50% Electric cars in Switzerland:

Impacts on the electricity market and the environmental impact of mobility

DRAFT

Marco Miotti

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Abstract

The energy demand of the world is increasing, and especially mobility on the rise. In 2009, electricity contributed 23.9% to the energy consumption of Switzerland, traffic (including electricity based traffic) 34.8%. This study discusses the impacts of mobility if 50% of the gasoline/diesel based on-road traffic was replaced with electricity based transportation, using battery electric vehicles (BEV). It found that this reallocation would increase the electricity demand by 12.5%. Analyzing the impacts on the electricity market, it was found that the energy price depends on the production costs of the marginal technologies which would supply the increased demand. These production costs tend to be lower if BEV would mainly be charged during times of low load, that is, nights. The same applies concerning environmental impacts of BEV; however, from a consequential point of view, the time of charging does not influence the environmental impacts. Generally, the climate change impacts of the fuel (electricity) of BEV was found to be lower as the one of gasoline/diesel, as long as the electricity mix is not significantly worse (regarding greenhouse gas emissions) as the average UCTE countries' mix.

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1. Introduction

When climate change is discussed, it often doesn't take long until mobility comes into play. People travel more and more, which causes more and more emissions of greenhouse gases, and increases the demand for energy sources. In 2008, transport made up 27.3% of the world's energy consumption (International Energy Agency). While this number has not changed significantly in the past 10 years, the absolute energy demand has grown by nearly 20% (International Energy Agency). Since most of the transport is driven by petroleum derivatives (such as gasoline and diesel) and kerosene, mobility also contributes significantly to the global greenhouse gas emissions, and is mostly based on non-renewable resources (MacLean and Lane 2003). Emerging economies as China and India drive the global demand ever higher. At the same time, the future provision of major energy sources such as oil becomes less and less certain. Together with economic fluctuations, this results in unprecedented uncertainties concerning the energy world (World Energy Outlook 2010).

Because of the high uncertainties especially regarding oil, and the significant climate change contributions of oil driven transport, alternative propulsion systems are looked for with a lot of effort. As for road transport, especially private cars, there are several alternatives to internal combustion engine vehicles (ICEV) available or in development. The major ones are battery containing electric vehicles (BEV), hybrid electric vehicles (HEV) and fuel-cell electric vehicles (FCEV) (e.g. Chan 2002, Emadi et al. 2008). While HEV still require fossil fuels to run their engine, BEV and HEV run entirely with electric motor drives (Chan 2002). In case of BEV, the power is provided by an internal battery which has to be charged. On the other hand side, FCEV run on fuels such as hydrogen (H_2) and thus require appropriate fueling stations. Also, hydrogen has to be produced out of water (MacLean and Lane 2003). Compared to oil, the source for the fuel, water, is virtually infinitely available. However, the production of hydrogen currently requires a lot of energy, which again has to be produced by some means (MacLean and Lane 2003).

This paper addresses the question how large an effect the substitution of 50% of the oil based energy for domestic road transportation with electric energy for BEV would have. This question will be analyzed for the general energy situation (which will be discussed quantitatively) and for the electricity market (which will be discussed qualitatively). Also, a first assessment of how the environmental impacts of transportation would change will be given. These considerations allow for a first judgment of whether BEV should be supported by government policies or not.

50% was chosen because the range (km per full charge) of BEV is not yet sufficient to allow for long distance traveling and may still not be in the near future. For these applications, plug-in hybrids may be an option. They could use the battery supplied electricity until empty, and then switch to the gasoline engine for longer distances. Also, the transportation of goods (which has a much smaller share of domestic energy use than the transportation of people, see section 2) may not be as susceptible to BEV technology yet as the transportation of people. The economic attractiveness of BEV (and therefore, whether it is possible that BEV may reach a share of 50%) is not taken into account, since the analysis focuses on the consequences if BEV actually reach that high a market share.

The paper focuses on the situation in Switzerland, relying on data for the Swiss energy and electricity market. The reason for the focus on the situation in Switzerland instead of a global perspective is that the energy use (total and shares of different sectors), energy sources and systems are very heterogeneous. Also, data availability and quality for Switzerland is very good. However, the significance of the results gained in this paper for the global situation will be discussed at the end.

As a simplification, FCEV are ignored, because these vehicles are still in development, the technology in general is not mass market ready because of several issues, and the most likely used energy sources for hydrogen are still uncertain (e.g. MacLean and Lane 2003).

