Bachelor Thesis

Economic evaluation of the investment required in Switzerland for the implementation of electric freight transportation

Ignacio Belanche Guadas

August 2020

Supervisor

Prof. Dr. Konstantinos Boulouchos

Advisor

Dr. Albert Mancera Sugranes

Abstract

To assess the impact of growing emissions, the decarbonisation of the heavy-duty freight transportation is considered. This sector of the road transport accounts for 25% of the emissions. Its electrification would have a significant influence in achieving the objective of net-zero emissions by 2050. However, the introduction of electric vehicles in the road network will cause an impact to the electricity market.

This study evaluates different approaches for freight transportation full electrification and the necessary investment to accomplish it. In chapter 2, a full analysis of the Swiss energy sector is done. Then, chapter 3 makes an analysis of the Swiss freight transportation sector. Chapter 4 presents the Swiss power grid, its characteristics and the consequences to the grid of having an electric freight transportation sector. Finally, the following chapters address the methodology, results and discussion, respectively, of the required investment for electrification of the sector.

Acknowledgments

I would like to express my sincere gratitude to my supervisor Dr. Albert Mancera Sugranes, who accompanied me through this thesis, suggesting new ideas all along, understanding my work and giving me advice to express myself in the best way possible. Thank you also to Prof. Dr. Konstantinos Boulouchos and the rest of the Energy Systems Group of LAV and the learning lab of Future Transport Systems in SCCER mobility for offering me the opportunity to work with them, always kind and respectful throughout all my thesis. Finally, a modest mention to my family, whom without their support this could have not been possible.

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List of Abbreviations

AC	Alternating Current
AF	Alternative Fuel
BE	Battery electric
BFE	Bundesamt für Energie = Swiss Federal Office of Energy
BFS	Bundesamt für Statistik = Swiss Federal Statistical Office
BWR	Boiling water reactor
CH_4	Methane
CHF	Swiss francs
CHP	Combined heat and power
CNG	Compressed Natural Gas
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CoM	Charge on the Move
CoS	Charge on the Stop
DC	Direct Current
EFTA	European Free Trade Association
EV	Electric Vehicle
EZV	Eidgenössische Zollverwaltung = Federal Customs Administration
gCO_2eq	Gram carbon dioxide equivalent
GHG	Greenhouse gases
GWP	Global warming potential
H_2	Hydrogen
HC	Hydrocarbons
HDV	Heavy duty vehicle
ICCB	In-Cable Control Box
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
IPT	Inductive Power Transfer
LCOE	Levelized costs of electricity
LDV	Light duty vehicle
LHP	Large hydropower
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
MPLW	Maximum Permissible Laden Weight
NOx	Nitrogen oxides
O_3	Ozone
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaics
PWR	Pressurized water reactor
RSE	Residual Standard Error
RSS	Residual Sum of Squares
SE	Standard Error
SHP	Small hydropower
SO_2	Sulphur dioxide
t-km	Tonne-kilometres
TSS	Total Sum of Squares
v-km	Vehicle-kilometres
VOCs	Volatile organic compounds
WP	Wind Power

1. Introduction

Anthropogenic emissions added to the already existing gases emitted by nature itself before human era, are changing the environment. Climate change, endangered species, health issues are some of the most important problems that environment alteration is causing among others.

There have been set specific objectives for 2050 that will try to mitigate or even stop the damage to the ecosystems. These targets are primarily aimed at greenhouse gas (GHG) emissions. One of the most important contributors for the emissions is the transportation sector. In Switzerland, this sector accounts for a 41% of the total GHG emitted to the atmosphere. Therefore, electro mobility powered with energy produced from renewable sources is a promising alternative to reduce the total emissions.

Increasing the number of electric vehicles (EV) has a direct impact on the electric power systems. Vehicles need of a constant energy supplier in order to power the mechanics of the vehicle. There are various technologies of supplying energy for electric vehicles such us overhead transmission lines, inductive power transfer (IPT) or carrying charged batteries. All of them have something in common, an electricity source is a must. Higher amount of EV on the streets, means higher electricity demand.

The scope of this thesis is to carry out an evaluation of the current transmission grid and the energy sector in Switzerland, whether is capable of supplying an additional electricity demand due to the electrification of the road, or an investment in current technology is needed. More specifically, a special focus is put in the heavy-duty freight transportation sector. Even if this sector accounts for a 3% of the total vehicle fleet in Switzerland, a 25% of the road transportation emissions are emitted by these types of vehicles.

In order to fully decarbonise road transportation there are different pathways that technically could achieve this objective. According to a study made by Transport & Environment the possible pathways are the following: first of all, direct electrification of vehicles with overhead catenary and electric batteries. Second of all, hydrogen fuel cell electric vehicles. And third of all, internal combustion engine (ICE) vehicles fuelled by liquid or gaseous electrofuels (Fournols et al., 2020). However, this thesis is going to be evaluating the full or partial direct electrification of the heavy-duty freight sector vehicles through electric batteries, i.e., part of the first pathway presented above, although overhead catenary is not considered. Moreover, these electric batteries are charged using conductive charging stations. Static stations in which energy flows from the grid into the battery and recharges it. This process is possible via a plug and a cable connecting vehicle and station.

2. Environment, climate and energy

a. Global environmental framework

GHG are changing ecosystems. Environment, animal and human health are being harmed by these mostly human-made gases. GHG alter the climate balance on Earth. Global temperature is increasing due to their accumulation in the atmosphere, acting as a barrier for the heat radiation to fly away the planet. Basically, these fluids absorb the radiation and reradiate the planet. The most common GHG in the atmosphere are carbon dioxide (CO_2), methane (CH_4) and water vapour. However, water vapour is not considered as an originator of global warming because it does not last more than a few days in the atmosphere. These gases are also produced by nature itself. However, the share of naturally generated gases is not the cause of global warming.

Natural generated GHG are a part of the atmosphere natural cycle. The planet has been capable of absorbing and cycling those natural generated GHG, until anthropogenic GHG were added to the total existing emissions. GHG of natural sources comes mainly from forest fires, oceans, lakes, permafrost areas, volcanoes and mud volcanoes. 90% of the GHG emitted in a forest fire is CO_2. These events account for a 37.8% of the total emissions from natural systems. Oceans play a major role acting as a carbon sink. Around a 60% of the amount of CO_2 absorbed by oceans is released again to the atmosphere. Basically, CO_2 is absorbed into the ocean and then used by the marine life in the water (Arcadia, 2017). The rest of wetlands (marshes, peat lands and lakes) have a high GHG emissions rate too. The dominant gas emitted is natural CH_4. As for areas where the ground is permanently frozen for 2 or more years, they are referred to as permafrost. These three different forms of water storage have a weight in the naturally generated emissions of 21.05%, 20.64% and 17.20%, respectively. “Volcanoes and mud volcanoes contribute relatively low amounts of GHG emissions, i.e., approximately 1-3% of the total”. Thus, total emissions from natural systems account for an estimated value of 29.02 Gt CO_2-eq per year, while human generated GHG were just above 36 Gt CO_2-eq per year (YUE & GAO, 2018). Figure 2.1 shows a comparison between natural and anthropogenic produced GHG. The planet is not capable of handling that extra amount of gases, hence an alteration in natural processes occurs.

