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Sensitivity to techno-economic conditions

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On-site renewable electricity production and self consumption for manufacturing industry in Ireland: sensitivity to techno-economic conditions

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Abstract

The technical and economic feasibility of on-site renewable energy production from solar and wind for a specific manufacturing plant in Ireland is assessed. The energy load of the plant during a typical year is identified through the analysis of gas and electricity consumption, based on internal monitoring and billing information. Solar and wind potentials are modelled for a period of 22 years using historical meteorological data. The distributed system is sized based on the physical limitations of the site and the effect on the net demand is calculated. As expected, solar and wind energy are generally decoupled. The solar energy presents a more predictable daily and seasonal trend; the wind system introduces a high variability on the net demand. Based on this real case study, a model is implemented to simulate the economic viability of the installation in different scenarios by assessing the influence that technical and economic input parameters have on the Net Present Value. Thus, it is possible to find the conditions in which the project would be viable and evaluate the needed economic policies and/or technical improvements to move in that direction. It is concluded that while a technical opportunity does exist, the economic conditions necessary (specifically, reduction in initial cost of investment, significant subsidy, and long payback period) to make on-site renewable generation a viable option in manufacturing industry in Ireland are too onerous to make it attractive.

Keywords: distributed renewable generation, energy system integration, manufacturing energy consumption, energy economics

1. Introduction

Over the last century, human activities have contributed to warm the planet by releasing into the atmosphere greenhouse gases. The main contributor, with over 60% share, is the energy sector, which includes many sub-sectors such as power generation, industry, transport and HVAC. The industrial sector accounts directly for 21% and indirectly (electricity taken from the grid) for another 11% of global greenhouse gas emissions (IPCC, 2014). The main reason for the high level of emissions produced by this sector is found to be the massive electric and thermal energy demand to manufacture consumer products. In the specific context of Ireland, given a final energy consumption of 11,339ktoe in 2015, industry has been responsible for 2,398ktoe consumption (21%) (SEAI, 2016). A partial solution for decreasing the environmental impact of the energy sector is to rely more on low-carbon electricity sources such as solar, wind and hydro.

The traditional grid based on a one-way power flow connecting centralized power plants to end users through the electricity grid has become an old paradigm and is now facing radical changes (Driesen and Katiraei, 2008). Consumers are now becoming also producers at a local level: they produce distributed energy with decentralized systems located nearby, satisfying part of their own energy needs and even producing a surplus that could be sold to the grid. As a consequence the mono-directional power flows are becoming bi-directional. The cost reduction of Renewable Energy Source (RES) technologies, driven by both technological improvements and government policies, and the impelling necessity to decrease the carbon intensity of the grid, are leading to an increasing penetration of renewable distributed generation. Mehigan et al. (2018) give an exhaustive definition of distributed generation and identify the main factors that influence the future role that it will have in the electricity systems. A review of the available tools to simulate the impact of higher penetration of distributed systems on the grid is presented. While it concludes that at the moment no tool can be used to simulate the interactions of all the factors with each other since they are all strongly interconnected, many studies in the literature have identified what are the main challenges that have to be faced to successfully integrate distributed RES into the energy system. Verzijlbergh et al. (2017) present an overview of the main technological and institutional barriers: one of these is the high variability and uncertainty that characterize some renewable sources (e.g. solar and wind), which makes the balance of electricity demand and supply more challenging. A possible way to address this problem is to exploit hybrid energy systems that could better provide the balance of demand and supply by integrating power systems based on different (or complementary) energy sources. Vishnupriyan and Manoharan (2018) present a stand-alone hybrid power system based on solar PV panels and diesel generators that could supply the residential energy demand for six different climate locations in India. Diab et al. (2016) discuss the design and optimization of a hybrid PV-wind-diesel system for an environmental friendly factory in Egypt, where the frequent blackouts lead to significant economic losses. Khare et al. (2016) present a comprehensive review of the main features of hybrid renewable systems, discussing pre-feasibility analysis, sizing optimization, RES modelling and reliability issues. All these studies show that the integration of different energy sources increase the overall reliability of the RES systems.

A large share of renewable capacity, which has doubled over the last decade, reaching over 2 TW (IRENA, 2017), comes from utility-scale and residential systems and many investments are flowing into new systems. In 2016, the worldwide investments for utility-scale projects dominated the renewable market with 187.1 billion USD and small-scale PV installations accounted for 39.8 billion USD (REN21, 2017). The industry sector is, at this time, a smaller contributor to new renewable power generation capacity installed. In this context, manufacturing sites represent a potential opportunity for renewable energy generation which are often based on low power density technologies. In fact, they typically occupy larger spaces in non-residential areas compared to commercial sites in urban areas since they require open spaces for production machinery, parking facilities, appropriate routes for supply and delivery, dedicated connections to national utility grid and other environmental considerations (e.g. noise pollution). While the effect of on-site generation in residential and utility-scale applications has been widely analysed from both a technical and economic point of view (La Monaca and Ryan, 2017; Ruf, 2018; Castaneda et al., 2017; O'Shaughnessy et al., 2018), it is not clear the impact that the switch to on-site generation by manufacturing facilities (industry sector) would have. Given the high energy consumption that characterizes manufacturing facilities (2.5MW$_{el}$ and 5MW$_{th}$ for the medium size manufacturing facility analysed here) compared to the average electric and thermal power demand of a house (480W$_{el}$ and 1,255W$_{th}$ (CER, 2017)), the potential impact could be significant and may bring to light new challenges for the grid and the electricity market.

In this study, the power demand of the facility will be produced on-site by a properly sized renewable distribution plant and it will be instantaneously and locally consumed reducing transmission and distribution losses. The usage of storage will not be required due to the high and almost constant electricity consumption profile which is typically found at manufacturing sites. A model is built to study the sensitivity of on-site renewable electricity generation to different economic and technological parameters in the context of the Irish manufacturing industry. The model's design and validation is based on a real case study with available electricity consumption data in half hour intervals. The use of data from a real Irish manufacturing facility allows a technical and economic assessment of the proposed scheme taking into account the interaction with the grid.

2. Methodology

In order to design a model for the assessment of on-site renewable energy production and consumption applicable to the Irish manufacturing industry, a real facility is analysed. The chosen facility is part of an international pharmaceutical company with 69,000 employees all over the world. The Irish manufacturing site counts more than 800 employees; it has an electricity and natural gas usage which is almost constant during the year and a continuous steam requirement for the production lines. It is a 24/7 batch production process with no shut-down during the year except for one short scheduled maintenance period. The required inputs for the model are shown in Figure 1: the electricity demand is based on the real data provided by the company.

The implemented model calculates as output the technical and economic feasibility of on-site electricity generation in different scenarios. The selected renewable sources for this analysis are solar and wind, which are less site-specific and therefore are more suitable for a widespread deployment that could be applied to different facilities located elsewhere.

The trend of the facility's electricity demand during a typical year is analysed and constitutes the first input of the model. Since the PV and wind systems convert solar and wind energy into electricity, the focus is on this particular energy vector.

When long-term datasets are taken from real facilities using production instrumentation, the most common problem that is encountered is the limited penetration of transducers and the occasional unavailability of these devices. To overcome this problem, data from both internal meters and bills have been compared and integrated.

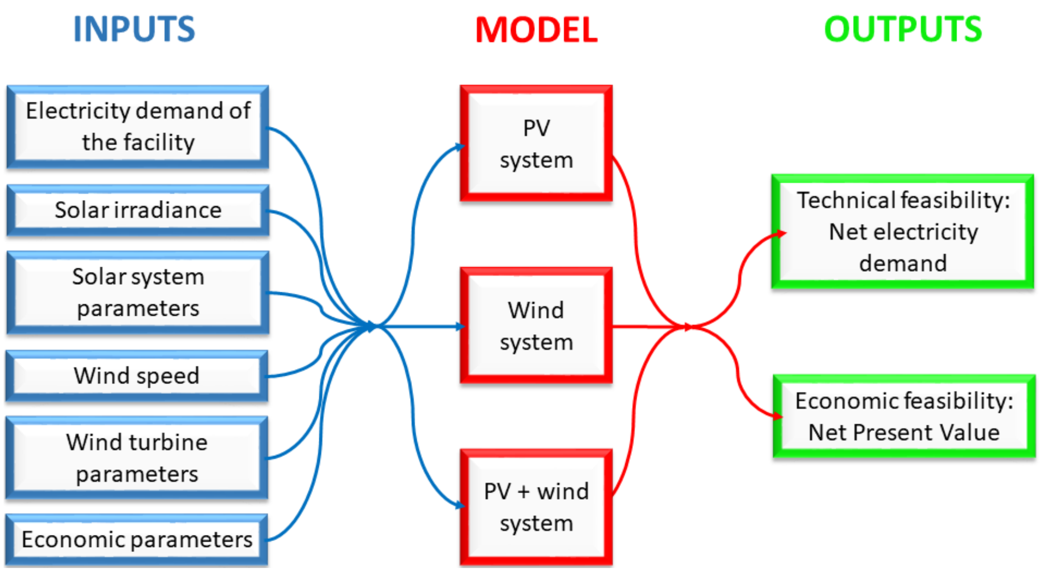


Figure 1: Inputs and Outputs of the implemented model

Once the electricity load and its variability during the year are known, the distributed systems of a PV and a wind plant can be properly sized. A preliminary study has been done with the software HOMER Pro to confirm that these two sources are the most suitable for this application. HOMER, Hybrid Optimization of Multiple Electric Renewables, is a modelling and simulation tool widely used in literature for the optimization of hybrid Distributed Energy Resources (DER) systems (Diab et al., 2016; Lambert et al., 2006; Lilienthal et al., 2004; Weber et al., 2016; Goodbody et al., 2013). The results show that the best economic solution that minimize the cost of the overall system is to use only wind turbines, which are less expensive than PV systems for the same peak power installed. However, there are other factors that are not taken into account in the preliminary analysis such as the strong regulations and physical limitations that apply to wind systems (Department of Housing, Planning and Local Government, 2018; World Bank Group, 2018).

