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Freight distribution with electric vehicles: A case study in Sicily. RES, infrastructures and vehicle routing

Giuseppe Napoli[a,*], Salvatore Micari[a], Giorgio Dispenza[a], Laura Andaloro[a], Vincenzo Antonucci[a], Antonio Polimeni[b]

[a] Institute for Advanced Energy Technologies "Nicola Giordano", National Research Council of Italy, Salita S. Lucia sopra Contesse 5, 98126 Messina, Italy
[b] Department of Enterprise Engineering, "Tor Vergata", University of Rome, Viale del Politecnico 1, 00133 Rome, Italy

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ABSTRACT

This paper deals with the issue of the production of electricity required for an electric delivery van to carry out its daily mission. In particular, the technical solutions adopted for the generation and management of energy from renewable energy sources will be illustrated. Subsequently a vehicle routing problem with time windows is formulated in order to optimize the freight distribution at urban level completing the exploration of two aspects, infrastructures and management of the service, considered fundamental for dealing with the distribution of freight in a system scenario. The article describes a case study for the delivery of freight within the last mile in which the installation of renewable energy production plants is proposed in the same place where the urban distribution center has been planned. The area dedicated to freight handling is thus proposed in the work as an energy platform as well as logistics. The optimization of a freight delivery service is performed in order to reduce the energy used by the vehicle in its daily travels and some aspects related to the governance (i.e. time windows allowed for the delivery/pick-up operations) are included in the problem constraints. A test application, considering a set of 84 retailers, has been carried out as case study in the Capo d'Orlando municipality (Sicily, Italy).

1. Introduction

In 2016, in Europe, total freight transport increased by 4,6% compared to the previous year, the largest increase since 2010. Also in Italy after years of generalized decrease in volumes, the logistics and transport sector (particularly road transport which represents almost 75% of the total transported freight) is reversing the trend thanks to a positive export recovery. The vehicles weighing less than 3.5 t are responsible of about the 16% of CO_2 emissions respect to the total emissions due to the all transport services (passengers and freight). This percentage increases until the 33% by considering only the road freight transport [1]. Innovative and sustainable logistics services and operation can make a decisive contribution to reducing polluting emissions deriving from road freight traffic [2]. Only an integrated, and not sectoral, approach, which therefore takes into account all the components relating to electric mobility in an urban environment, can guarantee to achieve the long-term vision of the EU for the freight transport. However, integrated and sustainable logistics requires integrated and sustainable infrastructure. New planning tools and regulations that allow for the allocation of appropriate spaces to logistics activities for freight vehicles in urban areas are among the strategic elements indicated in [3] where infrastructure measures has been considered the most substantial category of operation in order to make urban freight logistics more sustainable. Within this overall vision it is also necessary to take into account the process of energy efficiency obtainable from a correct planning of the routes that Electric Vehicles (EVs) perform for the delivery of freight.

The objective of the article is to show, through a case study, the salient, technical and operational aspects, to implement a very sustainable process of freight transport in the last mile in an urban environment. The paper completes an overall vision by the authors which, starting from the design phases of a new concept vehicle discussed in [4] and arriving at the description of the freights distribution service within the last mile, aims to represent the potential of sustainable logistics also through the analysis of the plants and territorial infrastructures necessary to carry out a full process with zero emissions. Particularly, the fuel production and the freight distribution aspects are discussed in deep here. Fig. 1 shows the methodological scheme used which, starting from the three main topics of the inner ring, lead to the determination of the project constraints (outer ring) through the main areas of analysis.

The primary objective of the entire work and the main element of novelty is represented by the possibility of describing a case study in

* Corresponding author.
E-mail addresses: giuseppe.napoli@itae.cnr.it (G. Napoli), salvatore.micari@itae.cnr.it (S. Micari), giorgio.dispenza@itae.cnr.it (G. Dispenza), andaloro@itae.cnr.it (L. Andaloro), antonucci@itae.cnr.it (V. Antonucci), antonio.polimeni@uniroma2.it (A. Polimeni).

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Fig. 1. Representation of the methodological scheme. The inner ring represents the main topics.

which, through an experience in the field, the three aspects described are related. For each of the topics addressed, the available data, the method of analysis used and the main project constraints that make up the logical connection of the different issues addressed together with the results achieved are reported.

The paper is organized as follows: after the Literature Review reported in Section 2 the Renewable Energy Source (RES) plant, implemented in order to produce and distribute the electricity necessary to an Electric Delivery Van (EDV), is described in Section 3. Section 4 shows the VRP formulation and the solution procedure while in Section 5 the application test is described and an estimation of the emission saved by the use of the proposed vehicle is calculated. Finally, the main points and significant results of the paper are summarized in conclusions.

