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Energy demand analysis via small scale hydroponic systems in suburban areas – An integrated energy-food nexus solution

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ABSTRACT

The study is a qualitative approach and looks into new ways for the effective energy management of a wind farm (WF) operation in a suburban or near-urban environment in order the generated electricity to be utilised for hydroponic farming purposes as well. Since soilless hydroponic indoor systems gain more and more attention one basic goal, among others, is to take advantage of this not typical electricity demand and by managing it, offering to the grid a less fluctuating electricity generation signal. In this paper, a hybrid business model is presented where the Distributed Energy Resources (DER) producer is participating in the electricity markets under competitive processes (spot market, real-time markets etc.) and at the same time acts as a retailer offering – based on the demand – to the hydroponic units for their mass deployment in an area, putting forward an integrated energy-food nexus approach.

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1. Introduction

Under the approach of our electric future (*Our Electric Future*, 2016; *Planning Our Electric Future: A White Paper for Secure, Affordable and Low-carbon Energy*, 2011) that has been gaining more and more attention over the last decades, traditional production is evolving following alternative paths. Indoor farming has started leaving its mark. Farmers initiated examining alternative ways that could assist them to: a) produce indoors being protected from harsh environment and intense climatic conditions (either rough winters, or dry and hot summers), b) produce in a relatively isolated environment, controlling growth conditions, and c) avoid tares or other exogenous ground factors that influence productivity. Hydroponics is a method of growing plants using direct feeding of nutrients, light, water solutions, often in a soilless environment. This requires constant electricity supply (lighting, A/C and ancillary equipment), water, and

heating in order to surrogate natural processes. This means that for large scale deployment, isolated environments, electricity, and heating (at least) are required. A promising solution is buildings. Buildings meet the requirements for a controlled environment, electricity, heating and water. In the building industry there is a tendency of growing interest to integrate systems into constructions. Integrated renewable energy systems (Kalogirou, 2016) is not the only obvious option; lately, buildings are operated similarly to batteries. Smart grids applications (Sossan et al., 2016; Behboodi et al., 2016) and demand side management programmes for communities (Xydis et al., 2013) have converted consumers to prosumers (Xie et al., 2008). End-users have the ability to respond according to the signal from the utility, and according to the demand response (DR) program chosen.

Providing electricity, heating and maintaining a proper indoor environment shall increase costs for those investing in this type of farming. It sounds as a comparable solution for all dry arid and semiarid (desert, steppe), polar, alpine, and subarctic climates and perhaps in cases for intense mountainous or even tropical environments. Even in Mediterranean climates and mild maritime climates, hydroponic systems for certain types of farming could be profitable. By increasing the number of harvests per year – based on the selected cultivation each time – profitability is also increased. Therefore, by selecting an efficient cultivation (e.g. with a harvesting rate of 20 times a year), this will ensue in crop output growth, and thus in maximizing profits. The immediate social impact out of this, is that consumers have easy access to fresh vegetables produced locally, throughout the year, avoiding transportation – and therefore CO₂ emissions – from distant areas (Ohyama et al., 2008). Indoor farming units, promote also food supply security in cities and achieve optimization of resources utiliza-

Abbreviations: B, blocks of flats available; DER, Distributed Energy Resources; DR, demand response; FIP, Feed-in Premium; FIT, Feed-in Tariff; GIS, Geographic Information Systems; IRR, Internal Rate of Return; kWh, kilowatt-hours; m.a.g.l., meters above ground level; m/s, meters per second; MW, megawatt; MWh, megawatt-hours; QGIS, QuantumGIS; RES, Renewable Energy Sources; RIX, Rugedness Index; SMP, System Marginal Price; *Ted*, total electricity demand; *U*, ratio of buildings located in urban environment; *VD_p*, number of vacant dwellings in Peloponnese; *VD_T*, vacant dwellings in Tripoli; WAsP, Wind Atlas Analysis and Application Program; WF, wind farm; WT, wind turbine

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tion contributing to the prosperous smart cities concept. Soilless cultivation methods are gaining ground – in comparison to the population-related increasing needs of available agricultural land – due to their improved space, energy, material and resources utilization (D'Autilia and D'Ambrosi, 2015; Ronay and Dumitru, 2015; Putra and Yuliando, 2015).

