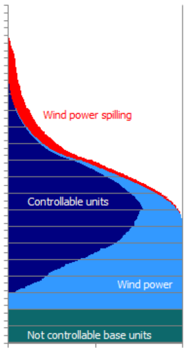


The Dual IC model

A model to describe the way intermittent power interacts with power systems, the resulting energy and power balances, CO_2 emissions reductions and other consequences thereof.

Marc Deroover; Sept. 2017

Summary

This article considers a typical load supplied by a set of identical controllable units. More and more wind power is then added to the production system, and the simulation shows how the system behaves and how the wind power is used.

The analysis considers only the energy and power balances at system level, using the LDC representation of the load. No consideration is given to the network constraints, power prices and other similar topics. It is basically a theoretical exercise that uses simple hypothesis and modelling techniques to simulate the injection of intermittent power into a classical thermal system, and tries to illustrate what intermittent power is, how it works and what are its intrinsic limitations.

When a wind turbine begins to produce power, some running mirror controllable unit must reduce its output: this is backdown power. The amount of reduced power must remain ready to be produced again if the wind stops blowing: this is backup power. The wind turbine is so tightly coupled with its mirror controllable unit that from the point of view of the network operator they cannot be treated separately. Using this approach, it is possible to describe the way the wind power is inserted into the system, and to calculate the expected resulting output of the various units.

The model shows that the intermittent power is not "added" to the controllable power but is rather "merged" with it, partly replacing the controllable power and energy by its own. It explains why installation of wind power could not result in a reduction of installed conventional power. It describes how wind power destroys the power system by forcing controllable units to run in base. It shows the limits on installed wind power, and that these limits are mainly related to the availability of storage capacity. It asserts that the lack of storage capacity becomes critical when the total installed wind power exceeds some identified thresholds. Finally it describes how we could quantify the savings of CO_2 emissions due to wind power - and shows that there are probably no savings at all.

Abbreviations and symbols

U_x	Name of power unit X, or simply unit X		**LDC**	Load Duration curve (load)
E_x	Energy produced by unit X	MWh	**IDC**	Intermittent power Duration Curve
P_x	Maximum power output of unit X	MW		
p_x	Instantaneous output power of unit X	MW	The X symbol is often replaced by:	
			B	Base power unit
K_x	CO2 rate curve of unit X	Kg CO2/MWh	**C**	Controllable power unit
Q_x	Quantity of CO2 produced by unit X	Kg CO2	**I**	Intermittent power unit
$SMPF_x$	Spinning mode penalty factor of unit X	p.u.	**IC**	Intermittent-Controllable (IC) unit
LF	Load factor (of the load)		**L**	Load
LFx	Power load factor of unit X		**W**	Wind power

Mirror controllable unit and Dual IC unit

Suppose we have an intermittent power source U_i that can produce up to P_i MW, and let's assume that at a given moment it produces p_i Mw.

Unit U_i needs p_i MW of some controllable unit U_c as "backup" power, in case p_i goes to zero (the wind stops blowing).

> *Backup power is to be understood in the usual way: power that is normally not produced, but could be produced if required.*

Unit U_i also requires (P_i - p_i) MW of some controllable unit U_c as "backdown" power, in case p_i increases up to P_i (the wind blows at full force).

> *Backdown power is like backup power, but the other way around: it is power that is normally produced, but could be reduced if required.*

Because unit U_c has to produce (P_i - p_i) MW in backdown power, and be ready to produce p_i MW as backup power, the total power P_c controlled by the U_i unit is always equal to the maximum power P_i of the unit U_i:

$$P_c = (P_i - p_i) + p_i = P_i \qquad (1)$$

At each moment we have:

$$p_c = P - p_i \qquad (2)$$

Unit U_c is called the "mirror controllable unit" of the intermittent unit U_i.

U_c and U_i are so tightly linked together by (2) that in effect U_c is out of control of the network operator. Nature will decide how much wind power is available, and p_c will follow rule (2).

From the network operator point of view, U_i and U_c constitute therefore a unique Intermittent-Controllable unit that I call a "Dual IC unit".

I like to see this as "the basic axiom of intermittent power". It could be formulated in different ways, for example:

> *"For network reliability reasons, there could be no such thing in a power system as an intermittent power source. The only entity that can be considered at system level is the Dual Intermittent-Controllable (IC) unit constituted by the intermittent unit and its mirror controllable unit"*

In this article we will use this approach to understand what happens to power systems into which intermittent power is forcibly and randomly injected.

We will begin by looking at the IC unit and its properties, and then we will simulate the merging of the load and the intermittent power and see what happens.

The Dual Intermittent-Controllable (IC) unit

Let assume that we want to supply a 1 MW load during 1 unit of time with some intermittent power unit U_i of 1 MW maximum power output.

Because U_i is intermittent, it cannot cover the whole load. Its output power p_i will vary between 0 and 1 MW, and the energy produced by the intermittent power will be:

$$E_i = LF_i$$

where LF_i is called the load factor of the intermittent unit. This is shown on figure 1 where the intermittent energy is represented under the curve (in blue).

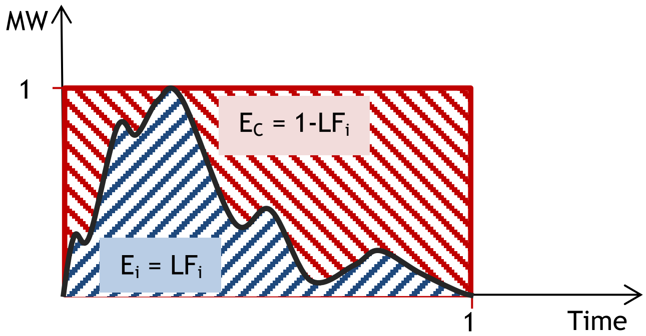


Figure 1 : Inside the Dual IC unit

To supply the full load, the remaining red area above the load curve must be filled by a mirror controllable unit U_C. At each moment we have:

$$p_C = 1 - p_i$$

The energy produced by the controllable generator is (MWh):

$$E_C = 1 - LF_i \quad (4)$$

We can now represent the Dual IC unit as follows:

Figure 2: IC unit fully loaded

The left rectangle represents the energy produced by the controllable unit, and the right rectangle the energy produced by the intermittent unit.

➢ The IC unit has a load factor of 1

The most important characteristic of the IC unit is that it has a load factor equal to 1.

An IC unit will thus always run as a base unit.

We can also see this as a consequence of the backdown requirement: the unit used to mirror some wind power must always run when there is no wind power and therefore must be used as a base unit.

This is one of the reasons the intermittent power destroys the electrical power systems: controllable units must go into the base to mirror the intermittent power source, and will then force a generally well optimized base unit to work as a controllable unit or be switched off

➢ Intermittent power does not increase installed power

The IC unit has a constant power output equal to $P = P_c = P_i$.

It means that although we have P MW of intermittent power and P MW of controllable power, we can only insert under the load curve a power of P MW, and not 2xP MW as expected.

Therefore the intermittent power does not increase the installed power defined as the sum of all power that could be put on line.

