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Abstract:

The major priority of the carmakers is to reduce the energy consumption and the emissions of the future passenger cars and to deliver an efficient mobility service for the customers. The number of electrified vehicles increases in the mobility market. The range and the energy storage of the vehicle on board are important. The recharging of the vehicles and their connection to the energy grid became an important question. In this article, the energy system is extended and includes the energy storage and conversion of vehicles and their connection to the grid. The extended energy system is modelled on vehicles flows on the highway and a single objective optimization is performed to define the optimal energy storage capacity of the vehicles and the optimal number of recharges of from the grid. The time and the occupation rates of the chargers are as well evaluated. The optimality is researched for long way drives on electric mode. The results illustrate a method to rethink the usage and the energy management on the vehicle during the driving. As well it is researched how to adapt the recharging capacities and their location on the grid, by using a holistic approach. The target is to propose a high quality service for the electric mobility for long way drives.

Keywords:

Electric vehicles, Charging infrastructure, Long way electric mobility, Smart energy system, Single objective optimization

1. Introduction

Decarbonisation and emission reduction from road transport are the main drivers for the electrification of the vehicles. Around 2030 electric vehicles are expected to increase their market penetration and to bring evolution concerning the main technologies for energy storage, conversion and energy management [1] and connection with the electricity grid. Several scenarios are researched through simulation and optimization studies to build viable energy planning for the massive integration of the electric vehicles in the energy sector.

The authors present in [2] a significantly improved optimization model for the planning of the charging infrastructure for electric-drive vehicles, where the optimization objective function is the minimization of overall (installation, maintenance, operation) placement costs of charging stations. The constraints involve the electric power system reliability check, ensuring charging reliability and the required quality of service of the charging infrastructure. The study illustrates numeric results for the optimal charging stations placement layout and overall costs placement for different driving ranges and the required quality of service level by including a power system reliability check. The results are useful for the charging infrastructure investors and electric power system operators. The authors made in [3] the analysis of economic implications of innovative business models in networked environments for electro-mobility. Mainly the high investment cost for the EV and for the infrastructure are difficult points in the economic model. The research question that is investigated in [4] is where to install the charging stations to facilitate the long-distance travels and to meet the urban (local) demands considering both the existing stations and the installations are to be realized by legal regulations. The study in [5] introduces a multistage chance-constrained stochastic model for strategic planning of battery electric vehicle (BEV) inter-city fast charging infrastructure. A mixed integer programming model is developed to determine where and when charging stations are opened, and how many chargers are required for each station to meet the growing BEV inter-city demand. The optimization problem is solved by genetic algorithm. This study showed that investment in inter-city charging infrastructure is vital to alleviate the range anxiety. Other conclusion is that planning decisions depend on many factors, such as the design level of service and the vehicle range. The work in [6] established a mathematical model to optimize the layout of charging infrastructure based on the real-world driving data of 196 battery electric vehicles. The work have studied the connection of the number increase of charging points and retention rate. When the number of charging points increased from 60 to 220, the retention rate was 97% for slow charging and 95% for fast charging.

The authors developed a stochastic model in [7] that includes driving and charging behavior of BEV owners in Japan. The model is based on Monte Carlo methods and was implemented in MATLAB. They conducted simulations with this model to find out whether the existing infrastructure is adequate for the charging of a large number of BEVs. The results indicate that Japan has 6 fast chargers for 100 electric cars and for this ratio - on average -, waiting probability at DC (direct current) fast chargers ranges lower than 5%, which is an acceptable value for BEV owners. The literature review shows that different simulation and optimization methods are used to optimize the energy planning and the resources and EV charging infrastructure distribution. The BEV charging infrastructure is characterized with high investment cost and impacts on the electric grid. For this reason, optimal techno-economic optimization for planning of the energy systems is needed.

The scarcity of not only fuel resources but also the adverse effects of the operation of energy intensive systems on the environment (pollution, degradation) have to be taken into consideration. Thus, the system can be properly designed and operated. The systematic consideration of thermodynamic, economic and environmental aspects for this purpose is called environomics [8]. Environomic analysis is an extension of thermo-economics [9]. In addition to flows of energy, exergy and costs, flows of other resources consumed as well as flows of pollutants enter in the picture. Environomic design of electric and hybrid electric vehicles are studied in [10] and [11].