On the other hand, although it seems a far distant goal – yet so relevant – Renewable Energy Sources (RES) integration to the grid (in practice exactly where is mostly needed, where the demand is high, in the urban environment) can be maximized via hydroponics dynamic development in cities. A wind power integration analysis via DR of such units can be proven a powerful tool for minimizing wind power losses, due to curtailment. A detailed analysis was implemented aiming at identifying the opportunities for integration via a significant amount of hydroponic farming in urban areas. The main need of the independent power producer (IPP) is to offer (bid) the generated power into the electricity markets. There are high demand periods and low demand periods and thus, the integration requirements of the system can vary significantly. However, it should be stated that the regulation cost – which may influence the system price when RES integration is significant – is not considered in this study. A large scale deployment of urban indoor small scale hydroponic units can work towards integration of greater quantities of generated wind power – participating in the market as an authorised electricity supplier as well – and at the same time create career opportunities in cities in a protected environment for the weather-sensitive agricultural products.

In Greece, there is a large number of available building resource with more than 450,000 dwellings and 270,000 commercial buildings unrented and on top of that another 350,000 unused. These buildings are losing their market value since owners do not have the intention to rent or sell them for various reasons (ELSTAT, 2014; Liaros et al., 2016). Thus, buildings could act as a virtual batteries or virtual power plants by participating in DR programmes, assisting in achieving higher shares of renewables into the grid. Furthermore, taking into account the buildings' usage on setting up hydroponic systems, the perspective of WF development in an area, and according to the local power absorption, the option of WF extension is examined. For the extension of the WF, wind resource assessment results identify one by one the new wind turbines sites. Therefore, based on the wind resource analyses results and on the integration options, the final WF layout can be decided and a detailed economic analysis of the proposed layouts can specify the benefits for both the grid and the investor.

2. Methodology

In order to take this matter further, and investigate the concept in practice, a detailed wind resource assessment of the focus area is needed. Yearly measurements were taken and wind analyses and spatial analyses implemented to accurately determine the wind energy integration and urban plant units development perspectives of the area determining the WF layout and optimising the sales in the electricity markets (Fig. 1).

2.1. Wind resource assessment results and mass scale hydroponic deployment

Detailed wind speed and direction measurements are crucial in order to identify areas with wind resource at exploitable levels. For the wind resource assessment in the focus area, including the WF development area and the wind mast exact location, near the city of Tripoli

Fig. 1. A detailed flowchart of the proposed methodology.

in Peloponnese (Fig. 1), Geographic Information Systems (GIS) tools, such as the open source QuantumGIS (QGIS) (QGIS Development Team, 2016), WAsP (Mortensen et al., 1993), and WindRose (*WindRose — A Wind Data Analysis Tool. User's Guide*, n.d.) software tools were used as spatial and wind assessment tools, and a wind map was developed displaying the wind speed at 80 m above ground level (m.a.g.l.) in the area (Fig. 2).

The mean speed and power density maps are shown in Fig. 3. The tools were used for processing the yearly measurements and generated estimates of speed/power outputs. Fig. 2 includes information on the elevation of the area, where it is seen that the focus areas are approximately at 1000 m.a.g.l.

Based on the analysis, it is evident that sites with satisfactory wind power density are a lot fewer than those of good wind speed. It should be noted that developing a WF along the ridge and simulating that with WAsP does not create inaccuracies since the Ruggedness Index (RIX) towards the ridge is on average below 17° (low complexity site) and therefore flow separation shall not be significant or at least the most crucial factor (Wallbank Tristan, 2008). It can be seen that there are several sites that their wind resource is at exploitable levels. The light blue and green areas have wind speed lower than 4.0 m/s, yellow and light orange coloured areas are 4.0–6.0 m/s, while intense orange and red are in the range of 6.0–7.0 m/s and these are the sites that attract the investors' interest. In this case study, this is highly required for the small scale hydroponic units' development in urban and suburban environment, and in specific near the city of Tripoli. In order to reach to bankable wind energy projects that via small scale hydroponic systems shall synergistically work towards achieving higher energy management effi-

Fig. 2. A satellite image and a wind resource map of the area including the WF siting.

Fig. 3. Elevation, power density, and mean speed maps of the area.

ciencies, the city's potential availability in such units needs to be studied.

The population of the city of Tripoli is approx. 47,250 inhabitants out of 577,800 of Peloponnese in total, which is the 8.2%. Based on the 2011 population and housing census (ELSTAT, 2014), the vacant dwellings in Tripoli, VD_T , are:

$$VD_T = 8.2\% \cdot VD_P \cdot B \cdot U = 6,988 \quad (1)$$

where VD_P is the number of vacant dwellings in Peloponnese, B the blocks of flats available, and U the ratio of those located in urban environment. 44.7% of the total of conventional dwellings are in blocks of flats, with the big majority of them (96.1%) are located in big urban centres (ELSTAT, 2014). Therefore, the local available dwellings are 6988 in the city of Tripoli.