> *This is why the total installed controllable power is not reduced when intermittent power is added to a power system: in Germany, they have added 90 GW of intermittent power, but the 100 GW of controllable power have not been reduced consequently*

- Intermittent power is not added to but merged with the power system

Looking at the way the IC unit works, we see that each time a MW of intermittent power is produced, it replaces the same amount of power of the controllable unit, and its energy replaces the same amount of energy of the controllable unit.

> *The intermittent power is not added to the controllable power. It is rather merged with it, partly replacing its power and energy by its own - when available*

The Dual IC unit under partial load

Let's now see what happens when the load to be supplied has a load factor LF < 1.

This will happen when the IC unit has to be loaded at such a level that it needs to produce power only a fraction of the time, as is shown on figure 3. Figure 4 shows what happens inside the IC unit (not to scale).

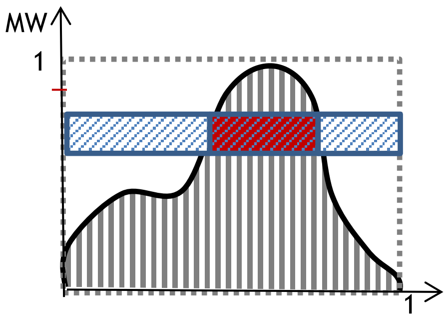


Figure 3: Chronological load

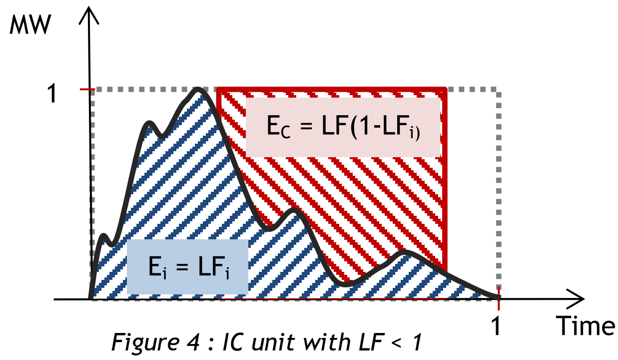


Figure 4 : IC unit with LF < 1

Unit U_C will run LF % of the time. During this time, the load factor of the IC unit will be equal to 1. Thus LF x LF_i % of the load will be provided by the U_i unit, and LF x (1-LF_i) % by its mirror U_C.

The remaining (1-LF) % of the time, the U_C unit will not run but the wind will blow and the U_I unit will produce an additional (1-LF) x LF_i MWh. This energy cannot be used by the system; it is called "spilling" (by analogy with what happens with hydro power).

The Dual IC unit under partial load can thus be represented as follows:

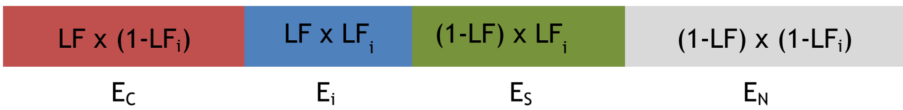


Figure 5 : IC unit partially loaded

with:

	Description	Mwh (pu)
E_C	Energy produced by the controllable unit Uc	LF x (1-LF_i)
E_i	Energy produced by the intermittent unit Ui and used by the system to supply the load	LF x LF_i
E_S	Energy produced by the intermittent unit Ui that cannot be used by the system to supply the load. Also called "Spilling"	(1-LF) x LF_i
E_N	Energy not produced. This is also the additional energy that unit Uc should produce if the IC unit was to run in base.	(1-LF) x (1-LF_i)

Note also that E_C+E_i = LF and E_I+E_S=LF_i and finally that if LF=1, we are back to the previous case.

CO2 emissions of the Dual IC unit

➢ CO_2 emissions of the Dual IC unit fully loaded

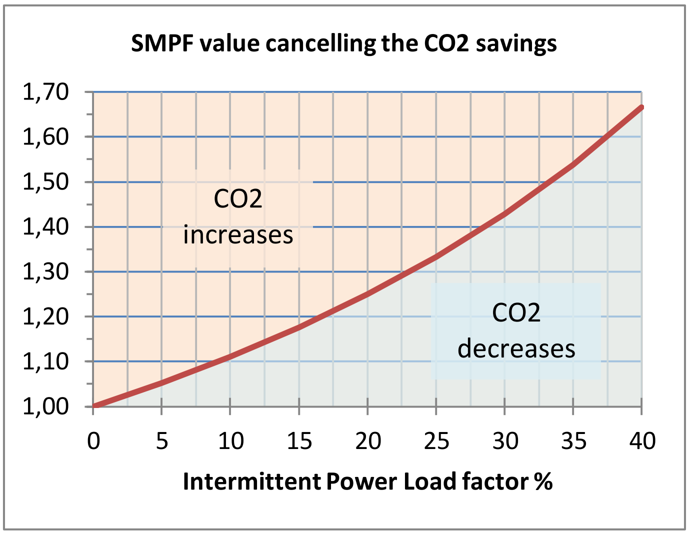
Inside the IC unit things are as shown in figure 1, and the important point is that the U_c unit is working in "Spinning reserve mode", or "load following mode", in any case outside its optimal conditions.

Therefore the CO_2 rate of unit U_c is to be multiplied by a "Spinning reserve mode penalty factor" $SMPF_C$, and the CO_2 rate of the IC generator is then (kg CO_2/MWh):

$$K_{IC} = K_C \times SMPF_C \times (1-LF_i) \qquad (5)$$

where K_C is the CO_2 rate of unit U_C running at stable nominal power.

If there is no intermittent power, the CO_2 rate of the IC unit is K_c.



If we compare K_{IC} with $K_{c,}$ we find the increase of CO_2 emissions due to the use of intermittent power inside the dual IC unit:

$$\Delta K_{LFI} = K_C \times SMPF_C \times (1-LF_i) - K_C$$

$$= K_C \times (SMPF_C \times (1-LF_i) - 1)$$

This value becomes positive, meaning there is actually an increase of CO_2 emissions due to the intermittent power, when:

$$SMPF_C > \frac{1}{1-LFi} \qquad (6)$$

For example, with an intermittent power load factor of 20%, a CO_2 rate increase of the mirror unit of 25% will cancel all benefits of using the intermittent power.

To know if CO_2 emissions are reduced with wind power, the spinning mode penalty factor of its controllable mirror unit is the key parameter.

➢ CO_2 emissions of the Dual IC unit partially loaded

Inside the IC unit things are as they were for the case LF=1 for LF% of the time. So we have:

$$K_{ICp} = LF \times K_C$$
$$= K_C \times SMPF_C \times LF \times (1\text{-}LF_i) \qquad (7)$$

And similarly:

$$\Delta K_{LFIp} = LF \times \Delta K_{IC}$$
$$= K_C \times LF * (SMPF_C \times (1\text{-}LF_i) - 1) \qquad (8)$$

The condition to have an increase of CO_2 emissions due to the intermittent power is the same as if the unit was fully loaded.

- CO_2 emissions due to a "change of technology"

To avoid spilling, the IC unit must run in base. Therefore, if Uc was not running in base before becoming the mirror of an intermittent unit, the IC unit will have to take the place of some other base unit B.

I call this a "change of technology" because it is often the case that units B and C use different technologies (ex: some nuclear base unit is replaced by an IC wind-gas unit).

