

Electric Mobility and Charging: Systems of Systems and Infrastructure Systems

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Abstract – *In light of European and worldwide environmental programs, reduction of CO₂ emissions and improvements in air quality receive a lot of attention. A prominent way to improve on both aspects is the replacement of Internal Combustion Engine Vehicles with Electrical Vehicles. Yet, simply replacing vehicles will not result in proper electric mobility because using Electrical Vehicles depends on many systems and infrastructures including the chargers, parking sites and payment structures. In this paper we will take an explorative view on Electric Mobility and match developments in that area with Systems of Systems Engineering. We will also present a case study on charging many Electric Vehicles, where we will match business opportunities and technical feasibility to the transition from early adopters to the early majority as main Electric Vehicle users.*

Keywords: Electric Mobility, Case study, Systems-of-Systems, Modeling.

1 Introduction

The introduction of electric vehicles requires adaptations in several types of infrastructure and in many related systems. In this paper, we discuss strategies for charging. Charging of electric vehicles has more impact on the use of the vehicle and trip planning than fueling in traditional cars.

Figure 1 shows that abstract social-economic policy systems, infrastructure systems, other physical systems, and human stakeholders interact in electric mobility. For electric mobility to work smoothly, all these systems and stakeholders with their diversity need to interoperate.

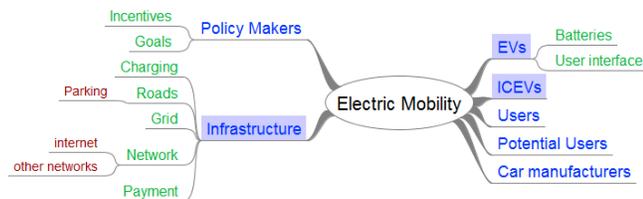


Figure 1. Simplified electric mobility context diagram. It is clear that successful Electric Mobility requires integration of, or cooperation between systems. The shaded nodes represent physical systems, non- shaded are stakeholders.

The replacement of fueling by charging is a major change for several reasons:

- The energy infrastructure for storage and distribution moves from physical oil and gas to electricity.
- The commercial parties delivering energy change.
- The business model of delivering energy may change, as well as the underlying payment systems.
- The charging operation itself: due to technical limitations, charging is slow to very slow.
- The charging characteristics result in stations with increasing differences in charging speed, location, payment method and connectors.
- Drivers will get support from information and communication systems to charge conveniently.

In the current early adaptor phase of electric mobility, there are many competing concepts for storage, charging, payment, and business models. Standards appear, however the playing field is still rather dynamic. Governments and regulations are significant drivers in the development of electric mobility since current technology is not yet competitive with cars using fossil fuel. Another aspect is the shift from Electric Vehicle (EV) adoption by early adopters to early majority, as identified by Rogers [1].

In this paper, we elaborate drivers for electric mobility with respect to the aspects mentioned above, using influence diagrams in Section 3. From there, we identify ways of bootstrapping Electric Mobility (Section 4). We will discuss a case study in Section 5 to illustrate the way of working. A discussion, conclusions and Future work are discussed in Sections 6 and 7.

2 SoS State of the Art

After the change from developing products to developing systems, we are now facing a shift towards developing systems of systems (SoS). In the shift from products to systems, the increased interaction between product and environment was central: Systems are not only influenced by their context, they also impact that same context, including users, developers, maintenance engineers etc. But also the impact on the environment has received more attention. While not so long ago cars were designed to

achieve high top speeds and fast accelerations, now cars are developed to minimize the impact on air quality, fossil fuel usage and noise. So, the embedding of the System Under Design in its development and operational context has become more important.

SoSes are generally characterized as being large-scale systems, constituted by many individual systems. The overall system objective is achieved by orchestrating the operation of these individual systems [2, 3]. The relative autonomy and uncoupled life cycles of the constituting systems are important aspects to consider. Taking the car case as an example, to enable further improvement of air quality and reduce fossil fuel usage, electric mobility will become more important because of the inherent higher efficiency and zero exhaust by the vehicle. Yet, the introduction of EVs is not only determined by the quality of the vehicles itself; also the availability of charging infrastructure, incentive programs and the opinions of other EV users affect the uptake of EVs (see Figure 1, and [4-7]). Each of these aspects represents systems by themselves. Either technological (the charging infrastructure), societal (the incentive programs) or interpersonal (the other EV users). Each individual system works by itself, but has a large impact on the functioning, development and life cycles of the other systems.