Regarding electricity, it can be seen, based on a number of studies (Aldrich and Bartok, 1994; Hernandez, 2016; Wallace and Anciso, 2016; Putera et al., 2015) that the average electricity consumption is between 14–17 kWh/m² per year, depending on the hydroponic unit structure (e.g. number of tiers and real cultivated area) and the produced product. However, an indoor hydroponic unit can and shall -

many times throughout a year-change cultivation. Therefore, as soon as the structure of the specific indoor unit is finalised, it is then known what the operational costs of the unit really are.

Assuming that the real cultivated area in every flat is 100 m², the electricity demand, Ed , reaches 1400–1700 kWh/yr per flat (average: 1550 kWh/yr per flat). Therefore, for the total electricity demand Ted for the available dwellings in Tripoli, and assuming – rather conservatively – that only 100 m² is the real cultivated area, there is a demand of:

$$Ted = VD_T \cdot 6,988 = 10,831 \text{ MWh annually} \quad (2)$$

which means – since the concept started being developed with wind turbines – that there is a need of 4–5 MW installed (e.g. at least 2 wind turbines of 2 MW each). Based on the initial siting of the WF (Fig. 1), the Gross Annual Energy Production can be seen in Table 1. Taking into account that on average the WF losses could be 10% (or sometimes more in cases where the interconnection is difficult or the WF installation altitude is high etc.) (Xydis, 2012), the Net Annual Energy Production (AEP) can reach 10,427 MWh which can barely meet the demand estimated in Eq. (2).

Table 1

Results of the initial siting plan of the 2 WT, 2 MWs each.

WT	X-coords [m]	Y-coords [m]	Elev. [m]	Height [m]	U [m/s]	Gross AEP [GWh]	Loss [%]
WT1	363,240	4,155,191	1100	78	6.72	5.707	0.25
WT2	363,035	4,155,648	1100	78	6.86	5.879	1.24
Sum						11.586	

2.2. New business models in the Greek RES market

In comparison with the Feed-in Tariff (FIT) scheme existing in the Greek market, a more “market oriented” design is the Feed-in Premium (FIP), which is expected to be put into force soon. Renewable energy based project generators that operate under this policy are selling their generated electricity directly to the market receiving a premium payment above the System Marginal Price (SMP) (Eq. (3)).

$$\text{FIP} = \text{SMP} + \text{Premium} \quad (3)$$

The FIP policy can be further distinguished into two main subcategories. The first refers to a scheme in which the premium which is added on top of the system marginal price is always remains constant. For that reason this scheme is called constant FIP. One major drawback of this scheme is that it can lead to higher payment levels thus making the policy more expensive to be implemented. Furthermore, these higher payments can also distort the fair competition in the market as it can skyrocket the profits of renewable energy based projects. The other option of FIP was introduced in the first place by Spain with the RD 661/2007. The policy makers of the country in order to avoid the overcompensation risk of the renewable generators in times of high demand, introduced the “floors” and “caps” system which turned the added premium into a variable that rise when the electricity prices are falling and decreases when the prices increase. In this system the “floor” is the lowest “guaranteed” payment that the generators will receive. That “floor” combines the system marginal price that electricity markets is cleared plus a premium, while the “cap” system is a price which the total payment cannot exceed.

Under this policy scheme, it's not at all sure that renewable energy generators shall be in a position to bid in the market under a competitive process and ensure their projects' profitability. Therefore, innovative business models should be considered, such as combining offering to the market when possible at a profitable rate and the amounts that cannot be absorbed by the system, offered to support the development of hydroponic units selling their power at retail prices. In this paper, in this case study, this was thoroughly examined. The electricity price was taken to be 0.12 €/kWh based on recent reports from Eurostat (2015), however many pricing scenarios were examined.

Following the cash flow analysis of Xydis (2013) for the development of a WF in Kythira Island – adjusting the tool to the FIP mechanism –several scenarios under the new proposed schemes are examined. The bottom line of all the scenarios is the 0% of state subsidization. Due to the long-lasting crisis and requirements for fiscal reforms, state subsidy is not applicable for new RES projects. Although it is discussed that for wind projects of capacity less than 10 MW the feed-in-tariff scheme will remain, in this analysis is conservatively considered that the FIP mechanism shall stand for all new projects.

Regarding crucial assumptions for this study, an average SMP and the corresponding FIP for the investor in the range of 30–75 €/MWh was taken (based on the cups and floors concept) into account along with the assumption that the investor sells 50–100% of the generated

electricity to the spot market and accordingly the remaining either directly or via storage systems and DR to indoor farming (Wells, 2014) at retail prices. Therefore, new business models in the Greek RES market are developed trying to combine the vital need for food production, and at the same time meet the requirements for higher shares of renewable energy sources into the grid.