The increase of the CO_2 rate due the change of technology is simply:

$$\Delta K_{B\text{-}C} = K_C - K_B \qquad (9)$$

When calculating the savings of some wind turbine, we should not forget to compare things with the situation before the wind turbines appeared. For example in Belgium, before having gas and wind turbines, we had nuclear power and the cost of abandoning nuclear is by itself about 500 kg CO_2/MWh...

A brief reminder: the LDC load representation

We will often use the concepts of LDC (Load Duration Curve) or IDC (Intermittent Power Duration Curve) in this document. So let's quickly remember what it is.

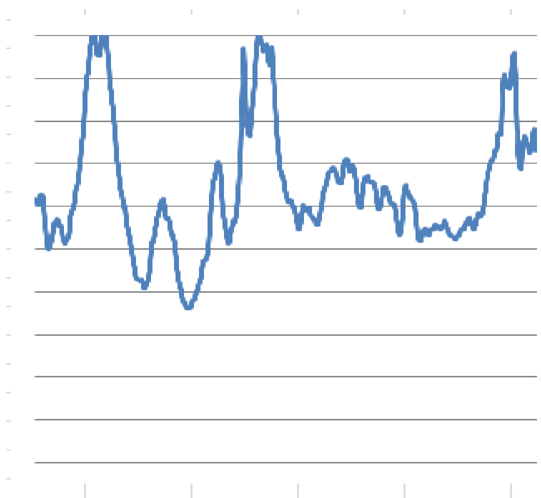


Figure 4: Chronological load (MW)

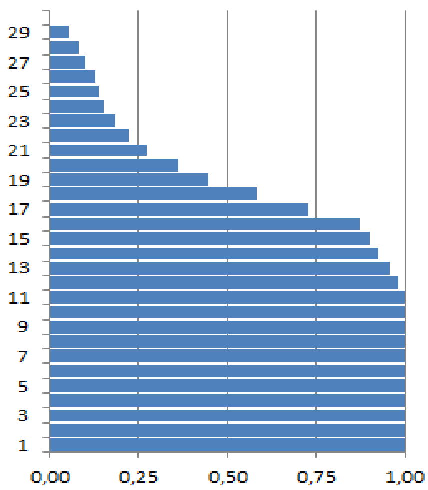


Figure 5: LDC

Formally, the LDC is the cumulative of the distribution function of the load.

The length of one horizontal bar in the LDC represents the fraction of time the load will reach the corresponding level. The area of the bar represents the energy that a 1 MW unit loaded at that level will produce to supply the load.

P_L is the peak load value (29 in our example). P_{KNEE} is the highest value of the load with LDC = 1; it is also the base load value (11 in our example). The load factor LF = energy produced/ P_L = area under the curve / P_L.

We will call this duration curve "LDC" when the data represents some load, and "IDC" when the data represent some Intermittent power.

It is important to see that once we use the LDC representation of the load, we have lost all chronological information: the LDC is a probabilistic tool that tells how much energy a unit is expected to produce, but not when it will produce it. It is widely used in the world by all electrical utilities to model their power systems.

Merging Wind Power with controllable power

We suppose that we have a load with a peak value of 20 MW, and that we supply this load with 20 similar controllable units of 1 MW each. This load and the corresponding LDC showing the expected production of each unit is shown on figure a.

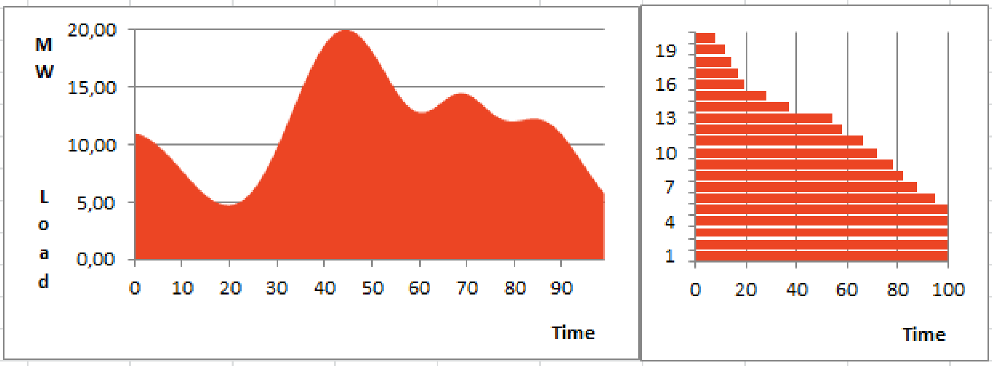


Figure a : The load to be supplied

Now we want to use the wind power provided with a power profile as shown on the left of figure b. On the right is shown the corresponding IDC. The IDC has been split into horizontal bands of 1 MW each to match the LDC representation. It is as if the wind power had been split into multiple units of 1 MW each. The length of each bar is the intermittent power load factor LF_i of the corresponding unit.

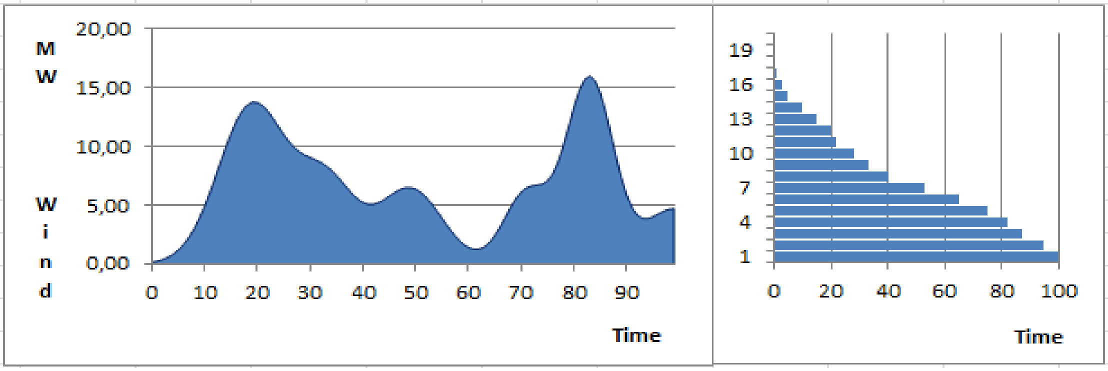


Figure b : The load wind power profile

The result of merging the two systems is shown on figure c:

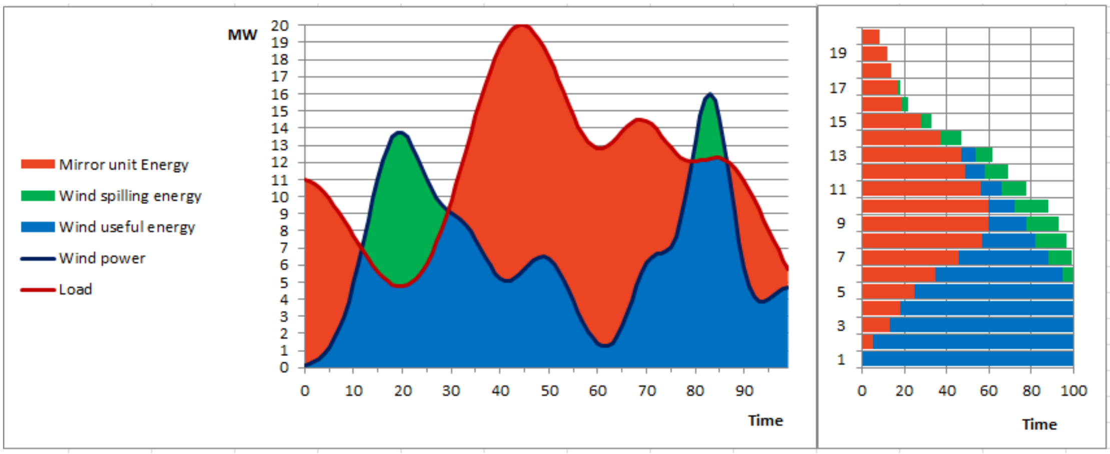


Figure c : IC model of Wind Power / controllable power merging

The blue color shows the wind energy that can be used by the system. The green color shows the wind energy that the system cannot use because the wind power exceeds the load. The red color shows the energy produced by the mirror controllable unit.