In Ireland, wind turbines have to be at least at a distance equal to the height of the turbine and blade from national and regional roads and railways and at least 23m from power transmission and distribution lines. The site has to be selected, in order to avoid the shadow flicker effect in buildings nearby and if the designed system includes more than a single wind turbine the minimum distance between them to ensure optimal performance is at least three times the rotor diameter. Spatial limitations and the morphology of the territory are not variables considered in the HOMER analysis.

While this may not represent a problem for utility-scale plants that select the most suitable land after the power generation system has been designed, it is a limit for existing manufacturing facilities which have a finite surrounding area and roads nearby. Further more, relying only on a single renewable source often leads to occurrences of significant and rapid fluctuation of the net demand. The selection of two generally decoupled renewable sources could diminish these fluctuations. Based on these considerations, both a solar and a wind system have been considered for distributed electricity generation and the potential benefits of their integration have been studied.

The maximum power installed is chosen based on the load and on the site limitations. The electricity potentially produced is a function of the resources' availability, assessed based on historical meteorological data. As input for the solar model, MET EIREANN, the official Irish meteorological service, provided the hourly Global and Diffuse Horizontal Irradiance (GHI and DHI) measured in a meteorological station less than 100km away from the facility, with a difference in latitude of 0.75°. It has been verified that the difference in latitude between the facility and the meteorological station does not substantially influence the economic results: the annual electricity produced is estimated to vary less than 4%. The meteorological data are available from 1986 to 2007 (22 years). The conventional number of consecutive years used in the scientific field for a proper meteorological analysis of RES availability is 30 years. However, while wind speed has been measured for some time, solar irradiance data from real measurements have only been available recently for some locations, therefore it is not possible to analyse a longer period for the selected site. In order to optimize the pitch angle of the panel (β), it is necessary to calculate the beam irradiance at its original direction (DNI) and not projected on a horizontal surface. This procedure is not necessary for the diffuse irradiance (DHI), which does not come from a single direction but it is scattered in the atmosphere. The methodology used is widely recognised in literature and described by Myers (2013) and Basunia et al. (2012). The position of the sun every hour of the year has been simulated in order to calculate the angle θ between the sun and the normal to the tilted panel.

The optimum pitch angle β_{opt} that maximize the sum of the hourly Global Tilted Irradiance (GTI) over an entire year is calculated with eq. 1 and in the analysed location is found to be 30°.

$$\left\{ \beta_{opt} \;\middle|\; \sum_{h=1}^{8760} GTI = \sum_{h=1}^{8760} \left(DNI\, \cos(\theta) + DHI\, \frac{1+cos(\beta)}{2} \right) = max \right\} \tag{1}$$

In order to define the total amount of energy potentially produced by the PV plant some parameters are assumed, based on NREL available information (Wagner and Gilman, 2011). The main technical features of the solar system are summarized in Table 1. The efficiency curve of the solar inverter (η_{inv}) as a function of the load percentage has also been taken into account in the calculation.

Table 1: Solar system parameters

Description	Parameter	Value
Average horizontal global irradiance	$\overline{GHI}$	0.117kW/m^2
Average horizontal diffuse irradiance	$\overline{DHI}$	0.062kW/m^2
Optimum pitch angle	β_{opt}	30°
Orientation of the panels		South
Peak power installed	kW_{peak}	2020kW
Total area of the PV system	A_{PV}	10,700m^2
Efficiency of PV panels	η_{panel}	0.19
Module degradation		0.3% per year
System losses		14%
Annual electricity produced	kWh_{PV}	1,883,500kWh
Capacity Factor	CF	0.13
Capital expenditure	$CapEx_{PV}$	3,721,100€
Operational expenditure	$OpEx_{PV}$	138,022€ per year
Discount rate	r	0.075
Annual cost inflators		1.5% per year
Operational lifetime		25 years

The AC electricity production has been calculated for every year n of the project (kWh_{PV}) based on the solar irradiance of the analysed 22 years (eq. 2).

$$kWh_{PV_n} = \sum_{h=1}^{8760} \{GTI \times A_{PV} \times \eta_{PV} \times \eta_{inv} \times (1 - 0.003(n-1)) \times (1 - 0.14)\} \tag{2}$$

The average annual electric energy produced for the last 5 years of the dataset (2003 to 2007) is 1,863MWh (average power = 212kW). In order to verify the implemented model, the system has been simulated with PVWatts Calculator (Dobos, 2014; Qazi, 2016), using the same parameters and for the same location. The two estimates agree within 0.86%. The last year with available meteorological data has been chosen as solar energy input to simulate the feasibility of the project. In 2007, the total energy that would have been produced is estimated to be 1,883MWh. This value differs only by 1.9% from the value simulated by PVWatts and by 2.0% from the value simulated by System Advisor Model (SAM) (Wagner and Gilman, 2011; da Silva, 2017), therefore it can be used as average production of the solar system for the entire lifetime of the installation, considering a performance decay of 0.3% every year.

Wind speed data are available from Met Eireann for a meteorological station less than 20km away from the manufacturing facility. The same period of the solar irradiation sample has been analysed and 2007 has been chosen as representative year. The height of the measurement tower is 10m; the hubs are located at 50m from the ground. Equation 3 is suggested in literature for estimating the variation of wind speed with height (Lubosny, 2003; Heier, 2014):

$$v_i = v_0 \times \left(\frac{z_i}{z_0}\right)^{\alpha} \tag{3}$$

where v_i is wind speed at the required height z_i, v_0 is the known wind speed at the height z_0 and α is the Hellman exponent, a coefficient that depends on the site (close to 0 for an open and undisturbed environment, its value increases with the presence of obstacles). This method, however, can be used only for a rough estimation of the wind speed variation with hub height since it is difficult to exactly estimate the coefficient α on a theoretical basis. An alternative and more accurate option is to calculate the coefficient α a posteriori, by using wind speed data at two different heights measured at a near location with a similar shape and characteristics of the land.

The second method has been used: the Hellman exponent is calculated from available wind speed data at two different heights. These data are available from MERRA-2 for a location less than 100km away from the facility both at 10m and 50m height. MERRA-2, Modern-Era Retrospective Analysis for Research and Applications version 2 , is a system of atmospheric data provided by NASA (Gelaro et al., 2017; Reichle et al., 2017; Wang et al., 2018). It uses a systematic approach (reanalysis) to produce datasets used in meteorological monitoring.

By using equation 3, the value of the coefficient α is calculated for every hour of the year. As shown in Figure 2, α is very variable over time therefore it is more accurate to use in the calculation its value in the specific moment of time considered, instead of the average value over a year (0.23).

