



Sustainable Mobility: Environmental and Economic Analysis of a Cable Railway, Powered by Photovoltaic System

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ABSTRACT

Nowadays, the massive use of fossil fuels, required to satisfy the energy needs of modern society, has caused evident climate changes which are dangerously destabilizing the ecosystem.

Currently, among the sectors responsible for the increased energy consumption are the building industry and the transportation systems. As regards the latter, in particular, the main issue consists in conjugating the growing demand for personal mobility with the safeguard of the environment, providing for policies aimed at discouraging the use of private cars and increasing the use of alternative low-impact energy sources.

In this context, the paper aims to analyze the effectiveness of a collective transport system which, being powered by renewable sources and designed to reduce the private car flow directed to and coming from the Mediterranean University of Reggio Calabria, is an example of sustainable urban mobility action.

To fulfill this purpose the expected outcome generated by the described measure has been evaluated by both the economic and environmental point of view.

Keywords: Smart city, Air pollution assessment, Transport policy, Photovoltaic plant, Net present cost.

1. INTRODUCTION

Our industrial civilization is at a crossroads. Oil and other fossil fuels that make the current lifestyle possible are running out. Oil based technologies are close to being obsolete and the related industrial infrastructures need maintenance.

In addition, climate changes caused by activities based on fossil fuels are acknowledged to be an alteration that threatens to destabilize the planet's ecosystems [1].

In this context the European Union, undertaking policies aimed at reducing both energy consumptions and pollutant emissions, has laid out the basis for a sustainable and zero-emission economic era. Specifically, since energy consumptions are mainly due to the building industry and to the transport sector, urban settlements, where these consumptions are mostly concentrated, represent the explicit target of EU policies [2]. The measures adopted to face these challenges are crucial with a view to fulfilling the smart and sustainable society designed by the European strategy as a goal to be reached by 2020 and beyond.

Particularly among the factors influencing the quality of urban life, environment and public health [3], urban traffic plays a pivotal role [4]. Presently, in fact, urban transportation systems, affected by the mobility demand growth and unbalanced for the predominance of private transport, are becoming unsustainable.

In general, in Europe private road transport represents the largest share of the modal split regarding both passengers and

freight [5-6], so that, due to the growing number of vehicles traveling on roads and highways, the age of the vehicular fleet and the massive use of highly pollutant fuels, heavily compromise the environmental quality.

In this regard, indeed, the European directives on sustainable mobility commit the Member States to adopt specific laws ruling urban transports, which have to be mainly aimed at the improvement of the fuel quality, the usage of diversified energy sources, the improvement of emission Standards and the promotion of good practices.

After this, Italian legislation has adopted strategies mainly focused on the use of low impact fuels, car fleet renewal, and modification of the modal split with a view to enhancing the share of the public transport by improving its efficiency.

Hopefully, in the next years, even though the mobility based on passenger cars is supposed to maintain a pivotal role in the planning of transport policies, the promotion of alternative and more sustainable systems (public transport, electric vehicles, etc.) should represent the main target of the strategies addressing the issue of sustainable mobility in urban area. This is the current main challenge for politicians, planners and administrators, actually compelled to strike a balance between the growing mobility demand and the necessity of reducing the impacts on the environment.

2. CASE STUDY. CABLE RAILWAY IN THE CITY OF REGGIO CALABRIA

As a case study, a measure of sustainable mobility, to be implemented in the city of *Reggio Calabria*, is proposed. It consists of a transport system in its own protected lane, powered by a photovoltaic system, at the service of the University campus.

2.1 Characteristics of the transportation system

In *Reggio Calabria* the University buildings are situated in a campus, located in the Northern area of the city, about 2 km distance from its center. Presently, in the absence of an integrated public transport system serving University users, the features of public transport are not very attractive, being the connection to the nodes of modal interchange and to the city center lacking and inefficient, thus making private cars the most used transportation mode.

In order to satisfy students' increasing mobility demand and reduce the incidence of private transport toward the University campus, an advanced public transport system has been designed.

It consists in a transmission line cable in its own protected lane [7], connecting the campus with two strategic interchange poles of the city, the harbor and the *Reggio Lido* railway station. The system is constituted by a multiple shuttle, with only one runway for the two travel directions and with interchange areas for the crossing of vehicles located in correspondence of the intermediate stations. The vehicles placed on special rails, are driven by a steel cable, driven by a propper motor.