The right part of figure c can be computed from the chronological data working segment by segment. For each segment, the total length of each color is measured on the left figure, and reported on the right figure in the corresponding segment. If we paint the blue into red, we will get the original LDC, with some additional green area representing the spilling (wind energy that cannot be used to supply the load).

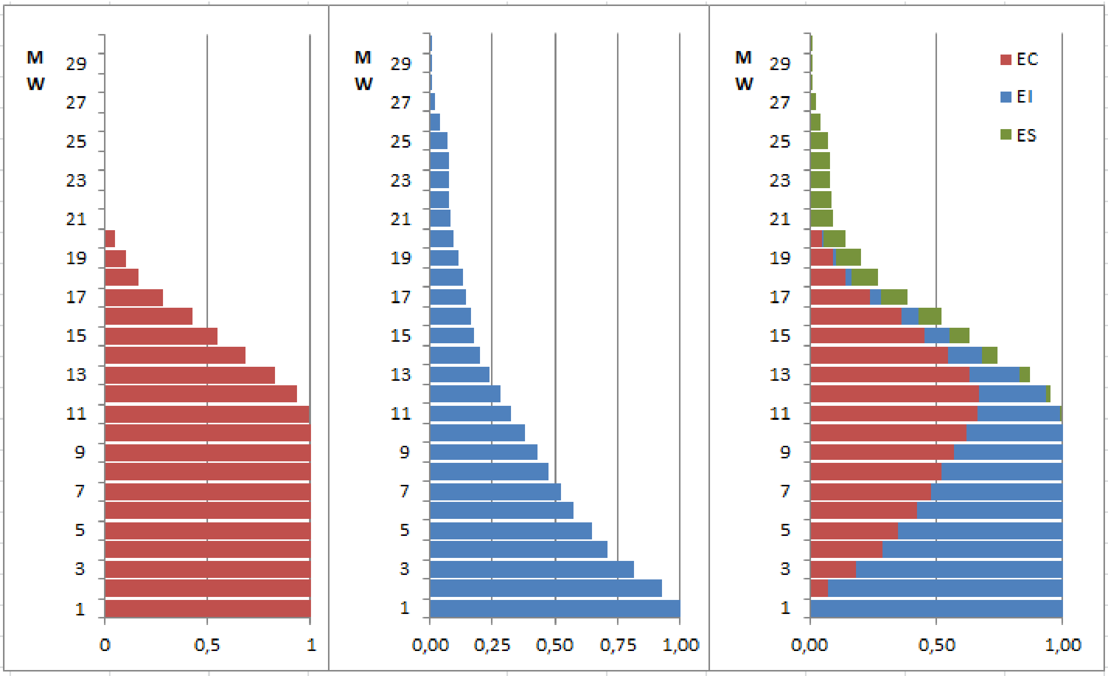
Can the right part of figure c also be calculated directly from the LDC and the IDC? Well, yes and no. The way to do it is to take each segment of the wind power (with a load factor LF_i) and to link it to the corresponding segment of the LDC (with a load factor LF). Together they constitute an Intermittent-Controllable Dual IC unit, and its production can be calculated as described in the section "The dual IC unit under partial load". However we would not get exactly the same values, but rather the "most expected" value, because the IDC and LDC does not contain any time related information.

In other words, to simulate the effects of wind power integration into the controllable power system, we don't need to make complicated hypothesis on the chronological values of the wind power. By providing only the average values contained in the wind power profile (the IDC), we can directly get the most expected values of the various results. This is the methodology we are going to use in the remaining part of this document.

Simulation of a power system with the IC model

We will use for our simulation a simple 20 MW load supplied by 20 identical controllable units, merge it with different IDC (intermittent power duration curve), and see how the power system is modified.

So the values that you will read are for this very specific little system. Some of them may be extrapolated to any system, others not. But the goal here is to understand how things are working.



LOAD				***WIND profile:***	Gjan17			***IC MODEL***	(MWh)	
Peak:	20	MW		Installed power:	43	MW		*Ec:*	*7,33*	*49%*
Knee:	10	MW		Peak:	30	MW		*Ei:*	*7,67*	*51%*
Energy:	15	MWh		Energy:	8,83	MWh		Useful energy:	15,00	93%
LF:	75%			Load factor:	21%			Spilling MWh:	1,17	7%
Kc:	500	Kg CO2/MWh						Total energy:	16,17	
Qc:	7500	Kg CO2						Spilling MW:	20	
SMPF:	1,40								(kg CO2)	
								Qc:	5133	**dK**
								dQc:	-2367	**-32%**

➢ Load Duration Curve LDC

The figure on the left shows the load duration curve LDC.

The LDC has been split into horizontal bands corresponding each to a controllable unit U_c with a 1 MW output power.

The peak load is 20 MW, the global load factor 75%, and the energy to be provided is equal to 15 MWh.

All units use the same technology and have the same CO_2 rate K_c = 500 kg CO_2/MWh. Total CO2 emissions amount to 7500 Kg CO2. The spinning mode penalty factor is equal to 1.4 (40% more CO2 while spinning).

➢ Wind Power Duration Curve IDC

The figure in the center shows the intermittent power duration curve IDC.

The IDC has been split into horizontal bands of 1 MW each to match the LDC representation. The installed wind power is 43 MW. The peak power is 30 MW (70% of the installed power). The load factor is 21%, and the energy available is 8.83 MWh.

➢ Running the simulation

The results of the simulation are shown on the figure on the right.

The production of each unit is calculated as described in section “Merging Wind Power with controllable power”, and the figure shows what the various IC units are producing:

- The blue area represents E_i, the wind energy that can be used to supply the load. There is more wind energy at low power level
- The red area represents E_c, the energy produced by the U_c controllable units. Their production increases as the wind load factor decreases up to the knee of the LDC, and then decreases according to the load factor reduction of each unit and the wind power profile.
- The green area represents E_S, the wind energy that cannot be used to supply the load. It is called “spilling”. Spilling appears as soon as the wind power exceeds the knee of the LDC. Once the peak load has been reached, all the available wind power is spilling.

