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Development of integrated solutions using RES to supply domestic electric vehicle charging stations

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Abstract. According to the Portuguese Roadmap for Carbon Neutrality 2050 (RNC2050), Portugal aims to achieve carbon neutrality by 2050. To achieve this goal, it is necessary to decrease the consumption of primary energy from non-renewable sources and increase the consumption of energy from renewable sources. Portugal has a high potential for energy production through solar energy, and the country has a large solar potential that can be used. Thus, this work focuses on the study of the reliability of charging electric vehicles through photovoltaic energy, being sized electric vehicles charging stations, with different topologies, for domestic consumption, for different types of user profiles. At the same time this study evaluated technically and economically the proposed solutions. The research concluded that this type of technology proves to be a viable solution, especially if storage systems do not need to be implemented, as the limited useful lifetime of batteries substantially increases investment amortization times.

Key words. Photovoltaic Systems, Electric Vehicle, Charging Stations, Energy Efficiency, Techno-Economic Study.

1. Introduction

The European Union's legislation includes the 2018/2001 directive [1] which sets targets and measures to promote the reduction of greenhouse gas emissions and the energy transition, one of which is to promote the use of renewable energy and promote the use of EVs (electric vehicles) in Europe. It is also the 2018/2002 directive [2] which aims to increase energy efficiency in the European economy. As a result of this legislation, Portugal has transposed the Portuguese Roadmap for Carbon Neutrality (RNC2050) [3] which aims to achieve carbon neutrality by 2050 and has also transposed the National Energy and Climate Plan 2030 (PNEC2030) [4] which sets out a series of targets to increase energy efficiency and increase the consumption of renewable energy in the country. Portugal is therefore facing a challenge to meet the targets set, with the need to increase energy production from renewable sources and electrification in the transport sector.
Portugal's geographical location is favorable in terms of its solar potential. In terms of sun exposure, Portugal is one of the countries in Europe with the most hours of exposure per year, with the highest insolation values occurring in the Lisbon, Alentejo and Algarve regions [5].

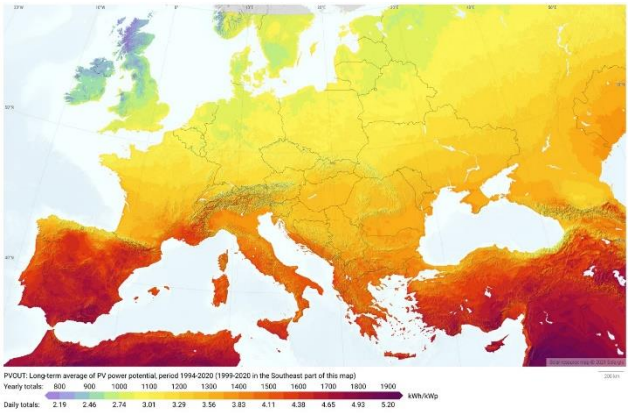

Fig.1. - Photovoltaic Electric Potential in Europe [6]

Therefore, with the EV market growing and with a view to achieving the goals set for 2030, charging EVs using photovoltaic energy could be an interesting option.
The subject of charging electric vehicles using renewable energy sources (RES) has been approached by various authors in different ways and with varying applicability, a few works are highlighted below.
In [7]a study was carried out that gathers information on the behavior of EV owners when it comes to using them. The study evaluates the average daily distances travelled for different types of use, from private to commercial use, the times at which they are used, the times at which they are charged and some other topics that can be used as valuable references for other studies in the area, bearing in mind that the data analyzed comes from real events involving the use of EVs in some European countries.
In [8] the possibility of charging EVs using indigenous renewable resources in Romania is evaluated, the design of an isolated system, i.e. without using the grid, consisting of a photovoltaic system and batteries, its sizing and the simulation of EV charging through it.
In [9], a grid-connected photovoltaic system with photovoltaic production and storage is designed to assess the possibilities of cooperation between the different elements of the system from the point of view of their energy balance and to demonstrate the different possibilities of using energy storage using mathematical modelling.

