Scenarios of Photovoltaic Production, Energy Storage and Electrification of Mobility and Residential and Service Sectors in the LMA

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Abstract

The RNC2050 establishes carbon neutrality trajectories for Portugal until 2050 based on the increase of its share of endogenous RES and the reduction of its energy dependence levels. The LMA is an important pole in the country's energy transition as it represents a large part of its energy consumption. Through exergy analysis and projections of consumption of useful and final exergy, based on different economic growth rates of the RNC2050, LMA's decarbonisation feasibility in 2050 was studied through scenarios, which consider the electrification of three sectors of activity (residential, services and transport) and the use of decentralized solar photovoltaic power with battery storage. In the transport sector, the electrification was studied by replacing the ICEVs' fleet with BEVs, considering different vehicle charging profiles. For each scenario, PVs and batteries capacities required to meet the LMA's consumption were calculated, as well as PVs' installation areas and LCOE. In the scenario with the highest economic growth where BEVs can be charged day and night (P-C1), the PV capacity is 31,77 GWp and the battery storage capacity is 35,45 GWh, corresponding to a PVs' installation area of 124,56 (4,1% of the total area of the LMA). For all scenarios, grid parity is attained in 2020, the P-C1 scenario presents a LCOE of 0,228 €/kWh in 2020 and 0,114 €/kWh in 2050.

Keywords: Energy Transition, Exergy Analysis, Electrification, Solar Photovoltaic, Battery Storage, LCOE

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1. Introduction

In 2015, with the Paris Agreement, the global community established long-term goals to contain the global average temperature increase, which implies a high reduction of GHG emissions in all sectors of activity. In order to meet the agreed targets, carbon neutrality must be achieved in the EU by 2050. These challenges represent an opportunity for Portugal to lead the energy transition, increasing its share of energy production through renewable energy sources (RES), and simultaneously, reducing its levels of energy dependence. However, since RES have variable characteristics, high shares of RES imply an increase in energy storage capacity, namely through batteries.

It is also important to understand the role of cities and metropolitan areas in the energy transition. Since 2007, more than half of the world's population has lived in cities, and this share is projected to increase to 70% by 2050 (Smil, 2019). Additionally, most homes, services, industries and transport are concentrated in urban areas, which increases their energy consumption rates per unit area. Therefore, it is important to characterize these regions energetically and to consider their contribution to the energy transition.

Unlike conventional energy analysis, exergy analysis considers the quality of energy flows and the efficiency of their conversions. In Serrenho et al. (2016), the long-term exergetic flows of Portugal (1856 to 2009) were studied. In addition to this, exergy intensity, which is the relationship between the use of exergy and economic growth is explored (primary, final and useful). Final exergy intensity decreased over time. Useful exergy intensity was approximately constant for about 150 years which means that the decrease observed in final exergy intensity resulted from the increase of the final-to-useful efficiency and not a decrease of the useful exergy.

In 2017, the preparation of the Portuguese Carbon Neutrality Roadmap (RNC2050) began, which, according to macroeconomic and demographic projection for 2050, outlines carbon neutrality scenarios (off-track, platoon and yellow jersey) for various sectors of the Portuguese economy, such as energy, residential, services and transports. The trajectories of the RNC2050 imply an increase in the share of RES for the power sector, with PV solar energy (centralized and decentralized) being one of the main pillars of this transition, with capacities between 26 and 26,4 GWp in 2050, i.e., approximately 48% to 50% of the total installed capacity. Battery power represents 7% to 8% of the total installed capacity, i.e., between 4 and 4,1 GW in 2050. By 2050 emissions reductions will be 95% and 100% compared to 2015 values, in the residential and services sectors, respectively. Electrification of uses will be the main driver of emission reductions in both sectors and should represent over 80% of the energy consumed in the domestic sector and over 90% in services. In the transport sector, CASE (connected, autonomous, shared and electric) mobility will play a key role in decarbonising the sector. The passenger fleet electrification is the main factor in reducing vehicle emissions, with ICEVs practically extinct in 2050.

Solar photovoltaic is currently dominated by C-Si (crystalline silicon) technology, which is divided into two technologies: monocrystalline silicon (sc-Si) and polycrystalline silicon (mc-Si); with 33% and 62% market shares, respectively (Fraunhofer, 2019). Sc-Si cells have higher efficiencies of conversion, reaching a maximum of 26%. In 2017, Portugal had 585 MWp of solar PV power and produced 993 GWh of PV electricity, which gives a yield of 1697 kWh/kWp per year. According to data from Solis (2019), the potential capacity that can be installed on the roofs of the municipality of Lisbon is 2.8 GWp (an installation area of approximately 16,94 km^2) and the potential for solar electricity production is 2,85 TWh/year (a 1012 kWh/kWp per year yield). Assuming a performance ratio (PR) of 0,75, roofs' irradiation is 1350 kWh/m^2. In the LMA, PVs with an optimal slope exhibit global irradiation values greater than 1900 kWh/m^2 and yields greater than 1425 kWh/kWp (Comissão Europeia, 2019a).