The track consists of two terminal stations, an upstream (*Engineering Departments*), working as driving station, and a valley (*Lido Station*), in which the vehicle can reverse its travel direction; four intermediate stations are used for passenger embarkation and for vehicle crossing (Figure 1). In addition, a station has the function of connecting the two cable rings of the line, in order to reduce the excessive length of a single rope. The track length is 1860 m, its slope is variable between 3 and 10% and the average distance between stations is about 370 m. The infrastructure is made of steel profiles, on which the tires roll. To prevent transverse movements of the vehicle, the system is also equipped of rubber wheels, with vertical axis.

In order to reduce CO₂ emissions due to the electricity production for the system energy supply, a grid-connected PV plant, integrated into the funicular railway system, generates part of the required electricity. In this way more environmental benefits can be obtained, beyond those afforded by traffic reduction.

2.2 Design of the photovoltaic system

Several design choices have been assumed in order to make the PV system able to supply power to the cable railway transportation system. Particularly, three different types of panels (in monocrystalline, polycrystalline, and amorphous silicon) have been selected, placing them on different surfaces: only on the roof of the stations or, in addition, on the whole railway track canopy. Preliminarily, however, the power of the system and the energy required for its operation have been determined.

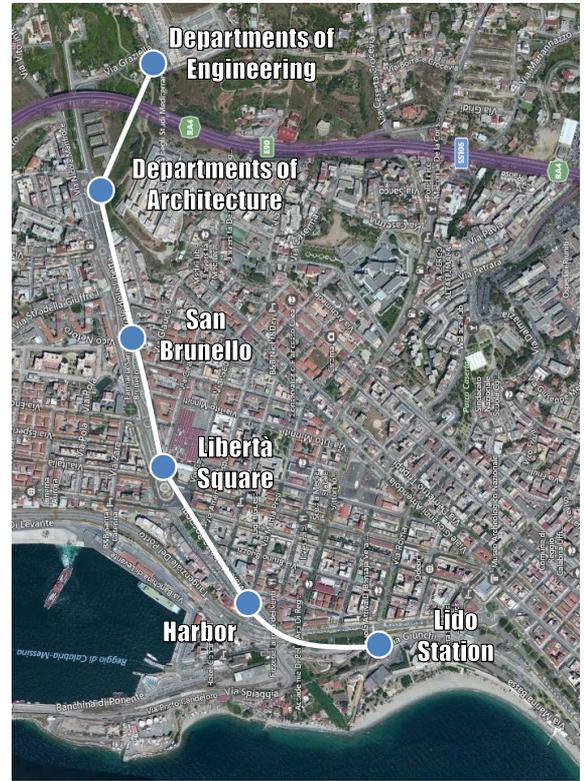


Figure 1. Route of the proposed system

2.2.1 System power and energy demand

The time-speed diagram adopted for the train running between two successive stations is trapezium type, consisting of three phases: acceleration, regime and deceleration (Figure 2).

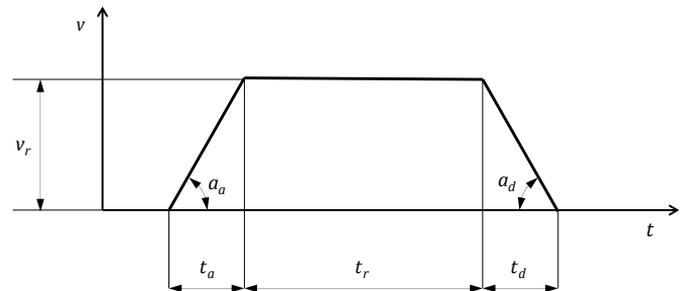


Figure 2. Time-speed diagram adopted for the system

In this hypothesis, the duration of the acceleration and deceleration phases, respectively t_a and t_d , are expressed by the following equations:

$$t_a = \frac{v_r}{a_a}; \quad t_d = \frac{v_r}{a_d} \quad (1)$$

in which v_r is the regime speed of the train, a_a and a_d the acceleration and the deceleration in the respective phases.

As a consequence, distances respectively covered during the two phases, d_a and d_d , are given by:

$$d_a = \frac{a_a t_a^2}{2} = \frac{v_r^2}{2a_a}; \quad d_d = \frac{a_d t_d^2}{2} = \frac{v_r^2}{2a_d} \quad (2)$$

Instead, during the regime phase, the travel time is:

$$t_r = \frac{d_r}{v_r} \quad (3)$$

and the covered distance, d_r , is:

$$d_r = L_T - d_a - d_d \quad (4)$$

where L_T is the length of the section. Finally:

$$t_r = \frac{d_r}{v_r} = \frac{L_T - d_a - d_d}{v_r} \quad (5)$$

Energy demand for each lap has been calculated as a function of the system power in the different driving phases (in both peak and soft hours) and of their respective travel times:

$$E_l^k = 2 \times \sum_{i=1}^{N_l} \left(P_a^k t_{a,i} + P_r^k t_{r,i} + P_d^k t_{d,i} \right) \quad (6)$$

where:

- the k apex indicates the peak or soft period;
- the l index indicates the generic lap;
- the i index indicates the generic section between two subsequent stations;
- N_l is the number of section;
- P_a , P_r and P_d are the power in the acceleration, regime and deceleration phases;
- t_a , t_r and t_d are the travel times during the acceleration, regime and deceleration phases.

