SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY

SPSD II

THE ROLE OF RENEWABLE ENERGY TECHNOLOGIES IN SECURING ELECTRICAL SUPPLY IN BELGIUM

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GENERAL ISSUES

AGRO-FOOD

PART 1

SUSTAINABLE PRODUCTION AND CONSUMPTION PATTERNS — ENERGY

TRANSPORT

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SCIENTIFIC SUPPORT PLAN FOR A SUSTAINABLE DEVELOPMENT POLICY
(SPSD II)

Part 1:

Sustainable production and consumption patterns

FINAL REPORT

THE ROLE OF RENEWABLE ENERGY TECHNOLOGIES IN SECURING ELECTRICAL SUPPLY IN BELGIUM

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Contents

Technical Report

This report analyzes the role of renewable energy technologies in securing the supply of electrical energy in Belgium. The development of the study consists of six Work Packages which deliver necessary information in every step of the analysis, except for WP1 which is the task of coordination of the project. The goals of every WP are described here.

1 Work Package 1: Project coordination (K.U.Leuven)

The task included: platform meeting coordination, centralised reporting, administrative tasks, dissemination towards scientific audience and governmental bodies (publication coordination, workshop co-organisation).

2 Work Package 2: Inventory of electrical aspects influencing the security of the supply (K.U.Leuven)

From the viewpoint of a secure electrical grid operation, the relevant technical aspects are categorized and ordered in priority with respect to the connection levels of renewable energy (RE) generators. These include energy balancing and ancillary services such as reactive power support, spinning reserve, etc. For this task, foreign grid codes as well as the Belgian practice, reflecting in simulation models of the grid (used in the cluster project), are considered. An internal working document with relevant information for the partners investigating different RE technologies was generated, which is attached as 'Overview of electrical aspects that have impact on the security of supply in grids with renewable energy generation'.

2.1 Overview of electrical aspects that have impact on the security of supply in grids with renewable energy generation

2.1.1 Introduction

This contribution gives an overview of the electrical aspects that have an impact on the security of electricity supply.

This paper results from WP 2, and gives a proposal for the definition of the tasks that are to be performed by the project partners, within the context of WP 3.

2.1.2 Electrical aspects of security of supply

2.1.2.1 Machine Power Range, Machine Voltage, Grid Injection Voltage, Relative Fraction of Power Supply

- **General information**

The range for installed powers of one RE generator unit depends on the energy source [1]:

- wind power:
    - ~ 5 kW - 200 kW – 5 MW per turbine,
    - ~ 2 – 30 MW per wind farm onshore
    - ~ 10 - 300 MW per wind farm offshore

- biomass:
    - ~ 100 kW – 1000 kW (waste gas, silt, manure …);
    - ~ 10.000 kW (waste burning, co-burning of biomass with fossil fuel)

- the power ranges for solar power may vary widely: an assumed range for Belgium is 0.5 – 50 kWp per installation.

The rated voltage at which RE generators (REG) are connected may vary in the range:

- low DC voltage (PV: photovoltaic electricity);
- 230 V (household CHP units or 'urban' wind turbines) ;
- 3 kV (multi-MW wind turbines);
- 20-24 kV (generators of conventional power plants that are partially fuelled with biomass, large hydropower generators);

The voltage level of the grid in which the generated energy is injected may vary from

- 400 V (household)
    - PV
    - small wind turbines up to ~10 kW or 200 kW (usually 690 V line voltage)

- 10 – 15 – 30 - 36 kV (distribution grid)
    - biomass installations operating on biomass only
    - wind turbines, wind farms up to ~ 30 MW

- 70 – 150 -400 kV (high voltage transmission grid):
    - large wind farms (on- and offshore)
    - conventional power plants co-fuelled with biomass

The installed power is deciding for the dimensioning of the power cables and transformers. Or, vice versa, the present power cables and transformers are one deciding factor for the amount of installed power that can be installed in the grid.

- **Desired input from the project partners**

The project partners were asked to perform a market research in their branch, in order to either confirm or modify/actualize of the values that are summed up above. It should apply for the Belgian case, with regard to the actual situation and the prospects up to 2005 on the one hand, and 2015 on the other hand.

Preferentially, in order to obtain uniformity in the input from the different partners, the input is suggested to be given in the default format of *Table 1* (the grey italic numbers are only for illustration). The table may contain as many columns as the project partners consider necessary for satisfying accuracy. The table refers to 'REG power plants', which implies, for instance, that the rated power for wind farms connected to one grid point is desired, rather than the rated power of single turbines.

Optimally, the project partners deliver various scenarios for *Table 1*, each with their expected installed power and expected rated capacities of power plants. Those different scenarios refer to either a conservative or progressive view on the future.

<table>
<tr><td colspan="5">REG source, either:
- Solar
- Wind, (for instance) subdivided into:
o small onshore
o large onshore
o offshore
- Biomass, (for instance) subdivided into:
o generators only fuelled by biomass
o co-burning with fossil fuel (total rated power of REG plant applies to the fraction of the generator power that is fuelled by biomass)</td></tr>
<tr><td colspan="3">Expected installed power in 2005 (2015) in Belgium</td><td colspan="2">200 MW</td></tr>
<tr><td></td><td colspan="4">Total rated power of one REG power plant</td></tr>
<tr><td></td><td>< 0.2 MW</td><td>< 1 MW</td><td>< 2 MW</td><td>< 10 MW</td></tr>
<tr><td>relative amount of total installed power in Belgium</td><td>10 %</td><td>40 %</td><td>90 %</td><td>97%</td></tr>
<tr><td>typical voltage for grid connection point for given installation size</td><td>400 V</td><td>10 kV – 36kV</td><td>10 kV – 36kV</td><td>150kV – 400kV</td></tr>
</table>

Table 1. Desired input format for generator data, concerning installed power and grid voltage

2.1.2.2 Average Annual Power Production

- **General information**

Apart from the installed power, also the annual average power production as well as the production variability is a matter of great interest.

The capacity factor *C* is defined as the actual annual energy output divided by the theoretical power output, if the machine were running at its rated (maximum) power during all of the 8760 hours of the year. Although one would generally prefer to have a large capacity factor, it may not always be an economic advantage. This is often confusing to people used to conventional or nuclear technology. In the context of wind energy, for instance, in a very windy location it may be an advantage to use a larger generator with the same rotor diameter (or a smaller rotor diameter for a given generator size). This would tend to lower the capacity factor (using less of the capacity of a relatively larger generator), but it may mean a substantially larger annual production.

Another way of looking at the capacity factor paradox is to say, that to a certain extent the choice can be made between a relatively stable power output (close to the design limit of the generator) with a high capacity factor - or a high energy output (which will fluctuate) with a low capacity factor.

- **Desired input from the project partners**

The project partners were asked to fill out the suggested default table that is shown in *Table 2*. Each REG-source has its own table. Again, it is proposed to subdivide the REGs from wind into 'small onshore', 'large onshore' and 'offshore', and to subdivide biomass into 'fuelled by biomass only' and 'co-burned with fossil fuel'.

The table gives an expected capacity factor for (for instance) the first 50 MW installed, then for the next 50 MW and so on. Probably, it may be assumed that the first installed MWs of each technology will be on the optimal location, and therefore will have the highest capacity factor. The next installations are expected to be on a suboptimal location, which will imply a lower capacity factor. This assumption justifies the division as in *Table 2*, namely the division into classes according to the amount of installed power that is already present before installation of the new REG.

REG source, either:

- Solar
- Wind, (for instance) subdivided into:
  - small onshore
  - large onshore
  - offshore
- Biomass, (for instance) subdivided into:
  - generators only fuelled by biomass
  - co-burning with fossil fuel *(total rated power of REG plant applies to the fraction of the generator power that is fuelled by biomass)*

	0 - 50 MW	50 - 100 MW	100 - 130 MW	130 -160 MW	160 - 200 MW
Expected capacity factor	0,45	0,40	0,35	0,35	0,30
Comments, preference for installation	(e.g. for wind: coastal region)	further inland			

Table 2.Classification of renewable energy generators

2.1.2.3 Production Variability

- **General information**

The true economic and ecologic value of a REG is the equivalent capacity of conventional power generation that it can replace. Thus, the production variability determines to a large extent the actual value of an installed generation plant.

Production may vary severely during the operation time of a REG. This variation can be periodical or arbitrarily fluctuating. In the cases of PV and wind power, a fluctuating noise signal is superposed on a periodical day-night variation of the power infeed. *Figure 1* shows the varying wind power infeed in the E.ON grid. The average difference between day peak and night dip is in the figure around 3000 MW, which can rise to more than 4000 MW in extreme cases. These figures must be compared to the total installed wind power capacity in the E.ON grid, which was around 5600 MW in the period when *Figure 1* was recorded.

Wind and solar power infeed depend on the season and on the hour of the day. A clear daily periodicity is always noted for solar power as well is for wind power.

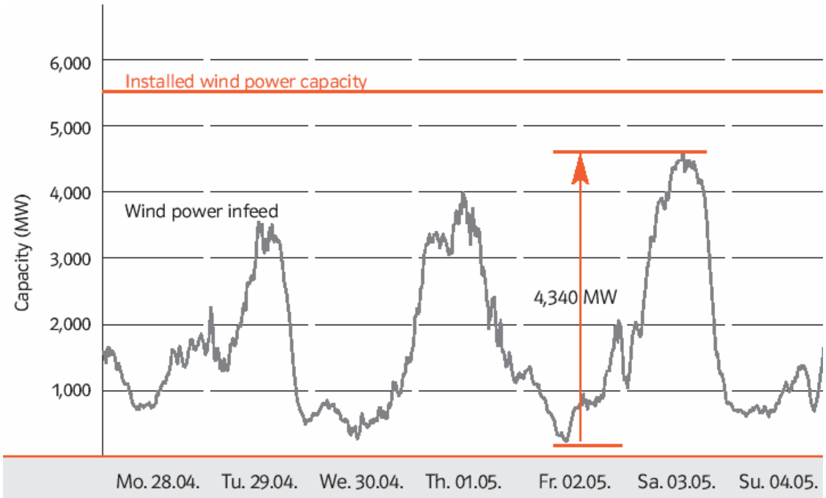


Figure 1. Strongly fluctuating wind power infeed in the E.ON grid (Germany) [2]

- **Proposed modelling strategy of RE supply for SPSD II project**

It is proposed to model fluctuating energy input from wind and solar power installations (optionally also for biogas installations) by means of Markov chains. First order Markov chains will be used to generate time series of wind and solar power input with a sample time of 15 minutes.

Markov chains are stochastic processes that can be parameterized by empirically estimating transition probabilities between discrete states in the observed systems. The Markov chain of the first order is one for which each subsequent state depends only on the immediately preceding one. Markov chains of second or higher orders are the processes in which the next state depends on two or more preceding ones.

Let $X(t)$ be a stochastic process, possessing discrete states space $S= 1,2,\ldots,K$. For example, $X(t)$ is the production of a solar panel on a given location. A system behaves stochastically as a first-order Markov Chain if, for a given sequence of time points $t_1 < t_2 << t_{n-1} < t_n$, the conditional probabilities are:

$$Pr\ \{ X(t_n) = i_n \mid X(t_1=i_1,\ldots,X(t_{n-1})=i_{n-1}\ \} \ = \ Pr\ \{ X(t_n)=i_n \mid X(t_{n-1})=i_{n-1}\ \} \qquad (1)$$

The conditional probabilities $Pr\ \{X(t)=j|X(s)=i\ \} =P_{i,j}(s,t)$ are called transition probabilities of order $r=t-s$ from state i to state j for all indices $0\leq s<t,$ with $1\leq i$ and $j\leq k$. They are denoted as the transition matrix P.

For k states, the first order transition matrix P has a size of $k\times k$ and takes the form:

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,k} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,k} \\ \vdots & \vdots & \vdots & \vdots \\ p_{k,1} & p_{k,2} & \cdots & p_{k,k} \end{bmatrix} \tag{2}$$

The state probabilities at time *t* can be estimated from the relative frequencies of the *k* states. If *nij* is the number of transitions from state *i* to state *j* in the sequence of speed data, the maximum likelihood estimates of the transition probabilities is:

$$p_{ij} = n_{ij} / \sum_{j} n_{ij} \tag{3}$$

The transition probabilities of any state vary between 0 and 1. The summation of transition probabilities in a row equals one. Mathematically, it can be expressed as:

$$\sum_{j=1}^{k} p_{ij} = 1 \tag{4}$$

In order to be able to use first order Markov Chains, the power feed-in by each RE power plant is divided into discrete states, for instance:

- state 1: instantaneous production = 0 % of the RE plant rated power;
- state 2: instantaneous production = 0 -10% of rated power;
- state 3: instantaneous production = 10 -20% of rated power;
- state 4: instantaneous production = 20 -30% of rated power;
- …
- state 11: instantaneous production = 90 – 100 % of rated power;
- state 12: instantaneous production = 100% of rated power

- **Example: proposed transition probability matrix for wind power**

A transition probability matrix ***P*** for a wind farm production, according to a first-order Markov Model and divided into 12 states as described above, looks like:

$$\mathbf{P} = \overbrace{\begin{bmatrix}
0.5 & 0.3 & 0.1 & 0.07 & 0.03 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.3 & 0.4 & 0.1 & 0.1 & 0.05 & 0.02 & 0.01 & 0.01 & 0.01 & 0 & 0 & 0 \\
0.2 & 0.15 & 0.3 & \boldsymbol{\mathit{0.15}} & 0.1 & 0.05 & 0.01 & 0.01 & 0.01 & 0.01 & 0.01 & 0 \\
0.1 & 0.1 & 0.15 & 0.3 & 0.15 & 0.1 & 0.05 & 0.01 & 0.01 & 0.01 & 0.01 & 0.01 \\
0.01 & 0.1 & 0.1 & 0.15 & 0.3 & 0.15 & 0.1 & 0.05 & 0.01 & 0.01 & 0.01 & 0.01 \\
0.01 & 0 & 0.1 & 0.1 & 0.15 & 0.3 & 0.15 & 0.1 & 0.05 & 0.01 & 0.01 & 0.02 \\
0.01 & 0 & 0.03 & 0.07 & 0.1 & 0.15 & 0.3 & 0.15 & 0.1 & 0.05 & 0.01 & 0.03 \\
0.01 & 0 & 0.01 & 0.01 & 0.02 & 0.1 & 0.15 & 0.3 & 0.15 & 0.1 & 0.1 & 0.05 \\
0.01 & 0.01 & 0.01 & 0.01 & 0.01 & 0.05 & 0.1 & 0.15 & 0.3 & 0.15 & 0.1 & 0.1 \\
0.05 & 0.01 & 0.01 & 0.01 & 0.01 & 0.01 & 0.1 & 0.1 & 0.1 & 0.2 & 0.1 & 0.3 \\
0.05 & 0.01 & 0.01 & 0.01 & 0.01 & 0.01 & 0.05 & 0.05 & 0.1 & 0.1 & 0.2 & 0.4 \\
0.1 & 0 & 0 & 0.01 & 0.01 & 0.01 & 0.01 & 0.01 & 0.05 & 0.1 & 0.3 & 0.4
\end{bmatrix}}^{\textit{Probabilities that power feed-in is in state (given by column number)...}}
\begin{array}{c}
\textit{... given the state of the} \\
\textit{previous time sample} \\
\textit{(given by row number)}
\end{array}$$

P is determined as a 12 x 12 matrix. Note that the sum of all elements in one row has to be equal to 1. The sum in each column indicates the global probability that the wind farm production is in the corresponding class.

As an example, the bold italic '***0.15***' (in the third row and fourth column of ***P***) indicates that the probability that the average 15 minutes wind farm production is between 20% and 30% of the farm rated power (class 4, 4^{th} column), given that the average farm production in the previous 15 minutes was between 10 and 20% percent of the rated power (class 3, 3^{rd} row) is 15%.

Note that:

- the diagonal elements of ***P*** tend to be large, as the probability that wind power (or solar power) is in the same class as during the previous 15 minutes is relatively high;
- the first column of ***P*** has all non-zero elements, as there is always a chance that the production in a 15 minutes time span is zero, regardless of the production during the previous 15 minutes (e.g. due to an emergency stop or in the case that the cut-out wind speed is reached);
- Other Markov matrices are found in the appendix.

This transition probability matrix can be used to generate a time series of wind power input values with similar statistical properties as the given farm; using a Matlab random number generator that takes the given probability functions into account. An example of generated time series is shown in *Figure 2.*.

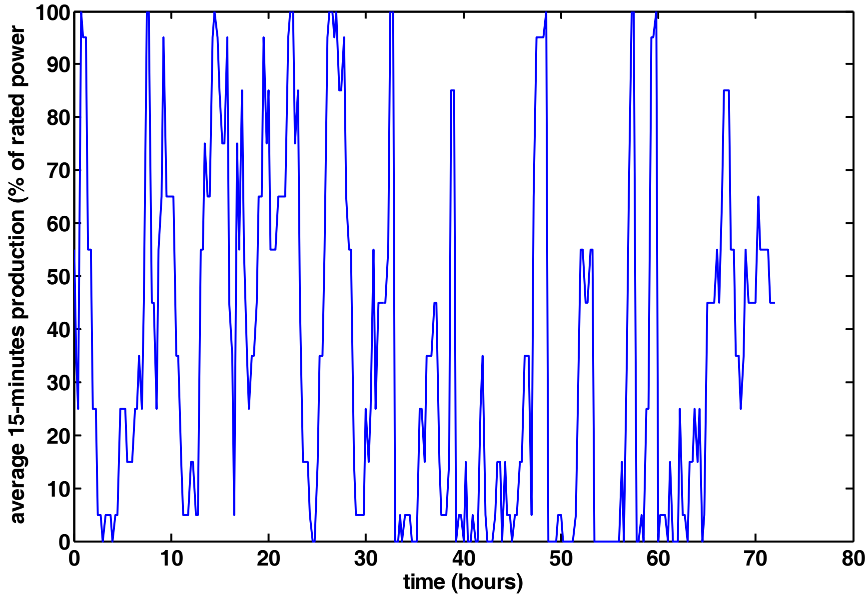


Figure 2. Generated time series with first-order Markov Chain

The (daily and seasonal) periodicity of the power feed-in from REGs can be modelled in various ways:

- by using a higher – order Markov chain: this requires the double amount of statistical parameters and does not make use of any physical knowledge of the modelled process;
- by applying weighting factors to the generated time series, that takes the hour of the day and the day of the year into account;
- by making either the weighting factors or the 1st order probability transition matrices time-dependent.

The second method is proposed for the day-night periodic behaviour, as this behaviour for solar power input, and - to a less extent – wind power feed-in, is partially deterministic.

The weighting factors to model the day night behaviour may be visualized as a periodic wave (sine, block, trapezoid…). An example is shown in *Figure 3*. For solar power, the weighting factor may be zero during the entire night. The final time series of power feed-in is then the product of the Markov-chain time series from *Figure 2* with the weighting factor. Obviously, all values are limited between 0% and 100%. The final result is shown in *Figure 4*.

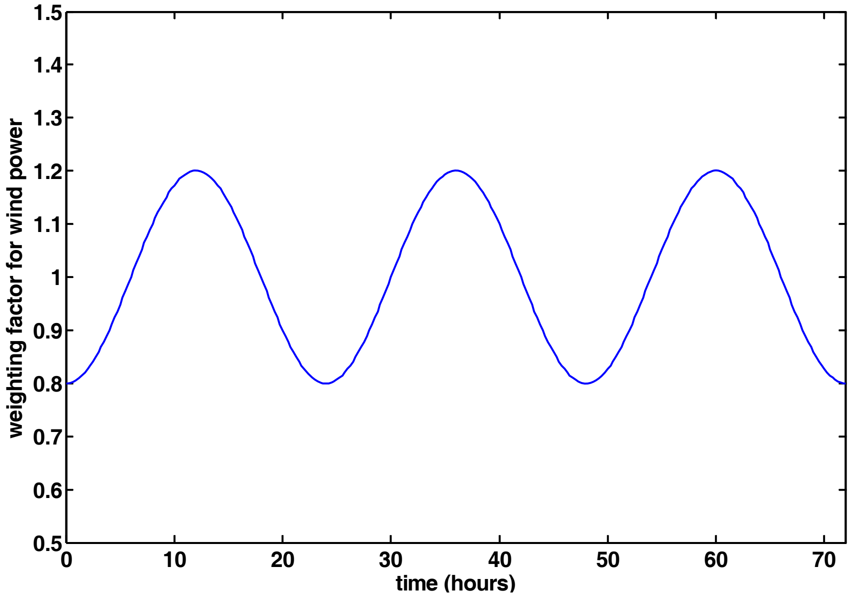


Figure 3. Proposed weighting factor to model the day-night behaviour of wind power

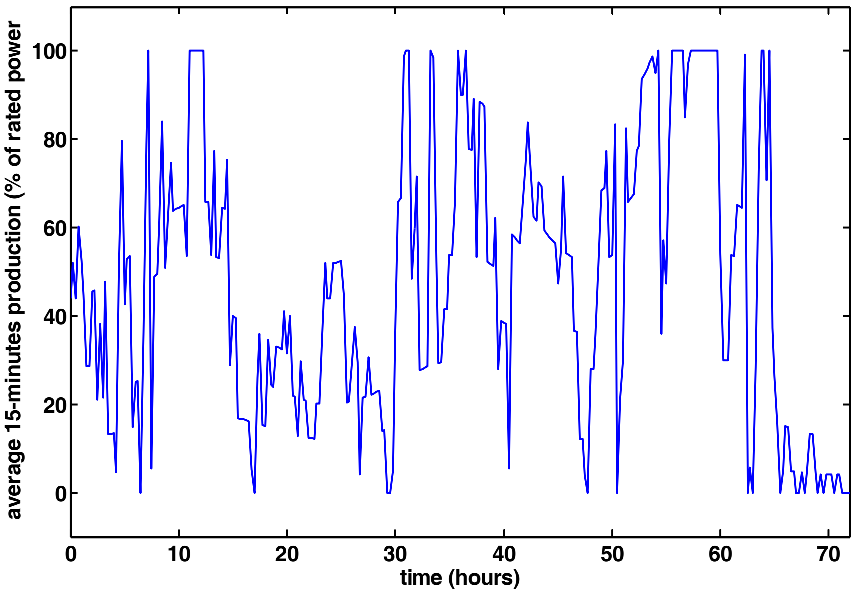


Figure 4. Generated time series with Markov chain, taking into account daily periodical behaviour

The proposal to approximate the seasonal variation is to use three different sets of weighting factors: one for summer, one for winter and one for intermediate season. Optionally, each season may have its own probability transition matrix P (for instance, if higher variations of energy feed-in are to be expected in a specific season).