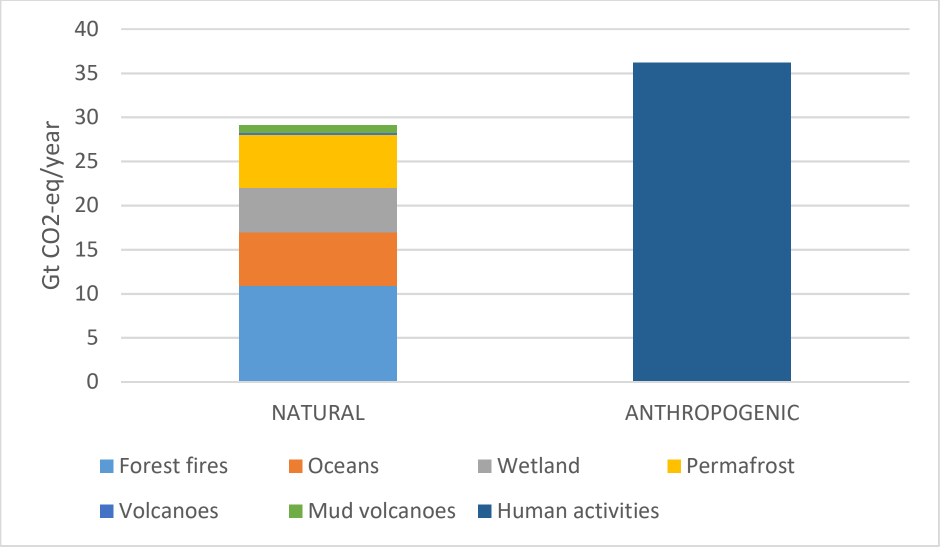


Figure 2 1: Greenhouse gases emissions from global natural systems and human activity (YUE & GAO, 2018)

As for human-made gases, a few more should be mentioned, as their presence in the atmosphere is significant too, ozone (O_3), nitrogen oxides (NOx) and chlorofluorocarbons (Mann, 2019). NOx are generated in combustion processes at high temperatures. Therefore, they are a by-product of industrial activities and combustion of fossil fuels, as well as agricultural practices. Their accumulation may cause smog and acid rain. Concerning chlorofluorocarbons (CFC), they have been extensively used as refrigerants, aerosol applications and solvents. CFC accretion will contribute to the reduction of the present O_3 in the atmosphere (Carey, 2008). The ozone layer protects the humans from harmful ultraviolet radiation from the sun. The chemicals referred to as ozone depleting substances have been regulated under the Montreal Protocol, approved the 15th of September of 1987 and ratified by every country belonging to the United Nations. The agreement reduces gradually the use of these chemicals. (OzonAction, n.d.)

GHG are characterized by their global warming potential (GWP). Each GHG has a different GWP. GWP of a gas is a measure to quantify the energy it traps in the atmosphere relative to the amount of CO_2 that would be needed to trap the same amount of energy, for a given period. The time period normally used is 100 years. CO_2 is the gas to which the rest will be correlated. Thus, it has a GWP of 1. For instance, 1 kg of CH_4 emitted to the air is relative equivalent of emitting 32 kg of CO_2, hence the GWP of CH_4 is 32. Nitrogen oxides have a GWP of 282 over 100 years. These three gases are the main GHG emitted, although the equivalence is applied to all GHG. The given GWP values are an average within a range of values that vary depending on the atmospheric conditions of the measuring site (*Understanding Global Warming Potentials*, 2017). This is the reason why GHG emissions are measured in CO_2 equivalents, where all the GHG are joined and represented together.

Modern civilization has been very dependent on fossil fuels since the Industrial Revolution. Fossil fuels main advantage is their capacity of generating high thermal energy, which is very convenient for electricity production. The higher the thermal energy, the more and faster amounts of heat can be achieved. Fossil fuels are able to develop a very stable exothermic reaction. For example, in a thermal power station where electricity is generated by the spin of a turbine due to pressure produced by water vapour, which drives an electrical generator, fossil fuels would be a good choice to heat up the water to produce the vapour. Thus, a higher amount of electricity would be generated. Nevertheless, the amount of GHG produced by these resources are extremely high compared with the zero direct emissions that renewable energies have. That is the main reason why many countries, those responsible of generating 55 percent of the global emissions, have come to an agreement in reducing the carbon footprint, i.e. gases produced by daily human actions will be minimized.

CO_2 is the gas that lasts longer in the atmosphere and the most abundant, compared to the rest. Therefore, it may be classified as the most important GHG mainly emitted trough the burning of fossil fuels. Around 1840s when the Industrial Revolution started, as the blue line in Figure 2.2 shows, CO_2 human emissions started to rise exponentially. Nowadays, the concentration of CO_2 in the atmosphere is almost double as it was before the revolution (Lindsey, 2020). In 2016, China accounted for 29% of global CO_2 emissions, being the country that emits the most GHG in the world (Wood, 2019). The minimization of GHG emissions will be carried out through stablishing short- and long-term objectives, in order to reduce at the earliest and as much as it is possible the damage to the environment.

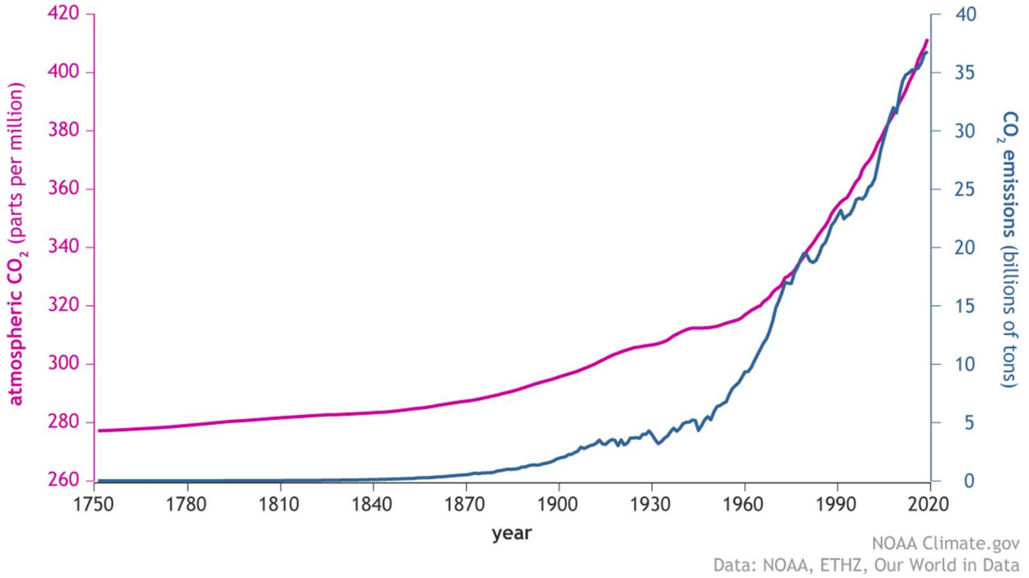


Figure 2 2: CO_2 in the atmosphere and annual emissions (1750-2019)

b. Shift to utilisation of cleaner energy sources

The main action to reduce the carbon footprint is to stimulate the use of cleaner energy sources. This energy comes from natural sources that are constantly replenishing themselves, i.e., the resources used are unlimited. They are commonly known as renewable energy sources. Nonetheless, direct and indirect emissions of each of these renewable energy generation processes have to be taken into account.