Daily consumption, different in weekday or holiday, is a function of the number of daily trips in the respective k (peak or soft) period:

$$E_{|d,m} = \sum_{k=1}^2 E_{|d,m}^k = \sum_{k=1}^2 \left(h_m^k \times n_c^k \times f_m^k \times E_l^k \right) \quad (7)$$

in which:

- the d index indicates the day;
- the m index indicates the peak or soft period;
- h are the daily working hours;
- n_c is the number of simultaneously on line trains;
- f is the frequency of service.

Finally, yearly required energy, $E|_y$, is calculated as a function of the total operation days of the system, $N_{g,m}$:

$$E|_y = \sum_{m=1}^2 \left(N_{g,m} \times E_{|d,m} \right) \quad (8)$$

Regime speed of 8 m/s (29 km/h), acceleration and deceleration of 0.8 m/s² have respectively been assumed.

Subsequently, the number of trains simultaneously driving on the track has been estimated from the required hourly flow [7]. Particularly three trains with three carriages each (40 seats/carriage) are necessary in the peak period, whereas only two trains endowed with two carriages are required in the soft one. Finally, the maximum power in the acceleration phase has been determined in relation to the number of carriages respectively running in the peak and soft hours. Table 1 reports the main characteristics of the analyzed system.

365 operating days, 240 of which are weekdays and 125 holidays, have been assumed. On the basis of the described assumptions, the required yearly energy is 476 MWh/year.

2.2.2 Analysis of energy production

The available area for the installation of photovoltaic panels has preliminary been identified. The station roof surface resulted equal to 3200 m², whereas the total area of the station roof and the railway track canopy was equal to 11000 m².

Table 1. Characteristics of the transport system

Parameter	Symbol	Peak hours	Soft hours
Maximum power (acceleration phase)	P_a (kW train ⁻¹)	100	70
Maximum power (regime phase)	P_r (kW train ⁻¹)	60	42
Maximum power (deceleration phase)	P_d (kW train ⁻¹)	60	42
Frequency	f (trip train ⁻¹ h ⁻¹)	4	2
Train simultaneously on the track	n_c (train)	4	3
Number of train carriage	(carriage train ⁻¹)	3	2
Daily operating hours (weekdays)	h (h)	8	8
Daily operating hours (holidays)	h (h)	0	16

In relation to both surfaces and to the three selected panel typologies, whose technical characteristics are reported in Table 2, the total power of the PV plant has been determined (Table 3). Subsequently, using *Homer* software [8], the yearly produced energy has been calculated, pointing out the purchased and sold rates (Tables 4-5 and Figure 3).

The simulations showed that the energy produced, on an annual basis, is always greater than the energy demand, except when amorphous silicon panels are placed on the station roof only; in this case an integration with an energy withdrawal from the grid is needed.

Obviously, in all the cases, an energy withdrawal from the grid is required in the periods of insufficient or lacking energy production. The exceeding energy production is always sent to the grid.

Table 2. Technical characteristics of the PV panels

Panel typology	Peak power (Wp)	η (%)	NOCT (°C)	β (%/°C)
Amorphous	135	9,6	46	-0,24
Polycrystalline	230	14,1	47	-0,45
Monocrystalline	327	20,1	45	-0,38

Table 3. Peak power of the various configurations of the PV plant

Panel typology	Peak power of the plant (kW _p)	
	Installed on the station roof	Installed on the railway track canopy and on the station roof
Amorphous	308	1 020
Polycrystalline	446	1 468
Monocrystalline	642	2 193

Table 4. Energy rates when PV panels cover the canopy of the stations only

Panel typology	Energy rates (MWh/year)		
	Produced	To the grid	From the grid
Amorphous	438	183	284
Polycrystalline	622	317	242
Monocrystalline	910	551	209

Table 5. Energy rates when PV panels cover the canopy of the stations and of the whole railway track