- **Desired input from the project partners**

With the project partners, the following was discussed:

- determination of the modelling strategy with Markov Chains and weighting factors is acceptable for their renewable energy branch;
- time series of production data of REGs, data of various years are probably necessary, preferentially the sample time is 15 minutes;
- present annual, daily and other periodicities in the power generation of REG, determine a suitable waveform (sine, block…) to model the short-term (daily) periodicity;
- particular seasonal variations of production by REGs, and a way to model them. The proposed way is to generate various sets of weighting factors, one for each season;
- transition probability matrices that model the production behaviour of a renewable energy power plant;

Note that the optimal input for the project is representation of the production of a REG power plant as one generating unit (this is in contrast to representation of meteorological data e.g. wind speed, and also in contrast to the representation of the production of a single wind turbine that is part of a wind farm).

2.1.2.4 Spinning reserves

This part will be fully developed in 5.1.2.3.

2.1.2.5 Production Forecast Capability

This part is only mentioned, as it is not strictly in the scope of this project.

As it is shown in *Figure 5*, the demand can be forecasted with a high level of accuracy, while the wind power production presents a larger level of forecast error.

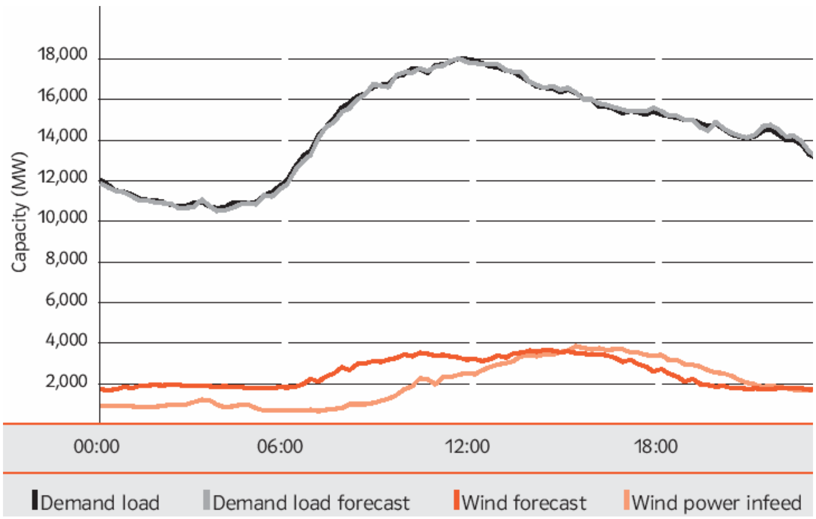


Figure 5. Real and forecasted demand, real and forecasted wind power infeed in the E.ON grid[2]

Figure 6 shows the frequency distribution of the forecast error for wind power infeed in 2003 in the E.ON control area. In this case a negative error deviation is found.

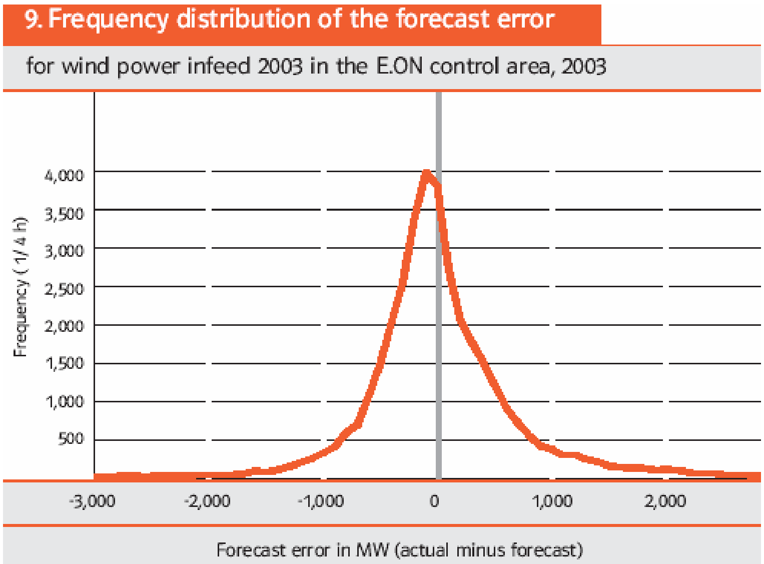


Figure 6. Frequency distribution of the forecast error for wind power infeed in the E.ON control zone [2]

2.1.2.6 Voltage controllability

This part will be fully developed in 5.1.2.2.

2.1.2.7 Ride-through Capability

This part will be fully developed in 5.3.

2.1.2.8 Switching Transients

- **General**

In most cases, electrical generators can only operate properly within a defined speed range. An induction generator, for instance, can only operate as a generator when its rotational speed is above its synchronous speed n_s (e.g. 1500 rpm). At speeds below n_s, the machine operates as a motor and consumes power. *Figure 7* and *Figure 8* show the speed and active power of an induction generator during start-up. The driving mechanical torque of the machine is constant during the simulation and equal to 50% of the rated torque. It is noticed that, for this example, the machine operates as a motor during the first second, with a peak consumption even larger than the rated generator power. A 'soft-starter' may be used to limit the inrush-currents, which results into a larger run-up time, but lower peak values.

Although most switching transients can be alleviated by using power electronic devices, it is expected that a large number of renewable energy generators may have a behaviour as in *Figure 8*. A large penetration of renewable energy generators in the grid, and a high number of on/off switching occurrences may cause severe grid disturbances. Switching transients need therefore to be assessed properly.

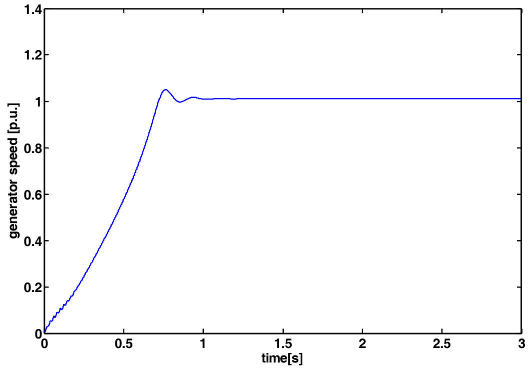


Figure 7. Induction generator speed during start-up

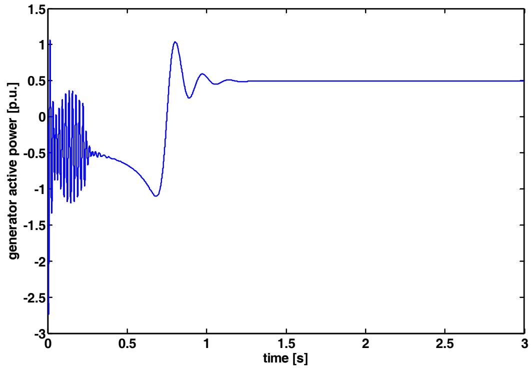


Figure 8. Induction generator active power during start-up

- **Proposed model for switching transients**

The proposed dynamic model for switching transients is shown in *Figure 9*. The high frequency transients are neglected in this model.

The model contains the following parameters:

- $P_{start,peak}$: the peak power consumption during start-up;
- $P_{start,steady}$: the steady power consumption during start-up (e.g. in case a soft-starter is used);
- P_{peak} : the peak generated power during start-up, (power overshoot)
- P_{steady} : the generated power after the switching transients have disappeared; and before the impact of fluctuating primary energy input (wind…) is noticed;

The significance of $t_1 - t_5$ are clear from *Figure 9*.

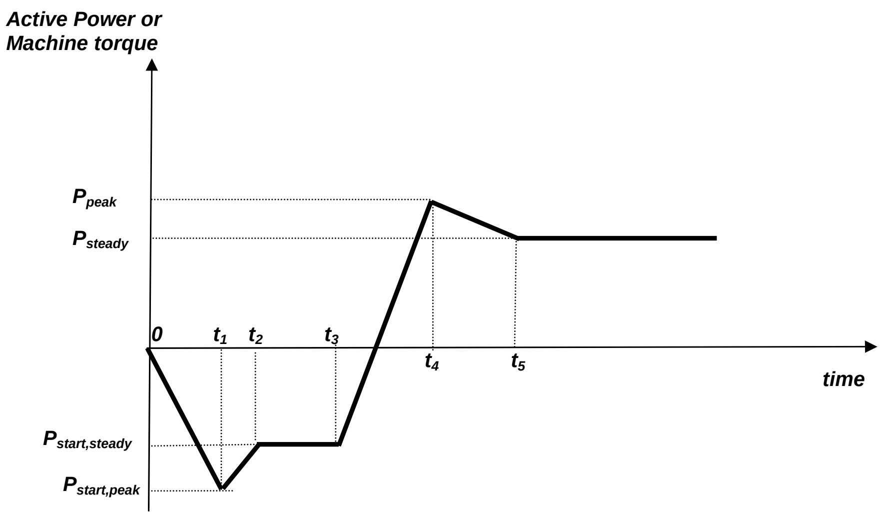


Figure 9. Proposed dynamic model for switching transients

- **Desired input from the project partners**

Relevant parameters are given in *Table 3*. A subdivision has been made for various classes of rated power for each type of REG, depending on the necessary number of subdivisions for accurate modelling, and whether the required parameters are a function of the machine rated power or not. The subdivisions for power classes made in *Table 3* are preferentially the same as those in *Table 1*.

Also a subdivision has been made for various values of P_{steady}, the generated power after start-up. It is assumed that, for instance for a wind turbine, the dynamic starting behaviour is different in case of switching in at cut-in wind speed or at rated wind speed. Again, it is up to the project partner to decide the required number of subdivisions for P_{steady}. It is well possible that some parameters coincide, like P_{peak} being equal to P_{steady} and t_4 equal to t_5 if no overshoot in power generation occurs.

It is proposed that all time values are given in seconds, and that P_{peak}, $P_{start,peak}$, P_{steady}, $P_{start,steady}$ are given as percentage of the machine rated power.

Total rated power of one RE power plant	*< 0.2 MW*			*0.2-1 MW*			*1 -2 MW*			*2 - 10 MW*		
P_{steady} (fraction of rated power)	*25%*	*50%*	*100%*	*25%*	*50%*	*100%*	*25%*	*50%*	*100%*	*25%*	*50%*	*100%*
t_1	…	…	…	…	…	…	…	…	…	…	…	…
t_2	…	…	…	…	…	…	…	…	…	…	…	…
t_3	…	…	…	…	…	…	…	…	…	…	…	…
t_4	…	…	…	…	…	…	…	…	…	…	…	…
t_5	…	…	…	…	…	…	…	…	…	…	…	…
$P_{start,peak}$	…	…	…	…	…	…	…	…	…	…	…	…
$P_{start,steady}$	…	…	…	…	…	…	…	…	…	…	…	…
P_{peak}	…	…	…	…	…	…	…	…	…	…	…	…

Table 3.Parameters for the proposed dynamic model for switching transients

3 Work Package 3: Characterisation of renewable energy sources with respect to security aspects (predictability/ancillary services) of electrical supply

Each of the partners assessed the RE source it is specialized in with respect to the grid operation aspects. This includes an assessment of the reliability of prediction of the energy production forecast (error margins) and also the extent op to which the conversion technology (as identified in the cluster projects) can be used to provide ancillary services. This information is presented as appendixes, with a brief summary given here.

3.1 Solar power

Appendix 1 describes the characterization of the solar power impact in the Belgian grid, according to the processing of real measurements and further conclusions. Appendix 2 shows the recent technological developments and next generation of PV power systems.

3.2 Wind onshore

The availability of onshore wind generators is explained, together with the case of offshore wind generators in Appendix 3, under the title 'Capacity credit of renewable energy generators'.

3.3 Wind offshore

Detailed in Appendix 3

3.4 Biomass

Appendix 4 shows the state-of-the-art of biomass in the Walloon Region, including technologies, biomass classification and energy production.

4 Work Package 4: Characterisation of maintainability / reparability / accessibility of renewable energy converters (3E / K.U.Leuven)

An additional aspect, valid for off-shore wind, is its limited accessibility for maintenance and repairs due to high seas. This aspect affecting the predictability of the energy production and delivery of ancillary services is considered in depth due to the relevant importance of off-shore wind in the use of RE in Belgium in the future. In this task, the requirements for access are compared to the sea conditions.

4.1 Availability and reliability of offshore wind farms

4.1.1 Introduction

Offshore wind farms are more difficult to access than wind farms on shore. At times, maintenance and repair can be impossible due to high seas. In case of unscheduled outages this may affect the predictability of the energy production and the delivery of ancillary services. Because of the relative significance of offshore wind energy in the use of renewable energy in Belgium in the future, the availability and reliability of offshore wind farms on the Belgian continental shelf are estimated here.

The concepts of technical availability and reliability are examined in the following section. Afterwards the methodology is presented. Then, experiences from existing wind farms in the Baltic and the North Sea are reviewed and analysed. These experiences are extrapolated to the situation on the Belgian continental shelf. Finally, the derived availability data are analysed with regard to economic impact on the wind farm operation and with regard to the security of energy supply.

4.1.2 Theoretical Concepts and Definitions

The terminology for a reliability assessment of electricity generation equipment is not always clear. Below, we quote the different terms as proposed in [3] for the context of offshore wind farms.

> **Reliability** of a system is the probability that the system will perform its tasks. For a wind turbine this indicates percentage of time it is producing the power that corresponds to the acting wind according to its nominal power curve.

> **Availability** is the probability that the system is operating satisfactorily. The major difference between reliability and availability is the O&M strategy of the system. A system can be very reliable: i.e. its failure frequency is extremely low, but when no maintenance or repair action is taken after a failure its availability becomes very poor.

Maintainability is a more qualitative issue that addresses the ease of repair issue. It can though be expressed in terms of hours needed to complete a repair action.

Failure is the termination of the ability to perform a required function of a system.

Accessibility is the percentage of time that a (offshore) construction can be approached. Evidently the accessibility depends upon the equipment used.

Note that the parameter reliability usually applies to components, single wind turbines or entire wind farms. The parameter availability typically applies to single wind turbines or wind farms.

The calculation of availability can be based on time or on energy. If based on time, availability of a wind farm reflects the total fault free hours of operation for all turbines as a fraction of the potential total hours of operation. Energy availability is defined as the actual electricity production as a fraction of the potential production. While outages due to scheduled maintenance usually occur during at low wind speeds, outages due to faults rather occur at times of high wind speed. Therefore, for offshore wind farms the energy availability is slightly higher than the time-based availability.

4.1.3 Methodology

The availability of a wind farm on the Belgian continental shelf is estimated based on theoretical considerations and on empirical data from the two large Danish wind farms that have been in operation for more than a year:

- Horns Rev, North Sea
  Distance from shore > 14 km
  80 turbines of 2 MW = 160 MW
  manufacturer Vestas
  access from the sea and from the air

- Nysted, Baltic Sea
  Distance from shore > 10 km
  72 turbines of 2.3 MW = 166 MW
  manufacturer Siemens Wind Power (formerly Bonus)
  access from the sea only

Two offshore wind farms are currently planned on the Belgian continental shelf, namely, by C-Power NV on the Thorntonbank and by Eldepasco on the 'Bank zonder naam'. Details are publicly available only for the Thornton Bank:

- Thornton Bank
  Distance from shore ≈ 30 km
  60 turbines of 3.6 MW = 216 MW
  manufacturer GE Wind Energy
  access from the sea and from the air

Note that the turbine selection for the Thornton Bank project is not yet final. The envisaged 3.6 MW turbines from GE Wind Energy have already been erected at other offshore wind farms. Therefore, we assume that the turbine reliability does not differ significantly from the one of the Vestas and Siemens Wind Power machines.

The availability of offshore wind farms is determined by its reliability and by its accessibility according to their conditional stochastic relationship. For offshore wind farms it can be calculated by means of Monte Carlo simulation. The considerations for the Belgian case are based on theoretical considerations that have already been published in [4] and on real working experience from the two large Danish offshore wind farms. The relationship between reliability, accessibility and availability is indicated in Figure 10. Note that this description originates from a study carried out back in 1998 mainly on a theoretical basis [5]. As will be shown in the following section, existing offshore wind farms had a higher availability than it would be estimated based on this figure.

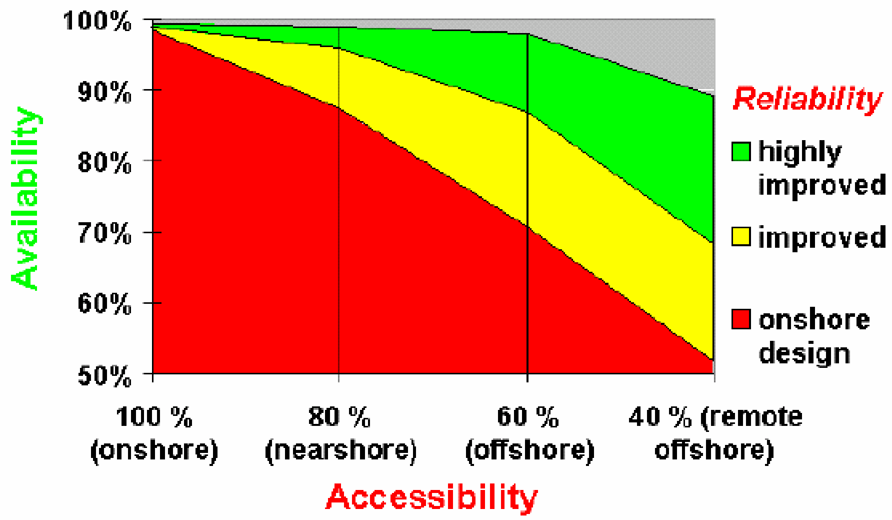


Figure 10: Calculated relationships between availability and accessibility for different grades of wind turbine reliability [6]

During the design process the reliability is determined by the reliability of the applied components: blades, gear boxes and bearings, generator, power electronics, control system, hydraulics, transformer and switchgear. Wind turbines for offshore application are designed for an extraordinary high reliability. For these turbines an ARM analysis (availability, reliability, maintainability) makes part of the design process.

In addition, reliability data from offshore wind turbines are available from existing wind farms. In [4] a turbine reliability level was classified as either onshore design reliability, improved reliability or highly improved reliability. After early bad experiences with small pilot wind farms and with the 160 MW wind farm at Horns Rev in the Danish North Sea where all nacelles had to be dismounted and brought to shore for retrofit, the current technology can be classified as of improved reliability. This is confirmed by the operational data from the two largest offshore wind farms currently in operation: the 160 MW Horns Rev wind farm and the 165 MW wind farm at Nysted in the Danish Baltic Sea.

The accessibility mainly depends on the way of access and on the environmental conditions. Today offshore wind turbines can be accessed from the sea by vessel and in some cases from the air by helicopter hoist.

The accessibility from the sea is mainly determined by the wave height. The turbine manufacturer Vestas considers the maximum significant wave height for turbine access from the sea to be about 2.1 m [6]. The owner Elsam states for the Horns Rev wind farm a maximum significant wave height of 1.1 m [7]. In practice, the accessibility from the sea is also affected by currents and wind direction and by the type and the size of the vessel that is deployed.

Main factors for access from the air are atmospheric conditions, namely a visibility beyond 5 km, a cloud base higher than 500 feet and no icing or lightning. High wind speed is generally spoken not a limiting factor for hoisting by helicopter. Finally, helicopter hoisting puts stringent limits to the number of passengers and the weight of the freight. As a consequence, only few people and light material can be transported and hoisted by helicopter [7].

4.1.4 Availability of Existing Wind Farms

The Nysted wind farm has an overall availability of 96.8%. More detailed the plant availability of the wind farm itself was 97.0% in the first year of operation and 97.6% in the second year. The 2.4% reduction in plant availability of the wind farm in the second year can be split up according to their cause [8]:

- scheduled maintenance: 0.6%,
- faults not requiring a technician's visit (remotely resetable): 0.1%,
- faults requiring technician's visit but no physical correction: 1.1%,
- faults requiring physical correction: 0.6%.

This plant availability has to be further reduced by 0.5% due to the limited accessibility of the wind farm of 80%. The author of [8] calculates this further reduction as

$$1.7\% \cdot 0.2 \cdot 1.5 = 0.51\%, \qquad (5)$$

with the 1.7% accounting for the faults requiring a technician's visit and the factor 0.2 the fraction of time when the wind farm is not accessible. The factor 1.5 is applied in order to account for the fact that faults occur more often during high wind speed. Adding the further reduction of 0.51% from (*5*) to the availability loss of the wind farm itself yields an overall availability of 96.8% on average and 97.1% in the second year of operation.

By far the largest reduction in plant availability (1.1%) is caused by small faults requiring no physical correction. These are typically due to sensor failures, noisy signals, etc. They can be reduced considerably by simple measures like redundant sensors and controllers. Siemens Wind Power assumes that by such measures faults requiring a technician's visit but no physical correction could be reduced considerably which would increase the overall availability of the same wind farm by 1% [8].