In [10], an EV charging system independent of the distribution network is designed, consisting of an energy storage system and photovoltaic production to increase the use of electric vehicles in remote locations and minimize overloads in the distribution network. The proposed system was implemented in MATLAB/Simulink to verify its performance.
In [11] the possibility of charging EVs in workplaces is investigated, with the design of charging stations using photovoltaic energy in the Netherlands. Two scenarios were considered, one where charging takes place only during weekdays and another where it takes place during the weekend as well. It is concluded that optimal storage reduces dependence on the grid by 25%.
In [12] a study is made of the feasibility and economic aspects of an EV charging system made up of photovoltaic panels and battery storage connected to the grid. Graphs are presented on the return on investment in this type of system for some utilization profiles combined with different types of systems and graphs with their respective energy balance.
The aim of this paper is to study the implementation of an electricity production system using photovoltaic panels with storage for charging EVs at household level in the Vila Real area and the technical and economic evaluation of the investment based on different usage profiles.
This work is organized as follows: section 2 focuses on the operation of photovoltaic panels, section 3 on the case study, section 4 on the economic analysis of the case study and finally in section 5 some conclusions are drawn.

2. Photovoltaic Systems

The photovoltaic effect is the creation of an electric current or voltage in a material after it has been exposed to the sun. Photovoltaic panels are made up of photovoltaic modules, which in turn are made up of silicon solar cells. A pure silicon photovoltaic cell lacks mobile charge carriers to produce electricity. Doping creates N-type (free electrons) and P-type (free positive charges) semiconductors, forming a P-N junction with a potential difference. Photons move electrons to the conduction band, directing them to the negative terminal and gaps to the positive terminal. This generates an open-circuit voltage and current, dependent on intensity of incident light when a load is connected.
The equivalent circuit of a photovoltaic cell can be represented by an equivalent electrical circuit, as shown in Figure 2, where Rs and Rp represents the series and shunt resistance. The shunt resistance represents the losses that result in electrons travelling straight between the terminals and the series resistance accounts for all current losses due to poor charge transfer between layers.

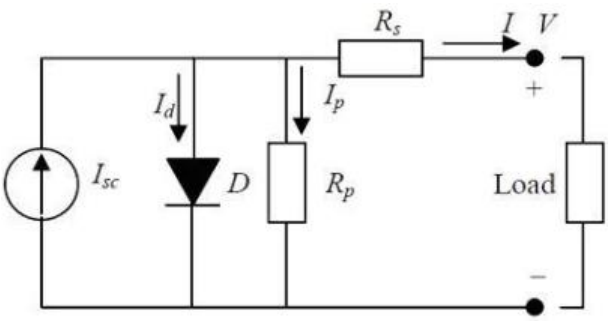

Fig. 2: Equivalent Circuit of a Photovoltaic Cell

It should be noted that the value of the cell's operating temperature, θ_C, is unknown, but it is possible to calculate it using the value of the ambient temperature of the location, θ_a. Thus, θ_C can be related to the incident radiation, G, and to θ_a using the expression (1):

$$\theta_c = \theta_a \frac{G \cdot (NOCT - 20)}{800} \quad (1)$$

Where NOCT is the normal operating temperature of the cell supplied by the manufacturer.
We must also take into account the thermal potential, V_τ, which represents the contact potential arising from the thermal agitation of carriers in the silicon and can be represented by the expression (2):

$$V_T = \frac{K \cdot T}{q} \quad (2)$$

Where K is the Boltzmann constant ($k = 1.38 \cdot 10^{-23} J/k$), T is the absolute temperature of the cell in Kelvin (T=273.16 + θ_C) and q is the electric charge of the electron ($q = 1.6 \cdot 10^{-19} C$).
The diode's ideality factor, m, can be calculated from (3):

$$m = \frac{V^r_{max} - V^r_{OC}}{V_T \cdot ln(1 - \frac{I_{max}}{I^r_{SC}})} \quad (3)$$

Where V^r_{max}, V^r_{OC}, I_{max} and I^r_{SC} represent the maximum reference voltage, the open-circuit voltage and the maximum and short-circuit reference currents respectively.
The maximum voltage, V_{max}, and the maximum current, I_{max}, can be calculated from (4) and (5) respectively:

$$V_{max} = m \cdot V_T \cdot ln\left(\frac{\frac{I_{SC}}{I_0} + 1}{1 + \frac{V_{max}}{m \cdot V_T}}\right) \quad (4)$$

$$I_{max} = I_{sc} - I_0 \cdot \left(e^{\frac{V_{max}}{m.V_T}} - 1\right) \quad (5)$$

Where I_{SC} represents the short-circuit current and I_0 the maximum reverse saturation current of the diode.
The maximum power that can be produced is given by (6):

$$P_{max} = V_{max} \cdot I_{max} \quad (6)$$

3. Case of study

To carry out the case study for this project, we considered the JAM66S30 500/MR photovoltaic modules, which are composed of the parameters shown in Table I.