Panel typology	Energy rates (MWh/year)		
	Produced	To the grid	From the grid
Amorphous	1 451	1 017	181
Polycrystalline	2 052	1 544	164
Monocrystalline	3 109	2 486	151

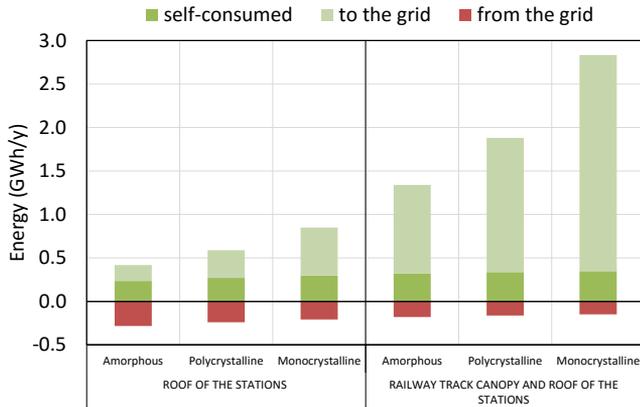


Figure 3. Yearly self-consumed, sold and purchased energy

3. ECONOMIC ANALYSIS

The economic analysis of the designed system has been carried out assessing the *Net Present Cost (NPC)*:

$$NPC = \sum_{j=1}^n \frac{C_j - B_j}{(1+r)^j} + I_0 \quad (9)$$

where C_j and B_j are respectively the costs and the revenues that occur within the j^{th} year, I_0 is the cost of the whole investment, r is the discount rate, n is the number of years forming the project lifetime.

The cost of the investment incorporates the cost of the PV plant and its supporting structures, whereas, for the analyzed cases, yearly costs and revenues are due to energy purchases and sells respectively.

In order to estimate their value, average tariffs were singled out. Assuming that the energy sell to the grid is ruled by the dedicated withdrawal regime [9], the electricity withdrawal price, which is equal to the hourly zonal price on the power exchange, is 0.048 €/kWh, with a yearly operating cost of 0.6 €/kW_p.

In addition, with a view to calculating the annual revenue B_j , the possible profits derived from white certificate schemes, also known as Energy Efficiency Titles (EET), have been considered. In this case the incomes, which, for the Italian law, only regard the first five years, are yielded by EET trades and a price of 110 €/toe has been esteemed [10].

As a consequence, the annual revenues are:

$$B_j = 0.048 \times E_{w,j} + 110 \times E_{wP,j} \quad \text{if } j \leq 5 \quad (10)$$

$$B_j = 0.048 \times E_{w,j} \quad \text{if } j > 5 \quad (11)$$

where $E_{w,j}$ is the withdrawn electricity during the year j , $E_{wP,j}$ is the primary energy delivered to the grid during the year j .

As far as the energy purchase is concerned, in order to esteem the annual cost, the Single National Price (SNP) settled by the Italian Authority [9] has been used. Its value is equal to 0.10 €/kWh.

Consequently, the annual costs are:

$$C_j = 0.10 \times E_{p,j} + 0.6 \times P_p \quad (12)$$

where $E_{p,j}$ is the purchased energy during year j , P_p is the peak power of the PV plant.

Finally, assuming a discount rate $r = 3\%$, the results reported in Tables 6-7 were obtained, where the global amount of the initial investment I_0 , the yearly cash flow $F_j = C_j - B_j$ and the *NPC* at the end of the project lifetime ($n = 25$) are shown.

Specifically, Table 6 reports the outcomes related to the case in which only the canopy of the stop stations is covered with PV panels, whereas Table 7 is referred to the case in which also the whole cable railway path is covered. For both cases the reported outcomes refer to all the analyzed configurations of the project, which differ for the presence of the PV plant and for the PV module typology.

In order to single out the most cost-effective solution, the cases reported in Tables 6 and 7, in which the transportation system is equipped with a PV plant, have been compared to the configuration without PV generation, in which the needed electricity is delivered by the grid. In this last case the cash flow is 47 558 €/y and the *NPC* is 828 129 €.

Table 6. Costs and revenues PV panels cover the canopy of the stations only

Panel typology	Initial investment I_0 (€)	Cash Flow F_j (€/anno)	<i>NPC</i> (€)
Amorphous silicon PV panels	184 680	19 777	511 934
Polycrystalline silicon PV panels	374 228	9 186	504 470
Monocrystalline silicon PV panels	769 889	-5 114	628 944

Table 7. Costs and revenues PV plant covers the canopy of the whole railway path

Panel typology	Initial investment I_0 (€)	Cash Flow F_j (€/anno)	<i>NPC</i> (€)
Amorphous silicon PV panels	2 092 906	-30 079	1 473 417
Polycrystalline silicon PV panels	2 700 822	-56 867	1 565 497
Monocrystalline silicon PV panels	4 178 656	-102 932	2 152 532

The results of this comparison are reported in Figure 4, where the *NPC* values at the end of the project lifetime ($n = 25$ years), for all the considered configurations, are plotted.

