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Levelised cost of energy analysis: A Comparison of urban (micro) wind turbines and solar PV systems

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Abstract—

The relatively high capital cost associated with micro wind energy systems and the resulting long payback periods, makes for a challenging argument for these technologies. However, as the global population becomes increasingly concentrated in urban areas, the potential for accessing any available renewable energy resource, including wind and solar PV, could become a necessity. This infers that the economics associated with small/micro energy systems need to be better appreciated. This paper presents a levelised cost of energy (LCOE) analysis for rural/urban small/micro wind energy systems that is contextualised by a solar PV system comparison. Further insight is offered through a design of experiments (DOE) consideration that affords an understanding of how system parameters, such as primary energy (rural/urban wind resource and solar insolation), capital cost and loan/finance interest rate individually and collectively affect the respective technologies. The results suggest that from an economic justification perspective, urban installations are difficult to justify and solar PV systems, with the associated lowering system costs, are challenging the viability of small/micro rural wind energy systems.

Index Terms—Microgeneration, Levelised Cost of Energy (LCOE), sensitivity analysis.

I. INTRODUCTION

Wind energy is a major renewable energy resource and in a European context, wind energy accounted for the largest share (44.2%) of total 2015 power capacity installations. The majority of this new renewable capacity comes from larger plant (such as wind farms), but the residential sector's influence should not be neglected. In 2011 the residential proportion of total electricity consumption accounted for 36.3% [3] and 30.9% [4] in the US and Euro zone respectively. In comparison, solar PV is a fast growing market. According to the *Fraunhofer Institute for Solar Energy Systems* 2015 report, the compound annual growth rate (CAGR), or the mean annual growth rate of investment in solar PV systems globally was 44% (2000 to 2014). When this is compared to wind energy in a European context, the CAGR is 9.8% over the same period [5].

Unlike solar PV however, wind energy within urban environments has yet to be embraced in any meaningful way. Here demand is greatest and they could possibly supplement centralised generation, which by virtue of fossil fuel reliance, is carbon emission intense [6]. In rural environments, the average wind speed is relatively high and the homogeneous landscape promotes laminar air flow and stable (relatively)

wind direction. However, since the population centres are the urban centres, implementation of all forms of micro-generation for urban dwellings is essential if renewable energy targets are to be achieved [6].

Ireland has a relatively robust distribution network with active engagement policies for the integration of large wind projects. In this regard, Irish commitment to renewable share of electricity demand is 40% by 2020 [7]. Micro generation systems in Ireland, on the other hand, do not feature so readily. Micro generation systems are regulated since 2008. In 2009 the Department of Communication Energy and Natural announced a payment scheme €0.19 for spill energy 'exported' onto the grid i.e. the excess energy than the demand of the installation [8]. This scheme was based on two financial components; the first €0.09 being the price advocated by the regulator (CER) and the remaining €0.10 being a subsidy from ESB Customer Supply (now Electric Ireland). Currently €0.09 is offered for every kWh exported to the (Irish) distribution network by micro energy systems. However even with a technical and fiscal infrastructure, microgeneration uptake to date has been relatively poor and since April 2012, this scheme has been indefinitely suspended.

From an economic viability perspective and not withstanding broader issues such as market structure and associated regulation, the most important parameters in evaluating the viability of micro wind turbine systems are the initial cost and the cost associated with generating the energy. These parameters depend on the primary resource (average wind speed), turbine type, size, mechanical design and the ability to optimise the generation output. Cost and in particular the capital outlay, remains the main challenge in the dissemination of small wind energy systems [9]. These viability parameters however, are also relevant to solar PV systems, i.e. resource inconsistency and technology (capital) cost and associated technical limitations.

This paper discusses various issues that influence the viability of micro wind and solar PV through cost of energy analysis. In this regard, the analysis is further considered through a *design of experiments* (DOE) consideration of inter-dependencies concerning the evaluation of LCOE. The priority in the analysis is to compare urban/rural wind energy performance against a PV plant of comparable capacity; particularly in the context of increasing competition from the PV market. a *design of experiments* DOE consideration [10, 11] of how system specific parameters, such as primary

energy (wind resource and solar insolation), capital cost and loan/finance interest rate individually and collectively affect the cost of energy for both technologies.