The novelty of the present study is the modelling and the application of the single optimization methodology for optimal design and operation parameters of the vehicle energy system to an extended energy system. The optimization manage the minimization of the vehicles waiting time on the charging stations. On that way the relation to the energy grid, is considered, as well. Methods, techniques to analyse, improvement and optimizations of energy systems have to deal with not only the energy consumption and economics of the electric vehicles, but also with the availability and the distribution of the charging infrastructure. The target is to propose strategies to manage the recharging plan of the electric vehicles for long way trips.

2. Methodology

The developed prospective method serves to evaluate different options for the vehicles and the recharging technologies related to the density of the recharging installation and the investment capacities. A technical evaluation is given for considered vehicles and recharging technologies. The method includes the mapping of the charging stations on the driving ways and also the information management of the charging grid, considering the need of the vehicles.

The developed methodology combines models of recharging and vehicles conversion and storage technologies, in a computational platform. In a first stage a single objective optimization techniques are used to explore the superstructure possibilities and to find the optimal charging plan solutions. The master optimization is done by using a genetic algorithm and mixed integer nonlinear programming. Such an integrated approach is innovative in comparison of the traditional heuristic design engineering method, based on iterations of designs and their cost evaluation. The method proposes optimized usage strategies of the electric vehicles to maximize their range, especially for the long way drives and to minimize the waiting time for recharge, in consideration of the available charging infrastructure.

The developed method allows rethinking the usage and the energy management on the vehicle during the driving but also to adapt the recharging capacities and their location on the grid, by using a holistic approach. The energy system has to consider the vehicle and the recharging technologies, the economic and the environmental models of the technologies and the electricity mixes. Figure 1 shows the energy system definition, where the vehicles are related to the energy grid.

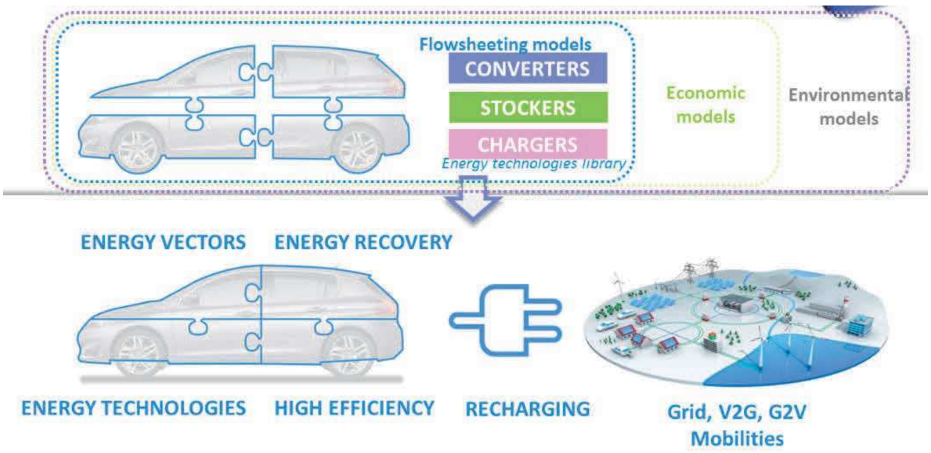

Figure 1. Energy system and holistic design method.

Figure 2 illustrates the generic computational framework for optimization of the extended and integrated vehicle energy system. The superstructure contains the simulation models and the optimizer. The optimizer is based on a genetic algorithm. The set of decision variables includes the types and the size of the equipment.

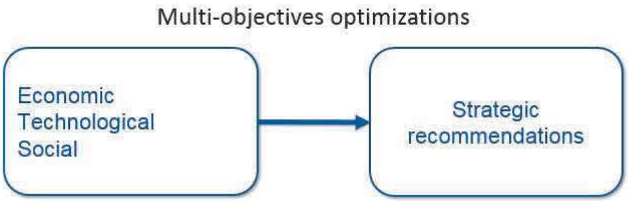

Figure 2. Multi-objective optimization framework.