2. Literature review

Currently, the last mile is considered a critical point within the supply chain, both for environmental and logistics cost aspects. For this reason, in the last years, city logistics measures are proposed, assessed and implemented in order to mitigate impacts [3]. Since an important share of the total logistics costs are spent right in the last mile distribution, logistics and transport companies are increasingly considering new technologies and new business models as alternative means to tackle the growing problem of the last mile in urban area [5,6]. In Lebeau et al. [7], the authors explore the possible integration of EVs in urban logistics operations. The results show that in the segments of small vans and quadricycles, EVs are often the most competitive technology and demonstrates the feasibility and the economic relevance to introduce them in urban distribution. The integration of EVs in logistics and transportation activities also raise some additional challenges from the strategic, planning, and operational perspectives. For example, it is required to provide recharge stations for electric-based vehicles, and decisions need to be made about the number, location, and capacity [8,9]. Moreover, vehicle range must be take into account in order to design efficient distribution routes [10]. On the other side, based on the current primary energy mix, the production of electricity for mobility would cause an increase of about 50% above the CO_2 already emitted from the normal production of electricity [11]. These numbers show that e-mobility offers no appreciable contribution to environmental protection in the intermediate term if no initiative is put in place to ensure that the energy required for electric vehicles is produced from renewable sources [12]. The design of an energy infrastructure system to support sustainable logistics is therefore a fundamental element in a systemic perspective.

In [13] a framework to evaluate policy options for supporting EVs in urban freight transport is described. Taefi [14] assessed and compared policies about distribution carried out with EV against other prospective options by multi-criteria analysis. The study finds that electric medium-duty vehicles are only financially competitive at higher mileages, if the savings achieved by lower operational costs are greater than the costs for battery replacements. A research on traffic modeling developed for evaluating traffic derived from a freight distribution service operated using electric medium-sized vans is described in Deflorio and Castello [15]. In [16] the diffusion of low-impact commercial vehicles in urban areas by considering the associated key operational factors is addressed. Tan et al. [17] propose a solution for last mile transportation based on a platform for remote driving. A case study that addresses the effects of replacing vans by small electric vehicles on city logistics operations in the city of Oporto (Portugal), considering public and private stakeholders' interests is reported in [18]. An evaluation about the impact of using electric vehicles in collaborative freight transport networks from a multi-objective perspective is reported in [19] where the relationship between delivery cost and environmental impact, in different cities transport systems, is addressed.

Regarding the distribution service in city areas it is necessary to consider several aspects. In 1999, Taniguchi et al. [20] introduce the concept of city logistics to define the operations related to the logistics and transport activities by private carriers in urban areas (last mile distribution). The topic has been much discussed in literature, with various approaches ranging from the analysis of the quantities (commodities based models, [21,22] to the analysis of vehicle trips [23]. The user behavior is another aspect considered in literature [24,25]. The analysis of freight distribution can be made considering the restocking procedure, if own account or third party transport [26]. In first case (own account) the sender (i.e. a producer) or the receiver (i.e. a retailers) use an own vehicle to move the freight; in second case the sender or the receiver resort to a private carrier. In both cases, a flow of freight vehicles moves on the city, interacting with the other traffic components, influencing the road network performances (e.g., travel time and travel cost, [27–30]. To reduce the flow of freight vehicles in the city (and, in the same time, reduce the travel costs) some authors propose the introduction of an intermediate warehouse [31,32], where the freight is collected (i.e. from the producers) and when delivered (i.e. to the retailers). This warehouse can be view as a logistic hub associated with various functions (storage, de-consolidation, package…). The literature on logistic hub is, in general, related to location, size, management [20]. The problem is formulated in order to minimize the costs (travel costs to reach the end-users, operative costs and so on) reaching all the end-users [33,34]. Commonly an Urban Distribution center (UDC) is a logistic hub where several senders can store the freight waiting to be delivered to end-users, contributing at the reduction of vehicle travel time, emissions, and environmental impacts [35]. Following the classification of city logistics measures provided by Russo and Comi [26] the UDC is a physical infrastructure requiring also immaterial, equipment and governance measures, connected with the infrastructure characteristics [3]. The introduction of an UDC modifies some aspects in freight distribution in terms of vehicles, routes, fuel consumption, pollution, costs [36]. An analysis of cost-benefits of the UDC relies with different aspects [37, 38]: physical and organizational characteristics of the UDC (size, location, and provided services), UDC governance (e.g., public or private), type of freight (e.g., perishable or not). The effects of the introduction of an UDC are reported in [39] that consider the air quality, the travelled distance, the number of freight vehicles in the city. Other aspects analysed in literature are related to the retailer's behavior in introducing an UDC [40], the UDC location and size [34], the UDC management [41].

When the freight is stored in the UDC, it is necessary to design the distribution in the urban area: the problem can be expressed referring to the VRP, assuming the UDC as the central depot for urban distribution. The VRP was firstly introduced by Dantzig and Ramser [42] in a seminal paper, solving the problem to optimize the routes of a gasoline trucks fleet. Various methods are possible to classify the VRPs, the main are based on solution approach [43] or on problem type [44]. Without presuming to be exhaustive, follow some works from the literature referring mainly to the cost involved in the problem.