Increasing the RES share in electricity will imply greater flexibility in the electricity system. Energy storage, which provides a wide range of complementary services to RES, could facilitate the transition to a decarbonised and RES-dependent electricity sector. Lithium-ion (Li-ion) batteries, which represent 59% of the installed capacity of electrochemical storage, exhibit favorable characteristics for stationary applications: response times in the order of milliseconds and high values of power density (1500-10000 W/l) and energy density (150-500 Wh/l). Although Li-ion batteries are not restricted to transport applications, the scale-up of electric mobility led to a 73% cost reduction from 2010 and 2016. The prospects for the performance of Li-ion batteries until 2030 are also positive: their lifespan could increase by 50%, the number of cycles up to 90% and their efficiency could be between 88% and 98%, depending on battery chemistry (IRENA, 2017).

Off-grid PV systems include the following components: PV panels, a hybrid inverter, connecting DC-AC conversion cables, support structure and batteries. There is also the option of using a generator as a backup for charging the batteries. The storage ratio, batteries capacity (MWh) by PV capacity (MWp), is an important sizing factor of these types of installation. Several off-grid installations range from a 1,25 to 5,88 storage ratio. However, according to Vartiainen *et al* (2019), in optimally storage sized systems, storage ratios range between 1 and 2 kWh/kWp.

The concept of peer-to-peer (P2P) applied to energy trading presupposes two-way energy trading in a direct and decentralized manner, where peers (producers, consumers and prosumers) can sell or buy energy without intermediaries, which is more beneficial for all parties involved when they exhibit different consumption profiles. According to Zepter *et al* (2019) P2P and energy storage contribute to greater integration of decentralized power generation sources and a reduction in electricity costs by half. In Portugal, recent legislation (*Decree-Law n.º162/2019)* established the legal framework of collective self-consumers and renewable energy communities (RECs). This decree opens an opportunity for RECs, condominiums and self-consumption groups to install self-consumption production units (SCPUs) and to trade electricity in their neighbourhood.

The levelized cost of energy (LCOE) is the discounted production cost of installing and operating a project and it is expressed in €/kWh. This variable is an economic indicator that allows the comparison between power generation technologies with different scales, life cycles, capital expenses, return and risk. LCOE can also be used to check if PV and storage systems have equivalent costs compared to the network (grid-parity).

Large scale (50 MWp) systems that include both PV panels and batteries were studied in Vartiainen *et al.* (2019) for several cities in Europe from 2019 to 2050. In the LCOE calculation, two storage ratios per PV capacity were used: 1 kWh/kWp and 2 kWh/kWp. In 2019, for Rome, whose yield (1570 kWh/kWp) is close to Lisbon's, the LCOE, for both storage ratios, is not only below average electricity prices, but also at the average spot market price. In 2050, the LCOE of PV plus storage of this city is 0,015 €/kWh and 0,020 €/kWh for storage ratios of 1 and 2 kWh/kWp, respectively.

In this paper, an exergy analysis performed between 2011 and 2017 to the LMA and the municipality of Lisbon along with economic growth projections of the RNC2050, served as a basis for building scenarios of exergy consumption in the transport, residential and services sectors. Assuming complete electrification of all sectors and different consumption profiles for each sector, several variables were computed: the LMA's PV capacity and battery capacity for each scenario, the CO_2 emissions reduction, the installation area, and the LCOE.

2. Methodology

2.1. Exergy Analysis (2011-2017)

The methodology used to calculate primary, final and useful exergy and CO_2 emissions from energy consumption and sales data reported by DGEG is presented in Figure 1.

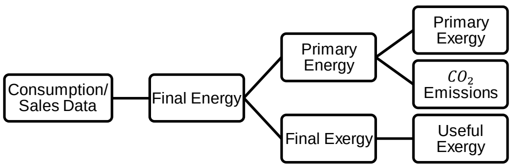

Figure 1 – Exergy Analysis Scheme

Five sectors were considered for the exergy characterization: Agriculture, Industry, Services, Transport and Residential.

Final energy was calculated from electricity consumption (kWh), natural gas ($10^3 Nm^3$) and fuel sales (ton) data. To convert each energy vectors data to the same unit, toe(fe), final energy conversion factors for the energy vectors were taken from DGEG (2018). η_c $\eta_{engine} \times \eta_t$

Converting final energy into final exergy, depends on the capacity that different energy vectors (electricity, natural gas, LPG, gasoline, diesel, fuel oil and biodiesel) have to deliver work, hence exergetic factors (final energy to final exergy) obtained from Serrenho *et al.* (2016) were considered.