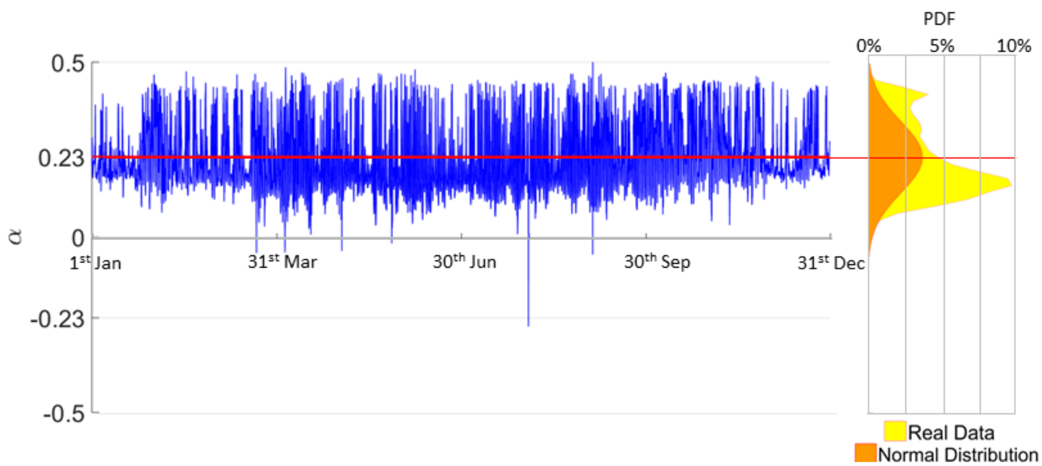


Figure 2: Coefficient α: variation during 2016 and its Probability Density Function

Considering the same coefficient α calculated with MERRA-2 dataset, the wind speed v at 50m height in the original location can be then calculated for a certain moment in time as:

$$v_{MetEireann@50m} = v_{MetEireann@10m} \times \frac{v_{MERRA@50m}}{v_{MERRA@10m}} \tag{4}$$

Two Enercon E-44 900kW wind turbines have been selected (Enercon). The analysed year is 2007, as for the solar model. The main features of the wind system are listed in Table 2. Once the technical parameters of the wind turbine have been defined, the power P potentially produced by the wind system can be calculated as function of the wind speed (eq. 5-8).

Table 2: Wind system parameters (Staffell and Green, 2014; Kealy et al., 2015)

Description	Parameter	Value
Turbine model		Enercon E-44 900kW
Average wind speed	$\overline{v}$	6.7m/s
Power installed	kW_{peak}	2 × 900kW
Cut-in speed	v_{cut-in}	3.0m/s
Rated speed	v_{rated}	15m/s
Cut-out speed	$v_{cut-out}$	34m/s
Density of air	ρ	1.2kg/m^3
Swept area	A_{swept}	2 × 1521m^2
Hub height		50m
Performance decay		1.6% per year
Capacity Factor	CF	0.23
Annual electricity produced	kWh_{wind}	3,609,800kWh
Capital expenditure	$CapEx_{wind}$	2,768,675€
Operational expenditure	$OpEx_{wind}$	100,000€ per year
Discount rate	r	0.075
Operational lifetime		25 years

$$v < v_{cut-in} \qquad P = 0 \tag{5}$$

$$v_{cut-in} \leq v < v_{rated} \qquad P = \frac{1}{2} \times Cp \times \rho \times v^3 \times A_{swept} \tag{6}$$

$$v_{rated} \leq v < v_{cut-out} \qquad P = kW_{peak} \tag{7}$$

$$v \geq v_{cut-out} \qquad P = 0 \tag{8}$$

Cp is the coefficient of performance and its variation with wind speed has been taken into account in the calculation.

The regulations for wind turbine location and spacing represent a practical limitation on the wind energy potential of the site (Draft PPS 18: Renewable Energy). The performance decay of the system is assumed to be 1.6% per year as reported by Staffell and Green (2014).

The technical characteristics of the installation are modelled to assess the average net electricity demand and the variability introduced on the grid for every year of the project's lifetime for 3 scenarios: the PV plant only; the wind plant only; both solar and wind.

The initial investment ($CapEx$) in manufacturing context is often considered acceptable if the resulting Return Of Investment (ROI) period is assessed to be shorter than 5 years. The economic feasibility of the project is valued using the cumulative Net Present Value, given by the sum of the annual NPV (NPV_n) calculated with eq. 9.

$$NPV = \sum_{n=1}^{lifetime} NPV_n = \sum_{n=1}^{lifetime} \frac{(Saving_n - CapEx_n - OpEx_n)}{(1+r)^n} \tag{9}$$

$$= fn(CapEx, OpEx, Saving, r, \eta_{PV}, CF) \tag{10}$$

The initial cost of investment ($CapEx$), the operation expenditure ($OpEx$), the savings achieved by generating on-site renewable energy and the applicable discount rate (r) have been estimated for each system based on available information on existing plants. The Pay Back Time (PBT), or Return On Investment (ROI) period, is defined as the number of years required to reach a cumulative $NPV = 0$€. The NPV is a function of different technical and economic parameters (eq. 10) that are likely to change in the near future; therefore to make this model applicable to potential future changes, the NPV is calculated for a wide range of parameters' values and not just for the actual estimated conditions. Since the cost of investment ($CapEx$) for PV and wind systems is likely to decrease (IRENA, 2016) and the electricity price paid by the company is likely to increase in the future (National Grid Future Energy Scenarios), the model considers the normalized $CapEx$ (€/W_{peak} installed) ranging from 50 to 110% of the actual estimation and the price paid by the industrial company to the grid for the electricity consumed between 0.08 and 0.35€/kWh. The variation of the $CapEx$ takes into account also uncertainty in the estimation of the initial cost of the distributed systems, due to unavailability of commercially sensitive information. The Operation and Maintenance ($OpEx$) costs for photovoltaic and wind plant have been estimated based on existing plants data. While for the PV plant an annual increase of 1.5% in this item of expenditure has been considered (Ryan et al., 2016), for wind plant the historical $OpEx$ costs are inaccurate and not applicable today given the significant improvements of the last decade (IRENA, 2016). The $OpEx$ costs of the wind system has been considered constant for the lifetime of the project.

The parameters that influence the NPV have been identified and the effect of their variation on the economic viability of the project is discussed:

- Normalized cost of investment ($CapEx$);
- Levelized Cost Of Energy ($LCOE$);
- Discount rate (r);
- Efficiency of PV panels (η_{PV});
- Capacity Factor (CF).

The Levelized Cost Of Energy, $LCOE$, is an economic variable used to compare the cost of producing a unit of electricity through different technologies. It is calculated as the total cost of building and operating the power plant divided by the total electricity produced over its lifetime. In this study, $LCOE$ represents the specific price the manufacturing company pays the grid for the electricity and it influences the NPV of the renewable system as avoided cost, also identified as $Saving$. It varies between 0.08 and 0.35€/kWh in the presented analysis to simulate different scenarios.

Three values of discount rate have been considered (Ryan et al., 2016): 0.05; 0.06; 0.075. The efficiency of PV panels is 0.19 in the actual scenario; two other values, 0.25 and 0.30, have been investigated as future technological improvements of commercially available technologies (e.g. triple junction modulus).

The effect of the Capacity Factor of the PV solar system has been assessed for CF values of 0.13 (obtained from the simulation under the selected conditions), 0.2 and 0.25. This parameter is mostly influenced by the solar irradiation availability (latitude and sky conditions) and by the maintenance of the plant.

3. Results and Discussion

3.1. Renewable electricity production

The total amount of electricity consumed in 2016 registered by internal metering was 23,296MWh; the trend of the electric power required by the facility and its variation over the year are displayed in Figure 3. The bills provided by the facility report a total consumption of 23,247MWh in 2015 and 23,331MWh in 2016. The two sources registered consistent data, differing by less than 1%, suggesting that the internal meters are reliable.

The electric load in 2016 is displayed in Figure 3-a: it is almost constant during the year without seasonal variations. The range of hourly electricity consumption (maximum to minimum difference) and its standard deviation for every week of 2016, using both raw hourly data and a 1-week moving average to remove rapid fluctuations, are displayed in Figure 3-b and 3-c. Most of the time during the year, the fluctuations in the electricity consumption during a week are low. In fact, if the 9 weeks with the unusual high drops are excluded, the gap between the maximum and minimum power load relative to the average one registered in that week is below 33% for raw data while using a 1-week moving average it decreases below 7%. The periods with an unusual trend during the year are marked in Figure 3-a by 4 ovals: these regions represent cumulatively 9 weeks of consumption. The electricity demand drops at the beginning (week 1) and at the end (week 52) of the year are caused by a reduction of the working shifts in the facility for Christmas holiday. The electricity demand does not drop to zero: a base-load demand is still present, even if reduced. The other highlighted regions (weeks 12, 13, 29) show the electricity consumption dropping to zero in late March and again in July. The event in March is an isolated data point, and seems to be a problem with the data logging. The event in July, however, spans 29 consecutive hours. The internal monitoring and external billing data are consistent, and so it is concluded that it is due to plant outage.

The ensemble average of hourly and daily consumption over 2016 is shown in Figure 4. A diurnal variation is seen on weekdays (Monday-Friday), while the weekend hourly average is flat. The weekdays are comparable to each other both in terms of hourly trend and range of variation. The weekday diurnal trend is more or less additional to the weekend average and is approximately 5% of the mean electricity consumption. The range of variation at the weekend is twice that of weekdays and is approximately 10% of the mean consumption. This suggests the possibility that the diurnal variation during weekdays is not related to changes in manufacturing processes which will continue on a 24/7 basis, but rather reflects secondary activities, such as back-office operations, although there is no operational data to support this.

