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Design of wind and solar energy supply, to match energy demand

S. Mertens

Faculty of Technology, Innovation & Society, The Hague University of Applied Sciences, The Hague, the Netherlands

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ABSTRACT

Renewable energy sources have an intermittent character that does not necessarily match energy demand. Such imbalances tend to increase system cost as they require mitigation measures and this is undesirable when available resources should be focused on increasing renewable energy supply. Matching supply and demand should therefore be inherent to early stages of system design, to avoid mismatch costs to the greatest extent possible and we need guidelines for that. This paper delivers such guidelines by exploring design of hybrid wind and solar energy and unusual large solar installation angles.

The hybrid wind and solar energy supply and energy demand is studied with an analytical analysis of average monthly energy yields in The Netherlands, Spain and Britain, capacity factor statistics and a dynamic energy supply simulation. The analytical focus in this paper differs from that found in literature, where analyses entirely rely on simulations. Additionally, the seasonal energy yield profile of solar energy at large installation angles is studied with the web application PVGIS and an hourly simulation of the energy yield, based on the Perez model.

In Europe, the energy yield of solar PV peaks during the summer months and the energy yield of wind turbines is highest during the winter months. As a consequence, three basic hybrid supply profiles, based on three different mix ratios of wind to solar PV, can be differentiated: a heating profile with high monthly energy yield during the winter months, a flat or baseload profile and a cooling profile with high monthly energy yield during the summer months. It is shown that the baseload profile in The Netherlands is achieved at a ratio of wind to solar energy yield and power of respectively $E_w/E_s = 1.7$ and $P_w/P_s = 0.6$. The baseload ratio for Spain and Britain is comparable because of similar seasonal weather patterns, so that this baseload ratio is likely comparable for other European countries too.

In addition to the seasonal benefits, the hybrid mix is also ideal for the short-term as wind and solar PV adds up to a total that has fewer energy supply flaws and peaks than with each energy source individually and it is shown that they are seldom (3%) both at rated power. This allows them to share one cable, allowing “cable pooling”, with curtailment to -for example-manage cable capacity. A dynamic simulation with the baseload mix supply and a flat demand reveals that a 100% and 75% yearly energy match cause a curtailment loss of respectively 6% and 1%. Curtailment losses of the baseload mix are thereby shown to be small.

Tuning of the energy supply of solar panels separately is also possible. Compared to standard 40° slope in The Netherlands, facade panels have smaller yield during the summer months, but almost equal yield during the rest of the year, so that the total yield adds up to 72% of standard 40° slope panels. Additionally, an hourly energy yield simulation reveals that: façade (90°) and 60° slope panels with an inverter rated at respectively 50% and 65% Wp, produce 95% of the maximum energy yield at that slope. The flatter seasonal yield profile of “large slope panels” together with decreased peak power fits Dutch demand and grid capacity more effectively.

1. Introduction

At the moment, The Netherlands is almost locked for new grid connected renewable energy projects the coming years. The electricity grid is overwhelmed by the large feed in of energy by solar and wind parks and grid operators locked large parts of the grid for new projects. These locations are provided by (Netbeheer-Nederland, 2021) in a map of the Netherlands and they are indicated with a red, orange and yellow colour according to the severity of the situation (see Fig. 1).

According to the obvious red coloured map of the Netherlands, the situation is severe and this is the start of investments in energy storage and transport capacity. But energy storage and transport capacity are expensive and they are linked to losses. A direct move to storage and transport capacity, without an analysis of alternatives, is premature.

E-mail address: s.mertens@hhs.nl.

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The costs for the infrastructure, including storage and transport, are a result of two mismatches between supply and demand of energy. Firstly, a mismatch in location. An example of this mismatch is that big solar parks are mostly located in the east of the Netherlands where there is enough affordable space at scarcely populated areas. On these scarcely populated areas however, the grid is too weak to accommodate large solar parks as there was no need for a strong grid at scarcely populated areas (red areas in Fig. 1). Secondly, a mismatch in time. An example of this is that solar energy is delivered at day-time, but it is predominantly needed in the evening. The mismatch in time is reflected in the extreme (negative or positive) wholesale market electricity prices (Entsoe, 2021) (see Fig. 2).

It is interesting to bin the number of occurrences of lowest and highest wholesale market prices in The Netherlands found at (Entsoe, 2021) to the hour of the day (see Fig. 3).

This reveals that lowest wholesale market prices in The Netherlands in 2020 mostly occur around 4:00 and 15:00 h, while the highest prices occur around 8:00 in the morning and 19:00 in the evening. This is the result of the mismatch in time of supply and demand of energy.

Furthermore, the costs for the infrastructure (including storage and transport) are linked to the peakiness of the energy supply. Peakiness of our energy supply results in an inefficient and expensive use of our infrastructure because of high loads during peak "production" of renewable energy in windy and sunny days and underloads during