Considering the cost variables involved in the problem (generally travel time and monetary cost), some authors introduced environmental costs and energy consumption. Suzuki [45] proposes an approach to minimize the fuel consumption and the pollutant emissions linking the consumption with the vehicle load and optimizing the route so that the heavier freight is unloaded first. Kopfer and Kopfer [46] propose an Ecologically Oriented VRP (EOVRP) with the aim to minimize CO_2 emissions. Ćirović et al. [47] propose a neuro fuzzy model to design the routes of freight vehicles in urban areas to guarantee the service minimizing operative and environmental costs (air pollution and noise level). Kwon et al. [48] propose a carbon emission based heterogeneous vehicle routing problem (C–HVRP) with the aim to minimize the sum between operation costs and carbon emission costs. Figliozzi [49] introduces the Emission VRP (EVRP) with the objectives to minimize emissions and costs while Conrad and Figliozzi [50] define the Recharging Vehicle Routing Problem (RVRP) where EVs with limited range must serve a set of users and may recharge the battery at certain customer in order to continue the travel. Erdogan and Miller-Hooks [51] introduce the Green VRP (GVRP) supposing that the fuel consumption (and, consequently, the emissions) is proportional to traveled distance; similarly, Kara et al. [52] propose a GVRP linking the consumption with the vehicle load. Bektas and Laporte [53] propose a pollution-routing problem (PRP) where the objective function take into account monetary costs and greenhouse emissions.

The topic addressed in this paper article is related to the description of a case study for last mile logistic where the installation of renewable energy production plants and the urban distribution center are in the same place. In this approach, the same area works as energy and logistic platform.

3. RES plant and charging infrastructures

Generally, there are emissions associated with the majority of electricity production and, when measuring well-to-wheel emissions associated with Electric Vehicles (EVs), the results are not always encouraging. According to the European Directive 2014/94/EU [54] on the deployment of alternative fuels infrastructure, electricity can play a fundamental role in the future of transportation. With the intention of avoid delocalization of pollution emissions, in the case study proposed, the energy needed to EDV is produced entirely from RES [55–57].

3.1. Energy assessments and sizing of the production plant

The production plant was designed to be at the service of different types of vehicles powered by hydrogen and/or electricity. Although having opted for a grid-connected architecture, which ensures greater versatility from an energy point of view, in the preliminary phase the sizing was carried out in order to guarantee autonomously the possible daily missions of a Fuel Cell Hybrid Electric Vehicle (FCHEV) for transporting people and a Battery Electric Vehicles (BEV) freight vehicle [12,58]. For the latter, a daily consumption of between 25 and 50 kWh was initially assumed. During the design phase of the production plant, the analysis of the data relating to the electric Light Commercial Vehicle (LCV) sold on the market led to consider a consumption of between 85 and 217 Wh/km. In the worst case, the plant could thus have guaranteed a daily journey of between 115 and 230 km, sufficient to cover most of the intended use missions for urban goods delivery. With regard to the energy needs of the FCHEV vehicle (reported in this article exclusively to motivate the design needs of the entire system), a daily consumption (by the electrolyser) of not more than 240 kWh was assumed, sufficient to refill two DyneCell cylinders (Dynetekw150) containing each 3.58 kg of hydrogen compressed at 350 bar. Considering preliminary the energy efficiency of FCS in the range $46 \div 52\%$, the energy available to the battery, or to the motor (depending of the operating modes), was estimated to be higher than 110 kWh [12].

3.2. Plant description

Following the indications given in Section 3.1 the plant implemented in the project includes a photovoltaic generator with a power of 100 kW_p and an estimated energy production of 150 $MWha^{-1}$, an energy storage