3 State of Affairs in Electric Mobility

Electrifying transport is for many countries a prominent way of improving air quality, reducing CO₂ emissions and use of fossil fuel. There are in fact two steps in meeting these goals:

1. Creating a more energy-efficient drive train in the vehicle.
2. Employing more efficient or even completely renewable energy sources.

Due to the simplicity of the EV drive train, and the inherently more efficient energy conversion in electrical machines, an EV will be able to drive further on one kWh of energy than an Internal Combustion Engine Vehicle (ICEV). The crucial parameter for goal 1 is the Tank to Wheel (TTW) efficiency. For goal 2, the efficiency is called Well to Tank (WTT) efficiency. Overall is called Well to Wheel (WTW) efficiency. Electric Vehicles distinguish themselves from ICEVs in the TTW efficiency: 48% (for the drive train only: 80-90%), versus 22% [8].

The WTT efficiency is largely dependent on infrastructure. For ICEVs, the efficiency in extracting, transporting and refining fossil fuels defines the WTT efficiency. Due to the long history and large capital involved, these processes have been refined and efficiency has gone up to about 80% [8]. For electricity, on the other hand, two paths can be identified: using current fuel-burning generation (thus minimizing capital investments), or employing renewable sources like sun, wind and hydropower (resulting in shutting down fuel-burning generators). Burning fuel has a limited efficiency of about 40% [8, 9]. Taking that as source for

fuelling the EVs thus results in a WTW efficiency of about 19%. This is only marginally better than the WTW efficiency of an ICEV: 17%.¹ If, on the other hand, renewable sources are used, the picture changes. In principle, the sun, wind and hydro are unlimited energy sources. A low efficiency in solar power can be mitigated by increasing the area of panels. Hydropower at this moment already accounts for all of Norway's electricity demand. Additional benefits of electric mobility versus fossil fuel mobility are improved air quality and less noise [4, 6, 7].

Looking at Electric Mobility from a systems point of view, we can create the simplified context diagram in Figure 1. While the context diagram gives an overview of the scope of electric mobility, an influence diagram, and/or causal loop modelling provides insight in the behavior over time. An influence diagram we developed is shown in Figure 2; a causal loop diagram of ours is in Figure 3.

From these two diagrams, one can conclude that policy makers cannot directly influence CO₂ emissions, individual mobility or the individual chance of buying an EV. Instead, policy makers have to act indirectly, influencing the user via financial measures and/or opinion making, or the car companies by regulation. At the same time, there are

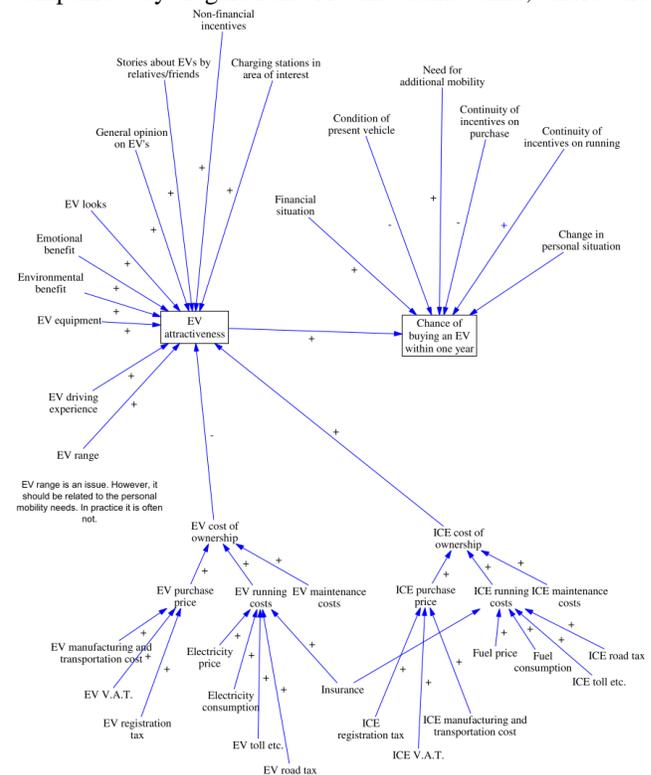


Figure 2: Influence diagram used to investigate the likelihood of a user buying an EV within a year.

