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Article

Confronting Urban Electricity Demand with Wind Energy Supply: Case Study in Ecuador

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Abstract: On 2013 the Villonaco wind farm (16.5 MW), the first wind farm in continental Ecuador near the city of Loja, began operations. The power generated is delivered to the National Interconnected System (SNI), which services the city. This research confronts two sets of real data, the electricity use of the urban area of Loja, and the power generated by the Villonaco Wind Farm. Electricity use follows clearly defined daily and weekly cycles, and wind power has a seasonal behaviour. The study shows that wind power integration cannot be a long-term stable power source regardless power or generation surplus. Another essential finding is that time series can be used as a statistical source to determine the need for short- (seconds) and long- (days, weeks) term energy storage. Strategies to further the energy autonomy of the urban area through the expansion of the wind farm by a factor of 2 are discussed.

Keywords: wind power; urban areas; power management

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1. Introduction

Urban energy systems are essential for any city, which require a reliable an abundant source of electric power, as well as other services such as drinking water, fuels for transportation, or food [1]. On the other hand, the double fossil fuel crisis (availability and pollution) impulses an urgent and unavoidable energy transition towards renewable sources [2–4]. A detailed analysis of electricity use and its relation to local energy resources, economic activity and the environment provides a very valuable information that can be used as a base to plan the energy transition of urban areas [5].

The current energy system must therefore transition in order to integrate Distributed Energy Resources (DER) and Demand Response programs (DR) [6,7]. This paradigm shift introduces new challenges to the management of electricity systems. On one hand, utilities and distributors will need to implement systems to monitor and control the electricity grid in order to integrate distributed generation, especially on the medium- and low-voltage networks, and on the other, electricity users, that historically had been regarded as passive subjects, will gain an active role as prosumers [8–10].

The integration of DER and DR into the electricity system introduces power continuity and reliability issues, which brings up the need for utility scale energy storage systems. Current energy storage systems have a limited capacity and can only cover short-term intermittencies [11]. Therefore, in order to have a reliable energy system in the long term without using fossil fuels, the current energy infrastructure needs substantial systemic changes [12].

The worst case scenario is a quick depletion of fossil fuel reserves [13] compounded with the lack of a viable utility scale electricity storage technology that would allow high penetration of renewable energy in the energy system. This situation could jeopardize the mid- and long-term viability of electricity systems with the current service availability and continuity standards.

Renewable energy sources can supply most of the electricity demand. However, renewable electricity generation depends on the instant availability of renewable energy resources. For instance, wind power intermittency is substantial even when considered over large geographical areas [14].

The large-scale introduction of DER in all levels of the electricity system (high-, mid-, and low-voltage) requires a back-up of fast response generation systems in order to ensure grid stability and quality of supply. Using different intermittent systems combined, or in large geographical areas, makes the intermittency easier to manage as they often compensate each other. Characterising DER over large areas is a task that is necessary to optimize the energy mix to reduce intermittency. DER generation simulations [15,16] are a first step towards this optimization, but they lack the comparison with electricity demand.

This research compares the electricity demand of an urban area with the power supply based on the DER generation of a nearby wind farm. The urban area electricity use follows daily, weekly and yearly patterns. Electricity generation depends on wind availability, which is determined by weather conditions, so it has a very high variability, although it also follows a seasonal pattern.

This analysis is based on the aggregated measurements of the electricity uses within the Loja urban area measured at its substations, and the data from the Villonaco wind farm SCADA. The study assumes that power generated by the wind farm is used at the urban area, and the National Interconnected System (SNI) of Ecuador supplies the reminder of the demand, covers generation gaps, and serves as a power sink whenever there is a generation surplus.

Loja is located at the end of a radial branch of the National Interconnected System (NIS), which entails a high vulnerability of becoming isolated. Therefore, the scenario where the urban area of Loja becomes isolated from the NIS is also considered.

The main results from matching electricity generation and use data are quantitative. The Villonaco wind farm does not provide a continual supply during some time intervals, even when considering an expansion by a factor of 2, since when the wind speed is lower than the cut-off value of the turbines no power is generated.

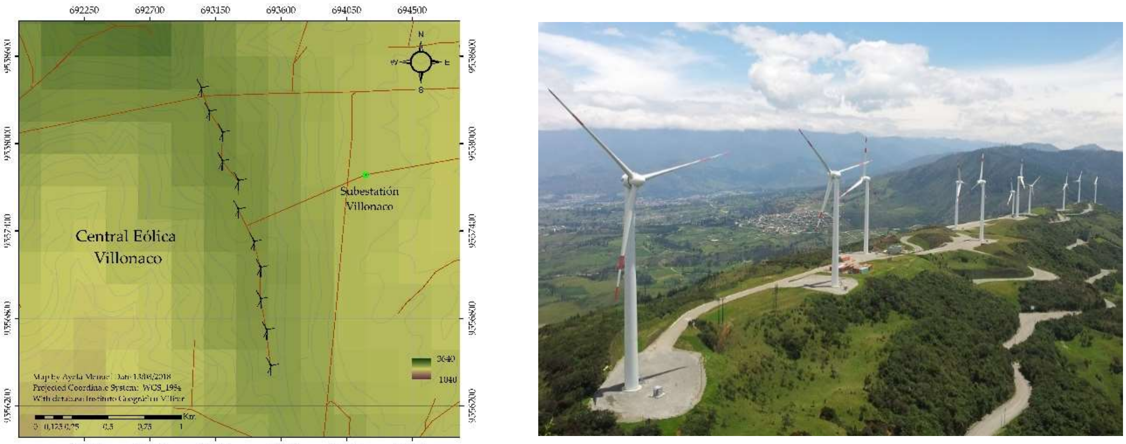
The analysis of the generation shows some degree of seasonality, with months from January to March presenting more frequent and longer generation gaps, and an overall lower power generation than the rest of the year. This knowledge will be useful to set up storage systems both for the short term (seconds) and the long term (days or weeks).