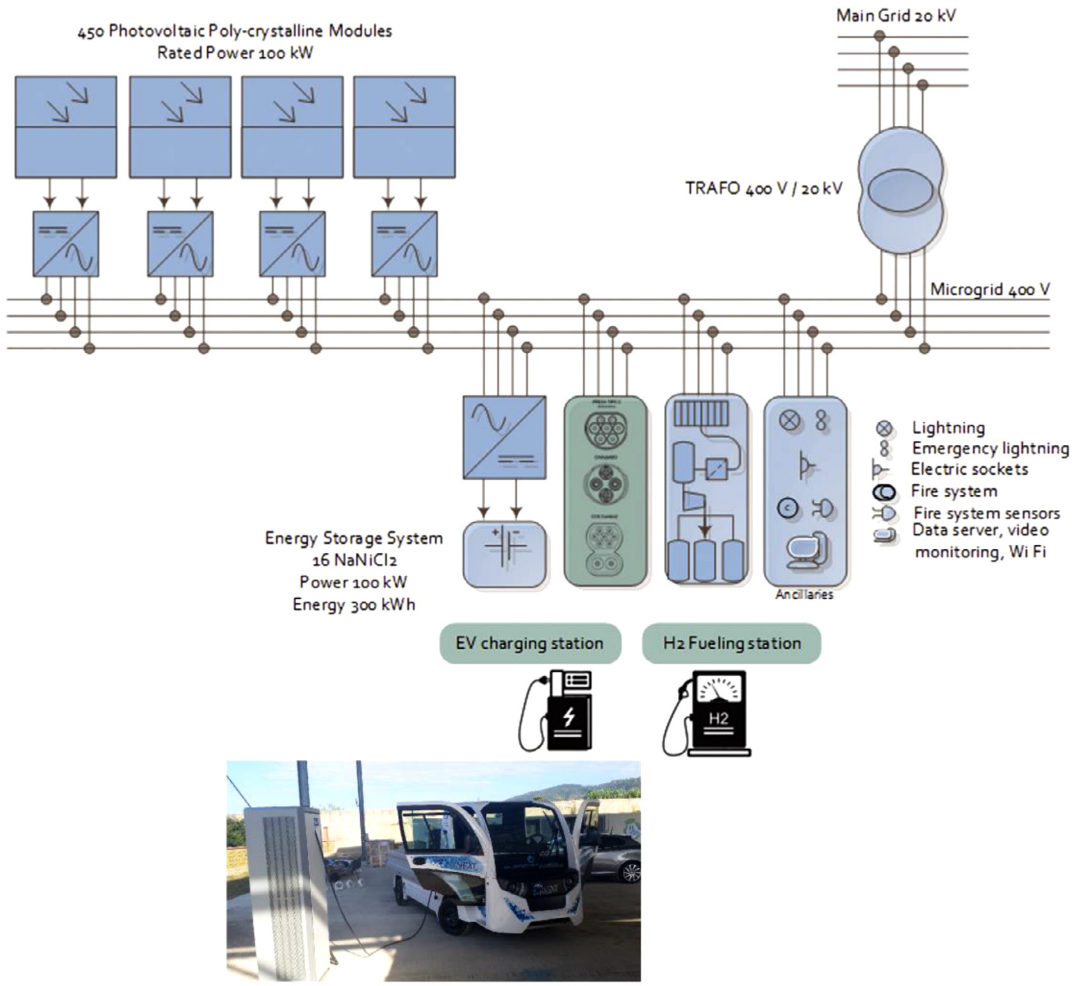

Fig. 2. Electrical block diagram of the refueling infrastructures.

Fig. 3. Photovoltaic plant.

system with a nominal power of 100 kW with a nominal capacity of 300 kWh and an electric charging station that operate with a maximum power of 22 kW (Fig. 2) [59]. Electricity produced supplies both an on-site hydrogen plant (production by water electrolysis, compression and distribution system) and an electric charging station needed for BEV, Fuel Cell Electric Vehicle (FCEV) and (FCHEV).

The photovoltaic plant is installed on the roof of UDC shed used for vehicles recovering (area of 720 m^2). 450 photovoltaic polycrystalline modules splitted into four strings compose the plant (Fig. 3). Each string is connected to an inverter with rated power of 25 kW. The Energy Storage System (ESS) is connected to the micro-grid by a 100 kW bidirectional inverter and 400 V/20 kV transformer is used to connect micro-grid with the main grid.

The Battery Energy Storage System (BESS) is equipped with 16 sodium nickel chloride high-temperature batteries and it is connected through a bidirectional inverter to the 400 Vac micro-grid (Fig. 4). The BEES function is to balance the energy coming from renewables and loads, in order to minimize the energy exchange with the grid and supporting the energy independency of the overall system.

Recharge infrastructures consist of a hydrogen refueling station integrated in the whole hydrogen plant and an electric charging station able to charge in 22 kW AC, 20 kW DC

Table 1
Battery capacity and consumption data relating to the electric LCV sold in the Italian market (category N1).

Manufacturer	EDV	ALKE'	CITROEN	NISSAN	PEUGEOT		PIAGGIO		RENAULT
Model	*New Concept*	ATX340EX	ATX340ED	Berlingo Van Full Electric	e-NV200	Partner Full Electric	Porter ElectricPower	Kangoo Z.E.	Master Z.E. PANEL VAN
Battery Energy (kWh) [Chemistry]	*29,6 [Lithium ion]*	14.4 [Lead Acid] 13.2 [Gel]	14.4 [Lead Acid] 13.2 [Gel]	22,5 [Lithium ion]	24 [Lithium Ion]	22,5 [Lithium ion]	17 [Lead Gel]	33 [Lithium ion]	33 [Lithium ion]
Range (km)	*150*	90	85	170	163	170	110	217	120

Table 2
Vehicle field test paths and energy consumption.

Path	Length [km]	Maximum slope [%]	Load [kg]	Average consumption [Wh/km]	Traction	Reference application
1	14,7	2%	0	115.44	2WD - Front	Urban
2	13	2%	400	143.18	2WD - Rear	Urban
3	11	2%	800	187.43	2WD - Rear	Urban
4	11,6	12%	400	171.72	4WD	Urban/Suburban
5	16,3	12%	800	231.59	4WD	Urban/Suburban
6	34,9	16%	800	268.40	4WD	Suburban
7	4,62	18%	800	307.91	4WD	Suburban

Fig. 4. BESS.

CHAdeMO and 20 kW DC CCS (Fig. 5). On board the Electric Delivery Van an AC power recharge interface has been implemented by a Type 2 connector (IEC 62,196) (Fig. 6).