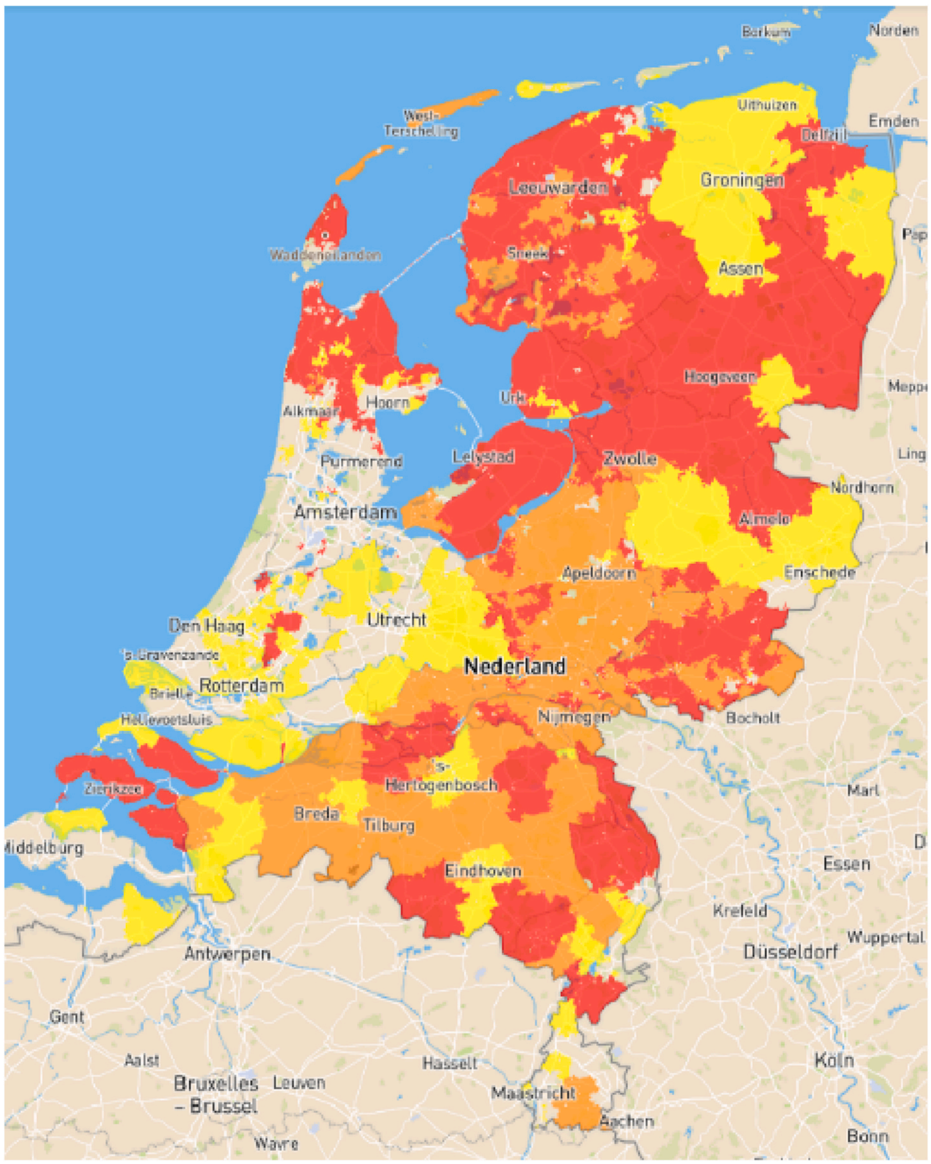

Fig. 1. Locations with a too weak grid provided by (Netbeheer-Nederland, 2021). With: a grid that does not allow the feed-in of solar and wind parks (Red), a weak grid with a preliminary notice on structural grid capacity problems (Orange), a grid with upcoming grid capacity problems (Yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

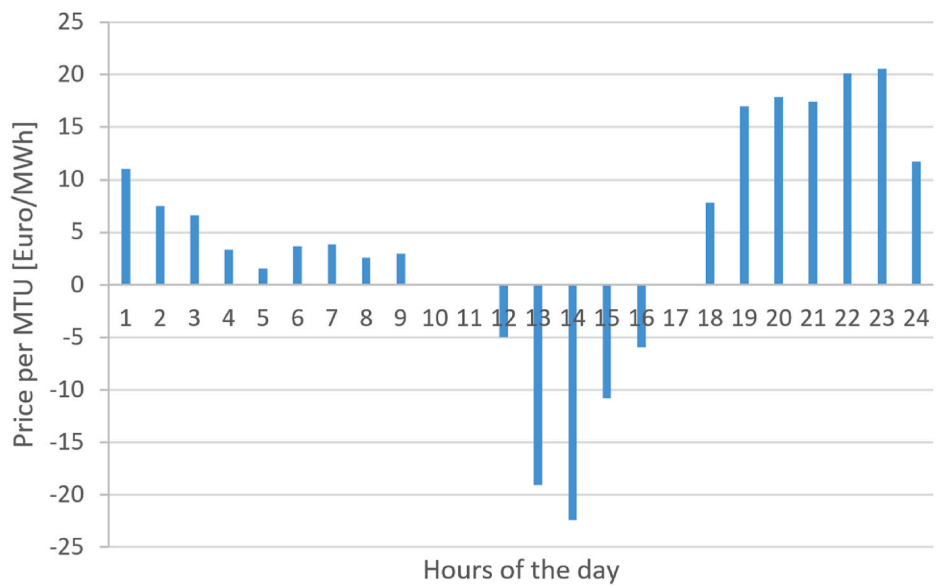

Fig. 2. Wholesale market day-ahead prices of electricity at 29-03-2020 are negative because of too much supply compared to the demand for energy.

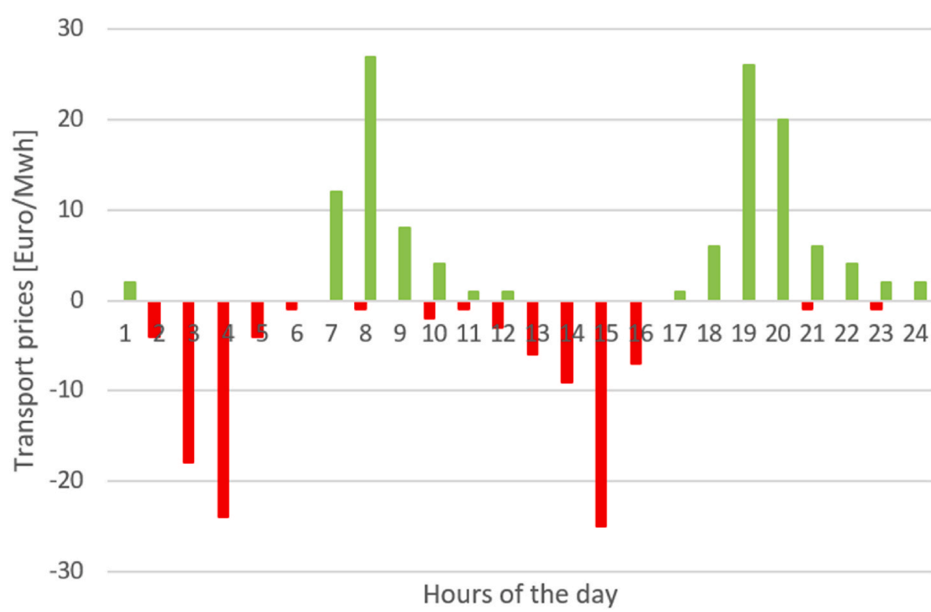

Fig. 3. Negative (red bars) and positive (green bars) wholesale market prices in The Netherlands found at (Entsoe, 2021) and binned to the hour of the day for February 2020 to July 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

"Dunkelflautes" or hours in absence of sun and wind. So prevention of peakiness of our energy supply is also important.