2. Materials and Methods

2.1. Wind resource data

The Villonaco wind farm is located in the region of Loja, on top of the Villonaco hill at 2 700 meters above sea level, in an area which is considered orographically complex. It began operations on 2013 [17]. Figure 1 (**a**) shows the spatial distribution of the wind turbines, and Figure 1 (**b**) is a picture of the wind farm.

The wind farm site enjoys a wind resource of an exceptional quality, due to the temperature difference between both sides of the Villonaco hills, with Loja, at 2 100 m a.s.l. on the west, and Catamayo, at 1 000 m a.s.l. on the east. This orographic peculiarity produces the Föhn effect, with an eastward movement of air that generates steady winds in that direction. The result is a high density of wind resource in the area where the wind farm is located. Indigenous people call this type of orographic phenomenon Huayrapungo (wind gate in Quechua language).



(**a**) (**b**)

Figure 1. Villonaco wind farm (**a**) geographic setting; (**b**) the farm and its surroundings

The wind farm consists of 11 direct drive wind turbines model GW70/1 500 of 1.5 MW capacity each, for a total installed capacity of 16.5 MW.

Table 1 shows the coordinates and base altitude of each wind turbine.

Table 1. Geographic coordinates and altitude of the wind turbines

Wind turbine	Latitude (S)	Longitude (W)	Altitude (m a.s.l.)
V1	-3.9934°	-79.2612°	2 753.4
V2	-3.9949°	-79.2606°	2 743.7
V3	-3.9962°	-79.2598°	2 745.0
V4	-3.9980°	-79.2598°	2 745.0
V5	-3.9992°	-79.2589°	2 730.8
V6	-4.0010°	-79.2588°	2 738.6
V7	-4.0030°	-79.2576°	2 706.2
V8	-4.0046°	-79.2575°	2 704.3
V9	-4.0065°	-79.2574°	2 704.5
V10	-4.0085°	-79.2571°	2 700.5
V11	-4.0107°	-79.2568°	2 667.6

Source: CELEC EL GEN SUR.

The wind resource is measured with weather stations located 80m above the ground, on the nacelle. Data are taken for mean wind speed, wind direction, temperature and air density on a 15-minutes frequency.

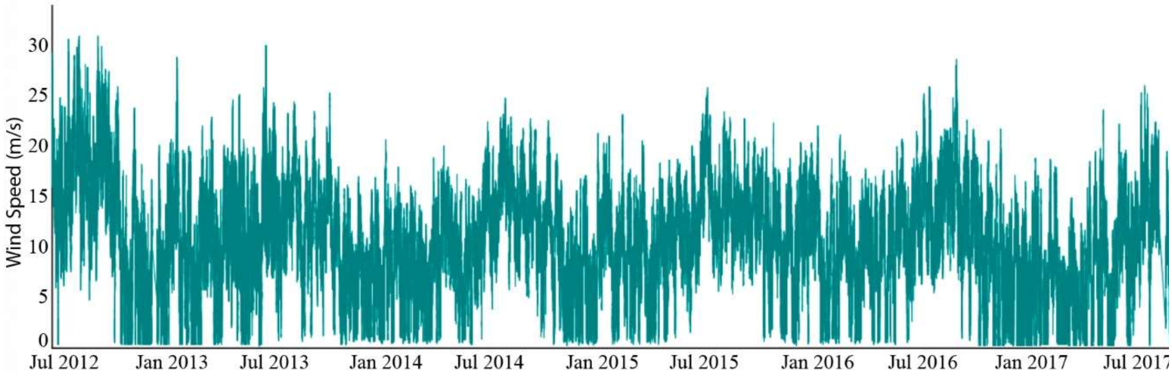


Figure 2. Wind speed at 80 m, July 2012- July 1017

Figure 2, shows the wind speed readings from July 2012 to July 2017. The readings show a yearly pattern characterized by strong winds between July and September and a lower wind availability from January to April, resulting in frequent generation gaps during these months. This showcases the natural shortcomings of renewable energy systems and how they compromise generation continuity, and singles out some of the challenges of the management of renewable energy systems. In this case, the management of a wind farm as the main energy source with the support of the NIS to cover generation gaps.

The study period was defined from May 2015 to April 2016 due to the good quality of data for a full year, with sporadic missing data (< 0.2%).

The integration of energy for the superposition period was calculated using an interval integrator based on the Riemann theorem. It considers Generators $G = \{g_1, g_2, \dots, g_G^u\}$, Loads $D = \{d_1, d_2, \dots, d_D^u\}$, and time $\mathcal{T} = \{1,2,3,\dots,n\}$ divided into equal intervals Δt.

