Analysis of the potential for PV rooftop prosumer production: technical, economic and environmental assessment for the city of Valencia (Spain)

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Highlights

- ~~A method for the estimation of the rooftop area and number of buildings for the city of Valencia has been developed~~
- ~~A detailed analysis of the p~~Potential energy generation with rooftop~~ installed~~ PV~~solar~~ panels has been ~~performed~~ estimated~~, considering 5 types of reference buildings ("hot spots")~~
- Rooftop PV can cover almost completely the domestic electricity demand~~, and roughly 37% of the total electric demand of the city~~
- Best- and worst-case scenarios for economic investments have been estimated ~~according to the type of building and prosumption scheme~~
- Environmental considerations and emission estimations are reported~~, giving encouraging results for the potential abatement of contaminants in the city of Valencia~~

Abstract

Cities are expected to be protagonists of the energy transition and, among other challenges, the decarbonation of the residential consumption could greatly benefit from photovoltaic generation in the built environment. To assess its potential, t~~T~~he present study analyses the possibility to cover the electric demand of the city of Valencia with rooftop-installed PV panels. Specific types of buildings has been selected to study the potential of each one of them with respect to their demand and with a specific production/consumption model. The total potential energy production for the city of Valencia is estimated to be enough to satisfy the demand of domestic electricity. The economic investment scenario has been analysed (best- and worst-case scenarios), and the corresponding environmental benefits have been studied. The results of the present article are encouraging in ~~a~~ the context of a global energy transition~~ framework~~, necessary ~~needed~~ in the present times to keep human consumption within the planetary ~~boundaries~~ limits.

Keywords: E~~-~~nergy ~~P~~prosumer, Self-consumption, ~~Net-metering,~~ Energy transition, Rooftop ~~Photovoltaics~~PV, Urban solar potential

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1. Introduction

Energy has played a critical role throughout human society's demographic, economic and social development. Nowadays humankind is facing an era that is experiencing unprecedented social inequalities and environmental issues, climate change being the most challenging one. Society is in desperate need of an inclusive and sustainable social, energetic and economic model that can provide resilience on a long-term basis.

Our fossil fuel dependency has created very low energy resilience, and an ever-increasing rate of greenhouse gas (GHG) emissions. There is a growing consensus that weaning society off fossil fuels and onto renewable sources would be sensible even in case climate change was not a problem. Energy transition to a renewable powered society and a reduction of consumption levels is at the moment the only viable solution in the face of increasingly scarce fossil-fuel resources.

In all this scenario, which is the role the cities can play?

Cities are major players in the implementation of EU policies, such as the Urban Agenda for the EU or the Sustainable Development Goals on cities and settlements [ref ~~missing~~Tomás]. While many consider cities as examples of unsustainability [1], others are convinced that urban centers embed a context, ready for a rapid necessary change thanks to the presence of research centers, modern businesses and strategic resources, that can enable a shift towards a more ecological and resilient economy and future [2,3]. While climate change, pollution and energy scarcity are profound global concerns, mitigation and/or adaptation measures can be regarded as deep local issues [4], not exempt of complexities and controversies [5-7]. In this sense, urban centers play a crucial role in managing greenhouse gas emissions and adaptation measures.

On that same line, the idea that decentralized energy production systems could revolutionize our way of consuming and producing electricity is little by little gaining ground [8,9]. Decentralized electricity production systems offer the advantage of improving the energy resilience of a city, facing global energy scarcity, reducing in this way the influence from external factors, such as intermittent supply of external sources, dependence on fossil fuel price oscillations, increasing source diversity etc., while developing energy infrastructure in line with a more democratic and just clean energy transition [10].

One of the main solutions applied and studied nowadays in many cities worldwide is the production of electricity by means of building-integrated photovoltaic (PV) systems, for example rooftop installations [11-20].

It could be useful at this point to introduce the concept of "prosumer". In the field of energy production, a "prosumer" is a customer or a group of jointly acting customers who consume and can store or sell electricity generated on their premises or in collectively owned renewable energy projects, including through aggregators, provided that these activities do not constitute their primary commercial or professional activity.

Rooftop solar PV has been demonstrated so far to be a very effective way to produce benefits from a social, economic, and environmental point of view [18]. It can help promote local energy security and lead to improvements in local air quality [5,21]. Also, it can provide a very effective alternative to PV plants on extended agricultural lands. As humanity is facing a substantial problem with limited agricultural lands available for food production in an ever-increasing world population, using rooftops is a very fruitful and sustainable alternative that allows to avoid touching another planetary boundary related to land use and soil.

From a social aspect, producing electricity with household rooftop PV installations empowers citizens in their energy sovereignty, in their control over their own energy supply, in their reduction of their carbon footprint, their bills and they can pay off their investments in a few years.

1.1. Context and motivation

Comentado [CVS2]: Yo quitaría este título, no suelo poner subapartados en al introducción, en todo caso creo que no es importante.

The electric market in Spain has a high noticeable penetration of renewables, mainly due to wind energy generation. As of 2017, the contribution of renewable energy to the total energy production in Spain is 32.2%, where 18.2% is wind energy, 7.0% hydroelectric, 3.2% solar PV, 2.0% solar thermal and 1.7% all the rest of renewables. Despite Spain's vast solar resource [20] and the availability of space for solar plants, solar PV fed into the grid only accounts for a relatively small percentage. Most of it comes from centralised plants owned by large corporations, with only 23.9926.75 MW of installed capacity corresponding to self-consumption distributed energy PV installations registered, according to MINETAD databases available[autoconsdet].

Comentado [T.B.3]: Actualizado diciembre 2018.

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In terms of renewable energy generation distribution across regions (autonomous communities), *Comunidad Valenciana* accounts for only 3.8% of the total renewable energy generation. In local terms, this means that 27% of the installed capacity in Valencia is renewable, that is 2,256 MW, or 19% of its electricity generation, that is 3,228GWh, according to *Red Eléctrica Española*. However, as aforementioned, only a small percentage of this local renewable energy comes from self-consumption installations[autoconsdet]. On the other hand, it was predicted that *Comunidad Valenciana* has one of the highest potentials for rooftop PV installations among all Spanish regions, according to Izquierdo et al. [17].

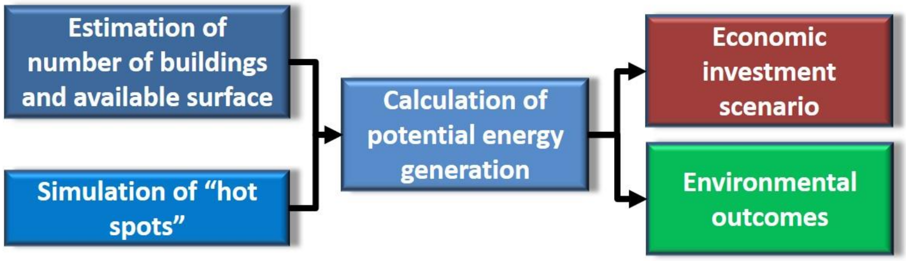
In Spain, the introduction of legislation regulating self-consumption in 2015[RD900/2015], that has come to be known as the "sun tax", has greatly harmed the citizens' trust in governmental support of distributed energy generation. Although this package has been revoked in September 2018, its implications have generated long-lasting misinformation among consumers[1].