One should opt for a balance between the three main thoroughly related areas: transport capacity, storage capacity and time management between supply and demand of energy (see Fig. 4).

The process of striving to the final "right balance" is very complex. It requires so called action research (Kemmis and McTaggart, 2000) with the various stakeholders in these analyses, or: a striving towards a final ultimate goal -satisfaction for all stakeholders-with an iterative approach.

This paper deals with the time management of the supply side of energy, or Supply Side Management (SSM) related to time management. Firstly, this paper provides analyses and methods to prevent long term or seasonal unbalance between supply and demand of energy. These analyses are based on seasonal sun, wind and demand profiles. The seasonal profiles are translated into gonio formulas with curve fitting of the seasonal data. The resulting gonio formulas form the tools to prevent seasonal unbalance. These analyses and methods, that could be qualified as "analytical", differ from those found in literature that rely on "simulations".

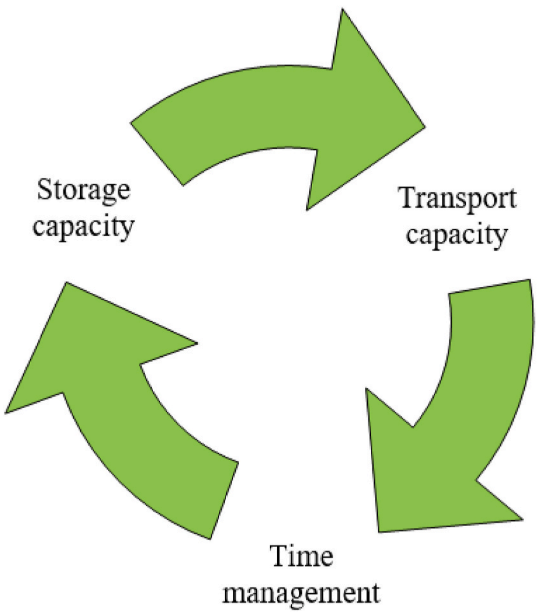

Fig. 4. The balance between three main thoroughly related areas: transport capacity, storage capacity and time management between supply and demand of energy.

Secondly, simulations are used to quantify the seasonal energy supply of solar panels on unusual angles such as facade PV and on the power output of the inverter needed to harvest the provided energy.

Thirdly, the analyses and methods presented in this paper do also provide solutions for the short term unbalance. This third part of the analyses is focused on statistics of the sun and wind profiles.

In the past, the research on matching the supply and demand of wind and solar energy was concentrated around stand-alone applications. At that time, distribution of energy via the grid was a no-brainer. Nowadays, it is recognized that this is not true for our future predominantly solar and wind based energy supply. Various references show that a good and cost efficient match between supply and demand of energy could be achieved with a mix of solar and wind energy. This hybrid mix allows a more efficient use of the local infrastructure (Liander, 2016) as it mitigates "the effects of wind variability on power output" (López et al., 2020) and provides a better chance of integrating it into the electricity supply and avoid excess electricity production (Lund, 2006). On the other hand, an optimal hybrid mix is also important for a European power supply system as "it leads to a pronounced minimum in required stored energy" (Heide et al., 2010). Such minimum in stored energy is related to the seasonal variations in supply and demand, but a well-designed hybrid mix is also able to better match the hourly variation of supply and demand (Geem, 2012).

The provided references make clear that a well-designed hybrid mix could prevent issues linked to: storage, peak loads, energy transport capacity, etc.. The best keywords for an additional literature search on the focus area of this paper are: Hybrid Renewable Energy Systems (HRES), Off-Grid or Stand-Alone Renewable Energy Systems (OGRES or SARES). See for instance (Zohuri, 2018) for an introduction to both.

2. Sun and wind mix

In the Netherlands wind energy has highest monthly energy yields during the winter and solar PV has highest monthly energy yields during the summer. With the right mix of both, the total supply profile can be adjusted to a specific demand profile. This could be applied:

- locally; for villages/cities or industries, or
- nationally; for a small country, linked to the size of "typical weather" in the sense of solar and wind energy properties.

A bigger control area than a small country is not feasible as wind and solar supply profiles change as a function location. Benefits from the international transport of sun- and wind energy in order to mitigate the influences of weather systems are not part of this analysis.

2.1. *Matching energy supply and demand with solar and wind energy*

Today, it is often proudly mentioned that buildings achieve "Zero at the meter". This means that our energy metering shows net zero energy consumption on a yearly basis and this totally skips the issues with matching on a shorter time frame.

On a monthly basis, the energy profile of solar and wind energy varies. In The Netherlands, solar energy yield peaks in the summer months and wind energy yield peaks in the winter months. The demand for heating, that peaks during the winter months, opts for a supply that also peaks during the winter months: wind energy. Solar energy is more suitable to match the demand for cooling in the summer months.

On an hourly basis, the supply of solar and wind energy should also match our demand profile during the day (Geem, 2012). Moreover, on an even shorter time frame, the supplied power of solar and wind energy should preferably also match our power demand. The supply of energy should match our demand at all time scales. We will provide some insights in the following chapters.

2.2. *Monthly supply profiles of solar and wind energy*

The following paragraphs provide the average monthly supply profiles of solar and wind energy in the Netherlands.

2.2.1. *Monthly solar profile for PV at maximum energy output*

The monthly solar profile in The Netherlands, for PV directed to the South and mounted at an approximately 40° slope, can be found from available data. The average monthly energy yields for the years 2002–2015, available at (Segaar, 2019), are normalised to a sum of 1 for the total yearly energy supply. The result is shown in Fig. 5 below with yellow markers.

The monthly energy yield of solar PV is based on the angle of the sun. A fit of the monthly energy yield E_S of solar PV could thus be based on the following gonio formula

$$E_S = C_1 + C_2 \times \cos\left(\frac{m \times \pi}{6}\right) \tag{1}$$

where C_1 and C_2 are constants and m is the number of the month (1 … 12). The best fit, given in Table 1, is calculated with a least square criterium applied to the total error between fit and datapoints (see Fig. 5).