Energy generated E_g and energy demand E_d are the result of the sum of all active power generated and demanded at a given time interval Δt.

$$E_{g,d}(t) = \sum_{\varepsilon_1,\dots,\varepsilon_n=0}^{1} (-1)^{\varepsilon_1+\dots+\varepsilon_n} P_{g,d}(\varepsilon_1 a_1 + \bar{\varepsilon}_1 b_1, \dots, \varepsilon_n a_n + \bar{\varepsilon}_n b_n), \quad \bar{\varepsilon}_i = 1 - \varepsilon_i \tag{1}$$

Where P_g and P_d are power generation and power demand, and $\varepsilon_1, \dots, \varepsilon_n$ are summation indexes (thus integers) that run from 0 to 1. Therefore, the sum of the term 2^n with $n \in 1, 2, etc.$ can be read as follows:

$P_{g,d}(b_1) - P_{g,d}(a_1)$,
$P_{g,d}(b_1, b_2) - P_{g,d}(b_1 a_1) - P_{g,d}(a_1 b_2) + P_{g,d}(a_1 a_2)$, etc…

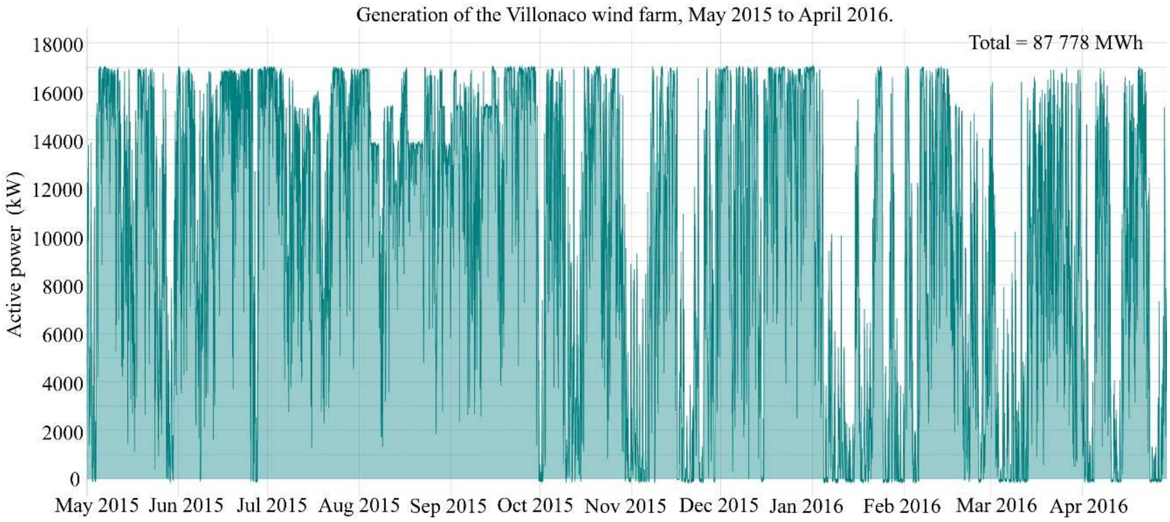


Figure 3. Total Energy supplied by the Villonaco Wind Farm to the urban area of Loja, Ecuador

Figure 3 shows the integrated generation of the Villonaco wind farm for the study period, that amounts for 87 778 MWh.

2.2. Electricity use

The data regarding electricity use in the urban area of Loja were provided by the Empresa Eléctrica Regional del Sur (EERSSA), the local utility, and were aggregated at substation level for this study. These are high quality data that characterize the energy consumption of the urban area, with 15-minutes intervals for a span of 5 years.

Like generation data, the period that goes from May 2015 to April 2016 was subset for this study, as shown in Figure 4.

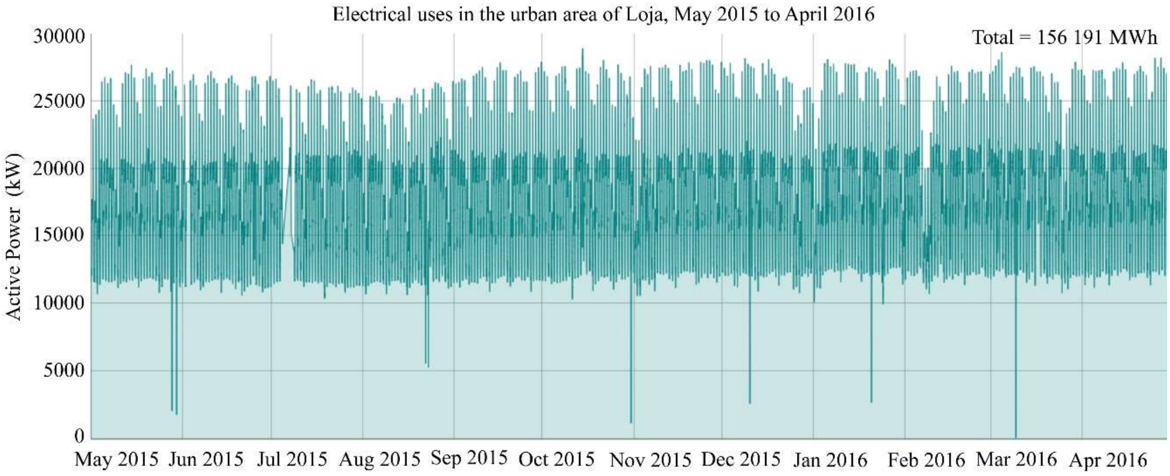


Figure 4. Electricity use in the urban area of Loja from May 2015 to April 2016

The total electricity use for the study period was 156 191 MWh, and the maximum active power was registered on Friday 4th March, 2016, at 19:30h, with a peak demand of 29 689 kW.