II. METHODOLOGY

In the analyses presented here, the *Hybrid Optimization Model for Electric Renewables (HOMERTM)* optimisation software, is employed. *HOMER* facilitates a simplified means to evaluate the LCOE based on the associated energy source data, system components and a given load demand [12]. Essentially, as illustrated in Fig. 1, *HOMER* applies the renewable (primary) energy resource (wind speed and or solar insolation) to a wind turbine solar and/or PV generator model, which in turn interacts with a defined grid that includes load data.

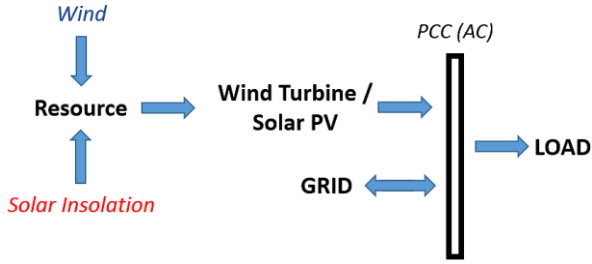


Fig. 1. System configuration and *HOMERTM* implementation structure

The annual energy produced by the wind turbine (and solar PV) and the cost of energy demand, are measured against the cost of energy production. The cost of energy production considers the initial cost and maintenance costs over the life time of the turbine and is calculated through a net present cost evaluation for generation of unit energy. In this regard, *HOMER* performs energy balance calculations (demand/generation) for the representative system configurations. Each case study is analysed on an hourly basis over the course of a year (8760 hours) through a net metering evaluation.

A. Economic Parameters

The financial context applicable for both systems, as employed by *HOMER* in evaluating LCOE, is illustrated in Table 1. The wind turbine considered is the Sky stream 3.7 (2.4kW) [17] and the PV system considered were modelled to have the same peak power capability [18].

TABLE I
ECONOMIC PARAMETER COMPARISONS

	Wind System	PV System
Capacity (kW)	2.4	
Capital cost (€)	14,520 [17]	6240 [18]
Cost/kW (€)	6050	2600
Real interest rate (%)	5	
Annual Maintenance Cost (€)	436	50
Unit cost (purchase) (€)	0.18	
Unit cost (sale) (€)	0.09	

The operation and maintenance cost (O&M) for wind turbines is estimated to be 1.5%-3% of the turbine cost but increases with time as the turbines get older [19] and for this analysis, 3% O&M was considered for the wind turbine. Maintenance is less an issue for solar PV panels as long as their inclination is greater than 15° and in this regard a

nominal annual maintenance of €50 (0.8%) was considered. The life time of the system for each case study is set at 20 years.

The real interest rate illustrated in Table 2 depends on national policy and reflects an attempt to identify the future value of investment as the associated cash flows devalue over time. The interest rate in this regard is employed as a discount factor. In other words, it facilitates a consideration of the economic, business and political/social stability and level of risk associated with each investment and how they contribute to the future value of the investment. Essentially, the value of discount reflects the cost of time, risk and expected inflation in the future. One way of considering the discount factor is in terms of the national (case study) cost of borrowing, i.e. the 10 year bond rates with some estimated risk factor included. In this regard, Ireland currently has a low interest rate (0.05%). However, in Ireland, the Department of Public Expenditure and Reform suggests a test discount rate for economic evaluation and appraisal purposes of 5%

B. (Primary) Energy Resources

The power generated by (small) wind turbines is reliant on the site specific prevailing wind characteristics, which are dependent on terrain conditions, obstacles, elevation and global wind potential. Cities are aerodynamically (very) rough with a highly localised and complex wind environment. The wind resource in rural locations on the other hand, are relatively unimpeded and statistically consistent. In either environment, air flow will interact with the underlying landscape to acquire its distinctive characteristics. The height positioning of the turbine, by virtue of the cubic relationship associated with wind speed, significantly affects the energy harnessing of such technologies. Furthermore, this cubic relationship, in terms of a fluctuating or turbulent wind resource, makes for very challenging wind energy extraction opportunities within urban environments. In contrast, when one considers the generation profile associated with Solar PV, the peak in the associated primary energy (solar irradiance) always occurs around midday.