2 Energy situation in Switzerland

2.1 Shares of different energy carriers

Traffic as a sector makes up more than one third (34.8%) of Switzerland's energy consumption, which is more than the aforementioned international average of 27.3% (Figure 1a; International Energy Agency, 2010), although the data come from different sources. The second largest share of consumption by sectors comes from households (28.7%), followed by the industry and services.

When looking at the energy carrier shares, the figure for power/motor fuels (33.4%) correlates quite well with the share of the traffic sector, which is not surprising given that

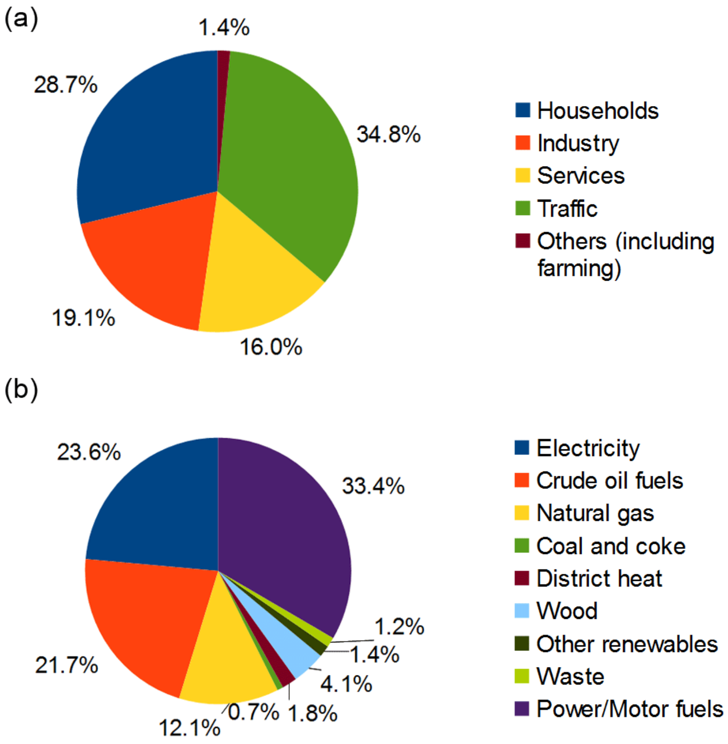

Figure 1: *Shares of energy consumption in Switzerland in 2009. The total consumption was 877.6 PJ (a) Energy consumption by sector (b) Energy consumption by energy carrier. Data source: BFE (2010)*

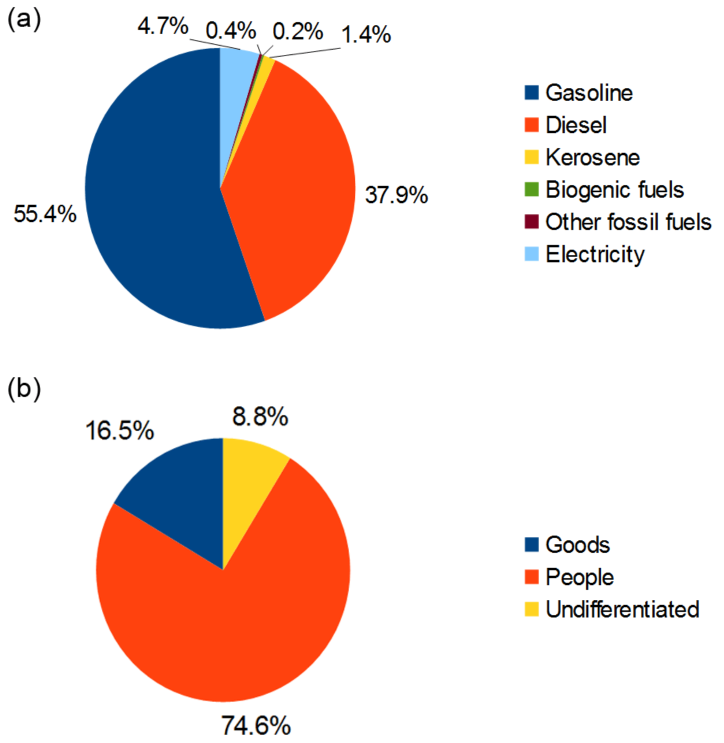

Figure 2: *Shares of energy consumption within the traffic sector in Switzerland in 2009. The total consumption was 226.2 PJ (a) Consumption by energy carrier (b) Consumption by transport purpose. Data source: BFE (2010)*

most of the traffic is fuel based (Figure 1b). The share of electricity is 23.6% and crude oil (mainly for heating) contributes 21.7%.

Within transportation, virtually all of the energy consumption comes from gasoline and diesel (together 93.3%, Figure 2a). Electricity, which is used for trains, trams, buses with an electric motor and BEV / plug-in HEV, only made up 4.7% in 2009.