The accessibility of the Nysted wind farm in this first two years was 80% of the time. The owner Energi E2 estimates that an increase in accessibility up to 90% should be possible by deploying a larger and more powerful vessel [8] [9].

The Horns Rev wind farm is situated in the North Sea where the weather and sea conditions are much harsher. In general, for offshore plant in the North Sea an accessibility of approximately 60% is assumed [4][7]. Also in [7], Elsam specifies that over the year the accessibility of the Horns Rev wind farm by boat was around 65% annually with a lot of variations over the year. The accessibility of the wind farm by helicopter hoisting was 90%.

For an offshore wind farm on the Belgian continental shelf we assume an accessibility of 60% by boat and 90% by helicopter as in the case of Horns Rev. Note that in practice there are some differences. Firstly, the designated zone for offshore wind energy in Belgium is much farther from the shore than Horns Rev which additionally reduces the accessibility. A regular service vessel will need more than two hours to arrive at the Thornton Bank and even more to arrive at the 'Bank zonder naam'. Secondly, the wind and wave climate is not exactly the same in different parts of the North Sea. Nevertheless, we assume the proposed accessibility values as a best estimate.

4.1.5 Availability for the Belgian Continental Shelf

For the calculation of availability with different accessibility, Siemens Wind Power gives an estimate based on its experiences in the Baltic Sea (see previous section). We have based the calculations on the second year of operation with the assumption that the availability during the first year of operation was affected to some extent by infant diseases. Correcting the decrease in overall availability as calculated in (*5*) for the differing accessibility in the North Sea yields the results shown below. We have looked at three cases depending on accessibility and plant reliability.

Case 1: Worst case

Assumptions:

- accessibility 60%
- plant availability 97.6%
- faults requiring a technician's visit 1.7%
- all interventions are taken from the sea

Case 1 is the worst case. We assume that virtually all interventions have to be undertaken from the sea which is impossible during 40% of the time. Transferring the estimate from (*5*) to this case yields a reduction of availability due to the limited accessibility of

$$1.7\% \cdot 0.4 \cdot 1.5 = 1.02\%. \qquad (6)$$

Including scheduled maintenance and remotely resetable faults and accounting for weather-caused inaccessibility the overall availability of the wind farm in the worst case becomes 96.6%.

Case 2: Helicopter and boat access

Assumptions:

- accessibility 60% by boat and 90% by helicopter
- plant availability 97.6%
- faults requiring technician's visit but no physical correction: 1.1%,
- faults requiring physical correction: 0.6%,
- interventions for physical correction must be undertaken from the sea
- interventions requiring no or minor physical correction can be undertaken by helicopter

Case 2 is a realistic estimate. Only large interventions, requiring a larger crew, works on several machines or large equipment or spare parts must be undertaken by boat with an accessibility of 60%. The much more frequent interventions requiring no or minor physical correction can be done by helicopter when necessary with 90% accessibility. We then calculate the reduction of availability due to the limited accessibility as

$$1.1\% \cdot 0.1 \cdot 1.5 + 0.6\% \cdot 0.4 \cdot 1.5 = 0.525\%. \qquad (7)$$

Including scheduled maintenance and remotely resetable faults and accounting for weather-caused inaccessibility the overall availability of the wind farm becomes then 97.1% as it is in Nysted in the Baltic Sea.

Case 3: Increased plant reliability

Assumptions:

- accessibility 60% by boat and 90% by helicopter
- plant availability 98.5%
- faults requiring technician's visit but no physical correction: 0.1%,
- faults requiring physical correction: 0.5%,

- scheduled maintenance: 0.8%
- interventions for physical correction must be undertaken from the sea
- interventions requiring no or minor physical correction can be undertaken by helicopter

Case 3 is characterized by a higher effort for scheduled maintenance in order to keep the plant reliability up. As a consequence the need for larger interventions is slightly reduced. Moreover, faults requiring no physical correction are reduced significantly, for example, as a consequence of increased redundancy in design. Applying (*7*) to these data yields the reduction of availability due to the limited accessibility as

$$0.1\% \cdot 0.1 \cdot 1.5 + 0.5\% \cdot 0.4 \cdot 1.5 = 0.315\%. \qquad (8)$$

With the assumed plant availability of 98.5% the overall availability of the wind farm would then be 98.2%.

Cases 1 and 2 show clearly the importance of helicopter access for wind farms in the North Sea. Especially as long as minor faults need to be reset manually at the wind turbine, the helicopter can contribute to a significant increase in availability. Case 3 is relatively optimistic if compared to the operational results from Nysted and Horns Rev. It rather describes a situation that should be pursued in the long run by increasing turbine reliability.

All cases have in common a higher reliability than it would be derived from *Figure 10* based on the level of improved technology. This is mainly due to the underlying plant reliability which in Nysted has turned out to be relatively high. This underlines the importance of applying proven wind turbine technology.

Finally, in all three scenarios the wind farm operator has to make a trade off between costs for maintenance and repair on the one hand and for lost energy generation on the other hand. The economic optimum in this respect may result in a slightly lower availability than the technical optimum. Assuming that the wind farm operators of the farms at Nysted and the Horns Rev pursue the economic optimum the given availability data can be considered as close to the economic optimum. In the further text no difference between economic optimum and technical optimum of availability has been made.

4.1.6 Analysis of Results

The calculated spread in availability lies between 96.6% up to 98.2%. If the applied wind turbine technology turned out to be less reliable than the turbines applied in Nysted and Horns Rev, the availability could still be somewhat lower.

While a plant availability of 97 to 98% would be good onshore, for an offshore plant it is associated with additional costs for access by boat or helicopter and for the maintenance crew.

For the economical viability of an offshore wind farm, more efforts need to be undertaken to keep up availability. The following factors are therefore essential:

- high reliability of wind turbines and components including a high redundancy,
- good planning for scheduled maintenance,
- good preparation of interventions (tools, spare parts, communication),
- high flexibility of the maintenance crew.

For the security of energy supply these availability values are not critical. The calculated availabilities for an offshore wind farm on the Belgian Continental Shelf are totals of turbine availability for all wind turbines. Usually, a fault in the wind turbine occurs only at one single or few wind turbines at a time and during repair the turbines continue operation. Only faults at the high-voltage connection to the shore, the main transformer offshore or the main switchgear would lead to an outage of the full installed capacity. Such faults only make a negligible part of the reduction in availability as calculated above.

Finally, a wind farm on the Belgian continental shelf can be expected to produce no power during 2 to 3% of the time due to low wind speed. On this background the event of the full installed capacity being unavailable due to technical faults is considered negligible.

4.1.7 Conclusions

The overall availability of an offshore wind farm is determined by the plant reliability and by its accessibility. The plant reliability is type and manufacturer dependent and in the most recent large offshore wind farms it has turned out to be satisfying. Nevertheless, significant improvements could be achieved especially by increasing the redundancy of components and thus decrease the need for small interventions not requiring physical correction. In any case an integrated design for reliability is the key.

Accessibility depends on the site and on the chosen access options. Offshore plants in the North Sea are accessible by boat only during approximately 60% of the time. Therefore, facilities for hoisting service staff on the turbine from a helicopter and a landing platform on the transformer station are recommended. Helicopter access is possible about 90% of the time. Finally, the number of passengers and the amount of heavy equipment is limited with access by helicopter. Hence, and taking into account the costs, access by boat will always be the first choice as long as the wave height allows.

The availability of a wind farm on the Belgian Continental Shelf has been estimated on the basis of real experiences from the first years of operation of two large offshore wind farms in the Baltic Sea and in the North Sea. For the first wind farm on the Belgian Continental Shelf helicopter access is planned. The availability of this wind farm will then be around 97.1% with the assumption of state-of-the-art wind turbines. Without helicopter access the availability would be around 96.6% and with helicopter access and increased plant reliability it could become 98.2%.

Due to the high expenses for intervention by helicopter or boat, variation within this range from 96.6% up to 98.2% is significant and the owner of the wind farm should pursue the upper part of this range by means of a good maintenance strategy and reliable machines.

For the security of energy supply these availability values are not critical. Most faults occurring to offshore wind farms are single-turbine faults not affecting the other turbines. Faults which lead to a shut down of the entire wind farm only make a negligible part of the reduction in availability as calculated above and they are negligible in comparison to the 2 to 3% of the time during which the farm produces no power due to low wind speed.

5 Work Package 5: Estimation of the impact of possibilities to contribute to the ancillary services (K.U.Leuven)

In this task a synthesis and global validation will be made of the outcomes of WP 3 and WP 4. This information is used to perform validating computations on the simulation model of the Belgian grid (developed for use in the cluster project) in order to evaluate the practical implementation extent of these technologies in aspects such as the provision of grid operation support task, in realistic scenarios, as in the cluster project. A synthesis report is generated based on internal reports and the validations.

5.1 Ancillary services

5.1.1 Definitions

In order to maintain the correct operation of the grid and to ensure the power supply in the established terms and conditions, a wide group of services is defined. These so-called "ancillary services" guarantee the rights of the consumer and imply requirements for the supplier.

According to Eurelectric (Union of the Electricity Industry) [10], ***ancillary services*** are all services required by the transmission or distribution system operators to enable them to maintain the integrity and stability of the transmission or distribution systems as well as the power quality.

A different number of services can be included in this group, depending on the country. In Belgium, the most important ancillary services considered are the following [10]:

- Frequency control;
- Voltage control;
- Spinning reserve;
- Black start capability;
- Remote automatic generation control.

5.1.2 Analysis of the ancillary services

5.1.2.1 Frequency control

The electric frequency of the grid is set at 50 Hz. This value gives a notion of the rotating speed of the synchronized generators of the system. When the consumers demand more power, the generators, due to their inertia, expressed in a "statism", tend to decrease their speed if the driving torque is not increased, and thus, the frequency of the system. In the same way, when the power demand decreases, the generators tend to increase their rotational speed and the frequency of the grid.

Hence, the frequency control ensures the stability of the grid frequency in the allowed range which guarantees the safety of supply. The primary control reserve must be activated after a frequency deviation of 200 mHz or more [11], demanding from the generators an increase or decrease of the power produced to minimize the difference between demand and supply and stabilize the frequency of the grid.

- **Contribution of Wind Power generation to the frequency control**

Wind power hardly ever contributes to primary frequency regulation, as can be extracted from the position paper from UCTE (Union for the Coordination of Transmission of Electricity) about wind power in Europe [12].

According to UCTE, the impact of wind power on frequency control is caused by the fact that wind is uncontrollable. The variability of wind on a range from 15 min to hours complicates the load following with the conventional units that remain in the system, as well as the demand curve to be matched by these units (system load minus wind power generation) is far less smooth than it would be without wind power as the unpredictability now comes from the loading as well as from the generation. This heavily affects the dispatch of the conventional generators when wind power is present in sufficient amounts.

B. Kirby and E. Hurst [13][14] also state that generators differ dramatically in how well they follow the system operator's commands to supply regulation. Hydro units typically track control signals quite well while thermal units have more difficulty. This is one reason that the amount of regulation required by two similar size control areas can differ substantially. *Figure 11* compares the requested and actual regulation movements for two large coal fired generators.

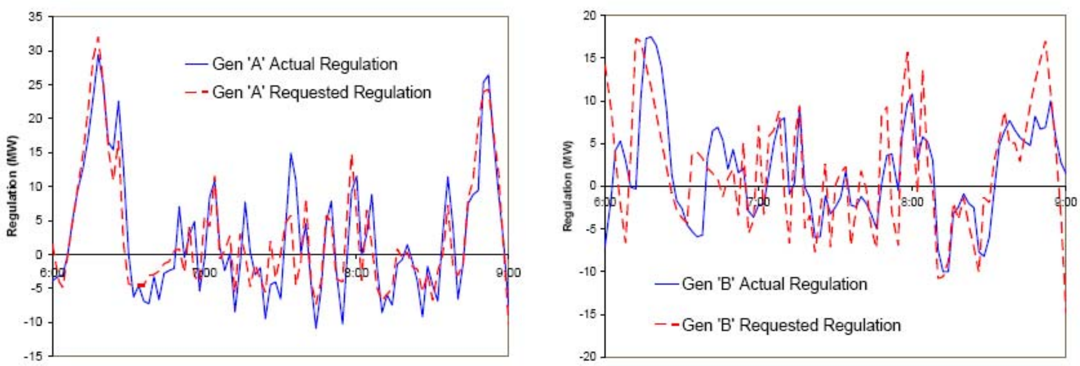


Figure 11. Following of regulation signals with different generators. Gen A and Gen B are two coal fired generators [13].

The variability of the aggregated wind output power in a shorter term (<1 min) for a larger number of wind turbines are very much smoothed and are generally not considered problematic. The turbulence which induces these fluctuations is stochastically quantified when many turbines are considered.

B. Kirby [13] mentions the positive effects of wind turbines *aggregation* in the regulation requirements to the wind farms. Relative regulation requirements decrease whenever larger aggregations are considered. A 202 MW wind plant would have required 18.2 MW-hr of regulation during a particularly volatile week if it had to compensate for its variability independently but would require only 9.4 MW-hr when integrated into this control area, a 48% reduction for the wind plant. Aggregation is a powerful tool for reducing regulation requirements that benefits all participants.

The impact of wind power on frequency control and load following becomes more severe the higher the wind power penetration level is. The higher it becomes, the larger the impact of wind power on the demand curve faced by the remaining conventional units. Thus, the requirements on the ramping capabilities of these units must be stricter in order to match the remaining demand curve and to keep the fluctuations of the system's frequency, caused by unbalances between generation and load, within acceptable limits. It is, however, impossible to quantify unambiguously the wind power penetration level at which system-wide effects start to occur because of the differences in, for example, conventional generation portfolio, wind speed regime, and geographical spread of the turbines, demand curve, and network topology between various power systems as discussed in [12].

The Horns Rev wind farm (Denmark), participates in the frequency control following the characteristic shown in *Figure 12*, where all settings are adjustable, i.e. dead band, control band gain, and max/min.

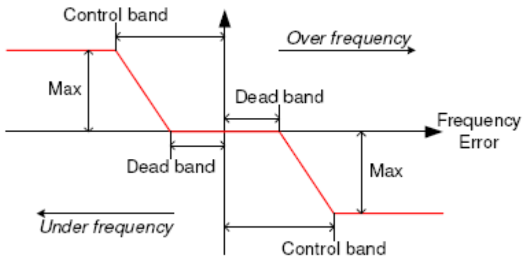


Figure 12. Characteristic of frequency control in Horns Rev[15].

- **Contribution of CHP units to the frequency control**

The units without power electronic interface such as, for instance, the CHP units (diesels, gas engines, gas turbines…without inverters) have to be considered separately. EDF R&D (France) has characterized the behaviour of the CHP plants providing ancillary services [16].

The cogeneration function is often allocated to these technologies to increase the global efficiency of the installation. For CHP based schemes, their operation is heat rather than electricity driven. Often CHP plants are specified such that the gas turbine runs at full load in order to optimize the efficiency. A consequence of such arrangements is that the operating envelope of the gas turbine, and hence the electrical generator, is severely constrained by the demands of the industrial process requiring heat. Thus, provision of AS with CHP plants leads to a drop of the efficiency and is limited by the heat requirement. However, some large CHP connected to the French transmission system contribute to primary frequency and voltage control [16].

- **Contribution of other types of generation to the frequency control**

The contribution of other types of generation (e.g. photovoltaic) is far from significant in order to provide frequency control to the grid. The ability of solar power for providing this type of ancillary services is nowadays in research, but the real need for solar power in frequency control is practically null as the PV penetration in Belgium is not significant.

5.1.2.2 Voltage control

A simple definition of voltage control is given by Eurelectric [10], where voltage control is explained as the maintaining of the voltage in a grid through injecting or absorbing reactive power, in case of a system with a high X/R ratio (inductive lines), by means of synchronous or static compensation. The relation between reactive power and voltage is used in this case to control the voltage level locally by increasing or decreasing the appropriate power in that location. In systems with a low X/R ratio (resistive lines, e.g. cables) the usual reactive power – voltage control performs poorer. As this can be the case for distributed generation connections, a deeper approach is carried out.

As the previous droop control method neglects the resistance of the line (assuming inductive lines), a new method for controlling voltage and frequency in island grids and resistive lines is presented in [17] considering both X and R of the power lines.

By imitating a voltage source with complex finite-output impedance, voltage droop is obtained. Frequency droop control results from synchronizing the power source with the grid. This method exhibits superior behaviour considering the mitigation of harmonics, the short-circuit behaviour and in the case of a non-negligible line resistance, the 'efficient' control of frequency and voltage.

- **Contribution of Wind Power generation to the voltage control**

According to [12], the impact on the dynamics and stability of a power system is mainly caused by the fact that, in wind turbines, generating systems are applied that are not based on a conventional synchronous generator. The specific characteristics of these generating systems are reflected in their response to changes in terminal voltage and frequency, which therefore differs from that of a grid-coupled synchronous generator. It is possible to comment on the impact of the three main wind turbine types on power system dynamics and stability in a qualitative sense by analyzing their properties.

Squirrel-cage **induction generators** used in constant-speed turbines can lead to voltage and rotor-speed instability. During a fault, they accelerate due to the unbalance between mechanical power extracted from the wind and electrical power supplied to the grid. When the voltage restores, they consume much reactive power, impeding voltage restoration. When the voltage does not return quickly enough, the wind turbines continue to accelerate and to consume large amounts of reactive power. This eventually leads to voltage and rotor-speed instability. Opposite to what applies to **synchronous generators**, whose exciters conventionally increase reactive power output at low voltage and thus accelerate voltage restoration after a fault, squirrel-cage induction generators hence tend to slow down voltage restoration [12].

When the penetration level of variable-speed turbines in the system is high and they disconnect at relatively small voltage dips, a voltage dip in a wide geographic area could lead to a large generation deficit. Such a voltage dip could, for instance, be caused by a fault in the transmission grid. To prevent this, some grid companies and transmission system operators facing a high contribution of wind power in their control area are currently proposing more demanding connection requirements. They prescribe that wind turbines must be able to withstand voltage dips of certain magnitudes and durations, in order to prevent the disconnection of a large amount of wind power at a fault. In order to meet these requirements, manufacturers of variable-speed wind turbines are implementing solutions to reduce the sensitivity of variable-speed wind turbines to grid voltage dips [12].

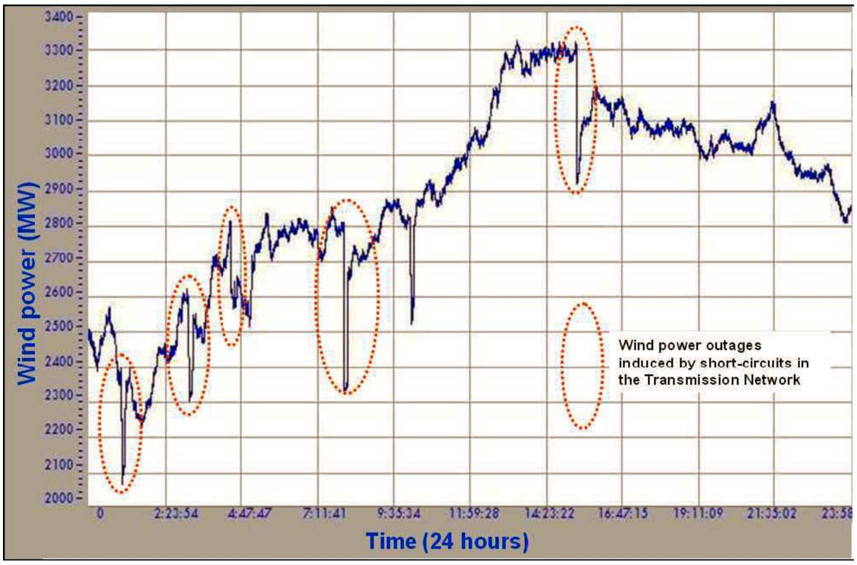


Figure 13. Recorded wind power and wind power outages induced by well-cleared shortcircuits in the Transmission Network (Spain) [12].

- **Contribution of CHP units to the voltage control**

As stated in the previous section, under the title 'Contribution of CHP units to the frequency control', these units can provide voltage control to the grid in the case that they run with synchronous generators. Some large CHP plants are already contributing with these ancillary services to the grid in France [16].

5.1.2.3 Spinning reserve

Also according to the definitions in [10], spinning reserve means the increase or decrease in generation or reduction in consumption that can be provided at short notice, carried out by partially loaded generation units and interruptible costumers.

In case of an unexpected increase in the consumption, e.g., the generators that are not working at full capacity can increase their production relatively fast to provide the power needed, with no need to start another generation unit, which would be slower and expensive.

- **Contribution of Wind Power generation to spinning reserve**

The progressive introduction of wind power into the grid increases the need for a larger spinning reserve from the conventional power plants. The reason is that if a wind farm does not reach the nominated production, based on a forecast, then this power not provided must be filled in by another generator in order to fulfil the demand, being the best option to use the spinning reserves from the 'faster' power plants (hydro power plants, gas turbines…) because of their short time of reaction. If this is not possible, the next option is to turn to thermal power plants, whose reaction is slower than hydro and gas. This would result in a number of thermal power plants running with a lower efficiency than the optimal value, modifying their production according to the output of the wind farms.

Comparing to frequency control, spinning reserves control the power output of the power plants in order to fulfil the commitment of supply, while frequency control acts over the speed of the generators within an area in order to keep the frequency within its acceptable limits.

This relation between penetration of wind power and increasing of spinning reserves raises another question. Is it really clean energy what wind power provides? The higher amount of spinning reserves running means, the more generators will be producing at a low rate, decreasing their efficiency as well as increasing their emissions substantially.