For the calculation of primary energy from final energy data a conversion factor of 1 toe(pe)/toe(fe) was used for all energy vectors, except electricity, whose primary to final conversion factors were calculated for each year.

CO_2 emissions were computed using emission factors, kgCO_2/toe(pe), for each energy vector, except electricity. These emission factors can be found in Lisboa E-Nova (2014). The emission factor of electricity was calculated for each year, considering the primary energy consumption mix associated to electricity production.

The useful exergy categories considered were: heat, mechanical work, cooling, lighting, electronic uses and electrolysis. Heat and cooling are further subdivided in different types of use. The types of use associated with heat are: hot water, cooking, space heating uses and air conditioning. Refrigeration and air conditioning are the two types of use of cooling. The final-useful exergy efficiencies for the period 2011-2017 were mostly obtained from Serrenho *et al.* (2016), except for electricity, whose efficiencies and fractions of useful exergy category were obtained from Felício et al. (2019).

2.2. Energy Transition Scenarios

2.2.1. Transport Sector

In 2013, the sales of diesel, gasoline and LPG reached minimum values both in the LMA and the municipality of Lisbon, considering the 2011-2017 period. Using specific mass values of these three fuels (kg/l) and the average fuel consumption (l/km), annual kilometers performed by these vehicles were computed. Once again, in 2013, the lowest values were observed in the LMA, $1{,}63 \times 10^{10}\ km$ and in the municipality of Lisbon, $3{,}20 \times 10^{9}\ km$.

For both regions, these values were assumed to be the maximum travelled distance in 2050, as they were considered to represent reasonable limits of traffic quality, i.e., lower levels of congestion. It is also assumed that the current fleet will be completely electric in 2050, i.e., all ICEVs will be switched by BEVs.

BEVs' final to useful exergy conversion follows the scheme in Figure 2.

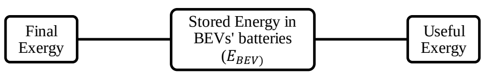

Figure 2 - Final to useful exergy conversion for BEVs

Final to useful exergy efficiency for BEVs is given by (1), where η_{engine} is the electric engine efficiency, η_c is the charging efficiency and η_t represents BEVs transmission efficiency.

$$\varepsilon=\eta_{engine}\ \eta_c\ \eta_t \qquad (1)$$

Thus, from final exergy values it is possible to calculate the average consumption power of BEVs in 2050 using (2).

$$\bar{P}_{BEV_{2050}}=\frac{\text{Final Exergy}_{BEV_{2050}}}{365\cdot 24} \qquad (2)$$

2.2.2. Residential and Services Sectors

The electrification of the residential and services sectors by 2050 followed a two-step approach. Initially, useful exergy was projected, using, macroeconomic and demographic projections. These projections were later combined with assumptions of technological improvement, i.e., higher final to useful exergy efficiencies for 2050 and final exergy projections were computed.

2.2.2.1. Useful Exergy Projections

Firstly, the average useful exergy intensities were computed for the residential (RSEI) and services (SSEI) sectors from 2011 to 2016. These values were assumed to be constant until 2050, which is supported by the results of Serrenho et al. (2016), where it was observed that useful exergy intensity has remained approximately constant over more than 150 years for Portugal. Then, using GDP per capita growth rate projections of the RNC2050 scenarios (Table 1) and the LMA population projections from 2012 to 2060 of the INE's central scenario, constant-price GDP projections were computed for the LMA.

Table 1 - Portuguese GDP per capita growth rates projections (RNC2050)

GDP per capita growth rate	2016-2020	2021-2030	2031-2040	2041-2050
OT	2,20%	1,60%	1,30%	1,60%
P	2,20%	1,80%	1,50%	1,80%
YJ	2,20%	1,60%	1,60%	1,80%

Finally, useful exergy, for each year i, was projected for the residential and services sectors using (3) and (4), respectively.

$$\text{Useful Exergy}_{RS_i}=\text{RSEI GDP}_{LMA_i} \qquad (3)$$

$$\text{Useful Exergy}_{SS_i}=\text{SSEI GDP}_{LMA_i} \qquad (4)$$

2.2.2.2. Final Exergy Projections

Final exergy projections for 2050 comprise the following three-step methodology:

1. Electricity shares of useful exergy for each use category and type of use in 2050.
2. Final to useful exergy efficiencies for each use category and type of use in 2050.
3. Final exergy projections for 2050.

It was assumed that the shares of useful exergy by category of use and type of use are the same used for the 2011-2017 period, except for space heating uses and air conditioning, where the latter becomes the main type of use. However, due to the change in energy vectors, i.e., the electrification of categories and types of use, electricity shares are different than the ones used for the 2011-2017 period.