From the analysis conducted, given the almost constant trend and the overall relatively small diurnal, weekly and seasonal variability of the electricity demand, it is concluded that the electricity consumption profile of a manufacturing site differs from that of a typical consumer and the nature of on-site manufacturing processes is that deferred consumption is not viable. Therefore, the commonly adopted strategies for Demand Side Management (DSM) are not easily applicable in this case.

With the introduction of renewable on-site electricity generation, the electricity load is provided by both the RES systems (based on the RES availability) and by the grid. The simulated quantity of electricity that would be produced by the proposed PV and wind systems and the resulting net demand profile are respectively shown in Figure 5 and 6 for every hour of 2016. The electricity potentially produced by the PV plant (Figure 5-a) increases during summer, following an overall seasonally predictable trend.

The electricity produced from wind, instead, is very unstable and not predictable (Figure 6-a). Given the unsteady nature of wind speed, the variance of the wind output is almost double that of the photovoltaic plant. However, the high peaks in wind speed allow the wind turbines to produce more energy than PV plant, even though the nominal capacity is lower.

The difference between the electricity consumption and production represents the net demand on the grid as shown in Figure 5-b and 6-b. This is negative (i.e. power sold into the grid) mainly for the wind plant on rare occasions in the winter months (76 hours over the year), resulting in a curtailment of 0.84% of the total wind power if net metering is not applicable. As explained before, the event in March may be due to a problem with the data logging while the event in July may be due to plant outage. It is also worth noting that problems with unavailable or mistaken data happen frequently in SCADA systems in large manufacturing operations and this is a real world complication that has to be faced. Nonetheless, these data drop-outs will not significantly effect the net impact on the grid, which is summarized in Table 3. The variability of the solar and wind resources on a monthly and weekly basis in the analysed location is shown in more detail in Figure 7 and 8. Visibly, the wind resource has wider fluctuations within a month but overall a lower daily variation.

Table 3: Renewable energy generated in the first year [MWh]

	PV System	Wind System
Electricity requirement	23,296	23,296
RES generation	1,884	3,610
Electricity from grid	21,426	19,717
Electricity over produced	14	30

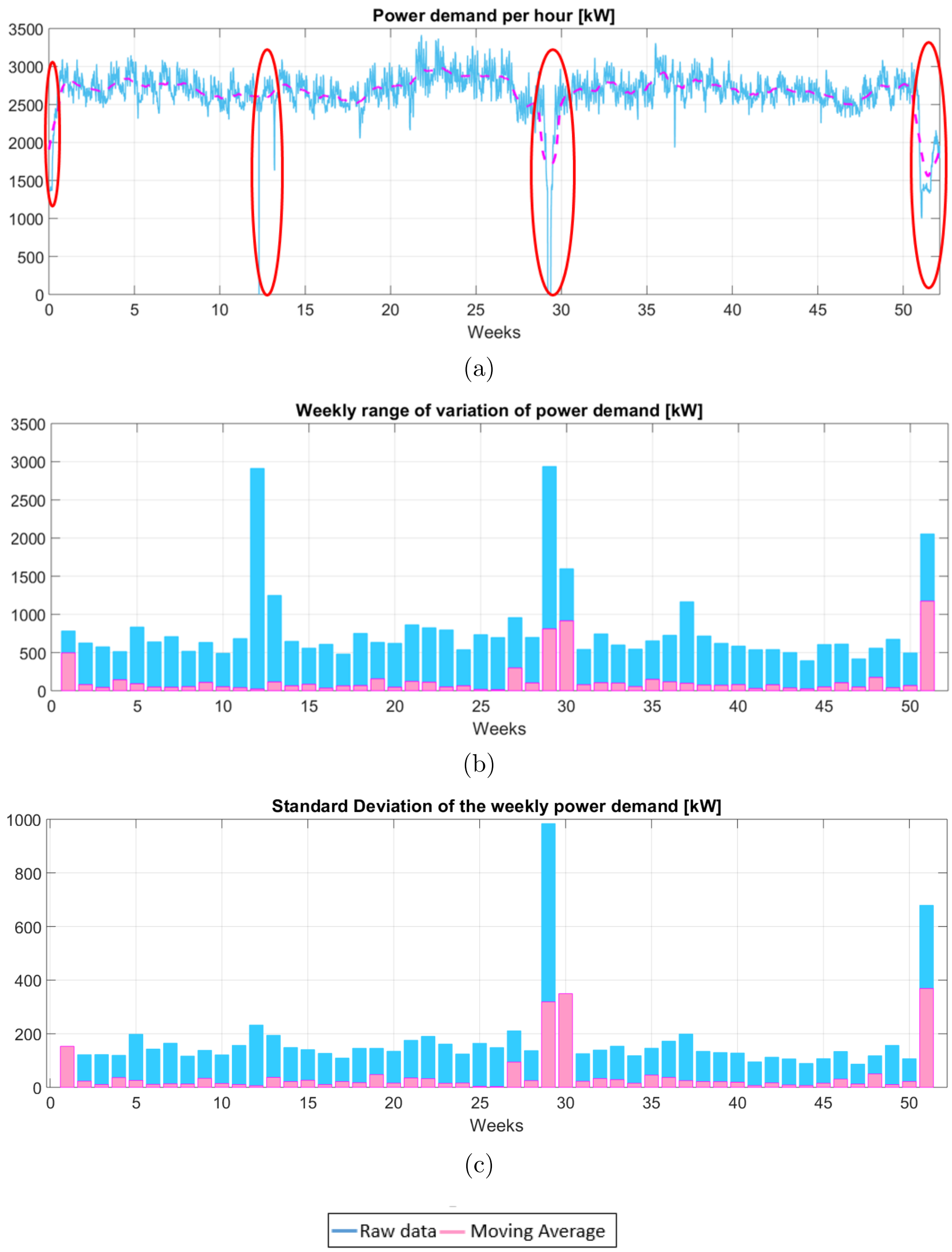


Figure 3: Electricity demand trend in 2016

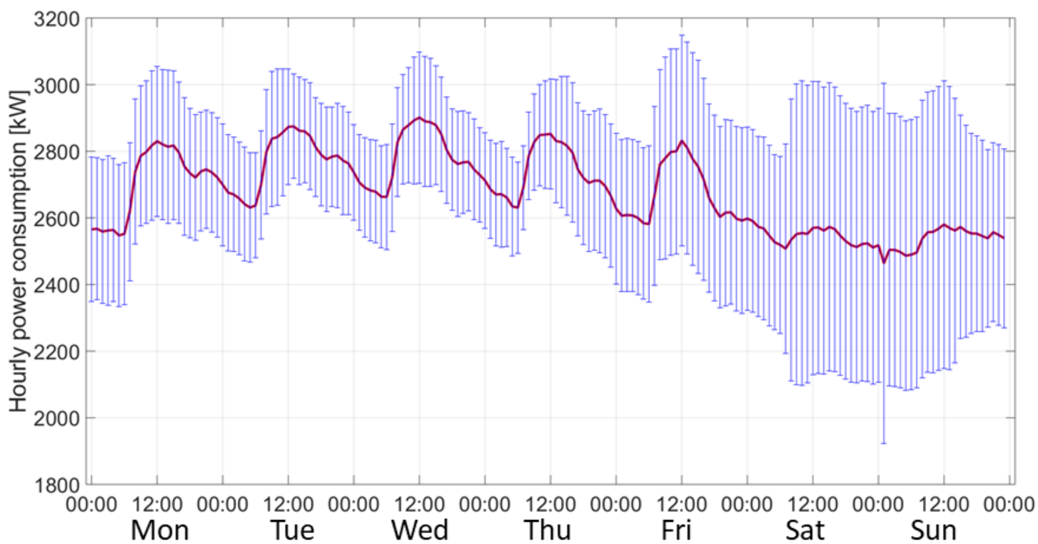
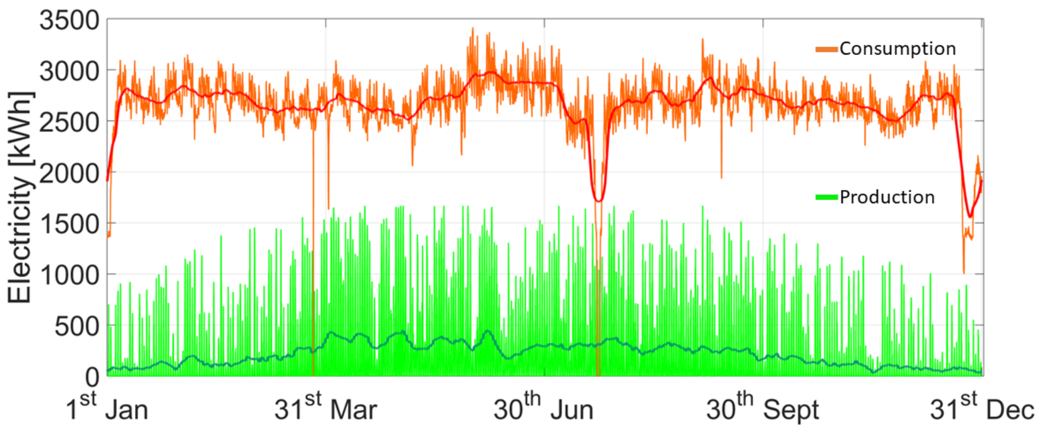
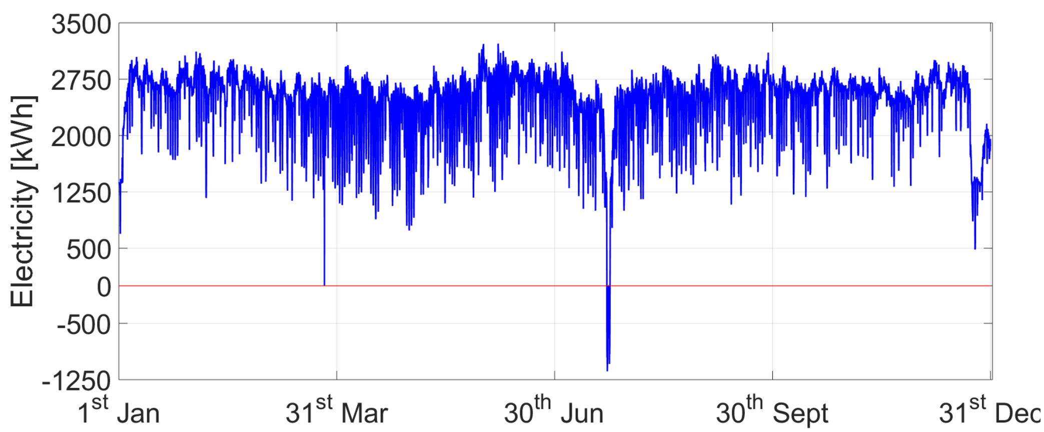