At the same time, three quarters of the energy used by transportation was used to transport people, and only 16.5% were for goods (8.8% undifferentiated). Because of these figures, it is not surprising that “on-road” transport contributed 86.5% to the energy consumption. It is important to note, however, that the numbers in figure 2 do not include international air traffic (only domestic, which is small in Switzerland), and that the total of 226.2 PJ differs quite largely from the 305 PJ for traffic from figure 1 (34.8% of 877.6 PJ). This may be because a different modeling technique was used and the system boundaries were set differently. I will rely on the 226.2 PJ, because for the 305 PJ, no further information about consumption shares (such as these in figure 2) were given.

Since traffic causes some 35% of the energy use in Switzerland, people transportation causes some 75% of the traffic energy consumption, and most of the energy for traffic utilities comes from petroleum derivatives (gasoline and diesel), substituting these energy sources with others (such as electricity) can be expected to have a large impact on the energy situation in Switzerland.

2.2 Electricity consumption and production

The electricity demand in Switzerland was 207 PJ in 2009 (see figure 1b) or 57.5 TWh. The gross electricity production consists of nuclear energy (39.3%), running river hydroelectric power plants (24.2%), reservoir hydroelectric power plants (31.6%) and other (including thermal, 4.9%) (BFE 2010, see also figure 3). The main difference between the gross and the net production is the energy used to run the reservoir pumps, which is about 2.55 TWh per year. Because some 95% of the domestic energy production of Switzerland come from nuclear and hydroelectric energy, it is quite clean in terms of climate change impact.

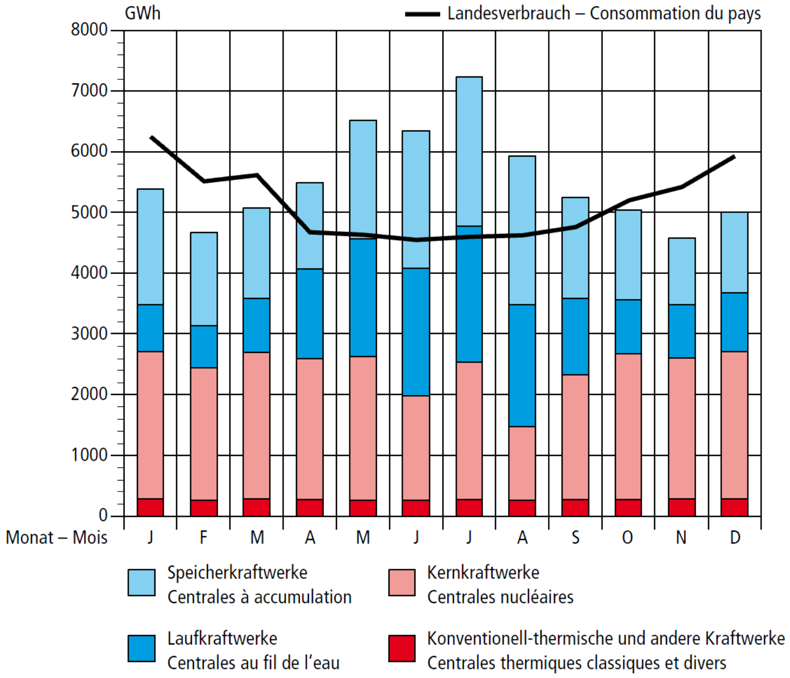

Figure 3: *Domestic energy production (columns) by category and energy demand (black line) for each month, Switzerland, 2009. Figure taken from: BFE (2010)*

However, the trading volume is very large. One reason is that during winter months, when the hydroelectric power generation is much lower than in summer, energy has to be imported to satisfy the demand (figure 3). However, in 2009, 52 TWh were imported, and 54 TWh were exported (BFE 2010). While this results in an export surplus of 2 TWh and there has been an export surplus in 18 of the past 20 years, the trading volumes are virtually as large as the actual production, and much larger than what is necessary to cover the energy demand during winter.

The fact that the revenues from the energy exports are much larger than the expenditures from the imports (generally by about 50% higher, BFE 2010) despite the similar volumes suggests that much more “clean” hydroelectric energy is sold than clean energy is imported. Therefore, it is probable that there is more climate intensive energy in the Swiss energy mix than the domestic production would suggest. This is also confirmed by the EcoInvent database for life-cycle assessments, which suggests a 18.4% share of UCTE grid mix electricity within the Swiss energy mix (year average), and only 36.7% hydroelectric power (instead of the 55.8% share of domestic production).