A calculation based on Estonian and Danish data reveals that the integration of considerable capacity of wind turbines would increase the fuel consumption and emissions of thermal stations about 8-10%. It is also noted that situations can appear where probably no environmental gain is achieved at all [18]. But in the case of Belgium the frame of reference is different than in Estonia, where there are no hydro power plants to supply the possible lack of wind power and they have to rely completely on thermal power plants. Hydro is also renewable and clean, and it responds quite fast. The best way to limit the emissions is using hydro power plants (pumped storage) to balance the discontinuities in wind power output. Further research is proposed to find a possible solution in this direction with Belgian hydro plants.

Wind power can play a role in the reserve provision by holding back a part of the power output as a reserve [19]. An interesting example to look at from Belgium is the Wind Farm Main Controller in the Horns Rev wind farm in Denmark [15]. In this demonstration project, the 160 MW offshore wind farm supplies active power for frequency control and spinning reserve as an integral part of the unit commitment strategy of the energy supplier Elsam. A brief explanation of the power control modes described by Elsam is given here:

- **Power control modes**

In order to obtain a participation in the control tasks as a conventional power plant, in Horns Rev wind farm (Denmark) four power control modes have been developed [15]:

1. Absolute production limiter

During periods with reduced transmission capacity in the grid (e.g. due to service or replacement of components in the main grid) the wind farm is able to operate at reduced power levels with all turbines running.

2. Balancing control

The wind farm is able to participate in the regional secondary control.

3. Power Rate Limitation

Passing weather fronts and thunderstorms can cause large and fast variations in the power production. Obviously, decreasing wind speeds cannot be avoided, but when the wind speed increases, the wind farm is able to impose a positive rate of change (dP/dt) limitation.

4. Delta Control

In some periods it may be advantageous to run the wind farm as a spinning reserve. To make this work properly the wind farm is controlled so the power production is an adjustable number of MWs below the possible power. This is used for primary (frequency) control purposes.

The principle of all the mentioned control functions is illustrated in *Figure 14*.

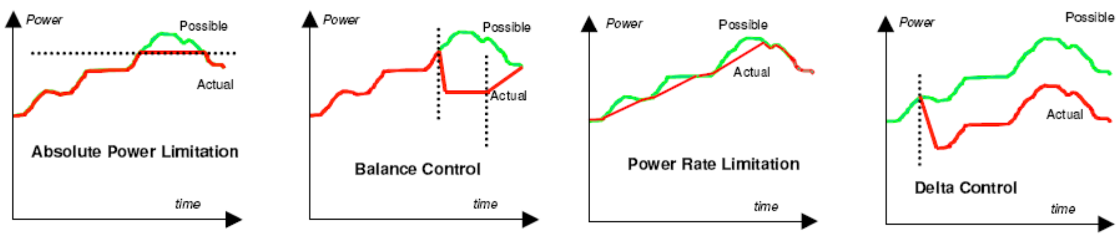


Figure 14. Outline of the output power control functions. The plots show the possible power and the actual active power with the different control functions [15].

5.1.2.4 Black start capability

Black start capability refers to the ability to start a generator and maintain operation independently from the electricity system, e.g., after a blackout. This is an essential prerequisite for system security as a plant can be called on during a blackout to repower the grid.

The procedure for a black start can be described as follows [20]:

1 The system operator determines the nature, cause, and extent of the outage and whether the black start plan should be implemented;

2 The system operator communicates with appropriate utility departments, neighbouring utilities, and the regional reliability council;

3 Loads are disconnected and the transmission system is sectionalized, either directly from the control centre or by the system operator directing field personnel to perform the operations;

4 The system operator directs one (or multiple) black start generators to begin operation;

5 Once such a unit has started itself, the system operator begins the complex process of re-energizing a portion of the transmission system and providing power to other generating units;

6 Generators without black start capability return to service as soon as possible after offsite power has been restored to them to allow restoration of the overall system to continue;

7 The system operator directs the reconnection of loads to the system as additional generation is returned to service, initially to help stabilize the generation and later to restore normal operations

8 As individual islands of balanced generation and load grow, the system operator coordinates their resynchronization into the interconnection;

9 Service is restored to the remaining customer loads.

All these steps must protect equipment and personnel, and maintain voltages and frequency near their reference values.

- **Contribution of Wind Power generation to black start capability**

Wind generation has no black start capability. A wind farm is not able to restore the power in the system after a blackout. Also no requirements are asked from the grid in this respect. According to this ancillary service, wind generation is neither affected by nor influencing the planned operation of the system. Hence, it can be stated that wind power has no contribution to black start capability.

- **Contribution of CHP units to black start capability**

In the case of large CHP plants, it is possible to provide the restoration of the system power after a blackout in order to start the repowering of the grid.

5.1.2.5 Remote automatic generation control

Remote automatic generation control is defined in [10] as a means of regulating frequency by controlling the output through a centrally-based control system. It automatically adjusts the generation in a control area to maintain its interchange schedule plus its share of frequency regulation..

The aim of this service is to control the power output from a generation area in order to maintain the system frequency or the determined interchange between the different areas. With the automatic generation control, the balance between demand and supply is guaranteed second-to-second as well as the right power flow between different areas.

- **Contribution of Wind Power generation to remote automatic generation control**

An overview of the state-of-the-art over wind power related to automatic generation control is found in [21]. This report states that from the perspective of automatic generation control, wind generation effectively adds uncertainty to the volatility of load fluctuations. The magnitude of the uncertainty is dependent on many factors such as location, turbulence, technology and so on.

The second-to-second fluctuation from a single large wind farm will tend to be relatively small. They will also tend to have no correlation with load variations in the same time frame. Thus, they may or may not add to the level of control action required. At modest levels of penetration, the impact is insignificant. At moderate levels of penetration, additional regulating resources may need to be committed to provide this service. It is possible that high levels of penetration could influence the type of resource committed (i.e., resources better suited to meeting the required amplitudes and rate of power variation).

The wind industry is beginning to develop new concepts for smoothing output and providing grid friendly dynamic response. These concepts hold promise for dynamic performance that may be superior to that presently achieved by conventional generation resources.

5.2 Safety and protection mechanisms

The impact of distributed generation on the following three aspects of safety and protection is qualitatively discussed below:

- unintentional islanding;
- relay selectivity;
- fault detection.

5.2.1 Unintentional islanding

'Islanding' can be defined as the continued operation of a distributed generation unit tripped from the main grid, due to a grid fault or for grid maintenance purposes. The grid section including the embedded generation in islanding is referred to as a power island [22].

Intentional islanding is possible without causing difficulties if the power island contains at least one generation unit that controls the voltage of the energised grid section. This is for instance the case for uninterruptible power supply systems where a power island is maintained intentionally in order to securely supply critical loads.

Unintentional islanding can occur if a grid section is disconnected from the mains with its power balance approximately in equilibrium. This compromises the safety of maintenance staff working on the disconnected grid section. It is part of line working procedures in most countries to take all reasonable steps to check that the circuit is not energised.

The transition to islanding mode is mostly detected by a disturbance in voltage magnitude or frequency on the power island. However, these transition phenomena may be minimal if the power island is in equilibrium for both active and reactive power. A rigorous implementation of island detection is not straightforward. In [22], a report of laboratory testing with four inverters from different manufacturers indicates that for every inverter, conditions can be provoked in which unintentional islanding is not detected. The exact conditions under which islanding occur depend on the inverter type, and on whether specific island detection schemes are implemented or not. However, also with specific islanding detection schemes, unintentional islanding may still occur in specific conditions, e.g. when the instantaneous load and generated power in the power island is very small, i.e. less than 20% of the rated values.

In practice unintentional islanding is only probable for grids with a significant fraction of embedded generation. With little embedded generation in a distribution system, unintentional islanding is virtually impossible. Therefore, special attention should be paid to design and reliability of the islanding protection function in the field, rather than to ever more sophisticated worst-case testing in the laboratory.

5.2.2 Selectivity

'Selectivity' refers to the protection system ability to isolate the faulted zones, with the smallest possible disruption to other zones [23].

The 'selectivity' principle guarantees that the smallest possible amount of grid users in case of a fault is isolated, only isolating a larger amount if the security equipment nearer to the fault suffers from failures.

However, when distributed generators are installed in the grid, the opening of the circuit breaker further upstream the fault and the distributed generators does not guarantee a total isolation of the grid fault.

The general rule of thumb for implementing selectivity is to increase the relay switching time delays after fault detection in a radial branch with decreasing distance from the main grid. The presence of distributed generators however implies that this principle cannot be applied anymore, as it does not guarantee a total disruption of current towards the fault. In general, an increased amount and performance of switching relays are necessary in the presence of distributed generators

5.2.3 Fault detection

The magnitude of a fault current depends on the local short-circuit power and the fault impedance, but is mostly an order of magnitude larger than the rated line current. In a radial grid, this fault overcurrent is detected by all relays upstream the fault. Their switching order is determined by the selectivity principle, as discussed above.

In the case with installed distributed generation on a line, the fault current is to some extent supplied by the distributed generators. The current at the fault location is the same with or without distributed generation. If the nearest circuit breaker fails to isolate the fault, the circuit breaker further upstream the fault, has to isolate it. The detection of the fault upstream in the case with distributed generation is however not guaranteed. The fault current that is supplied from the main grid may be a small fraction of the total fault current, not exceeding the rated current of the line, and thus not considered as being abnormal.

5.3 Stability and ride-through behaviour

5.3.1 Context

In general, generators that are grid-connected through power electronic interfaces need very fast tripping in case of grid disturbances, as the power electronic interfaces are easily damaged by overcurrents or overvoltages [24].

With grid-connected induction generators, unstable behaviour may result from a grid disturbance. As an example, *Figure 15* [24] shows the reaction of an induction generator, operating at rated power, to a voltage dip to 15% of rated voltage, lasting 50 ms (a) or 150 ms (b). The voltage imposed for the simulation is shown in the upper part; the lower part shows the generator speed.

During the voltage dip, the electromechanical generator torque disappears, resulting in acceleration. In this simulation, the generator is able to return to a stable behaviour in case of a voltage restoration after 50 ms, but continues to accelerate if the voltage dip lasts for 150 ms.

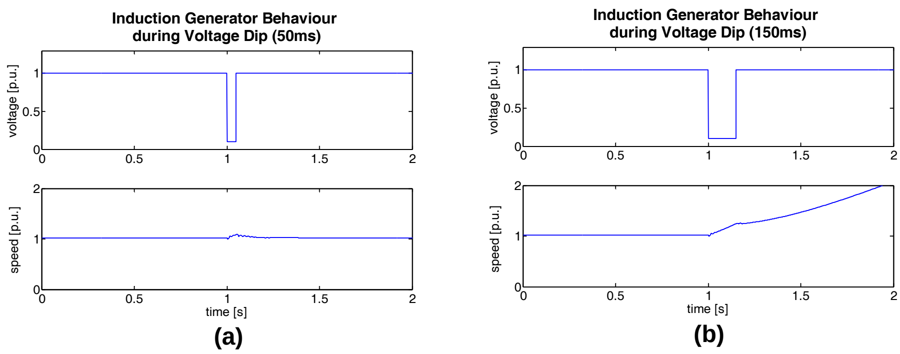


Figure 15. Induction generator behaviour during voltage dip lasting 50 ms (a) and 150 ms (b) [24]

This example has shown that induction generators are vulnerable to instable behaviour in case of grid disturbances of a certain extent. Operators of distributed induction generators thus traditionally choose for a very conservative protection scheme, tripping the generator already in case of small disturbances.

However, tripping a generator implies loss of power injection, causing another grid disturbance. When a large amount of distributed generators is installed nearby, this fast reaction might result in a cascaded tripping of other generation units, resulting in a considerable generation loss.

To prevent such incidents, distributed generators are required to remain grid-connected during (or to 'ride through') grid faults, in order to actively support the grid and maintain its stability. The extent of the grid faults that may not lead to a disconnection is defined by the TSO in each control zone.

5.3.2 Voltage dip ride-through requirements issued by TSOs

Specific grid connection requirements and fault ride-through requirements for distributed generators are issued by the TSOs to prevent further grid disturbances in case of a first grid fault. Some TSOs issue specific ride-through requirements for wind power only, as of all distributed generation technologies; wind power has known the fastest increase in both installed power and technical generator capabilities [24].

Fault ride-through requirements specify the extent and duration of a voltage or frequency dip or rise that may not lead to a disconnection of the generator. Research institutes, TSOs and generator manufacturers recognise that the most critical grid disturbance is a voltage dip, as this is a disturbance that regularly occurs, but also provokes most easily unstable generator behaviour and cascaded tripping.

Figure16 [24] gives an overview of the voltage dip profiles as defined by various grid operators or regulators in Europe, specifically for distributed generators or in some cases only for wind power generators. Any voltage that does not cross the lines should not lead to a disconnection of the generator. The Flemish Technical Regulation imposes Figure 16(i) and *Figure* (j) as minimum ride-through requirement for respectively short and long voltage drops, applying however only for generators with grid connection at voltages between 30 kV and 70 kV.

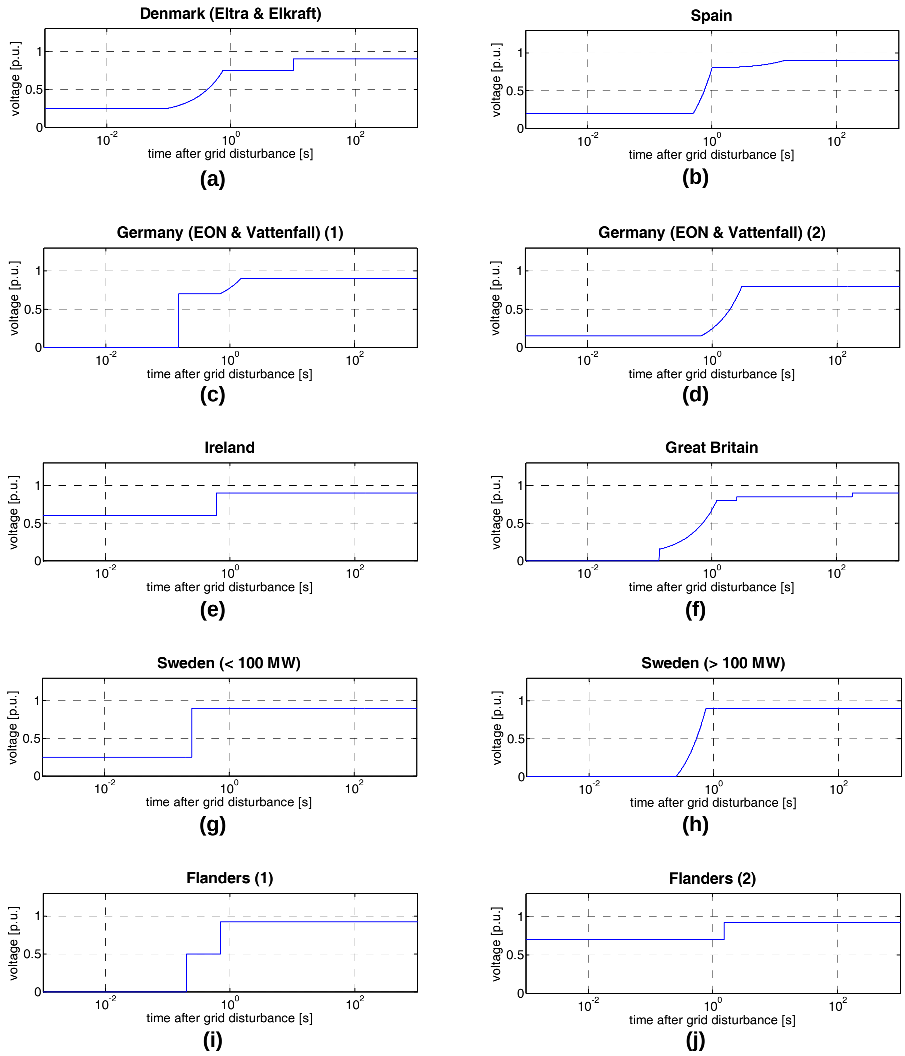


Figure 16. Voltage dip ride-through requirements from various European grid operators [24]

.

Similar ride-through requirements exist for frequency disturbances. A good overview of these requirements for some selected countries can be found in 83[25]

Figure 16 illustrates the differences in regulations by various grid operators, making it difficult for generator manufacturers to standardise their products. As for the reactive power requirements, it is concluded that the ride-through requirements lack uniformity in the various European zones.

6 Work Package 6: Identification of the environmental impact of alternative operation modi of renewable energy converters (FUL, 3E)

The outcome of V indicates the feasibility of different operation strategies for RE generators to enhance the security of supply. In general, this may indicate that due to, for instance, an increased reserve margin, a somewhat smaller amount of RE is converted and has to be replaced by perhaps 'grey' energy. The environmental consequences, e.g. the impact on the CO_2 balance, are assessed in this task.

6.1 Impact of Alternative Operation Modes of Large Wind Farms on Greenhouse Gas Emissions

6.1.1 Introduction

In the previous sections, the ability of renewable energy generators to contribute to security of supply was studied. The provision of ancillary services like voltage support, reactive power and active power for primary control was studied. Different alternative control modes are already applied today to the Danish offshore wind farm at Horns Rev.

Especially, an operation mode allowing to supply active power, for primary control or for tertiary control implies that, while active power for supplying these ancillary services is kept available, the wind farm cannot run at the maximum possible output as determined by the wind speed. If such operation modes are applied during a large fraction of time, the wind farm will necessarily generate less power than possible. Regarded on its own this will reduce the revenues from power production and possibly green certificates as well as the associated savings in CO_2 emissions from fossil fuelled power plant.

6.1.2 Alternative Operation Modes in Practice

Today, the only significant project world-wide where active power is controlled by a grid-connected wind or PV plant is the 160 MW offshore wind farm at Horns Rev in the Danish North Sea. Although a number of publications is available explaining the applied wind farm controller in Horns Rev [26][15][27], these publications do not make quantitative statements about the amount of wind energy wasted (or lost) by this control mode. Neither do they assess the economic value to the wind farm owner or the effect on power plant commitment for dispatch within the power system of Western Denmark. The operator Elsam considers this information as confidential.

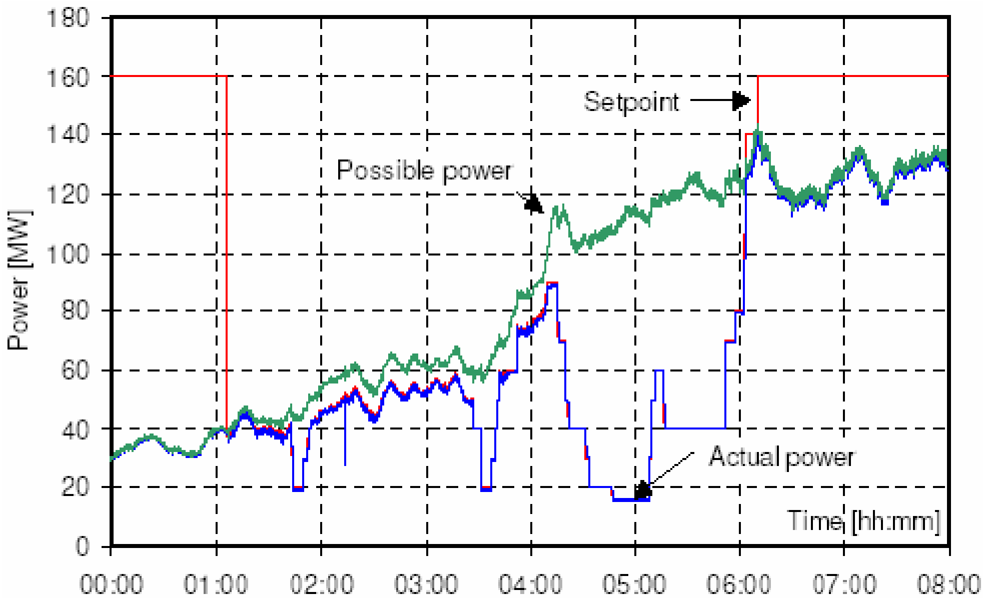


Figure 22: Balance control and reservation for frequency control at the same time [16]

Figure 22 shows a typical generation profile from the wind farm. At night between 1:45 h and 4:15 h the wind farm is working in delta control mode generating about 10% of rated power less than available. This margin is available as primary reserve to frequency control. In the early morning between 4:15 h and 6:00 h the output is limited stepwise to fixed power values. The wind farm then participates in balance control. From 6:00 h on the wind farm is operating at full power.

Upon personal request [28], Elsam confirms that power losses due to constant power control mode or delta control are relatively low and commercially compensated for by improvements for unit commitment of power plant for dispatch. These modes of operation where ancillary services from the Horns Rev wind farm are possible, are only applied during times of the day when Elsam actually expects the need of services from the wind farm.

The use of delta control mode during night time allows reduced spinning reserves from fossil fuelled power plant during the time of low load. Limiting output power to a constant, relatively low, set point during early morning hours while coal and combined cycle plants are started up, allows Elsam to set these controllable units directly to a good operation point instead of working at low partial load during a longer time.

An educated guess on the loss of wind energy generation can be made as follows:

- assume that while operating in delta control mode or in constant power mode, on average 15% of the available wind power is lost;
- assume that delta control mode or constant power mode are active during 10% of the time;
- assume that the application of different control modes is not correlated to wind speed.

With these assumptions we can estimate the loss of energy due to alternative control modes to 0.1 x 0.15 = 0.015; hence, 1.5% of the available energy will be lost.

In Belgium we can expect from an offshore wind farm with modern turbines and 98% availability 3500 up to 3800 h of full load [5]. Based on 3800 h the annual energy loss would then amount to 57 MWh per installed MW.

Note that this 3800 h is a relatively high yield that may only be expected for modern turbines with relatively high availability and a hub height of 110 m. At lower hub height, onshore, or with a lower availability, this figure must be corrected downwards and in practice the first Belgian offshore wind turbines may generate less. This will however, not affect the estimated relative figure of 1.5% loss of energy due to alternative control modes.