Figure 4: Electricity demand trend in 2016: Monday-Sunday hourly ensemble average

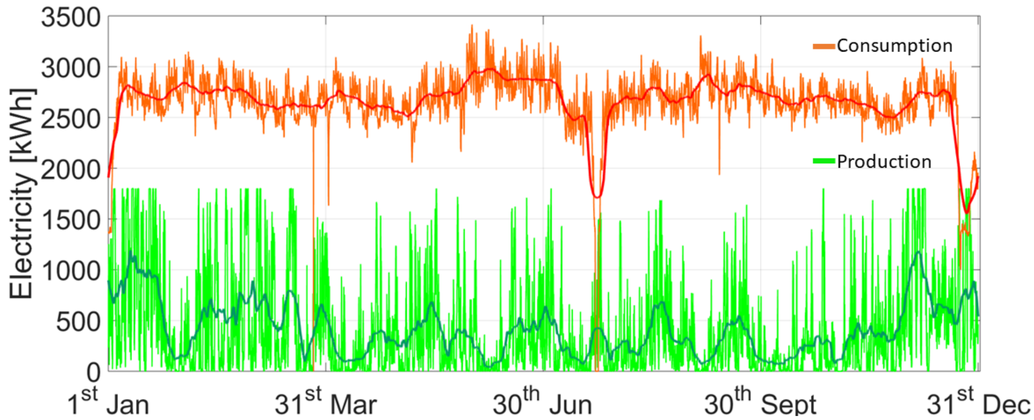


(a) Electricity demand and PV electricity generation: raw data (lighter line) and 1-week moving average data (darker line)

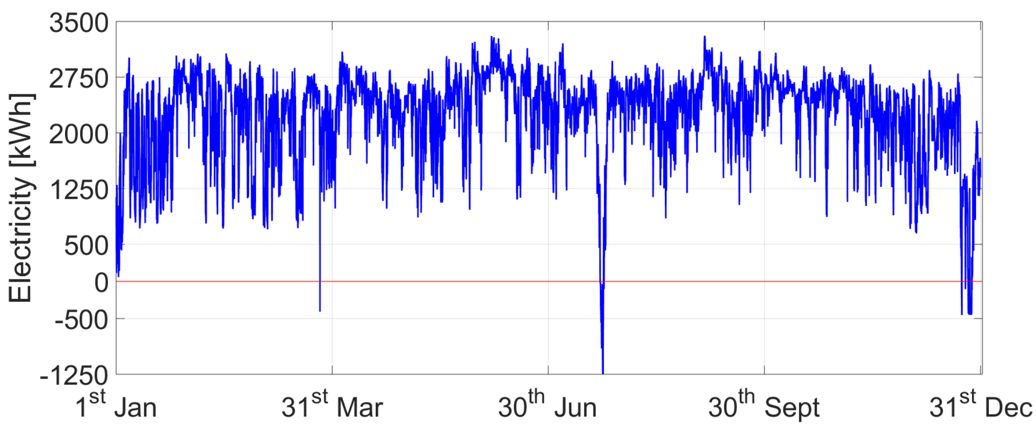


(b) Net demand

Figure 5: PV system: RES electricity generation and net demand in 2016

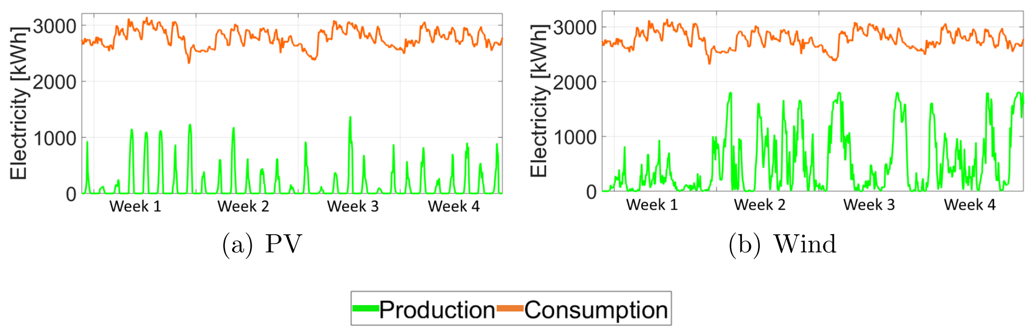


(a) Electricity demand and wind electricity generation: raw data (lighter line) and 1-week moving average data (darker line)



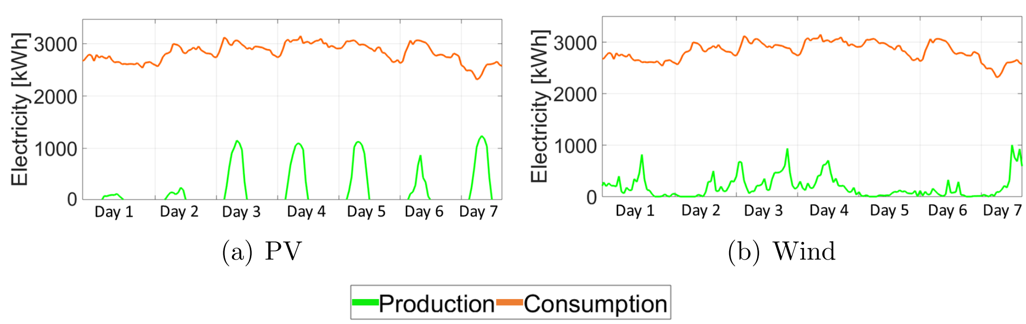
(b) Net demand

Figure 6: Wind system: RES electricity generation and net demand in 2016



(a) PV (b) Wind

Figure 7: RES generation profile: one month zoom of (a) Figure 5-a and (b) Figure 6-a



(a) PV (b) Wind

Figure 8: RES generation profile: one week zoom of (a) Figure 5-a and (b) Figure 6-a

3.2. Economic analysis: sensitivity of NPV

The Return On Investment (*ROI*) period is a key consideration for ongoing process development in a manufacturing context. The Net Present Value (*NPV*) of investment in on-site renewable generating plant is assessed for a range of capital expenditure (*CapEx*), normalized per Watt installed, and Levelized Cost Of Energy (*LCOE*), which in this case is equal to the specific price paid by the facility for grid electricity. When the NPV of the renewable plant reaches 0€, the $LCOE$ of the renewable system equals the price of grid electricity, since the total cost of building and operating the RES plant equals the savings from the electricity not bought from the grid.

Figure 9 shows the 0€*NPV* curves for a range of time frames, up to 25 years for photovoltaic plant, wind plant and both system integrated together in the base case scenario. The effect of some form of carbon pricing is also included (Figure 9-d). For reference, the current actual price paid for grid electricity is indicated with a dashed line parallel to the x-axis, and the normalized *CapEx* value based on current commercial prices is indicated with a dashed line parallel to the y-axis. The project is considered to be economically viable for a manufacturing facility in all the conditions that lie on the curve that represents the $NPV = 0$€ after 5 years. This criterion is arbitrary and it is based on the economic decisions of facility managers. The managers of the analysed manufacturing facility set a maximum ROI period of 5 years.