The new regulation passed in October 2018 [RD-L 15/2018](RD-L 15/2018, 2018) and further developed in April 2019[RD 244/2019] (RD 244/2019), improved prosumers' economic conditions and simplified administrative procedures. These changes have been shown to increase the profitability of PV electricity production (for residential, commercial and industrial installations) and might set the basis for the emergence of new business models. At the same time the new regulations reduced the legal uncertainty by increasing the legal status and rules [22].

On the other hand, Spanish consumers are the most motivated to reduce their energy bills, since Spain has one of the highest electricity relative prices in the EU (on average 0.22 €/kWh[Eurostat]). Therefore, demonstrating that sound economic cases for self-consumption (and/or selling the surplus electricity) are possible, will be especially determinant for the uptake of prosumption among –consumers. At research level, encouraging results have been obtained by several groups all over the country, confirming a serious commitment from public centres to push for a shift towards a renewable society, highlighting the potential of Spanish cities to incorporate PV generation into buildings[17-19].

[1] For example, many consumers believe that the double taxation scheme outlined in the law was also applied for small installations (under 10kW) and off-grid installations, which was not the case.

As already shown previously [23], awareness of the economic benefits for consumers thanks to household PV installations, is fundamental in promoting acceptance. In this article we are thus providing a technical and economical assessment for the potential to cover the local electric demand through solar PV energy installed on rooftops, and expected environmental consequences. The main objective is to highlight business opportunities and environmental benefits of energy “prosumption”. Also, in the present paper we highlight how a *Net energy metering* scheme could be highly beneficial from a social and economic point of view, but also indirectly from an environmental point of view. Although this scheme is not in vigour yet, we believe it is crucial to understand the impact of such a consumption/production model and make it public in the hope policymakers could consider this possibility.
This article is a follow up of a preliminary assessment that justified the feasibility of the present study [24]. In the following block diagram, we report on the methodology we followed for the estimation of the potential for prosumption in Valencia.



We are profoundly convinced that the findings of this research article can be beneficial for both the government and the private sector, as well as policy makers and urban planners.

2. Estimation of number of buildings and rooftop available surfaces

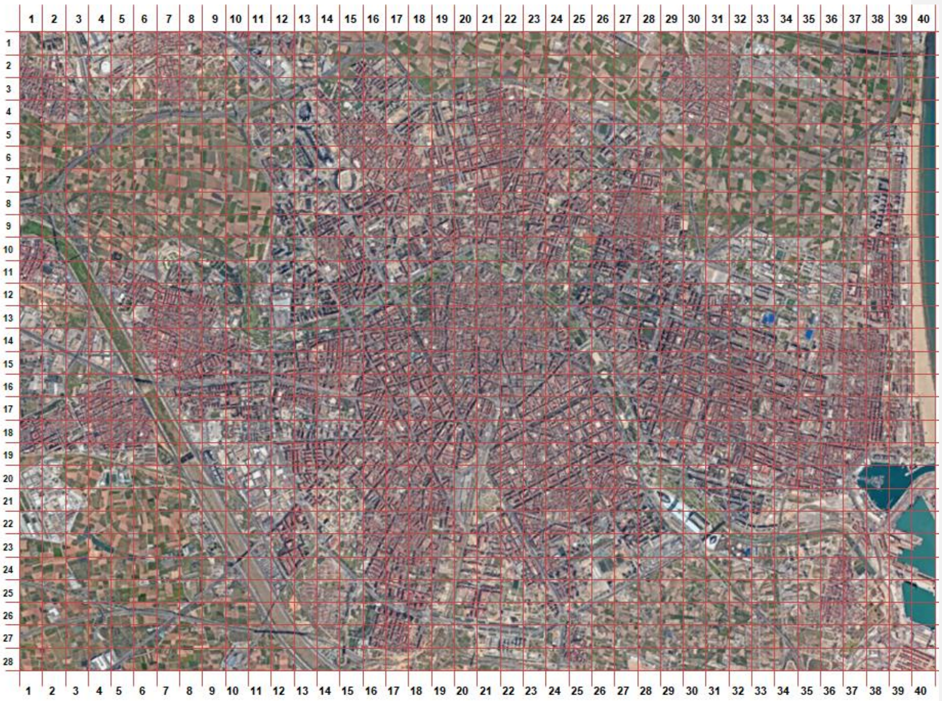


Figure 1: Sampling of the city of Valencia. Each square is 250 x 250 m^2 (62 500 m^2). The total number of squares is 1120 (Image from Google Earth).

To estimate the potential for rooftop solar PV electricity generation we need an estimation of the available rooftop surface in the city. This is the most restrictive step since there is no direct data available that can give an estimation of the rooftop available area. On the other hand, we have conducted research ~~similar~~ comparable to other studies of literature. However, we have introduced some improvements in the methodology, compared to those studies. First, we apply statistics to simplify the procedure of calculation and make it is feasible for human intelligence instead of artificial intelligence. Secondly, we have considered the actual solar radiation on the surfaces, discounting shadows and other barriers. Finally, we have carried out simulations of the energy generation and consumption based on available data and HOMER® software, instead of calculating only the potential electric generation, which allows for a more realistic analysis of the techno-economic benefits of PV generation in the built environment.

Thus, f~~F~~ollowing a procedure similar to previous works [11-16], we have divided the city map in 28 x 40 squares (1120 squares) of 250 x 250 m^2 each. Therefore, each square contains 62500 m^2 and a total area of 70 km^2 (see figure 1). For simplicity of calculations, we limited our study to the urban area rather than the full municipal term.

As there is little information about the current situation, the common formula to calculate the sample size "n" was applied to the whole city, see equation 1, based on [Reference]. In the formula, "N" is the

Comentado [TGN4]: Forbes, C., Evans M., Hastings N., Peacock B., 2010. Statistical Distributions, 4th ed. ed. Wyley, New York, NY, USA. https://www.wiley.com/en-us/Statistical+Distributions%2C+4th+Edition-p-9780470390634 population, the total number of the squares in which the map was divided into (1,120). Then, wWe set the error to be 0.05% (e=0.05), that is to say, the maximum difference allowed between the obtained mean of the sample and the actual mean of the population. The probability of including all types of eligible rooftops for PV generation[2] "p" is set to 0.8, as an estimation on the safety side of the safety of

[2] In this case the phenomena are the number of different houses in the city, and their features.

the probability of including all types of eligible rooftops for PV generation[3]. Hence, as and "q" is the probability of the contrary, (q = 1 – p) is set to 0.2 (q = 1 – p). Besides, we set the uncertainty to 0.05% (which means that $Z\alpha = 1.96$), and it shows - how confident we want to be that the actual mean falls within our margin of error "e".