Direct emissions refer to the GHG emissions that an electricity production plant produces by the utilisation of any other sources in order to generate the desired demand of electricity. Contrarily, indirect emissions refer to emissions produced by external activities of the plant to generate that amount of electricity demanded. An example for each of the previous definitions applied to renewable energies brings a better understanding of the difference between both concepts. Aforementioned, renewable energy production processes main resources are constantly naturally regenerated. Current technology is capable of converting the energy possessed by these resources directly to electrical energy, i.e. no additional processes are required, whilst fossil fuels possess the so-called chemical energy, hence they would have to be burned in order to generate energy. That is the reason why renewable energies do not have any direct emissions. As a result, all the GHG emissions of renewable energies are due to indirect emissions. Indirect emissions account for the construction, maintenance and dismantling of the plant among others. To sum up, the main characteristics of renewable energies are that the resources used to generate the energy are unlimited, and they do not have direct emissions. That is the reason for willing to have them as main sources for power generation.

The utilization of clean sources is necessary to achieve a net-zero GHG emissions scenario. Net-zero concept implies that all GHG generate by human life must be removed from the atmosphere by reduction measures. The measures comprise the improvement of the actual combustion engine systems through the electrification of the transport sector, and the implementation of plants for capturing carbon dioxide directly from the air. Nonetheless, in order to accomplish net-zero emissions, both short and long-term targets are required. Short-term objectives will reduce the emissions, such as with the improvement of the efficiency that current combustion processes have, as aforementioned. And long-term objectives will cease the emissions. Thus, a severe mitigation of GHG emissions to the atmosphere would be carried out, stabilising the global temperature and the natural environment.

The objective for the reduction of the carbon footprint was reflected under the Paris Agreement. The consensus was stipulated between 2015 and 2016 and got effective the 4th of November 2016, targeting a maximum global temperature increase of 2°C. Even a further limit was proposed, pursuing a maximum temperature increase of 1.5 °C (United Nations, 2015). As for Switzerland is concerned, on the 6th October 2017 the agreement was ratified, setting two principal objectives: by 2030, a reduction of 50 percent of the emissions would be achieved compared to 1990 levels; and by 2050, the reduction would have to be up to 75-80 percent (FOEN, 2019). Since then, long term developments were discussed, and the Swiss Federal Council decided on 28th of August 2019 that Switzerland should reduce its GHG emissions to net-zero by 2050, to comply with the restrictions set by the Paris agreement. Consequently, net-zero emissions have become the dominant target for the Swiss industrial sector.

c. Energy sources and electricity sector of Switzerland

i. Swiss topography

Switzerland has a total surface of 41285 km^2. With around 1500 lakes which cover 3.5% and glaciers, 2.8% of the total surface, i.e. 1422 km^2 and 1140 km^2, respectively, and plenty number of rivers through all over the country. Lakes and rivers account for around 4% of the total surface. The geographical region of the Alps covers around 60% of the country (FOEN, 2013, 2017). Altogether, provide Switzerland for an exceptional topography to explode natural resources. Most importantly, the water flow available over the territory has provided the opportunity to generate the electricity based on hydropower.

ii. Swiss energy sector overview

Over the 1970s, Switzerland was producing up to 90% of the total electricity consumed in the territory by hydroelectric power plants. Even though, at this time the nuclear energy sector started to get important as new plants started to be built. Over less than ten years, four new nuclear power plants were constructed, and keep generating energy today. Consequently, the production of electricity based on hydroelectric power plants decreased to levels of 60%, and nuclear energy around 30% (BFS, 2019a). Nowadays, the share of hydroelectric and nuclear energy generation remains unchanged. The rest of the production comes mainly from renewable energy sources as biofuels, waste, solar and wind.

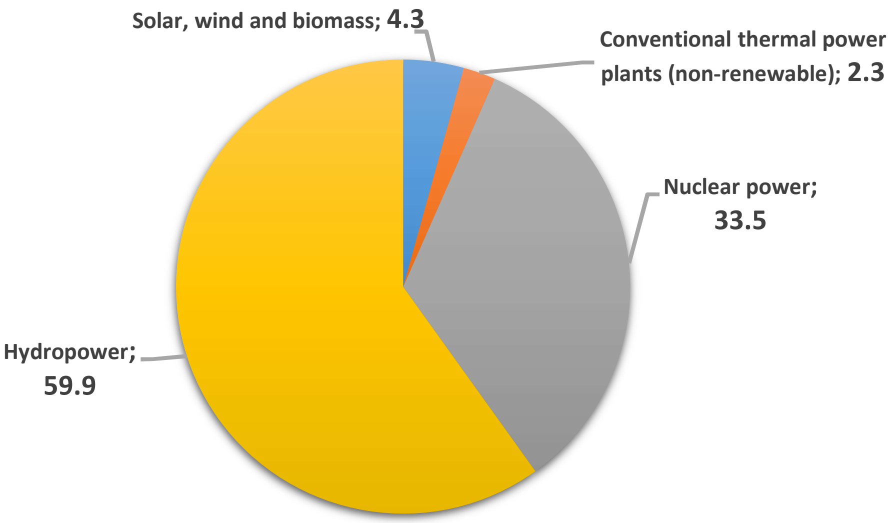


Figure 2 3: Electricity generation technologies share in Switzerland (Federal Department of Foreign Affairs, 2019)

Renewable energies have indirect emissions. These emissions must be considered too thus they play a significant part as the generation of GHG, such as in the process of building the energy plant. An additional example where indirect emissions are produced is when pumping water upstream in a pumped storage hydroelectric power plant. Conveniently, the electricity used to pump the water is generated from another renewable energy to minimize the emissions through the process. GHG emissions presented further on are quantified using a Life Cycle Assessment methodology and thus represent the complete fuel cycle/energy chain (Bauer et al., 2017).

iii. Swiss energy sector specifications

Besides the GHG emissions produced during the electricity generation process, a further issue to be concerned are the costs to produce that electricity. In 2018, the Swiss electricity market produced a total of 63.5 TWh for net domestic electricity. Contrarily, the electricity consumed in that year accounted for a quantity of 57.6 TWh. The difference between electricity produced and consumed is close. The closer it is the better, since it means that the efficiency of the generation processes increases, and electricity already produced is not lost. Otherwise, as the country generates more than consumes, it is able to export the extra electricity.

