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Relationship between spatio-temporal electricity cost variability and e-mobility

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Abstract

Charging cost of electric vehicles depends on the selection of the charging strategy when operating in a spatio-temporal electricity pricing market. In such scenario, selection of the charging strategy can be critical in order to keep the charging cost minimum. Furthermore, a coordination of charging strategies is required to prevent the electric grid from overloading during peak demand periods. Hence, a cost optimization model is implemented for individual travelers in a coordinated context. Individuals minimize their cost and are constrained by power delivery constraints in space and time. The charging strategy optimization applies to the scenario where the electric energy price varies with time and location. When all trips are fixed in time, interesting low cost charging time slots may be unavailable to a particular individual. Hence, in order to charge at such cheap moments, a shift in traveling moments is proposed in this work. Furthermore, a comparison between cost savings and the required agenda adaptations also is discussed in the paper.

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Keywords: Electric vehicle; mobility; electric grid; charging strategy; Relation in charging cost and mobility

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1. Introduction

During recent years, researchers are working to find solutions to integrate the electric vehicles into the electric grid. Electric vehicles can pose huge challenges to regulate the electric grids to balance the demand and production of electricity at different times of the day[1]. When electric vehicles are introduced in the electric grid, variation in electric price can produce sharp peaks in electric demand. To meet the aimed penetration rate of electric vehicles in the market, there are still many open challenges to be solved yet[2]. Driving cost can be reduced using electric vehicles, on the other hand it might increase the CO_2 emissions if conventional electricity generation methods are used to feed the electric vehicles. To reduce the CO_2 emissions, renewable energy is recommended to power the electric vehicles. Like many developed countries, in Belgium, excess of renewable energy production is installed already[3]. Figure 1 shows that the percentage of renewable (solar and wind) power to the overall power production in Belgium on average varies between 3 to 20 percent during summer and between 6 to 12 percent during winter time. Variable electricity cost is advised by the grid operators to balance the electricity demand and supply when renewable power production sources are used. In addition to variable electric energy cost, a coordinated charging scheme is required to elude the electric grid from overloading during high demand peaks. To ensure the fulfilment of grid capacity constraints, a distribution grid model is also required which provides the information about the distribution capacity in each locality.

In this scenario, charging cost of an electric vehicle depends upon the availability of the power at particular location and time, and on the travel agenda of the vehicle. Any possibility to lack power at the required location and time, any change in travel agenda of the vehicle and any change in charging strategy selection will influence the electric vehicle charging cost.

In particular, if a vehicle changes its stop duration at any of its parking locations, it may result in a charging cost difference depending upon the state of the charge of the vehicle's battery. For example, if an electric vehicle is about to depart from a particular location, and it needs another 30 minutes charging to successfully finish its scheduled successive trips, then it has to terminate the charging and leave for the next location where it can restart the required charging. If the vehicle delays the departure from one location to charge the battery for some extended required time, the charging cost can vary. In this work, a relationship between adaptation in starting time of travel and charging cost of the vehicle is explored. A conclusion is presented at the end to demonstrate the found facts about significance of the charging cost variation and change in travel starting time.

An activity-based model FEATHERS is used to generate the travel demand; it is described in section 3. A framework, described in detail in section 4, modeling a synthetic power grid is used to incorporate the grid capacity limitations. Section 6 describes the details about the adaptation of travel starting time of the vehicle. The comparison between charging cost variation and travel starting time difference is described in section 7.
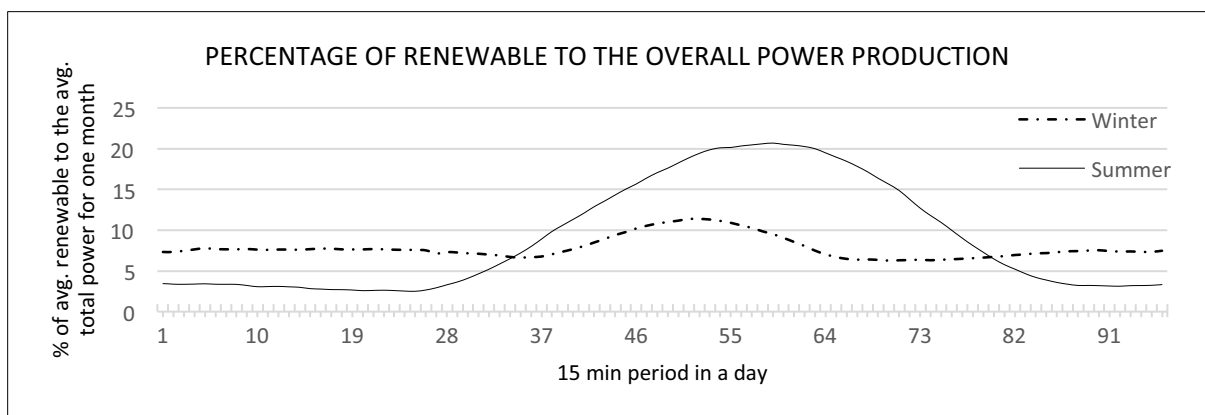