N is the total number of the squares in which the map was divided into (1120). According to the

$$n = \frac{Z_{\alpha}^{2}\, N\, p\, q}{e^{2}(N-1) + Z_{\alpha}^{2}\, p\, q}$$

We set the error to be 0.05% (e=0.05), "p" to 0.8 as an estimation on the side of the safety of the probability of including all types of eligible rooftops for PV generation[4], and "q" is the probability of the contrary (q = 1 – p). Besides, we set the uncertainty to 0.05% (which means that $Z\alpha = 1.96$). N is the total number of the squares in which the map was divided into (1120). According to the previous formula, the sample (n) must include as a minimum 39 squares, but 50 were taken for the study, again from the side of safety.

Fig.2 Representative sampling of rooftops in a 250x250 m2 square (left), combined with solar mapping from *Huellasolar* (right).

Within each square we counted the number of buildings and measured rooftop surface available (with mapping software *Goolzoom*[Goolzoom] and *Google maps*[Googlemaps]) selecting qualitatively the rooftops with bigger hours of sun exposure, according to the mapping resources obtained by *Huellasolar*[Huellasolar] software. In fig.2 we show an example of rooftop area sampling combined with the sun exposure map. To stay on the conservative side, in case the pitched rooftops were facing north or east-west, they were not considered appropriate for PV installation. We only considered rooftops with north-south (south-east / south-west) orientation, and only the south-facing surfaces. An example can be found in figure 3.

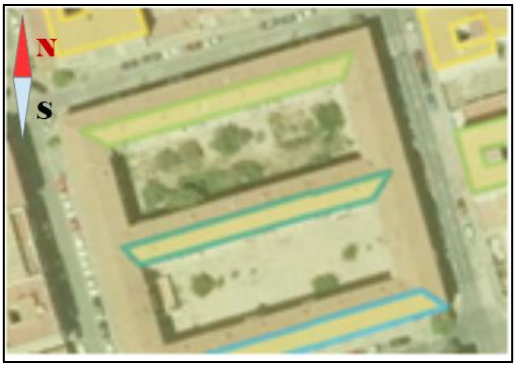


Fig.3 Example of pitched rooftops oriented north-south. Only the highlighted area has been considered for the rooftop surface estimation.

Taking into account that tThe combination of error and uncertainty for the overall estimations can get up to 10%, t. The results of the sampling estudy are reported in table 1. Among all the available buildings of the city of Valencia, we have identified 5 types of opportunities (or "hot spots") for rooftop PV electricity generation:

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1. Standalone building of 1 household (single family house)
2. Building of several households in different floors (multi-storey building)
3. Standalone building of 1 household capable ~~potentially~~ of going off-grid (*Alquerias*). Different form case one as normally those bildings do not have enough available surface for all the PV generation demanded.
4. Commercial/industrial standalone building
5. Public standalone building. Different restrictions and demand curves from type 4 buildings

Tab.1 Estimation of the total number of buildings/households and measured rooftop surface

Type of building	Number of buildings with a certain number of floors	Number of households	Rooftop surface measured (m^2)
Residential buildings	**1 floor**	**1,053 single family houses**	**143,696**
	2 floors - 560 buildings (291 duplex and 269 two households-buildings)	**291 duplex households**	**25,917**
		538 households	**26,678**
	3-6 floors – 10,595 buildings	**107,229 households**	**2,398,995**
	> 6 floors – 17315 buildings	**313,510 households**	**4,116,202**
***Alquerias*[5]**	**560 isolated houses**		**48,250**
Standalone commercial buildings	**202 standalone buildings with pure commercial use**		**198,218**
	896 industrial buildings		**1,281,123**
	45 private schools and educational centres		**68,706**
	45 hotels		**19,264**
Standalone public buildings	**246 public education centres.**		**266,202**
	45 buildings for healthcare		**83,440**

[5] *Alquerias* are typical farmhouses, with an agricultural field annexed, that are present in the municipality of Valencia. They are connected to the electrical Spanish grid, but in this study, we considered them as residential houses that will~~could~~ ~~potentially~~ disconnect from the national grid with PV power and storage (theoretical situation). Hence, it represents a ~~special~~ different case form~~of~~ type 1.

	470 public buildings (general)	**333,894**

We will use the numbers reported in tab.1 for the estimation of the number of buildings and rooftop surface in the following sections. In the next paragraph we will simulate the installation details according to the prosumption scheme and the 5 hot spots identified.

3. Software modeling and methodology

For each one of the 5 hot spots identified in the previous paragraph, we modeled the PV installation and the relative parameters. For the assessment of the models, the software HOMER® has been used. It has been developed by the U.S. Department of Energy's National Renewable Energy Laboratory (NREL)[Homer] and it examines all possible combinations of energy system types in a single run, and then sorts the systems according to the optimization variable of choice. In our case we used the Levelized Cost of Energy (LCOE)[6]. In order to build the models in HOMER®, several assumptions, estimations and calculations were needed. The main ones are listed below:

- In the first place, no economic constraints of the prosumers have been considered, That is to say, the study has assumed all investments would be possible.
- OOnly PV panels have been considered (no thermal solar panels or any other combination of renewable sources of energy). Thus, all the available surface on the roofs has been devoted to PV panels.
- The goal for the simulations has been to maximize the economic profit and, in second place, to maximize the energetic and environmental benefits.
- The lifespan considered for the installation is 25 years. Panels are estimated to last 25 years, converters 25 years, batteries 20 years (two sets of batteries replaced every 10 years), and all the rest of the installation (wires, meters, actuators, etc.) need not be replaced in the lifetime of the installation. After this time, equipment must be replaced.
- For equipment costs the maximum costs of the IVACE[DOGV8299]have been taken as prices. Those prices are an overestimation of the real prices and, hence, the results obtained will remain on the conservative side. The interest rate for the present costs has been set at 1%.
- The price of electricity has been considered as 20.85 c€/kWh including both the fixed and the variable part[autoconsdet]. This value was considered more accurate compared to Eurostat reported value (on average 22 c€/kWh) and also the results of the work will stay on the conservative side.
- For electricity sale prices and other costs of being connected to the grid, those suggested in the simulations by the *Asociación de Agencias Españolas de Gestión de la Energía* (EnerAgen) have been selected. In particular, electricity sale price: 5.00 c€/kWh; costs of connection to the grid: 0 c€/kWh
- The peak power that can be installed will be based on the ratio **7 m^2/kWp** used by the EnerAgen in their simulations[autoconsdet].
- For simplicity, in the simulations, all panels have been considered horizontally installed, tilt angle = 0º. This also stays on the conservative side.