Final to useful exergy efficiencies for 2050 were computed for each category and type of use, according to the definitions presented in Serrenho *et al.* (2016) and Felício *et al.* (2019). Then, according to literature projections for 2050, several variables were assumed for the computation of final to useful exergy efficiencies.

Ultimately, final exergy projections were computed for 2050 for both sectors and their average consumption power was calculated using (5) for the residential sector and (6) for services.

$$\bar{P}_{Residential_{2050}}=\frac{\text{Final Exergy}_{Residential_{2050}}}{365\cdot 24} \qquad (5)$$

$$\bar{P}_{Services_{2050}}=\frac{\text{Final Exergy}_{Services_{2050}}}{365\cdot 24} \qquad (6)$$

2.2.3. Power Production/Consumption Profiles

2.2.3.1. Consumption Profiles

In the transport sector, three scenarios were studied for BEVs' charging:

1. Scenario 1 (C1) was obtained from Faria et al., (2019), where BEVs could be charged at daytime or nighttime for any day of the week.
2. In Scenario 2 (C2), charging only takes place between 9:30 am and 4:30 pm, with constant consumption power over that time. This scenario was created to examine the battery capacity reduction, when charging at sun hours.
3. In Scenario 3 (C3), charging takes place from 0:30 am to 8:30 am and from 5:30 pm to 11:30 pm and the power consumption is constant during this period. Here, charging occurs when solar radiation is low or non-existent.

Figure 3 shows the daily power share profiles for the three BEVs' charging scenarios.

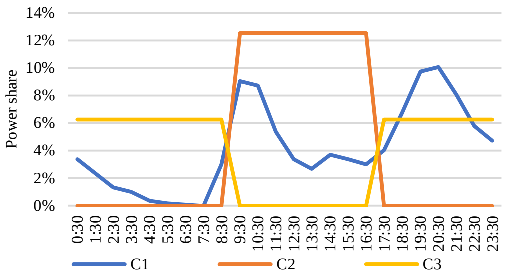

Figure 3 - Daily power share profiles (%) for different BEVs' charging scenarios

Consumption profiles of the residential and services sectors were obtained from the standard low voltage profiles (BTN) installations, with the simple tariff option, being distinguished by classes (A, B and C) according to the contracted power and the energy consumed annually (ERSE, 2019). It was assumed that BTN B would represent the services sector, as it is the class with the highest annual energy consumption values and the maximum values occur between 1 pm and 8 pm. BTN C was allocated to the residential sector, as its annual energy consumption is lower than that of the BTN B class and also because the BTN C profile exhibits a typical residential behavior, with a peak at 9 pm and maximum consumption values between 8 pm to 10 pm (dinner time). Figure 4 shows the normalized consumption profiles for BTN B and BTN C classes for the last week of January, as this was the week where the highest consumption values were verified.

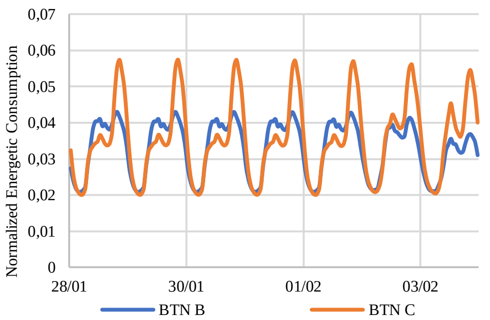

Figure 4 - Normalized energetic consumption profiles in the last week of January for BTN B and BTN C, adapted from ERSE (2019)

The hourly power consumption profiles at the hour t of the residential ($P_{Residential_{2050_t}}$) and service sectors ($P_{Services_{2050_t}}$) were obtained with (7) and (8), respectively. c_{BTNC_t} and c_{BTNB_t} represent the normalized consumption at the hour t of BTN C and BTN B, respectively; $\bar{c}_{BTNC}$ and $\bar{c}_{BTNB}$ are the annual averages of normalized consumption of BTNC and BTNB, respectively; $\bar{P}_{Residential_{2050}}$ and $\bar{P}_{Services_{2050}}$ represent the average annual consumption power in 2050 of the residential and services sectors, respectively.

$$P_{Residential_{2050_t}} = \frac{c_{BTNC_t}}{\bar{c}_{BTNC}} \bar{P}_{Residential_{2050}} \quad (7)$$

$$P_{Services_{2050_t}} = \frac{c_{BTNB_t}}{\bar{c}_{BTNB}} \bar{P}_{Services_{2050}} \quad (8)$$

2.2.3.2. PV Production Profiles

PV production profiles for the last week of January were computed from the normalized production profile (Figure 5) of a self-consumption production unit (SCPU) obtained from ERSE (2019).