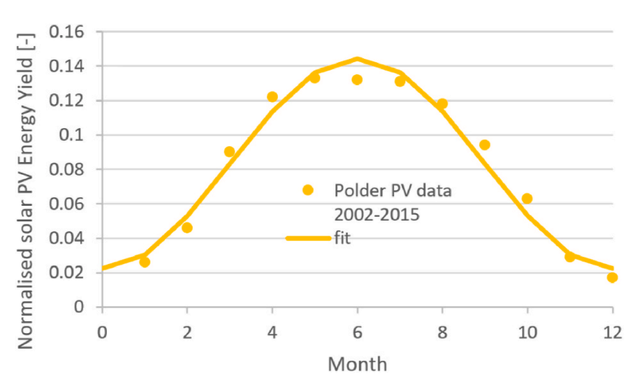

Fig. 5. Normalised monthly energy yield of solar PV for 2002–2015 from data available at (Segaar, 2019).

Table 1
Fit constants for a monthly Solar PV energy yield, based on data for the years 2002–2015 found at (Segaar, 2019).

C_1	C_2
0.083	−0.061

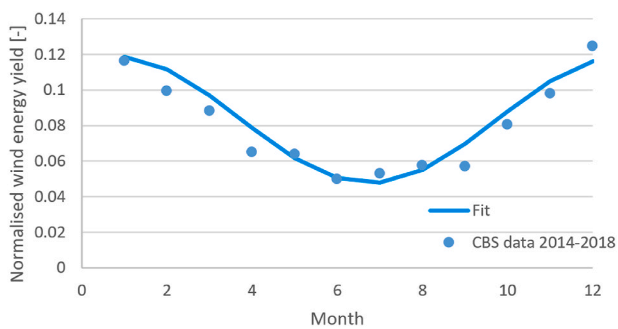

Fig. 6. Normalised monthly energy yield of wind energy, based on data for the years 2002–2015 found at CBS (2019a, 2019b).

Table 2
Fit constants monthly wind energy yield.

C_3	C_4	C_5
0.083	0.036	−0.75

2.2.2. *Monthly wind profile*

The monthly yield profile of wind energy can be found by curve fitting of data available at for instance (CBS, Windenergie; elektriciteitsproductie, capaciteit en windaanbod, 2002–2019, 2019). The average monthly energy yield in kWh's for the years 2002–2015 available at (CBS, Windenergie; elektriciteitsproductie, capaciteit en windaanbod, 2002–2019, 2019), normalised to a sum of 1 for the total yearly energy supply, is shown in Fig. 6 below with blue markers.

The wind speeds are a result of the solar irradiation but likely with a phase shift because of the heating of the earth by the sun. Thus we try the same gonio fit as wit solar PV but with a phase shift.

$$E_w = C_3 + C_4 \times \cos\left(\frac{(m + C_5) \times \pi}{6}\right) \tag{2}$$

where C_3 and C_4 are constants, m is the number of the month (1 … 12) and C_5 is the phase shift. The best fit, given in Table 2, is calculated with a least square criterium applied to the total error between fit and datapoints (see Fig. 6).

Apparently there is a delay of wind energy compared to solar energy of 3/4 of a month (i.e. $C_5 = -0.75$).

3. Monthly demand profiles

The following paragraphs provide information on the demand profiles of: heating, electricity and cooling in the Netherlands.

3.1. *Monthly demand profile heating, electricity and cooling*

The monthly demand for gas and electricity in the Netherlands can for instance be found at (EBN, 2020). The data show that the monthly electricity demand is flat. For the energy use for heating, we have to look at the use of fossil gas in The Netherlands. According to (Segers, Van den Oever, Niessink and Menkveld, 2019), approximately 76% of the energy use for heating originates from fossil gas. The fossil gas use in the Netherlands is thus strongly linked to heating and the graph thus provides that the monthly energy demand for heating peaks during the winter months.

In the Netherlands we will abandon the use of fossil gas in the near future. So, we have to heat our buildings with for instance heat pumps in the future and consequently change our fossil gas demand into an electricity demand.

De cooling demand is strongly linked to the solar energy profile as solar energy is responsible for the temperature rice, especially in well isolated buildings with little effort to block the solar energy from entering the building. It is interesting to note in this context that, according to (WE-adviseurs, 2018), the cooling demand will rise in the coming years. This rise is a result of more well insulated buildings with little solar blocking and the transition to heat pumps, as a heating source that is also capable to provide cooling capacity.

We distinguish three main profiles: the heating profile that peaks during the winter months, the flat electricity demand or base load profile and the cooling profile that peaks during the summer months.

We should carefully choose our energy supply profile in accordance with our energy demand profile. A large portion of wind energy is required for matching of the heating profile, while a large portion of solar energy is required to fit the cooling profile.

According to the discussion above, the countries of the European Union (EU) that are located in the south of the EU do best with more solar energy than wind energy, while the countries in the North of the EU are best fitted with a mix with more wind energy than solar energy. The flat electricity demand or baseload profile deserves some special attention.

4. Matching the monthly profiles of supply and demand

The matching of supply of solar and wind energy with the demand of energy will be analysed in the following paragraphs.

4.1. *Matching a flat monthly electricity demand with a solar wind energy mix*

The total monthly energy supply from a combination of solar E_s and wind energy E_w is found by

$$E_{tot} = E_s + C \times E_w \tag{3}$$

where the multiplication with C denotes that C times more wind energy is used than solar energy. A flat monthly supply profile E_{tot} will be

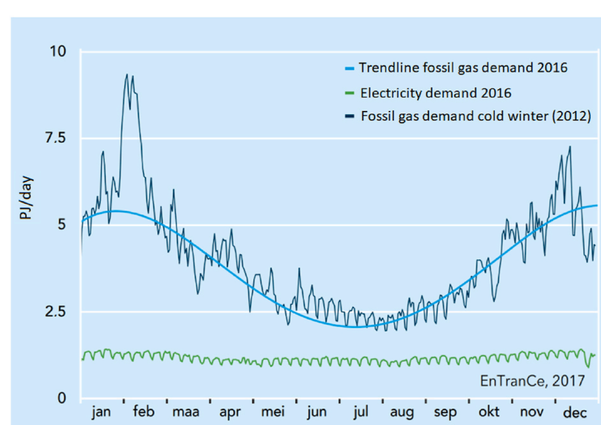

Fig. 7. Daily energy demand of fossil gas (according to (KNMI, February 2012, 2012), the large peak demand of gas in February is caused by one of the coldest first 10 days in February ever) and electricity found at (EBN, 2020). In green the electricity demand and in blue the fossil gas demand with the trend line in light blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

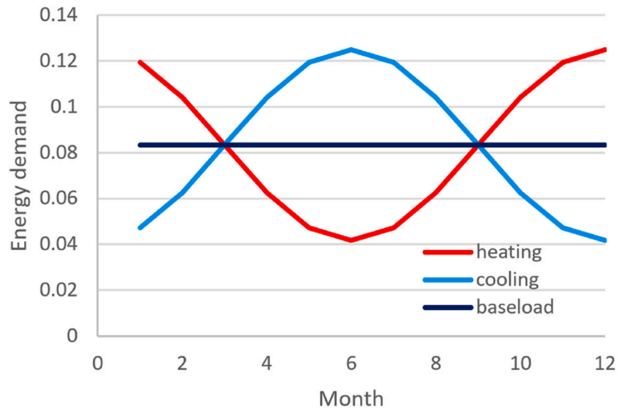

Fig. 8. Illustration of the three normalised main energy demand profiles: the heating profile, the cooling profile and the baseload profile.