6.1.3 Greenhouse Gas Emissions Substituted by Wind Energy

At the current low share of wind energy generation capacity in Belgium one can assume that wind power substitutes marginal power from traditional power plant without affecting the process of unit commitment. In this situation wind power substitutes fossil fuel while nuclear power will not be affected yet. We can then assume a CO_2 intensity of 687 kg/MWh according to the share of coal- and gas-fired plant in Belgium [29].

With an increasing share of wind energy in the generation capacity, this assumption of marginal substitution will become less justified. With several gigawatts of wind power and distributed generation installed in Belgium, unit commitment will have to take wind energy into account. At that time it may happen that fossil fuelled power plant work at low partial load and bad efficiency in order to supply ancillary services while wind farms operating at maximum available power would profit from priority dispatch. In the power system of Western Denmark this situation occurs from time to time today.

In practice, only with a high share of wind energy in the generation capacity, there is need for alternative operation modes and ancillary services from large wind farms. If available today such facilities on a decentralized generator would barely be used. Hence, alternative operation modes will mainly occur with a high share of wind energy. Then, as in the case of Horns Rev, these facilities will reduce the need for fossil fuelled generators as suppliers of ancillary services. In conclusion, wind farms with the ability to supply ancillary services will then contribute to maintain the efficiency of the remaining traditional fraction of the generation portfolio.

Calculating with marginal substitution as it happens today yields the following CO_2 values for a modern offshore wind farm:

- utilization: 3800 h per year,
- marginal CO_2 intensity at intermediate load: 687 kg/MWh,
- CO_2 savings per installed capacity: 2610.6 t/MW.

A yield reduction by 1.5% due to alternative operation modes would then mean:

- utilization reduction: 57 h per year,
- reduction in CO_2 savings per installed wind power capacity: 57 h · 687 kg/MWh = 391.6 t/MW.

While this estimate is correct for the first offshore wind farm, the relative CO_2 savings could become less when priority dispatch for wind energy affects the traditional unit commitment [22]. When this happens, traditional methods of unit commitment must be adapted, also under the influence of the free market, and a demand for ancillary services from wind energy will emerge.

The estimated reduction in wind energy yield of 1.5% would then compensate for the need of operating traditional power plant at inefficient operation points mainly for the supply of ancillary services. Although there are no reliable quantitative data describing the interaction of ancillary services from large wind farms with the operation of the centralized production park, facilitating alternative operation modes for wind farms looks very promising with regard to future scenarios with a high share of decentralized generation.

In conclusion, with a high share of wind energy in the power system, wind energy will supply certain ancillary services equally to fossil fuelled plants today. This facilitates the grid integration wind power and the closing down of existing fossil fuelled plants which otherwise had to be kept in operation only for supply of ancillary services. While the supply of ancillary services from fossil fuelled plant also causes the emission of CO_2 this is not the case for ancillary services from wind power plant. Then, ancillary service supply from wind power plant should be preferred to that from fossil fuelled plant.

6.1.4 Conclusions

Today in Belgium photovoltaic installations, small hydro power plants and wind power plants are always operated at the maximum available power in order to maximise their utilization and, thus, their environmental end economic benefits. However, especially for large wind farms alternative operation modes are discussed in order to enable the wind farm to supply ancillary services. Today, this way of operation is practiced at the 160 MW wind farm at Horns Rev in the Danish North Sea.

Although no quantitative data about this way of operation can be found in literature, an educated guess was formulated estimating that 1.5% of the available output power would remain unused due to alternative operation modes. For an offshore wind farm of the next generation on the Belgian continental shelf this would mean a yield reduction by 57 h of full load per year.

This yield reduction may lead to an equivalent reduction in CO_2 savings in comparison to a wind farm always running at full load. However, ancillary services from large wind farms will only be needed when wind energy reaches a significant share of the total installed generation capacity. Then, ancillary services from wind farms can substitute for these services from traditional power plant which otherwise had to keep running and emitting CO_2 at low partial load. Therefore, a 1.5% reduction in yield can be justified when substituting for fossil fuelled generators running at low partial load and supply from wind power plant should be preferred to that from fossil fuelled plant.

Finally, it is noteworthy that no quantitative figures from such wind farm operation are publicly available. Therefore, the given considerations are only rough estimates.

Appendix 1.- Characterization of the solar power impact in the Belgian grid

Introduction

In Belgium there is currently 1.06 MWp of PV power installed [30]. A further development of the solar power in Belgium requires the study of factors such as availability, impact on the grid, efficiency, or costs, amongst others. The aim of this analysis is to characterize the behaviour of the solar power in Belgium to be able to predict the response that different levels of penetration of PV installations might have in the grid. The study is based on real measurements of existing solar installations in Belgium and the results give a notion of the consequences for the grid expected from a future development of the solar power layout.

Real measurements from existing PV installations

- **DC to AC**

In order to obtain the most realistic approach, measurements from existing PV installations have been used for this project. The power output of the solar cells is DC power, which must be converted into AC power to be delivered into the grid. This specific converter has an efficiency of about *94.4%* according to [31]. Most modern converters are found in this very narrow range of efficiency around that value, usually [*94-95%*]

Seasonal behaviour

It has been noted that a seasonal behaviour is found in the analysis of the solar power measurements. The position of the sun influences the incidence of the solar rays on the solar cells, resulting in a noticeable variation of the power output. Also the hours of sun vary with the time of the year. The solar power decreases in the autumn and winter and is higher in spring and summer. This different behaviour of the solar power in the four seasons is taken into account for all the calculations.

The comparison between the solar output in one day of the four different seasons (see *Figure 23*) is a suitable example to show this seasonal behaviour.

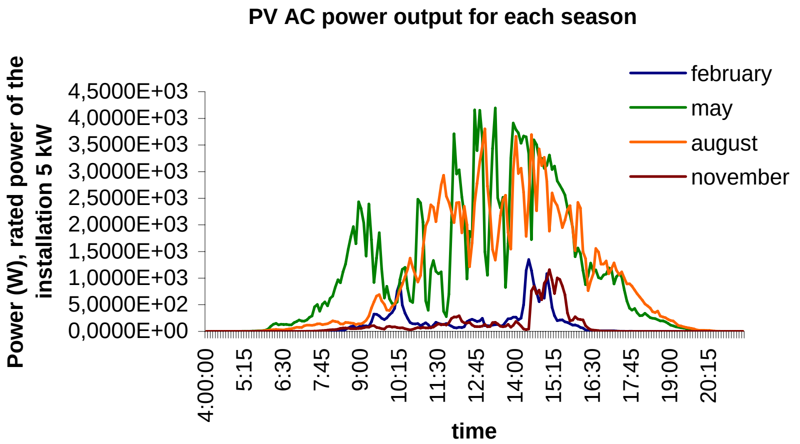


Figure23. Power output of a PV installation according to the season

The power obtained from a solar cell can be expressed as a percentage of its rated power. Studying this percentage of the rated power, a clearer comparison between the output in the different seasons can be established. The following histograms (see *Figure 24*) represent, for each season, the number of observations that have occurred in each percentage of the rated power.

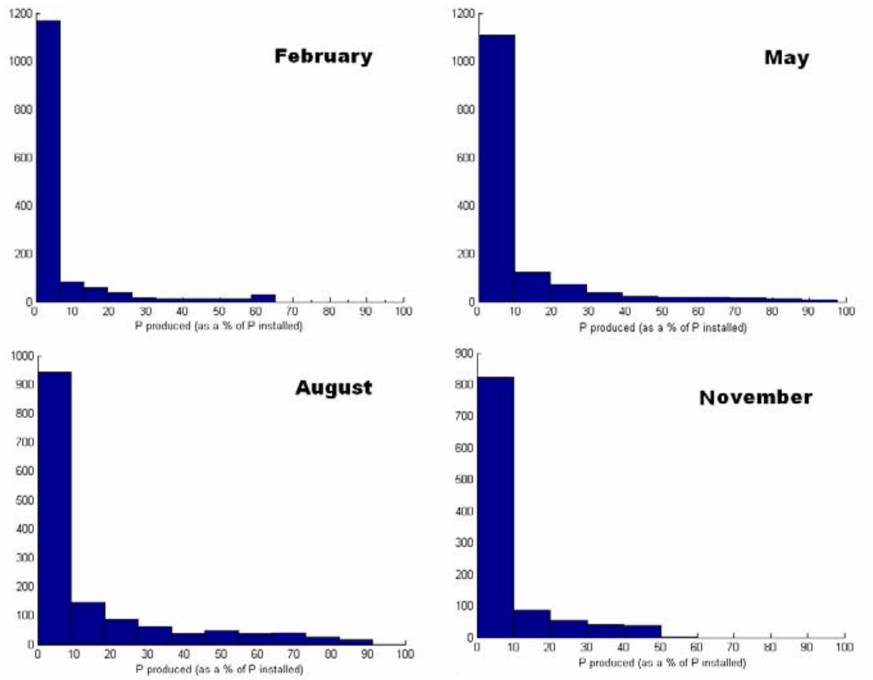


Figure 24. Histograms of the PV power output according to the season

Using Markov matrices to simulate series

The real measurements from the PV installations are used to create new values for solar power series. This is done to simulate the random character of the solar behaviour (as it is done for every natural source of energy, mainly wind). The suitability of the Markov chains models to generate simulated series for these natural sources [32] has been until now only too well justified.

As also stated in [32], a Markov chain represents a system of elements moving from one state to another over time. The *order* of the chain gives the number of time steps in the past influencing the probability distribution of the present state, which can be greater than one. For example, a first order Markov chain takes into account the value of the last step to influence the present state, and a second order Markov chain takes into account the last two steps.

Many natural processes are considered as Markov processes, for instance the pattern of the wind behaviour or weather dependant events (as the temperature or the rainfall). But they are not a suitable method to simulate events with 'no memory', as for example the consecutive throwing of a coin. Each element of the matrix represents probability of passage from a specific condition to a next state.

Creating a first order Markov algorithm

- **Defining states**

The first step is defining the states (intervals) where a value for the solar power can be found. For example, (-10 m/s, -5 m/s) is not a valid state because all the values for power will be positive values. From zero to the maximum power values regular intervals are defined.

- **Transition matrix**

Next step is defining a transition (square) matrix where the size is the number of states we have defined. Each element of the transition matrix will represent a probability in the following way: **the element P_{ij} represents the probability that the current state is j if the previous wind speed state was i.** The transition matrix then will look like this (for the first order):

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,k} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,k} \\ \vdots & \vdots & \vdots & \vdots \\ p_{k,1} & p_{k,2} & \cdots & p_{k,k} \end{bmatrix} \quad (9)$$

For a second order Markov algorithm, the actual state would be influenced for the past two states, so each P_{ijk} would represent the probability that the next state is k if the current state is j and the previous state was i.

But in this case a first order Markov algorithm is sufficient, as a second order algorithm is too laborious for the low improvements in the results in the working magnitude (solar power has a similar unpredictable behaviour and random components, so there is no need for higher accuracy in this method, as this accuracy will be lost with the addition of other random factors).

For each row of the matrix, all the possibilities that one state can get are represented. That means that there is no other possibility for the present state that being in one of the states of the row. Talking about probabilities, this means that the sum of the elements of the row is 1. Next step is to make sure that all the elements of the row sum 1. Then the correct transition matrix is generated, and an example of a transition matrix is the following:

$$P = \begin{bmatrix} 0.317 & 0.407 & 0.174 & 0.036 & 0.009 & 0.002 & 0.001 & 0.001 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.166 & 0.446 & 0.313 & 0.059 & 0.012 & 0.004 & 0.000 & 0.001 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.051 & 0.243 & 0.504 & 0.163 & 0.028 & 0.008 & 0.002 & 0.001 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.017 & 0.083 & 0.304 & 0.390 & 0.160 & 0.035 & 0.008 & 0.002 & 0.000 & 0.000 & 0.000 & 0.000 \\ 0.010 & 0.034 & 0.099 & 0.277 & 0.381 & 0.158 & 0.031 & 0.007 & 0.001 & 0.001 & 0.000 & 0.000 \\ 0.006 & 0.021 & 0.043 & 0.108 & 0.294 & 0.343 & 0.146 & 0.030 & 0.005 & 0.002 & 0.000 & 0.000 \\ 0.005 & 0.016 & 0.027 & 0.047 & 0.110 & 0.302 & 0.325 & 0.142 & 0.021 & 0.004 & 0.002 & 0.000 \\ 0.006 & 0.016 & 0.030 & 0.033 & 0.055 & 0.127 & 0.365 & 0.239 & 0.105 & 0.022 & 0.002 & 0.000 \\ 0.009 & 0.019 & 0.014 & 0.019 & 0.042 & 0.065 & 0.140 & 0.326 & 0.270 & 0.079 & 0.014 & 0.005 \\ 0.014 & 0.055 & 0.055 & 0.014 & 0.027 & 0.027 & 0.041 & 0.205 & 0.288 & 0.164 & 0.082 & 0.027 \\ 0.000 & 0.000 & 0.000 & 0.040 & 0.000 & 0.000 & 0.080 & 0.120 & 0.160 & 0.240 & 0.280 & 0.080 \\ 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.200 & 0.000 & 0.200 & 0.600 & 0.000 \end{bmatrix}$$

- **Cumulative probability transition matrix**

Based on the calculated transition matrix, the cumulative matrix will be calculated by cumulative sum of the elements of the same row. Each P_{ij} in the cumulative probability transition matrix is the sum of the P_{ij} in the old transition matrix and all the previous elements in row *i*. The last of the elements for each row will be 1 because it is the total sum of all the elements of the row. This is the general look for the cumulative probability transition matrix:

$$P = \begin{bmatrix}
0.371 & 0.778 & 0.952 & 0.988 & 0.997 & 0.998 & 0.999 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 \\
0.166 & 0.612 & 0.924 & 0.983 & 0.995 & 0.999 & 0.999 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 \\
0.051 & 0.294 & 0.798 & 0.961 & 0.989 & 0.997 & 0.999 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 \\
0.017 & 0.100 & 0.403 & 0.794 & 0.954 & 0.989 & 0.997 & 0.999 & 1.000 & 1.000 & 1.000 & 1.000 \\
0.010 & 0.045 & 0.144 & 0.421 & 0.803 & 0.960 & 0.991 & 0.998 & 0.999 & 1.000 & 1.000 & 1.000 \\
0.006 & 0.027 & 0.070 & 0.178 & 0.473 & 0.816 & 0.962 & 0.993 & 0.997 & 1.000 & 1.000 & 1.000 \\
0.005 & 0.021 & 0.048 & 0.095 & 0.205 & 0.507 & 0.831 & 0.973 & 0.994 & 0.998 & 1.000 & 1.000 \\
0.006 & 0.022 & 0.052 & 0.085 & 0.140 & 0.267 & 0.632 & 0.871 & 0.976 & 0.998 & 1.000 & 1.000 \\
0.009 & 0.028 & 0.042 & 0.060 & 0.102 & 0.167 & 0.307 & 0.633 & 0.902 & 0.981 & 0.995 & 1.000 \\
0.014 & 0.068 & 0.123 & 0.137 & 0.164 & 0.192 & 0.233 & 0.438 & 0.726 & 0.890 & 0.973 & 1.000 \\
0.000 & 0.000 & 0.000 & 0.040 & 0.040 & 0.040 & 0.120 & 0.240 & 0.400 & 0.640 & 0.920 & 1.000 \\
0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.000 & 0.200 & 0.200 & 0.400 & 1.000 & 1.000
\end{bmatrix}$$

- **Generating solar power series [32]**

The initial state (i) is selected at random, as there are no previous data. Then random values between 0 and 1 are generated with a uniform random number generator. For next state, the next random number is used and compared with the elements of the ith row of the cumulative probability transition matrix. If the random number is greater than the value of the previous state but less than or equal to the value of the following state, the following state is adopted. In the end, a list of power states is obtained, which is the solar power series needed.

Calculated Markov matrices for solar power

Following the Markov chains algorithm described above, the Markov matrices for the solar power values of each season are calculated, these are the basis to generate later the solar power series that are used for further analysis. Due to the importance of the Markov matrices, these are represented in *Figure 25*.

February

$$\begin{pmatrix}
0.905 & 0.071 & 0.012 & 0.012 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.109 & 0.691 & 0.164 & 0.036 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.054 & 0.270 & 0.324 & 0.216 & 0.054 & 0.027 & 0.027 & 0.027 & 0 & 0 \\
0 & 0.04 & 0.440 & 0.240 & 0.200 & 0.040 & 0.040 & 0 & 0 & 0 \\
0 & 0 & 0.188 & 0.313 & 0.375 & 0.063 & 0 & 0.063 & 0 & 0 \\
0 & 0 & 0 & 0.333 & 0.111 & 0.333 & 0.111 & 0 & 0.111 & 0 \\
0 & 0 & 0.111 & 0 & 0.111 & 0.222 & 0.444 & 0.111 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.090 & 0.090 & 0.090 & 0.636 & 0.090 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.100 & 0.100 & 0.700 & 0.100 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.077 & 0.923
\end{pmatrix}$$

May

$$\begin{pmatrix}
0.949 & 0.049 & 0.002 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.179 & 0.701 & 0.090 & 0.007 & 0.015 & 0.007 & 0 & 0 & 0 & 0 \\
0.014 & 0.157 & 0.443 & 0.143 & 0.100 & 0.043 & 0.057 & 0.029 & 0.014 & 0 \\
0 & 0.083 & 0.333 & 0.333 & 0.111 & 0.056 & 0.028 & 0.028 & 0.028 & 0 \\
0 & 0 & 0.185 & 0.148 & 0.370 & 0.074 & 0.074 & 0 & 0.174 & 0.074 \\
0 & 0.056 & 0.167 & 0.167 & 0.166 & 0.167 & 0.167 & 0 & 0.056 & 0.056 \\
0 & 0.048 & 0.143 & 0.143 & 0 & 0.286 & 0.333 & 0.048 & 0 & 0 \\
0 & 0 & 0.167 & 0 & 0 & 0.083 & 0.167 & 0.333 & 0.250 & 0 \\
0 & 0 & 0.768 & 0.077 & 0.154 & 0 & 0 & 0.231 & 0.231 & 0.231 \\
0 & 0 & 0 & 0.222 & 0 & 0 & 0 & 0.111 & 0.333 & 0.333
\end{pmatrix}$$

August

$$\begin{pmatrix}
0.862 & 0.124 & 0.014 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.153 & 0.644 & 0.136 & 0.034 & 0.017 & 0 & 0.008 & 0.008 & 0 & 0 \\
0.041 & 0.219 & 0.466 & 0.178 & 0.041 & 0.027 & 0.027 & 0 & 0 & 0 \\
0.024 & 0.071 & 0.239 & 0.214 & 0.143 & 0.119 & 0.071 & 0.095 & 0.024 & 0 \\
0 & 0.059 & 0.147 & 0.088 & 0.235 & 0.353 & 0.088 & 0.029 & 0 & 0 \\
0 & 0.022 & 0.067 & 0.133 & 0.156 & 0.378 & 0.178 & 0.022 & 0.022 & 0.022 \\
0 & 0.026 & 0.026 & 0.103 & 0.154 & 0.179 & 0.308 & 0.154 & 0.026 & 0.026 \\
0 & 0 & 0.029 & 0.057 & 0.057 & 0.029 & 0.200 & 0.343 & 0.257 & 0.029 \\
0 & 0 & 0 & 0 & 0 & 0.042 & 0.042 & 0.333 & 0.292 & 0.292 \\
0 & 0 & 0 & 0.067 & 0 & 0 & 0.133 & 0.200 & 0.267 & 0.333
\end{pmatrix}$$

November

$$\begin{pmatrix}
0.926 & 0.066 & 0 & 0.004 & 0.004 & 0 & 0 & 0 & 0 & 0 \\
0.175 & 0.650 & 0.107 & 0.039 & 0.010 & 0.019 & 0 & 0 & 0 & 0 \\
0 & 0.174 & 0.413 & 0.152 & 0.109 & 0.043 & 0.065 & 0.043 & 0 & 0 \\
0.028 & 0.139 & 0.194 & 0.306 & 0.167 & 0.056 & 0 & 0.056 & 0.056 & 0 \\
0.029 & 0.088 & 0.147 & 0.206 & 0.294 & 0.176 & 0.059 & 0 & 0 & 0 \\
0 & 0.043 & 0.043 & 0.043 & 0.261 & 0.304 & 0.087 & 0.130 & 0.087 & 0 \\
0 & 0 & 0.130 & 0.043 & 0 & 0.130 & 0.348 & 0.087 & 0.130 & 0.130 \\
0 & 0 & 0 & 0 & 0.11 & 0.056 & 0.222 & 0.333 & 0.111 & 0.167 \\
0 & 0.043 & 0 & 0.087 & 0 & 0 & 0.087 & 0.087 & 0.522 & 0.174 \\
0 & 0 & 0 & 0.133 & 0.200 & 0 & 0.133 & 0 & 0.200 & 0.333
\end{pmatrix}$$

Figure 25. Markov matrices for the solar power of the different seasons

Obtained solar power series

According to the obtained Markov matrices, simulated solar power series are generated with the algorithm previously described. The Markov matrix imposes the probability of changing from one range of values to another one for the next value of the series.

Every power series contains the variations according to the pattern of the correspondent Markov matrix. This means that even though each series is random, a part of its behaviour is similar to the other power series generated for the same season.

For instance, the Markov matrix for February contains the way that the values from the solar power in February change every 5 minutes, but also the Markov algorithm leaves a part of the prediction to the random character of the solar power. As a direct consequence, a series for February will be more similar to another series of February, even though they will always be different.

As an example, a generated solar power series for the month of November is shown in *Figure 26*.