For the analysis presented here, the rural wind energy system is considered in terms of wind observations at a synoptic weather station at Dublin Airport, where observations are recorded at 10m. The urban wind speed reference was acquired from a meteorological weather station located on the outskirts of the city centre. This weather station is placed at the top of a 10 m tower, which itself is fixed on the roof of a 16 m building. *HOMER* facilitates logarithmic scaling of the respective wind speed observations (z_{anem}) in terms of a surface roughness description (z_0), to a 20m turbine hub height (z_{hub}) (1). In this regard, generic surface roughness lengths, z_0 are chosen; 0.02m and 1.1m at the rural and urban locations respectively (based on the Davenport scale [13]). The annual average wind speed observed at the urban (Airport) site was 5.4m/s whereas at the urban location, the annual average wind speed observed was 3.4m/s.

$$\frac{u_{hub}}{u_{anem}} = \frac{\ln(z_{hub}/z_0)}{\ln(z_{anem}/z_0)} \quad (1)$$

The solar insolation consideration was facilitated through data acquired from NASA's *Surface Solar Energy Data Set* [14], which is facilitated through *HOMER*. This data is based on a latitude and longitude specification (53°, 20° and 6° and 15° respectively) and specification of *clearness index* for the location, which is a measure of the clearness of the atmosphere. This clearness index is the fraction of the solar radiation that is transmitted through the atmosphere to strike the surface of the Earth. It is a dimensionless number between 0 and 1, defined as the surface radiation divided by the extra-terrestrial radiation. This global horizontal radiation is the total amount of solar radiation striking the horizontal surface on the earth. *HOMER*, by defining the slope of the PV panel (30° in the context of a Dublin installation) and the azimuth (the direction towards which the surface faces) calculates the solar radiation incident on the surface of the PV array. The average solar radiation on the modelled PV array (2.4kW_p) was 2.43kWh/m²/d.

C. Technologies

Wind turbines extract kinetic energy from moving air, converting it into mechanical energy via the turbine rotor and then into electrical energy through the generator. The two defining aspects of a wind turbine's performance are the blade sweep area and the associated power curve for the turbine. The blade sweep area defines the amount of power that can be captured from the available wind whilst the power curve illustrates the turbines performance against varying wind speeds. The mechanical energy captured by the wind rotor is described by (2).

$$P_{Mech} = \frac{1}{2} \cdot c_p \cdot \rho_{air} \cdot A_{rotor} \cdot u_{hub}^3 \quad (2)$$

Based on the hourly average wind speed (extrapolated to the turbine hub height, as explained by (1)), *HOMER* refers to the wind turbine's power curve to calculate the power output that wind speed under standard conditions of temperature and pressure. Fig. 1 illustrates the turbine power characteristic and operation parameters.

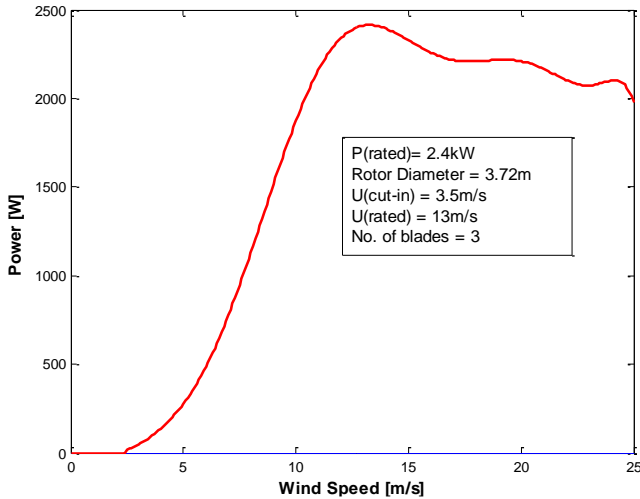


Fig. 2. Skystream 3.7 (Manufacturer) Power Curve including turbine operating characteristics

For the solar PV consideration, *HOMER* uses the following equation to calculate the output of the PV array (excluding cell temperature effects)

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}} \right) \quad (3)$$

where P_{PV} is the electrical power output from the solar PV generator (kW), Y_{PV} is the rated capacity of the PV array (power output under standard test conditions (kW)). \overline{G}_T and $\overline{G}_{T,STC}$ are the solar radiation incident on the PV array in the current time step (kW/m²) and incident radiation at standard test conditions (1 kW/m²) respectively. The PV derating factor (f_{PV}) is a scaling factor that *HOMER* applies to the PV array power output to account for reduced output in real-world operating conditions compared to the conditions under which the PV panel was rated.