The optimization is solved by an algorithm with the objectives of the minimization of the energy consumption from the grid during the charging, the minimization of the waiting time and the recharging time on the charging stations (Fig.3) .The optimization results converges to solutions represented in Pareto curves.

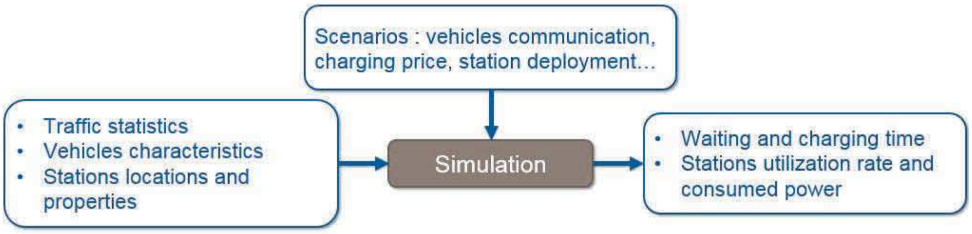

Figure 3. Computational framework of technical simulation for vehicle energy integrated system.

3. Results- single objective optimization

3.1 Problem definition

The vehicle is considered as a part of the electric grid, when is in charge to fill its high voltage battery. For optimal operation, the battery state of charge is considered variable between 30% and 80% of the total battery capacity. In some cases the vehicle should fulfill the entire battery, in some other cases a given percentage of the battery. The problem of the energy demand and supply of the electric vehicles on the highway has to be modelled and optimized. Figure 4 introduces the graphical representation of the highway and the recharging infrastructure.

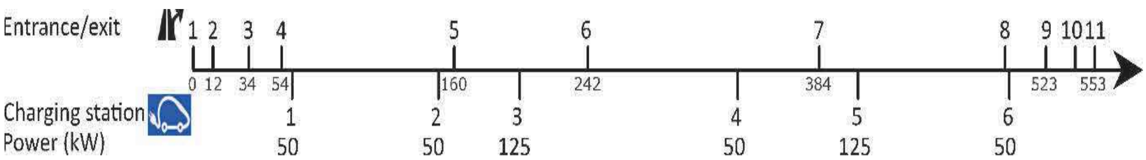

Figure 4. Highway with charging stations installations.

The charging stations characteristics located on the road are given in Table 1:

Table 1. Initial charging stations characteristics

Localization of the station (km)	Power output (kW)	Number of chargers
60	50	1
150	50	1
200	125	1
334	50	1
408	125	1
501	50	1

The charging stations are located on different spots and the distance between them is not equivalent. The electric vehicles have different battery capacities stored on board (100 kWh, 60 kWh and 41 kWh). These capacities correspond to future electric vehicles deployed on the markets. The recharge of the vehicles on the highway is considered to occur between 15% and 80 % of the State of charge (SoC) of the high voltage battery. The recharging power is high and it is not recommended because of the durability of the battery to full the battery on fast charging. The battery can be fully recharged in the home installation, which are with charging powers lowers than 50 kW. The vehicles have to quit the highway with at least 20% of the state of charge (SoC). To recover this condition of minimum SoC when leaving the highway, the vehicles have to stop on the closest recharging station.

The flows of the electric vehicles entering on the highway are characterized with the following types, described in Table 2:

Table 2. Vehicles types for the flows constitution

Parameters	Vehicle type 1	Vehicle type 2	Vehicle type 3
Battery capacity [kWh]	100	60	41
Minimal SoC [-]	15	15	15
Maximal SoC [-]	80	80	80
Power of charge	125	350	44
Electric consumption [kWh/100km]	18	15	15
Max speed [km/h]	130	130	110
Final SoC required (Quitting the highway) [-]	20	20	20

Here one starts with the modelling. Figure 5 presents the study case that considers the modelisation. A fleet of electric vehicles enters on the highway. The vehicles have different levels of charging of the batteries and different capacities, all vehicles want to perform long drives (> 500 km). The road has different gates with numbers (1 to 6) (Fig. 4), which allow the vehicles to leave the highway. Charging stations are located along the highway – A, B, C (Fig.4). The vehicles can stop on the charging stations and charge fully or partially their batteries. The following simulation is after that applied.