Figure 1 Percentage of renewable to the overall Power production

2. Background

The framework, presented in previous work[4], plans the charging strategy for electric vehicles. This planner requires the information about price of the energy at each time of the day and scheduled trips for the vehicle. For each trip, information about the distance to travel and the destination location is required. At each destination location, when the vehicle will be parked during the stopover i.e. at home, work, shopping, leisure etc., the planner requires following information about charging point at that particular location:

1- Availability of a charging point at that particular location,
2- If a charging point is available, what is the charging power of the charging switch?

Using all the required information, the planner devises a charging strategy for the vehicle for the next planning horizon. In this work, a 24 hour period is used as planning horizon. Charging strategy optimizer takes into account the energy prices at each time unit, the vehicle's energy consumption rate, the vehicle battery constraint and the power rating of the charging points. The previous framework uses the total renewable power (solar and wind) production at each time unit to test the simulations without accounting for grid power capacity constraints.

The new framework, extends the previous work to integrate the grid power capacity constraints in the charging optimization process. Details about the estimation of regional demand in Flanders, Belgium are described in section 4. The new framework enhances the charging planning procedure presented in previous work. In this work, travel agendas are shifted over the time to find a more efficient charging strategy which results in less charging cost. Then, a relation is drawn between shift in time and charging cost difference.

3. Activity based model to predict the daily schedules

The presented framework assumes that all EV owners know their traveling agenda prior to start the charging strategy optimization process. The FEATHERS activity-based model is used; it predicts the travel agendas for the complete population of the study area. FEATHERS is a large scale activity-based modelling framework which predicts the daily agendas for complete population of Flanders (Belgium)[5]. FEATHERS predicts the agenda containing the details of each trip for the given day for each individual.

The daily agenda of each individual starts after the last home arrival from the previous day and ends at the last trip to home for the current day. Each tuple of the predicted trip contains information about origin, destination, start time, duration, travel mode, and the type of the activity. Activity types are: home-activity, work, leisure, shopping, pick/drop, or social visit. EV specific travel schedules are distinguished from regular car transportation trips as they cover a predefined maximal distance between charging opportunities. To test the proposed framework, the FEATHERS predicted EV schedules are used as input data. FEATHERS predictions have been used in a previous work to calculate the electric power demand generated by EV charging for each zone in Flanders as a function of time under several charging behaviour scenarios, EV market share and charging opportunity (at home, at work) assumptions[6].

Like in FEATHERS, study area in this work covers the Flanders region in Belgium. The area of Flanders is divided into small 2386 Traffic analysis zones (TAZ) having on average 5 km^2 area each.

4. Description of the disaggregation method of the existing background electricity demand

In order to assess the impact of electric vehicles (EVs) charging on the electric grid at regional level, it is necessary to have a detailed information about the total electricity demand in each traffic analysis zone.

Unfortunately, only national aggregated time-depending electricity consumption is available, and it is necessary to disaggregate this demand spatially for each TAZ, using a procedure similar to the one proposed in report[7].

Firstly, the total electric demand for Flanders region is obtained by weighting the national demand for the whole country (obtained from Eli – Flemish power transmission operator's website[8]) by a scaling factor proportional to the Flanders population.

This total demand for Flanders is composed by two components and must be disaggregated for each TAZ. These components are:

- Domestic load demand per TAZ.
- Additional electric load demand per TAZ.

4.1. Domestic load per TAZ evaluation

To estimate the domestic load demand for each TAZ, it is necessary to evaluate the number of households per TAZ and then assign an average electricity consumption per household. The population available in each TAZ is obtained from FEATHERS and the number of people living in each Flemish house is derived from online data[9], using the ratio between the Flemish and Belgian population. From this information, the number of households per TAZ is derived. Multiplying this value by the annual synthetic average domestic load per house (extracted from online data source[10]), allows to obtain an estimation of domestic load per TAZ.

4.2. Additional load demand per TAZ evaluation

To the best of our knowledge, there is no information available about the current industrial electrical consumption per TAZ in Belgium. The rest of electric consumption in Flanders region is calculated by subtracting the total electric demand in Flanders and the sum of the electric domestic demand for all TAZs, evaluated in the previous subsection. The obtained additional consumption is distributed proportionally to the number of inhabitants in each TAZ.

