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Electric Mobility in Sicily: An Application to a Historical Archaeological Site

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Abstract- Transports should be a key focus in the close future for decarbonization efforts, if the optimistic climate change mitigation objectives to be reached by 2050 on a global scale are to be met. Choosing an emblematic and historical location in the center of Sicily as object of the study, the potential for decarbonization and the reduction of the energy and environmental impacts in the site for electric mobility is assessed, by considering electric mobility scenarios based on different shares of electricity generated through renewable energy technologies. The analysis is performed by means of a life-cycle approach, through the use of the Life Cycle Assessment methodology. A parametric analysis investigating the impact of different electricity penetration levels in the local transports system is performed. The results identify relevant energy savings in the electricity mobility scenarios (5-6%) as well as a mixed trend for the environmental impacts: some indicators would show some relevant reductions (e.g. -70% for GWP) but others would grow as relevantly (e.g. +50% resource consumption for PV generated electricity). **Keywords** Electric mobility, Life Cycle Assessment, renewable energy, scenario analysis.

Acronyms

Global Energy Requirement	GER
Global Warming Potential	GWP
Ozone Depletion Potential	ODP
Human toxicity, cancer effects	HT-c
Human toxicity, non-cancer effects	HT-nc
Particulate matter	PM
Ionizing radiation HH	IR
Ionizing radiation E (interim)	IRi
Photochemical ozone formation	POCP
Acidification potential	AP
Terrestrial eutrophication	TE
Freshwater eutrophication	FE
Marine eutrophication	ME
Freshwater ecotoxicity	FEx
Land use	LU
Water resource depletion	WRD
Mineral, fossil & renewable resource depletion	MFRD

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1.Introduction

Sustainable transport systems [1] should provide transportation that is safe, socially inclusive, accessible, reliable, affordable, fuel-efficient, environmentally friendly, low carbon and resilient to shocks and disruptions, including those caused by climate change and natural disasters.

As it is now [2], transports are not sustainable. Even with deep cuts in CO2 from all other energy sectors, if transportations do not reduce CO2 emissions well below (50%) current levels by 2050, it will be very difficult to meet targets such as stabilizing the concentration of greenhouse gas emissions (GHG) in the atmosphere at a level of 450 ppm of CO2 equivalent.

All sectors of transports need to be involved in the decarbonization process that would need to take place in order to meet the CO_2 reduction target at 2050, including the private sector in any area of the world.

One of the potential aspects to approach the problem can be the use of electric cars in the larger picture of developing smart grids and developing energy flexible buildings and communities [3 - 8].

As an example, improvements in battery design are likely to make possible the widespread use of Electric Vehicles (EVs) for personal mobility, since they are seen as one of the solutions to reduce global Greenhouse Gases emissions, improve air quality, reduce oil dependence and increase energy security [9]. The penetration rate of EVs is increasing and it is expected that in the future a large share of vehicles will be battery powered [10-11].

In particular, EVs have the benefits of high energy efficiency and zero tailpipe emissions, which make them suitable for personal mobility in urban areas.

It is accepted that electric cars have the potential to reduce carbon emissions on a larger scale, thanks to fuel switching, off-peak battery charging, etc.[12], but it is important to realize this potential is dependent on the type of electricity charging the battery: the electricity mix feeding the electric cars should be as low-carbon [13, 14] as possible to achieve the best trade off between charging-related and life cycle emissions and the zero tailpipe impacts.

Moreover, it is not enough to limit the analysis on life cycle of electric vehicles only to life cycle energy, CO2eq or merely pollutant emissions [15 – 17], since a variety of variables and effects are involved: a wide set of indicators should be used to approach in an interdisciplinary way the modeling.

In this context, the paper proposes an analysis of the potential for decarbonization and the reduction of the energy and environmental impacts through the use of electricity powered vehicles in the Sicilian transport context. A Life Cycle Assessment (LCA) approach is proposed: this methodology allows to investigate the whole life cycle of a product or of a system and to determine all the impacts 'hidden' in all life cycle steps e.g. the production or the end-of-life [18-21].

An exemplary and historical archaeological site in Sicily was selected as focus: the Valley of the Temples [22] is a wonderful location of proven historical value that attracts a wide number of tourists every year. It is chosen as the exemplary location to quantify the energy and environmental impacts of transportation directly connected to the site. One of the most relevant examples of Magna Grecia in Italy and a UNESCO Heritage Site since 1997, the Valley of the Temples (Fig.1) overlooks the city of Agrigento in Sicily and includes some of the most notable buildings of the ancient Greek civilization still standing today.