The inputs in the described model are:

- the battery capacity of the electric vehicles: Q_{bat} in kWh
- the maximal power of the charging: $P_{charging}$ in kW
- the number of the In-/ Outcomes from the highway: N_{in}, N_{out} in [-]

- the SoC of every electric vehicle on the Income: SoC_{in} , in [-]
- the SoC of every electric vehicle on the Outcome: SoC_{out} , in [-]
- the departure time of every vehicle, $t_{departure}$ $t_{departure}$ in [h]

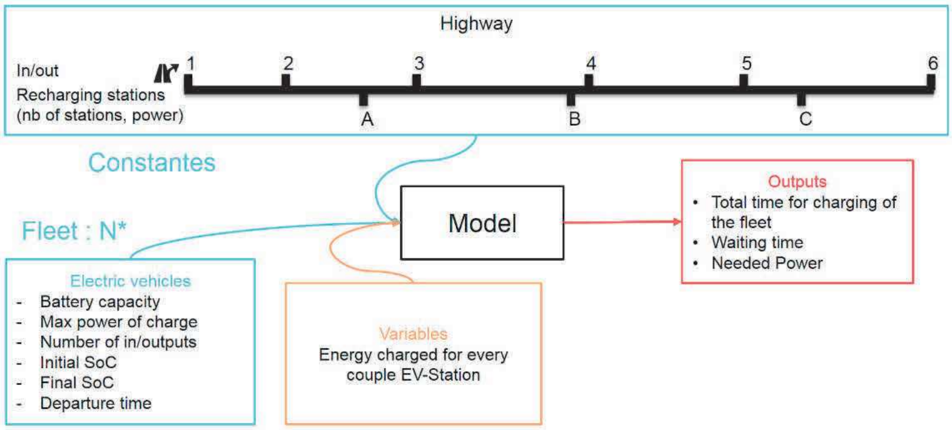

Figure 5. Charging on the highway: use case for long way drives.

The variable is the quantity of the charged energy for every vehicle and for every station. The charging energy is different for every couple electric vehicle- charging station, and depends on the quantity of the compensation of the SoC difference between the initial and final state of the vehicle.

The outputs are:

- the total time of charging of every vehicle to run the distance, $Time_{charging\_i}$ [h]
- the total time of charging for the fleet, $Time_{charging\_fleet}$ [h]
- the waiting time for every vehicle, $Time_{waiting\_i}$ [h]
- the needed power for every station and for the highway $P_{charging\_i}$ in [kW]

The objective is to evaluate the power that is needed to be delivered by the charging stations, the waiting time and the total time of charging as a function of the vehicles numbers in the fleet and the distance to run. The optimization is performed according to the following criteria:

- minimize the energy quantity of the charge , $E_{charging}$ in kWh
- minimize the number of stops, N_{stops} in [-]
- minimize the waiting time, $Time_{waiting\_i}$ [h]
- minimize the investment cost of the infrastructure, $Cost_{investment}$ in [€]

The flow is considered optimal if the vehicles charge:

- the minimal quantity of charged energy, $E_{charging}$ in kWh
- with the minimal number of strops, N_{stops} in [-]

- minimizing the waiting lines, $Time_{waiting\_i}$ [h]

Thus, the optimization problem is defined in (1) as:

$$\min(Time_{waiting}(x)), x \in X_{decision\_variables} \quad (1)$$

The decision variables for the powertrain design are defined in Table 3:

Table 3. Decision variables for powertrain design

Decision variables for design	Range
Number of charging stations [-]	[1-6]
Number of chargers per charging station [kW]	[1-150]
Charged Power [kW]	[0-350]
SoC per vehicle [%]	[20-80]

3.2 Results of the optimization

Optimization of the waiting time is performed for a flow of 10 electric vehicles, driving on the highway (2):

$$\min(Time_{waiting}(x)), x \in X_{decision\_variables}, 10\_Vehicles \quad (2)$$

The flow is composed of 10 vehicles. The random function of Matlab is used to distribute the vehicles, their battery capacity and state of charge, the numbers of in-/out-comes from the highway and the time of their entrance. The random generated traffic configuration is summarized in Table 4. The highway disposes with 6 chargers, disposed according to the Figure 4.