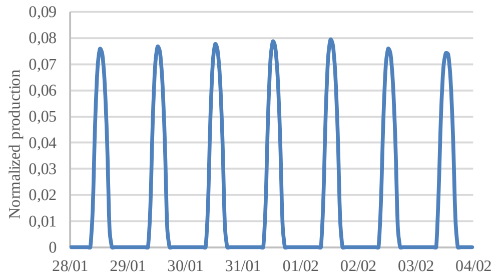

Figure 5 - Normalized production profile of a SCPU in the last week of January, adapted from ERSE (2019)

The nominal power of the PV panels at each hour t, P_{PV_t} [GW] was obtained using (9), where G_t represents the global irradiance at the hour t, $P_{PV_{Peak}}$ [GW] represents the peak power and PR is the performance ratio, which was assumed to be 0,75.

$$P_{PV_t} = \frac{G_t}{1000} P_{PV_{Peak}} PR \quad (9)$$

The value 1000 that appears in the denominator is a consequence of the definition of peak power ($P_{PV_{Peak}}$), which represents the maximum power under standard test conditions (STC) stipulated by international standard IEC-60904-1 (1000 W/m^2 across the surface of the module and module temperature equal to 25 ° C).

The global irradiance at each hour t, G_t [W/m^2], can be computed using (10), where p_t represents the normalized production at each hour t, $\bar{p}_i$ represents the average monthly normalized production at each month i and $\bar{G}_i$ [W/m^2] is the average global irradiance at each month i.

$$G_t = \frac{p_t}{\bar{p}_i} \bar{G}_i \quad (10)$$

The monthly average global irradiance, $\overline{G}_i$ was acquired from (Comissão Europeia, 2019b), for Lisbon coordinates (38º42'28,8"N 9º08'13,2"W), a module slope of 0º and an azimuth angle of 0º (south facing modules).

2.2.4. PV and Batteries Capacities

Three areas can be identified when daily consumption and PV production power profiles are overlapped (Figure 6). Area A represents the total daily consumed energy, E_C, area B corresponds to the total produced PV energy produced daily, E_{PV}, and area C represents the directly consumed energy, E_{Cd}.

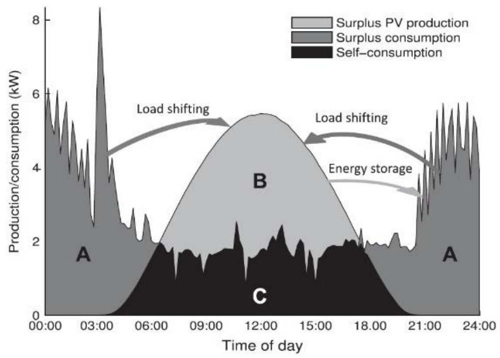

Figure 6 - Daily consumption and PV production power profiles, obtained from Luthander et al. (2015)

From these three areas it is possible to compute the production surplus, E_{SPV}, and the consumption surplus or indirect consumption, E_{Ci}, from equations (11) and (12), respectively.

$$E_{SPV} = E_{PV} - E_{Cd} \tag{11}$$

$$E_{Ci} = E_C - E_{Cd} \tag{12}$$

Self-consumption can be defined as the fraction of the consumed energy, E_C, that is guaranteed by PV production, E_{PV}. From this definition and as explained by Figure 6 there are two ways to maximize self-consumption: firstly, load-shifting indirect consumption to PV production hours and, secondly, by using batteries that store surplus production, E_{SPV}, which can be used for indirect consumption. The first option was studied with BEVs' charging scenarios. In the second option, battery energy losses must be accounted. This means that the energy that can be used after storage in the batteries, E_B, is obtained from (13).

$$E_B = E_{SPV}\,\eta_{roundtrip} \tag{13}$$

where

$$\eta_{roundtrip} = \frac{Output\ Battery\ Energy}{Input\ Battery\ Energy} \tag{14}$$

PV and battery capacities that guarantee the total consumption of the last week of January may be computed, from production and consumption profiles, presented in sections 2.2.3.1. and 2.2.3.2.. The energy provided by the batteries on each day j is given by (15), PV power is computed from inequation (16) which ensures that in each day the energy provided by the batteries is equal or greater than the energy consumed indirectly. The storage capacity corresponds to the maximum E_{B_j} divided by the battery efficiency ($\eta_{roundtrip}$).

$$E_{B_j} = \begin{cases} E_{SPV_j}\eta_{roundtrip} + (E_{PV}-E_C)_{j-1} & \text{if } (E_{PV}-E_C)_{j-1} \geq 0 \\ E_{SPV_j}\,\eta_{roundtrip} & \text{if } (E_{PV}-E_C)_{j-1} < 0 \end{cases} \tag{15}$$

$$(E_B - E_{Ci})_j \geq 0 \tag{16}$$

2.2.5. PV Technology Evolution and LCOE

After calculating the PV capacity (GWp) to be installed and batteries capacities (GWh) by 2050, it was assumed that the implementation of both technologies will take place in a phased and proportional manner over the 2020 and 2050 period. The PVs and batteries' installation was assumed to be at the same rate of a conservative PV panels annual market growth rate scenario (7,5%/year), according to Mayer et al. (2015); ensuring that for each scenario the total $P_{PV_{Peak}}$ values are guaranteed in 2050.