3. Analysis

3.1 Energy reallocation

First, the amount of additional electricity demand has to be estimated. As a basis, the amount of energy used for transportation on roads has to be known, of which 50% will be reallocated from petroleum derivatives to electricity. According to the data displayed in section 2, traffic caused the consumption of 226 PJ of energy. 93.3% of that energy was supplied by petroleum derivatives, and 74.6% of the same amount (226 PJ) was used to transport people. 86.4% of again the same amount was for “on-road” transport. If 50% of the gasoline/diesel consumption for the on-road transportation of people was replaced by electricity for BEV, the amount of energy to be replaced is approximately $226\,PJ\cdot 0.933\cdot 0.5=105\,PJ$.

The amount of energy (in J) required may change due to the reallocation, since transport and distribution as well as vehicle internal efficiencies may differ (see figure 4). The transport and distribution efficiency in Switzerland can be estimated from the relationship between the consumed energy and the produced energy (net, i.e., without the energy demand of the pumped storage power stations) minus/plus net trading volumes:

$$\eta_{TranspDistrib\,,\,BEV}=\frac{E_{consumed}}{E_{produced\,,net}-E_{trading\ surplus}}=\frac{57.5\,kWh}{64.0\,kWh-2.2\,kWh}=0.93$$

In case of oil based fuels, the transmission and distribution losses consist of the energy used for the transport (of physical mass, i.e., the fluid fuels) and the operation of infrastructure such as fuel stations. In a comprehensive study by the DeLuchi of the U.S. Department of Energy (1991), the energy intensity of transportation is estimated to be about 1% of the energy contents of the fuels transported. The energy consumption of the

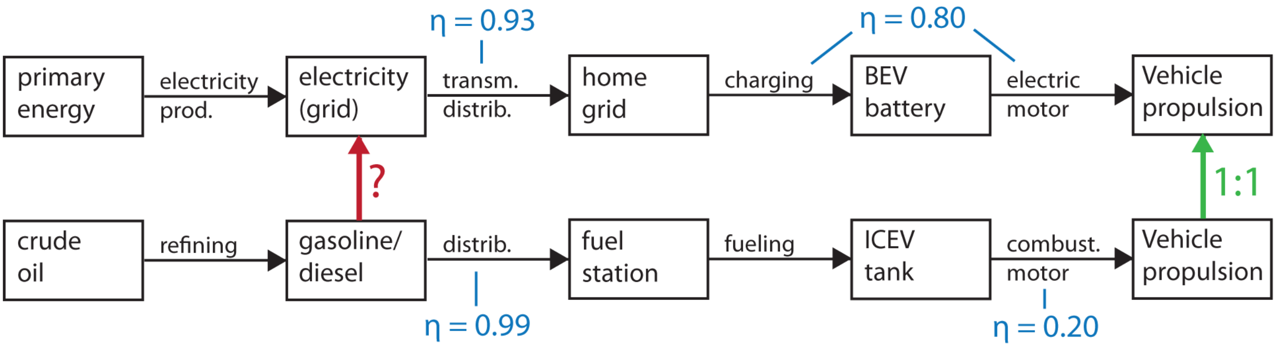

Figure 4: Schematic e*nergy paths from the primary source to vehicle propulsion for battery electric vehicles (BEV, top) and internal combustion engine vehicles (ICEV, bottom) including efficiencies (η) for certain processes*

fuel stations is hard to estimate and, given that the impact of transportation is so low, is neglected in this study. Thus, the efficiency of gasoline/diesel transportation is estimated to be 0.99.

Based on indications found in literature (e.g., DeLuchi 1991; Weiss et al. 2000; Granovskii et al. 2006), I assume the motor efficiency of BEV to be 80% (including charging and the battery), and the one of ICEV to be 20%. The respective exact efficiencies depend on many factors, such as specific technologies and fuels (diesel/gasoline) used, location/speed (city or highway driving), driving style, features used (such as air conditioner), wind speed and direction, etc. Above considerations finally lead to a relationship between ICEV energy and BEV energy of:

$$\frac{E_{BEV}}{E_{ICEV}}=\left(\frac{0.95\cdot 0.8}{0.99\cdot 0.2}\right)^{-1}=0.26$$

This ratio compares well to the ratio used by Granovskii et al. (2006), which is 0.28 ($\frac{67.2\,MJ\cdot 100\text{km}^{-1}}{236.8\,MJ\cdot 100\text{km}^{-1}}$).