It is worth noting that, from an economic point of view, the optimal configuration is the one that entails the installation of the PV panels on the canopy of the stations only. As a matter of fact, in this condition, the minimum NPC values have been assessed.

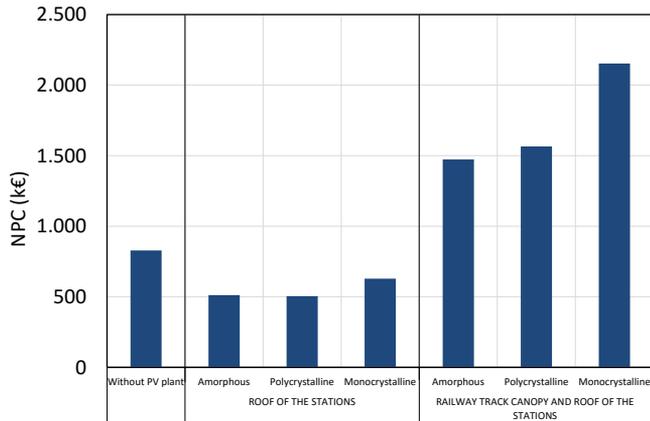


Figure 4. NPC for the analyzed configurations

4. POLLUTANT EMISSION ASSESSMENT

Two pollutant typologies were analyzed: the first one regards the emissions having a local impact [11] on the environment and consists of the combustion products discharged by vehicles in the University area (CO, NMVOC, NO_x, NH₃, PM, N₂O); the second one involves the emissions having a large scale action and was assessed in terms of CO₂ rate [12]. Both vehicle fleet and cable railway, which is electrically powered, are source of this last type of pollutant.

4.1 Assessment of the pollutant emissions having a local impact on the environment

Being the cable railway electrically powered, the studied fleet is the only source of pollutant with local impact. It is constituted by the road vehicles (passenger cars or motorcycles) involved in the movements directed towards or coming from the *Mediterranea* University of Reggio Calabria.

Obviously, these vehicle flows are modified by the construction of the new transportation system, as well as the related emissions. Therefore, while the current flows were assessed by means of sample measurements regarding the actual fleet, predictions based on reliable hypothesis were made to evaluate the possible flow evolution after the implementation of the new system.

The daily amount of emissions discharged by the specified road vehicles were assessed in correspondence of the two configurations. In this aim the TIER 1 method of the dell'EMEP/EEA *emission inventory guidebook* 2009 [13] was used.

Accordingly to this procedure, the fleet has to be split up into classes which comprise vehicles homogeneous for the rates of the emissions discharged in the environment. In this view, the daily emission amount of the pollutant *i* discharged by all the vehicles composing the fleet, *E_i*, is assessable as:

$$E_i = \sum_{v=1}^{N_v} n_v \times C_v \times FE_{i,v} \quad (13)$$

where:

- N_v is the number of vehicle classes;
- n_v is the number of vehicles belonging to class v ;
- C_v is the daily fuel consumption of the average vehicle belonging to class v ;
- $FE_{i,v}$ is the emission factor of the vehicle belonging to class v and related to the pollutant i .

The emission factors [13] related to every considered pollutant having a local impact on the environment are reported in Table 8.

Table 8. Emission factors for pollutants emitted by vehicles [13]

Pollutant	Emission factor (g/kg fuel)		
	Cars		Motorcycles
	Gasoline	Diesel	Gasoline
CO	132	4.7	490
NMVOC	14	1.1	114
NO _x	14.5	11	9.5
PM	0.037	1.7	2.7
N ₂ O	0.213	0.087	0.059
NH ₃	0.173	0.018	0.063

The daily fuel consumption of the average vehicle belonging to category v was evaluated by means of the following expression:

$$C_v = c_v \times d \quad (14)$$

where c_v is the specific consumption of the vehicle v and d is the average length of the typical trip (Table 9), assumed equal to 3 km.