The historical site is visited each year by a number of guests variable between roughly 550,000 to 620,000 people between 2010 and 2015. Average monthly values are reported in Fig. 2, showing a variable number of visitors to the park during the year, with a peak in August.

Fig. 1. Panoramic view of the Valley of the Temples in Agrigento, Sicily (Italy).

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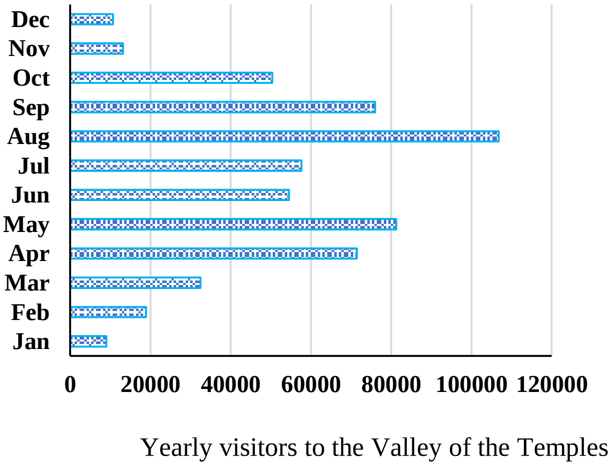

Fig. 2. Average yearly visitors to the Valley of the temples since 2010.

2. Methods

The aim of the study is the assessment of the energy and environmental benefits that a rise in the use of electric mobility might have on the transport sector in Sicily, through an application to the Valley of the Temples.

The LCA methodology is applied to assess the energy and environmental impacts of transportation. The first step of the analysis was the assessment of the energy and environmental impact related to the transportation of 1 person * km in the case of different car engines and for electricity generated by different sources. In detail, by elaboration of literature data [23], the use of the following vehicles was assessed:

- Diesel powered vehicles,
- Gasoline powered vehicles,
- Electric powered vehicles, electricity generated by the Italian generation mix,
- Electric powered vehicles, electricity generated by Photovoltaics (Mix of different façade and roof PV technologies at Italian level),
- Electric powered vehicles, electricity produced by Wind generators (mix of on-shore and offshore wind generators at EU level, power range 800 kW – 2 MW).

For each kind of vehicle, the following system boundaries were taken into account:

- the construction, the use and the end-of life of the vehicles;
- the construction, the use and the end-of-life of the batteries to be used in the electric vehicles;
- the construction, the maintenance and the end-of-life of the road;
- the life cycle of gasoline, diesel and of electricity.

Data refers to middle class passenger cars [23]. The indicators used to quantify the environmental impacts are the standard International Reference Life Cycle Data System (ILCD) ones [24], the Global Energy Requirement is calculated through the cumulative energy demand method [25].

The energy and environmental impacts of each of the above vehicles, referred to 1 person * km, are showed in Table 1. As it is clear in the GER results, the most energy intensive technologies are diesel and gasoline powered vehicles.

Tab.1. Energy and environmental impacts of 1 person * km

	Gasoline	Diesel	Italian mix	PV	Wind
GER (MJ)	3.12E+00	3.05E+00	2.67E+00	1.97E+00	1.84E+00
GWP (kg $CO_{2\ eq}$)	1.81E-01	1.77E-01	1.39E-01	5.84E-02	5.13E-02
ODP (kg CFC-11 $_{eq}$)	2.41E-08	2.53E-08	1.31E-08	6.88E-09	5.29E-09
HT-c (CTUh)	1.17E-08	1.15E-08	1.86E-08	1.66E-08	1.61E-08
HT-nc (CTUh)	4.23E-08	4.16E-08	1.21E-07	1.17E-07	1.09E-07
PM (kg PM2.5 $_{eq}$)	5.20E-05	7.46E-05	7.26E-05	4.48E-05	4.17E-05
IR (kBq U235 $_{eq}$)	3.71E-02	3.64E-02	4.59E-02	4.67E-02	4.44E-02
Iri (CTUe)	1.13E-07	1.11E-07	1.40E-07	1.42E-07	1.35E-07
POCP (kg NMVOC $_{eq}$)	8.22E-04	7.83E-04	4.66E-04	2.63E-04	2.37E-04
AP (molc H+ $_{eq}$)	7.82E-04	7.71E-04	9.03E-04	4.52E-04	4.11E-04
TE (molc N $_{eq}$)	2.19E-03	2.62E-03	1.41E-03	6.94E-04	6.25E-04
FE (kg P $_{eq}$)	2.55E-05	2.46E-05	8.58E-05	7.21E-05	6.58E-05
ME (kg N $_{eq}$)	1.83E-04	2.39E-04	1.34E-04	6.85E-05	6.12E-05
FEx (CTUe)	1.02E+00	1.01E+00	2.88E+00	2.78E+00	2.58E+00
LU (kg C deficit)	4.77E-01	4.47E-01	2.94E-01	2.01E-01	2.08E-01
WRD (m^3 water $_{eq}$)	7.66E-02	7.55E-02	1.69E-01	1.32E-01	1.05E-01
MFRD (kg Sb $_{eq}$)	4.45E-06	4.39E-06	8.45E-06	4.94E-05	8.38E-06