D. Load

The Irish energy regulatory authority, *Commission for Energy Regulation* (CER) commissions the *Retail Market Design Service* (RMDS) to develop load profiles for the Irish Market [15]. For the analysis here, consumer hourly demand is based on an annual consumption of 5074kWh of electricity [16], which represents an average hourly demand of 0.571kW.

III. ANALYSIS

A. Levelised Cost of Energy (LCOE)

The levelised cost of energy (LCOE) in €/kWh may be represented as

$$LCOE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}} \quad (4)$$

where $C_{ann,tot}$ is the total annualised cost of the system (€/Year), and E_{prim} is the primary load served (kWh/Year), E_{def} is the deferrable load served (kWh/Year) and $E_{grid,sales}$ is the total grid sales (kWh/Year). The total annualised cost of the system ($C_{ann,tot}$) is the sum of the annualised capital cost ($C_{ann,cap}$), annualised replacement cost and annual operation and maintenance cost. The annualised capital cost is:

$$C_{ann,cap} = C_{cap} \cdot CRF(i, R_{proj}) \quad (5)$$

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (6)$$

where C_{cap} is the initial capital cost in € (which includes the costs of the power converter and connection to the grid), $CRF(i, N)$ is the capital recovery factor, i is the annual real interest rate, R_{proj} is the project lifetime and N is the number of years.

Power generation is determined in *HOMER* with grid sales and purchases being calculated by considering hourly based wind/irradiance data, energy generation and demand data over the course of a year.

B. Design of Experiments: Sensitivity Analysis

A designed experiment [10, 11] contextualises how factors such as capital, resource and interest rate, influence the LCOE for the wind and solar energy systems. In this regard, +/- 5%

variation in the respective nominal values is considered. A Pareto chart is subsequently developed to display the importance of a factor and the interactions between factors.

IV. RESULTS

Figure 3 provides a monthly summary of the wind turbine output in terms of net grid purchases (grid import) and grid sales (grid export) for each location. Based on its power characteristic, the *Skystream 3.7* wind turbine can generate 4477 kWh/year in rural Dublin and 1339 kWh/year in urban Dublin. The annual household electricity demand considered in the energy balance equations facilitated by *HOMER* is 5074 kWh/yr. At the rural (Airport site), grid sales over the year are 1820kWh, whereas the associated net purchases of electricity were 598kWh. In comparison, at the urban, grid sales are only 12% of those achievable at the rural site (215kWh), whereas net purchases are 621% more (3735kWh).

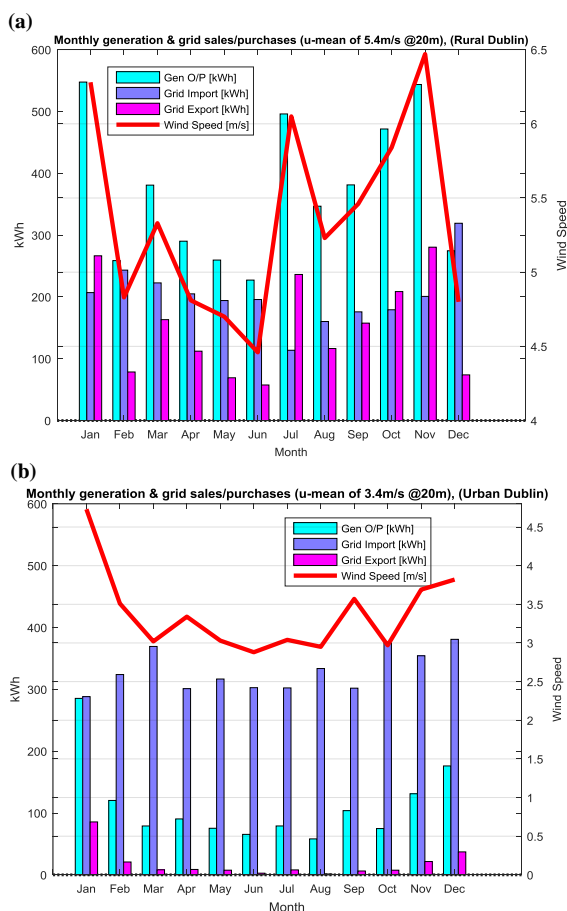


Fig. 3. Monthly mean wind, energy production and grid purchases for the rural (a) and urban (b) locations

Fig. 4 provides a monthly summary of the PV array output in terms of net grid purchases (grid import) and grid sales (grid export). In comparison to the wind energy potential, the modelled PV array can generate 2250kWh/year in a Dublin city installation context. Based on the annual solar insolation exposed to the PV array, grid sales are 823kWh, whereas the

net purchases were 2823kWh, based on grid purchases of 3646kWh.