Table 9. Consumptions of the analyzed vehicles [13]

Consumption	Cars		Motorcycles
	Gasoline	Diesel	Gasoline
specific (g/km)	60	70	35
daily (kg/day)	0.180	0.210	0.105

As regards the structure of the current fleet, the input data needed for its assessment were derived from sample measurements regarding the actual flows. These surveys yielded that, per day, 7759 people travel by means of passenger cars whereas 1565 people use motorcycles [7].

In order to single out the vehicle classes [14] for the studied case, the composition of the fleet running in the urban area pertaining to the Municipality of Reggio Calabria was taken into account [7]. Specifically, the studied fleet can be effectively classified by fuel type, so that two categories can be distinguished: gasoline or diesel fueled vehicles. As far as passenger car is concerned, gasoline fueled vehicles are the largest share (about 62%) of the fleet distribution by fuel, while only the remnant 38% is related to diesel cars. [7]. On the other hand, motorcycles are gasoline fueled only.

Therefore the number of vehicles of type v is assessable as:

$$n_v = \frac{Q_v}{t_{o,v}} p_v \quad (15)$$

where:

- n_v , is the number of vehicles of type v travelling every day in the considered fleet ;
- Q_v is the number of people per day travelling on the vehicle v ;
- $t_{o,v}$ is the occupancy rate of the vehicle v ;
- p_v is the percentage of vehicles of type v .

Assuming an occupancy rate of 1.56 for passenger cars (whatever fueled) and of 1.30 for motorcycles, the results reported in Table 10 were derived.

Table 10. Current composition of the studied running fleet

Vehicle type	Fuel type		Total
	Gasoline	Diesel	
Passenger Car	3 084	1 890	4 974
Motorcycle	1 204	-	1 204

In order to assess the evolution of the mobility demand caused by the impact of the new transportation system, the following hypotheses were made:

1. the modal split is changed by the impact of the new system and the shift towards the collective mode has been assumed to regard an average percentage of about 25% of the former demand;
2. the new mode of transport attracts new customers and causes an enhancement of the global mobility demand, assumed equal to 5%.

The results of this calculation are reported in Table 11, where the evolution of the mobility demand, divided per transport mode, is shown. Starting from the new transportation demand and assuming that the occupant rate does not change, the number of vehicles belonging to each category v can be assessed by means of equation (15) and the outcome of this calculation is reported in Table 12.

Table 11. Mobility demand (people/day) after the realization of the new transportation system

Mode of transport		
Passenger cars	Motorcycles	Cable Railway
5 919	1 115	2 752

Table 12. Number of vehicles (vehicles/day) running after the realization of the new transportation system

Vehicle type	Fuel type		Total
	Gasoline	Diesel	
Autovetture	2 332	1 462	3 794
Motocicli	858	-	858

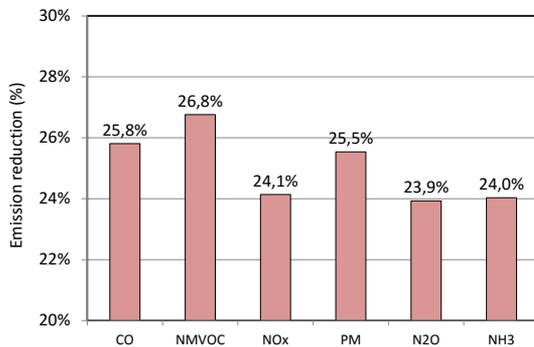


Figure 5. Emission rates before and after the implementation of the transport system

Moreover, knowing the fleet distribution, the emission rates can be calculated by means of equation (13). The results are reported in Figure 5, which shows the rate of the emissions having a local impact only. It is worth noting that the emission rate reduction is of about 25% for every pollutant. The results related to the pollutants having global impacts, expressed in terms of CO₂, are reported in the following specific paragraph

4.2 Assessment of the emission rates related to pollutants having a large scale action.

The cable railway is electrically powered; therefore the emission rates are related to the electricity consumptions and are referred to pollutants having a global impact on the environment. Specifically, using carbon dioxide as a representative indicator of these pollutants, the annual emission rates E_m can be assessed provided that the energy consumption E and the electricity emission factor FE_{el} (equal to 0.468 kg/kWh [15]) are known:

$$E_m = E \times FE_{el} \quad (16)$$

The emission rates were assessed for the various studied configurations which differ for the presence of the PV plant and for the typology of the PV panels. The energy consumption E has been esteemed in a former paragraph using the nominal features of the engine of the transport system, its operation periods, and the characteristics of the transport service [7].