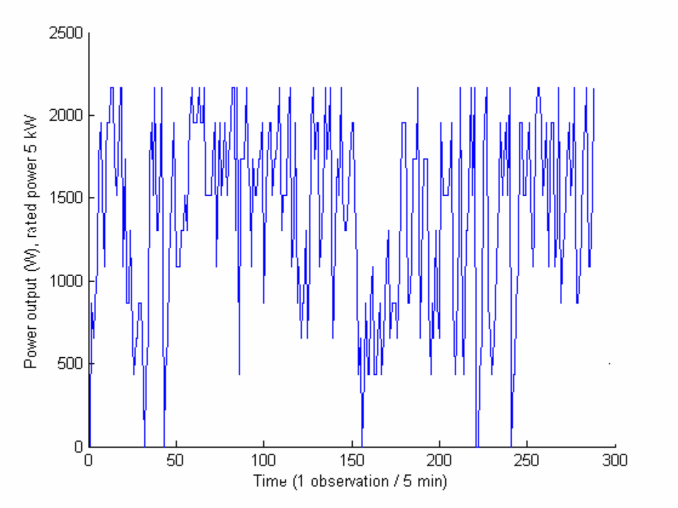


Figure26. Solar power series for the month of November

- **Modelling the day-night behaviour**

At a second glance, another characteristic of the solar behaviour becomes obvious. These power series are not yet suitable to define a real power output from a solar installation due to the day-night pattern.

The power series must be modelled with a weighting factor which reduces every value to zero in the range of time where no sun is shining. And during the part of the day that the light of the sun reaches the solar cells, the pattern of the fluctuations of the power can be seen in previous *Figure 26*.

A sinusoidal wave affected by the restriction of the zero value for the hours of darkness is a good approximation to the behaviour of the power output from the solar cell. The amplitude and scale factor of the sinusoidal wave depends of the hours of light and the maximum value that the power can reach. And that leads consequently to the selection of a different weighting factor for every season, according to the different patterns obtained in the real measurements of the existing PV installations. For instance, in May there are more hours of sun and in November the maximum of the output curve is the lowest. The weighting factors used to model the day-night behaviour of the solar power series obtained can be compared in *Figure 27*.

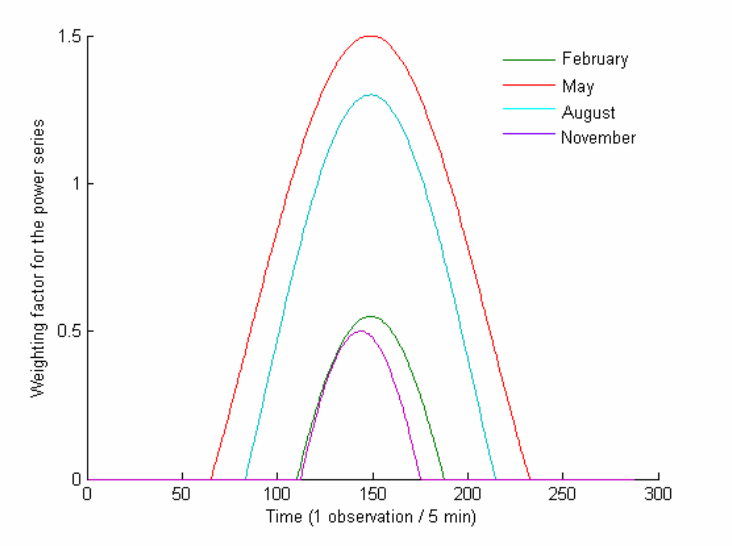


Figure 27. Weighting factors for the power series in the different seasons

- **Modelled solar power series**

Affecting the obtained power series with those proposed weighting factors, a more suitable set of series is calculated. The new power series takes into account then the seasonal pattern and also the day-night behaviour of the solar power. An example of the new power series obtained for the month of November is shown in *Figure 28*.

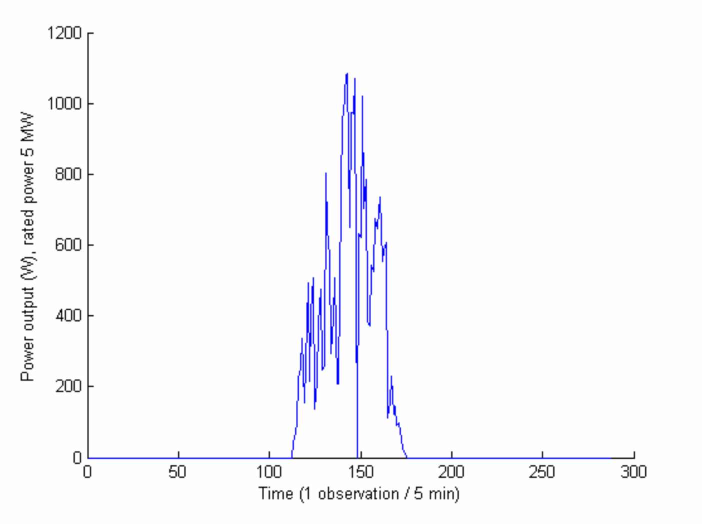


Figure 28. Solar power series modelled with the weighting factor

Response of the grid

- **Parameters of the simulations**

The solar power series already modelled with the weighting factor according to the season are applied into the grid. In order to study the response of the grid in every case, different levels of penetration of the PV power in the country are also taken into account.

The current amount of solar power installed in Belgium is 1,06 MWp, according to [30]. This value means that the solar power contribution to the grid is far from noticeable. The criterion for the selection of the levels of penetration is on one hand, not to be too far from the reality, and on the other hand, to be high enough to be able to notice the impact of the increase of power in the grid.

Hence, the levels of penetration for the simulations carried out in this study are 5 MWp, 10 MWp and 15 MWp. Also the difference between the different seasons are studied, thus, the ***parameters*** involved in the simulations are:

- **Season of the year**
  - Month of February
  - Month of May
  - Month of August
  - Month of November

- **Level of penetration**
  - 5 MWp of solar power
  - 10 MWp of solar power
  - 15 MWp of solar power

Algorithm

The suitable nodes for the input of power are selected from the database of the Belgian grid. The total installed power for the country is divided equally between those nodes, considering a regular layout of the PV installations.

The modelled power series affect this installed power in order to acquire a real pattern of the behaviour of the sun influencing the power output in every moment. Thus, in each suitable bus, an additional input following a curve like in *Figure 23* is detected. This additional power is introduced into the grid just like any other source of generation, affecting the rest of the buses and consequently, the whole grid. The total amount of power injected is calculated for every moment as well as the power flows all over the country.

In the beginning and the end of the day the null injection of power is simulated according to the solar pattern (see *Figure 23* and *Figure 28*). In the middle of the day the progressive increasing of the solar power injection can be detected in the buses, and is studied in the power flows.

Simulations

Simulations are carried out for the possible combinations of parameters previously described In all cases the influence of the injection of solar power is noticed but the magnitude is very small. The power flows are higher in the moments of sun but the amount of power injected is so small that only in a tiny order of magnitude can be noticed. The grid is strong enough to absorb those small changes in the generation without any problem. The response of the grid, even when small, can be tracked in the results.

As an example, the power flow in one of the lines of the Belgian grid in the month of August, for a total installed power of 5 MWp all over the country, is showed in *Figure29.*

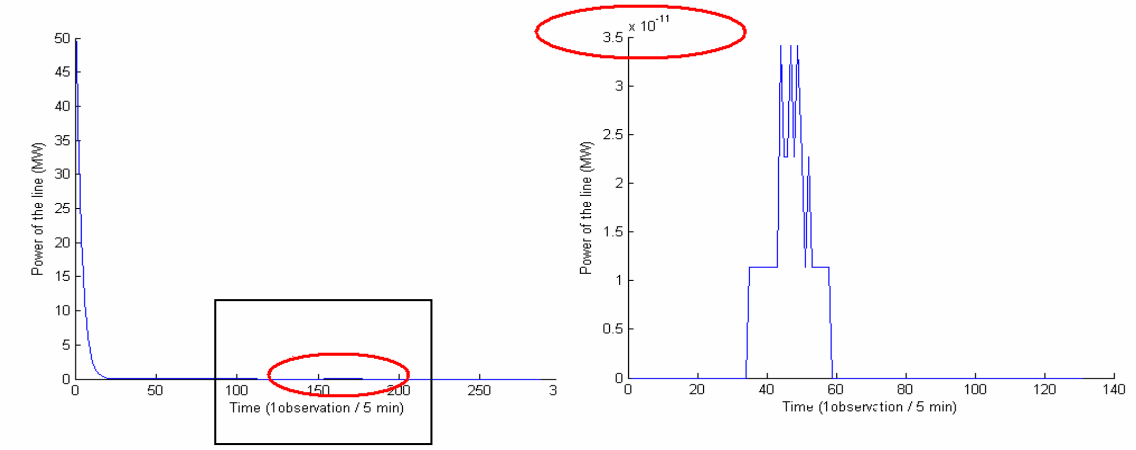


Figure 29. Power flow of a line of the grid after injection of the solar power (and zoom)

In this example the order of magnitude of the influence in the grid is shown for the case of 5 MWp of penetration. The increasing of the power flow in the line is less than 3.5 x 10^{-11} MW. This value gives a notion of the scarce impact of these amounts of solar power injected in the Belgian grid

For the case of a penetration level of 15 MWp and in the month of August, which could be one of the most critical cases, the increasing of the power flow is also not higher than 3.5 x 10^{-11} MW.

From the results extracted from the calculated power flows, it can be concluded that the Belgian grid can easily absorb the impact of a level of penetration of solar power until 15 MW at least. The study for higher level of penetration is not carried out because due to the low amount of PV power installed nowadays in Belgium such a high increasing in the development does not agree with the reality.

Achievements of this study

- **Characterization of the solar power pattern**

An analysis of the real solar power data for Belgium has been carried out to define the parameters that influence the solar power pattern. The seasonal behaviour observed lead the project to divide the analysis into four parts of the year, due to the different power output obtained from the solar cells in terms of hours of production and ranges of the power values.

The day-night behaviour is clearly the most important restriction to the PV technology. This factor is taken into account also in the characterization of the pattern, as well as later in the generation of the solar power series.

- **Calculation of the Markov matrices for the solar case**

The algorithm of Markov chains of first order has been used to generate Markov matrices for the study of the solar power pattern. This algorithm has been sufficiently validated for the analysis of natural sources of energy, as for example wind power. The use here of Markov matrices for the solar data confirms again the validity of the model.

Markov matrices for the months of February, May, August and November have been calculated representing the pattern of the solar power behaviour for each one of the four seasons. These results are used later in the generation of the series of solar power data.

- **Generation of solar power series**

Based on the Markov matrices, series of solar power data have been generated for every season. These series of data have also been modelled to simulate the day-night behaviour of the solar pattern and the range of maximum values that in every season can be reached.

In the solar power series generated two components can be detected. One component is defined by the seasonal pattern of the sun, this is invariable and defined by the Markov matrix. The other component gives also the random character of every natural source that is necessary to achieve the perspective of reality.

- **Estimation of the impact of the solar power in the Belgian grid**

The generated solar power series are used as an input in the buses of the Belgian high voltage grid to run simulations involving different levels of penetration of the PV installations. The power flows in the lines of the grid are analyzed in order to characterize the response of the Belgian grid.

According to the results of the grid power flows obtained in the simulations, an insignificant influence of the injection of the considered levels (5 MWp, 10 MWp, 15 MWp) of solar power is revealed. The Belgian grid can easily absorb any power in this range of values. The further development of the solar power penetration in Belgium is safe from the point of view of the grid impact.

Appendix 2.- PV power systems: the next generation

Outlook: emergency power and grid support

In addition to the potential of PV plants to provide renewable energy to the grid, it is more and more recognized that these systems could also be used for emergency power supply purposes. In this sense PV plants could provide electric energy after events leading to a breakdown of the conventional grid.

In principle three operation modes should be possible.

- During daytime the PV system could provide sufficient power to operate critical components in a building like the control and operation of a heating system (not electric heaters) including circulation pumps.
- When including a battery the emergency power supply system could also work during night time and provide peak power in excess of the actual PV power.
- In a third step a combination of the PV system with combined heat and power (CHP) could even form a reliable long lasting power supply forming a mini-grid for an individual building or even a group of buildings.

To exploit this interesting potential it is necessary to change the characteristic of the inverter and the safety philosophy, however. When changing from grid-connected to stand-alone mode the inverter has to switch from current-source to voltage-source mode. This change can be performed using the same power electronics hardware but requires a change in the internal control. As a second consequence action against islanding must be taken out of function because islanding-operation is requested in this special case. Reliable safety philosophies will have to be developed together with this new and attractive approach.

Further, power quality improvement can become an additional benefit of PV systems. Using high-quality inverters it will become possible to improve the power quality of the grid through active compensation of reactive power and active filtering leading to the reduction of harmonics. While active filtering can be performed locally, reactive power compensation needs an external input to the inverter. This input can be provided by the local grid management through adequate communication structures. Since it is expected that a further merging of the grids for energy and information continues, the development of inverters providing interfacing with communication networks may take place in the near future.

This development has to be seen in the context of changes which have to be expected through the appearance of new distributed generators as variable speed CHP plants, small building mounted wind turbines, power storages devices and fuel cells.

Recent developments

Research and development on micro AC grids integrating renewable energy sources has been carried out by ISET in Kassel, Germany, in cooperation with inverter manufacturer SMA and supported by the European 5th Framework DISPOWER project.

- **Microgrids**

A promising aspect is the possibility for parts of the network comprising sufficient generating resources to operate in isolation from the main grid, in a deliberate and controlled way. Grid portions with such a capability are called Microgrids.

Flexible systems with modularly structured components are achieved by coupling all consumers and generators on the AC-side (*Figure 30*). Nowadays, this technology is commonly used in the power range above several kWs. Different renewable and conventional energy converters are also suitable to be added to the system to form a hybrid energy system. Since all converters, storage and back-up units of the decentralized systems can generate AC power of grid compatible characteristics; they are also suitable to be connected to the utility grid. Moreover, this supply structure can be simply expanded by integrating further components or generators in order to cover the rising energy demand. Such structures are typically used to supply rural villages of developing countries.

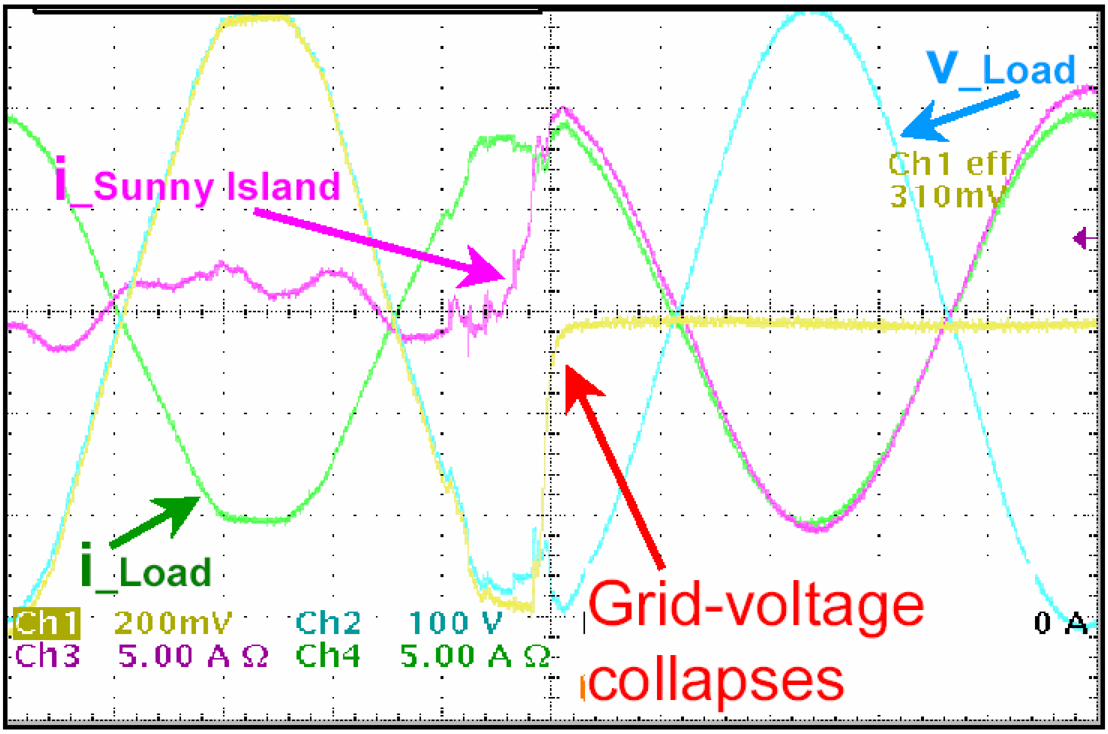


Figure 30.Grid voltage collapse

A critical factor in order to exploit the potential offered by the microgrid concept is the presence of micro-sources, with fast-acting power electronics interfaces to regulate voltage and frequency and ensure proper load sharing among the various sources, when operating in isolated mode. In interconnected mode, the micro-source and central micro-grid controllers regulate the power exchange with the grid, monitor grid conditions and ensure proper separation.

Micro-source controllers suitable for this task are being developed and implemented in inverters, which could support the operation of microgrids. In [Georgakis 2004], a prototype, laboratory-scale microgrid is presented, which comprises a PV generator, battery energy storage, local load and a controlled interconnection to the public LV grid. Its objective is to explore control concepts and operating policies and demonstrate the feasibility of the microgrid concept.

- **New control mechanisms**

In order to be able to utilize all the advantages of "Pure AC-coupling" new control algorithms for battery inverters so called V/f-statics- or droop-mode control were developed by and successfully implemented in Sunny Island® battery inverters by ISET e.V. and SMA Comparable to the control of a pool of conventional power plants (e.g. the European electrical power supply grid UCTE) the concept of droop-mode-control is based on active power/frequency-statics and reactive power/voltage-statics (see Figure 4). This droop mechanism is inherent in standard AC-generators as e.g. the frequency decreases while the load (active power) increases.

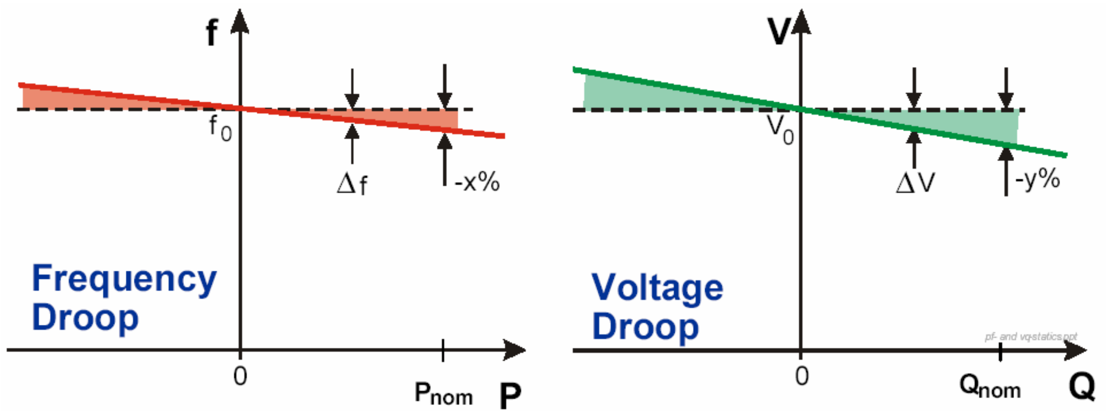
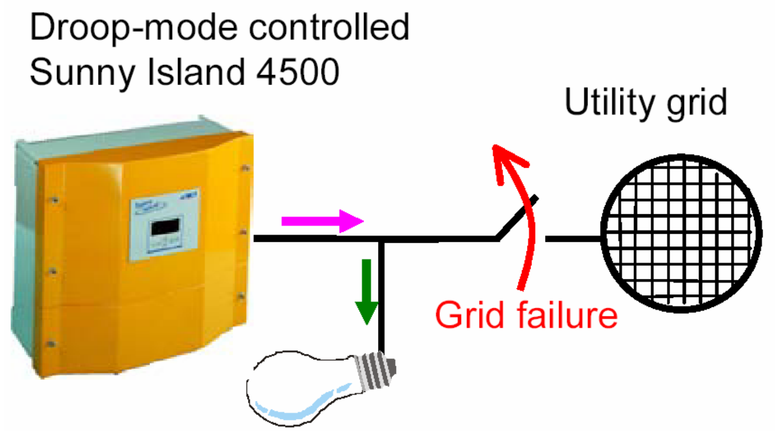


Figure 41: Typical active power/frequency-statics and reactive power/voltage-statics used in droop-mode-controlled inverters

Due to the following advantages and as demonstrated in many applications the "Pure AC-coupled" systems with droop-mode controlled Sunny Island® inverters show an outstanding performance in terms of parallel operation of several battery inverters with (diesel) generators and grid - even in three-phase operation:

- expandable to any number of inverters
- no (high speed) communication necessary for paralleling inverters. Due to this, droop-mode controlled inverters are applicable to systems with distributed generation with very long distances between parallel inverters
- increased overload capability of the system. The Sum of power of all generators is available to the load (real generator support).

- Ultra-fast transition times in Back-up/UPS systems in case of failures or other modes of operations (see *Figure 42*)



1. Grid and Sunny Island present **2. Grid failed but Sunny Island supplies load**

Figure 42: (a) Circuit diagram and (b) measurement of operational behaviour of a droop-mode controlled system in case of a grid failure

Technical inquiries and results from other projects show the necessity of a grid disconnection (anti island) unit which does not disturb the public grid and reliably avoids unintended islanding. Therefore following devices have to be developed:

- Preparation of a new type of disconnection unit for the use in commercial products. The unit will work according to an algorithm patented by ISET.
- Development of a configurable anti islanding unit with bi-directional communication and controllability (implementation of additional functions e.g. RCD, energy meter will be examined).