Figure 5 is a detail of May 2015. It clearly shows the daily and the weekly cycles, which are very stable and only interrupted occasionally by national holidays. Weekends are highlighted in light red, and have a lower power demand than working days.

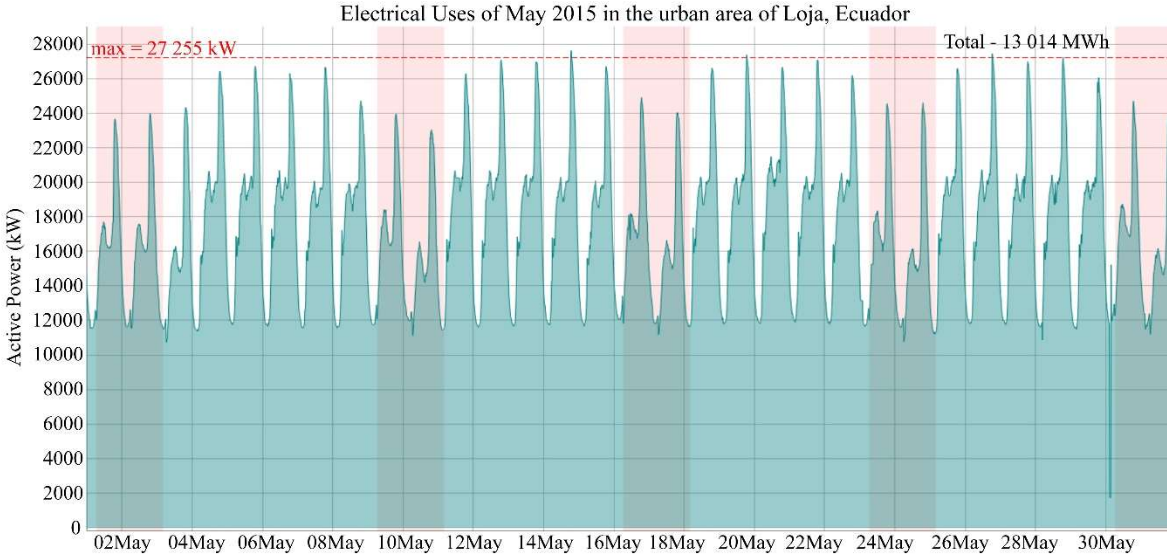


Figure 5. Electricity use of the urban area of Loja on May 2015

The total consumption that month was 13 014 MWh. The highest active power demand was 27 669 kW on Thursday May 14th at 19:20h, and the minimum active power demand was 10 788 kW on Sunday May 24th at 06:30h.

Both data sets, generation and use, were synchronized and overlapped, creating a time series with 15-minutes intervals. The time format used is RStudio’s standard (%d-%m-%Y %H:%M:%OS), so that it is easy to compare data from different sources.

3. Results

The analysis confronting electricity generation and demand considers three scenarios:

1. Base scenario. The urban area of Loja and the Villonaco wind farm are connected to the National Interconnected System (SIN).

2. Isolated system scenario. The urban area of Loja and the Villonaco wind farm are not connected to the INS.
3. Wind farm expansion scenario. The Villonaco wind farm is expanded to twice its capacity (33 MW).

In the base scenario, the urban area of Loja prioritizes the electricity generated by the Villonaco wind farm, and relies on the NIS to cover the rest of the electricity demand, especially peak demand that overshoots the wind farm capacity, and generation gaps from the wind farm. However, moving towards a 100% renewable electricity system and considering that Ecuador is facing its post-oil phase, this scenario may only be feasible in the long run during the rainy season, as the NIS generates most its renewable electricity through hydropower. According to CENACE, there are some periods during the dry season when the NIS requires up to 40% power from thermal plants to cover all the national electricity demand. Therefore, it is relevant to consider a scenario where Loja can’t rely on the NIS and has to operate as an isolated system.

Furthermore, Loja is located at the end of a radial branch of the NIS, and therefore there is only one power line connecting it to the system. This causes an inherent vulnerability with a high risk of a temporary situation of isolation of the urban area. In this scenario, it is reasonable to optimize the network management using electricity storage systems.

The third scenario studies the effect of doubling the nominal power of the wind farm, up to 33 MW by expanding it to neighbouring hills.