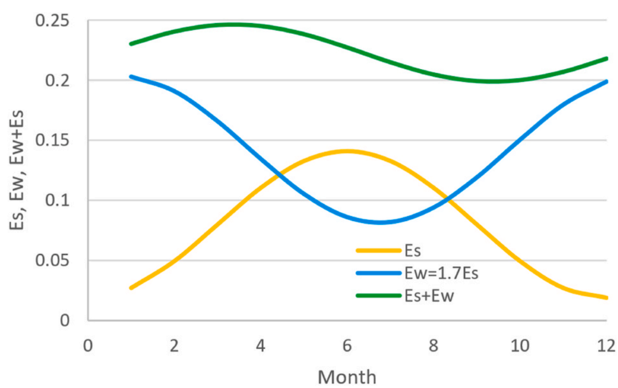

Fig. 9. Illustration of the resulting Dutch profiles for solar PV: E_s , wind: $E_w = 1.7E_s$ and the total energy $E_w + E_s$.

supplied by combining solar and wind energy with equal amplitudes of solar C_2 and wind energy $C \times |C_4|$. Thus if

$$C_2 + C \times C_4 = 0 \tag{4}$$

Based on the results in Tables 1 and 2 and formula (4), we find

$$C = \frac{-C_2}{C_4} = 1.7 \tag{5}$$

We thus found that this particular ratio, with according to formula (3) and (5) 1.7 times more wind energy than solar PV energy, provides the "most constant" average monthly energy supply. Most constant refers to the fact that the baseload profile is as flat as possible but only exactly flat in absence of the phase shift of wind, i.e. $C_5 = 0$. For the Dutch phase shift $C_5 = -0.75$ the situation is as showed in Fig. 9 below.

4.2. *Matching shorter time-scales*

Until now, our investigation was focused on matching the monthly supply and demand of energy, but the supply and demand of energy should of course also match at shorter times scales. Moreover, the supply and demand of power should match. This section focusses on matching supply and demand of energy on time scales shorter than a month.

4.2.1. *Solar and wind correlation*

The correlation of solar energy (Q [J/cm^2]) and wind energy [m/s], on an 24-h basis, that we found from the Dutch met-office data provided by (KNMI, Uurgegevens van het weer in Nederland, 2019), helps to gain insight on the supply of energy by solar and wind energy. We find a very weak negative correlation ($R^2 = 0.077$) on a 24-h basis and with a bit more frequent windy if it is not sunny and the other way around. So, solar and wind energy are slightly able to complement each other on a 24-h basis.

The small correlation factor however indicates a very weak correlation. On an even shorter time frame, like for instance on an hourly basis, our analysis of the Dutch met-office data from KNMI shows that the correlation between solar and wind energy is absent. This matches with findings from others (Solbakken et al., 2016) (Widen, J., 2011).

The very weak or almost absent correlation of the 24-h and hourly data of solar and wind energy justifies the conclusion that solar and wind energy can be treated as independent on that time frame.

Table 3
Baseload mix of solar and wind energy.

	Ratio
Energy yield	$\frac{E_w}{E_S} = \frac{-C_2}{C_4}$
Installed power	$\frac{P_w}{P_s} = \frac{-C_2}{C_4} \times \frac{c_{f,s}}{c_{f,w}}$

4.2.2. *Capacity factor solar energy*

The capacity factor $c_{f,s}$ of solar PV, or in other words the percentage of time that the power of solar PV is at rated power P_s, can be calculated from the specific energy yield E_s in the Netherlands of 875 kWh/kWp as found in (Sark, 2014). According to the definition of the capacity factor, we thus find that

$$E_s = c_{f,s} \times P_s \times 365 \times 24 \tag{6}$$

or

$$c_{f,s} = \frac{875}{365 \times 24} = 0.10 \tag{7}$$

Thus, solar PV produces peak power at about 10% of the year in The Netherlands.

4.2.3. *Capacity factor wind energy*

The capacity factor of wind energy depends on the site condition, i.e. the wind conditions such as wind speed and shape factor of the probability distribution of the wind speed. On a windy site, for instance off-shore at the Gemini wind park, according to the data of (CBS, Windturbines in Nederland, 2019), the capacity factor can be as high as 50%, while the capacity factor at moderate wind conditions will be 20%. According to the rated power and energy production of the wind turbines in The Netherlands, as given in (CBS, Windturbines in Nederland, 2019), the average on-shore capacity factor $c_{f,w}$ of wind energy in The Netherlands in 2018 is

$$c_{f,w} = 0.237 \tag{8}$$

while the average capacity factor of off-shore wind energy in 2018 reads

$$c_{f,w} = 0.434 \tag{9}$$

We will furthermore work with an average capacity factor $c_{f,w} \approx 0.3$ for average wind speeds.

4.2.4. *Installed power at baseload mix*

It is interesting to know the required amount of installed power for a baseload mix of solar and wind energy. We are able to find this with use of the relationship of the capacity factors of wind and solar. We have

$$c_{f,s} \times T \times P_s = E_s \rightarrow$$

$$P_s = \frac{E_s}{c_{f,s} \times T} \tag{10}$$

and

Table 4
Fit constants monthly Solar and wind energy yield in The Netherlands, Spain and Britain based on data of * (Segaar, 2019) and (CBS, Windenergie; elektriciteitsproductie, capaciteit en windaanbod, 2002–2019, 2019), ** (López et al., 2020), *** (Bett and Thornton, 2016).