¹ Husain has a mostly US point of view. The main electricity source is there fossil fuels, so that is why he used the low 40% as efficiency for WTT for EVs.

negative influencers like the currently owned vehicle and habits of the user. An issue here is that it is not easy to determine what effective means of influencing are. Surveys (with reported results like [6, 7]) merely capture past and present behavior. Models that base on such data are useful, but only for extrapolating such data. SERAPIS uses systems dynamic modeling to create such sophisticated projections [4, 5]. Yet, future behavior is hard to predict. Instead, *design* can help to change the future. That is, not trying to mimic the behavior of current solutions (ICEVs) as much as possible, but finding a mix that meets the users' needs. A systems of systems engineer should take the perspective of seeing each system as part of a larger whole. In the next section, we will discuss ways to use the SoS engineering approach to develop Electric Mobility further.

4 Bootstrapping SoS approach in EM

Starting from Figure 3 that displays influences on the chance of an individual user buying an EV within one year, and aiming at reduced CO₂ emissions, we can conclude that this can be achieved by:

- Increasing the EV/ICEV ratio, or
- Reduce collective mobility

The EV/ICEV ratio can be influenced by:

- Price policy (increasing the ICEV price, and/or reducing the EV price; this is current Dutch policy through taxation);
- Technical developments (increasing the EV range, for instance) and developments that increase EV attractiveness;
- Other EV benefits (use of buss-lanes, free charging etc. as currently implemented in Norway).

We also see a negative relation between individual and collective mobility. When one increases, the other decreases (due to congestion, crowded public transport etc.). From a policy-makers' perspective, price policy and promoting other EV benefits seems the only way. Models like SERAPIS use a similar approach to investigate consequences of policy, incentives and other (collective) developments.

From an individual users' point of view, CO₂ emissions are not crucial. Range and aspects of individual wellbeing are more important. Looking at Figure 3, we see a more detailed picture. Here, a cost of ownership comparison between an EV and an ICEV largely determines EV attractiveness. Yet, the most direct influencers of the chance of buying an EV within one year are the personal situation including the financial situation and (dis)continuity of policy. For the former, an interesting idea is that changes in personal situations are triggers to change habits and/or adopt new technology [10]. The latter is a means for policy makers to have a quick impact (stopping certain incentives caused large car sales of a particular type towards the end of 2013 and the end of 2014 in the Netherlands). On the other hand, many changes of policy result in distrust in the government and will negatively affect the uptake of EVs. In an SoS approach interfaces and federative cooperation between individual systems is appreciated. Using that, we can identify these constituting systems:

- The EV as technical and as emotional systems
- The incentives
- The rules and regulations
- The energy system
- The charging infrastructure
- The road and building infrastructure