Comentado [CVS6]: Reviewer 1: The context is explained in a very throughout, though concise, manner. Parts of the developed methodology were selected from cited references. However, it is not explained in a sufficiently explicit manner what parts of the proposed methodology is not based on existing work, i.e. what the methodological contribution of this paper is.

Comentado [CVS7R6]: Response: The methodology has been improved adding xxxx (No sé si seria interesante hacer un diagrama de flujo de la metodología). To contrast the present methodology to scientific works carried out, some references has been added: [XX, XX, XX]

Comentado [CVS8]: No creo que haga falta cambiarlo porque no han dicho nada y es difícil que lo noten, pero este valor hay que cogerlo con pinzas, la media de 2020 fue 3,3 y la de 2019 4,5 c€/kWh, aunque es verdad que es antes de impuestos por tanto también se ahorraría el IE y el IVA.

[6] The LCOE is an economic assessment of the average total cost to build and operate a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime. The LCOE can also be regarded as the average minimum price at which electricity must be sold in order to break even over the lifetime of the project. It allows the comparison of different technologies (e.g., winds, solar, natural gas etc..) of unequal life spans, project size, different capital cost, risk, return and capacities.

- Solar Radiation will be that provided by the database of PVGIS[PVGIS].
- The case studies selected do not have shadows or barriers to solar radiation other than random cloudy days. Those cloudy days were simulated by Homer based on PVGIS statistical data. The shadows and barriers to solar radiation are dealt with as explained later.
- As there are no data~~statistics~~ about the "representative" demand curve for electricity, in most of the cases the one provided by the Spanish Electric Grid (REE)[BOE2017] has been selected. In particular, the one for contracts under the tariff 2.0A – 2.1A (installed power < 15kW) for households, while for larger buildings we considered the tariff 3.0 (installed power < 450kW) and a demand curve as the one of Open Energy Information[openei].
- For the avoided emissions, as every household may have a different supply company, an average conversion factor (CF) has been selected. The CF is the one given by REE for year 2017[ree]: 285 gCO_2e/kWh.

The models considered in the simulations are the following:

- *Self-consumption (SC)*: in this case the prosumer is neither selling nor storing the excess electricity produced during sunny hours. The potential surplus electricity is not used~~wasted~~.
- *Self-consumption with storage (Storage)*: in this case the surplus electricity is stored in batteries. The total cost of the installation includes the storage costs.
- *Selling to the grid (Sale)*: in this case the excess electricity is sold to the grid.
- *Net energy metering (NEM)*: NEM is a scheme already used in several countries [25,26], in which consumers can use the electricity generated anytime, instead of using it only at the moment of generation. In practical terms it means that a balance is done between the energy generated and the energy consumed. What comes out from the difference between the two, is converted to the electricity rate to be paid by/to the consumer[7]. In this scheme, the models have considered one month of inputs and outputs of electricity, before paying or being paid. As purchasing and sale prices are different (the first being higher than the second), the longer the period for the balance the better for the user. However, as the NEM is a demand rather than a reality, if it will ever be applicable in practice, it is likely that distribution companies will demand to adjust to the billing period, and this is normally one or two months. Therefore, one month remains on the conservative side.

Tab.2: Results from simulations with HOMER.

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[7] If the balance result is a negative number for the consumer to pay, the amount is not paid, i.e. the prosumer will not earn money out of the residential PV generation.

Building/ Model		Power installed (kWp)	Total investment (€)	Total electricity consumption (kWh/year)	Grid purchases (kWh/year)	PV power (kWh/year)	Electr. Surplus (kWh/y)	Inverter Output (kWh/y)	GRID %	PV %	LCOE (c€/kWh)	Payback time (y)	GHG Avoided (kg/y)
1	S-C	1.5	5061	4636	2881	2461	460	1801	62	38	22,14	29,60	532
	Sale	2	5829	4636	2685	3282	1003	2051	57	43	21,48	24,70	709
	NEM	4,5	10345	4636	2351	7384	4361	2721	46	54	19,56	19,56	1595
2	S-C	20	32466	55480	33535	32816	7589	22704	60	40	19,26	13,76	6227
	Sale	20	31726	55480	33535	32816	7448	22831	59	41	18,50	11,45	6261
	NEM	20	31726	55480	33535	32816	7448	22831	59	41	17,20	9,17	6261
3	Storage	9	27533	4636	0	14767	10131	4172	0	100	38,12	61,05	1113
4	S-C	150	169690	509902	319683	246119	34761	190222	63	37	8,95	12,55	45653
	Sale	200	216536	509902	293185	328158	78298	224874	57	43	8,4	11,75	51573
	NEM	200	216536	509902	293185	328158	78298	224874	57	43	8,2	11	51573
5	S-C	100	113261	310990	200414	144718	21866	110567	64	36	10,92	13,60	26536
	Storage	110	761593	310990	193458	159189	28609	117522	62	38	11,13	15,6	28205
	Sale	200	210148	310990	152560	298435	97567	180781	46	54	10,14	13,8	61436
	NEM	200	210148	310990	152560	298435	97567	180781	46	54	9,5	12,32	61436

Note: ~~Tab.2: Results from simulations with HOMER.~~ The numbers for the hot spots refer to the list in paragraph 3. We used a sample building representing the general case for each model. ~~The demand curve for households was obtained from Spanish Electrical Grid (REE), in particular the one for contracts under the tariff 2.0 A – 2.1 A (installed power <15kW).~~ The average total power is 4636 kWh/year for 1 household of a single-family house. The model 2 was simulated considering a multistorey building 5 floors high, with 3 households per floor (average building based on ~~from~~ statistics). For the cases of model 1 and 2 the possibility of storage was always disadvantageous, meaning that the installation of batteries never helped to decrease costs or payback, and hence they were discarded from the analysis. For the model 3 and 5 ~~(~~Storage~~)~~, the batteries considered were HOPPECKE Power VL 2-1150, 12 V, of 1500Ah in C100: 16 units (model 3) and 24 units (model 5 ~~(~~Storage~~)~~). The model for commercial/industrial buildings considered a representative example (supermarket) with a demand curve obtained combining the one by REE for tariff 3.0 and consumption lower than 450 kW, with the consumption curve of a similar Supermarket in Barcelona and the demand curves of some examples from ref [openei]. ~~of the website: https://openei.org/wiki/Main_Page.~~ In the table, the lines with the LCOE cell in green (LCOE<20.85c€/kWh) represent cases with profitable installations.

Comentado [CVS9]: Reviwer 1.
Tab.2: for buildings of type 3, it seems that just the case with storage is considered. Could the authors explain further why they have not considered other scenarios in this case? - "Having a quick look at the results, the power installed in the case of SC is, in all models, lower than the case for Sale and NEM": the LCOE is higher, so the case is worse. However, saying "lower" may seem confusing to the reader

Comentado [CVS10R9]: Habiendo leído el paper en diagonal, aquí tengo la misma duda del revisor. Hay cuatro casos y 5 modelos, no se podrían ver en la tabla todos los casos para los 5 modelos?