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3.2 Impacts on the electricity market

How will the energy reallocation change the electricity market in Switzerland? First of all, the electricity demand would increase and the demand for oil would decrease. While the small market of Switzerland alone would not have a significant impact on the global demand for oil, a global energy reallocation would. Still, for the considerations of this paper the decreased demand for oil does not matter from a electricity grid mix perspective, since oil based electricity production is not present in the Swiss energy grid mix (except for imports). Thus, the decrease in oil demand is not considered further.

In a balanced market, demand and supply are usually in an equilibrium (see figure 5), which determines the price (Taylor 1975). The slopes of the demand and supply curves are determined by the respective elasticities (Taylor 1975). The elasticity indicates by how much the demand (or supply, in case of a supply elasticity) changes if the price changes by one unit.

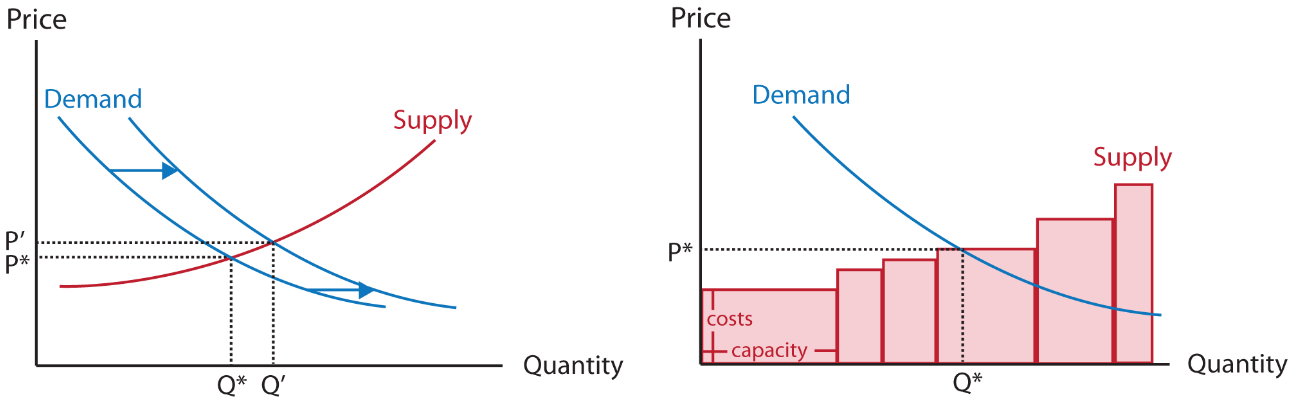

Figure 5: *(left) Demand and supply as calibrated elasticity functions, determining quantity of the good/service (Q) and price (P) in equilibrium (right) Supply as an aggregation of single technologies with a limited capacity and marginal production costs for each technology*

If new technologies (such as BEV) increase the demand level at a certain price, the curve will be shifted to the right. As long as the price elasticity of demand does not change, the slope (shape) of the curve will stay the same (figure 5, left).

The supply, electricity, is usually very heterogeneous, because the energy sources for electricity differ. Thus, the supply curve can be broken down into electricity sources with certain production costs and capacities (figure 5, right). As demand rises, the source with the lowest production costs will be used. Since this is only possible as long as the capacity of this technology is not reached, the next production technology (called marginal technology) will be activated if the demand is larger than the capacity of the first technology. More and more technologies will be used until the supply meets the demand. The electricity mix is then reflected by the technologies used up to the equilibrium point. Taxes would increase the production costs of a technology (usually because they internalize a part of the external costs caused by the technology) and may lead to a different production costs ranking, thus changing the electricity mix.

From above considerations, it becomes clear that the key to analyze the behavior of the energy market for a significant increase in demand is to find the marginal energy technologies and their costs. The relationship of the production costs of the margin technologies and the production costs of the technologies already in use today also determines by how much the energy consumption actually increases due to an increase in demand.