Electricity in Switzerland is distributed by 630 supply companies, also called utilities. 90% of them are owned by the public sector. The utilities produce electricity using the aforementioned industrial processes. They need to cover taxes, costs of personnel, materials, maintenance, construction and dismantling of the plant, etc. (Axpo, 2018). The current electricity generation costs for the different technologies are expressed using the concept of levelized costs of electricity (LCOE). This unit represent "the present value of the price of the produced electrical energy (usually expressed in units of cents per kilowatt hour), considering the economic life of the plant and the costs incurred in the construction, operation and maintenance, and the fuel costs" (Ragheb, 2017).

Hydropower

There are 638 hydroelectric power plants in Switzerland (Federal Department of Foreign Affairs, 2019). There exist mainly four types of hydroelectric power plants in Switzerland. First of all, and most important one, storage hydropower, with a capacity of 8,223 MW (17,208 GWh/year). Second of all, run-of-river plants, with a capacity of 4,132 MW (17,687 GWh/year). Third of all, pumped storage hydropower plants, 2,562 MW (1,554 GWh/year). Finally, basic water flow plants, 562 MW, much alike to the pumped storage plants, but the main difference is that the quantity of water that goes through the turbines is the same as the one pumped into the reservoir, i.e. no additional or natural water is required. In pumped storage plants, it is important to point out that less than the total water through the turbine is pumped. Obviously, in storage plants, there is no pumping.

It is required to point out that, as an exception, in hydropower there are specific direct GHG emissions during the operation of the hydropower plant due to the decomposition of organic matter. This type of emission starts when the reservoir is first filled with water. The reservoir of the plant contains the water that will be used to turn the turbines. Thus, GHG will be generated by the flooded vegetation and the new aquatic plants and plankton that will grow and rot in the reservoir. These emissions of GHG are produced during the lifetime of the plant. Basically, the main GHG are CO_2 and CH_4. On the one hand, most of the CO_2 emitted is due to the process of photosynthesis carried by the vegetation. On the other hand, CH_4 is produced by the decomposition of the organic matter (Hou, 2008).

Reservoir emissions are influenced by many parameters. The most important one is the type of ecosystem where the plant is located. Tropical ecosystems have a faster biodegradation than boreal ecosystems. The more the degradation, the more GHG are produced, hence tropical reservoirs generate the most emissions among the other types of ecosystems. Moreover, it is important to consider the influence of the depth and shape of the reservoir, the climate of the region where the plant is settled, and the type of hydropower plant designed. Therefore, while comparing between energy generation processes, the reservoir emissions produced in a hydropower plant have to be taken into consideration since their share of the total emissions of the plant is significant (Dones et al., 2004).

According to “Life Cycle Inventories of Hydroelectric Power Generation” by Karin Flury and Rolf Frischknecht, an average of a storage hydropower station has a capacity of 95 MW and an expected net production of 190 GWh/year. In the mean model proposed are include three types of hydropower plant of the mentioned above, due to their similarities. These plants are common storage plants, pumped storage plants and basic water flow plants. Including the emissions for the process of constructing and dismantling the plant, and emissions during their life-cycle, common storage plants sum up to 10.8 gCO2-eq/kWh, pumped storage and basic water flow, sum up to 155.1 gCO2-eq/kWh (Flury & Frischknecht, 2012). These last two have a much higher emission rate because they need more energy to pump water again into the reservoir.

Furthermore, as for run-of-river hydropower stations is concerned, an average design would have a capacity of 8.6 MW and an expected net production of 38.5 GWh/year. This translates in a quantity of emissions of 3.617 gCO2-eq/kWh (Flury & Frischknecht, 2012).

Knowing the different capacities of each of the hydropower plants types, it is possible to calculate the total amount of emission due to the generation of electricity via a hydroelectric system.

For hydropower companies there is a special expense called water fee. The water fee accounts for an average of 23% of the total expenses of the plant (Betz et al., 2017). This fee is a remuneration that must be paid to the owner of the water resource. Moreover, pumped storage plants have the highest costs, since their complexity is higher. Water needs to be pumped. Lately there have been large construction projects to expand existing pumped storage plants. For instance, in the Forces Montrices Hongrin-Leman hydroelectric plant, two new 120 MW turbines were added in 2017 (Harris, 2017).

Hydroelectric plants are going to be divided into large (LHP) and small (SHP) hydropower. On the one hand, LHP account for plants with capacities above 10 MW. On the other hand, SHP have an installed capacity below 10 MW. For both divisions, capital costs and amortization represent the largest share of the LCOE. Although, operation, maintenance and water fees are important cost factors too. The electricity generation costs for a run-of-river or a storage LHP are in a range of 7-30 Rp./kWh. For a run-of-river or a storage SHP, the generation costs vary between 12-28 Rp./kWh. Costs vary depending on plant site-specific investment aspects. (Bauer et al., 2017)

Nuclear power

The four new aforementioned reactors are: Benzau 1 and 2, both with a net capacity of 365 MWe each, Goesgen, net capacity of 1010 MWe and Leibstadt, with 1220 MWe (Nuclear power in Switzerland, 2020). There was a fifth called Mühleberg that started its operation around 1970s too. Although, in 2019 was permanently switched off. The administrative court ruled the decommission for security reasons. Basically, Mühleberg had an insufficient resistance to earthquakes and a lack of cooling (“Mühleberg plant to close in 2019,” 2013). The aim declared by the Swiss Federal Council in the ‘Energy Strategy 2050’ is the phase out of nuclear power (Federal Department of Foreign Affairs, 2019). The dismantling of Mühlebergs plant is the first step to achieve the termination of electricity generated via nuclear power plants.

On the one hand, the plant in Leibstadt is a boiling water reactor (BWR). On the other hand, Benzau and Goesgen plants are pressurized water reactors (PWR). These plants belong to the second generation of nuclear reactors. Developments required due to the pressure to increase safety and remain cost-competitive are driving nuclear plants to the third generation.

It was made a lifecycle study about the GHG emissions of the nuclear industry called “Dones et al., 2004c” where it was estimated that the emissions were between 5-12 gCO2-eq/kWh (Sovacool, 2008). From the Swiss Federal Office of Energy, using a life cycle assessment too, emissions were determined to be between 10-20 gCO2-eq/kWh (Bauer et al., 2017). That is the data that will be considered in further calculations, because the rest of technology emissions rates for electricity production in Switzerland are based on calculations of the same federal energy office document.