Comentado [CVS11]: Imagen que no se puede editar, cambiar comas a puntos.

Comentado [CVS12]: El nombre de la tabla me parece muy largo, yo deajría un nombre más corto y lo explicaría en el texto, de momento no lo modifico.

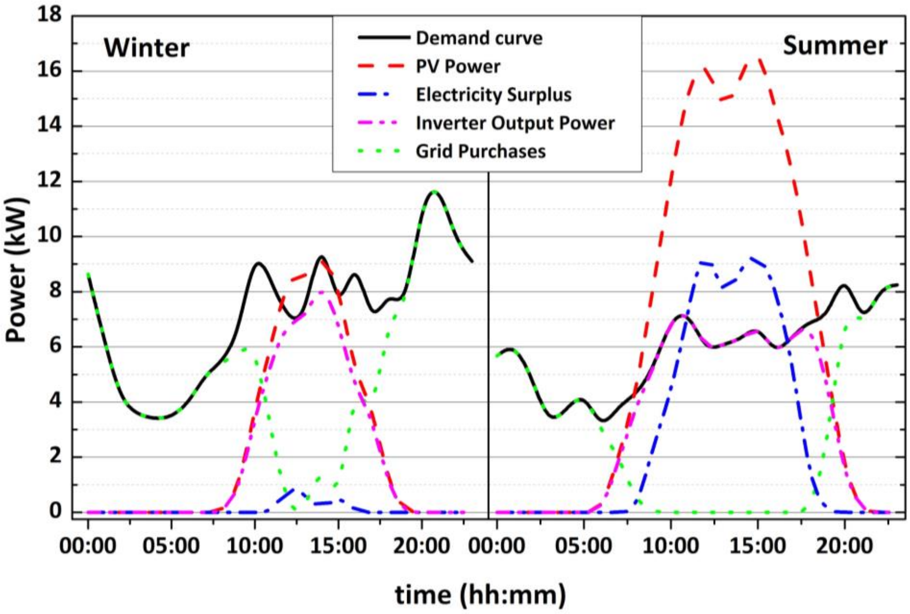

Fig. 4 Representation of the main features of the simulations for two representative days in the winter (15th of January) and in the summer (15th of July) for a 5-floor residential building.

Note: **The model used for the simulation is self-consumption. In the graph we show the results from the simulation related to the demand curve, the power from the PV installation, the surplus generated by the installation, the power converted by the inverter and the power purchased from the grid. The lines are smoothed for clarity.**

Having a quick look at the results, the power installed in the case of SC is, in all models, lower than the case for Sale and NEM, and yet with a higher LCOE. This is due to the fact that, to optimise the installation by minimizing the LCOE, the best scenario for self-consumption case is not the one that uses all the available rooftop area with panels. In other words, the installed capacity is not the full possible capacity for the rooftop. Figure 4 shows the behaviour of the main values of the simulations along a day for a 5-floor residential building in the winter and in the summer.

The case for the single-family house will not be profitable in self-consumption, self-consumption with storage or sale to the grid. The main reason for that is the high prices of equipment[DOGV8299]. Also, we use the hypothesis that the selling to the grid is fixed to the price of 5c€/kWh. The case for NEM model is the only scheme profitable for single family houses, being the LCOE lower than 20.85 c€/kWh. Also, this is the case where the environmental benefits are higher. As explained, tThe case for storage in case of single-family houses and multi-storey buildings was discarded as there is no combination with accumulation that obtains a lower LCOE or Payback.

The model for residential buildings with more than 2 floors was simulated considering a multistorey building 5 floors high, with 3 households per floor. This sums up 12 total households considering the ground floor dedicated to shops. The demand curve is twelve times the demand curve for the single-family house. In this case PV installations are always profitable, although as in the previous case, NEM is the most profitable scheme. In this case, the taller the building, the more households to aggregate, the more profitable the PV power system; up to a point where all the available surface for generation is used, and all the generated PV electricity is consumed, substituting electricity from the grid. From that point onwards, aggregating more households only makes the "per household" savings smaller, but the other overall economic features remain the same.

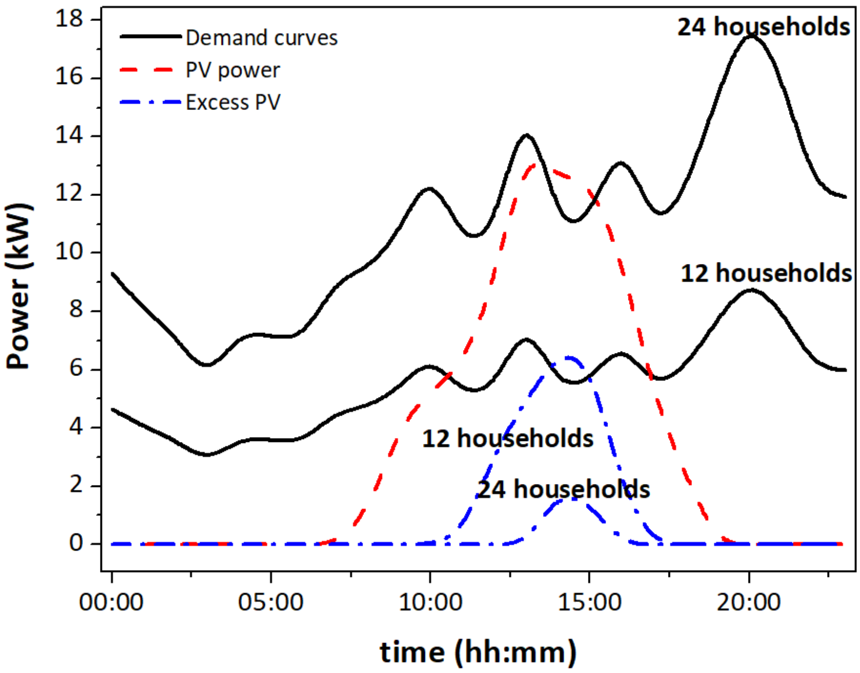

Fig.5: In the graph we show a comparison between buildings with different heights, with exactly the same demand curve per household and the same rooftop area.

Note: We took a representative day in October for the comparison. PV power and Excess PV for the 12 households' case are data obtained from the simulation, while the demand curve for the 24-household' case was obtained by multiplying by two the 12-household one. The Excess PV for the 24-households case was obtained by subtracting the PV power to the demand curve.