  As we can see, it is not true to pretend that wind power is only reducing the load to be supplied by controllable units

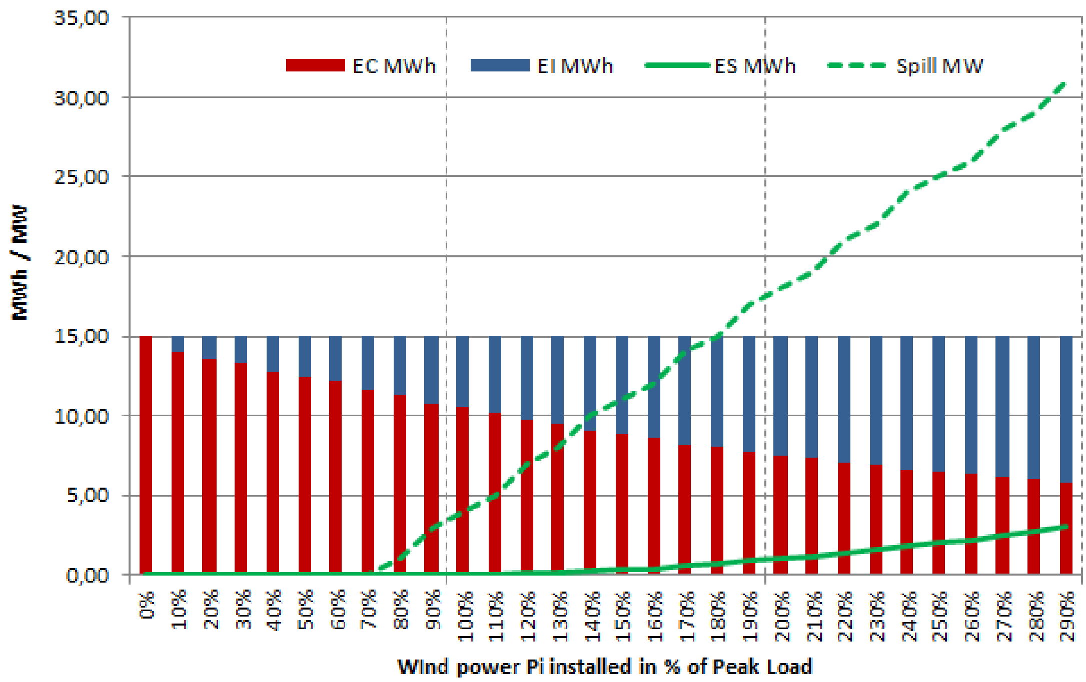
➢ Results of the simulation

If this was a real study, we could say that the main result would be that the emissions of CO2 have been reduced by 32%.

But look again: for this configuration to work there should be some exportation or storage capacities able to take 1.17 MWh (7% of the load) with a capacity of 20 MW, or 100% of the peak load. And the installed wind capacity is supposed to be 43 MW, or 215% of the peak load…

Before looking at the values obtained with a more realistic system, let’s see some other things we can learn from the model.

➢ Energy balance versus total wind power installed



This figure shows the evolution of the energy and spilling values when the installed wind power increase from 0% to 300% of the peak load P_L. We use % P_L values because our demo system is composed of 20 identical units, so the results can be extrapolated to any similar system, whatever its peak load is. All values are expressed in MWh, except for the spilling power (MW).

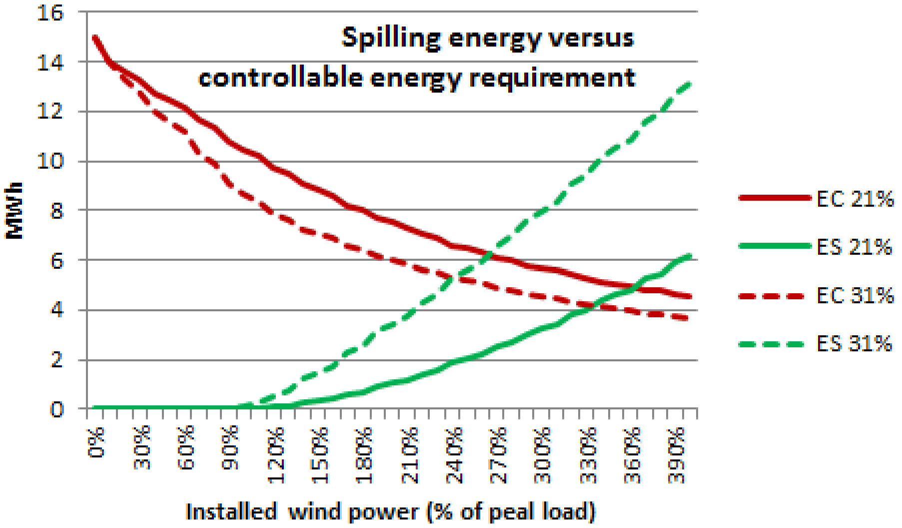
- The red bars represent E_C, the energy produced by the controllable unit. It starts at 15 MWh when there is no wind power and then decreases. It takes an installed wind power of 100% of the peak load to reduce E_C by a third of its value, but about two times more installed wind power to further reduce it by another third.

- The blue bars represent Ei, the wind energy that can be used by the load. It increases in the same way as Ec decreases.
- The full green line represents the spilled energy: the wind energy that cannot be used by the load. It begins slowly as soon as the wind power exceeds the knee of the LDC, and become significant when the installed wind power reaches 150% of the peak load.
- The dotted green line is the spilling power (MW). It also begins when the wind power exceeds the knee of the LDC, and when the installed wind power equals 110% of the peak load, it is already equal to 30% of the same peak load.

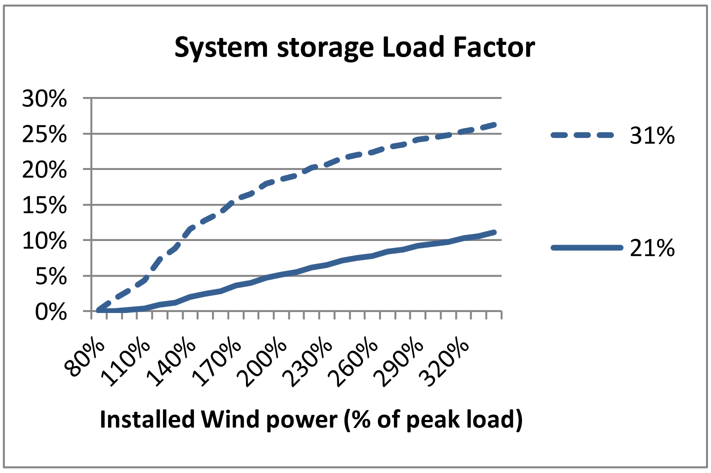
What about living of wind and storage?

The minimum condition to be able to live during a given period on wind and storage is that the spilled energy is at least equal to the energy that has to be produced by the controllable units.

The following figure shows the spilled energy E_S and the energy produced by the controllable units E_C as a function of the installed wind power, for two IDC with same peak power but different load factors of respectively 21% and 31%.



If the wind power overall load factor is equal to 21%, the spilling energy will be equal to the energy produced by the controllable units when the total wind power installed will reach 360% of the peak load. This value decreases to 240% if the wind load factor increases up to 31%



Look now at the figure on the left that shows the ratio spilling energy / spilling power for the two IDC (21% and 31% wind power load factor).