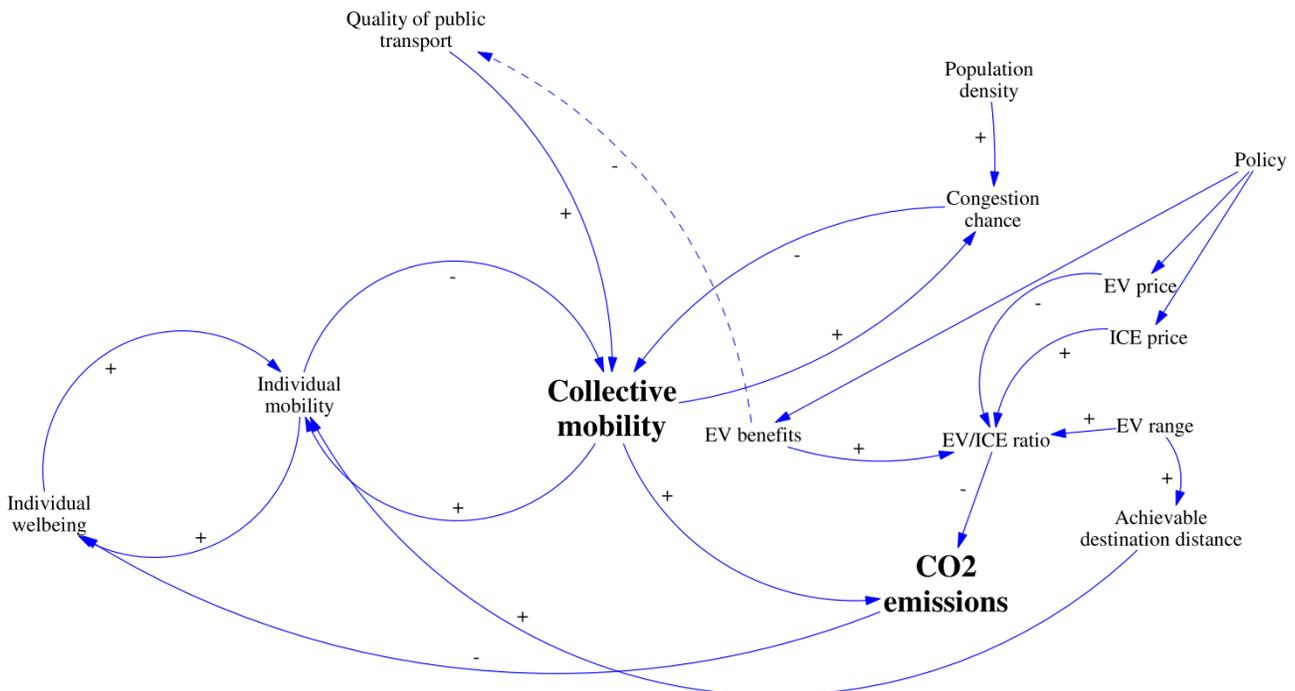


Figure 3 : Causal loop modelling of mobility, both collective and individual. This is a relative simple model to illustrate the approach.

- The information and communication network
- The (interface to) payment infrastructure
- The production and maintenance systems of car manufacturers

Each of these systems has its own history and future, and own stakeholders with corresponding concerns. Each of these systems has its own time frame and context of development and implementation. There even is a large variety in interface intensity between the various systems. Yet, to really promote the real-life adoption of EVs all of the systems have to work together. In the next section we will see an example of an initiative that integrates several of the identified systems.

5 Fornebu Case Study

5.1 Problem description

EV use is expected to follow Rogers' theory of adoption [1]. First an innovation is accepted by Innovators (2.5% of the population) and Early Adopters (13.5%). Next are the Early and Late Majority (34% each), followed by the Laggards (16%). In Norway, adoption has reached the early adopters [6]. These are typically higher educated and married men, 30-50 years of age. The income is above average; they live in cities and suburbs. To make the next step, more people have to be addressed. These have less education and income. More women are expected to take part as well. To address these people, the technology has to be easier accessible, improving the practical use of the EVs, maybe even surpassing the practicality of ICEVs.

Charging is often still a time consuming process. This is partly due to battery technology, partly due to electricity availability. A fast charger can deliver up to 50kW to the car, yet, a normal grid connection is 16-32 Amps, corresponding to 3.5-7kW. In order to be able to deliver 50kW, several of these outlets have to be combined, or a heavier grid connection has to be installed. Such an adaptation requires investments. For these to pay off, a payment and pricing strategy has to be devised. A Norwegian issue here is the low price of electricity, leading to users expecting charging to be free.

5.2 Approach

We have identified an opportunity at Fornebu (Norway) where the principles of parallelism and redundancy are connected into a "charging many" solution. Here charging is combined for a large number of vehicles in a combination of fast charging and normal charging.

Fornebu is a combination of residential buildings, offices (2000m²), a shopping center (24500m²) and a parking facility (36000m²). Solar panels are installed (130MWh/year). The mix of users contains fast charger customers (shopping audience, some employees) and normal charger customers (residents and office employees). The residents have their car parked during nighttime (and

are thus able to store the early sunrise solar energy), while the office users and shopping mall visitors' EVs can store the daytime solar power.