This point can be explained with the graph in figure 5, that shows PV power generation curve, surplus energy from PV and a comparison between demand curves of 1-household, 12-household and 24-household buildings with the same available surface and demand curve per household. We took an example from an average day in October. According to the simulations, the 12-household 5-floor building at midday produces enough electricity to cover the demand, and generate a surplus (Excess PV) which in the case of self-consumption, is wasted. If we then consider the same conditions (i.e., same available surface, same installed PV power, same demand curve per household) for an equal building with double the number of households, we can see that the PV power is barely enough to cover the demand of the building (i.e., all the produced electricity is consumed by the users, and the surplus is minimum or absent. depending on the day and season). This means that, keeping constant the rooftop surface of a building, from a certain number of floors (and households) onwards, the PV installation starts to become less interesting from a demand-supply point of view, although still economically profitable. It is hard to estimate at which number of floors this effect comes into play, but it is a rough estimation that has to be taken into account when planning a PV installation on a tall building. Therefore, if we consider the numbers of buildings from the official cadastre[27], we can state that for around two thirds of the households in Valencia, namely 205,000 in buildings with more than 7 floors out of 329,000 total residential households in buildings, the electricity demand cannot be covered with their own photovoltaic power generation Provided they could install PV panels on their roofs, the amount of clean electricity per household would be very small. Nevertheless, the LCOE would be very low because the installation would be optimised for the available space. On the positive side however, the aggregation of several demand curves from different households would better match the generation curve, a fact that is not easily visible in the present example since we used the same demand curve for simplicity of calculation. On the other hand, still one third of the residential buildings (less than 7 floors) produces PV surplus that, depending on the economic scheme, could in principle be flowing to the grid or to other households (in a~~n~~ Local Energy C~~c~~ommunity scheme for example) and better match the demand and supply.

In the case of Alquerias ~~potentially~~ disconnecting from the grid, the PV installation with storage provides the demanded electricity without power cuts. However, being an off-grid system it needs a high capacity of the batteries, which makes the LCOE significantly higher than a PV installation connected to a grid-tied system. The economic optimum was set at 9 kWp, even though more PV could be installed. One problem with this option is that approximately 10100 kWh/year of renewable clean electricity that could be~~is~~ generated is~~and~~ wasted, almost twice as much as the amount consumed.The option without batteries is not feasible due to the differences between the demand curve and the solar radiation curve. As there are no other renewable resources available such as wind, hydro, biomass, etc. a power system fueled with diesel was simulated. But, although the investment would be almost half, the LCOE would be 3.4 times higher (diesel was modelled to cost 1.2 €/litre). Besides, the emissions balance would be negative, i.e., the power system would emit about 5 times more CO_2 compared to consuming from the grid. Adding storage, simulations give better results in terms of LCOE, but still worse than without a diesel engine or connected to the grid. The best combination is the one that does not use the engine[8].

The cases for commercial and public buildings are always profitable from an LCOE point of view and payback time, being the NEM scheme the most profitable one, as expected.

The amount of renewable energy generation and emissions avoided are both significant in all the cases studied, even in cases where the installations are not profitable (self-consumption and sale to the grid of single-family houses).

4. Detailed calculation of the potential for PV generation

In the present paragraph we calculated the maximum potential total energy generation according to the estimated rooftop surfaces of paragraph 3.

[8] That is to say, the more the diesel engine is turned on the more consumption of diesel and the more expensive the electricity generation is, even considering the investment and operation costs of the batteries.

In all the calculations we considered the potential energy generated per meter square per year (PEG) as the following:

$$PEG = PVGIS(0^o) \times \eta_{panel} \times F_{loss} = 4960 \frac{Wh}{m^2\, day} \times 0.15 \times 0.8 = 592.2 \frac{Wh}{m^2\, day} = 217.25 \frac{kWh}{m^2\, year}$$

where PVGIS(0º) is the average value for the city of Valencia, at zero degrees (we consider as the best estimation to account for the variation in roof inclination among different buildings), η_{panel} is the panel efficiency and F_{loss} is the factor taking into account for all the losses related to distribution, temperature, maintenance etc.

The available surface for the calculation of the potential energy generation is the measured value (as in table 1). However, to be on the safe side, we have ~~,~~reduced it by a factor of 50%, taking into account other uses of the rooftops, possible shades not considered by the software Huellasolar, etc. (rows 1, 2, 3, 4 and 6 in tab 3). In two cases this discount was higher to count off protected ~~because of the possible~~ buildings ~~protection~~ (based on city council's statistics, an added 50% for hotels and an added 25% for private schools in row 5 of table 3).

The potential energy generation (EG) is calculated with the following formula:

$$EG = Available\ surface \times PEG$$

While the installed capacity is obtained by using the factor $7m^2/kW_p$ as discussed previously. The results of the calculations are reported in tab. 3

Tab 3.: Values of the estimated total available rooftop surface, installed capacity and corresponding potential energy generation

	Total available surface (m^2)	Installed capacity (MWp)	Energy generation (GWh/year)
Single family buildings *(1,344 houses)*	**84,807**	**12.12**	**18.4**
Buildings of 2 to 6 floors *(10,595+269 houses)*	**1,212,837**	**173.3**	**263.5**
Buildings of more than 6 floors *(17,315 houses)*	**2,058,101**	**294.0**	**447.12**
Alquerias *(560 houses)*	**24,125**	**3.4**	**5.2**
Standalone commercial and industrial buildings *(1,188 buildings)*	**764,072**	**109.15**	**166.0**
Public buildings *(761*	**341,768**	**48.8**	**74.3**

Comentado [CVS13]: Reviewer 1:
- It is not completely clear how the "available surface" is calculated ("The available surface for the calculation of the potential energy generation is the measured value (as in table 1), reduced by a factor of 50%, taking into account other uses of the rooftop, possible shades not considered by the software Huellasolar, etc. In two cases this discount was higher because of the possible building protection (an added 50% for hotels and an added 25% for private schools). ». The reviewer suggests to include mathematical equations in the paper to clarify this. Same comment for the section on "Economic investments scenarios", as it is unclear how the values were obtained for the worst-case scenario.

Comentado [CVS14R13]: No se si será conveniente pone un subapartado para explicar como se estiam el área disponible.nem

buildings)			
TOTAL	**4,485,710**	**640.8**	**974.52**

~~Tab.3.: Values of the estimated total available rooftop surface, installed capacity and corresponding potential energy generation~~

The value obtained for the maximum total potential energy generation is roughly the same (99%) as the total domestic electricity demand of the city of Valencia estimated as 985.01 GWh/year[statVLC]. If we consider the total electricity demand of Valencia (2,618 GWh/year)[statVLC], what we calculated can contribute up to 37% of the total demand[9].

Since most of the time we used a conservative approach, this result opens a window of optimism for the potential energy transition for the city of Valencia. Moreover, local economic opportunities can sprout in the field of PV panels and installations.