Although the electricity from the Italian generation mix allows for up to 14.38% reduction if compared to the gasoline, it is with the two renewable options, wind (-41.12%) and PV (-36.82%), that the energy requirements reduction in the examined life cycle reach the highest values.

The data identify some diversified trends in the environmental indicators: for GWP, POCP, ODP and TE the electrical based solutions guarantee a reduction of roughly 70% in comparison to the diesel and gasoline scenarios; the gasoline and diesel represent the best solution for the human toxicity indicators while for the resource consumption indicator the PV solution reaches the highest value of the impact, around one order of magnitude higher than the gasoline and the diesel options.

The second step of the analysis was the definition of different scenarios based on expected EV use increase in the local vehicles stock and on the yearly number of the Valley visitors.

In [26] an analysis on electric mobility reports hypotheses on the penetration of electric vehicles in the transportation sector in Italy, estimating roughly 40 million electric cars among pure electric and hybrid to be used in 2030 (around 25% of the total). Based on this scenario and under the hypotheses that the diffusion of electric cars might be lower in Sicily than in the rest of Italy, the electricity mobility scenarios at 2030 reported in Table 2 were developed, under the hypothesis that the share of electric cars on the total would not influence the features of the remaining vehicles that are assumed to be equally distributed between gasoline and diesel.

Table 2. Number of guests using a specific car typology in the Valley of the Temples – Scenarios modelled in the study

Scenarios	
0	50% Gasoline, 50% Diesel, 0% electric cars
1a	Italian electricity generation mix, 5% electric cars
1b	PV generated electricity , 5 % electric cars
1c	Wind generated electricity, 5% electric cars
2a	Italian electricity generation mix, 10% electric cars
2b	PV generated electricity , 10 % electric cars
2c	Wind generated electricity, 10% electric cars
3a	Italian electricity generation mix, 15% electric cars
3b	PV generated electricity , 15 % electric cars
3c	Wind generated electricity, 15% electric cars

Table 3a. Results of the 1A-1B-1C scenarios.

The data described in Tab.1 will be aggregated into the scenarios proposed in Table 2. All data related to 1 person * km for each car typology will be referred to the number of visitors of the Valley of the temples in 2015 (613,727) by balancing them on the percentages described in Table 2, obtaining nine different scenarios that will be described in detail in the following paragraph.

3. Results and discussion

The results for Scenario 0, representing the existing status of transportation in the Valley of the Temples, are reported in Tables 3a, 3b, 3c. Each table reports one class of results, respectively Scenarios 1 – 2 – 3