The German project SIDENA (http://www.sidena.de) deals with "*Safety aspects for distributed generation*". Here a special emphasis is put on the design of a utility interface. The project goes along with the new founded work group DKE 373.0.9. "bi-directional utility safety interface". Detailed investigations regarding the effect of a big number of DG units on the power quality are planned.

- **Commercially available products:**
    - **Sun Profi Emergency**

The company Sunpower (www.sunpower.de) brings a combination of grid tied inverter and a battery charger on the market (Sun Profi Emergency, with a nominal power of 1500W, 3000W, 5000W). In addition to the functions of a standard grid-connected inverter this equipment is provided with the functions "charge control" and "stand-alone operation". With an additional battery - the capacity depending on the desired time of emergency supply - an emergency power supply is available. The combination is able to continue to supply important loads at grid failure. At grid failure the Sun Profi Emergency automatically disconnects from the grid and switches to a separate emergency output. In stand-alone mode it supplies the connected emergency loads.

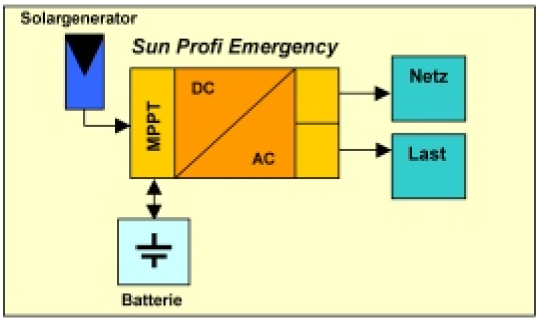


Figure 43.Sun Profi Emergency scheme

- **Features of the Sun Profi Emergency**

- Emergency power supply in case of grid failure
- Two operating modes: feeding into the grid and stand-alone mode
- Additional MPPT charge controller
- Wide input voltage range with automatic matching to the solar generator
- Low DC system voltage: 48 Vdc nominal battery voltage
- Sine wave output current when feeding into the grid, independent of the voltage shape of the grid-by synchronization of an ideal internal sine wave reference with the grid
- At stand-alone mode sinusoidal output voltage with very low harmonic distortions
- Highly accurate MPP-tracking (better 1%) also at partial shading, stable operation at fast insolation changes caused by clouds
- Battery charging with temperature compensation

- **SOLSAFE**

Swiss manufacturer Studer (www.studer-inno.com) offers an integrated combination under the name Solsafe, as a UPS PV power system. The concept consists of an on-grid inverter (also possible from other manufacturers), one of our inverter-chargers of the COMPACT series (XPC, C, HPC), an auxiliary relay module ARM-01, a battery and 2 external contacts. In case of grid breakdown, the external contactor switches over from utility to the batteries.

- **SINVERT solar**

The improvement of grid quality (reactive power by phase displacing and harmonics control) has being studied more recently and implemented in inverters for new, larger, centralized grid-connected PV, as for instance, in the form of Siemens SINVERT system. The active harmonic filter offsets existing voltage distortions by making network voltage into the pure sine form. Reactive power can also be provided to retain voltage in the network. This ensures almost totally interference-free operation even within weak power grids. The standard model also includes the dynamic phase offset for symmetrically loaded phases. In addition, a reactive power control option is available.

Appendix 3.- Capacity credit of wind energy generators

Intuitively, it is understood that the economical and ecological value of wind power are not quantified by its total energy delivery as such, but rather by the amount of conventional generation capacity that can be replaced by wind power. Therefore, a more correct valuation of wind power, taking into account the dynamic effects of fluctuating wind power and system load, uses the term '*capacity credit*', defined through the following steps ([47]-[50]):

- The **reliable capacity** is the amount of installed capacity in a power system available with a given reliability, to cover the system load.
- The **loss of load probability (LOLP)** is the probability that the system load exceeds the reliable capacity.
- The **capacity credit** of wind power is the amount of installed conventional power generation capacity that can be replaced by wind power generators, without an increase of the LOLP.

The capacity credit of a single wind turbine is virtually zero, as, due to the intermittent and relatively unpredictable nature of instantaneous wind speeds, one wind turbine cannot replace an amount of controllable conventional power generation without increasing the LOLP.

The capacity credit of wind power depends on the extent of the considered zone in which the aggregated wind power is evaluated. To the authors' opinion, evaluation of capacity credit of wind power makes most sense when considering the aggregated wind power within an entire power control zone (e.g. Belgium), or within a zone that has limited power exchange capability with other zones because of transmission bottlenecks.

Taking the time dependency into account, the definition of *capacity credit* is not considered sufficient anymore. Especially the word '*replaced*' calls for further elaboration. Estimates of capacity credit will dramatically diverge, depending whether the estimated investments on constructing new power plants that can be totally avoided due to replacement by wind power are considered, or whether the amount of power plants that must be in operation (either producing active power or providing primary and secondary reserves) at the considered moment can be decreased due to replacement by wind power. For the last interpretation, knowledge is needed about:

- the instantaneous power system load and generation, the load uncertainty and the actual power plants in operation;
- the instantaneous wind power generation;
- the season and time of day, as it is an input parameter for the estimated probability of wind power;
- the sample time length considered: for how many consecutive hours can wind power replace instantaneously operating power plants?

Methodology

The following procedure is used to obtain the capacity credit of each one of the previously proposed scenarios (see chapter 6.1.3). As a reminder, the characteristics of each scenario are here described:

- Scenario I: even distribution
    - 50% of the installed wind power consists of fixed speed stall-controlled turbines with hub height 40 m;
    - 50% of the installed wind power consists of variable speed pitch-controlled turbines with hub height 80 m;
    - all wind turbines are evenly spread over the entire area.

- Scenario II: concentration in the west
    - 60% of the installed wind power consists of variable speed pitch-controlled turbines with hub height 80 m (30% of the installed wind power) and 90 m (30%), these turbines are strongly concentrated in the western part of Belgium, i.e. the region with most wind resources;
    - the remaining 40% of the installed wind power consists of fixed speed stall-controlled turbines with a hub height 40 m; half of this wind power is installed in the western part of Belgium, the other half evenly spread over the rest of the area.

- Scenario III: only offshore
    - one offshore wind farm is installed, consisting of variable speed pitch-controlled turbines with hub height 110 m. The farm width is 5 km. This scenario computes the fluctuation of the large offshore wind farm only, without taking into account possible other wind power onshore.

- Scenario IV: on- and offshore
    - 60% of the total installed wind power is offshore, as in *scenario III*;
    - 40% is onshore, distributed as in *scenario II*.

The aggregated wind park, geographically spread according to one of the four scenarios described above is considered as a single new power plant. The capacity credit is considered over an entire year or for every season separately. Various assumptions for the total installed wind power in each scenario are made, ranging from 100 to 5000 MW.

Capacity credits for all scenarios

- **Capacity credit per year**

Following the methodology described above, the capacity credit of the aggregated wind park in Belgium is calculated, for all scenarios of geographical spread introduced and installed wind power ranging from 100 MW to 5000 MW. *Figure 48* shows the capacity credits of the aggregated wind park in absolute (a) and relative (b) terms, for all scenarios of geographical spread introduced in paragraph 8.4.1.

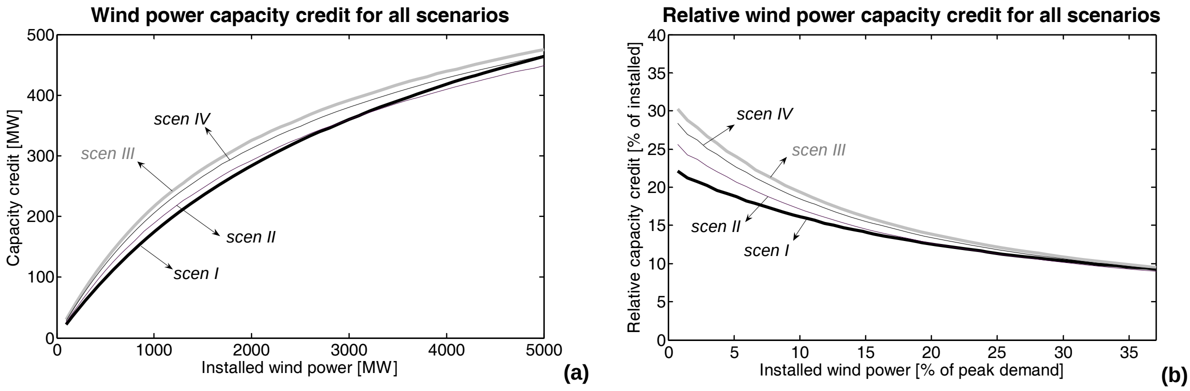


Figure 48. Capacity credit of aggregated wind park for all scenarios, in MW (a) and as percentage of installed wind power (b)

It is concluded that the capacity credit of wind power decreases monotonically for increasing values of installed power, to below 10% for an installed power of 5000 MW. For low values of installed power, the capacity credit for a given scenario is well approximated by, although not equal to, the annual capacity factor as given in *Table 14*.

scenario	*capacity factor [%]*	*annual amount of non-operating hours*
I	20	984
II	26	1519
III	31	1755
IV	29	1660

Table 14. Annual capacity factor and annual number of non-operation hours for each scenario

It is further noticed that the capacity credit for *scenario I* is the lowest of all scenarios for low values of installed wind power, but becomes the highest when the installed power increases. The benefit of the geographical spread of the turbines in *scenario I* and the resulting smoothened power time series then outweigh the disadvantage of lower overall wind resources and the resulting lower capacity factor. This effect is however only noticed for very large values of installed wind power. It was already concluded that the beneficial effect of geographical spread must not be overestimated, as simultaneous wind speeds are highly correlated in the entire Belgian control zone.

- **Capacity credit per season**

The capacity credit for all scenarios is calculated per season separately. For this, the approximation is made that the LOLP of the original power system is constant in time. This means that, if the LOLP is 4 h per year, it is assumed equal to 1 h per season. The cumulative probability density of the wind power generation is recalculated for each season separately.

The resulting capacity credit for all scenarios is given in *Figure 49* for Winter (a) and Summer (b). For all scenarios, the capacity credit is higher in Winter than in Summer. The results for spring and autumn are between the extreme cases of Winter and Summer.

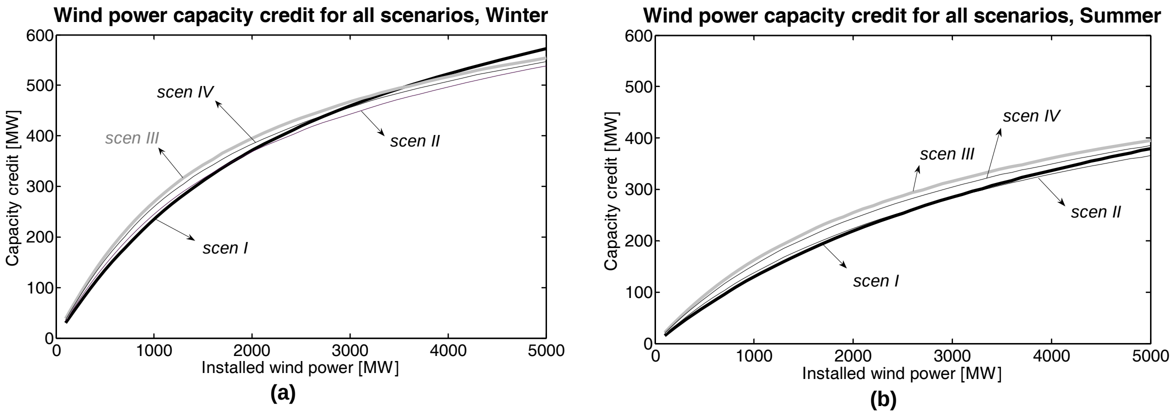


Figure 49. Capacity credit of the aggregated wind park for all scenarios, Winter (a) and Summer (b)

Appendix 4.- Biomass in the Walloon Region

Technologies and conversion yields

Figure 44 presents the three main groups of energy conversion technologies of biomass and the ways of final energy resulting, being the following:

- Those proceeding from thermochemical conversion (combustion, gasification, pyrolysis) for the dry biomass,
- Those proceeding from biochemical conversion (digestion, fermentation) usually for the humid biomass.
- From the extraction, which is a mechanical proceeding that allows the oil productions, for example, of bio diesel from rapeseed.

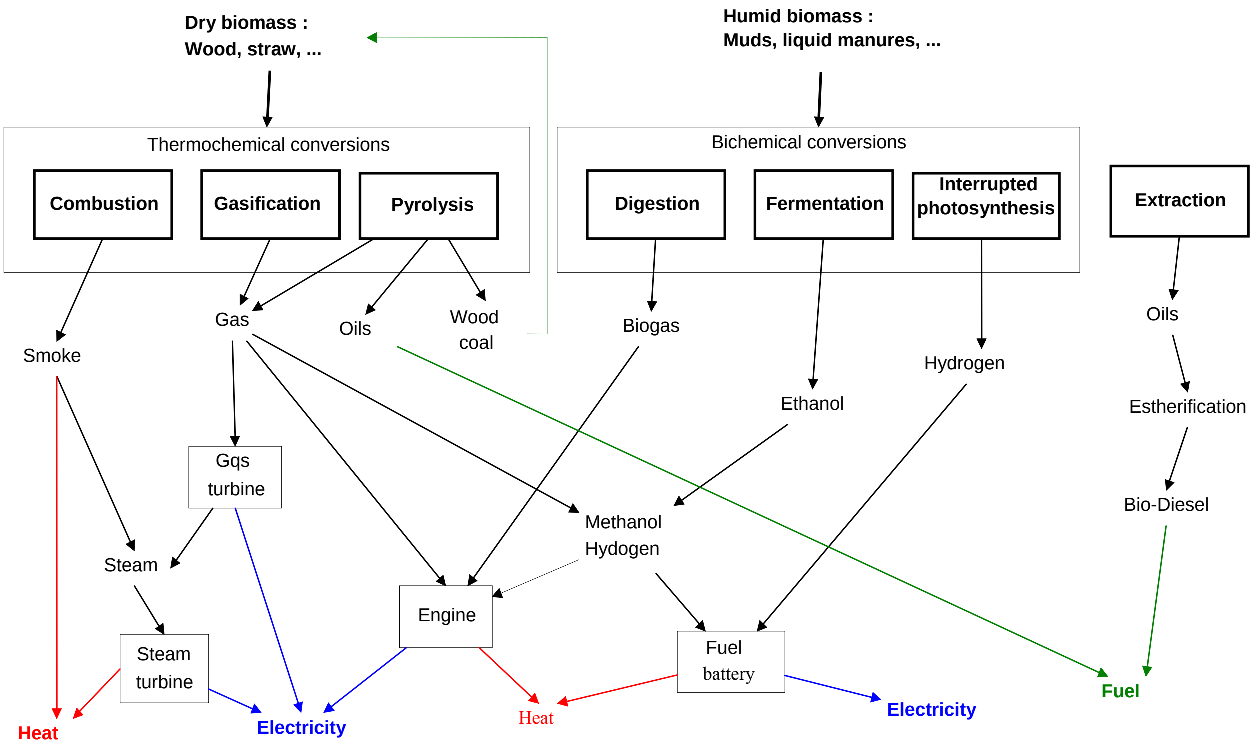


Figure 44: Energy production lines from biomass

The wood biomass thermochemical conversion is usually carried out by oxidation. Taking into account the fact that the oxygen used comes mainly from the air, the equation of oxidation can be written as follows:

$$CH_{1,44}O_{0,66} + 1,69\,(O_2 + 3,76\,N_2) \;\Rightarrow\; CO_2 + 0,72\,H_2O_{vapeur} + 6,35\,N_2 + 18,6\,MJ/kg\,bois \qquad (10)$$

The complete oxidation of 1 kg of dry wood produces thus18,6 MJ, a value decreased by the presence of the ashes. Nevertheless, the air volume supplied to the conversion process is not always equal to the stoichiometric air volume strictly needed for the complete oxidation of the fuel. Then it is convenient to define the air excess coefficient λ which is the ration between the really used air and the stoichiometric amount and to take it into account through the formulation of the conversion reactions, as follows:

$$CH_yO_x + l\ (1 + \frac{y}{4} - \frac{x}{2})(O_2 + 3{,}76\ N_2)\quad Þ \quad CO_2 + \frac{y}{2} H_2O_{vapeur} + wO_2 + zN_2 + énergie \qquad (12)$$

This coefficient λ is crucial and its value varies according to the proceedings described in *Table 5*.

Process	Air excess	Temperature	Main product	Main possible uses
Combustion	λ > 1	800-1300 °C	Hot exhaust gases	Hot water, steam or gas production included those for electricity production
Gasification	0.2 < λ < 0.5	700-900 °C	Gas with a low–medium ICP	Fuel gas for gas engines and dual-fuel, gas turbines and fuel batteries
Pyrolysis - carbonization	0 < λ < 0.2*	400-700 °C	Pyrolitic oils medium liquid ICP	Fuel for diesel engines or gas turbines Wood coal production

Table 5 :Base principles of the biomass thermochemical transformations

Historically and traditionally, the energy use of the wood was the combustion in the decentralized installations (wood stoves) for heating. This thermal use of the wood which is nowadays majority by far, is suitable to go through a remarkable development due to the new wood boilers, competitive and completely automatic, available in the market.

Wood, or in general, 'dry' biomass, which groups the wood coming form the forest explotation (residual forest), from industrial by-products (sawmills, woodwork, furnishing, palettes, …) or from energy cultivation (shavings (TtCR), …), can also be transformed in an energy verctor with a higher added value, the electricity. The TtCR is a cultivation of woody species with a high plantation density collected every three years. In the Walloon Region, the willow tree and the poplar are the most suitable species. The shavings are the energy cultivation that presents the most promising potential.

The adapted systems allow the electricity production use directly ('boiler –steam turbine') wood, or use indirectly ('gas engine') synthetic gas obtained by thermochemical transformation (gasification, pyrolysis) of dry biomass.

The direct electricity production in a boiler – steam turbine can reach in cogeneration very high energy yields (about 80%), although the electric yields are generally very low. In the case of low power, the important investigations are led to European levels to improve the yields.

Table 6 summarizes the performances, the application sectors and an approximation of the investment of the main technologies of energy conversion of dry biomass.

Sector	Technology	Power	Accepted fuel	Net yield therm	Net yield elec.	Investment
Domestic	Stoves	Up to 50 kW_{th}	logs, granules	15-75%	-	100-625 EUR/kW_{th}
	Boilers	10 to 100 kW_{th}	logs, granules, chips	70-90%	-	200-700 EUR/kW_{th}
Colective heating and PME	Boilers	0.1 to 10 MW_{th}	sawdust, chips,...	80-100%	-	100-1200 EUR/kW_{th}
	Gas-electric generator groups	0.1 to 0.5 MW_{th}	chips,...	50-60%	20-26%	1500-4000 EUR/Kw_{el}
Centralized electricity production	Steam cycles	> 3...5 MW_e	sawdust, chips, barks,...	50-75%	15-35%	1000-5500 EUR/kW_{el}
	Co-combustion	> 5 MW_e	sawdust, chips, barks,...		35-45%	600-1200 EUR/kW_{el}
	Gas cycles	> 5 MW_e	sawdust, chips, barks,...		30-50%	1000-5500 EUR/kW_{el}

Table 6: Performances and characteristics of the biomass thermochemical conversion technologies

The research is also financed at the regional level, in the frame of the mobilisateur program 'Cogeneration: the total energy'. The electricity production from gasification of the wood is also subject of research co-financed by the Walloon Region and reached the creation of Xylowatt, that furnishes and exploits the cogeneration plants by wood gasification. The aimed range of electric power is from 25 to 1000 kW, but the available installations are commercially constituted by modules of 300 electric kW/610 thermal kW. Many plants based in this technology are still under construction and the first has been welcomed by Electrabel in November 2005 after many months of exploitation.

Origin of the biomass used in Wallony for electricity production:

- **Dry biomass**

The dry biomass potential in Wallony is important. Many studies were carried out involving this subject. The evaluation of the potential of this dry biomass takes three resources into account:

- the 'residual forest', which means the waste from the forest exploitation (which involves 423.000 ton per year) ;

- the waste of wood first transformation industry (involving 260.000 ton) ;

- the energy cultivations, like the cultivation of shavings which could involve from 300.000 to 500.000 ton per year if a significant part (5 to 7%) of the working agricultural surface was affected.

Wood is a noble material; its main valuation should remain the raw material for furniture, construction materials, etc. The by-products of the forest and first transformation industrial exploitation (sawmills …) are also valued by the stationer sector and by the particle and fibre board sector. The new energy use of dry biomass will then be developed in the residual amounts and economic conditions that respect the existing lines.

Starting from the conservative assumption that a third of this potential could be used for electricity production from here to 2010, an electrical yield of 20% is taken into account, a potential of **595 GWh/year**, from which 370 GWh come from residual forest and 225 GWh from energy cultivations. This involves an electricity production of about 2,4 % of the Walloon consumption.

In what the heat production from dry biomass concerns, the aim is to reach about **4100 GWh** in 2010, being **a bit more than the 8% of the final thermal consumption or about the 3% of the final total consumption** in Wallony.

In 2000, about 3000 GWh-heat was based on products coming from dry biomass (forest waste, waste from first transformation of wood and wood heating). More than a half are products (simultaneously 149 GWh-electricity) in the place of Burgo Ardennes. A big part of the raw material is imported (about 80%). The rest is directly produced by combustion. In 2010, a heat production by cogeneration of residual forest is added to the production in Burgo Ardennes, waste from first transformation of wood and energy cultivations (about 700 GWh) and a heat production from combustion (about 400 GWh). This values are based on a third of the endogenous potential, except the part consumed by Burgo Ardennes which is nowadays imported.