The area occupied by the PVs is not only dependent of the evolution of the installed PV capacity, but also from the module efficiency evolution, η. It was considered that this efficiency will grow linearly from 16,5% in 2020 to 30% in 2050.

LCOE was computed using (17), where n represents project's lifetime, r is the discount rate, I_t represents de the investment cost in the year t, $C_{O\&M_t}$ represent operational and maintenance cost in the year t, R_v is the residual value at the end of the project's lifetime and E_t is the electricity produced in each year t.

$$LCOE = \frac{\sum_{t=0}^{n} \frac{I_t + C_{O\&M_t}}{(1+r)^t} - \frac{R_v}{(1+r)^n}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \tag{17}$$

Each PV LCOE's parameter considered constant over the 2020-2050 period is presented in Table 2. All parameters were obtained from Camilo et al., (2017), except for the degradation rate, d_{PV}, which was obtained from Jordan et al., (2013) and the PV's yield, which was computed. Initial investment costs were projected for the 2020-2050 period (Table 3). The investment cost in 2020 was assumed to be the average of the values presented in Camilo et al. (2017) and the remaining figures were projected every 5 years until 2050 using the cost reduction projections of scenario 2, obtained from Mayer et al. (2015). The lifetime considered for hybrid inverters is 11 years, which means that additional replacement investments, I_S, are required in the 11^{th} and 22^{nd} years.

Table 2 - PV LCOE's parameters

n	PV's yield, kWh/kWp	Degradation Rate, d_{PV}, %/year	r, %	$C_{O\&M_t}$, % of I_0/year	I_s, % de I_0
25	1188	0,6	4	1	15

Table 3 - Projections of the PV's initial investment, €/Wp (2020-2050)

PV	2020	2025	2030	2035	2040	2045	2050
I_0, (€/Wp)	2,04	1,80	1,63	1,50	1,37	1,24	1,13

The battery LCOE's parameters assumed for the 2020-2050 period are presented in Table 4, where all values were obtained from Tesla (2019), except the discount rate, r, which was the same used for PVs. For the initial investment costs projections (Table 5), the 2020 value was obtained from Tesla (2019) and represents the investment cost of Tesla's Powerwall, which uses Li-ion technology. These projections were computed from the Li-ion cost reductions projected by Schmidt et al. (2019). The assumed battery's lifetime was 10 years, which implies replacements in the 10^{th} and 20^{th} years. The residual value of the battery at the end of its lifetime, R_v, was calculated considering a linear depreciation of the last purchased battery, which will then have 5 years of operation, therefore 50% of the initial investment cost.

Table 4 - Battery LCOE's parameters

n	Degradation Rate, d_B, %/year	$\eta_{round-trip}$, %	r %	$C_{O\&M_t}$, % of I_0/year
10	3	90	4	2

Table 5 - Projections of the Battery's initial investment, €/Wh (2020-2050)

Battery	2020	2025	2030	2035	2040	2045	2050
I_0, (€/Wh)	0,619	0,383	0,259	0,203	0,180	0,169	0,158

3. Results and Discussion

3.1. Transport Sector

The electrification of the LMA's car fleet was studied together with the assumption that the kilometers traveled in 2050 will be equal to the lowest value of the 2011-2017 period, which happened in 2013. The integration of BEVs implies a reduction in both useful (-53%) and final (-80%) exergy, which represents an increase in final-energy efficiency in the transport sector from 33% to 78%. This increase is due to a higher final to useful exergy efficiency of BEVs (77,4%) compared to ICEVs with efficiencies close to 30%.

Table 6 - Final exergy, useful exergy and final to useful exergy efficiency (ε) in the transport sector in LMA in 2016 and 2050

Transport Sector LMA	Year	Electricity	Diesel	Gasoline	LPG	Total
Useful Exergy (ktoe)	2016	20,4	320,5	86,7	2,5	430,0
	2050	200,5	-	-	-	200,5
Final Exergy (ktoe)	2016	23,2	974,9	304,0	9,8	1312,0
	2050	256,2	-	-	-	256,2
Final-Useful Exergy Efficiency, ε	2016	88%	33%	29%	25%	33%
	2050	78%	-	-	-	78%

In the LMA, the final exergy consumption of BEVs is approximately 232,9 ktoe by 2050, an average annual power of 309,2 MW for this region. The municipality of Lisbon represents about 20% of this power (61 MW).