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	Scenario 0	**Scenario 1-A**	**Scenario 1-B**	**Scenario 1-C**
GER (MJ)	1.89E+06	1.88E+06	1.86E+06	1.86E+06
GWP (kg $CO_{2\ eq}$)	1.10E+05	1.09E+05	1.06E+05	1.06E+05
ODP (kg CFC-11 $_{eq}$)	1.51E-02	1.48E-02	1.46E-02	1.45E-02
HT-c (CTUh)	7.13E-03	7.35E-03	7.28E-03	7.27E-03
HT-nc (CTUh)	2.57E-02	2.82E-02	2.80E-02	2.78E-02
PM (kg PM2.5 $_{eq}$)	3.88E+01	3.91E+01	3.83E+01	3.82E+01
IR (kBq $U_{235\ eq}$)	2.26E+04	2.28E+04	2.29E+04	2.28E+04
Iri (CTUe)	6.86E-02	6.95E-02	6.95E-02	6.93E-02
POCP (kg NMVOC $_{eq}$)	4.93E+02	4.82E+02	4.76E+02	4.75E+02
AP (molc H^{+}_{eq})	4.77E+02	4.81E+02	4.67E+02	4.65E+02
TE (molc N $_{eq}$)	1.48E+03	1.44E+03	1.42E+03	1.42E+03
FE (kg P $_{eq}$)	1.54E+01	1.72E+01	1.68E+01	1.66E+01
ME (kg N $_{eq}$)	1.29E+02	1.27E+02	1.25E+02	1.25E+02
FEx (CTUe)	6.24E+05	6.82E+05	6.79E+05	6.73E+05
LU (kg C deficit)	2.83E+05	2.78E+05	2.75E+05	2.76E+05
WRD (m^3 water $_{eq}$)	4.67E+04	4.96E+04	4.84E+04	4.76E+04
MFRD (kg Sb $_{eq}$)	2.71E+00	2.84E+00	4.09E+00	2.83E+00

Table 3b. Results of the 2A-2B-2C scenarios.

	Scenario 0	**Scenario 2-A**	**Scenario 2-B**	**Scenario 2-C**
GER (MJ)	1.89E+06	1.87E+06	1.83E+06	1.82E+06
GWP (kg $CO_{2\ eq}$)	1.10E+05	1.08E+05	1.03E+05	1.02E+05
ODP (kg CFC-11 $_{eq}$)	1.51E-02	1.44E-02	1.41E-02	1.40E-02
HT-c (CTUh)	7.13E-03	7.56E-03	7.44E-03	7.41E-03
HT-nc (CTUh)	2.57E-02	3.06E-02	3.03E-02	2.98E-02
PM (kg PM2.5 $_{eq}$)	3.88E+01	3.94E+01	3.77E+01	3.75E+01
IR (kBq $U_{235\ eq}$)	2.26E+04	2.31E+04	2.32E+04	2.30E+04
Iri (CTUe)	6.86E-02	7.03E-02	7.04E-02	7.00E-02
POCP (kg NMVOC $_{eq}$)	4.93E+02	4.72E+02	4.60E+02	4.58E+02
AP (molc H^{+}_{eq})	4.77E+02	4.84E+02	4.57E+02	4.54E+02
TE (molc N $_{eq}$)	1.48E+03	1.41E+03	1.37E+03	1.37E+03
FE (kg P $_{eq}$)	1.54E+01	1.91E+01	1.82E+01	1.79E+01
ME (kg N $_{eq}$)	1.29E+02	1.25E+02	1.21E+02	1.20E+02
FEx (CTUe)	6.24E+05	7.39E+05	7.33E+05	7.21E+05
LU (kg C deficit)	2.83E+05	2.73E+05	2.67E+05	2.68E+05
WRD (m^3 water $_{eq}$)	4.67E+04	5.24E+04	5.01E+04	4.85E+04
MFRD (kg Sb $_{eq}$)	2.71E+00	2.96E+00	5.47E+00	2.95E+00

Table 3c. Results of the 3A-3B-3C scenarios.

	Scenario 0	**Scenario 3-A**	**Scenario 3-B**	**Scenario 3-C**
GER (MJ)	1.89E+06	1.86E+06	1.79E+06	1.78E+06
GWP (kg $CO_{2\ eq}$)	1.10E+05	1.06E+05	9.88E+04	9.82E+04
ODP (kg CFC-11 $_{eq}$)	1.51E-02	1.41E-02	1.35E-02	1.34E-02
HT-c (CTUh)	7.13E-03	7.78E-03	7.59E-03	7.55E-03
HT-nc (CTUh)	2.57E-02	3.30E-02	3.26E-02	3.19E-02
PM (kg PM2.5 $_{eq}$)	3.88E+01	3.97E+01	3.71E+01	3.69E+01
IR (kBq $U_{235\ eq}$)	2.26E+04	2.34E+04	2.35E+04	2.33E+04