The daily energy production by solar panels has been estimated as about 600 kWh/day during the summer season and about 200 kWh/day during the winter season [60]. The presence of the BEES and the grid connected architecture guarantee to the plant, together with the production capacity, enough flexibility and ability to respond to the energy needs of both the current electric LCV sold on the market and the EDV created as part of the i-Next Project (Table 1). In particular, tests carried out during the development of the vehicle show that for a complete recharge (from 20 to 100%) of the EDV are required 23.7 kWh (from 20% to 100% of the state of charge) allowing to travel 195.7 km under WLTP test cycle. Field tests show the possibility of covering a fairly wide range (from 77 to 205 km) depending on the type of route and the quantity of goods transported (Table 2)

In relation to the estimation of the costs-gains for energy production a cost analysis for the same plant is performed in [59] in order to highlight the benefits (both economic and environmental) deriving from the exploitation of the plant facility. Considering different cases (e.g. plant grid-connected or not, BESS recharge), a save in the whole electric bill during months from May to August can be underlined. The surplus of produced energy is sold to the main grid, guarantying a gain in these months. In the other months, the surplus of produced energy decrease, in particular in the months of January-February the production may be less than the demand, in this case energy from main grid is required. In conclusion, the plant facility allows to save from the 50% to the 61% of the whole electric energy cost. Furthermore, in terms of environmental benefits, it avoids CO_2 emissions.

4. Freight delivery services

In this section the E-VRPTW (Electric Vehicle Routing Problem with Time Windows) is formulated and the followed solution procedure is described. The proposed procedure allows to solve the problem by minimizing the energy consumption and the travelled distance respect to a set of constraints, particularly, vehicle range and time windows. For these reasons, this formulation could be viewed as a cross between a classical VRPTW and a RVRP (Recharging Vehicle Routing Problem) as the vehicle battery recharge is done before the delivery service (in the RVRP the battery can be recharged also between deliveries) and the time windows are respected strictly.

4.1. Problem formulation

The supply is represented by a graph **G** (**N, L**), where **N** is the set of nodes and **L** the set of links, each link is individuated by an ordered pair of nodes: $\mathbf{L} = \{(i, j) | i \neq j, i, j \in \mathbf{N}\}$. Let $\mathbf{C} \supset \mathbf{N}$ a set including the clients and the depot (in this work, it is identified with the UDC). Each element $r \in \mathbf{C}$ is characterized by a quantity q_r (> 0) of freight to deliver, a time window et_r and a service time ot_r. For the depot, quantity and service time are assumed equal to zero without time window constraint. For each pair r and s of elements belonging to the set **C** it is defined a distance, g_{rs} and a travel time tt_{rs}: the distance will be used to evaluate the energy consumption (also for not overtake the vehicle range), the travel time to verify the time window constraint. The distance g_{rs} is the length of the shortest path k between r and s, computed as the sum of the link length d_l:

$$g_{rs} = \sum_{l} \delta_{lk} \cdot d_l \quad l \in \mathbf{L};\ r,\ s \in \mathbf{C} \tag{1}$$

similarly, the travel time tt_{rs} is:

$$tt_{rs} = \sum_{l} \delta_{lk} \cdot t_l \quad l \in \mathbf{L};\ r,\ s \in \mathbf{C} \tag{1a}$$

where:

$\delta_{l,k}$ is a binary variable equal to 1 if the link l belong to the path k from r to s, 0 otherwise;

d_l is the link length;

t_l is the link travel time.

Fig. 5. Different standards available on the electric charging column.

Fig. 6. Charging phase for the EDV.

In general case, the link travel time depends on the link flow influencing the freight transport service [37]. But, in the study case reported in this paper, the town is sufficiently small to assume that this dependence is negligible.

The objective (Eq. (2)) is to minimize the energy consumption in the tour. It is assumed that the energy consumption is proportional to the travelled distance and not depend from the vehicle load. This second assumption [52] is plausible for light freight vehicles (weight less than 3.5 t). Data filtering will be necessary where deemed appropriate [61]. The value of energy consumption has been evaluated with some road test performed in different conditions, as reported in Section 4.

Objective

$$\text{minimize}\,\boldsymbol{\Theta}(\mathbf{X}) = \sum_{v}\sum_{r}\sum_{s} e_{rs}\cdot x_{rsv}\quad r,s\in\mathbf{C} \tag{2}$$

where:

e_{rs} is the energy request to move from r to s;

x_{rsv} is a binary variable (1 if the vehicle v move from r to s, 0 otherwise).