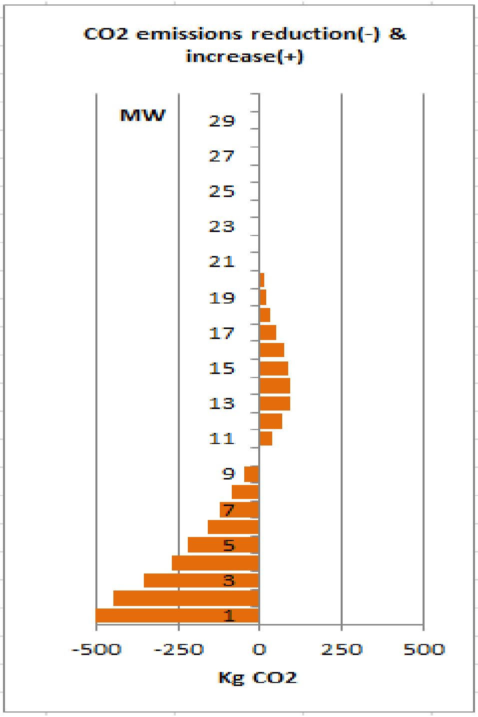
This value is the Load Factor of a system wide storage unit that could store all the spilled wind energy.

To store all the required energy the load factor of the storage engine should be between 12% and 22% (wind LF=21% and 31%).

Even if there is twice as much wind power than peak load value, the load factor of the storage engine reaches only 6% to 20% depending on the load factor of the wind.

To live from wind and storage, the installed wind power should be two to three times the load peak power, and the storage engine should store the spilling energy with a power of about twice the load peak power and a load factor well under 20%. And the 10% to 30% losses in the storage process have not been taken into consideration…. Let's say it will be difficult…

➢ CO_2 emissions



The figure on the left shows the decrease / increase of CO_2 emissions of each IC unit in our little system.

At the bottom of the figure the first units do save CO_2 emissions, because in our case the IDC has a big Load Factor at low load levels.

Then the gains will decrease up to higher load levels where there would actually be an increase of CO_2 emissions, because the IDC load factor becomes too small.

A somewhat useful way of using the wind energy would be to sell the bottom of the IDC to the electrical utilities that could use it with some benefits, and get rid of the remaining wind power using some storage capacity, or heating, or anything else but injecting it into power systems that cannot use it efficiently.

➢ How much « backup » does wind power require?

Wind power does not require « backup » but mirror controllable power.

The maximum required mirror power is equal to the peak load, but the actual value of the required mirror power varies with the actual wind power output, and is composed of both backup and backdown power.

The backdown power must cover the possible wind power increase. It is composed of controllable units that are producing power but could be switched off or put in spinning mode. To ensure sufficient backdown power, enough controllable units must be online when the wind power increases.

The backup power must cover the possible wind power decrease. It is composed of units that are either in "spinning mode" (running but not producing power), or units that can be put on line quickly enough. The maximum backup power required is given by the IDC. In our example, the wind power profile shows that the wind will produce 13 MW about 25% of time. Therefore, 13 MW of backup power will be required 25% of the time.

Of course, at times when the network operator can be absolutely sure that the intermittent power will not exceed some values within a given amount of time, the required mirror power will actually be less than the values given by the IDC. All will depend upon the predictability of the wind in a given area and the risk the network operator is willing to take.

Note also that both backup and backdown reserves must be able to provide the required power, but also the required ramp-up / ramp-down power.

➢ How much wind is too much wind?

The answer to this question depends on whether or not you allow spilling to occur – whether or not you have sufficient exportation or storage capacity to evacuate the spilling power. Remember that spilling occurs once the wind peak power exceeds the knee of the LDC, and that by definition spilling cannot contribute to the supply the load. So:

- If you do not allow spilling, the wind peak power must be less than the total controllable power that can be loaded under the knee of the LDC (running in base).
- If you allow spilling, you can have as much wind power as you want.

Nowadays, storage is not there and it will not be there for quite a long time – if ever. But the wind peak power continues to increase in many countries, so real problems are still to come

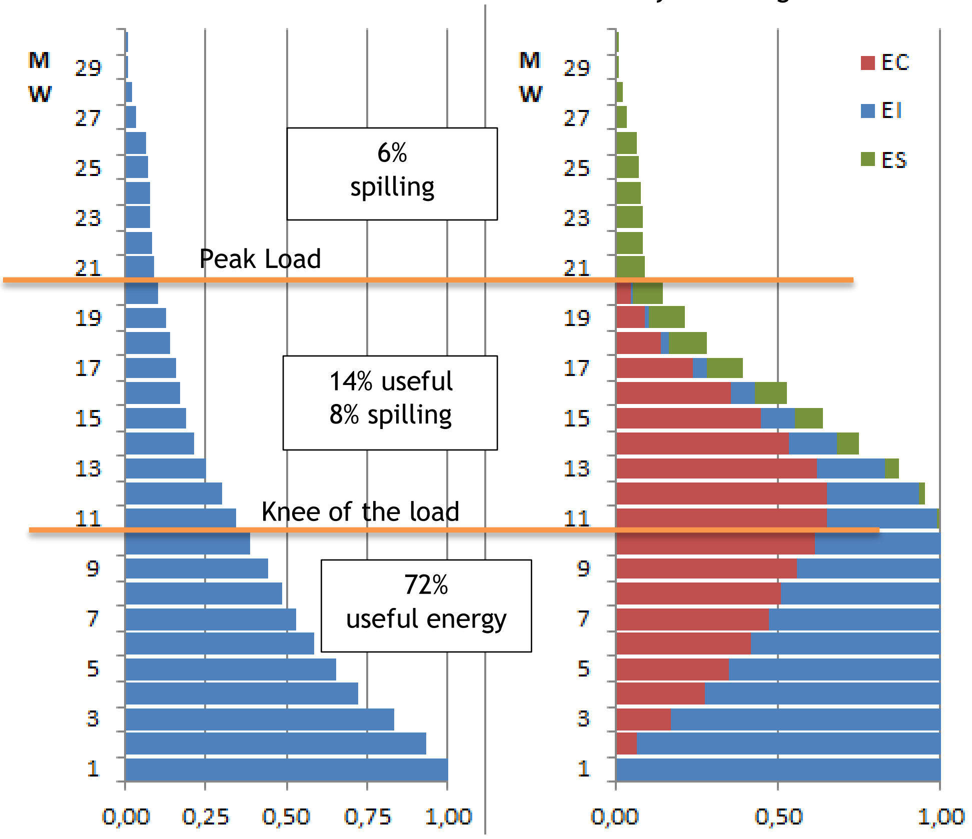
➢ What about forcing each wind producer to provide its own backup

Suppose a wind producer that operates 50x3MW wind turbines located in one area, for example along the see. If we want to oblige him to provide its own backup, he will have to install a 150 MW gas turbine to mirror its windmills. But they are two problems:

- Because the wind turbines are located in the same area, they will all run or stop at the same time, and the resulting IDC will have a very low Load Factor even at the bottom of the IDC, probably not far from the 20% LF of a single wind turbine. Therefore, according to (6), there will probably be no CO_2 savings at all – maybe even an increase of CO_2 emissions.
- If the wind goes from strong to zero in ten minutes, the gas turbines will have to provide ramping-up power of 15MW/minute. If standard gas turbines have a ramping rate of 10MW/minute, two smaller gas turbines will have to be installed, with probably further detrimental effects on the CO_2 emissions.