In consideration of the LCOE analysis, Fig. 5 illustrates the annual energy produced by the generation systems in terms of an electricity unit purchase and sale cost of €0.18/kWh and of €0.09/kWh respectively. This figure further illustrates the cost per unit (kWh) generated by the respective generation systems, expressed in terms of annual mean wind speed / solar insolation, an interest rate of 5% and an initial cost per kW (as presented in Table 2). In this regard, the LCOE for each technology context is highlighted by the solitary point in each chart ((a)-(c)). The respective lines in each sub-plot ((a)-(c)) trace the wind speed or solar insolation at which the wind turbine or PV system can provide a cost effective source of electricity (less than €0.18/kWh) in terms of the initial cost per kW. The colour bars illustrate the actual cost/kWh for each technology context in terms of a scaled annual primary resource (wind/solar). Table 2 summarises the LCOE for both wind generation contexts *vis a vis* the modelled PV consideration.

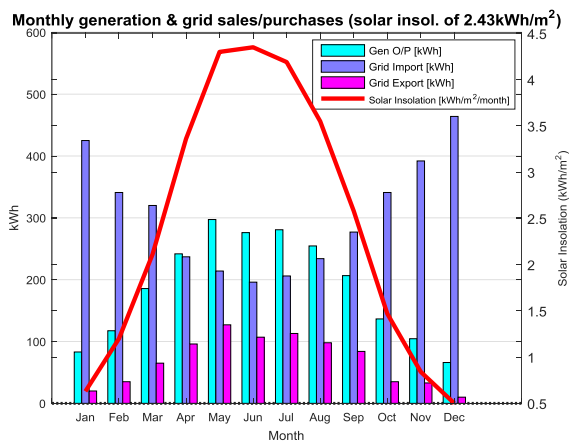


Fig.4. Monthly mean wind, energy production and grid purchases for the modelled PV array

TABLE 2 WIND/SOLAR SYSTEM LCOE IN RESPECT TO THE ANNUAL MEAN WIND SPEED / SOLAR INSOLATION AND RESPECTIVE CAPITAL COST ASSOCIATED WITH EACH SYSTEM

	Rural wind energy	Urban wind energy	(Urban) solar PV energy
Cost of wind / solar PV energy generations (€/kWh/[mean wind / mean irradiance])	€0.36	€1.20	€0.24