Constraints

$$\sum_{v=1}^{m}\sum_{s\in\mathbf{C}} x_{rsv} = 1 \quad \forall\, r\in\mathbf{C},\ r\neq d,\ s\neq d \tag{3}$$

$$\sum_{v=1}^{m}\sum_{s\in\boldsymbol{C}} x_{dsv} = m \tag{4}$$

$$\sum_{v=1}^{m}\sum_{s\in\boldsymbol{C}} x_{sdv} = m \tag{5}$$

$$\sum_{r\in\mathbf{C}}\sum_{s\in\mathbf{C}} q_s\cdot x_{rsv}\leq b_v \quad \forall\, v\in\mathbf{V} \tag{6}$$

$$x_{rsv}\in\{0,1\} \quad \forall\, r,s;\forall v\in\mathbf{V} \tag{7}$$

$$et_s\in\left[lt_s, rt_s\right] \quad \forall\, r,s\in\mathbf{C}-\{d\} \tag{8}$$

$$et_s+ot_s\leq rt_s \quad \forall\, r,s\in\mathbf{C}-\{d\} \tag{9}$$

$$\sum_{r}\sum_{s}\left(tt_{rs}+ot_r\right)\cdot x_{rsv}\leq T_{v,\max} \tag{10}$$

$$L_{\min}\leq\sum_{r}\sum_{s} x_{rsv}\leq L_{\max} \tag{11}$$

$$L_{\max}\leq\alpha\cdot AUT_v \tag{12}$$

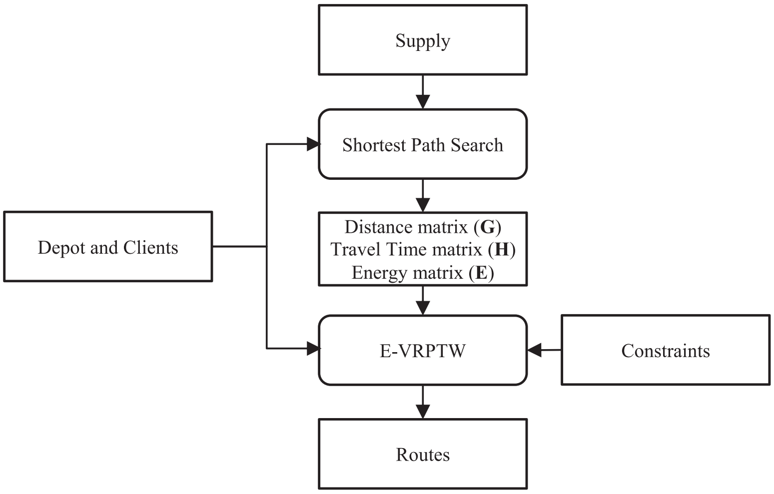

Fig. 7. General workflow of the procedure.

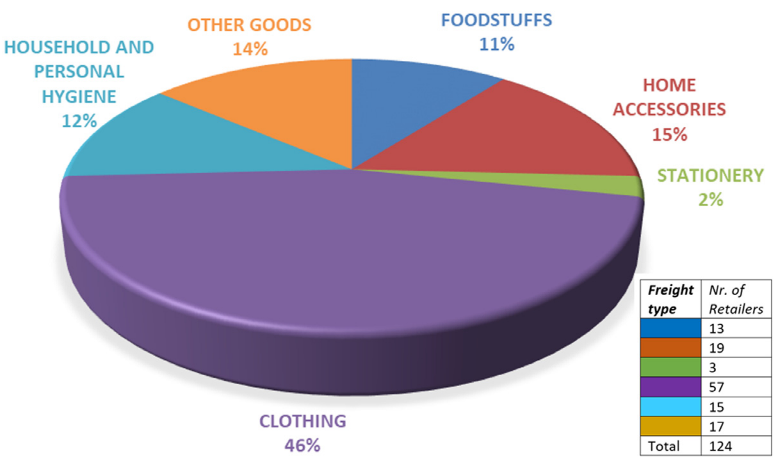

Fig. 8. Retailers distribution in the study area.

where:

q_s is the quantity delivered at node s;

$\boldsymbol{V} = \{1, 2, \ldots m\}$ is the vehicle set;

b_v is the vehicle capacity;

et_s is the arrival instant at node s;

$[lt_s, rt_s]$ is the time window at node s;

L_{min} and L_{max} are, respectively, the minimum and the maximum length of a route;

AUT_v is the vehicle autonomy;

α is a parameter less than 1 to avoid the total discharge of the battery.

The constraint (3) indicates that a node can be reached only once, (4) and (5) impose that the number of vehicles starting from the depot is the same number that return to it, (6) is related to vehicle capacity, (7) indicates that the problem variable is binary, (8) and (9) are the time window constraints, (10) is a constraint on maximum duration of vehicle route, (11) imposes the minimum and the maximum length of a route, (12) refers to the route length respect to the vehicle range.

4.2. Solution procedure

The problem (2) is solved by using the routing/logistics procedure provided by Transcad (Copyright © Caliper Corporation). From literature [65], TransCad is the second most used software to solve vehicle routing problem. The computational method implemented through TransCAD allows finding routes by using the TransCAD vehicle routing procedure, including restrictions on the time, on the total route length and duration [66]. This method requires as input a vehicle routing matrix (a matrix containing the distance/energy consumption and the travel time between the depot and the stops and between each pair of stops) and a vehicle table where fleet numbers and capacities are stored (in our case, just a vehicle type) and give as output the route performed by each vehicle and a list of the stops on each route [66]. TransCad is a GIS equipped with a routing problem solution feature with unlimited numbers of vehicles and users to visit, allowing modification of link cost functions and providing graphical outputs. TransCad makes it possible to evaluate distances and travel times based on the current shape of the road network (guarantying the accuracy of the solution), considering also that it is able to solve problems of (virtually) any size the choice of this software seems valid.