The wind power duration curve revisited

Let's have another look at the wind load curve and the way it is merged with the LDC.



First note that it is the resulting wind power load curve that is merged into the LDC, not the individual units. The resulting wind load factor at various load levels can therefore become much higher than the typical 20% load factor of a single wind turbine.

72% of the wind energy has been used to supply the base load, 14% to supply the variable load, and the rest is spilling.

The impact of intermittent power on a power system depends upon the intermittent power already installed. There are three different cases depending upon the relative value of the intermittent power:

- Below the knee of the LDC, intermittent power can technically be used by the system, provided some base unit's output can be reduced.
- Above the knee of the LDC, an increasing fraction of intermittent power will be spilled
- Above the peak load, all intermittent energy is spilling

"Spilling" energy is energy that cannot be used by the system, not because of some political choice, but because the laws of nature are what they are. Spilled energy must therefore be curtailed, exported or stored. To curtail intermittent power is not allowed by law. To export it is only a temporary solution (when your neighbor will have as much wind power as you, you won't be able to export your spilling). And storing such huge amounts of energy is certainly not for tomorrow – or even after-tomorrow.

So forget what you have been told: wind energy is mainly either base energy or spilling. It is certainly not peak power. If it is base power, it forces controllable units to come into the base and replace some well optimized base units. If it is spilling, it cannot be used by the system

Now look again at the way the wind power has been merged with the LDC. Each segment of the wind power has been merged with a correspondent controllable power unit. Each wind MW has replaced an equivalent power of controllable unit, and each wind MWh has replaced a corresponding energy produced by the controllable unit.

The load is provided by the controllable units as if there was no wind power. Then, a fraction of the various controllable units' output is being replaced by wind power when there is some. The total required power of controllable units is in any case not reduced by the presence of wind power.

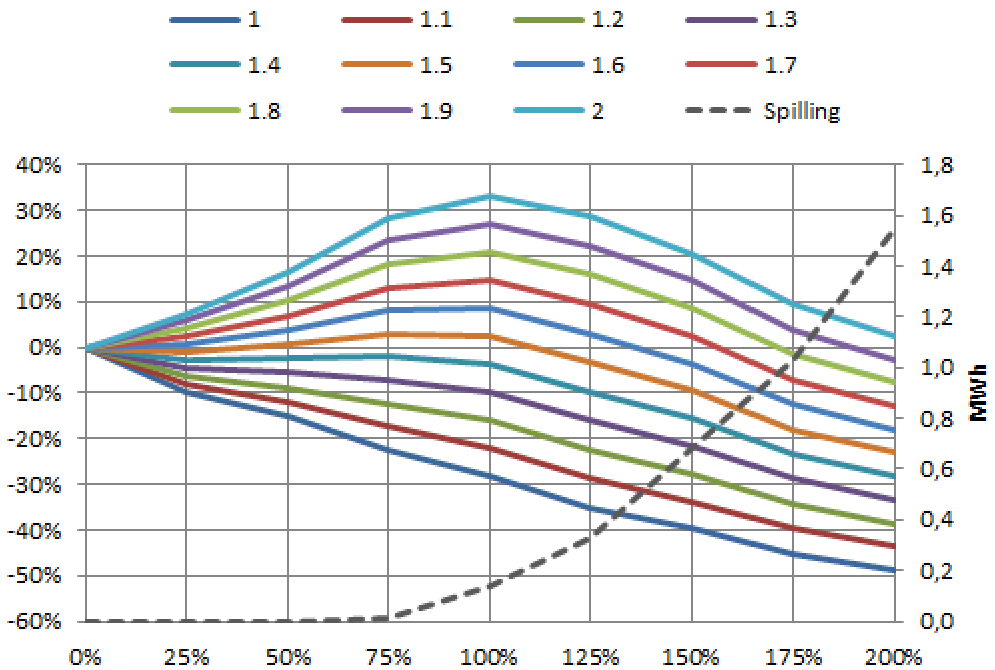
How do the CO2 emissions depend on the amount of wind power installed?

The variation of CO2 emissions can be calculated using formulas (7) (8) and (9). But these formulas use an average "spinning reserve mode penalty factor SMPF.

The value of this parameter is quiet difficult to evaluate and probably depends upon some other concepts like the "variability" of the wind. Indeed CO_2 emissions can only be well measured and optimized when a unit is running in stable conditions. When the unit is ramping up or down, the chemistry of the flame is perturbed, and nobody really knows how much more CO_2 is emitted. So spinning units probably produce a lot more CO_2 than one could believe looking only at the heat rate variations of the unit.

Although the model gives some values for the variation of CO_2 emissions, they are thus subject to a lot of uncertainties. That's why we will show the sensibility of the CO_2 emissions with respect to SMPF, rather than trying to find the exact value.

The following figure shows, for different values of the spinning reserve penalty factor SMPF, the evolution of the increase of CO_2 emissions of our system with respect to the total installed wind power. Negative value means the CO_2 emissions decrease. The figure also shows the correspondent spilled energy (on the right axis).



CO2 emissions variation with Pi (% PL) for various SMPF
Corresponding spilling (right axis)

When the installed wind power is below the load peak power, the CO2 emissions will increase or decrease depending upon the value of SMPF. If SMPF is greater than 1.5, the emissions will increase (up to 33% with SMPF=2), else they will decrease.

When the installed wind power exceeds the load peak power, the CO2 rate will decrease when wind power increases, but spilling energy will be generated.

Unless the spinning reserve mode penalty factor is very low, CO_2 emission will only begin to decrease when spilling do occur, that is when the wind power exceeds the peak of the load duration curve. But if there are no exportation or storage capacities, spilling is not possible…

Here are some key breakpoints:

- If SMPF=1.5, CO_2 emissions will increase by a few percent until the wind installed power reaches the peak load. They will then decrease.
- If SMPF = 2, CO_2 emissions will increase up to 30% when Pi=PL, and a wind power of more than 200% of the peak load needs to be installed before actually reducing CO2 emissions.
- If SMPF = 1.2, with a wind installed power of 100% of the peak load, there is a 16% saving of CO2 emissions.

To evaluate the increase of C02 emissions due to the injection of intermittent power into the power system, the spinning mode penalty factor is the key parameter. It's value is also one of the most difficult to find …

One should also never forget to take into consideration the change of technology that was required to integrate the wind power into the system. For example in Belgium, the wind power is mirrored by gas turbines that have been built on purpose. Before having the wind-gas IC units, we had nuclear power. So even if the use of wind energy would save some CO_2 inside the IC machine, there is an additional cost of about 500 kg CO_2/MWh due to the change of technology from nuclear to gas.