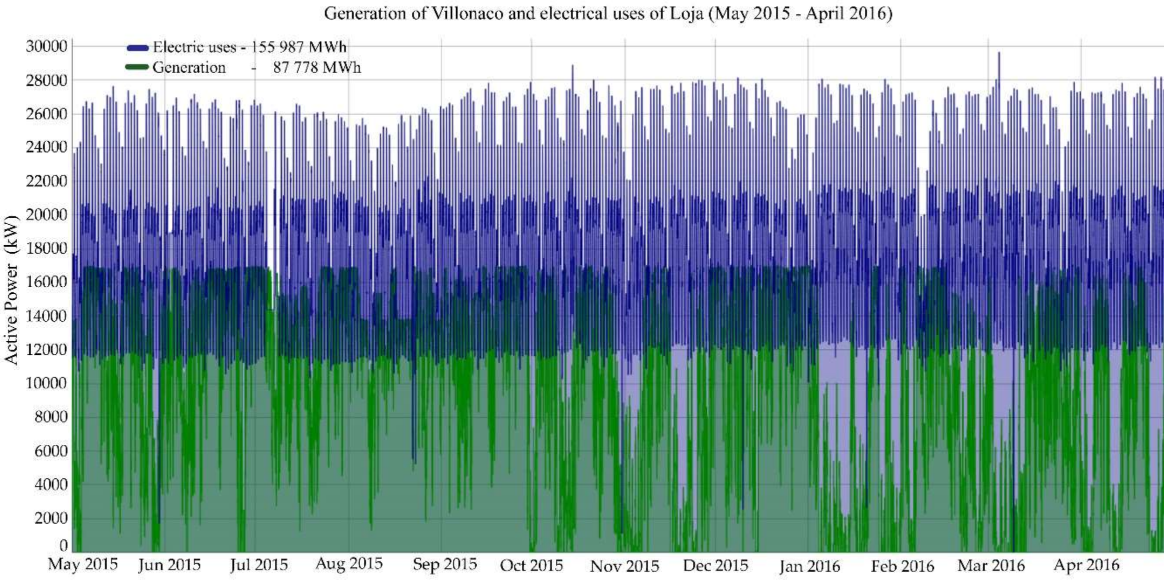


Figure 6. Superposition of generation and use data, May 2015 – April 2016

Figure 6 shows the time series contrasting both data sets for one-year period, with 35 132 measurements with 15 minutes’ intervals, from May 2015 to April 2016. During the study period, the wind farm generated 87 778 MWh, and the urban area used 155 987 MWh.

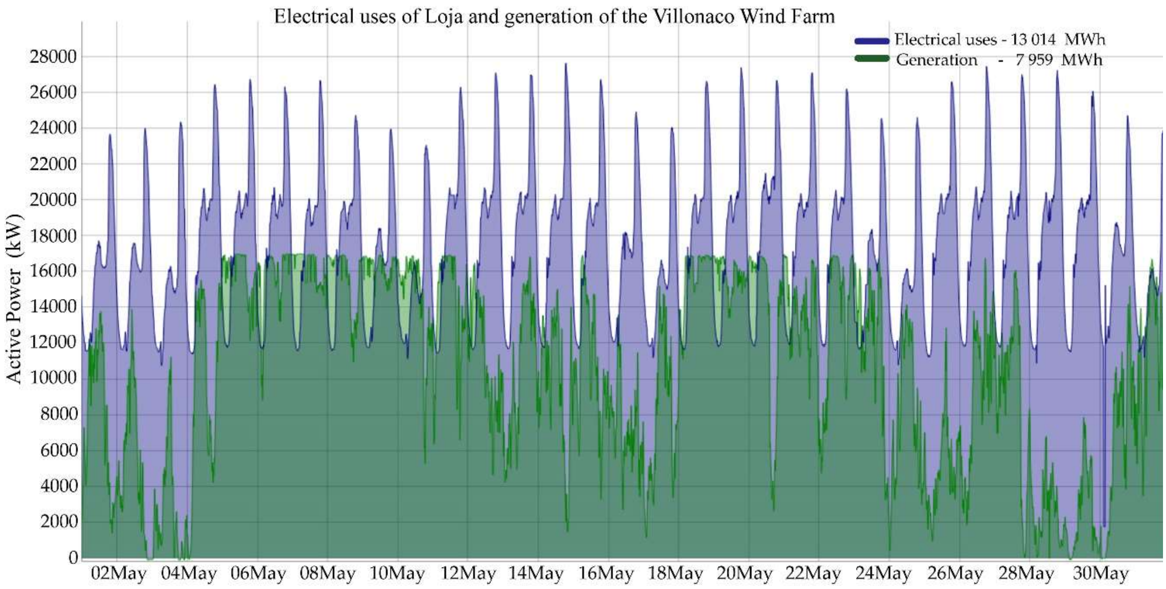


Figure 7. Superposition of generation and use data, May 2015

Figure 7 shows the synchronized data for May 2015. There is a generation gap from May 28th to 30th. In normal operation, the NIS provides the rest of Loja electricity needs –demand peaks and generation gaps–.