Table I. - JAM66S30-500/MR photovoltaic module

Maximum power	P_{max}	500W
Maximum voltage	V^r_{max}	38.35V
Open circuit voltage	V^r_{OC}	45.59V
Maximum current	I_{max}	13.04A
Short-circuit current	I^r_{SC}	13.93A
Normal operating temperature	NOCT	45
Number of cells	N^r_{SM}	132
Reference voltage	V^r_T	0.025

Since photovoltaic panels produce energy in direct voltage, inverters are needed to convert it into alternating voltage. The inverters considered are shown in Table II and Table III.

Table II. – SMA Sunny Boy 3.0-1AV-40 (3kW) Inverter

Rated power (at 230V, 50Hz)	3KW
PV Voltage Amplitude, MPPT	110-500V
Maximum yield	97%

Table III.- SMA Sunny Boy 3.0-1AV-40 (5kW) Inverter

Rated power (at 230V, 50Hz)	5KW
PV Voltage Amplitude, MPPT	175-500V
Maximum yield	97%

Firstly, the maximum power produced by a photovoltaic module was calculated, on average, per day, during the different months of the year, for the Vila Real region, represented in Table IV, using the formulae 1, 2, 3, 4, 5, 6 to the solar irradiation and ambient temperature data using PVGIS [13] and the values from the technical data sheet of the respective photovoltaic modules (Table I).

Table IV.- Maximum power produced by 1 photovoltaic module per day for each month

Month	G (W/m^2)	$\boldsymbol{\theta_a}$ (ºC)	V_{max} (V)	I_{max} (A)	P_{max} (W)
Jan	101.89	9.98	45.91	1.33	61.00
Feb	186.10	15.52	45.79	2.43	111.12
Mar	208.53	16.72	45.78	2.72	124.48
Apr	186.43	17.93	45.62	2.43	110.89
Mai	280.16	26.06	45.42	3.65	165.94
Jun	273.65	25.55	45.43	3.57	162.12
Jul	326.10	34.59	45.16	4.25	192.04
Aug	298.61	29.93	45.29	3.89	176.35
Sep	240.63	26.72	45.30	3.14	142.14
Oct	175.02	18.17	45.56	2.28	103.98
Nov	123.86	14.37	45.63	1.62	73.69
Dec	101.85	10.08	45.90	1.33	60.96

Next, the average energy produced per day for each month was calculated (Table V). The average energy produced per month depending on the number of photovoltaic modules implemented in the system was also calculated (Table VI).

Table V.- Average energy produced per day for each month

Month	P_{max} (W)	h/day	NDM	η_{max}	E (Wh/day)
Jan	61.00	24	31	0.25	1464.00
Feb	111.12	24	29	0.25	2666.88
Mar	124.48	24	31	0.25	2987.52
Apr	110.89	24	30	0.25	2661.36
Mai	165.94	24	31	0.25	3982.56
Jun	162.12	24	30	0.25	3890.88
Jul	192.04	24	31	0.25	4608.96
Aug	176.35	24	31	0.25	4232.40
Sep	142.14	24	30	0.25	3411.36
Oct	103.98	24	31	0.25	2495.52
Nov	73.69	24	30	0.25	1768.56
Dec	60.96	24	31	0.25	1463.04

Table VI.- Energy produced in kWh/month according to the number of photovoltaic modules in the system

Month	1 mod.	2 mod.	3 mod.
Jan	45.38	226.92	453.84
Feb	77.34	386.69	773.39
Mar	92.61	463.06	926.13
Apr	79.84	399.20	798.40
Mai	123.46	617.29	1234.59
Jun	116.72	583.63	1167.26
Jul	142.88	714.39	1428.78
Aug	131.20	656.02	1312.04
Sep	102.34	511.70	1023.40
Oct	77.36	386.60	773.61
Nov	53.05	265.28	530.57
Dec	45.35	226.77	453.54
TOTAL	1087.55	5437.79	10875.58

For the case study, two different vehicles were used as reference, the Tesla Model 3 Long Range Dual Motor and the Renault Zoe Z.E 40. It should be noted that the batteries in these cars behave in different ways depending on the situations to which they are subjected, such as temperature and driving mode. Therefore, using the technical data sheets for both cars, the average daily and monthly energy consumption was calculated, taking into account the different usage profiles available in them, as shown in Tables VII, VIII, IX and X. It should be noted that the number of kilometres travelled for the usage profiles used was based on [7].