5. Economic investments scenarios

The costs of the PV power installations can vary substantially depending on the size, the quality of the equipment, appropriateness of the rooftops, number of users, complexity of the distributions, existence or not of smart meters, etc. and also depending on the scheme adopted for the PV installation (according to the models of paragraph 3). To tackle the uncertainty in estimation and calculation we design a "best-case" and a "worst-case" scenario and calculate the investments accordingly. According to tab.2, the scheme for the best-case scenario is always the NEM, while for the worst-case scenario is the self-consumption.
After reviewing the prices given by EnerAgen and the International Energy Agency, we found Spanish owners paid 1.4 – 1.5 €/Wp (VAT excluded) for a PV power system in 2016[IEA] in a residential building. PV systems in commercial and industrial buildings were paid even less: 0.8 – 1.3 €/Wp. Finally, off-grid PV systems cost between 2.0 and 2.8 €/Wp for installations larger than 1 kW. Furthermore, in those provinces or communities where incentives or subsidies are in force, the investment can be reduced by around 35%[eneargen]. For best case scenarios for residential buildings (single or multi-storey) we considered 1400 €/kWp (VAT excluded), while for worst case scenario we used 3374 €/kWp as obtained from the simulation for the case of the model 1(S-C) (tab.2); for the Alquerias we used 2000 €/kWp (VAT excluded) for best case, and 3059 €/kWp for the worst case as obtained from the simulation for the case of the model 3 ~~(~~storage~~)~~ (tab.2). Finally, for public and commercial buildings we used 800 €/kWp (VAT excluded) for best case and 1200 €/kWp (VAT excluded) for worst case.

For the calculations we used the following formulas:

- The **installed capacity** in case of best-case scenarios is always the maximum possible capacity that can be installed on the full rooftop surface available. To calculate this, we take the total installed capacity estimated for the whole city for a particular hot spot (from tab.3) and divide it by the number of buildings/houses. In this way we obtain an average value for a certain type of building. In case of worst-case scenarios for single-family houses, commercial and public buildings the installed capacity is reduced by a factor, according to

[9] In the case of the businesses residing in the lower flat of a multi-storey building, we simplified the analysis considering them as a household. This fact keeps the study on the conservative side, as most businesses consume electricity in the central hours of the day, when solar energy is mostly available, compared to residential households that peak early in the morning and late in the evening.

Comentado [CVS15]: Reviewer 1:
This paper describes a methodology for assessing the potential in terms of PV electricity of the city of Valencia, Spain, and compares it to both the domestic and total electricity consumption of this city. The results show that 37% of the domestic demand could be satisfied by PV electricity from panels installed on the most favorably-oriented parts of Valencian roofs. However, this result does not seem to consider economic constraints on the prosumers, which should be indicated more clearly. However, an in-depth techno-economic analysis is carried out in the second part of the paper as well.

Comentado [CVS16]: Cambiar pie de página a bibliografía tab.2 (for single-family houses the installed capacity is reduced by 1/3, for commercial buildings the installed capacity is 75% of the maximum possible capacity and for public buildings it is 50%). For off-grid and residential with more than 2 floors the installed capacity is the same, since in both cases they need to put the maximum possible capacity available.

- In best case scenarios the **saved electricity** is the amount calculated and reported in table 3. The calculation for the worst-case scenario takes into account the fact that the installed capacity is lower than in the best case. We used two methods to estimate the worst-case scenario: first we used the values for "Inverter Output" from tab.2 (as it is the effective energy usable coming from PV panels) and multiplied by the number of buildings obtaining in this way the electrical energy produced, then we considered the percentage of PV (from tab.2) of the SC cases and calculated the corresponding electrical energy produced. The smaller values between the two is our worst-case scenario.
- The **total investment** is calculated multiplying the installed capacity by the price per kWp. We added the possibility of receiving subsidies (only in the best-case scenarios), which will reduce the total investment by 35%. The **cost of the investment** is basically the price used for the calculation of the total investment.
- The **money saved per unit** (household or building depending on the model) can be calculated by multiplying the saved electricity by the price of electricity, that we took as 20,85 c€/kWh. In this way we obtain the total money saved considering all the buildings. We divide, then, the value obtained by the number of units.
- The **payback time** is calculated by dividing the total investment by the total money saved.

In tab. 4 we summarise the results for the investments scenarios.

Tab 4.: Economic investment estimations. Both cases of possibility of subsidies or no subsidies were considered.

MODEL	**CASE**	**Power installed (kWp/unit)**	**Saved electricity (GWh/year)**	**Cost of investment (€/kWp)**		**Payback time (years)**		**Savings per unit (€/year)**
				No Subsidies	**Subsidies**	**No Subsidies**	**Subsidies**	
Residential single family	**BEST**	9	18.4	-1,694	1,101	5.4	3.5	2,854
	WORST	3	2.4	3,374	-	27	-	376
Residential ≥ 2 floors	-	16.6	710.6	1,694	1,100	5.3	3.5	351[10]
Alquerias	**BEST**	9	5.2	2,420	1,573	22.5	14.6	967

[10] In this case the unit is the household, while in all the others is the building.

off-grid	**WORST**	9[11]	5.2	3,059	-	28.5	-	967
Commercial /industrial buildings	**BEST**	92	166.0	968	-	3.05	-	29,134
	WORST	69	143	1,452	-	4	-	25,097
Public buildings	**BEST**	64	74.3	968	-	3.1	-	20,357
	WORST	32	52.6	1,452	-	3.2	-	14,400

~~Tab 4.: Economic investment estimations. Both cases of possibility of subsidies or no subsidies were considered.~~

6. Environmental considerations

As explained before, to characterize the environmental aspects of the electricity, as every household may have a different supply company, an average emission factor (EF) has been selected. The EF is the one given by REE for year 2017[ree]: 285 gCO2e/kWh (or tCO2e/GWh). CO2e (equivalent CO2) is the reference unit of Greenhouse Gases (GHG) that produce Global Warming.

Besides, the observatory of the European Environmental Agency (EEA)[EEA] adds that, per kWh generated, the electric power mix of Spain releases: 0.62 g of SO_2 and 0.42 g of NO_x. While Sulphur Dioxide contributes directly to Acid Rain and indirectly to Smog, Nitrogen Oxides directly produces Acid Rain, plus Smog and damage to human health like respiratory infections and asthma.

If the savings of electricity are turned into savings of air emissions, we have the figures of table 5. As can be seen, the yearly indirect savings of air emissions would be very important if all the potential for PV electricity generation could be exploited, such that the electricity from the grid is substituted with electricity from PV (keeping constant the environmental aspects of the electricity coming from the grid).

MODEL	**CASE**	**Saved electricity (GWh/year)**	**GHG saved (t/year)**	**SO_2 (t/year)**	**NO_x (t/year)**
Residential single family	BEST	18.4	5,244	11.4	7.7
	WORST	2.4	684	1.5	1.0
Residential ≥ 2 floors	-	710.6	202,521	440.6	298.4
Residential	BEST	5.2	1,482	3.2	2.2

[11] The worst-case scenario of the Alquerias maintains the same amount of power installed (i.e., surface available) of the best-case scenario. The reason is that the typical Alquerias suffer no restriction of spaces because of the land available to the owner. They might take advantage of fields or other structures for the installations, if necessary.

single family off-grid	WORST	5.2	1,482	3.2	2.2
Commercial/ industrial buildings	BEST	166.0	47,310	102.9	69.7
	WORST	143.0	40,755	88.7	60.1
Public buildings	BEST	74.3	21,175	46.1	31.2
	WORST	52.6	14,991	32.6	22.1

Tab. 5: Estimations of emitted greenhouse gases (GHG), SO_2 and NO_x

7. Conclusions

It is clear how urgent it is to shift to a low-carbon economy and to a different model of energy production and consumption. The rapid development of cheap technological solutions for PV self-consumption has multiplied the possible economically feasible business cases available for consumers. On the other hand, according to the CNMC (*Comisión Nacional de los Mercados y la Competencia*) [28] the electricity price has always been rising in the last 20 years, another factor that backs up the profitability of the PV installations and the present work. In order to move a step forward into prosumption, citizens must perceive that there is institutional support and a reliable framework for them to do so.