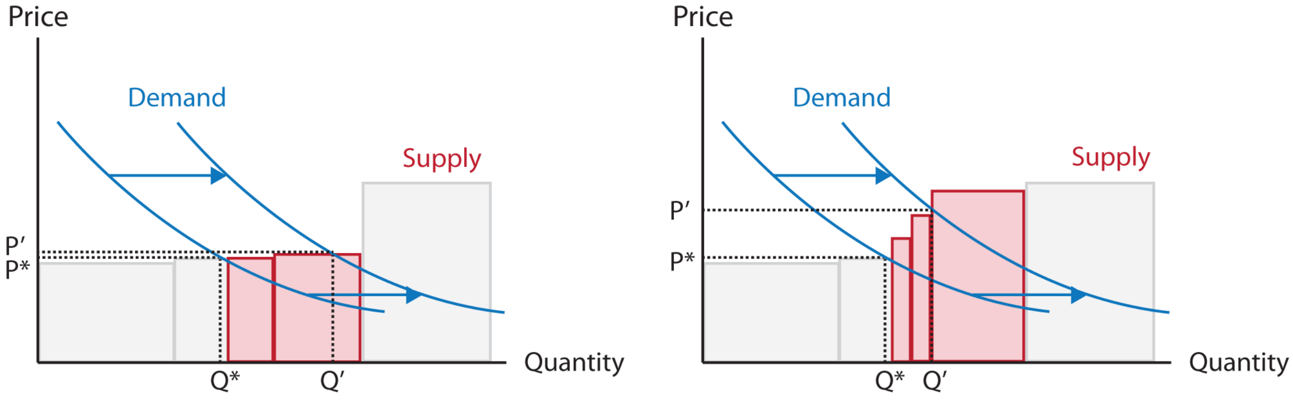

Figure 6: *(left) An increase in demand does not change the price if the added technologies have the same marginal production costs as the old price P*. The quantity Q rises by the same relative amount as the demand rose (right) If the marginal production costs increase in the transition zone, the price will rise due to the increase in demand. The quantity Q rises by a smaller relative amount than the increase in demand*

If the costs of the new technologies are the same (complete elasticity), the energy price won't change, and the energy consumption will change by exactly as much as the demand changes, which is the amount of electricity that has to replace the ICEV fuels (figure 6, left). The quicker the marginal costs of production increase with an increase in supply quantity, the lower the actual increase of electricity production due to the energy reallocation will be, and the higher the change in price will be (figure 6, right).

This model is however simplified. For example, the production costs may depend on the time of the day and/or the season (solar energy, pumped storage power stations, etc.). Also, government policies and votes may restrict or prohibit the operation of power plants, especially nuclear power plants.

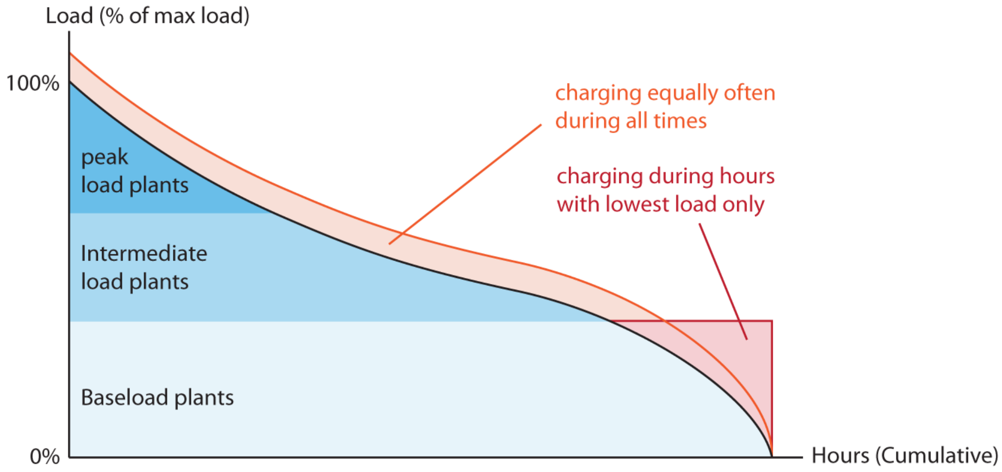

Figure 7: *Example of a load duration curve and the change of the curve if battery electricity vehicles (BEV) would be charged equally often during all times of the day (orange) and if the would be charged during hours with the lowest load (dark red)*

The first simplification, the time dependance of electricity demand, may in fact be quite relevant. This can be illustrated using a cumulative load duration curve (figure 7). The cumulative load duration curve shows how much electricity (in % of the peak load) has to be supplied during how many hours. The flatter the curve, the more equally electricity usage is distributed over time. If the BEV are charged randomly at any time of the day and year, the whole curve will be lifted, and all power plant types will have to be added by the same relative amount. In this case, it is likely that the electricity prices increase as long as the production costs of the added plants are higher than the average costs of the existing one (see above). However if BEV would be charged only when the load is lowest, it may even be that the current electricity generation infrastructure is sufficient to supply the additional demand. In that case, it is likely that the electricity prices do not increase, since the base supply plants tend to have rather high fixed costs and rather small marginal costs of production.