In order to promote the rising of this kind of projects, a Wood-Energy and Rural Development Plan has been shaped in collaboration with the Minister of Agriculture and Landscape. It aims to start and carry out in the Walloon territory around ten projects of automatic wood boilers, gas producers or other technologies adapted to the energy value of wood. This plan involves essentially the collectives and communities, with or without heat network. In the framework of this Plan, the information and sensitization actions are planned, the studies of feasibility are carried out (evaluation of the available resource, evaluation of the energy demand, evaluation of the URE potential) and assistance is provided for the setting up of the projects.

In 2004, 11.885 ton of wood waste were collected in the province of Namur by a network of 31 container parks and valued for cogeneration by the plant of Recybois in Latour-Virton. 7.562 ton of paper and cardboard were in addition collected by the container parks and door-to-door only valued in matter with Sita (company responsible for the waste management). In the next 2 to 3 years, the refuse collection door-to-door in the Province will be sorted resulting in a supplementary flux of wood waste of about 5.000 tonnes/year (also valued for cogeneration)[1].

[1] Communication du Bureau Economique de la Province de Namur, Service environnement

- **Humid biomass**

It is essentially constituted by green waste selectively collected in container parks, the muds from the purification stations, industrial effluents (sugar mills, breweries, farm-produce industries), the organic fraction of the waste in dumps, from which the fermentation product of the biogas has a high content in methane (50 – 65%), usable in the boilers, engines or gas turbines for energy production. In 2004, 31.721 ton of green waste collected in the container parks (composted by the composting centre in Naninne, exploited by the BEP Namur). The perspectives in the short term (2-3 years) forecast the selective collection of the fermentable fraction of the waste in the 75% of the province territory, which will allow recovering 12 to 15000 ton in preparation for their biomethanization forecasted in the territory of the city of Assesse.

In the Walloon Region, 225 plants with an electric power higher than 100 kW can be considered in the farmhouses (Tchouate, 2005). The next figure gives an illustration, the power values are classified in decreasing order. For many cities, the power determined by a micro-economic study in a city scale, is likely to increase, due to the fact that other available organic waste will be taken into account. The construction of these plants will allow besides the cities to create new qualified jobs, to contribute to the solution of the problem of organic waste reduction, to use reasonably the energy sources and to reduce the particles and gas emissions polluting the environment.

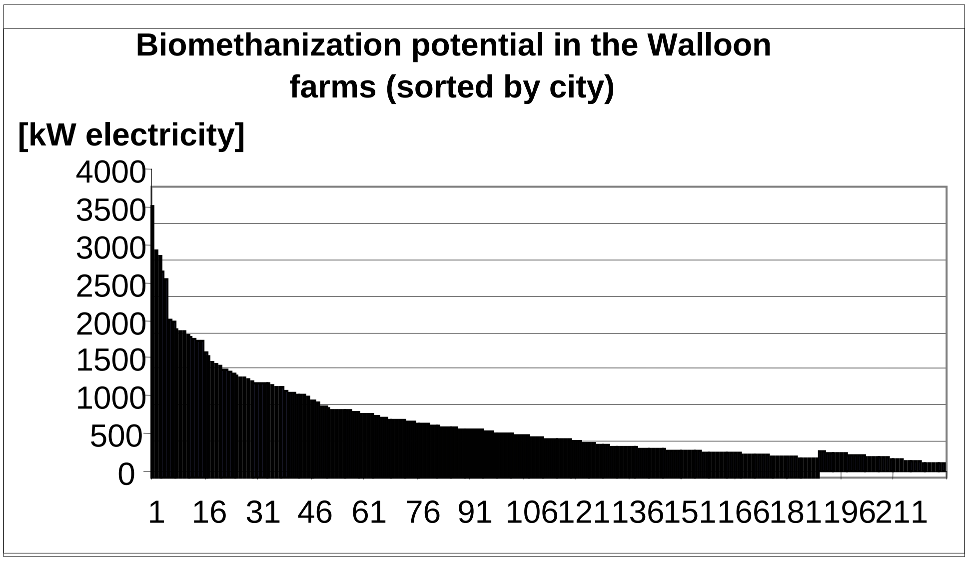


Figure 45 : Electricity production potential by biomethanization of liquid manure in the Walloon cities

Other biomass

Electrabel imports the olive oil and the palm oil from all over the world (Southern and Eastern Europe, South America, Thailand, Canada, Tunisia, South Africa) for the production of renewable electricity.[2]

[2] Communication of Laborelec

- **Biofuels**

o Rapeseed oil : 4 grinders in the installation with capacity for 300 ton pummelled rapeseed each

o Biodiesel : There is not production at the moment, but there are already projects. It is usually made from rapeseed oil.

o Cereal boilers installed in the Walloon Region.

Classification of the wood

In order to guarantee the quality of the fuels and allow a selection of the installation according to the assortment available, biomass can be classified as follows:

• Forest faceplates and faceplates coming from sawmills (PFS)

• Wood by-products resulting from the landscape maintenace and the clearing of resinous (SPEE)

• Sawmill chips (CS)

• Barks pulled to pieces (ED) and not pulled to pieces (END)

• By-products from the wood transformation (SPT)

• Yard by-products (SPC).

The classification takes into account the following criteria to define the fuel properties:

• Grading g

• Water content x

• Density in bulk d

• Nitrogen content N

• Needle percentage a

• Foreign bodies é

• Ashes content c.

These criteria are defined precisely in the classification in Table 3 and help often as a base for the supplying contracts. The same criteria are taken into account for the selection of the fuel transport and the heating system.

In the faceplates coming from the forest and sawmills, three different categories of grading can be distinguished, as well as three different levels of wood humidity. The small boiling plants burn the wood faceplates pulled to small pieces not much humid and from wood granules, while the bigger plants can also burn the assortments of big pieces with relatively higher water content. The wood resulting from the landscape maintenance and the clearing of spruces can be made of highly variable assortments – soft wood (poplar and willow tree) but also hard wood (hazelnut tree …) –, which has to be taken into account in the selection and the operation of the heating plant The maintenance of resinous forest produced by the wood clearing can present a high percentage of needles.

Biomass energy content

The following table presents the calorific power of different types of wood according to the classification adopted in Switzerland.

Wood assortment energy	Abreviation	g Dimensions mm	x Water content weight %, humid	d Density in vrac kg/m³, without water	N Nitrogen content weight %, without wat	a Needles weight %, humid	ê Foreign bodies [3] weight %, humid	c Ashes content [3] weight %, without wat	Calorific Power ICP humid Fluctuation range kWh/m³Pl	Calorific Power ICP humid Indicative value for the projects (Wh/m³Pl
Cardboard from forest and sawmills	PFS-g30-x35 [1] [2] [5]	30	20-35	> 130	< 0,5	< 10	< 1	< 2	Ep/sa: 550-650 Hê: 900-1'000	Ep/sa: 650 Hê: 1'000
	PFS-g30-x50 [1] [2] [5]	30	20-50	> 130	< 0,5	< 10	< 1	< 2	Ep/sa: 450-550 Hê: 800-900	Ep/sa: 550 Hê: 900
	PFS-g45-x35 [1] [2] [5]	45	20-35	> 130	< 0,5	< 10	< 1	< 2	Ep/sa: 550-650 Hê: 900-1'000	Ep/sa: 650 Hê: 1'000
	PFS-g45-x50 [1] [2] [5]	45	20-50	> 130	< 0,5	< 10	< 1	< 2	Ep/sa: 450-550 Hê: 800-900	Ep/sa: 550 Hê: 900
	PFS-g45-x60 [1] [2] [5]	45	20-60	> 130	< 0,5	< 10	< 1	< 2	Ep/sa: 350-450 Hê: 700-800	Ep/sa: 450 Hê: 800
	PFS-g90-x50 [1] [2]	90	20-50	> 130	< 0,5	< 10	< 1	< 2	Ep/sa: 450-550 Hê: 800-900	Ep/sa: 500 Hê: 850
	PFS-g90-x60 [1] [2]	90	20-60	> 130	< 0,5	< 10	< 1	< 2	Ep/sa: 350-450 Hê: 700-800	Ep/sa: 400 Hê: 750
Wood by-products from the landscape maintenance and clearing of resinous	SPEE [2]	90	< 60	> 100	< 2	< 20	< 5	< 5	250-800	500
Chips from sawmills	CS [2]	< 4	35-50	> 130	< 0.5	–	< 1	< 1.5	Ep/sa: 450 -550	Ep/sa: 500
Barks pulled to pieces	ED [2]	90	< 60	> 100	< 2	–	< 5	< 5		Ep/sa: 750
Barks not pulled to pieces	END [2]	a.c.	< 60	> 100	< 2	–	< 5	< 5		To be agreed
Wood transformation by-products	SPT [2]	a.c.	a.c.	a.c.	a.c.	a.c.	a.c.	a.c.		To be agreed
Yard by-products	SPC [2]	90	< 40	> 130	< 2	–	< 5	< 2	500-700	550

Table 7.Calorific power of different types of wood according to classification in Switzerland

The wooden pellets come from the sawdust densification and have a ICP of 18 GJ/ton. The dry farming residues used in Wallony present a ICP between 15 and 20 GJ/ton and they are converted in the Electrabel plants with an electric yield of 36%.

Generally speaking, the biomass energy content is influenced by its content of humidity and mineral matters. The following diagram shows an example.

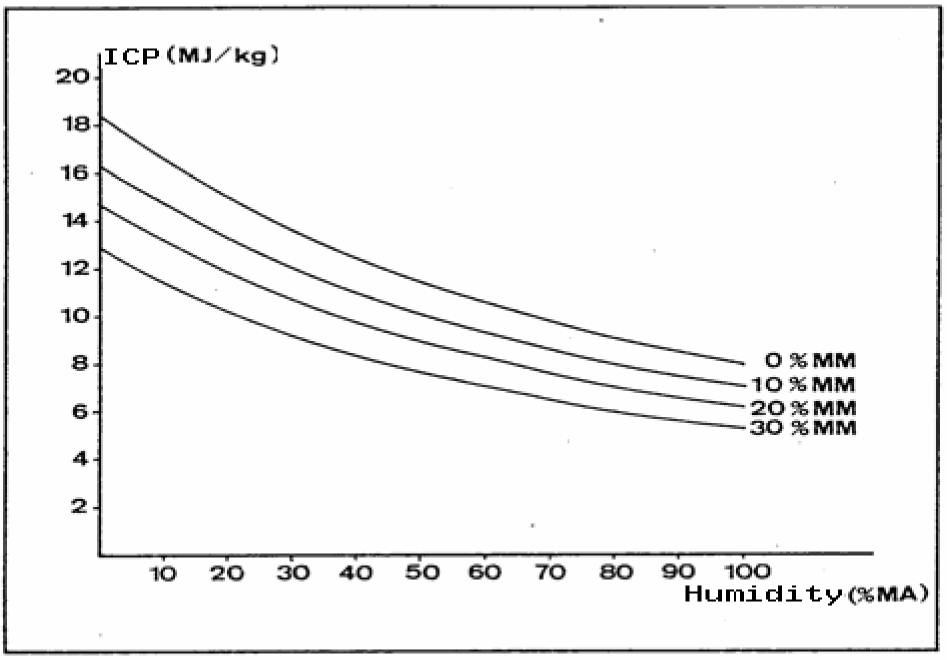


Figure 46: ICP variation according to the contents of humidity and mineral matters

State of the energy evaluation of biomass in the Walloon Region

Domestic waste is generally burnt but according to the convention (International Energy Agency (IEA) and Eurostat), only the organic fraction of this waste will be considered as a renewable source and counted as biomass value. In the same way; the statistics collected by the IEA separate the renewable and non-renewable fraction of the waste.

The energy evaluation is made by recovering of the heat produced as steam involving the alternator. The net yield of the electricity production is generally reduced. 4 incinerators give an added value to the domestic waste in Wallony and the amount of burnt waste is 454 400 ton. The gross amount of electricity produced by the incinerators in 2003 rises up to 220 GWh. The organic fraction is estimated to 35% of the total burnt by the ICDI, for the rest; the operator indicates a 15% for Virginal, 81% for IPALLE and 5% for INTRADEL. The primary energy considered as renewable reaches 23.4 ktep and, proportionally, the gross electricity production is 48.8 GWh.

- **Wood combustion for heating**

The wood combustion for domestic heating is evaluated in 2003 in 3893 TJ, meaning an increasing of 6,6% respect to 2002. The following table presents the main characteristics of the equipment used.

Equipment	Chimney	Heat recovering	Closed / inset fireplace	Fireplace	Cooking stove	Classic boiler	Inverse flame boiler
Heating possibility	1 room	1 or 2 rooms	many rooms	many rooms	habitation	habitation	habitation
Characteristics	Pleasure heating low performance (losses due to smoke and bad combustion)	Improves the chimney yield by air / water heat recovering Residue low performance	Better controlled combustion than an open fire Improvement in heat recovering	Mainly radiance heat transmission Significant heat in the room	Possibility of cooking food Significant heat in the room	Installed in boiler room Poorly controlled combustion Flexibility of use	Installed in boiler room Well controlled combustion due to fan Flexibility of use
Yield	5 to 15%	10 to 25%	40 to 80%	50 to 80%	55 to 65%	40 to 60%	75 to 85%
Autonomy	2 to 3 h	2 to 3 h	up to more than 10 h	up to more than 10 h	2 to 7 h	4 to 10 h	5 to 20 h
Heating type	Contribution heating	Contribution heating	Contribution heating	Contribution heating	Contribution heating	Central heating	Central heating

Table 8: Wood main equipment characteristics (Source Ademe)

The term 'vegetable by-products' involves wood, wood transformation waste, forest waste, paper waste and solid vegetable products. The recovering of paper waste for energy purposes in Wallony is carried out mainly in the factory of Burgo Ardennes in Harnoncourt.

Wood waste is burnt in boilers in the same way in some other factories (sawmills and wood second transformation sector). Concerning the data, they result from an estimation made over a survey comparing the different companies which had a wood boiler at their disposal.

At last, Electrabel burns since 2001 the (imported) olive pits in the unit 4 of the Awirs plant, and since 2002, also the Amercoeur plant burns the olive pits. The electric power and production values are calculated pro rata of the renewable energy income.

The steam and electricity productions from forest or agricultural waste combustion are here represented. The primary production is 207 ktep, in light decrease compared to 2002.

Total	Primary production	Produced steam	Gross electricity	Net electricity
ktep	207.2	174.1	18.0	13.3
GWh	2 409.2	2024.2	209.3	154.7
TJ	8673.1	7287.2	753.4	556.9

Table 9: Energy production from waste or agricultural waste in Wallony (2003)

- **The wood waste**

The following table summarizes the different categories of wood waste and the contaminants involved. Its energy evaluation is again limited to the incineration. The testing is carried out by the Thermodynamics unit of the Catholic University of Louvain with a view to its evaluation for gasification. The aim of the tests is to analyze the ability of the system to concentrate the pollutants in the ashes, easier to treat due to the concentration.

Materials	Chemical compounds	Quantity	Humidity	Main uses / comments
Packing				
palettes	low content in preservative products	<100ppm	15-20%	transport, PCP content decreases with the years
cagettes	glue in less than 5% of formaldehyde on 5% of the cagettes			food products transport
Demolition wood with paint				
With lead base	lead	1000 – 20000 ppm	6-20%	lead content in paint decreases progressively in years 50 to 70
With acrylic base	acrylic acid, styrene, nitrile, etc.	<0.1%	6-20%	
With metallic pigments	titanium dioxide, zinc chromate, aluminium. etc	<0.1%	6-20%	higher contents in the material surface
Panels				
Plywood	UF glue	1-4%	6%	indoors to be treated with preservative, fireproof products, etc.
Plywood	UF glue	1-4%	8-12%	outdoor
oriented strandboard	UF glue or PF / isocyanate	2-4%	8-12%	indoors
Particles	UF glue	5–13%	8-12%	indoors
MDF and other fibre panels	UF glue	5–13%	4-12%	indoors for coating
Highly adjuvant wood used outdoors				
CCA treated	copper chrome arsenic	1-3%	Variable acc. to substance and exposition	fences, current quantities very low
PCP treated	chlorophenols	1.2-1.5%		outdoors posts, current use reduced
Creosote treated	creosote containing 85% of HAP	14-20%		telephonic posts, railway beams, losses after treatment estimated in 20-50% after 10-25 years

Table 10.Different categories of wood waste and contaminants involved

Anaerobic fermentation

- **Fermentation of mud from purification plants**

Wallony had in 2003 at its disposal 8 purification plants (Bastogne, Herve, Hodeige, Leuze, Marche-en-Famenne, Seneffe, Wasmuel and Waterloo) equipped with biodigesters guaranteeing the biogas production by purification mud digestion. The biogas production was 744 244 m³, mainly evaluated in heat from the reheating of mud and building heating. In the absence of more accurate information for certain installations, a yield of 90% was estimated by the calculation of heat evaluated.

Total	Primary production	Heat produced	Gross electricity	Net electricty
Tep	437.9	286.7	48.4	45.6
MWh	5 092	3 333	563.1	530.7
TJ	18.3	12.0	2.0	1.9

Table 11: Energy production by biomethanization of the mud from purification plants in Wallony (2003)

- **Farming effluents fermentation**

The plants that give value to the farming by-products by biomethanization are located in the pig farm of mister Lenges in Recht, the farm of Fasscht, the Kessler brothers, in Attert and in the farm of mister Heck in Nidrum. The agronomical technologies centre in Strée disposes of a pilot plant for testing the heating of a greenhouse which is ocassionally in operation. A total of 955 700 m3 biogas are produced. The electricity has increased 258% compared to 2002.

- **Industrial effluents fermentation**

A large part of the energy valued by biomethanization in the industry comes from the sugar mills (purification plant for the washing of beet sugar). These are also located in 4 sugar mills, which have no further value than the biogas in Genappe and this is burnt in flare in Brugelette.

The biogas produced in Oreye and Hollogne-sur-Geer is completely used for drying the beet sugar pulp. In Fontenoy, it is burnt in a boiler in order to generate steam to 40 bars suitable for electricity production and steam in cogeneration units. In total; about 1 425 thousand m3 biogas are to be valued, with an increasing of 9% compared to 2002.

Total	Primary energy	Heat produced	Gross electricity	Net electricity
Tep	966	840	37	35
MWh	11237	9767	425	406
TJ	40.5	35.2	1.5	1.5

Table 12.Energy production from industrial effluents fermentation in Wallony (2003)

The company Van den Broeke - Lutosa à Leuze-en-Hainaut is the only Walloon farm-produce company equipped with a plant for biomethanization of industrial effluents. This plant was carried out in partnership with Electrabel, was inaugurated in the end of 2002 and is the larger plant for valuation of biogas for cogeneration in Belgium. Equipped with 2 engines with a total installed power of 2.5 MWe, gives an added value from heat of 2 MWth power and a steam production of 2 ton/h. The electricity production in 2003 was 3817 MWh (gross) and 3458 MWh net.

- **Dump gas recovering**

In total, more than 55 million m3 of gas are valued in the engines with an accumulate power of MW in 7 sites. The final energy is valued in net and consists of heat (11 GWh) and electricity (77 GWh).

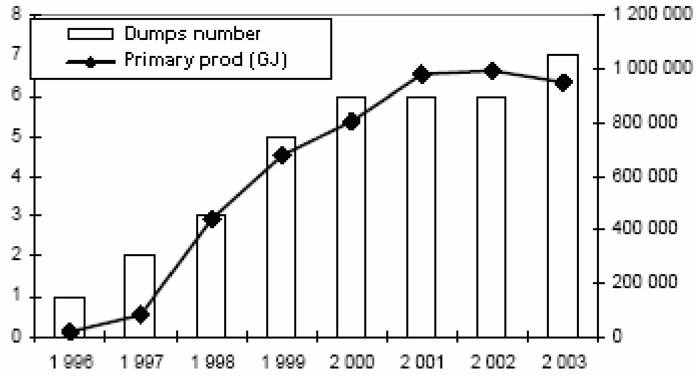


Figure 47: Evolution of the number and primary production of dumps in Wallony (1996-2003)

- **Fermentation gas recovering**

In August 2000, the biomethanization unit of the intermunicipal ITRADEC was inaugurated in Havré, near Mons. An investment of 15 million euro was needed. 54 000 ton organic waste will be treated each year and injected in the two biomethanization towers (3 800 m3 each) where they will ferment for 3 weeks before decomposing. In the fermentation a renewable gas is generated (containing 55 % methane).

Actually, the start up in 2000 was more difficult than expected and the production was not significant. The plant consists of 4 engines of 459 kWe each and 4 boilers of 1350 kWth each.

In 2003, about 3 million Nm3 were suitable to produce 4 540 MWh electricity and 10 000 GJ of heat used for the reheating of the fermentable products before the biomethanization.

Total biomass

The following table synthesizes the primary energy production data from biomass in 2003. Forest waste used in industries and wood for heating constitute the main part

Renewable energy type	Primary production (ktep)	Primary production (GWh)	Evolution 2003/2002	Part (%)	Net electricity (GWh)	Heat (ktep)	Total valued ktep
Domestic residue incineration	23.40	272.1	+8%	6.7%	45.3	0.0	3.9
Wood for heating	93.00	1081.4	+1%	26.5%	0.0	93.0	93.0
Agricultural and forest waste	207.19	2409.2	0%	59.1%	154.7	171.6	184.9
Organic waste biodigestion	1.46	16.9	+55%	0.4%	4.5	0.2	0.6
Dump gas	22.62	5.1	-5%	6.5%	76.7	0.9	7.5
Purifying mud fermentation	0.44	21.2	-30%	0.1%	0.5	0.3	0.3
Industrial effluents fermentation (1)	1.83	5.7	-14%	0.5%	3.9	1.2	1.6
Farm effluents fermentation	0.49	263.0	+210%	0.1%	1.6	0.1	0.3
Total	*350.43*	*4074.6*	*0%*	*100%*	*287.2*	*267.3*	*292.1*

(1) : Sugar mills and other food industries

Table 13. Summary table of the energy production from biomass in Wallony (2003)

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