Table VII.- Tesla Model 3 Long Range Dual Motor Features

Mode	Capacity (KWh)	Range (Km)	Consumption (Wh/Km)
City (cold)	74	450	164.44
City (moderate)	74	685	108.03
Highway (cold)	74	340	217.65
Highway (moderate)	74	445	166.29
Combined (cold)	74	395	187.34
Combined (moderate)	74	550	134.55

Table VIII.- Daily and monthly consumption of Tesla Model 3 Long Range Dual Motor

Mode	Travelled Dist. (Km)	Consumption (KWh/day)	Consumption (KWh/Month)
City (cold)	34.3	5.64	174.85
City (moderate)	34.3	3.70	114.87
Highway (cold)	34.3	7.46	231.42
Highway (moderate)	34.3	5.70	176.82
Combined (cold)	100	18.73	580.76
Combined (moderate)	100	13.45	417.09

Table IX.- Renault Zoe Z.E 40 Features

Mode	Capacity (KWh)	Range (Km)	Consumption (Wh/Km)
City (cold)	37	235	157.45
City (moderate)	37	360	102.08
Highway (cold)	37	165	224.24
Highway (moderate)	37	215	172.09
Combined (cold)	37	200	185.00
Combined (moderate)	37	275	134.55

Keeping in mind that if the energy produced by the photovoltaic system is not stored, it can only be used when it is being produced. Therefore, if the owner of the installation wants to charge his vehicle outside of production hours, it will be necessary to implement an energy storage system. For this purpose, a Huawei LUNA 2000 with 5KWh to 15Kwh modular system was considered, with the characteristics shown in Table XI.

Table X.- Daily and monthly consumption of Renault Zoe Z.E 40

Mode	Travelled Dist. (Km)	Consumption (KWh/day)	Consumption (KWh/Month)
City (cold)	34.3	5.4	167.41
City (moderate)	34.3	3.2	109.28
Highway (cold)	34.3	7.69	238.44
Highway (moderate)	34.3	5.90	182.98
Combined (cold)	100	18.5	573.50
Combined (moderate)	100	13.45	417.09

Table XI.- Technical characteristics of Huawei LUNA 2000 batteries

Module capacity	5 KWh		
No. of modules	1	2	3
Battery life	5 KWh	10 KWh	15 KWh
Maximum output power	2.5 KW	5 KW	5 KW
Nominal voltage (single phase)	360 V		
Operating voltage (single phase)	350-560 V		
Nominal voltage (three-phase)	600 V		
Operating voltage (three-phase)	600-980 V		

Based on the data obtained in the previous steps, it was possible to create graphical representations that made it possible to compare the photovoltaic production, storage and daily consumption of EVs. Below are the combinations that were considered the most relevant profiles and therefore used as a case study, represented in Figure 3 and Figure 4.

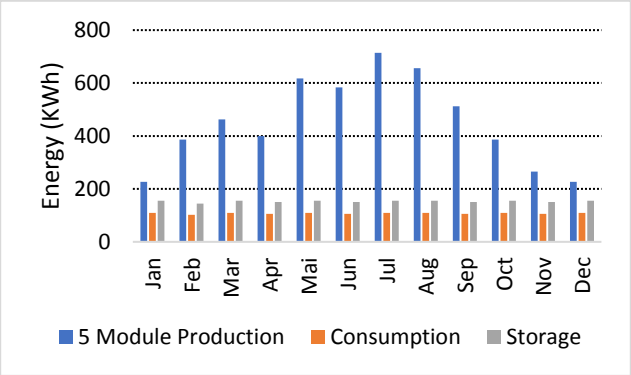

Fig.3. Renault Zoe Z.E 40, City profile (moderate), 5 Photovoltaic Modules, 5 KWh Storage