The lifecycle of a nuclear power plant includes a gran variety of processes starting with mining, through the enrichment of the uranium, the construction, operation and decommissioning of the reactor, fuel processing and conditioning, to the management and storage of the radioactive waste generated during the energy generation process. For example, the quantity of this last step in the emission of GHG is about 0.6-1 gCO2-eq/kWh (Dones et al., 2004). All these stages, as it happened with the hydroelectric generation, contribute to the generation of GHG emissions, making alternative electricity generation plants from fossil fuels still a non-zero emissions production.

Nuclear power plants are expensive to build. Although the operational costs and maintenance of the plant are low (Economics of Nuclear Power, 2020). The most important contributors to the LCOE for this technology are capital costs and interest rates. For the current operating plants Generation II in Switzerland, the electricity costs vary between 4-6 Rp./kWh. Nuclear plants belonging to the third generation would suffer an increase on the generation costs of 1.5 Rp./kWh, i.e., electricity costs would be a total of 7.5 Rp./kWh. (Bauer et al., 2017)

Besides hydroelectric and nuclear processes, the following energy generation processes supply the rest of electricity produced in Switzerland. They are a great approach to produce electricity under a net-zero emissions scenario. Since, they are in a developing phase, their share to the total is still low. These processes are biofuels and waste, solar and wind.

Biomass

Electricity produced from biomass is very heterogeneous. It can be generated from wastewater, agricultural manure or forest wood. The different electricity generation techniques with biomass are mostly classified as woody or non-woody biomass. Woody biomass has a low water content, hence they can be combusted directly. However, non-woody biomass is the opposite. It has a high liquid content. First, it must be treated with an anaerobic digestion, where biogas is produced. Then, this biogas is used to generate the electricity in a cogeneration (combined heat and power) plant.

A cogeneration plant produces two or more forms of energy from a single fuel source. This production model provides them with up to a 70% higher efficiency than single-generation facilities (Schleup, 2008). Basically, it is being utilised an output generated during the energy generation process that is normally wasted. Previously, it was mentioned the process of energy generation in a thermal power station. Heating up water and then produce water vapour, is the common process followed for electricity generation with biomass. In a cogeneration plant, besides the electricity generated, the heat and steam produced during the process are exploited too. For instance, they could be used in the heating and cooling systems for the building in which the plant is operating.

The current technologies for woody biomass generate electricity either by combustion or gasification in a cogeneration plant. Therefore, heat and electricity are produced. However, in Switzerland the most common technique is via combustion and mainly heat is produced. Upgrading this technique to a combined heat and power (CHP) process would rise the amount of electricity generated. “Woody biomass consists of forest wood, industrial wood residues, waste wood, and wood from landscape maintenance”. A range that represents the GHG emissions for the different combustion and gasification technologies in Switzerland is 10-120 gCO2-eq/kWh. Moreover, the average electricity generation costs for the available conversion technologies in Switzerland vary between 10-30 Rp./kWh.

Non-woody biomass includes “organic parts of household waste, industrial and commercial bio-waste, agricultural crop by-products, green waste, animal mature, and sewage sludge”. Via an anaerobic digester, biogas is produced. Electricity and heat are generated in an engine, turbine, or fuel cell. GHG produced from non-woody biomass feedstock comes mostly from methane leakages during the anaerobic digestion. GHG emissions available data for this type of biomass only applies to biogas produced on farms from manure. These emissions are between 150-150 gCO2-eq/kWh. Moreover, the electricity generation costs for this technique vary between 20-49 Rp./kWh.

Future improvements in this electricity generation source will focus on maximizing the electricity generated from the same amount of feedstock, “either by improving efficiency of the existing technologies or by developing new ones”. (Bauer et al., 2017)

Wind power

As for the wind energy industry, Switzerland has installed a total power of 75 MW. These turbines have an electricity production of around 132 GWh/year (IEA Wind TCP, 2017). The wind power (WP) industry is dominated by horizontal axis turbines with three rotor blades. The emission rate for Swiss wind turbines is around 5-30 gCO2-eq/kWh. Compared to European onshore turbines which have a rate of 5-25 gCO2-eq/kWh. As the previous technologies, capital costs dominate the LCOE. The electricity generation costs fluctuate between 11-19 and 4-16 Rp./kWh, respectively. Future developments in increasing turbines capacity will stimulate the decrease of the costs. An alternative location for WP farms is out in the water, commonly called offshore turbines. Offshore WP farms tend to be more expensive than onshore farms mainly due to site location. Offshore farms are located out in the water, hence building and maintenance is more challenging (Colby, 2019). For comparison only, an European offshore WP farm costs vary between 13-25 Rp./kWh. The emissions in this type of farms are pretty similar to onshore emissions rate. (Bauer et al., 2017)

Solar power

Nowadays, solar electricity generation is dominated by two mains types of panels. Panels made of mono-crystalline (mc-Si) and poly-crystalline (pc-Si) silicon cells. Each one of them have a GHG emissions of 73 gCO2-eq/kWh and 59 gCO2-eq/kWh, respectively (Dones et al., 2004). Pc-Si solar panels has less efficiency than the mc-Si, although they have a longer lifetime, cheaper production process and maintains the initial efficiency in the same values for a longer period of time (ABB, 2011). This reason is assumed to be the consequence for the lower gas emissions. Future developments will focus in reducing the costs of manufacturing and the improvement in efficiency. Solar electricity generation accounts for a 3.4% of the total electricity sector, with an overall power of 2172 MW (Luigi Jorio, 2019).

The most common photovoltaics (PV) installations in Switzerland are roof top. The most important installed capacity belongs to industrial and agricultural buildings. Around half of the installed capacity is in units below 100 kW. For a capacity of 100kW, the electricity generation cost is 15 Rp./kWh. In this technology, capital costs are the most important cost factor for LCOE. Module costs are expected to decrease in the near future, due to technology improvements. Module costs account for the direct and indirect expenses for purchasing and installing the equipment. Therefore, LCOE will decrease too. However, current electricity generation from PV technology is still comparatively expensive, “implementation within the next year will depend on governmental incentives and appropriate regulation”. This technology is the most promising to reduce costs, hence it will be a great alternative to the current electricity generation processes, as costs is concerned. (Bauer et al., 2017)

Figure 1.5 and Figure 1.6 show a compilation of the costs and emissions, respectively, for the electricity generation technologies available in Switzerland. Installed PV in Switzerland are half above 100 kW and half below 100 kW, and the majority of them have been assembled using crystalline-Silicon technology, as aforementioned. That is the reason why PV costs are represented as a power average of 100 kW, and only c-Si type panels are considered in the emissions graph.