3.2. Residential and Services Sectors

Useful exergy projections for 2050 of the residential and services sectors result from the different economic growth scenarios: Off Track (OT), Platoon (P) and Yellow Jersey (YJ).

The largest increase occurs for scenario P (highest economic growth), where between 2016 and 2050 useful exergy grows 75% and 82% in the residential and services sectors, respectively. In Scenario OT (lowest economic growth rate) the useful exergy increases 65% and 72% for the residential and services sectors, respectively. Useful exergy growth is higher in the services sector than in the residential sector, due to higher useful exergy intensities in services

(9,05×10^{-2} MJ/€2011) compared to the residential sector (5,34×10^{-2} MJ/€2011).

Final to useful exergy efficiencies of both sectors increase until 2050, driven by the shift from fossil fuel to electricity in all categories/types of use. This electrification results in higher aggregate final to useful exergy efficiencies, which increase from 17% in 2016 to 31% in the residential sector and from 17% to 33% in services.

These higher efficiencies decrease the final exergy until 2050, despite the large increase in useful exergy in both sectors during that period. Final exergy and the average power in 2050 for both sectors of the LMA are presented in Table 7.

Table 7 - Final Exergy and average consumption power in 2050 for the residential and services sectors in the LMA

Sector	Year	Scenario	Final Exergy (ktoe)	$\bar{P}$ (MW)
Residential	2050	OT	422	560
		P	448	594
		YJ	443	588
Services	2050	OT	500	664
		P	531	704
		YJ	525	698

3.3. CO_2 Emissions

The total CO_2 emissions of the LMA for the 2011-2017 period are presented in Figure 7. Total emissions ranged from 8,48 MTon (in 2013) to 10, 39 MTon (2017).

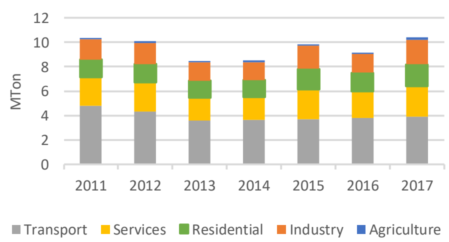

Figure 7 - Total CO_2 emissions for each sector of the LMA

The transport, residential and service sectors represent an average of 81% of total CO_2 emissions. Thus, the electrification of these sectors will have a significant impact on the decarbonization of this region. As for the CO_2 emissions reduction achieved in each sector for 2050, the results are: 97% to 98% in the transport sector, 100% in the domestic sector and 97% to 100% in the services sector, comparing to the 2011-2017 period.

3.4. PV and Battery Capacities in 2050

PV capacities to be installed until 2050 (Figure 8) range from 30 GWp (OT-C2) to 31,93 GWp (P-C3), a 6,4% increase.

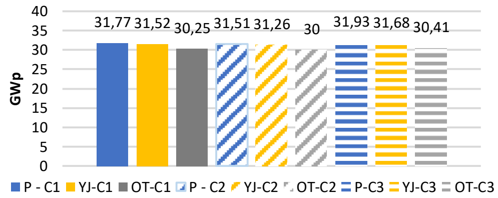

Figure 8 - LMA's PV capacities in 2050 for each scenario

Regarding the installation of batteries (Figure 9) there is a 28% increase from FP-C2 to P-C3. These superior differences between scenarios, when compared to PV capacities, are a consequence of the difference in BEVs' charging profiles between scenario C3 and C2. In C3 BEVs are only charged when the radiation and consequently the PV output is zero or negligible and in C2 BEVs are exclusively charged at sun hours.

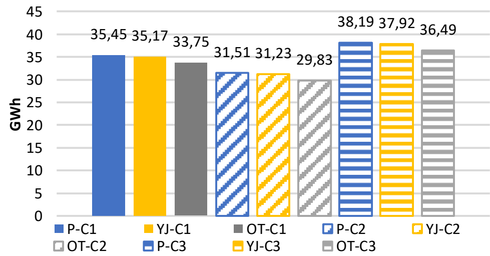

Figure 9 - LMA's battery capacities in 2050 for each scenario

Storage ratios, R, i.e., battery capacity per PV capacity (GWh/GWp), range from 1 (C2) to 1,2 GWh/GWp (C3). According to Vartiainen et al. (2019), the optimal interval for the storage ration is between 1 and 2 GWh/GWp, which holds true for all scenarios.