	C_1	C_2	C_3	C_4	C_5
The Netherlands*	0.083	−0.061	0.083	0.036	−0.8
Spain**	0.083	−0.061	0.083	0.036	−1.1
Britain***	0.083	−0.090	0.083	0.040	−0.8

Table 5
Baseload constants for The Netherlands, Spain and Britain based on data of * (Segaar, 2019) and (CBS, Windenergie; elektriciteitsproductie, capaciteit en windaanbod, 2002–2019, 2019), ** (López et al., 2020), *** (Bett and Thornton, 2016).

	$\frac{E_W}{E_S}$
The Netherlands*	1.7
Spain**	1.7
Britain***	2.3

$$c_{f,w} \times T \times P_w = E_w = C \times E_s \rightarrow$$

$$P_w = \frac{C \times E_s}{c_{f,w} \times T} \quad (11)$$

So that, by combining (10) and (11), with $C = \frac{-C_2}{C_4} = 1.7$ and $c_{f,s} = 0.10$ and the assumed average wind energy capacity factor $c_{f,w} \approx 0.3$ we (see section 4.2.3) finally arrive at

$$P_w = C\frac{c_{f,s}}{c_{f,w}}P_s = 0.6P_s \quad (12)$$

For a baseload mix in The Netherlands, the installed power of wind energy for average wind speeds is 60% of the installed power of solar energy.

The formulas for the baseload solar and wind mix provided in (5) and (12) in the paragraphs before are summarised in the Table 3 below.

Basically, every (part of a) country had its own baseload mix of sun and wind that depends on the sun and wind conditions in a particular a country. However, based on data of Spain, found in (López et al., 2020) and Britain (Bett and Thornton, 2016), solar and wind profiles are comparable with those from The Netherlands (see Table 4).

The fit constants in Table 4 result in the baseload mix constants E_W/E_S in Table 5.

So, the baseload mix is comparable for these different European countries. This must be caused by similar weather patterns that are basically a result of solar irradiation, so that it is likely that the baseload mix is also similar for other European countries.

4.2.5. *Capacity factor of a combination of solar and wind energy*

It is discussed that solar and wind energy show a very weak correlation on a 24-h basis, while the correlation is absent on an hourly basis. Solar and wind energy are non-correlated on a short time frame and thus the capacity factors of both are independent and the capacity factor of a combination of solar and wind energy can be found by multiplying of the capacity factor of solar and wind energy. With an assumed capacity factor of on-shore wind energy of 30%, the capacity factor of a combination of solar and wind energy, based on the capacity factor of solar energy of 10% thus reads

$$c_{f,t} = 0.3 \times 0.1 = 0.03 \quad (13)$$

A combination of wind and solar energy produces peak or rated power at only 3% of the time.

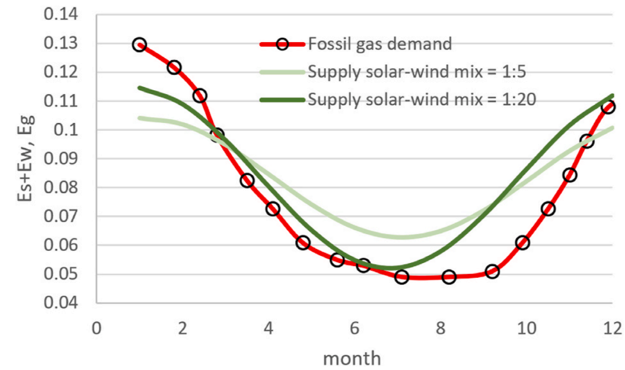

Fig. 10. Demand of fossil gas E_g based on the normalised data found in Fig. 7, mix of solar PV and wind energy supply $E_s + E_w$, with a ratio of respectively $E_s : E_w = 1:5$ and $E_s : E_w = 1:20$

This leads to the fact that solar and wind energy parks could deliver their total power on just one cable (see also (Liander, 2016)) and do cable pooling and be curtailed if both solar and wind reach their maximum power, but that is only at 3% of the time.

4.2.6. *Energy loss curtailment baseload mix*

For the baseload mix, we found with (12) that $P_w = 0.6P_s$. With this and (13), the curtailed energy loss of the baseload mix E_c can thus be found as

$$E_c = 0.03 \times (P_s + P_w) \times 365 \times 24 = 0.048 \times P_s \times 365 \times 24$$

The total energy yield without curtailment can be found from (6) and a similar formula for wind energy as

$$E_{tot} = 0.1 \times P_s \times 365 \times 24 + 0.3 \times P_w \times 365 \times 24 = 0.28 \times P_s \times 365 \times 24$$

So that the fraction curtailed energy is $E_c/E_{tot} = 0.048/0.28 = 0.17$. We lose 17% energy with curtailment of the baseload mix. Local battery storage of the peak power production is much more expensive as this approximately doubles the energy price (€ per useful kWh according to (Bluesky, 2018)) and cable pooling also cuts the costs for the transport of the energy.

4.3. *Matching the heating demand with solar and wind energy*

Our demand for fossil gas can be matched with a mix of solar and wind energy. For instance, the mix of solar and wind with ratios: solar: wind = 1 : 5 and 1 : 20. We find the results shown in the graph in Fig. 10

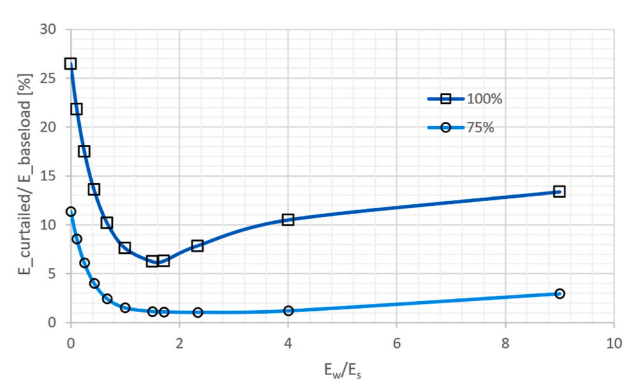

Fig. 11. Curtailed energy as a percentage of the required baseload demand for various ratios of solar E_s and wind E_W energy yield. Dark blue: 100% of the energy demand is covered by the solar and wind mix, light blue 75% of the energy demand is covered by the solar and wind mix. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

hereafter.

Obviously, the gas demand is best fitted with a very large amount of wind energy in the mix. But the mix should not contain too much wind energy because of the intermittent character of renewable energy and the fact that solar and wind energy are complementing each other. This will be discussed in the next chapter.