Figure 9-b shows that wind technology can be economically viable if small incentives are provided for the electricity sold to the grid or even just with a reduction in capital cost per W but only for long payback periods. It is highlighted that the wind speed data used for this simulation are taken from the year 2007, characterized by an average wind speed profile. The Return On Investment period decreases from 25 years up to 5 years if periods with a particularly high wind speed profile are chosen. This is the case of 1986, when the wind energy potentially produced would be 7,156MWh (compared to 3,610MWh in 2007). Furthermore, a slight variation in the specific electricity price paid by the facility could change the ROI period from 25 to 15 years, given the flat profile of the 0€ NPV curves.

On the other hand, for PV plant (Figure 9-a), a stronger support policy would be needed. By combining the two systems, the weak points of both are mitigated. The long *ROI* period of the solar system is reduced by the more economical technology of the wind plant (Figure 9-c). The wind system's variability and aleatory nature is balanced by the photovoltaic plant (Figure 7 and 8).

Different market conditions can improve the investment proposition (i.e. yielding a positive NPV):

- Decrease in normalized $CapEx$ (learning curve for solar technology, e.g. improved PV efficiency);
- Decarbonization incentives, effectively acting as subsidies for renewable energy generation;
- Incentives for electricity sold to the grid;
- Increase in electricity price.

Figure 10, 11, 12 and 13 are carpet plots that show how the cumulative NPV achieved by the system after 10 years varies as function of the price of electricity $LCOE$ and of the normalized $CapEx$. The highlighted dark line in each graph represents all the combined conditions of $LCOE$ and $CapEx$ that result in a 0€ NPV (PBT = 10 years) and it divides the region of combined conditions that lead to a $PBT > 10$ years (i.e. $NPV < 0$) located below the line and the ones that lead to a $PBT < 10$ years (i.e. $NPV > 0$) located above the line. As stated for the previous graphs, the dashed light lines indicate for reference the current actual price paid for grid electricity (parallel to the x-axis) and the normalized *CapEx* value based on current commercial prices (parallel to the y-axis).

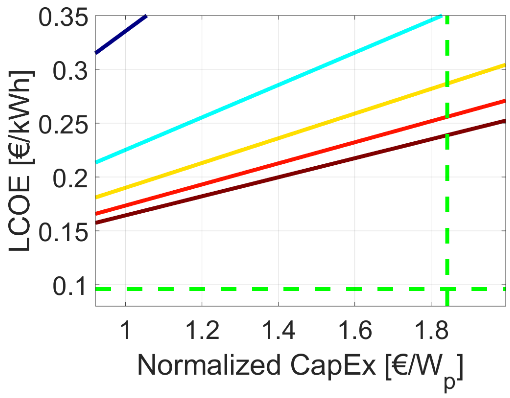
In Figure 10 the variation of the solar system NPV after 10 years is shown for different discount rates. The slope of 0€NPV lines slightly decreases if the discount rate r decreases, but the minimum price of electricity to make the project profitable remains high (0.205€/kWh).

In Figure 11, instead, it is noticeable that for the wind plant a decreased discount rate coupled with either a reduction in $CapEx$ or an increase in the electricity price could lead to a return on the initial investment in 10 years.

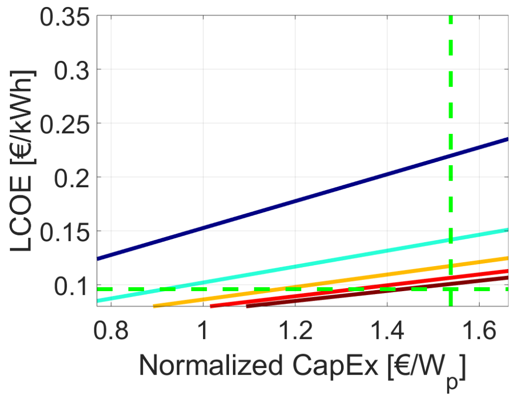
Figure 12 shows the NPV after 10 years for different efficiencies of PV panel. Increasing the efficiency reduces the normalized $CapEx$. Note that the slope of the 0€NPV curve is constant. A PV panel efficiency of $\eta_{PV} = 0.19$ and a discount rate of $r = 0.075$ and a 50% reduction of normalized capital cost would lead to a positive NPV after 10 and 25 years with, respectively, a minimum electricity price of 0.215€/kWh and 0.155€/kWh. For an efficiency of $\eta_{PV} = 0.3$ the 10 year 0€NPV can be achieved with a price of electricity of 0.165€/kWh.

The last analysed parameter is the Capacity Factor, which, for photovoltaic power station, depends not only on the latitude (52.6° is the latitude of the meteorological station proving the data) but also on local factors. It influences the normalized *CapEx* by varying the amount of electricity produced. Figure 13 shows the effect of PV plant Capacity Factor on NPV.

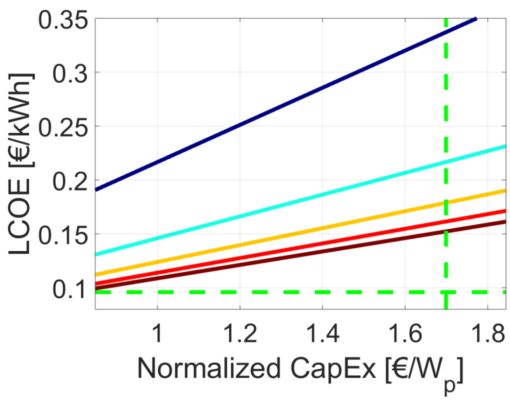
In order for the $LCOE$ of the PV system to be comparable to the current price of grid electricity paid by the facility (0.09€/kWh), the Capacity Factor would have to nearly double to 0.25.



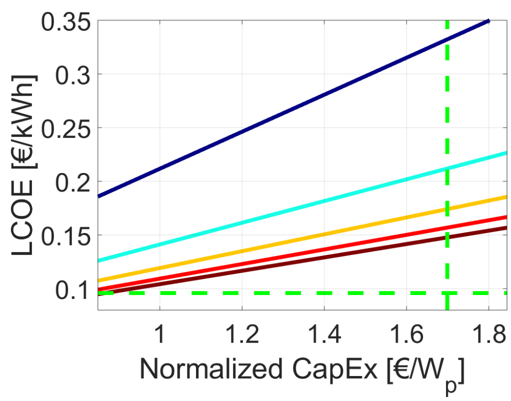
(a) PV plant



(b) Wind Plant



(c) Combined Plant



(d) With carbon tax

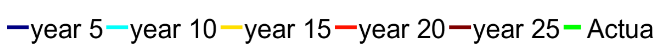


Figure 9: 0€ NPV curves as function of normalized $CapEx$ and cost of electricity