4.3. Flemish electric transmission grid

The transmission electric grid in Flanders is composed of 179 transmission substations with a nominal capacity from 40 MVA to 800 MVA[11].

Since there are more TAZs than substations, an algorithm is used to assign different TAZs to the nearest substation[12]. The total load of each substation is the sum of the total demand in all TAZs fed by each substation. In order to assess the impact of the EVs charging on the transmission grid, it is checked that the nominal capacity of each substation is not exceeded under any charging scenario.

5. Integration of substation power capacity constraints

Disaggregation of the background electricity demand in each substation is described in section 4, it also provides the remaining maximum capacity of each substation at any time of the day. Each substation feeds power to a set of TAZ. In the charging strategy optimization process, described in previous work[4], there is only one global power consumption tracker, which keeps the record of total consumed power (for all zones) at each time unit of the day. The global power tracker is used to verify that power consumed at each time unit does not exceed the production at the respective time. To be able to set up a realistic simulation scenario, data describing the renewable (solar and wind) power production during a day in the summer were taken from an online source[8].

In order to integrate the substation capacity constraints, a new power consumption tracker is introduced which records the booked power at each time unit in a day for each substation. When a vehicle requests a charging time-slot at a particular location, the local power consumption tracker calculates the available (non-booked) power at the requested time and grid location. If the substation has not reached its maximum capacity level, then global power consumption tracker calculates the available power at the requested time. In case both trackers do not report any violation of the respective capacity limits, as described in equations *1* and *2*, the minimum of both (global and local) available power is calculated and returned to the vehicle. Using this newly calculated available power at requested time and location, a vehicle can plan its charging strategy using the existing optimization process.

$$\sum_{\forall i} ch\_event_{t,l}^i \leq Grid\_Capacity_{t,l} \tag{1}$$

$$\sum_{\forall i} ch\_event_t^i \leq Global\_capacity_t \qquad\qquad \forall\, l \in Loc \qquad\qquad (2)$$

After planning the charging strategy, the vehicle sends the information about its planned charging events back to the power tracker. The power tracker registers the newly booked power with time and location information as described in equations 3 and 4. Figure 2 shows the energy consumption by electric vehicle charging in different transmission substations in the Flanders. The Map colour represents the power consumed by electric vehicles in each grid between 11:45 am and 12:00 pm.

$$Grid\_consumed_{t,l} \mathrel{+}= ch\_events_{t,l}^v \qquad\qquad (3)$$

$$Global\_consumed_t \mathrel{+}= ch\_events_t^v \qquad\qquad (4)$$
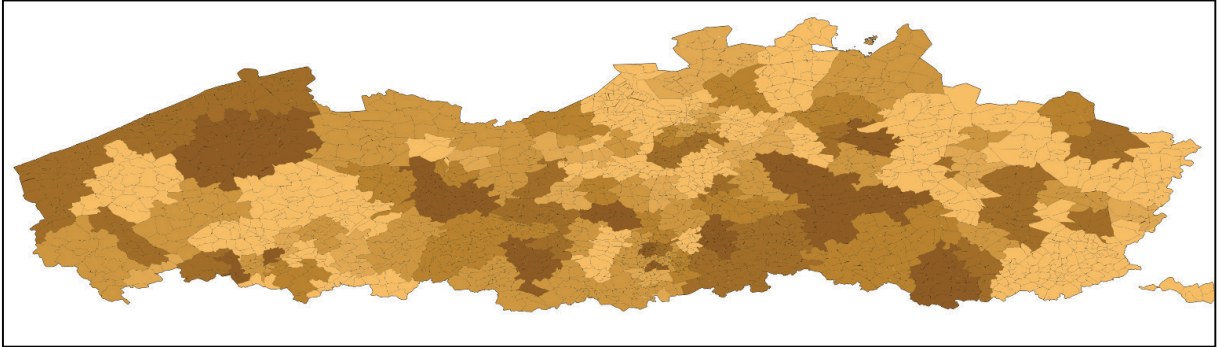

Figure 2 Power consumption by electric vehicles charging in different substations in Flanders between 11:45 am and 12:00 pm

5.1.   Spatio-temporal price of electricity

Electricity prices are calculated statically for each unit of time (15 minutes) to balance the power production and consumption. The electricity price calculation method does not consider the imbalanced demand of energy in particular spatial substations, it only creates an inverse replica of the total produced renewable power keeping the average price close to the Belgian electricity market price. Electricity prices, used in this work, are calculated using the following equation and have an average value of 0.217 €/kWh as shown in Figure 3.