Table 4. Electric vehicles flow on the high way – 10 vehicles

Vehicles number	Battery capacity	Number of the Incomes [-]	Number of the Outcomes [-]	Initial SoC (entering to the highway)	Time of entering (h)
1	100	7	10	70	6,49
2	60	1	10	96	7,50
3	41	3	10	90	8,15
4	41	2	9	100	8,62
5	60	1	3	82	9,10
6	100	3	4	58	10,19
7	41	1	5	58	11,19
8	41	2	10	80	11,23
9	60	5	7	96	11,75
10	100	1	10	64	11,90

The results of the minimization of the waiting time are given in Fig. 6. For this configuration of the traffic with 10 vehicles and 6 chargers on the road, the vehicles do not need to wait to recharge their batteries. The available charging infrastructure is enough to cover the recharging needs. Figure 6a represents the evolution of the State of charge (SoC) of each vehicle as a function of the time on the highway. When the vehicles are traveling, the SoC decreases. The charging periods of the highway stay are marked by the increasing of the SoC of the vehicles. The charging periods have different time durations, and deferent slopes. That is directly related to the battery capacity (Table 4) and the power of the charger (Table 1). There are different cases of trips. The trips represented on the Figure 6a are all optimal. They present minimal waiting time, minimal number of stops and minimal charged energy from the grid. According to the trip that they have to do, and their initial SoC, some vehicles enter, drive and quit the highway without any stops. This is the case of vehicle 1 and vehicle 9. The slope of discharge of their batteries is deferent, because the different capacity of the batteries on board. Both of the vehicles drive at 130 km/h of speed. Vehicle 1 has 70 kWh of energy in the battery when enters on the highway and quits it with 40 kWh. There is no need to stop and recharge the batteries on the highway. Vehicle 9 enters with 57 kWh of energy in the battery and quits it with 24 kWh of battery, which represents 40% of the battery capacity. Thus, in the case of vehicle 9, there is no need as well to stop and recharge on the highway. Vehicles have to stop in average 2 or 3 times to recharge, according to their battery capacity and the long distance trip that they have to perform. Figure 6a shows as well that the random flow of 10 vehicles stays on the highway for a total time of 11 hours. From illustrations on the Figure 6b one can see that none of the vehicles wait for an available charger. They arrive and can start to recharge without having queue length. Figure 6c shows that the Queue length is zero for all the chargers on the highway.

The time spent on the highway for each vehicle depends on the trip time, the waiting time to access the charger and the recharging time. Figure 6d illustrates the ratio between the stops time to the trip time for every vehicles. The ratio is defined by (3):

$$r = \frac{Time_{waiting} + Time_{charging}}{Time_{trip}} \text{ [-]} \quad (3)$$