Obviously, when no PV plant is present, the needed energy is totally fed by the grid, therefore, in this case, the whole energy consumption of the transport system contributes to the emission of pollutants. On the other hand, when the PV plant partially supplies the electricity needed to power the cable railway, the energy delivered by the grid is correspondently reduced and so are the related emission rates. Specifically, their reductions is equal to the electricity emission factor times the energy supplied by the PV plant. With regard to the CO₂ emissions due to the road vehicles, they were assessed, for both the ante and post operam situations, by means of the procedure detailed in the former section. The correspondent emission factors are reported in Table 13.

Table 13. Emission factors for CO₂ emitted by vehicles [13]

Emission factor (g/kg fuel)		
Cars	Motorcycles	
Gasoline	Diesel	Gasoline
3180	3140	3180

The results of the described analysis are reported in Figures 6 and 7.

Figure 6 depicts the annual emission rates discharged into the environment in correspondence of all the studied configurations and the emission rates avoided owing to the energy surplus delivered to the grid by the various typologies of PV plant (amorphous, polycrystalline or monocrystalline silicon).

Figure 7, on the other side, reports the emission rates resulted from the balance among the discharged and the avoided quantity.

It is worthy of note that the two cases respectively corresponding to the ante and post opera without PV plant configurations, are very similar (Figures 6 and 7). This is due

to the fact that the CO₂ emissions produced by the electricity consumptions of the cable railway when no PV plant is present (equal to 232 t/year) compensate the reduction of the CO₂ emission rates (240 t/year) caused by the decrease of the number of circulating vehicles occurring in the post-operam situation (Figure 6).

On the contrary, the presence of the PV plant, for all the studied configurations, reduces the CO₂ emissions discharged into the environment, being the electricity demand of the cable railway partially satisfied by a RES.

Furthermore, the use of more efficient types of PV plant (polycrystalline or monocrystalline silicon), with larger panel surfaces, raises the avoided emission rates (Figure 6), so that in correspondence of the optimal case (monocrystalline silicon panel covering the largest surface) the balance among discharged and avoided emissions is negative (-350 t/year - Figure 7), pointing out a global benefit (advantage) for the environment.

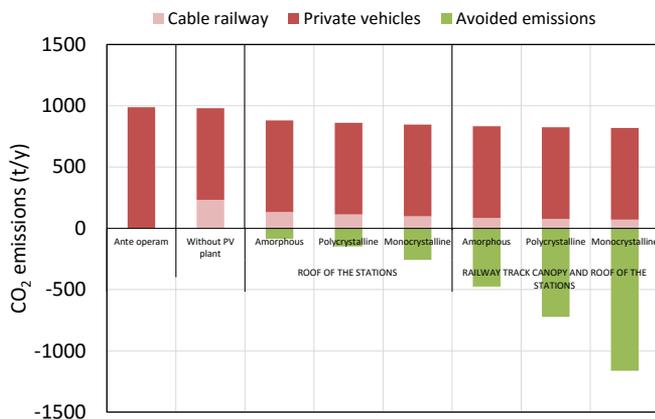


Figure 6. CO₂ emissions produced and avoided by the road vehicles and by the cable railway

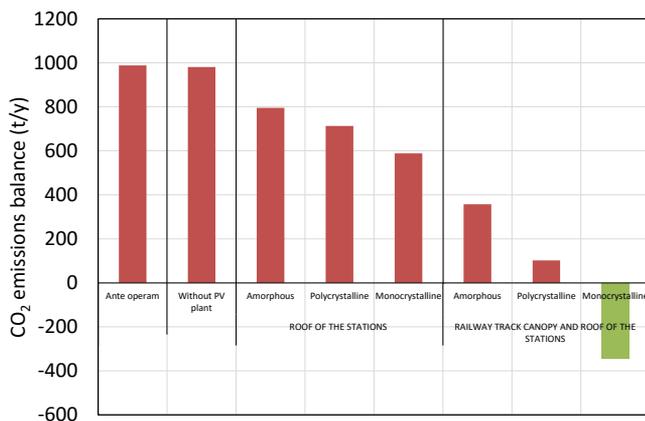


Figure 7. CO₂ emission balance for the different studied configurations

Finally, in order to try to strike a balance among the economic and environmental facets of the issue, a summary of all the obtained results is reported in Figure 8.

From this representation, it can be inferred that the optimal configurations are the ones in which the transportation system is equipped with a PV plant covering the station canopies only (with a limited surface). As a matter of fact, comparing this latter case with the configuration without PV plant, a reduction of both emission rates and NPC values is registered.