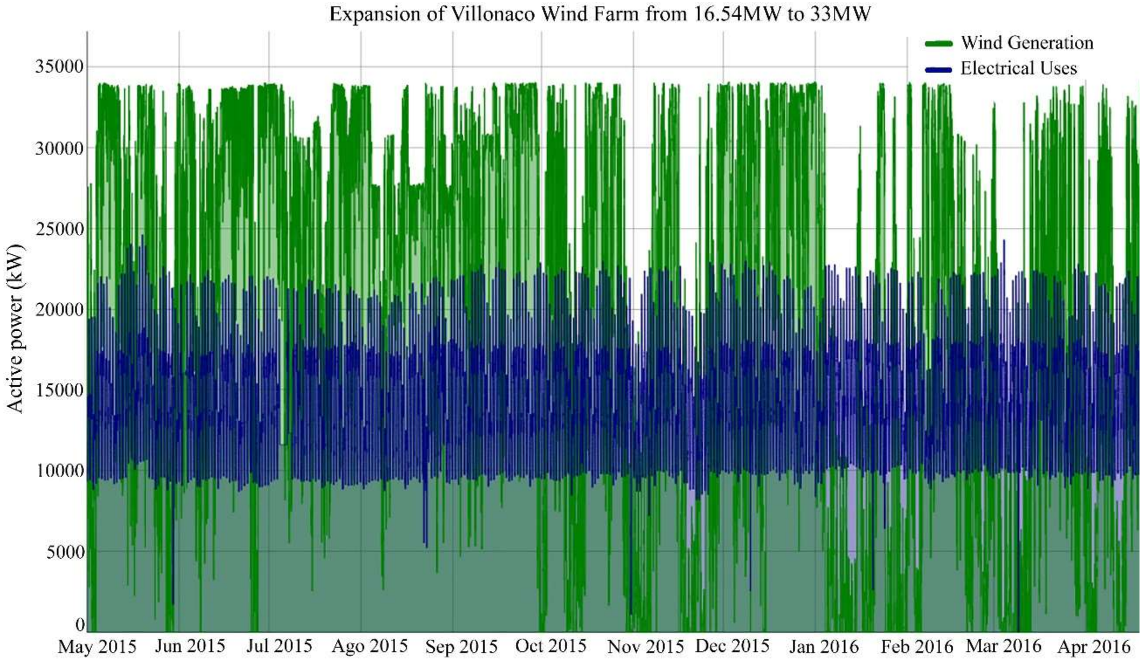


Figure 8. Wind farm expansion to 33 MW. Superposition of generation and use data May 2015 – April 2016

Figure 8 shows the synchronized data considering an expansion of the wind farm up to a capacity of 33 MW, 25% higher than the average peak demand. The total power generated is 175 611 MWh, 13% higher than the total electricity use of the urban area for the period, 156 028 MWh.

4. Discussion

4.1 Urban area of Loja as an Isolated system

This scenario considers the Villonaco wind farm as the sole power source for the urban area of Loja. This is a plausible situation because the Loja electric system is connected to the NIS through a single 138 kV power line, and thus only a single failure away from becoming isolated.

In order to maintain a reliable power supply in an isolated setting, the electric system needs to include energy storage and management systems. Contrasting the power supplied by the wind farm with the electricity demand of the city gives a picture of the storage needs and the extra generation that Loja would need to install as an isolated system.

The difference of the synchronized data for power sources and electricity loads in 15-minutes intervals determines the net energy surplus or deficit at every interval:

$$E_{balance}(t) = E_d(t) - E_g(t), \tag{2}$$

Periods where generated energy E_g is higher than energy demand E_d create an energy surplus. Otherwise there is an energy déficit.

$$E(t) = \begin{cases} E_d(t) - E_g(t) > 0, & deficit \\ E_d(t) - E_g(t) < 0, & surplus \\ E_d(t) - E_g(t) = 0, & equilibrium \end{cases}$$

The Ecuadorian electricity system, as most electricity systems in the world do, adjust electricity production to meet the electricity demanded by the system at any given time. The large scale integration of renewable energy sources requires a systemic change with a completely different approach to energy management, where energy demand is tailored to resource availability in order to maximize the system efficiency.

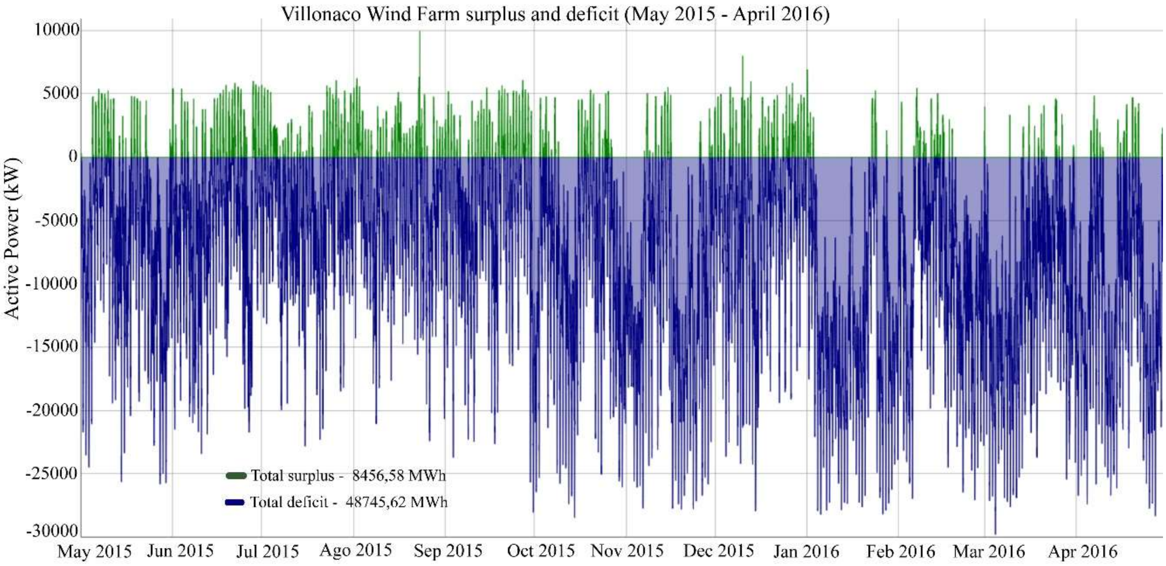


Figure 9. Generation surplus/deficit timeline of the Villonaco-Loja system from May 2015 to April 2016

Figure 9 shows the generation surplus and generation deficit of the Villonaco-Loja system during a 1-year period, from May 1st 2016 to April 30th 2016. The total energy use during this period was 155 987 MWh, while the wind farm generated 87 778 MWh, for a total deficit of 71 774 MWh, 46% of the total energy demand of Loja. The rest of the demand was supplied by the NIS.