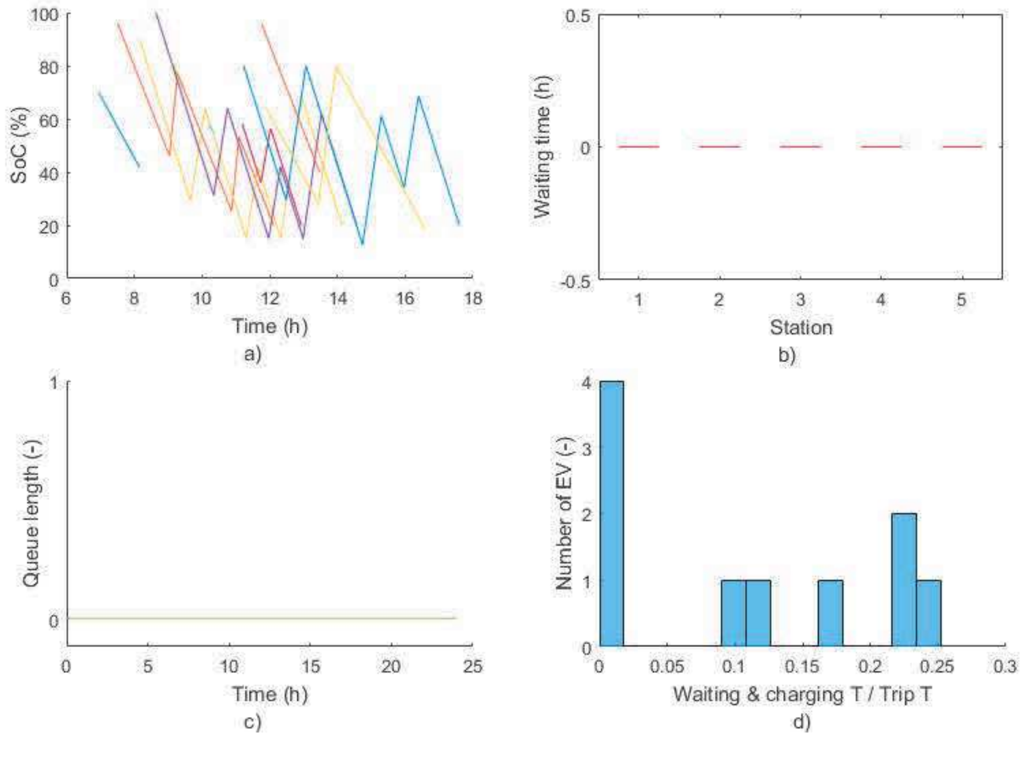

Figure 6. Results from the optimization: flow of 10 vehicles, minimization of the waiting time.

Figure 6d shows that four vehicles are characterized by zero waiting and charging time. One vehicle waits 10% of its trip time to recharge. Other two vehicles are waiting 20% of their trip time for recharging. The maximum of the ratio is reached for one vehicle that spends 25% of its trip time to recharge. This vehicle has battery capacity of 40 kWh and stays for 500 km on the highway and has to stop for recharge at least 3 times.

In order to test the performances of the optimization method, the number of the vehicles in the highway flow is increased to 30. Optimization of the waiting time is performed for a flow of 30 electric vehicles, driving on the highway (4):

$$\min(Time_{waiting}(x)), x \in X_{decision\_variables}, 30\_Vehicles \quad (4)$$

The flow is composed of 30 vehicles. The random function of Matlab is used to distribute the vehicles, their battery capacity and state of charge, the numbers of in-/out-comes from the highway and the time of their entrance. The random generated traffic configuration is summarized in Table 5. The highway disposes with 6 chargers, disposed according to the Fig. 4.

Table 5. Electric vehicles flow on the high way – 30 vehicles

Vehicles number	**Battery capacity**	**Number of the Incomes [-]**	**Number of the Incomes [-]**	**Initial SoC (entering to the highway)**	**Time of entering (h)**
1	60	1	8	80	6,82
2	60	4	9	88	6,95
3	60	2	7	83	7,23
4	41	4	7	75	7,53
5	60	6	9	66	8,01
6	60	6	8	52	8,14
7	41	2	11	86	8,43
8	41	3	11	84	8,66
9	41	2	8	81	8,77
10	60	5	9	90	8,81
11	100	2	11	80	9,06
12	60	1	8	64	9,29
13	41	6	10	92	9,45
14	60	2	11	90	9,49
15	41	6	10	57	9,53
16	41	6	11	57	9,61
17	60	5	8	77	9,72
18	60	1	10	56	9,95
19	41	7	11	60	10,08
20	41	3	11	53	10,27
21	41	2	11	53	10,38
22	60	3	10	74	10,38
23	41	6	11	100	10,49
24	41	1	10	77	10,67
25	41	3	8	66	11,06
26	41	5	11	99	10,10
27	41	7	11	82	11,40
28	41	2	7	88	11,42
29	100	4	11	100	11,44
30	60	1	11	93	11,45