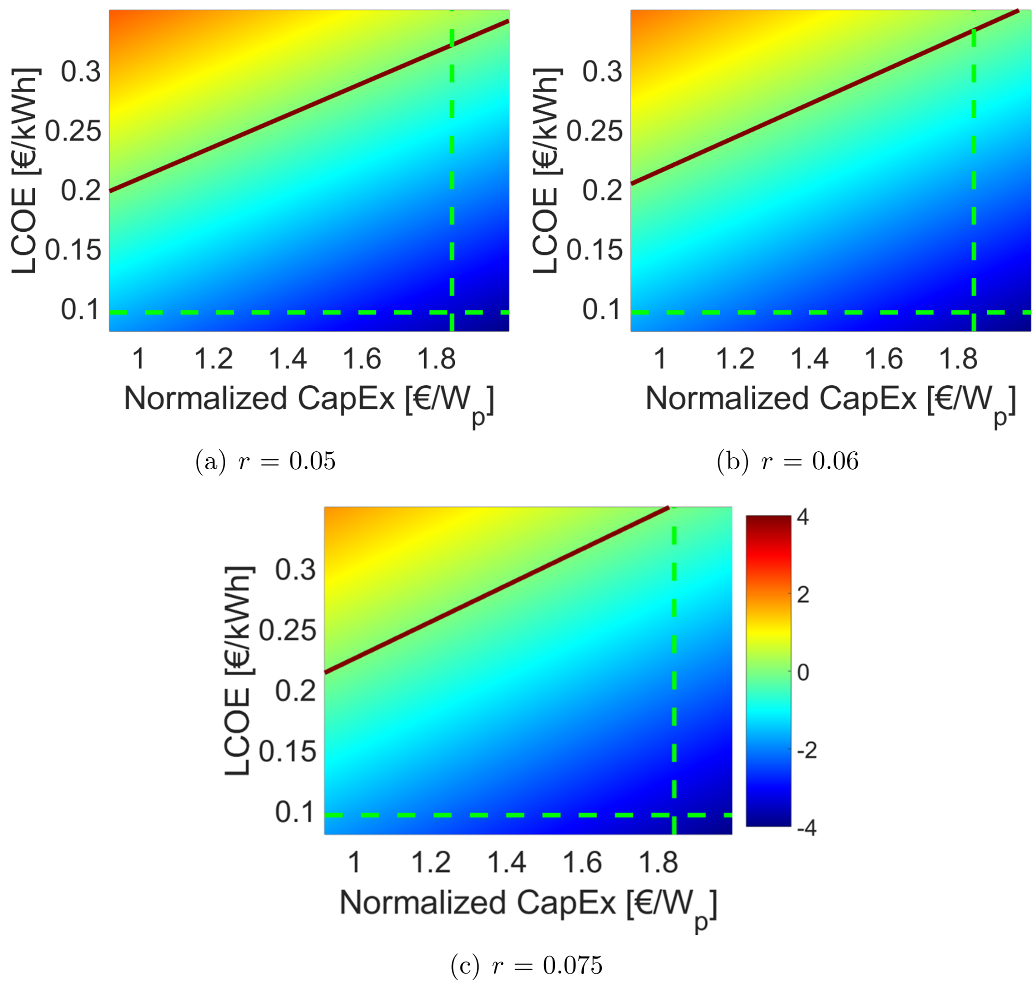
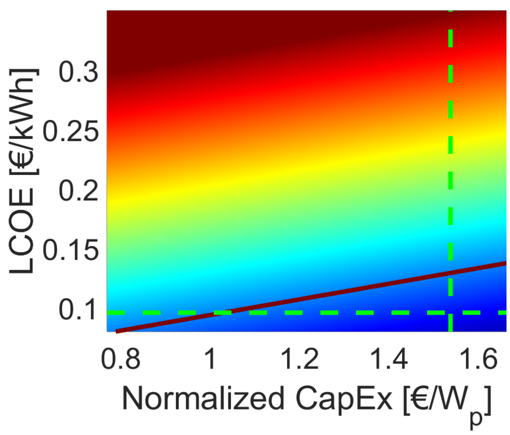
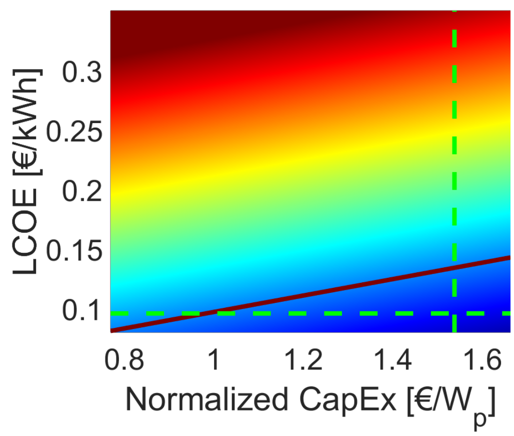


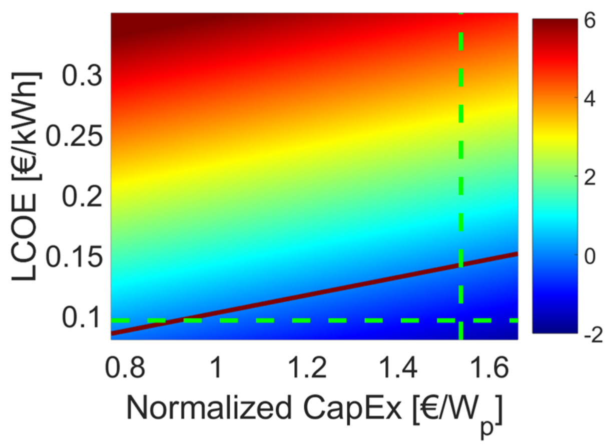
Figure 10: Solar System: NPV in M€ after 10 years for different discount rates (r)



(a) $r = 0.05$

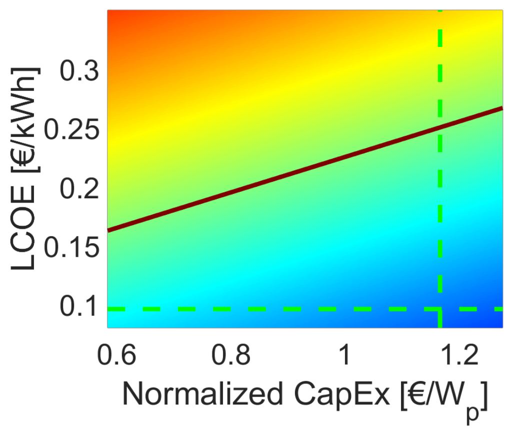


(b) $r = 0.06$

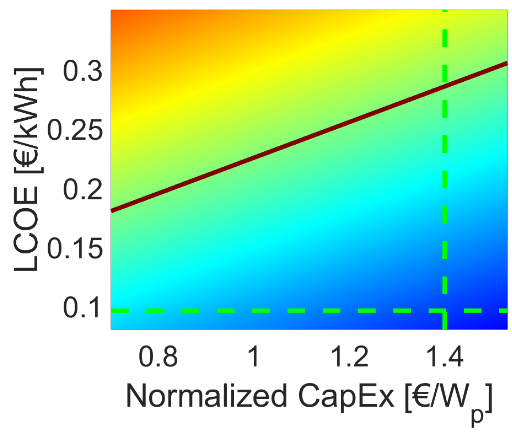


(c) $r = 0.075$

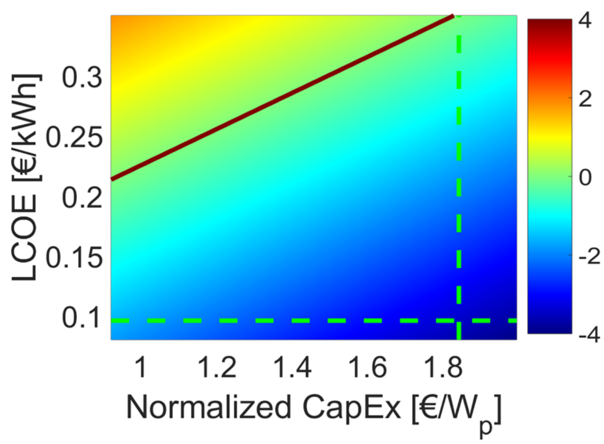
Figure 11: Wind System: NPV in M€ after 10 years for different discount rates (r)



(a) $\eta_{PV} = 0.30$

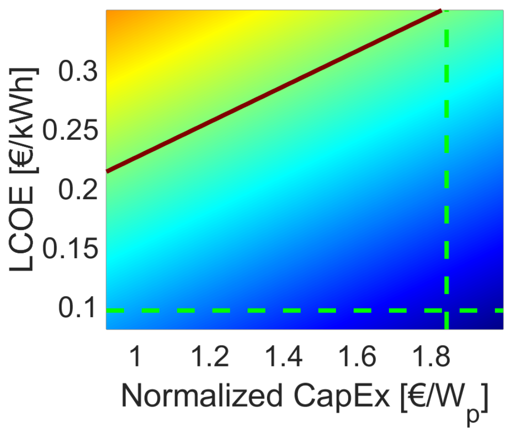


(b) $\eta_{PV} = 0.25$

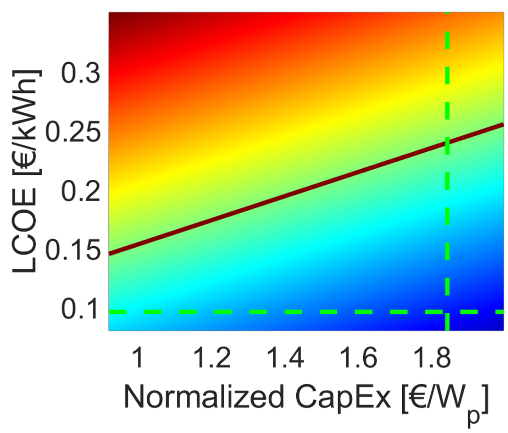


(c) $\eta_{PV} = 0.19$

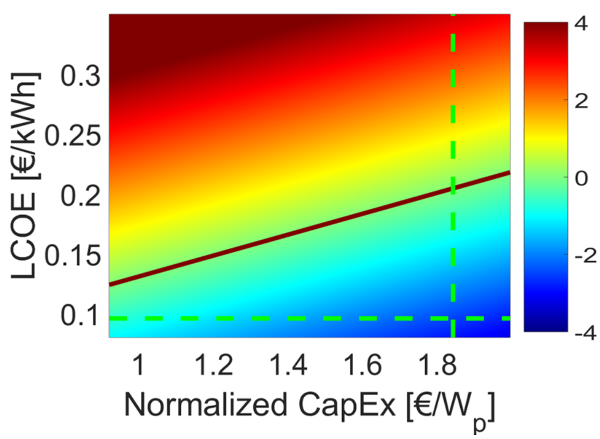
Figure 12: Solar System: NPV in M€ after 10 years for different panel efficiencies (η_{PV})



(a) $CF = 0.13$



(b) CF= 0.20



(c) $CF = 0.25$

Figure 13: Solar System: NPV in M€ after 10 years for different Capacity Factor (CF)

3.3. Integration of combined photovoltaic and wind plant

Since solar and wind have complementary advantages and disadvantages, it is interesting to study a complex integration of the grid with both these renewable sources.