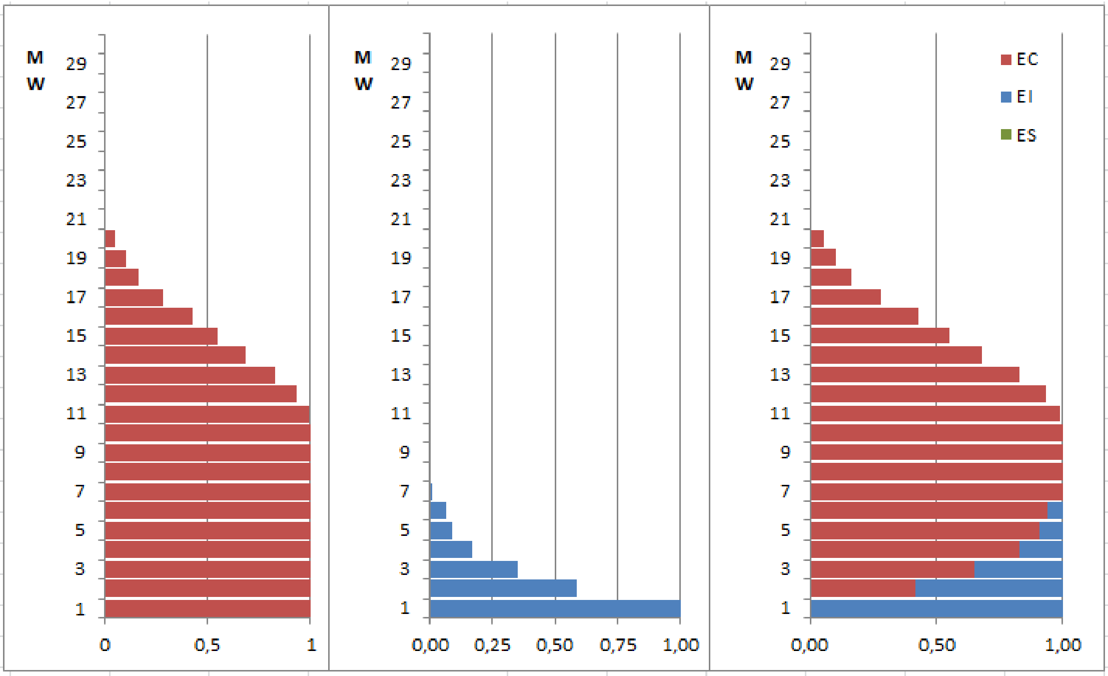
When the system evolves from nuclear power to wind-gas IC units, wind power never save any CO_2 and the people recommending wind power certainly have another agenda in mind than saving the planet.

A more realistic case

If you have read this article up to this point, you have understood that the interaction of wind and controllable units is a complex problem with many variables, and the calculations must be done on a case by case basis, taking into account the structure of the power system and the characteristics of the wind. The evaluation will even provide different results as the structure of the power system evolves with time, for example due to previously installed wind power.

To evaluate the impact of wind energy on a power system, they are no general rules. Each situation is different and evolves with time

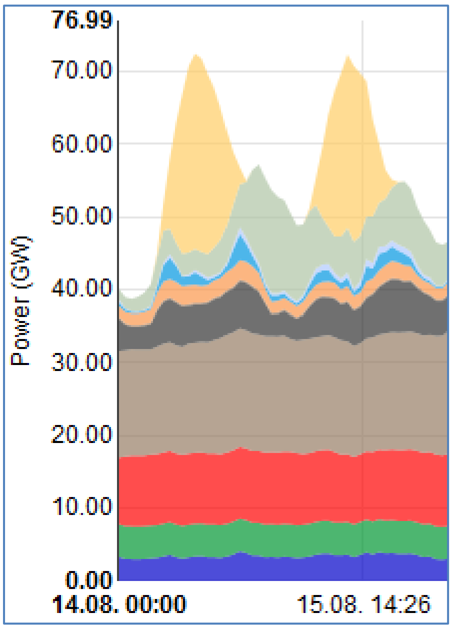
Although the results are subject to uncertainties, here is a simulation using the same LDC and IDC as in our demo example, but with only 10 MW of wind turbines, or 50% of the peak load, and SMPF = 1.6:



LOAD				***WIND profile:***	Gjan17			***IC MODEL***	(MWh)	
Peak:	20	MW		Installed power:	10	MW		*Ec:*	*12,74*	*85%*
Knee:	10	MW		Peak:	7	MW		*Ei:*	*2,26*	*15%*
Energy:	15	MWh		Energy:	2,26	MWh		Useful energy:	15,00	100%
LF:	75%			Load factor:	23%			Spilling MWh:	0,00	0%
Kc:	500	Kg CO2/MWh						Total energy:	15,00	
Qc:	7500	Kg CO2						Spilling MW:	0	
SMPF:	1,60								(kg CO2)	
								Qc:	7792	**dK**
								dQc:	292	**4%**

The wind peak power is now 7 MW. There is no spilling, and 15% of the load is supplied with wind power. There is a 4% increase of CO_2 emissions.

For a better representation of wind power interaction with controllable power



source: www.energy-charts.de

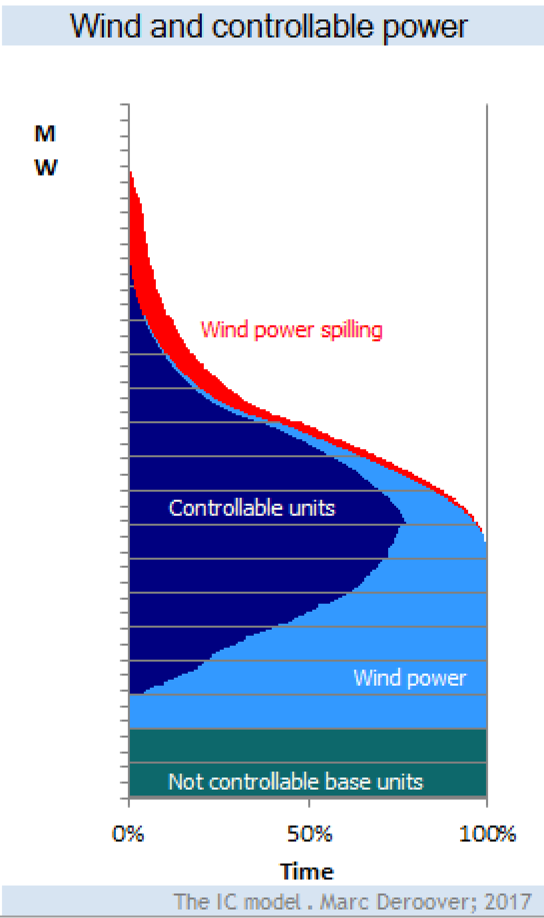
Electrical utilities like to present their load in the classical chronological manner shown here on the left. Each color represents a given type of power unit (light green for wind and yellow for solar).

This representation shows the wind and solar energy working in a "peak shaving mode", which really is not the case.

It somewhat hides the effects of wind power on the different units; for example, the spinning units are not shown.

It could also let people think that if there was more wind power available, controllable units would no longer be required.

The load could usefully be presented differently, as shown here below, using the LDC representation together with the IC modelling of each unit. The advantages of such a representation would be to clearly show:



- the base load units that cannot work as mirror for the wind turbines
- the units that are mirroring the wind turbines
- the percentage of load supplied by wind power at each level of the load and for each type of unit
- the spilling energy, which is the main limitation of wind power when there is no storage capacity

This representation of the load also helps to understand that all controllable units are used, even if they do not always produce power, and that wind power cannot "replace" the controllable units.

In other words, a wind turbine does not exist for the network operator as long as it is not coupled with some controllable mirror unit.