The results of the optimization converge on the results, illustrated in Fig. 7. The vehicles stay 12 hours on the highway. Their batteries are recharged between 20% and 80% of SoC on the highway, with the high power chargers. Some of the vehicles enter on the highway with fully recharged batteries, for that reason their SoC is superior to 80%. In the case of a flow of 30 vehicles and 6 chargers. Some of the vehicles have to wait for available chargers when they stop to the charging infrastructure. The waiting times are illustrated with the flat curves in Fig. 7a. For better visibility of the optimization results, the descriptive statistics are used in the Fig. 7b. The box plot diagrams of the vehicles waiting times are used for every charger station. The box plot diagram in descriptive statistic is a standardized way of displaying the distribution of data based on the five number summary: minimum, first quartile, median, third quartile, and maximum. In the simplest box plot the central rectangle spans the first quartile to the third quartile (the *interquartile range* or *IQR*). A segment inside the rectangle shows the median and "whiskers" above and below the box show the locations of the minimum and maximum (Station 1 and Station 4, (Fig. 7b)) .When the “whiskers” are absent means that the interval of data is important and the minimum and maximum are plotted with markers (Station 2, Station 3 and Station 6). From Fig. 7b one can see the maximal waiting times for every station. For example for the maximal waiting time on the charger on the station 1 is 0,62 h, the maximal waiting time on the charger on the station 2 is 0,9 h (which also the maximal time for the entire flow) and 0,62 h for the charger on Station 4.

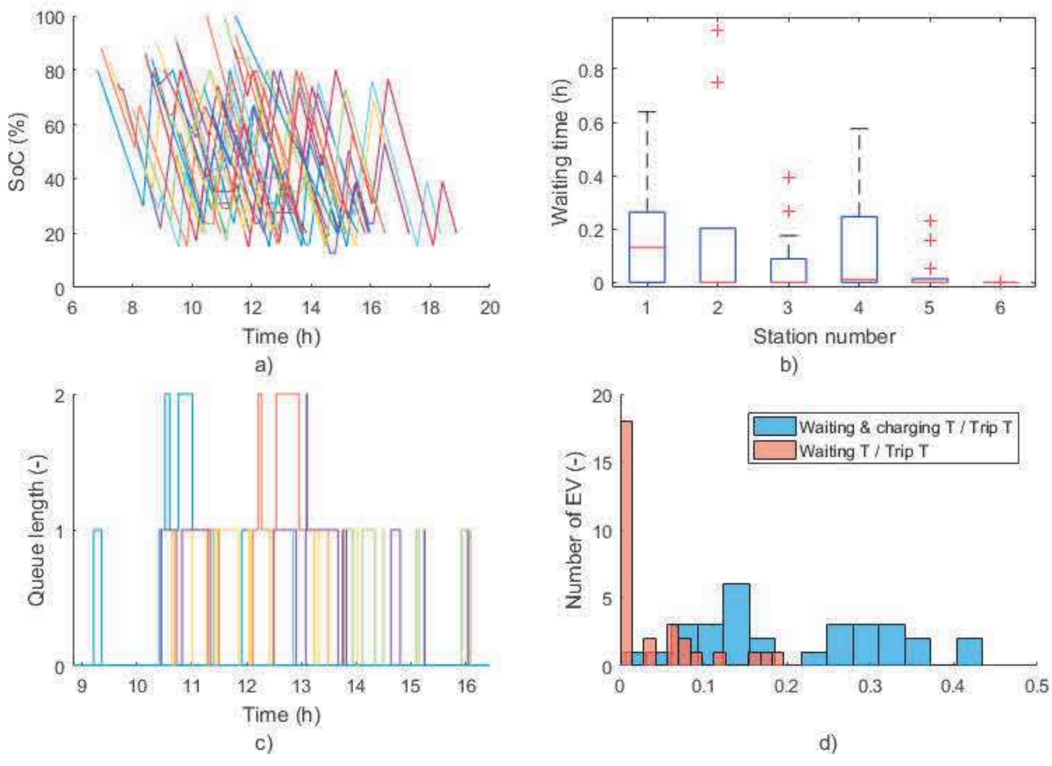

Figure 7. Results from the optimization: flow of 30 vehicles, minimization of the waiting time.