3. Results and discussion

In the case study examined in this paper, near Tripoli, the size of the proposed WF was decided based on the wind resource assessment results. The WF size is finalised – at the study level – based on the investment's extent and profitability-viability opportunity, which in this concept means the proper share of the wind power generated put up in the spot market and the indoor hydroponic units' exploitation. A 3D drawing of the scalable indoor unit is shown in Fig. 4.

This unit can be extended following the indoor arrangement of each dwelling. The typical layout of the floor adopted by Kozai et al. (Kozai, 2016) is illustrated in Fig. 4. Changing rooms for the workers are installed inside the operation room, working tables, a cooling room, a refrigerator unit, administrative office and a rest room area are also foreseen, however, the layout of Fig. 5 is only indicative.

Simulations are carried out for a proposed WF integrated in the power system considering the energy sector economic conditions as already stated. Model runs are carried out investigating the consequences of having different degrees of market integration when a significant energy demand option is small scale hydroponic systems and having different amounts of well-functioning intra-day market for the operation in terms of system costs and CO₂ emissions. The detailed

Fig. 4. Engineering drawing of the indoor unit.

Fig. 5. Typical floor plan of an indoor floor unit (Kozai, 2016).

technoeconomic analysis is focusing on presenting the relation to the market sales in comparison to the project Internal Rate of Return (IRR) of different project scenarios (Fig. 6).

For instance, “SCE_4MW_90%_75” means that the scenario examined was of a 4 MW wind farm (see Fig. 1 for the siting of the WF), selling 90% of the electricity produced on the market, with a FIP price of 75 €/MWh. It can be seen that several scenarios of electricity produced offered to the spot market were examined. What is obvious is that the difference in the sales, between 50–90% of selling in the market, is higher in high pricing (e.g. FIP at 75 €/MWh) and not so significant when the price is at 30–40 €/MWh, which is reasonable.

What should be noted, is that the higher the amount of electricity not offered in the spot market (therefore, offered to the local indoor hydroponic units) is, the higher the IRR of the project. Note that

0.12 €/kWh is the electricity price based on recent reports from Eurostat (2015).

Selling 100% to the spot market (which is, in practice, out of the scope of this study) is separately presented in Fig. 7. It should be stated, in order for an investor to have a profitable project (IRR = 12%), the generated electricity power should be offered at 75 €/MWh FIP, which is considered price at high risk, while selling at 40 €/MWh FIP – which is still considered a high price considering the marginal system price in different markets in EU – could make the project nonprintable (IRR = -4%). Selling with a FIP price 30 €/MWh, under these scenarios, was not examined.

It was noticed that by increasing the available output to the retailers, the more profitable the project becomes for the operator. Therefore, a storage mean or associated hydroponic related DR programmes are required. In order to approach the concept development realistically, three crucial questions should be answered:

Fig. 6. Scenario-based technoeconomic analysis results.

Fig. 7. IRR of the project when selling at different prices only in the spot market.

1. What is the maximum of the generated electricity that can be wasted (curtailment or just not offered neither to the spot market nor the hydroponic units) and still the project's payback period be less than 10 years (note that the new Renewable Energy plan aims to constrain projects' IRR to around 9% (PV Magazine, n.d.))?
2. What if the average retail price goes really low? What if they go unexpectedly high? How this can influence projects' profitability?
3. Are there any other options for the WF planning (e.g. smaller size WTs)? Is expandability an option in case higher amounts of electricity from wind energy could be integrated?

Regarding the first question, it is crucial to evaluate and understand under which pragmatic conditions such type of projects could be viable. Assuming 0.12 €/kWh is the electricity price in these scenarios and examining scenarios in the form of "SCE_4MW_50%-45%_30" which means that the scenario examined was of a 4 MW wind farm, selling 50% of the electricity produced on the market and 45% in the retail market (on the hydroponic units), with a FIP price of 30 €/MWh, the results are shown in Fig. 8. It is proven that even if the system operator requires the project to have up to 10% rejected (curtailment), the IRR of the project can be retained not lower than 8.6% and payback period no more than 10 years, which ensures viability. With a 2.5% curtailed and a selling price of 30 €/MWh, which can be a realistic scenario, the project can reach an IRR of almost 13%. All other combinations with curtailment more than 10% are proven not attractive for private investors to the concept.