Fig. 7 shows the general workflow of the procedure: starting from the supply (road network), a shortest path algorithm (takes as input the supply, the set of clients and depot) allows to obtain the distance matrix **G**, with entry g_{rs} (as in Eq. (1)) and the travel time matrix **H**, with entry tt_{rs} (as in Eq. (1a)). A skim of the distance matrix **H** is the energy matrix **E**, with entry e_{rs}, (in our assumptions, it is proportional to the distance matrix **G**). We would highlight that there are other cases (i.e. considering the congestion or the variations of vehicle weight due to the unload process) where consumption must be evaluated with other approaches. With the distance matrix, the client set and the depot position, the E-VRPTW allows to obtain the routes taking into account the constraints Eqs. (3)–((12)).

5. Application

A test application has been made in Capo d'Orlando, a city of about 13,000 inhabitants (about 40,000 in summer) located in Sicily (South Italy).

Fig. 9. Geographic location of the UDC.

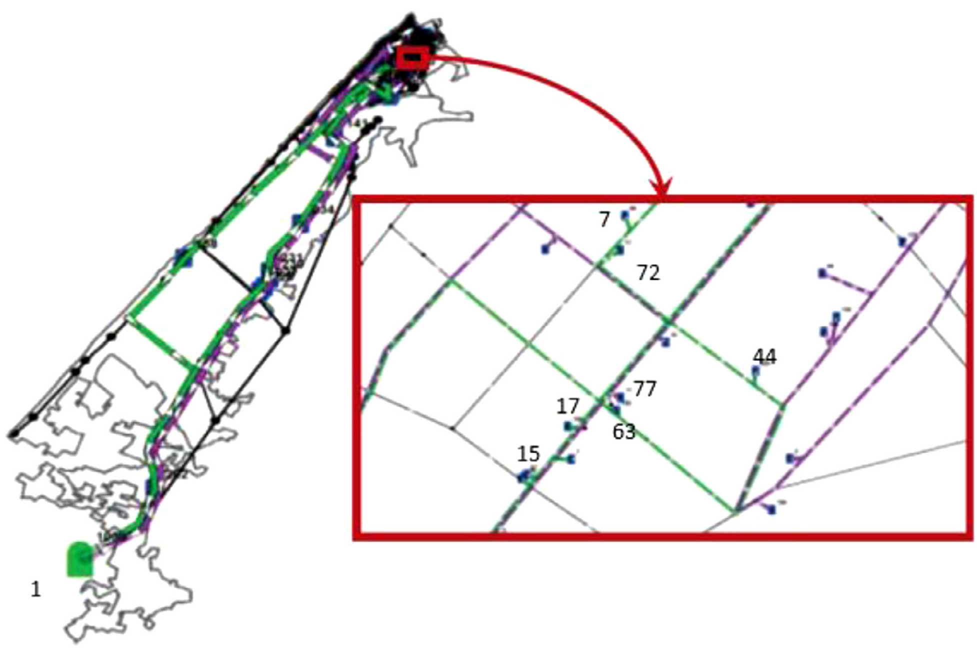

Fig. 10. Example of routes.

5.1. Study area

To perform the simulation of the freight distribution in a typical day, the retailers in the study area are identified and distinguished by type of freight purchased considering six classes of freight are considered [62]. Fig. 8 shows the number of retailers in the study area in relation to the freight type.

The number of considered retailers in the study area is 124, but because of them are very close, when possible are grouped. In this way, a set of 84 delivery point are located; note that in the following to indicate a delivery point is used the term “retailer”.

Actually the freight transport in the experimental site is performed by carriers that use depots located in Messina (about 80 km), in Catania (about 180 km) or in Palermo (about 140 km), using often vehicles weighing more than 3.5 t. The city is mainly reached by using the highway (the interchanges H1 and H2 are reported in Fig. 8).

The UDC (Fig. 9) is localized outside of the study area and it is linked with the road network by means the ways “SP148” and “SS113”. The position of UDC allows reaching all the retailers in the study area, the mean travelled distance is of about 4.83 km, the minimum of 0.91 km, the maximum 6.10 km. In the UDC suitable areas have been considered to stock the freight, to recover the vehicles and for the RES plants.

Table 3
Vehicle service.