By integrating these two systems, the average electric power taken from the grid decreases to 2,060kW (2,445kW with the solar system and 2,250kW with the wind system) since a higher share of the electric load is covered by the two decoupled sources combined together (Figure 14).

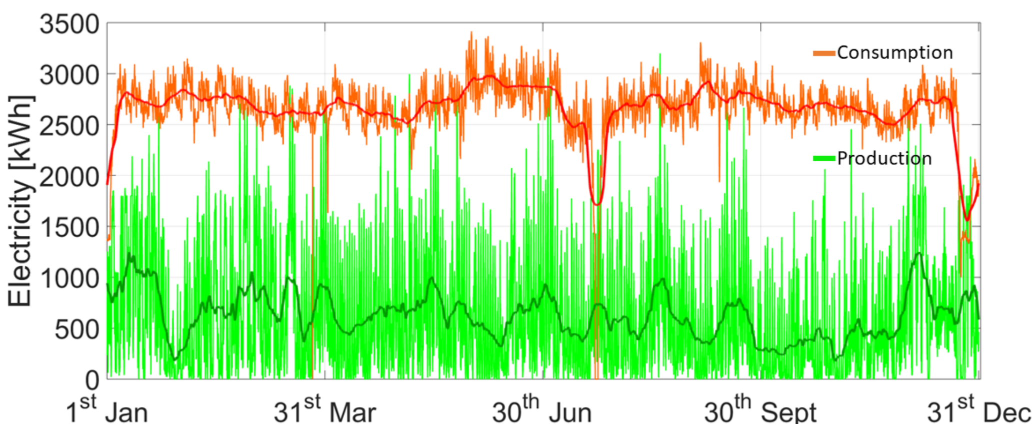


Figure 14: Electricity generated by the integrated system: raw data (lighter line) and 1-week moving average data (darker line)

The addition of wind plant introduces high variability, increasing the fluctuation of the net demand. The system has a signal variance of 1.9×10^5 $(\text{kWh})^2$ for solar, 3.6×10^5 $(\text{kWh})^2$ for wind and 4.5×10^5 $(\text{kWh})^2$ for both combined. It can be expected that the performance of PV and wind plant will gradually decrease over time, increasing the electricity requirement from the grid. Furthermore, while the manufacturing site is a net consumer of grid electricity, there are times when it is an electricity producer (see Table 3), which leads to curtailment of the extra renewable energy or to the increase in the total non-synchronous penetration on the grid.

A benefit of installing both wind and PV plant is visible in Figure 9-c. While the wind plant increases the variable demand on the grid as shown before, it improves the overall viability of the project. To achieve a *LCOE* of 0.11€/kWh after 25 years would still require a reduction of normalized *CapEx* by half.

Assuming a carbon tax of 20€ per tonne of CO_2, or other effective subsidies for on-site generation, the achieved saving increases. With a PV panel efficiency of 0.30 and a discount rate of 0.05, the *NPV* trend is shown in Figure 15. A carbon tax would make the profitability of the project easier to achieve, but a significant reduction in *CapEx* would still be required. This scenario considers a fixed value for the carbon tax during the whole lifetime of the project. However, the economic profitability of the project may be reached in a longer time if it is taken into account that the benefit of a carbon tax, here acting effectively as a subsidy, decreases as the grid is decarbonized.

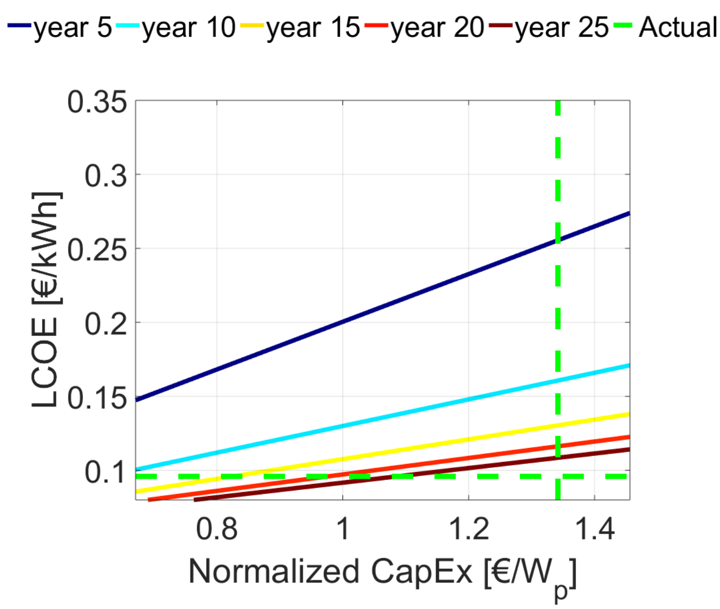


Figure 15: 0€ *NPV* curves including a carbon tax of 20€ per tonne of CO_2

4. Conclusion

This study suggests that the installation of PV and wind power plant on manufacturing sites for self consumption would be attractive only with a long Return On Investment period; a substantial subsidy (e.g. carbon tax); and the technological improvements yielding to a commensurate reduction in CapEx. Achieving all three conditions is probably unlikely, and so it is concluded that distributed renewable generation for manufacturing industry in Ireland does not make economic sense in isolation. Nonetheless, it may still be a reasonable policy goal to help reduce the carbon intensity of the national economy. A progressive decarbonization of the grid has to be achieved to decrease the environmental impact of the energy sector and on-site renewable generation for the manufacturing industry would represent a good opportunity to move towards this goal, given its peculiar features such as dedicated connections to the national utility grid, high land availability, reduction in transmission and distribution losses with RES generation plants located near the consumption point, and no need for storage.

Therefore, it may be interesting to apply the model to other manufacturing facilities in the same geographic area to assess the overall impact on the net demand since the direction of power flow at nearby manufacturing sites is likely to be correlated as the availability of renewable power will be regional. Further work is required to assess multiple manufacturing facilities following a strategy of on-site renewable generation, and how the Energy Systems can integrate.

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Glossary

Acronyms

DER	Distributed Energy Resource
DSM	Demand Side Management
HOMER	Hybrid Optimization of Multiple Electric Renewables
HVAC	Heating, Ventilation, and Air Conditioning
MERRA-2	Modern-Era Retrospective analysis for Research Applications, ver. 2
NASA	National Aeronautic and Space Administration
NREL	National Renewable Energy Laboratory
PDF	Probability Density Function
PV	Photovoltaic
RES	Renewable Energy Source
SAM	System Advisory Model
SCADA	Supervisory Control And Data Acquisition

Physical Quantities

α	Hellman exponent [-]
β	Pitch angle of the PV panel [°]
β_{opt}	Optimum pitch angle of the PV panel [°]
η_{inv}	Inverter efficiency [-]
η_{PV}	Efficiency of the PV modules [-]
ρ	Density of air $[kg/m^3]$
θ	Angle between the sun irradiance and the normal to the panel $[rad]$
A_{PV}	Area of the PV system $[m^2]$
A_{swept}	Wind turbine rotor swept area $[m^2]$
C_p	Coefficient of performance [-]
$CapEx$	Initial cost of investment [€]
CF	Capacity Factor [-]
DHI	Diffuse Horizontal Irradiance $[kW]$
DNI	Direct Normal Irradiance at its original direction $[kW]$
GHI	Global Horizontal Irradiance $[kW]$
GTI	Global Tilted Irradiance $[kW]$
kW_{peak}	Peak power of the system $[kW]$
kWh_{PV}	Annual electricity produced by the PV plant $[kWh]$
kWh_{wind}	Annual electricity produced by the wind plant $[kWh]$
$LCOE$	Levelized Cost of Energy $[€/kWh]$

n	Year of the project [-]
NPV	Cumulative Net Present Value [€]
NPV_n	Annual Net Present Value [€]
$OpEx$	Operational expenditure [€ $per\ year$]
PBT	Pay Back Time [$year$]
r	Discount rate [-]
ROI	Return On Investment period [$year$]
v	Fluid speed [m/s]
v_{cut-in}	Cut-in wind speed [m/s]
$v_{cut-out}$	Cut-out wind speed [m/s]
v_{rated}	Rated wind speed [m/s]
z	Height of the meteorological tower [m]

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