Iri (CTUe)	6.86E-02	7.12E-02	7.14E-02	7.07E-02
POCP (kg NMVOC $_{eq}$)	4.93E+02	4.62E+02	4.43E+02	4.41E+02
AP (molc H$^+$ $_{eq}$)	4.77E+02	4.88E+02	4.47E+02	4.43E+02
TE (molc N $_{eq}$)	1.48E+03	1.38E+03	1.32E+03	1.31E+03
FE (kg P $_{eq}$)	1.54E+01	2.09E+01	1.97E+01	1.91E+01
ME (kg N $_{eq}$)	1.29E+02	1.22E+02	1.16E+02	1.16E+02
FEx (CTUe)	6.24E+05	7.96E+05	7.87E+05	7.69E+05
LU (kg C deficit)	2.83E+05	2.68E+05	2.59E+05	2.60E+05
WRD (m^3 water $_{eq}$)	4.67E+04	5.53E+04	5.18E+04	4.94E+04
MFRD (kg Sb $_{eq}$)	2.71E+00	3.08E+00	6.85E+00	3.08E+00

For higher clarity, the same data is shown in Fig.3. The analysis of the results clarifies that by enhancing the availability of electric vehicles it is possible to obtain a reduction of the following impacts:

- GER, reduced from 0.67% to 6.05% respectively from the 1-A to the 3-C scenario,
- GWP, reduced from 1.11% in the 1-A scenario to 10.71% in the 3-C one;
- ODP with an impact reduction ranging from 2.34% (Scenario 1-A) to 11.78% (Scenario 3-C);
- POCP, which impact is reduced from 2.1% in Scenario 1-A to 10.57% in Scenario 3-C;
- TE, with an impact reduction ranging from 2.07 % in Scenario 1-A to 11.10% in Scenario 3-C;
- ME, which impact reduction varies from 1.82% to 10.65% respectively in Scenarios 1-A and 3-C;
- LU, variable between 1.82% (Scenario 1-A) and 8.46% (Scenario 3-C).

The reduction of the impacts is proportional to the increase of the electricity car share; while for scenarios characterized by the same number of electric vehicles involved, impacts are reduced from gasoline and diesel scenarios to the Italian energy generation mix, PV and wind scenarios.

The following impacts instead grow in all analyzed scenarios:

- -HT-c, which impacts grow from 1.95% (Scenario 1-C) to 9.18% (Scenario 3-A);
- -HT-nc, growing from 7.69 % to 28.06% respectively in Scenario 1-C and 3-A;
- -IR and IRi, variable from 1.03% to 4.04 % respectively in Scenario 1A- and 3-B;
- -FE with an increase variable from 8.15% to 36.43% respectively from Scenario 1-B and 3-B;
- -FEx, growing variably from 7.70% to 27.48% respectively in Scenario 1-C and 3-A;
- -WRD, with an increase ranging from 1.91% to 18.38% respectively in Scenario 1-C to 3-A;
- -MFRD, increasing by a variable 4.4% to 152.56% respectively from scenario 1-A and 3-B.

The impacts of the PM and AP categories are reduced for all the scenarios in which electricity is generated by renewables while they are increased in the case in which electricity is produced by the Italian generation mix.

From the analysis of the results, it is clear that, by approaching the comparison of oil-based versus electricity transportation there is not a single better solution. Some impact categories are increasingly better the higher the penetration rate of electricity vehicles (e.g. GER, GWP, ODP), for others the opposite is true.

It is indeed a result that ties the applicability of one solution in comparison to the other to local issues related to energy resource availability, environmental impacts, people health hazards, and goes back in the supply chain as the whole life cycle of the vehicles is involved in the analysis.

As an example, for an extremely polluted city it would be certainly beneficial to decrease the POCP impact of the vehicle stock even though some indicators would be affected negatively by it. But this could have consequences up to the production sites in the supply chain on the human hazard risks (Ionizing radiation and human toxicity indicators) and cause a high increase in materials use (e.g. for Photovoltaics based scenarios, up to 152% in Scenario 3-B).