The direct coverage of energy demand was 84 212 MWh, 53% of the demand and 96% of the generation, and there was a total generation surplus of 3 565 MWh that couldn't be absorbed by the city and was delivered to the NIS.

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The net balance with the NIS was a deficit of 68 209 MWh, which is a 43.7% of the electricity use of Loja.

Table 2 summarizes the monthly values for farm energy generation, energy use, deficit and surplus, and the direct supply and net balance of the Villonaco-Loja system.

Table 2. Wind generation, energy use, surplus and deficit, energy balance.

Period	Generation (MWh)	Uses (MWh)	Surplus (MWh)	Deficit (MWh)	Direct Supply (MWh)	Net balance (MWh)
may-15	7 959.02	13 014.89	286.31	5 342.18	7 672.71	-5 055.87
jun-15	9 131.98	12 635.06	462.49	3 965.58	8 669.48	-3 503.09
jul-15	9 580.25	12 792.96	421.33	3 634.04	9 158.92	-3 212.71
ago-15	9 752.27	12 647.48	477.16	3 372.37	9 275.11	-2 895.21
sep-15	9 851.47	12 788.82	559.60	3 496.95	9 291.87	-2 937.35
oct-15	7 004.40	13 352.29	247.06	6 594.95	6 757.34	-6 347.89
nov-15	4 842.44	12 835.18	175.69	8 168.43	4 666.75	-7 992.74
dic-15	9 928.06	13 355.41	485.27	3 912.63	9 442.79	-3 427.36
Jan16	3 482.30	13 469.37	137.51	10 124.58	3 344.79	-9 987.07
feb-16	6 153.12	12 402.72	164.03	6 413.63	5 989.09	-6 249.60
mar-16	5 247.52	13 521.88	60.26	8 334.62	5 187.26	-8 274.36
Apr16	4 845.18	13 170.95	88.36	8 414.13	4 756.82	-8 325.76
TOTAL	**87 778.0**	**155 987.0**	**3 565.0**	**71 774.0**	**84 212.9**	**68 209.0**

From November to April wind resource is scarcer and the direct supply is low. Energy deficit exceeds 50% of the demand during this period.

Generation surplus occurs during off-peak hours and is delivered to the NIS. In order to maximize the efficiency of the system it is advisable to use the energy at the time it is produced. One of the ways to achieve that is to set up demand response policies that encourage shifts in industrial schedules to match power availability. Electricity can also be stored using storage systems such as batteries or hydrogen, and can either be used to manage and balance the system or for other uses such as electric mobility or industrial activity that need high power rates.

Alternatively, generation surplus can use the current hydro plants of the NIS as equivalent storage capacity. In this setup, the NIS uses the excess generation from the wind plant in exchange for energy bonds, through an equivalence between usable electricity surplus and water saved from the dams.

The operation of the Villonaco-Loja system as an isolated system also requires a highly automated control system for the mid- and low-voltage networks to guarantee supply quality and stability.

Nevertheless, the current system generates very little surplus (2.6% of the total energy use), and it is not practical or economically sound to invest time, effort and money in storage or DR systems under these conditions. However, there is an expansion project for the Villonaco wind farm up to 33 MW installed capacity that will change dramatically the dynamics of the system.

4.2 Villonaco wind farm Expansion

The wind farm can be expanded to the neighbouring hills of Ducal and Membrillo, which present similar wind conditions as the Villonaco hill. The resulting installed capacity of 33 MW exceeds by 25% the average peak demand, and the energy generated by the expanded wind farm is 175 611 MWh, 13% higher than the city demand.