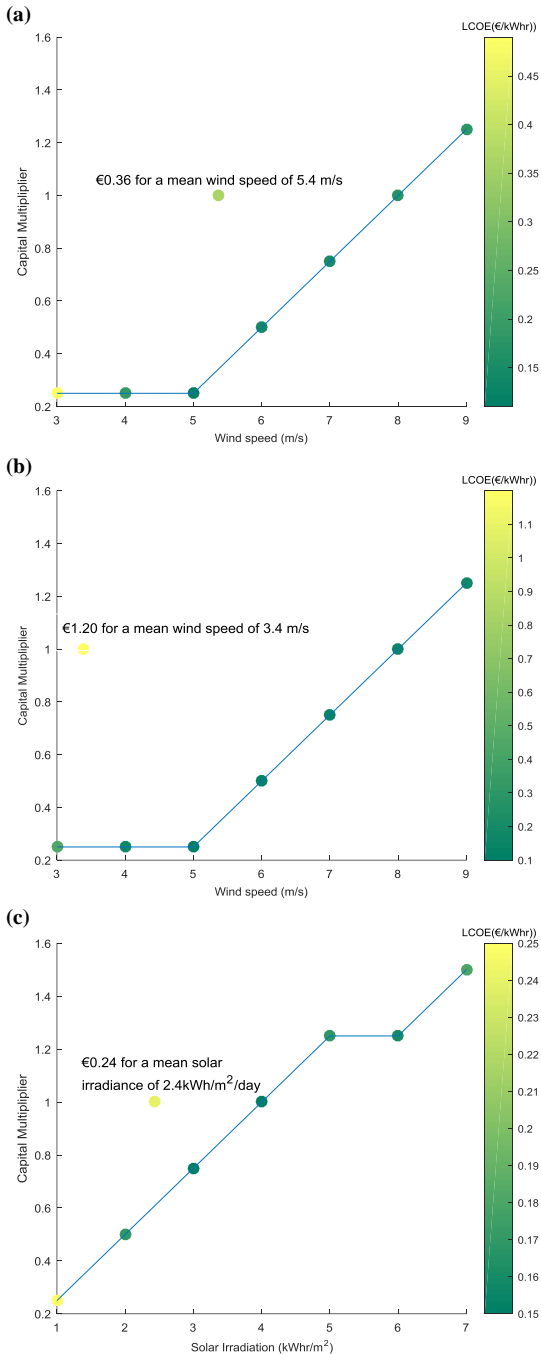


Fig. 5. Monthly mean wind/solar insolation, energy production and grid purchases for the rural wind (a), urban wind (b) and solar PV systems (c)

The LCOE for the energy generated in the respective contexts, provides for an economic appreciation of generator performance, but it does not facilitate an understanding of how it can be optimised. A Design of Experiments (DOE) analysis [10, 11] offers insight into how the parameters, as defined in Table 1, contribute individually - and collectively - to the LCOE calculated. Employing the methodology provided in [10], a Pareto chart is developed, as provided in Fig. 6, to display the importance of the capital, resource and interest rate in this regard.

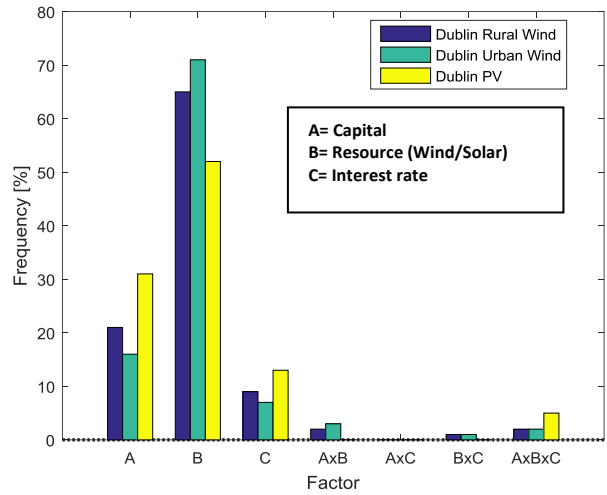


Fig. 6. The application of DOE in determining the significance of resource, capital cost and real interest rate

Fig. 6 clearly identifies that the main contributing factor to the LOCE for the wind energy systems is the local wind speed, with the capital cost playing a secondary role in its determination. From a PV system perspective, the resource is also identified as the main factor but the capital outlay is more influential. In both types of system the interest rate applied in the calculation of LCOE is less influential albeit slightly more so for the PV consideration.

V. CONCLUSIONS

From an Irish perspective, small wind / solar PV generation systems (microgeneration) face significant challenges if they are to effectively contribute in a future energy mix. In this regard this paper considered the primary energy resource as it applies to both wind and PV systems and the associated financial considerations as they apply to system performance evaluation. Physical considerations include the installation environment and available resource.

The financial considerations should be cognisant of system costs, which can be fixed (e.g. capital and O&M costs) and variable in nature. The variable costs depend on the consumer demand and turbine output, but also relevant is the real interest rate over the life time of the system. Ultimately, system (kWh) productivity and its effective system deployment are dependent on a good primary energy resource. The research presented in this paper primarily focuses on the system financial concerns. However, in evaluating the levelized cost, the intra effects of capital outlay, loan (real) interest rate and primary energy resource available at the location where the wind and solar PV generators are installed was considered through a Design of Experiments analysis.

The DOW analysis illustrated that the wind turbine productivity and its effective system deployment are dependent on a good wind resource. The same can be said about the solar PV system, but capital outlay is also influential. Ultimately however, the analysis shows that PV systems are more financially competitive than wind energy;

even in a rural context where the wind resource is more favourable.

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