3.5. Installation Areas and LCOE

3.5.1. Installation Areas

Installation areas in the LMA have relative differences between scenarios identical to the PV capacities. Therefore, maximum values are for P-C3, which requires an installation area of 125,44 km^2 (4.2% of the total area of the LMA). The minimum area, 117,96 km^2, occurs for the OT-C2 scenario. In the municipality of Lisbon, it was defined that the maximum area that can be occupied by PVs was the roofs' area (16,94 km^2). For all scenarios this limit was reached between

2042 and 2043, which means that the remaining PV capacity required for Lisbon's consumption must be installed in other LMA's municipalities.

3.5.2. LCOE (2020-2050)

LCOE projections show that grid parity is attained in the first year of operation (2020) for all charging scenarios, comparing with average "electricity prices for households" in 2018. LCOE calculation is not dependent on the project's scale but only on the storage ratio, R, (GWh/GWp), which means that only the BEV's charging scenarios (C1, C2 and C3) are significant. Figure 10 shows LCOE projections for different storage ratios, varying from 1 to 2 GWh/GWp, since according to Vartiainen et al. (2019) ideally R should range between these values. As it was observed in that study, higher storage ratios correspond to higher LCOE values, which means that maximum values occur for an R of 2 GWh/GWp. However, even for that R, grid parity is achieved before 2025.

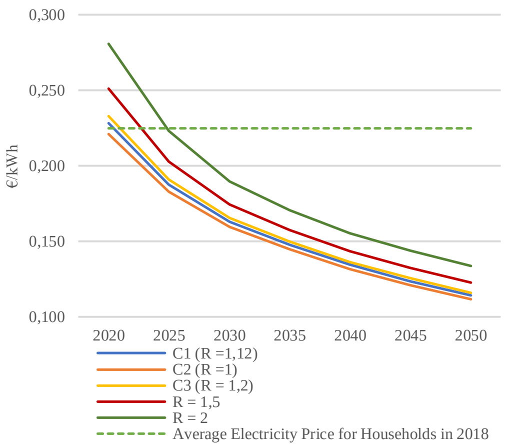

Figure 10 - LCOE projections (2020-2050) for different storage ratios and BEVs charging scenarios

In absolute terms, LCOE decreases from 0,221-0,233 €/kWh, in 2020, to 0,112-0,116 €/kWh, in 2050, considering the three storage ratios of the BEV's charging scenarios, a 50% reduction since the beginning of the installation (2020) until its completion (2050), which is the combined effect of falling PV and battery costs, 37% and 63 % of the total reduction, respectively.

4. Conclusions and Further Research

4.1. Conclusions

Portugal declared its objective of achieving carbon neutrality by 2050, while aiming to reduce its levels of energy dependence. Therefore, it is crucial to understand the synergies between different RES such as solar PV, with high potential in the Portuguese context, and battery storage, whose integration may enable the full potential of PV. In this dissertation, these synergies were studied for the LMA through scenarios of decentralized PV production and battery storage, where P2P electricity trade is allowed. Regarding consumption, it was assumed a full electrification of the transport, residential and services sectors.

The electrification of the uses combined with a 100% RES electricity supply represent final exergy reductions for all sectors in 2050 compared to 2016 (-80% in transport, -3% to -8% in residential and -8% to -14% in services). CO_2 emissions reduce significantly compared to the 2011-2017 period (-97% to -98% in transport, -100% in residential sector and -97% to -100% in services).

PV capacities range from 30 (OT-C2) to 31,93 (P-C3) GWp and battery capacities from 29,83 (OT-C2) to 38,19 (P-C3) 29,83 GWh. Maximum values occur for the P-C3 scenario, where the highest economic growth and nighttime charging occur. Storage ratios (R) depend only on the charging scenarios and range between 1 (C2) and 1,2 (C3) GWh/GWp.

Maximum installation area occurs for P-C3 with 125,44 km^2 (4,2% of the total area of the LMA). In all scenarios, the available roof area in the municipality of Lisbon is not enough to meet the region's consumption needs.

LCOE ranges are: 0,221-0,233 €/kWh, in 2020, and 0,112-0,116 €/kWh, in 2050; which means that grid parity is reached in 2020 for every scenario. The 50% decrease between 2020 and 2050 is explained by the simultaneous decline in investment costs that both PV and batteries suffer, which, respectively, represent a 37% and 63% of the reduction in the LCOE.

Finally, although energy transition faces several challenges, some of them can be overcome through decentralized PV production and battery storage. The variability of RES can be solved, if these sources are combined with batteries. Electricity costs can decrease until 2050, if P2P and a gradual installation of PVs and batteries occur. In the Lisbon municipality, which has high consumption power densities, fossil-fueled electricity (high production density) can be replaced by RES' electricity (low production density) if PVs and batteries are installed in other LMA's municipalities.

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