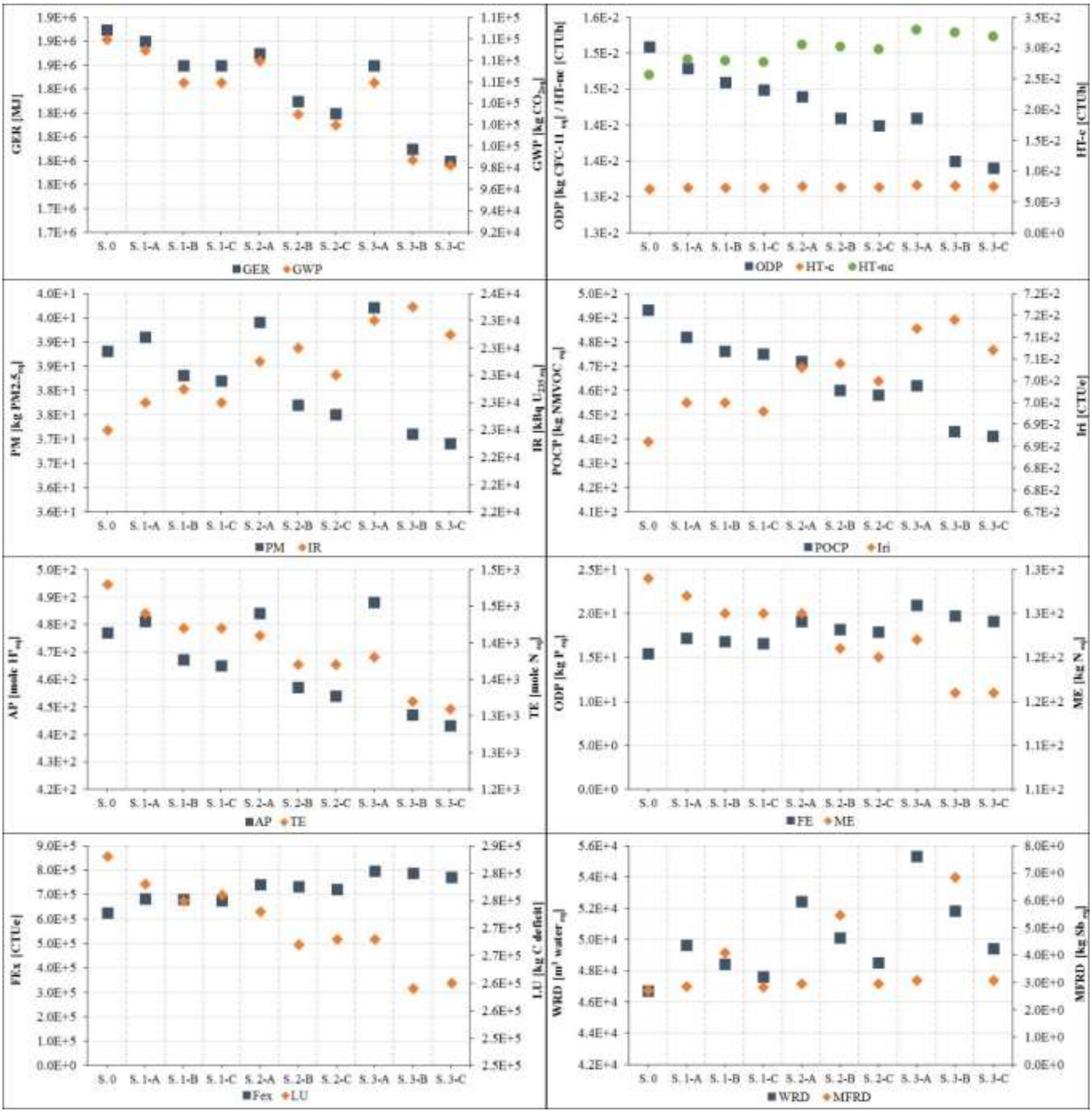

Fig. 3. Energy and environmental impacts of the scenarios

Conclusions

The paper presents a comparison of different electricity mobility penetrations rates in the Sicilian context applied to the mobility in the Valley of the Temples in Sicily.

The analysis of the energy and environmental effects of different scenarios of penetration of electric powered vehicles is discussed in the paper, with a particular insight on the source of generation of such electricity: if from the Italian generation mix, PV or wind generation systems.

The importance of a Life Cycle approach is clear, since a methodological approach describing a product from its cradle to its grave with such a broad range of indicators, allows having an integrated view on the matter.

The paper highlights that a clearly better and most sustainable solution is very difficult to identify. A mixed trend is identifiable among all the indicators included in the analysis: energy policy choices always need to be examined together with the local needs for reduction of a certain impact and the potential for enduring the increase of others.

In the case of PV based scenarios, as an example, several indicators would benefit of the electric mobility increase such as the GWP while others mostly tied to the human toxicity would obtain worse results, thus obtaining a diverse response of the indicators set to the same scenario. The multi-criteria approach proves fundamental when performing such comparative analyses of complex systems.

Since the achievement of the climate change mitigation objectives is particularly urgent, it is advisable to push towards the electricity vehicles deployment while simultaneously addressing the increase of impacts and hazards in the other domains highlighted in the paper through the improvement of eco-performances of manufacts and energy systems employed.

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