As for the situation in Switzerland, I would assume that it's mostly the nuclear power plants which supply the base load, and to a certain extent the hydroelectric power plants. Since both nuclear power plants and hydroelectric power plants can be assumed to be run already close to their maximum capacity, they cannot simply provide a higher output. Increasing the capacity of hydroelectric power through the installation of new plants is also hardly possible anymore within Switzerland. Also, this means that base supply will become even more limited when nuclear power plants are to be shut down soon. However, the pumps of some plants can be used to reallocate the supply. For example, reallocating base load supply to hours with higher loads is not only being done to fulfill the demand but also to increase the revenues from trading. Based on the findings from chapter 2, the rest of the (intermediate and peak load) supply consists of imported electricity from the European grid. Conclusively, the main reason why BEV should still be preferably charged during low load times (the night) is that pump energy and some (environmentally worse) electricity imports could be saved, because the load duration curve would be flatter.

To assess how exactly the Swiss energy supply would be affected for different charging behaviors, the capacities and operation costs of all relevant Swiss power plants as well as the import/export mechanisms would have to be known. However, this would go beyond the scope of this study.

3.3 Environmental Impacts

In order to assess the environmental impacts of the energy reallocation, both the impacts of the petroleum derivatives which are saved as well as the additional impacts due to increased electricity production have to be known. For the electricity production, the impacts are aggregated from the change of production in each relevant technology.

For this study, the impacts are taken from the EcoInvent database 2.2. Since this study focuses on climate change impacts, the IPCC Global Warming Potential (GWP) is taken. Specifically, the most recent indicator version (2007) for a time horizon of 100 years is used. A different time horizon would change the weighting of the global warming potential of greenhouse gases other than CO_2 in relation of CO_2. For the combustion of oil based products, as a simplification the impact of furnace burned refinery gas in Switzerland is taken, since it is readily available in the database. Both the gas combustion as well as the electricity supply were assessed from a life-cycle perspective, including the relevant cradle-to-gate impacts. As for the electricity, the impact of the Swiss grid mix is taken, which includes 20% electricity from UCTE countries.

Table 1: Global Warming Potentials (GWP) per MJ of energy for the combustion of refinery gas (as a simplified assumption for the combustion of gasoline/diesel) as well as different electricity mixes

	Impact [IPCC GWP 100a per MJ]
Refinery gas combustion, furnace, Switzerland	0.070
Electricity grid supply mix, Switzerland	0.031
Electricity grid mix, UCTE	0.142
Oil, burned at plant	0.868
Hard coal, burned at plant	1.088

Table 1 shows that the electricity mix of Switzerland has a lower GWP per MJ than the oil based fuel. On the other hand, the one of the UCTE countries mix (which consists of 24 countries) is more than double as high. The fact that the electricity production generally has a higher GWP than the oil based fuel combustion is related to the fact that the electricity is energy of “pure” quality (i.e., it consists of 100% exergy).

The drawback is that the efficiency to generate electricity from primary energy carriers is usually lower than the efficiency of generating gasoline or diesel from crude oil. From the quantitative energy reallocation estimates made in section 3.1, it is now possible to assess the changes in environmental impacts due to the reallocation.

Table 2 shows that even with the UCTE electricity mix, the GWP of the BEV is only about 54% of the GWP of the ICEV. If very climate intensive energy such as hard coal is used, the picture changes completely, and the BEV would cause about four times the climate change impact of ICEV usage. It is very important to note, however, that this analysis only assesses the GWP of the fuel itself. Neither does it consider the differences in GWP of the different vehicle types (BEV, for example, contain an environmentally rather unsound battery) nor are other environmental impacts besides the climate change impact considered. Granovskii et al. (2006) suggest that the higher GHG emissions of the vehicles themselves don't differ that much compared to the GHG emissions by the fuel consumptions, while the air pollution may indeed be a problem of BEV.

Table 2: Global Warming Potentials (GWP) of the reallocated amount of transportation energy as gasoline/diesel and as electric energy, considering different electricity grid mixes

	Reallocated energy	Energy carrier	Impact [IPCC GWP 100a]	Relative Impact
Situation now	105 PJ	Gasoline/Diesel	$7.35 \cdot 10^9$	100%
Swiss electricity grid mix	28 PJ	Electricity	$0.87 \cdot 10^9$	12%
UCTE electricity	28 PJ	Electricity	$3.98 \cdot 10^9$	54%
Oil	28 PJ	Electricity	$24.3 \cdot 10^9$	331%
Hard coal	28 PJ	Electricity	$30.46 \cdot 10^9$	414%

Applying these results to the findings of the impact on the electricity market, charging BEV during peak hours not only means higher electricity prices and higher operation costs for the vehicles, but also decreases the environmental performance of BEV operation compared to when charging them during low load hours.

However, charging BEV with climate friendly electricity removes this electricity from other consumers (e.g. exports), which have to use more electricity from other sources. This is often referred to as a consequential assessment approach and it means that, as long as the global total electricity production does not change, the total environmental impacts of production will stay the same, no matter when and where BEV are charged.