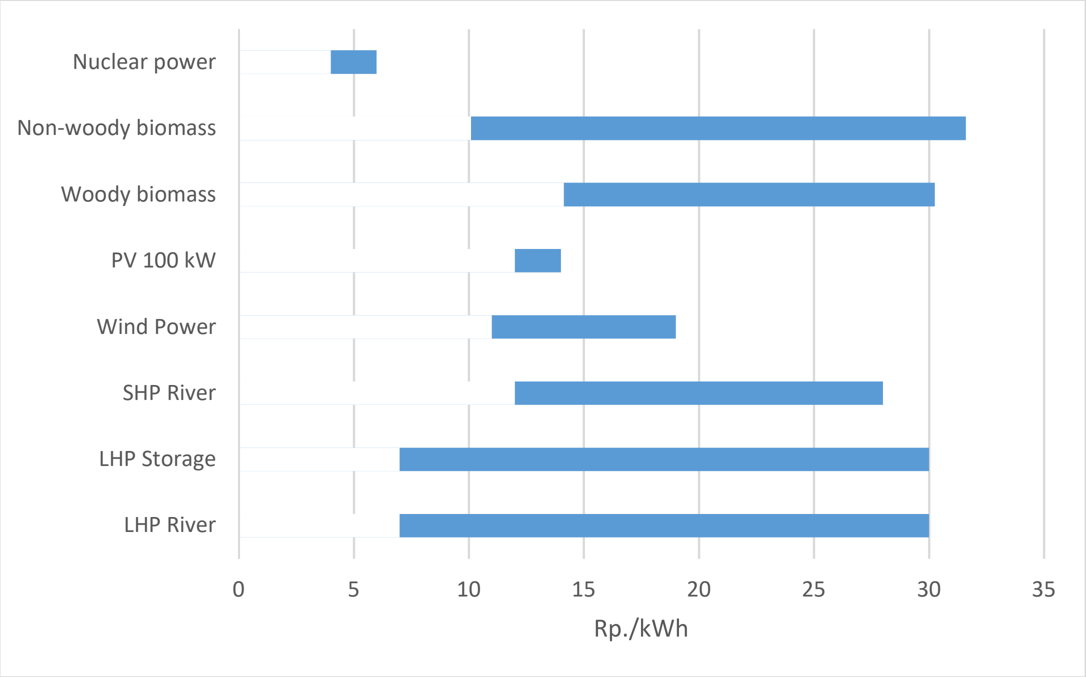


Figure 2 4: Electricity generation costs for each technology (Bauer et al., 2017)

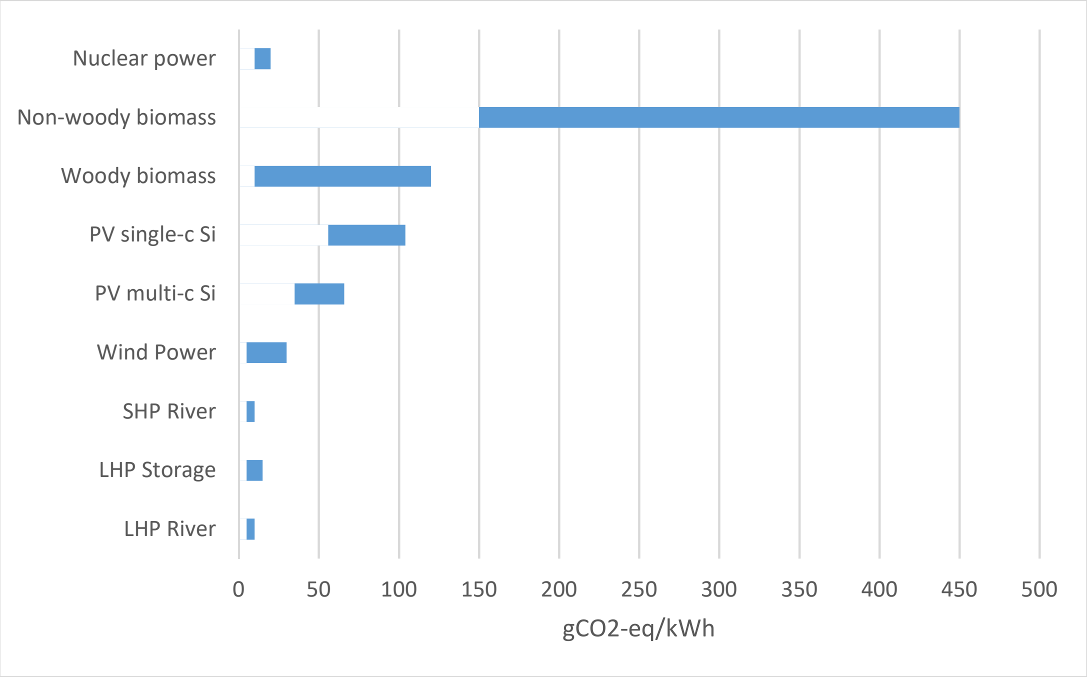


Figure 2 5: Electricity generation emissions for each technology (Bauer et al., 2017)

3. Swiss transportation sector

a. Road transport situation

The transportation sector concerns the movement of people and goods. These include from private cars, through trucks, to the transport infrastructure. In Switzerland this sector accounts for 41% of the total GHG emissions, a much higher share than in Europe, where the sector is responsible for 28% of the emissions. 98% and more than 70% of those emissions, respectively, are due to the road transportation (Thalmann & Vielle, 2019). Road transportation is mostly predominated by passenger cars, while heavy-duty transport vehicles represent only a 3% of the fleet. However, around a 25% of the road transportation emissions are due to these type of vehicle (Partners, 2016).

Road transportation emissions are characterized by the tailpipe emissions vehicles produce. Tailpipe emissions refer to GHG emitted during fuel combustion in the transportation sector. The chemicals emitted by a transportation vehicle are mainly carbon dioxide (CO_2), nitrogen oxides (NOx), hydrocarbons (HC), sulphur dioxide (SO_2), Ozone (O_3), particulate matter and volatile organic compounds (VOCs). On the one hand, HC generate when the combustion of fossil fuels is incomplete. HC mixed with NOx and sunlight forms photochemical pollution, i.e. smog. On the other hand, O_3 is not directly generated by vehicles. Although, O_3 is considered as a GHG, just ground-level ozone is accounted for. The formation of ozone occurs as a result of the reaction of NOx and VOCs with the sunlight. Concerning CO_2 and SO_2, these are generated by simply carrying out the combustion reaction (Tailpipe emissions, n.d.).

In order to have an estimation of the real emissions vehicles' transportation have, the determinant factor is vehicle-kilometre (how much registered vehicles are being utilised), since a stationed vehicle does not pollute. The freight sector vehicles are continuously on the road. The more a truck transports goods, the more revenue it produces, which is its economic purpose. That is the reason why the freight sector share is one of the most pollutant. The research evaluation is going to asses principally this consideration.