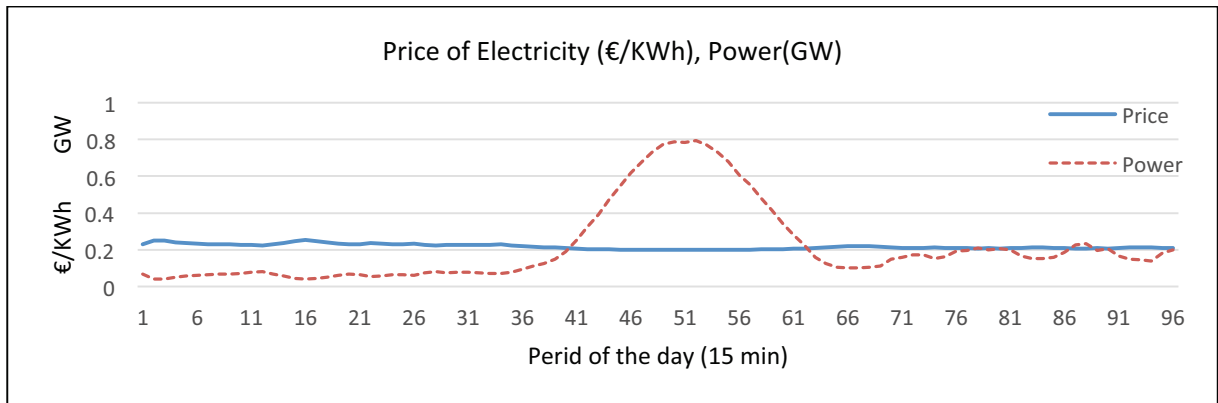$$Price_{l,t} \; = \; Price_t \; = \frac{K}{Power_t} \qquad\qquad (5)$$

Figure 3 Price of the electricity and available renewable power

6. Shift in travel timings

After the vehicle finishes its charging planning process, it shifts the trips in time to explore the potential reduction of the charging cost. To plan the charging at cheaper moments which are blocked due to traveling at those moments, travel periods are shifted backwards or forwards in time. Shifting a trip in time can influence (block) already planned charging events and violate the battery minimum state of charge (SOC) constraints. In order to resolve such scenario, all trips in the agenda are shifted one time unit (15 minute) either backwards, forwards or are kept at same time. This creates 3^n possible scenarios for adapting the original traveling agenda of the car where n is the number of trips in the agenda. Each possible traveling agenda is then evaluated for charging cost using the charging strategy optimizer. The cost values for all traveling agenda are calculated and compared to each other. The agenda which gets the minimum charging cost is used as rescheduled agenda while all others are dropped. The rescheduled and original traveling agendas are used to compare the difference in charging cost and total shift in the trips.

7. Comparison of charging cost and shift in trips after rescheduling

Shift in trip and charging cost of the daily schedules predicted by the activity based model is compared between *original* and *rescheduled* cases. Sum of the absolute shift in the starting time of all trips is calculated as shown in Figure 4 where absolute shift in one trip does not exceed the limit (15 min). Figure 5 shows the comparison between total absolute shift in starting time of trips and relative change in charging cost. Figure 6 shows the comparison between total absolute shift in starting times of trips and absolute change in charging cost. There is an average 17 minutes shift in the starting time of the travels for an average 6% relative change in charging cost (average of 0.03 Euro absolute cost saving). The relative change in charging cost k can be expressed as in equation (6).

$$k = \frac{2 * (Cost_{old} - Cost_{new})}{Cost_{old} + Cost_{new}} \qquad (6)$$
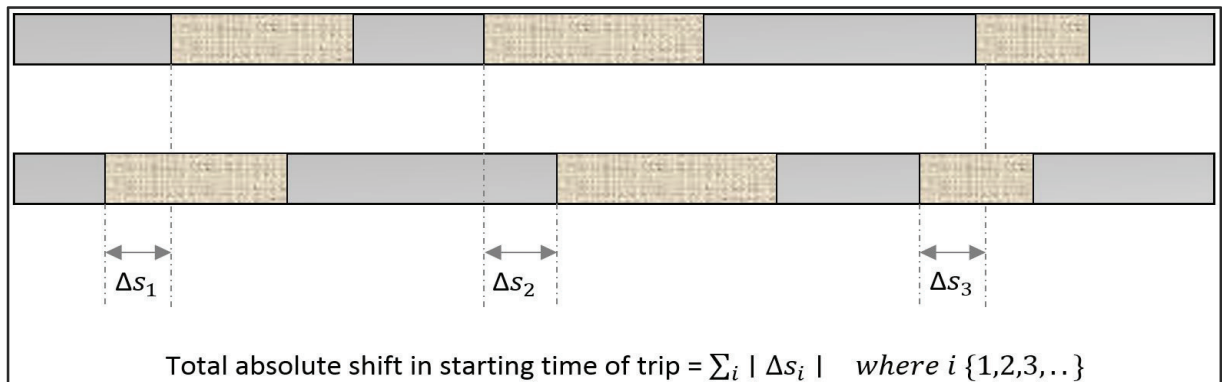