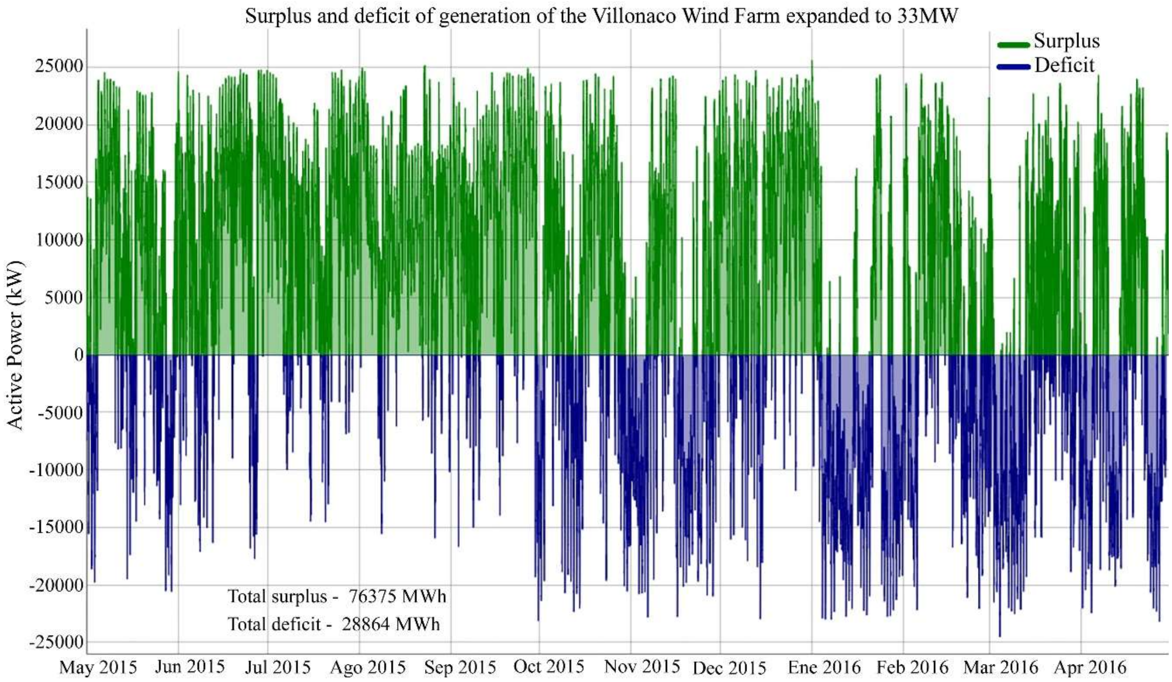

Figure 10. Generation surplus and deficit of the 33 MW expanded wind farm

Figure 10 shows generation surplus and deficit on a 15-minute basis for the study period when considering the expanded wind farm.

Table 3 shows that the expanded wind farm covers directly 115 890 MWh (74% of total demand) during the study period, while the total surplus is 59 692 MWh, and the total deficit is 40 108 MWh. This means that there is enough power generation to, in theory, cover 100% of the urban area's energy needs. In practice, these values must be adjusted considering the efficiency and the limitations of storage systems, such as energy and power limits, and operational range.

Table 3. Wind generation, energy use, surplus and deficit, energy balance with the wind farm expansion

Period	Generation (MWh)	Uses (MWh)	Surplus (MWh)	Deficit (MWh)	Direct Supply (MWh)	Net balance (MWh)
may-15	15 918.04	13 014.89	5 255.41	2 352.25	10 662.64	2 903.16
jun-15	18 263.95	12 635.06	6 947.44	1 318.55	11 316.51	5 628.89
jul-15	19 160.50	12 792.96	7 065.32	697.78	12 095.17	6 367.54
ago-15	19 504.54	12 647.48	7 363.89	506.84	12 140.64	6 857.06
sep-15	19 702.94	12 788.82	7 713.10	798.99	11 989.83	6 914.12
oct-15	14 008.81	13 352.29	4 478.51	3 822.00	9 530.29	656.51
nov-15	9 684.88	12 835.18	2 818.76	5 969.06	6 866.12	-3 150.30
dic-15	19 856.11	13 355.41	7 824.35	1 323.65	12 031.76	6 500.70
Jan16	6 964.59	13 469.37	1 901.69	8 406.46	5 062.91	-6 504.77
feb-16	12 306.24	12 402.72	3 495.45	3 591.93	8 810.79	-96.48
mar-16	10 495.04	13 521.88	2 299.60	5 326.44	8 195.44	-3 026.84
Apr16	9 690.37	13 170.95	2 501.90	5 982.48	7 188.47	-3 480.58
TOTAL	**175 556.00**	**155 987.00**	**59 665.00**	**40 096.00**	**115 890.00**	**19 569.00**

Considering the NIS as a perfect virtual storage system (infinite power and capacity, as well as 100% efficiency), the net balance with the NIS is a positive total of 19 568 MWh.

This scenario shows that the expansion of the wind farm could make the urban area of Loja self-sufficient in electricity, at the expense of implementing utility-scale energy storage to manage the energy surplus.

5. Conclusions

This research compares electricity generation and demand based on real data, measured in the urban area of Loja, Ecuador, and its wind farm Villonaco. Electricity demand in Loja is very regular throughout the year, with daily and weekly cycles interrupted occasionally by national holidays. Wind resource presents a yearly cycle, with a higher availability from July to September, and lower availability from January to April.

The wind farm generation can directly supply 53% of the electricity needs of the urban area, with only a small surplus generation during off-peak hours.

Doubling the capacity of the wind farm results in a 74% direct coverage. Further capacity increases do not result in higher real-time electricity coverage, since the limiting factor when the wind farm capacity exceeds peak demand is wind availability.

The expanded wind farm has an overall positive net balance with Loja, which suggests that the urban area could be self-sufficient with the expansion. However, this would require massive amounts of storage capacity, and even if these were available, there are limitations in power charge/discharge rates and capacity limits, as well as storage power losses. Not all the energy surplus is usable or can be stored, and peak demand doesn't always match peak generation, which decreases the overall efficiency of the system. Therefore, techniques like demand management to better fit the generation curve, generation prediction, and demand response for large consumers will have a central role in an optimized DER electricity system.

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Author Contributions: Manuel Ayala Chauvin conducted experimental work and data analysis and wrote the paper. Genis Riba discussed the results and contributed to the writing of the manuscript.

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