We have made an estimation of the charging needs during a typical weekday (see Figure 4), Saturday (offices closed) and Sunday (shops and offices closed). These estimations of required power in the course of a day, result in an average demand of about 90kW, and a peak power demand of about 150kW, see Figure 4. The grid can deliver 70kW, so other sources are required, or an updated grid connection has to be installed, requiring large investments.

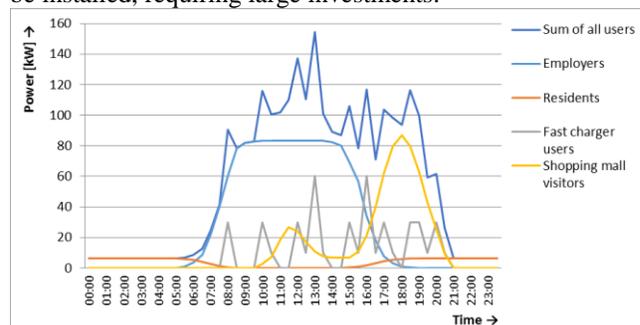


Figure 4: Estimation of power used for charging EVs at Fornebu, during a workday.

Given the capacity of parked residents' cars, there is a large power reserve available. Utilizing this reserve with Vehicle to Grid (V2G) operation, can deliver power in the peaks. Using for instance solar and/or wind energy can account for the deficit in the average power requirement.

Batteries have a limited life-span. Both calendar life and cycle life are limited at the required performance levels in EVs. Therefore, users may be hesitant to letting a facility use their EV batteries for load balancing. While this seems a drawback, it is the basis for an alternate solution. Batteries that no longer function well enough for EV use, can be replaced under guarantee, or at the EV-user's request. The old battery packs can be used relatively cheaply in other applications, at reduced performance (so-called secondary use). This consideration has led to dropping the V2G solution and adopting secondary batteries instead.

5.3 Design

We created various system overviews, including an electric topology (Figure 5), a proposal for a physical layout and a user interface (Figure 6). Together, these views give an impression of the proposed solution and relate to the systems identified in Section 4.

The basic concept is to have a 70kW grid connection assisted by solar panels that are estimated to deliver a maximum of 85kW. The outlets can switch between connected cars, and can act as normal chargers or fast chargers. The "Outlet Electronics" in Figure 5 adapt charging speed, depending on the user's preference, the type of car connected, the progress in the charge cycle, other cars in the parking facility and available power. A set of (secondary) battery packs is connected to its own outlet

electronics to manage the state of charge (SoC) of these packs. The energy stored is used on demand. A particular feature is the optional connection to the office buildings. The energy stored in the battery packs can be used to provide a stable power supply to the offices, negating the need for separate uninterruptible power supplies (the power reserve is even larger when V2G is used as well).

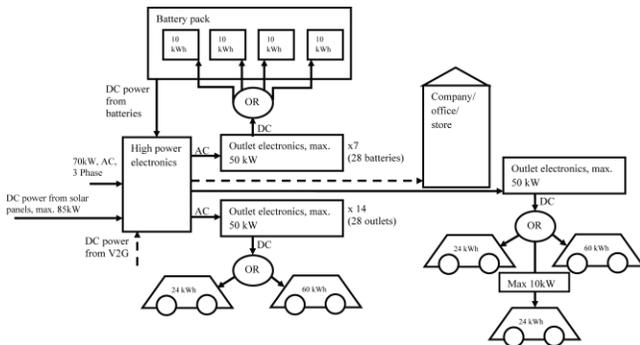


Figure 5 : An electric topology for the Fornebu case.

Further, the configuration allows for load balancing the grid, and even may provide a financial benefit by charging the battery packs at times with low electricity price, and delivering back to the grid at high prices. Also, the battery packs enable time-shifting energy that is generated with solar and/or wind installations.

The physical layout provides for orchestrated filling of the parking site. The aim is to distribute the incoming cars evenly over the outlets, so that at first each pair of outlets has only one car attached that can be charged at maximum power, see Figure 7. When the filling of the parking site continues, the outlet electronics have to manage the charging process of two (or even three) cars. Batteries can only accept the maximum current for a limited part of the charging cycle, so the charging speed reduction for each car will be limited. EV users can provide time of departure with the user interface, so that the overall charging process can be optimized.