Route	Total Time [s]	Distance [m]	Q [kg]	Cost [Wh]	Clients number
1–73–20–21–1	1998.38	11020.60	168.59	2353.23	3
1–9–10–12–1	1960.45	10565.43	177.15	2256.04	3
1–64–55–54–1	2024.29	11331.53	160.92	2419.62	3
1–69–11–13–14–15–17–63–77–44–72–7–51–50–48–56–1	6415.24	12182.88	182.03	2601.41	15
1–45–47–49–8–1	2280.12	10081.41	171.29	2152.68	4
1–6–71–70–53–1	2031.71	7100.49	171.29	1516.17	4
Total 1	**16710.20**	**62282.34**	**1031.27**	**13299.15**	**32**
1–2–3–29–68–31–84–81–34–35–1	4268.21	12338.54	187.70	2634.65	9
1–5–4–85–33–83–67–27–28–57–32–82–1	5052.49	13109.93	188.08	2799.36	11
1–79–22–23–24–80–26–25–30–36–37–66–59–61–62–58–65–74–75–46–1	7586.88	13282.51	130.85	2836.22	19
1–41–78–38–39–40–43–42–16–19–76–60–18–52–1	5379.86	12718.31	189.33	2715.74	13
Total 2	**22287.44**	**51449.29**	**695.96**	**10985.97**	**52**
Total	**49503.73**	**113731.64**	**1727.23**	**24285.12**	**84**

Table 4
Estimation of the emission saved by the use of the proposed vehicles.

CO [kg]	NO_x [kg]	VOC [kg]	PM_{10} [kg]	$PM_{2.5}$ [kg]	CO_2 [kg]
7.6	26.6	2.2	2.1	1.8	2840

5.2. Freight distribution simulation

In this simulation, the energy use is correlated with the travelled distance and the vehicle gross weight, considering also the energy recovered by the regenerative braking. With this assumption, the problem formulation (2) can be re-written as:

$$\text{minimize } \mathbf{\Theta}(\mathbf{X}) = \sum_v \sum_r \sum_s e_{rs} \cdot x_{rsv} = \gamma \cdot \sum_v \sum_r \sum_s g_{rs} \cdot x_{rsv} \quad r,\ s \in \mathbf{C} \quad (13)$$

where γ is the unitary energy consumption. By following a very conservative approach, γ has been set to 213.5 Wh/km, calculated as the average consumption measured on field (see Table 2) increased by 5%. The use of EV reduce to zero the emissions imputable to the vehicle travel, when the energy is produced by RES as in the case study reported, but it is anyway necessary the optimization of the vehicle routes in order to minimize the energy consumption (and hence the costs linked with the energy production). In the following it is performed the vehicle route optimization solving the problem (13).

In order to evaluate the amount of space occupied by the freight on the vehicle, it is introduced the volumetric weight [63].

Table 1 resumes some results obtained optimizing the vehicle routes (an example in Fig. 10). The UDC is labelled with *1*, and the other labels (from *2* to *85*) indicate the retailers. The solution of the optimization problem gives ten routes in order to perform the service respecting the constraints. The routes can be grouped and assigned to a vehicle respecting the constraints (10) on the maximum driving time and (11) on the vehicle autonomy. Fig. 10 shows an example of routes. With these considerations, two vehicles are sufficient to guarantee the service; the results are reported in Table 3 indicating the total time (travel time and operation time), the travelled distance, the quantity delivered, the energy spent and the number of retailers in the route. The plant described in paragraph 3 is suitable for guaranteeing sufficient energy to charge two EDVs (47.4 kWh from 20 to 100% of state of charge). It is assumed that the loading operations at UDC are 15 min (vehicle technology allows it).Fig. 7 General workflow of the procedure

A gain in terms of emissions, coming from other project activity, is summarized in Table 4, where is reported an estimation about emission saved in a year by the use of the EDV compared to the use of conventional vehicles [64].

6. Conclusions

This article analyses the potential of sustainable logistics through an overall scenario. After the description of the innovative features of the EDV, designed to be suitable also for suburban applications, a case study related to the realization of a plant for the production of electrical energy from RES functional to the service for the freight transport within the last mile is presented in the article. The optimization of freight distribution in an urban area through E-VRPTW has been introduced in order to design the routes. The goal has been to offer a technical scenario on the real feasibility of a zero emission supply chain for sustainable logistics. The role of charging infrastructures has been highlighted by emphasizing the ability to produce the energy required for propulsion from RES through a plant located in the same area of UDC. In the case study introduced the role of the UDC is therefore twofold: guarantees a space for unload-consolidation/deconsolidation-load for the freight and provides a space to produce energy avoiding the delocalization of pollution emissions. To perform the simulation, the retailers have been identified and distinguished by type of freight purchased. However, the study area, within the Capo d'Orlando municipality (Sicily, Italy), has been divided into 8 zones each of which takes into account the differences in the types of freight to distribute. The routes have been optimized minimizing the energy. As results has been calculated that the deliveries in a typical day can be made in about 13 h, traveling for 114 km and spending about 24.285 Wh. Taking into account the problem constraints, it is emerged that the service could be made with two EDV. An estimate of the emissions saved compared to the use of conventional vehicles was also reported.

Future developments about proposed E-VRPTW concern the specification of a more detailed energy consumption function depending simultaneously on travelled distance, road characteristics (i.e. slope) and interaction with the other vehicles on the road.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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