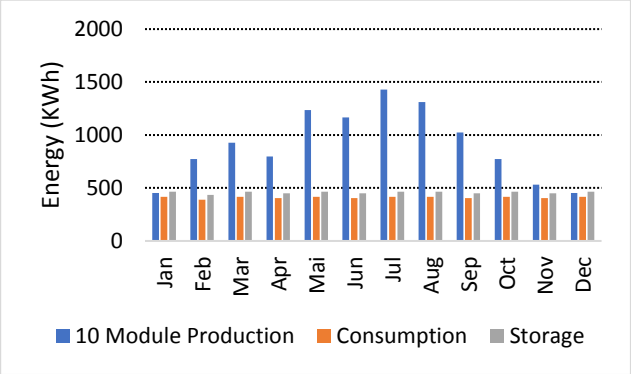

Fig.4. Tesla Model 3 Long Range Dual Motor, Combined profile (moderate), 10 Photovoltaic Modules, 15 KWh Storage

4. Economic Analysis

In order to determine whether the systems are economically viable, it is necessary to carry out an economic evaluation of each one. The following indicators were used:

The NPV (Net Present Value) is the difference between the discounted values of cash inflows and outflows during the project's lifetime and is calculated in (7).

$$NPV = \sum_{j=1}^{n} \frac{R_{lj}}{(1+i)^{j}} - I_{t} \qquad (7)$$

Where R_{lj} represents the net revenue for year j, n represents the useful life of the project, I_t represents the total investment updated to year 0 and i the discount rate. The IRR (Internal Rate of Return) is the discount rate that cancels out the NPV and can be calculated as shown in (8).

$$\sum_{j=1}^{n} \frac{R_{lj}}{(1+IRR)^{j}} - I_t = 0 \quad (8)$$

The return on investment is calculated using (9).

$$RI = \frac{\sum_{j=1}^{n} \frac{R_{lj}}{(1+i)^{j}}}{I_t} \quad (9)$$

In order to account for the profits from the sale of excess energy produced, the average reference tariffs for the Energy Price (EP) in 2023 were taken into account, which averaged around €85/MWh. This figure reflects the average in the liberalised market over the last six years, according to OMIE (Iberian Electricity Market Operator). However, the EP varies considerably every year, in this study, 25 years were considered for the lifetime of the project, taking into account an inflation rate of 7.8% per year. The EP can therefore be calculated using (10).

$$EP_j = EP_0 \cdot (1+e)^{j} \quad (10)$$

Where EP_j represents the energy price in year *j*, EP_0 the energy price in year 0 and *e* the inflation rate.
In order to calculate these indicators, it was necessary to determine the initial investment, for which Table XII shows the system's costs.

Table XII.- System implementation costs

	Renault	Tesla
Photovoltaic modules	500 €	1000 €
Inverter	1199 €	1430 €
Storage	3550 €	10650 €
Total	5249 €	13080 €
Total (+10% labour costs)	5773 €	13308 €

It should be noted that the price of photovoltaic panels was calculated according to the market value, which is around 0.2 €/W installed, according to Portal Energia [14].
In the case of the system implemented for the Renault Zoe Z.E 40, the NPV was 234.37 €, the IRR was 6% and the amortisation of the implemented system can be seen in Figure 5.

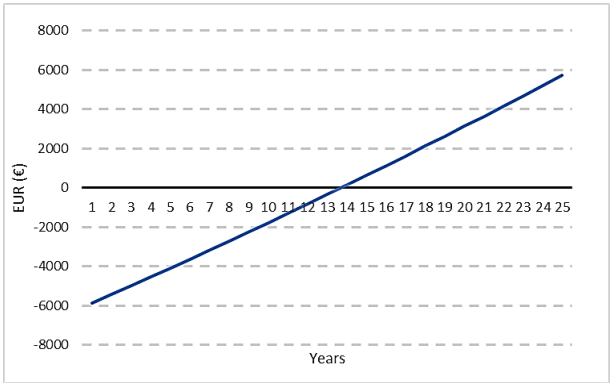

Fig.5. Amortisation, Renault Zoe Z.E 40, City Profile (moderate), 5 Photovoltaic Modules and 5 KWh Storage

In the case of the system implemented for the Tesla Model 3, the NPV was -1191.83 €, the IRR was 5% and the amortisation of the implemented system can be seen in Figure 6.