The repartition of the maximal waiting time can be explain by the fact that the chargers on Station 1, Station 2 and Station 4 had the lowest power of 50 kW. They are as well located in the beginning and the middle of the highway, and the number of vehicles is important on that section. The charger 6 has as well the same power of 50 kW but is located at the end of the highway, so the vehicle flow is not important to cause important queue of vehicles. The chargers on Station 3 and 5 have the power of 125 kW and allow charging the batteries on a rapid way.

The queue length as a function of the time is presented in Fig. 7c. One can see that the maximal queue length is composed of 2 vehicles. The waiting times on the chargers are different because the different vehicles have different capacities of the batteries.

Figure 7d illustrates the time repartition from the vehicles point of view. The ratio of the waiting time to the trip time and the ratio of the waiting and charging time to the trip time is illustrated per number of vehicles. One can notice that the maximal ratio of waiting time to the trip time is 0,2. The largest number of vehicles 18, never stops to recharge. The rest of the vehicles waiting are one or two, according as well to the representation in Fig. 7d. The histograms represented in blue include as well the recharging time to the waiting time. The maximal ratio is noted to 0,4. This means that two vehicles spend 40% of their trip time to wait and recharge. The rest of the values are divided between 0 and 0,4 , with maximal number of vehicles 7, sending 15% of their trip time to wait on the queue and recharge their batteries.

The discussed study cases of the vehicles flows (10 and 30 vehicles), illustrates the method and the simulation model, proposed to investigate the long-range mobility with electric vehicles. The results of the study cases show on a didactic way the impact of the vehicles flow density and the consideration of the model of the number of vehicles, the queue lengths to access the chargers on the stations and the time to recharge the batteries of the vehicles. The method allows identifying the frequency and the usage of the chargers. This analysis is useful to reduce the waiting and recharging times of the vehicles the placement of additional chargers can be tested. The investment cost of the charging stations can be as well considered in the decision criteria. The localization of the chargers has to be minimal from investment cost point of view. Techno-economic multi-objective optimization can be introduced to show the trade-off between the optimal number of chargers that have to be introduced to reduce the waiting times, and the total investment cost of the infrastructure.

4. Conclusion

This article presents the developed method and its modeling to find the optimal strategy for recharging on the highway for a flow of electric vehicles, in the case of long-range electric mobility. The flow are composed by different numbers of vehicles that have to travel long range distance on the highway. They have to stop and recharge their batteries on the chargers located on the stations. The model is illustrated with two simple study cases: randomly generated flows of 10 and 30 vehicles. The model simulates accurately the vehicles stops and their recharging strategy to reach the travel targets. The waiting and recharging times are evaluated, considering the stops, the occupation rate, and the location of the chargers. In a first level simple optimization is performed by minimizing the waiting time for charging. The order of the vehicles stops their recharging strategy come out as results. Differential evolutionary genetic algorithm is used to solve the optimization problem. The initial population of the vehicles flows is generated randomly and the genetic algorithm operators (evaluation, selection and mutation) are used to converge to the solutions. The results from the study cases show that an additional number of chargers are needed to be installed to minimize the waiting time on the highway and to reduce the waiting and the recharging time on the highway stops. The investment cost of the chargers and the infrastructure has to be as well considered. Multi-objective techno-economic optimization can be performed to evaluate the optimal trade-off between the waiting time and the investment cost in charging infrastructure on the highway.

Nomenclature

Abbreviations

BEV Battery electric vehicle

SoC State of charge

Q_{bat} battery capacity, kWh

V2G Vehicles to grid

G2V Grid to vehicles

$P_{charging}$ Power of charging, kW

N_{in} number of entrance in the highway, [-]

N_{out} number of gate to quit the highway, [-]

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