4.4. The effect of curtailing as a function of baseload coverage

We would often like to locally match the supply with the demand of energy. For instance because of a weak grid that does not allow the feed-in of large amounts of power or in case of stand-alone situations where there is no other energy source than solar and wind energy. In those cases we would like to match the yearly energy demand (yearly matching) as well as the power demand (instant matching). We therefore install just enough solar and wind power to match the yearly energy demand but we have to get rid of overproduction that occurs if both solar and wind energy produce at their maximum (rated) power. We apply curtailing of the overproduction. Underproduction issues are of course not covered by this measure. In case of underproduction, we have to decrease our demand.

Suppose we cover 100% of the yearly flat energy demand of a big industrial plant with a baseload mix of solar and wind energy ($E_w = 1.7 \ E_s$). Our dynamic simulation for the solar and wind condition at Haps (wind speed transformed into the wind speed at 100 m height) for 2011–2020 in the Netherlands than shows the results in Fig. 11 below.

First of all, it is interesting to see that the minimum loss is achieved at the calculated optimum baseload configuration ($E_w = 1.7 \ E_s$). This is of course the logical consequence of the fact that the baseload mix provides the flattest supply of energy that fits best on the flat demand (see Fig. 8).

The results of the dynamic simulation shown in Fig. 11 furthermore reveal a curtailing loss of approximately 6% if we at forehand try to cover 100% of the energy demand with our baseload mix. If we cut the coverage of the yearly energy demand to 75%, this drops to a curtailing loss of only 1%. So, the curtailing losses are limited, especially if we do not cover all of the demand.

5. Monthly solar profile for PV at vertical orientation

Solar PV panels are mostly used in their -at the moment-most profitable way in The Netherlands. They are mostly directed to the South and under 35° to the horizon. This orientation of the solar panels results in a big energy production during the summer months that is a mismatch with the biggest energy demand for heating. As a consequence of a large peak production at months with little demand, wholesale market prices of energy become negative. Other orientations of solar panels with smaller peak production at of little demand become increasingly popular.

Additionally, the built environment has ample vertical areas where solar PV has room to grow. Solar PV on noise barriers along highways or on facades of buildings starts to become popular. There are three main reasons for the popularity of facade PV as a Building Integrated PV (BIPV) option:

- recent solar panels have a comparable price to standard facade panels so that the energy produced by the solar panels is “for free”.
- the facade area of buildings is much larger than the roof area of buildings. According to (Behnisch et al., 2020) roughly twice as large in Germany.
- there is limited useful space on most roofs of bigger buildings because the roof is captured by ventilation exhausts, elevator shafts, air conditionings, etc.

But there is one more reason that vertical PV will become important in the near future. Compared to 35° south oriented solar PV, a vertical orientation of solar PV

- produces less energy in the summer months
- has almost the same monthly yield during fall, autumn and winter

and this is a better match with the energy demand for heating (see Fig. 7).

The monthly energy yield can for instance be found with a free to use online model (PVGIS, 2019), (NREL, 2021) for the irradiance of the sun. The model of (PVGIS, 2019) gives the following monthly profile for facade panels facing south with a slope of 40° and 90° for a certain (in this context irrelevant) example year somewhere in The Netherlands.

The yearly energy yield of 90° facade panels is indeed smaller than the yield of 40° solar panels. At 90°, the solar PV yield is approximately 72% of the yield at 40°. But the much smaller energy yield during the summer months is interesting too. The smaller yield in the summer months could result in a smaller peak power output of the inverter of facade panels. A smaller peak power in the summer months is interesting for a better match between supply and demand of energy, but it could also result in a smaller size of the grid connection.

5.1. Smaller inverter for facade panels

A smaller maximum power output of the inverter is only feasible if the peaks in production are not too frequent so that the energy delivered by the peaks is small and we could opt for a smaller inverter size compared to solar panels at maximum energy yield slope. We have to find out what clipping or sizing of the inverter does on the energy yield of the system. The only way to answer this is to do an hourly simulation of the energy yield with various inverter sizes.

We developed a simulation based on the model of Pérez (Perez et al., 1990) and simulated the hourly energy yields based on (KNMI, Uurgegevens van het weer in Nederland, 2019) data for solar irradiance without inverter and temperature losses (i.e. we simulated the basic solar PV yield).

The simulation provided the hourly energy yield as a function of the inverter nominal power as a percentage of the solar PV Wp. The results are shown in Fig. 13.

This graph makes clear that the inverter could be much smaller without a big influence on the energy yield. It can be concluded that the supply of energy by facade panels has a better match with the demand of energy because:

- Fig. 13 shows that an inverter of approximately 50% of the solar panel Wp delivers only approximately 5% less energy for facade panels and
- Fig. 12 shows that the monthly energy supply of a facade panel (90°) has a smaller summer peak compared to a more standard slope solar panel (40°).

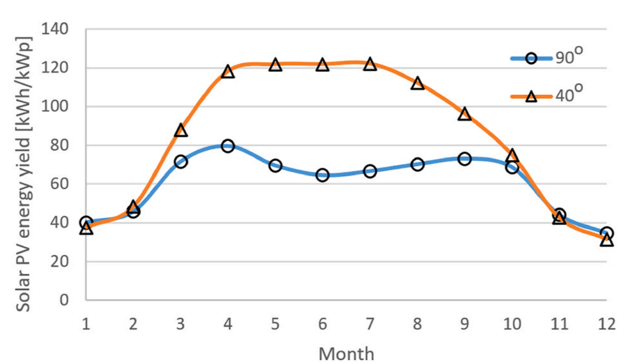

Fig. 12. Monthly energy yield of a facade panel (90°) of 1kWp for a South facing facade compared to the orientation for maximum energy yield, i.e. facing South at a slope of approximately 40°, according to (PVGIS, 2019).

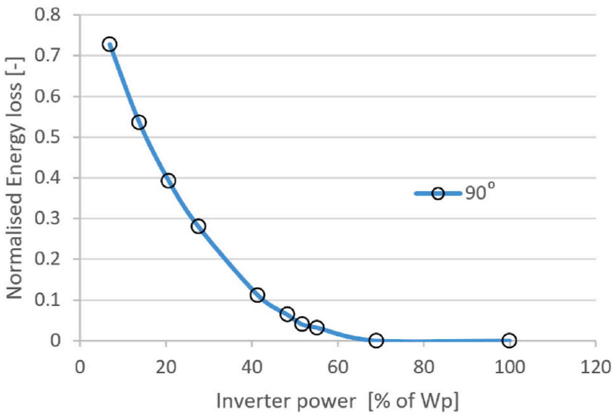

Fig. 13. Normalised energy loss of a facade panel (90°) as a function of inverter size (as a percentage of solar PV Wp, without inverter losses).