There are two approaches to show the variations to the vehicle fleet in Switzerland. The first factor is the vehicle stock. Vehicle stock refers to the number of vehicles registered in the canton/country where they are based. And the second factor is the number of new registrations. New registrations are included in the vehicle stock, but it has to be taken into account that there is a number of vehicles every year that are unregistered too. It can be concluded from Figure 3.2 that the number of new vehicles registered is higher than the number of vehicles unregistered, hence the vehicle stock increases. The vehicle stock together with the vehicle-km (v-km) covered by those vehicles are the factors that should be looked into in order to account the total emissions of the transport sector.

On 2019, the road motor vehicle stock was raised 0.76% than the previous year, and a 34% increase since 2000, summing a total of 6160262. Three quarters of this stock are passenger cars (BFS, 2020b), and 9% account for heavy-duty transport vehicles (IQPC, 2018a). In addition of the stock available, 409876 new motorised vehicles were registered, an increase of 3.7% compared to the previous year (BFS, 2020a). From the total newly registrations 2.5 percent were e-cars (Swissinfo, 2019), a modest indicator of the beginning to the electric transition. The passenger car industry is in an excellent path towards the electrification. The following step is to enhance improvements in heavy-duty vehicles (HDVs) to achieve the electrification of the road freight transport. Anyway, as Figure 3.3 shows, new registrations do not follow any specific trend. Every year has a particular variation. One of the few conclusions that can be taken out from the provided data in new registrations is the number of new electric vehicles that are being registered. Thus, it is known how the fleet is evolving into an electric fleet. Therefore, the emissions produced by the total stock of vehicles would be reduced, even though the number of vehicles registered increases.

Nowadays, there are a total of 35808 battery electric vehicles (BEVs) in Switzerland. It represents almost 50% of the total road fleet of alternative fuels vehicles. The Swiss BEVs also represent around the 3% of the total amount of BEVs in Europe (European Alternative Fuels Observatory, 2020). Besides BEV, other alternatives for an internal combustion engine are hydrogen (H_2), liquefied petroleum gas (LPG), compressed natural gas (CNG), liquefied natural gas (LNG) and plug-in hybrid electric vehicle (PHEV). Figure 3.1 shows the share of each alternative technology for road transport in Switzerland. BEV represents only the 0.6% of the total stock of vehicles in Switzerland.

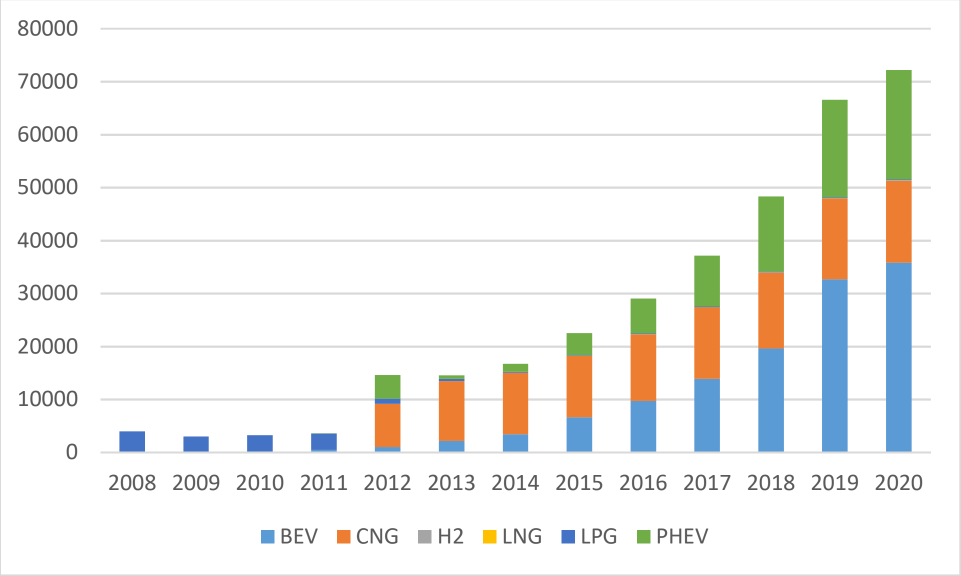


Figure 3 1: Total number alternative fuels vehicles in Switzerland (European Alternative Fuels Observatory, 2020)

In conclusion, the growth of road vehicles has a direct impact in the rise of GHG emissions. Nevertheless, the rise in the number of newly registered vehicles in the road does not imply an increase of the tailpipe emissions.

