria there was no overlap. For scenario WTP, we observed that the increased distance rule has a major affect on the criteria railway network, pipelines FETRAPI and SEVESO buildings.

Negative Boundary Conditions	#WTN	#WTP	%WTN	%WTP
Buildings	304	429	26.9	37.9
Residential parcels (Fl and Br)	274	274	24.2	24.2
Residential parcels within residential area (Wal)	0	0	0.0	0.0
Residential parcels outside residential area (Wal)	0	0	0.0	0.0
Planned residential area (Fl)	26	26	2.3	2.3
Planned residential area (Wal)	0	0	0.0	0.0
Undeveloped parcels in industrial areas (ZAE; Wal)	11	31	1.0	2.7
Vulnerable institutions (schools, retirement and nursing homes, etc)	9	9	0.8	0.8
Navigable waterway network	0	0	0.0	0.0
Railway network	22	65	1.9	5.7
High Speed Train infrastructure	13	13	1.1	1.1
Road network (highway and primary roads) (Fl and Br)	25	31	2.2	2.7
Road network (highway and primary roads) (Wal)	7	39	0.6	3.4
Planned infrastructure works (Wal)	1	1	0.1	0.1
Power lines (Elia)	0	0	0.0	0.0
Pipe lines (Fetrapi)	10	63	0.9	5.6
SEVESO buildings	51	116	4.5	10.3
Nuclear facilities	0	0	0.0	0.0
Air traffic and radar control - red zones (Skeyes)	11	11	1.0	1.0

Negative Boundary Conditions	#WTN	#WTP	%WTN	%WTP
Air traffic and radar control - orange zones (Skeyes)	217	217	19.2	19.2
Military air and radar protection zone - red zones (GCFOE)	35	35	3.1	3.1
Miltary air and radar protection zone - orange zones (GCFOE)	216	216	19.1	19.1
Constructed wind turbines	1131	1131	100.0	100.0
Licensed windturbines (Fl)	101	101	8.9	8.9
Natura2000	21	21	1.9	1.9
Nature conservation areas	1	1	0.1	0.1
Reserved zones for nature reserves (i.e. Visiegebieden) (Fl)	0	0	0.0	0.0
Designated silent zones (i.e. Stiltegebieden)	0	0	0.0	0.0
Flemisch Ecological Network (Fl)	0	0	0.0	0.0
Risks for birds and bats (Fl)	21	21	1.9	1.9
Nature, green and park areas (Wal)	4	4	0.4	0.4
Agroforestry zones (Wal)	12	12	1.1	1.1
Contiguous open space >1000ha (Fl)	13	13	1.1	1.1
Inundation risk (Fl)	85	85	7.5	7.5
Waterbodies (Fl)	9	9	0.8	0.8
Protected monuments	0	0	0.0	0.0
UNESCO protected zones (Fl)	0	0	0.0	0.0
Protected cityscapes	9	9	0.8	0.8
Protected landscapes	17	17	1.5	1.5
Catalogued landscapes and sites	0	0	0.0	0.0
Protected archeological sites	0	0	0.0	0.0
Heritage landscapes	0	0	0.0	0.0
Protected views (4km) around urban settlement (Wal)	334	334	29.5	29.5
High risk zones karst (Wal)	0	0	0.0	0.0
Medium risk zones karst (Wal)	4	4	0.4	0.4