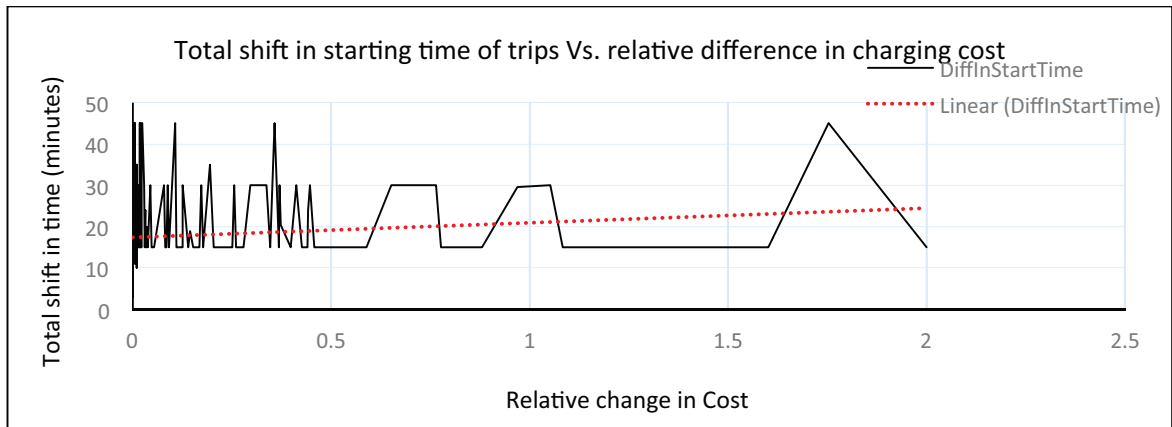Figure 4 Sum of absolute shifts in the starting time of the trips

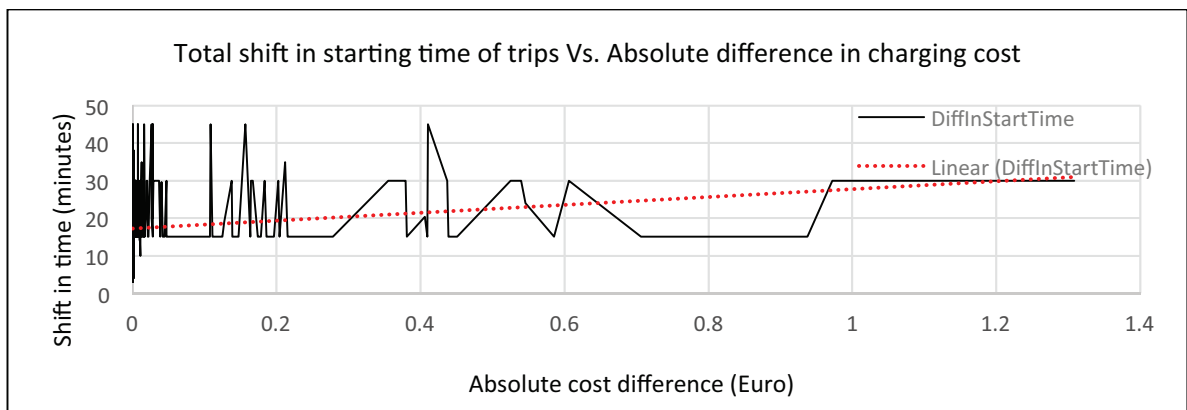Figure 5 Comparison between total absolute shift in trips and relative difference in total charging cost

Figure 6 Comparison between total absolute shift in trips and absolute difference in total charging cost

8. Conclusion

This work improves the electric vehicle charging cost optimization framework by integrating local power grid capacity constraints. This framework changes the starting times of the trips in a daily agenda to calculate the charging cost for each combination of the trips in the agenda. The simulation results (even if they are only an indicative scenario assessment) show that the potential cost savings at the personal level are probably too small to deal with the rescheduling inconveniences and induce behaviour change. The savings seem to be lower than what people can save on gasoline cost by avoiding to drive during congestion periods.

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