An important decision made for this case is the use of DC-charging only. Of the 13 inventoried EVs, only 4 cannot be charged with DC. For the others, DC is the fastest charging option. While not all cars can accommodate DC-charging, the benefit for the EV user and on system level is huge: the system can supply up to 50kW per outlet.

The business model of this layout has been created. The basis is a mix of residential EV users that have a permanent charging spot, office users and shopping mall visitors that pay per charge, and fleet operators that pay an annual fee to have their cars permanently charged. While there are numerous assumptions and uncertainties, the system is expected to have a pay-back time of little over six years.

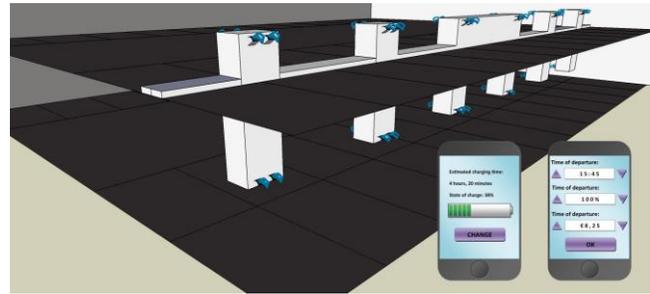


Figure 6 : Physical layout and User Interface for the case study.

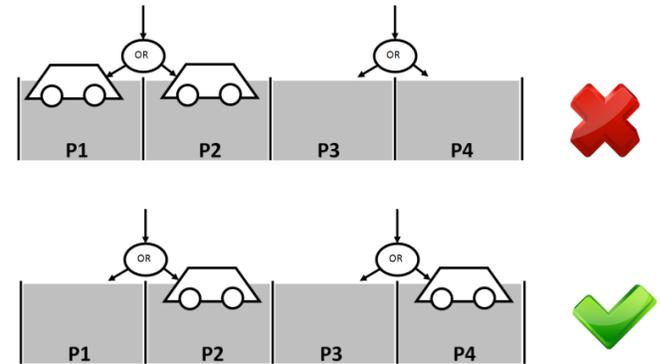


Figure 7 : Distributing incoming cars over the outlets.

5.4 Discussion

With the proposed design for the Fornebu case study, charging has become easier for all parties involved. Finding a parking/charging spot is made easier, the user is guaranteed to have a fully charged vehicle at the time of departure, and the facility manager can earn money, not only by providing parking spots, but also delivering the service of charging.

With a facility like this, we expect to help the early majority in adopting electric mobility. With lower income of this next group of adopters, the likelihood of having private parking and charging is reduced. Also, this product-service combination is better than for traditional ICEVs: charging takes place while shopping or working (no time lost with fuelling) and there is convenience in the way parking is arranged (directly guided to a vacant spot). This facility thus fills a need. Further, a feasible business model is proposed.

6 Next steps and future research

With the Fornebu case worked out, we intend to create a generic design. This will consist of a core structure with optional modules and guidelines for adapting to a specific situation. Moreover, we will look for specific differences between the Norwegian Fornebu case and the Dutch situation. Electricity prices in the Netherlands are significantly higher, and the mix of full EVs and plugin-hybrid vehicles is different. Also, the Netherlands has quite

a high percentage of lease-vehicles. This will result in adaptations and changes to both the business model and the system layout.

Further, we will try to find a test-site for trying out the charging many concept. The new to be built premises for the HBV (Buskerud and Vestfold University College) at Kongsberg may be used for this.

7 Conclusions

Electric mobility can be increased by various means, and through various systems. On the one hand, the (potential) users of EVs have to be addressed, such that exchanging their ICEV for an EV is sensible and attractive. The needs from the early majority differ from those of the early adopters. Yet, influencing the potential EV-user can hardly be done directly.

We have seen that by looking at electric mobility from a systems of systems point of view, provides handles for increasing electric mobility. In addition to the often used regulations and incentives system, improving the infrastructure system may lead to an increased uptake of electric mobility. We suggest to implement a charging many system to meet the stakeholders' demands.

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