The majority of the PV systems simulated in the present work are economically profitable today, particularly the larger ones in tall residential buildings, standalone commercial buildings and standalone public buildings. Other PV systems would be profitable if just the exceeding electricity could be sold to the grid at a reasonable price of 0.05 €/kWh. Finally, the rest of PV systems will be profitable if a monthly NEM system allows making a balance of electricity input and output before calculating the bill. The single-family houses, besides, should be able to sell their surplus of electricity in order to install as much PV power as the full potential of their roofs allows. That sale would be the most profitable if it could be done at the market price (in this study we considered 20.85 c€/kWh including the fixed and variable part).

Based on the calculations and estimations explained in this article, our conclusion is that the rooftops of the buildings of Valencia present the potential to generate up to 99% of the electricity demanded by the residential sector by means of PV power systems, and 37% of the total demand.

Considering the economic investment scenarios, it is clear that to foster rooftop installations in the residential sector we need consumer-friendly schemes such as the NEM, that we considered in our study.

At the present pace, electricity consumption is rising every year [29,30]. If we also take into account the shift already occurring from fossil-fuel based mobility and transportation to electric vehicles, the rates are expected to increase even more. That is, although we are conscious that it is very important to integrate several renewable energy systems (wind, PV etc.) to increase renewables penetration and energy resilience [31], the results obtained are encouraging. At the same time, we advocate that a bold consumption reduction plan is needed, for example through a general electricity saving program (at national and/or local scale).

Finally, the environmental benefits of rooftop PV installations for electricity generation would indirectly save an enormous amount of contaminants emissions that contribute to global warming, acid rain and Smog, among others.

[illegible]
sustainability, intended as a systemic problem, has not been considered here. In particular, the increase of adoption of NEM by prosumers ~~would~~has been said to ~~inevitably~~potentially create an imbalance in energy provision at specific time of the day, that ~~should~~might be compensated by either fast-producing power plants (gas, gasoil or similar) or storage (either batteries or Hydrogen-based technology) [Renner2020]. Having some of those technologies important environmental problems, ~~In this way~~ the real environmental benefits should be carefully estimated.

Also, the integration of renewable energy-based distributed generation systems into th electric grid has ~~many~~various challenges such as synchronization, control, power management and power quality problems, which has not been considered in this study[Celik2019].

That is, although we know that there are several issues related to PV-based ~~presumption~~prosumption schemes, at the moment it seems to be among the best options in the global Energy Transition framework.

Based on these conclusions, our recommendations for the promotion of the use of PV rooftop installations in Valencia would be:

- Develop a NEM program and make it available to consumers.
- Create a framework for the development of energy supply projects, whether wholly owned and/or controlled by communities or through partnership with commercial or public sector partners (Local Energy C~~c~~ommunities) [32,33].
- Create on-line platforms for self-design of PV-Grid electric systems.
- Development of virtual electric markets for Prosumers with virtual power plants (VPP). Consumers and producers could meet together in virtual markets where they would deal directly with each other, or by means of a trading company and a scheme of Guarantee of Origin (GO or GoO).
- Help for the adaptation of rooftops. In general, a credit line for those potential prosumers with difficulties for the investment. Indeed, a number of fuel poor families could alleviat their situation with the energy cost savings [reference].
- Energetic rehabilitation of buildings
- Start pilot projects as a claim for prosumers.

Comentado [TGN17]: Tomás Gómez-Navarro, María Calero-Pastor, Victoria Pellicer-Sifres, Pau Lillo-Rodrigo, David Alfonso-Solar, Ángel Pérez-Navarro, Fuel poverty map of Valencia (Spain): Results of a direct survey to citizens and recommendations for policy making, Energy Policy, Volume 151, 2021, 112162, ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2021.112162. (https://www.sciencedirect.com/science/article/pii/S0301421521000318)

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TEXT-EDITABLE TABLE 2

Building/ Model		Power installed (kWp)	Total investment (€)	Total electricity consumption (kWh/year)	Grid purchases (kWh/year)	PV power (kWh/year)	Electr. Surplus (kWh/y)	Inverter Output (kWh/y)	GRID %	PV %	LCOE (c€/kWh)	Payback time (y)	GHG Avoided (kg/y)
1	S-C	1.5	5061	4636	2881	2461	460	1801	62	38	22.14	29.60	532
	Sale	2	5829	4636	2685	3282	1003	2051	57	43	21.48	24.70	709

	NEM	4.5	10345	4636	2351	7384	4361	2721	46	54	19.56	19.56	1595
	S-C	20	32466	55480	33535	32816	7589	22704	60	40	19.26	13.76	6227
2	Sale	20	31726	55480	33535	32816	7448	22831	59	41	18.50	11.45	6261
	NEM	20	31726	55480	33535	32816	7448	22831	59	41	17.20	9.17	6261
3	Storage	9	27533	4636	0	14767	10131	4172	0	100	38.12	61.05	1113
	S-C	150	169690	509902	319683	246119	34761	190222	63	37	8.95	12.55	45653
4	Sale	200	216536	509902	293185	328158	78298	224874	57	43	8.4	11.75	51573
	NEM	200	216536	509902	293185	328158	78298	224874	57	43	8.2	11	51573
	S-C	100	113261	310990	200414	144718	21866	110567	64	36	10.92	13.60	26536
5	Storage	110	761593	310990	193458	159189	28609	117522	62	38	11.13	15.6	28205
	Sale	200	210148	310990	152560	298435	97567	180781	46	54	10.14	13.8	61436
	NEM	200	210148	310990	152560	298435	97567	180781	46	54	9.5	12.32	61436

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Con formato: Hipervínculo, Fuente: (Predeterminada) Calibri, Español (España)

Código de campo cambiado

Código de campo cambiado

Con formato: Hipervínculo, Fuente: (Predeterminada) Calibri, Inglés (Estados Unidos)

Con formato: Español (España)

Con formato: Hipervínculo, Fuente: (Predeterminada) Calibri, Español (España)

Código de campo cambiado

Con formato: Inglés (Reino Unido)

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Comentado [T.B.18]: De donde vienen esos datos?

Con formato: Resaltar

Con formato: Resaltar