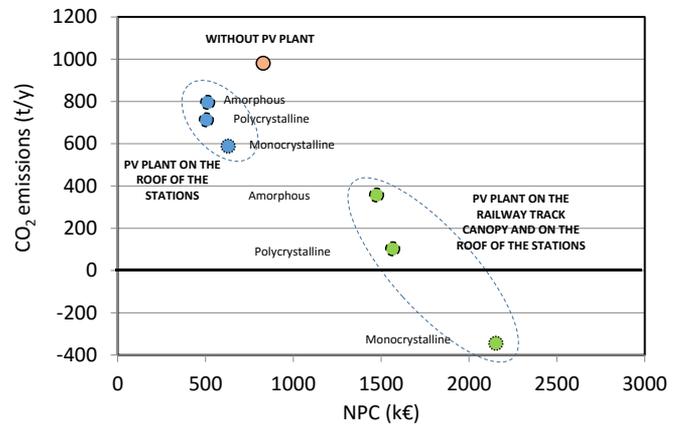


Figure 8. CO₂ emission rates versus NPC values for all the studied configurations

On the other hand, albeit enhancing the PV panel surface causes a remarkable reduction of the emission rate and, hence, has a positive effect from an environmental point of view, it also provokes a noteworthy rise of the costs which should be carefully considered in the decision process regarding the project.

5. CONCLUSIONS

The present configuration of the mobility model is no longer sustainable. In the last years, in fact, in the cities the number of circulating vehicles has markedly increased following a trend that, although slowing down, is urgent to be inverted. New mobility models, favouring the use of shared, collective and electric transportation means, fuelled with RES, are urgent to be adopted.

Within this frame, as an example of urban sustainable mobility, the present work illustrates a cable railway to be implemented in the city of Reggio Calabria. It connects, in a dedicated track, the university campus with two important urban hubs, the harbour and a strategic railway station.

The measure produces, as far as local pollution is concerned, a 25% average reduction of pollutant emissions thanks to the smaller number of circulating vehicles. As regards CO₂ emissions, on the contrary, the amount originating from the system electric power supply is comparable to the reduction obtainable for the fewer circulating vehicles, so that, on a global scale, emitted CO₂ shows no substantial variation.

In the aim to reduce emissions some design options, consisting in the installation of different typologies of PV modules (monocrystalline, polycrystalline and amorphous silicon), horizontally laid on different covering surfaces of the track (station roof or, in addition, railway track canopy) have been selected. The energetic analysis has been carried out by means of *Homer* software, whereas the economic one has been effected evaluating the *Net Present Cost*.

The analysis showed that yearly produced energy is, in all cases, greater than energy demand, apart from the case in which amorphous silicon panels are laid on the smallest surface, as in such case energy from the grid is required.

From an economic point of view, the optimal configurations are the ones that entail the installation of the PV panels on the canopy of the stations only. As a matter of fact, in this condition, the minimum NPC values have been assessed.

As concerns total CO₂ emitted by both vehicles and the transport system supply, being the energy needs of this latter partially satisfied by RES, reductions are observed for all PV configurations with respect to the case of their absence.

However, only configurations in which PV plants are installed on the station covering are simultaneously cheaper and less polluting than the configuration in which power is exclusively delivered from the national electric grid.

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NOMENCLATURE

Symbols

a_a	acceleration, m/s ²
a_d	deceleration, m/s ²
B	benefits, €/year
C	operating costs, €/year
C_v	consumption of the vehicle of typology v , g/kg _{comb}
d_a	distance covered during acceleration phase, m
c_v	specific consumption of the vehicle, g/km
d	average distance covered, km
d_d	distance covered during deceleration phase, m
d_r	distance covered during regime phase, m
E	consumption, kWh
E_i	emission of the pollutant i , g
f	frequency, train/h
FE_{el}	emission factor of the electrical energy, g/kWh
$FE_{i,v}$	emission factor of the pollutant i , due to the vehicle of typology v , g/kg
h	daily operating hours, hours
I_0	Investment cost, €
L_T	length of the section, m
n_c	number of trains simultaneously on the track, -
n_v	number of vehicles, -
N_g	days of operating, days
NPC	Net Present Cost, €
N_t	number of section of the track, -
N_v	number of vehicle typologies, -
P_a	power in acceleration phase, kW
P_d	power in deceleration phase, kW
P_r	power in regime phase, kW
r	discount rate, %
t_a	travel time in acceleration phase, s
t_d	travel time in deceleration phase, s
t_r	travel time in regime phase, s
v_r	speed of the train in the regime phase, m/s

Superscripts and subscripts

k	peak period or soft period
m	weekday or holyday
i	pollutant
v	vehicle