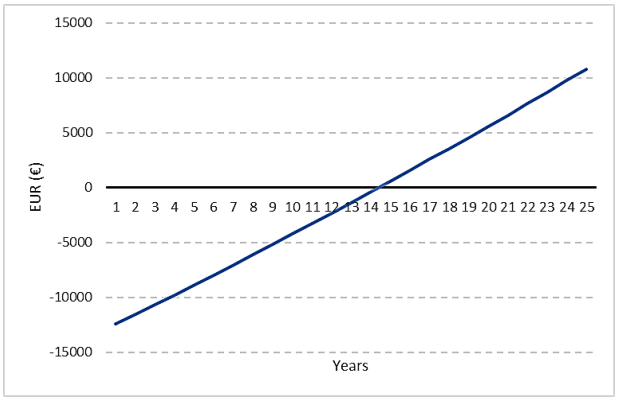

Fig.6. Amortisation, Tesla Model 3 Long Range Dual Motor, Combined Profile (moderate), 10 Photovoltaic Modules and 15 KWh of Storage

It's important to note that if it were possible to charge the EV during the energy production period, so that storage systems were no longer needed, the amortisation period would decrease significantly since they make up a large part of the initial investment.

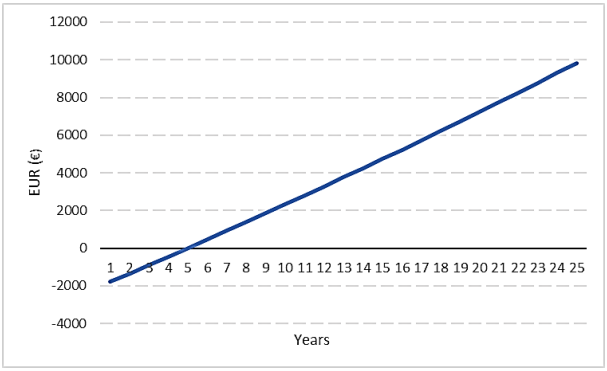

Fig.7. Amortisation, Renault Zoe Z.E 40, City Profile (moderate), 5 Photovoltaic Modules and no Storage

For example, as shown in Figure 7, the amortisation period would be greatly reduced for the Renault Zoe Z.E 40 if the storage system were not considered. The NPV of 234.37 € would become 3584.28 € and the IRR would go from 6% to 20%.

5. Conclusion

The results of the study show that a charging station based on photovoltaic energy sources is an efficient alternative to a conventional charging station that uses the electricity grid for certain situations. By using renewable energies, it is not only possible to reduce CO2 emissions, but also to reduce dependence on the electricity grid. Especially in the context of EVs, which can overload the grid, it's important to pay attention to charging stations that avoid a negative impact on the grid. This type of solution can be an asset in meeting national targets such as RNC2050 and PNEC2030. However, it should be noted that there are various types of EV usage profiles and that, depending on the usage profile, the vehicle's daily consumption can be

high, which leads to an increase in the number of photovoltaic modules in the system, the implementation of a higher power inverter and an increase in the storage system, as was the case with the Tesla Model 3 Dual Motor Long Range, where a Combined (moderate) profile was considered, where the vehicle's consumption was higher and more kilometres were travelled compared to the case determined for the Renault Zoe Z.E 40. Changing the system's components so that it was capable of producing enough energy to be able to charge the vehicle every month led to a significant increase in the cost of the initial investment. This increase was mainly due to the storage system, which is still quite expensive compared to the other components of the system. However, as it was considered that the surplus energy would be sold and the energy production was high, both systems implemented had an approximate amortisation period. Even so, the indicators calculated in the economic analysis showed that the investment for the Renault Zoe Z.E 40 system is economically viable, while for the Tesla Model 3 Long Range Dual Motor it is not. In short, this study has shown that, if properly dimensioned for certain profiles, EV charging systems using photovoltaic energy can be viable and an added value, especially in situations where it is possible to charge EVs during the energy production period, since they rule out the need for a storage system, thus greatly reducing the investment, and even for some situations where they assume a high initial investment, taking into account the return on investment and national and European policies.

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