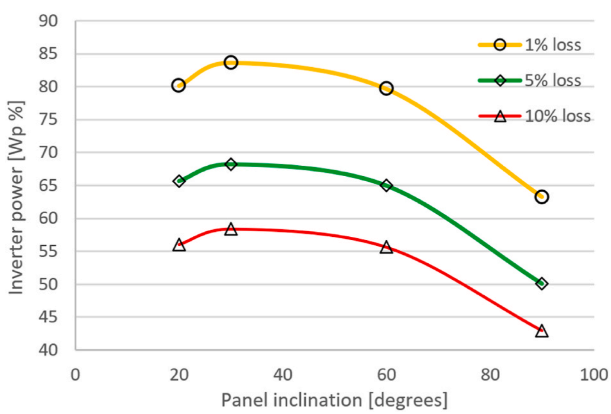

Fig. 14. Inverter power in % of the solar PV Wp as a function of slope of the solar PV panel for various energy yield losses caused by clipping of the inverter.

This is becoming increasingly important for costs related to infrastructure as we install an increasing number of solar panels every year and according to Fig. 3 this is already causing severe (congestion and unbalance) problems in the provincial energy infrastructure. But inverter sizing is also shown (Väisänen et al., 2019) to be important for the local economics, i.e. €/kWh. A proper inverter size is important for both the local as well as the surrounding infrastructure (see Fig. 4).

So, the inverter nominal power should be chosen carefully and in accordance with the slope of the solar panels or importance of peak power. In this choice, Fig. 12, Fig. 13 and Fig. 14 can be used as a design tool for Supply Side Management of solar PV..

5.2. Capacity factor facade panels

Based on the result of the simulation that the inverter power of the facade set up $P_{s,f}$ could have a 50% smaller nominal power than the standard power P_s, we have

$$P_{s,f} = 0.5P_s \tag{14}$$

While, according to chapter 4, the energy yield of the facade panels $E_{s,f}$ is approximately 72% of the 40° slope solar PV yield E_s

$$E_{s,f} = 0.95 \times 0.72 \times E_s \tag{15}$$

where the factor 0.95 comes from the inverter loss of 5% because of the choice for a 50% smaller inverter Wattage (see Fig. 13). Based on formula (6), we now have

$$E_{s,f} = c_{f,s,f} P_{s,f} \times 365 \times 24 \tag{16}$$

or

$$c_{f,s,f} = \frac{2 \times 875 \times 0.95 \times 0.72}{365 \times 24} = 0.14 \tag{17}$$

The maximum power output is smaller, while the capacity factor is increased. The capacity factor of facade panels is almost 1.5 times that of standard slope panels at a maximum energy yield production slope of 40°. We thus have a less peaky energy production. This is profitable for the use of the grid.

6. Concluding remarks and discussion

It is showed that Supply Side Management (SSM) with wind and solar power provides a number of advantages. The advantages are split into two separate items in this paper. The SSM utilizing hybrid wind and solar PV and the SSM with solar PV.

6.1. Hybrid solar and wind energy

A seasonal match of supply and demand of renewable energy saves storage and/or transport capacity as seasonal unbalance is a main driver for storage or transport capacity. This seasonal match is possible with a mix of solar PV and wind energy, because such a hybrid mix delivers:

- a more reliable and constant match with the energy demand at short time.
- a match with the energy demand for heating with 5–20 times more installed wind energy than solar energy yield
- a flat baseload mix with 1.7–2.3 times more wind energy than solar energy yield with:
  - o 100% supply match with a flat demand with the need of only 6% curtailment
  - o 75% supply match with a flat demand with the need of only 1% curtailment
- a match with the energy demand of cooling with more solar energy than wind energy
- a capacity factor of only 3% that allows cable pooling and curtailment with a resulting energy yield loss of 17% if the baseload mix is curtailed at 3% of the time.

We could benefit from a better fit of supply and demand of energy. Yet, little attention is paid to the benefits of SSM with solar PV and wind energy. This is for a large part caused by the lack of a problem owner that is able to control the supply with renewable energy, the preference of districts for solar power despite wind turbines (Yeşilgöz-Zegerius, 2021) and/or ignorance/acceptance on the consequences of a mismatch between supply and demand of energy, i.e. storage or transport capacity issues. Solar PV and wind turbines are installed without much control on the mix and this should change! As a European Union, we should focus on a hybrid solar PV and wind energy mix that matches the demand of a country and enforce the installation of such a mix per country or better: part of a country. This paper provides a simple tool and guidelines to establish the required hybrid mix.

The lack of attention paid to the before mentioned issues is reflected in a small number of scientific publications on SSM for larger areas such as provinces or countries as these larger areas are without a problem owner or at least without one that takes responsibility (governments could stand up) and a larger number of scientific publications on SSM with simple or more clearly to identify problem owners, such as scientific publications on:

- facade panels for building owners
- hybrid solar PV and wind energy for island/stand-alone purposes

A clear problem owner will increase the scientific effort in SSM for larger areas and this on its turn will help to prevent the issues with a mismatch of supply and demand.

6.2. Solar PV

Solar PV SSM provides a valuable contribution to a cost efficient infrastructure. It is shown that solar PV at larger slopes forms a good alternative to standard solar panels at a slope of 40° to the horizon, because:

- larger slopes of solar panels can be used to more evenly spread the monthly energy yield during the summer months and prevent high peak loads mid-summer.
- solar panels at slopes much larger than the standard slope can use a much smaller inverter rated power. At a cost of only 5% energy loss, the inverter can be:
  o 50% of the PV Wp at 90° slope (facade panels)
  o 65% of the PV Wp at 60° slope

There is however little attention for SSM with solar PV as long as the current situation with absence of a business case linked to infrastructure issues at the supply side remains.

Solar panels at larger slopes than the standard 40° can be equipped with a much smaller less costly inverter, but they also deliver less energy and the inverter costs are small compared to the rest of the solar PV installation. It is only in specific cases that the economics of solar PV at large slopes is interesting. Such specific case is facade PV, with an improved business case because of the multiple function of solar PV in that case, utilizing solar panels as facade panels with an additional energy yield.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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