Still, the results from table 2 are meaningful because they show that even when using the UCTE mix, the “fuel” of BEV has a lower climate change impact than the one of ICEV, and the potential to make this impact very small using renewable energy sources is very large.

4. Conclusion and Discussion

Replacing 50% of the gasoline/diesel vehicles with electric vehicles causes electricity demand to rise 12.5%

The first part of the analysis showed that a replacement of 50% of the petroleum derived energy carriers used for domestic transportation in Switzerland in internal combustion engine vehicles (ICEV) with electric energy used in battery electric vehicles (BEV) would result in an increase in electricity demand of 12.5%. While this is not a negligible amount and it is afflicted with quite a lot of uncertainty, it is not unrealistic to provide this additional demand either. Of course, other possible sources of increase (or decrease) of electricity demand are completely neglected in this study, but would have to be considered when assessing the whole Swiss energy/electricity system.

The electricity price behavior depends on the elasticity of demand, the elasticity of supply and on the load duration curve and its change. BEV should be charged during times of low duration, but this may be less important as the capacities of the base load power plants are strictly limited

The qualitative analysis of the impacts on the electricity market showed that the behavior of the market price due to this increase in demand depends on what the marginal technologies and their production costs are. However, both the marginal technologies and their production costs depend on the change of the cumulative load duration curve. If the vehicles are charged equally often during all times of the day, the marginal production costs (and thus the energy price) will be higher than when vehicles are mainly charged during low load times. Because of the induced elasticity of electricity supply, the additional electricity consumption will be lower than what the energy reallocation calculations would suggest, because people will use less electricity in general.

If the vehicles would be charged mainly during the night, when the load is low, the base load power plants (in Switzerland mainly nuclear energy and to a certain extent hydroelectric power plants, which together account for 95% of the domestic electricity production) may be able to supply parts of the additional energy required. Since these power plants have rather high fixed costs (especially nuclear power) and comparatively low marginal costs of operation, the increase in electricity prices would be lower than in the first case (where the BEV are charged equally often during all times of the day). However, the capacities are limited, and nuclear as well as hydroelectric power plants can be assumed to be run close to the maximum (legal) capacity. Additionally, the future of nuclear energy is quite uncertain. Therefore, I concluded that the main reason why BEV should still be preferably charged during low load times (the night) is that pump energy and some (environmentally worse) electricity imports could be saved.

In order to provide a incentive to charge the vehicles at night, the hourly energy prices would therefore have to correlate well with the demand at that time. Studies show that the real-time price elasticity of electricity use is rather low, especially when people are not fully aware of these differences and the costs they could save (Lijesen 2007). Therefore, people should be made aware of these price differences, and other instruments to shift the charging to the times where the electricity load is low may be taken into account.

In terms of operation (fuels only), the BEV cause less global warming as long as the electricity grid mix is not much worse than the UCTE average mix. However, from a consequential point of view, the total environmental impact of the world's energy production does not depend on which electricity is used when charging the BEV.

Since the time when BEV are charged influences the marginal technologies used, they also influence the environmental impacts. The rough impact assessment of the fuels (gasoline/diesel or electricity) showed that even with the UCTE countries' electricity grid mix, the global warming potential of the BEV operation would be lower than the one of the ICEV operation. However, as mentioned in section 3.3, the BEV have higher environmental impacts when also considering the life-cycle of the vehicles themselves, especially when including air pollution as an impact factor. The increased air pollution mainly results from the production of the battery, and may therefore be less close to large numbers of people than the pollution caused by the combustion of oil based fuels.

BEV technology is much younger ICEV, and it is reasonable to believe that it offers more space for improvements also from an environmental perspective. But even if BEV are regarded as environmentally friendly, the attractiveness (both economic and in terms of features) of BEV compared to ICEV will be an important factor to make a high market share even possible. Apart from purchasing and operation costs (which will depend on electricity prices), improvements concerning the range have to be made. If the range is increased, it will also be less attractive to charge the vehicle during the day, which may decrease electricity prices, which again leads to an increased attractiveness of BEV.

A global perspective

On a global level, the decrease in demand for oil due to the reallocation of oil based fuels may play an important role, since electricity generation using oil may become more attractive and causes a lot of climate change. Carbon taxes may be a means to increase the internal operation costs of electricity generation technologies with large impacts on the climate. Also, a large share of BEV among road vehicles means that each improvement in the global average of environmental impacts of electricity production will immediately result in an improvement of the environmental impacts of transportation, thus supporting a sustainable development.

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