Regarding the second question, a number of pragmatic scenarios were examined. Different retail prices under the 50–40% scheme, as explained below, and assuming among 0.07–0.31 €/kWh electricity price according to the Eurostat statistics for electricity and gas prices, for 2013–15 (Energy Price Statistics, n.d.). In specific, in order the reader to be able to conceive Fig. 8, the form of "SCE_4MW_30_0.11" means that the scenario examined was of a 4 MW wind farm, selling 50% of the electricity produced on the market and 40% (meaning 10% curtailment) on the hydroponic units (retail market), with a FIP price at 30 €/MWh and electricity prices for household consumers at 0.11 €/KWh. The simulation results are shown in Fig. 9.

The range for the retail prices for household consumers for the scenarios was taken based on the electricity and gas prices in EU-28 countries and this is the reason that a project can have an IRR above 9% with an retail electricity price greater than 0.121 €/kWh. It is obvious that if the retail price goes really high (e.g. at 0.3 €/kWh such as in the cases of Germany and Denmark (Energy Price Statistics, n.d.)) the payback period of such a project could go down at 2–3 years, with an IRR at 35–40%, however this influences significantly the end-user (via the monthly or bimonthly electricity bill) since these costs are significantly high and tough to be burdened. This is something that makes evident and profound the inequality among European markets and the imbalances that this could provoke in investment plans in the energy and other sectors in Europe.

Last, regarding the third question, working with an alternative scenario of WF siting in the same area (Fig. 10), an 800 kW WT was selected and a 6 WT WF, of 4.8 MW in total was proposed and examined.

According to the simulations (Mortensen et al., 1993), the total capacity had to be greater than 4 MW as in the basic siting scenario with the two WTs, 2 MW each, since the total productivity had to be the approximately the same for the scenarios in order to be comparable (Table 2).

It can be seen that the Project IRR and the payback time are significantly lower when using smaller WTs in comparison with the results shown in Fig. 7. It should be noted that there is also a significant difference in the IRR and in the payback time when examine different scenarios of the electricity retail price. In Fig. 8 the retail price it should be approximately at 110 €/MWh selling price to the end-user in order the project's payback period to be 10 years while in Fig. 11 the retail price is required to be at least 150 €/MWh.

4. Conclusion

In modern power systems the grid can efficiently achieve maximisation of wind power and other Renewable Energy Sources (RES) integration by promoting the participation in DR. The idea behind this work is to examine when power is elsewhere (in urban and suburban areas) needed, hydroponic units can minimise their power supply needs, allowing to the utility not to introduce expensive and less

Fig. 8. IRR results and payback period in scenarios with curtailment up to 10% at 30 €/MWh.

Fig. 9. Range of projects' viability with 10% curtailment, FIP at 30 €/KWh according to various electricity prices for household consumers.

clean thermal power plants into the system in order to cover the peak demand but meet the demand by postponing it via the DR option. The mass deployment of small scale hydroponic units was studied and economically analysed extensively producing various results depending on each scenario examined. The large number of scenarios examined different FIP policies (30–75 €/MWh), several electricity retail prices (75–310 €/MWh), 2 different sizes of WFs (4 and 4.8 MW) under a detailed wind resource analysis of the area and WF siting, and a 0–10% grid curtailment. Three realistic and crucial questions were answered pointing out the importance of the proposed concept/idea not only for the effective operation of power systems by means of efficient market transactions, but also by focusing on new market architectures and incentive policies for integrating DER and DR such as hydroponic units. Under the intense and long-lasting economic crisis in the country, energy cooperative models for a sustainable and shared energy approaches, based on the local community engagement, could lead to the reduction of the energy cost (however not taking into account the significant at times regulation costs), which has more than doubled in the country over the last decade, CO₂ emissions and become a catalyst for raising awareness and be the drive for the youngest generations towards circular economy and greener energy communities.

Fig. 10. Alternative WF siting using a 0.8 MW WT.

Table 2

Results of the alternative scenario of WF siting plan of the 6 WT, 0.8 MWs each.

WT	X-coords [m]	Y-coords [m]	Elev. [m]	Height [m]	U [m/s]	Gross AEP [GWh]	Loss [%]
WT1	363,069	4,155,723	1091	65	6.68	2.018	1.93
WT2	363,159	4,155,508	1091	65	6.54	1.942	1.86
WT3	363,223	4,155,285	1100	65	6.65	2.010	1.77
WT4	363,317	4,155,067	1100	65	6.57	1.965	1.41
WT5	363,490	4,154,861	1063	65	6.13	1.746	0.28
WT6	364,260	4,154,374	1135	65	6.32	1.849	0.46
Sum						11.530

Fig. 11. Comparison with the IRR and the payback results presented in Figs. 7 and 8.

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