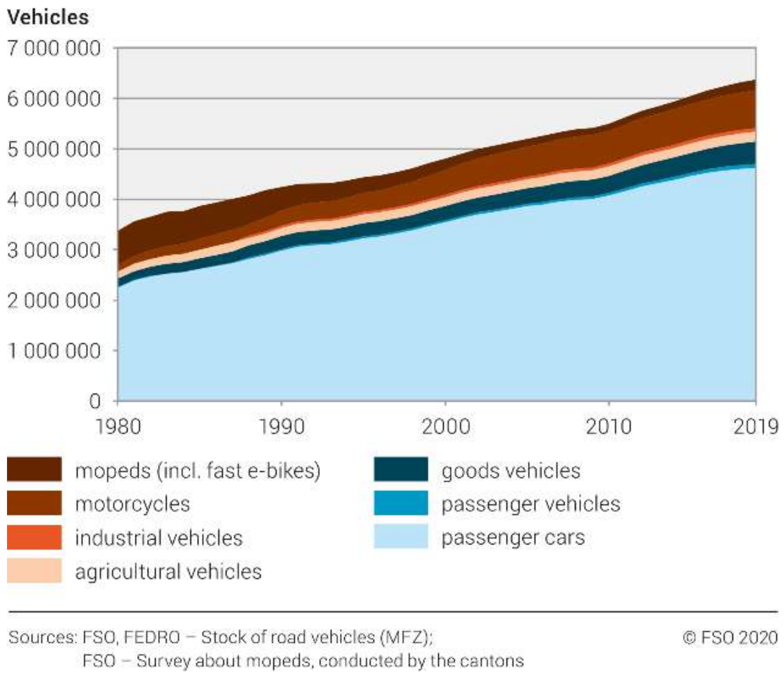


Figure 3 2: Stock of road motor vehicles

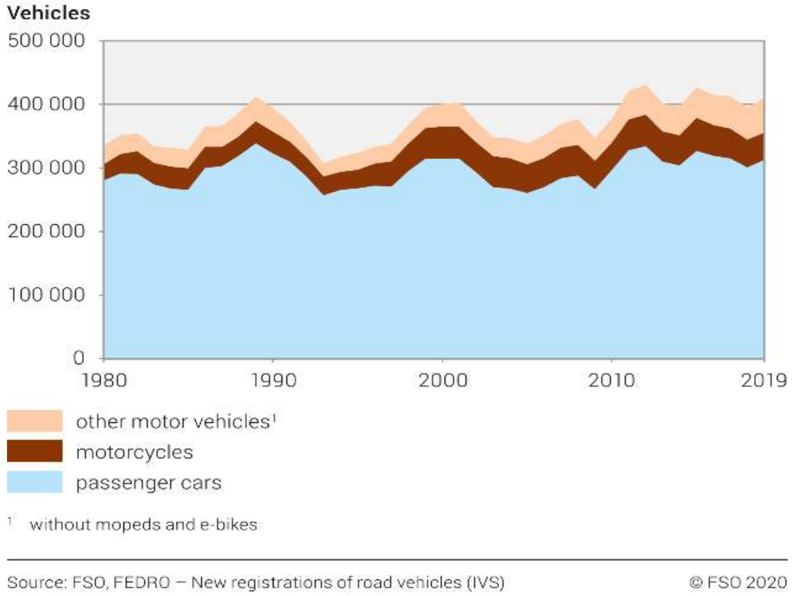


Figure 3 3: New registrations of road motor vehicles

b. Freight transport

Freight transportation is the process of transporting goods from one point to another, i.e., from an origin, where the good is assembled, to a desired destination. The last step of the transportation is the delivery of the product to the final consumer. During the transportation, goods may go throughout logistic facilities. These logistic facilities oversee the management of the freight in their way to their destination, e.g., warehouse, maintenance, reparation, assembling, packaging, etc.

Every logistic process applied to the product may be carried out in the same facility or in a different one. Consequently, it is necessary an additional transportation between those facilities in order to advance in the process of obtaining a final product. The combination of logistics and transport processes aforementioned is called transport chain. Figure 3.4 shows the schema of a transport chain.

Figure 3 4: Schema of a transport chain (Mancera Sugranes, 2017)

There are four main modes for transporting goods: air, rail, ocean/sea and road. Air freight transportation is the fastest mode of all four. However, it is the most expensive, hence it is suitable for goods that need to meet tight schedules (*Freight transportation*, 2020). “Rail freight strengths are in long distance transport, costs per unit transported, capacity, risk of accidents and pollution (compared to the other transport modes). Its weaknesses are mainly in the short distances and door-to-door as well as last mile shipments” (Mancera Sugranes, 2017). Ocean/sea freight transportation is the most inexpensive and simple mode. It is normally used by shippers whose products do not have time constraints (*Freight transportation*, 2020). Lastly, road freight transport. This mode of transportation is carried out by light-duty vehicles (LDVs) and HDVs. It is dominant in the short and medium transports, door-to-door deliveries. Nonetheless, it is an expensive mode per unit transported, due to the smaller capacity and need of personnel. And it produces a higher amount of GHG than the rest of the modes (Mancera Sugranes, 2017).

The transportation can be carried by multimodal or intermodal processes. Multimodal is a combination of two or more different modes of transportation. In which, during transport, the carrier has the option to repackage the goods to meet any requirements that the next carrier may have to continue the transport chain. Contrarily, in an intermodal process, carriers do not have permission to change the provided container, and therefore, from the origin to the end-costumer destination, goods are in the same package. The packaging for this type of process has to meet all the requirements of all those modes though which it is transported (Grabski, 2014).

Road freight transport sector can be divided into light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs). LDVs have a maximum permissible laden weight (MPLW) of less than 3.5 tonnes, while HDVs MPLW is higher than 3.5 tonnes. However, according to “Prospects for Electrification of Road Freight” (Nicolaides et al., 2018) a more detailed division of the sector in four main categories is done. The first category is ‘long-haul trucking’. It is responsible for the transportation of goods between national and regional (RDCs) and local distribution centres (LDCs) on the boundaries of the city. The routes that these vehicles use are mainly motorways and principal roads. The second category is called ‘urban delivery’. This group of freight transportation is in charge of deliveries within the edges of the city and LDCs to convenience stores inside the cities or even directly to individual shops. The supply is made mainly via principal urban roads with moderately short and predictable routes. The third category is ‘home delivery’. It comprises the transportation of goods from LDCs to end-consumers performed by LDVs. Finally, the last category involves “other operations within the area of municipalities, such us as refuse collection functions, buses, etc.”. It is denominated as ‘Auxiliary services’ (Nicolaides et al., 2018).

The freight transport sector in Switzerland accounts for a 7% of the total vehicle stock. This amount corresponds to around 441 thousand of good vehicles (BFE, 2020). As stated before, it does not necessary mean that each of those vehicles is active in the Swiss roads, i.e., make use of the road network. However, the majority of this type of vehicles are bought for delivering purposes. In other words, if a company owns one, it is because it is needed, and therefore it will be used, hence be an active vehicle. For example, it was estimated that the active fleet for HDVs is around 52800 (Çabukoglu et al., 2018). This translates in a 12% of the Swiss good transport vehicle fleet. This amount coincides with the number of HDVs in the stock presented by the BFS. Therefore, for the purpose of this thesis, this will be considered the total amount of active vehicles.

The thesis is focused in the road freight transport and its electrification. It is helpful to have an overview of it in order to design and estimate a better electrical distribution network for electric truck charging.

c. Swiss transport performance

GHG emissions are still rising. As previously mentioned, a decline of registrations does not mean that there are less vehicles on the road. Indeed, the fleet keeps increasing, as the goods and people transported do. Freight transport generated in Switzerland 17.7 billion tonne-kilometres in 2018, i.e., 30% more than in 2000. 95% of the total tonne-kilometres were performed by heavy good transport vehicles. On that same year, passenger transport accounted for a total of 135.7 billion person-kilometres (except aviation), i.e., 33% more than in 2000. 75.2% of the total person-kilometres accounted for private motorised vehicles. As it is shown in Figure 3.5a and Figure 3.6, the trend for the number of goods and people transported, respectively, is positive.

Firstly, tonne-km is an indicator that multiplies trucks pay load and travelled distance. Thus, the rise in tonne-km may be due to an increase in one or both factors. Secondly, vehicle-km or person-km are indicators calculated multiplying the number of vehicles or people, respectively, on the road, times the distance covered by them. Vehicle-km is measuring the kilometre performance, which refers to as the total distance covered by vehicles within a given period of time. Tonne-km and person-km are measuring the transport performance. Transport performance refers to the total of distances covered by goods or persons, respectively, within a period of time.

Freight transport covered 6.8 billion vehicle-km in 2018, an increase of 29% compared to 2000. Nowadays, LDVs have a higher share than HDVs have in Swiss roads, as Figure 3.5b shows. Moreover, private motorised road transported performed 61.5 billion vehicle-km, 30% higher than 2000.

In figure 3.5b, HDVs vehicle-km have been around a constant value of 2 billion since 1995, whereas in Figure 3.5a, the tonne-km for HDVs kept rising overtime. The conclusion of the comparison of both graphs is: the rise in tonne-km of HDVs is due to the rise of trucks payload transported. This includes a higher amount or higher weight of the goods transported. An explanation for this behaviour is that HDV vehicle-km have stayed constant, hence the number of HDVs and the distance covered by them are constant too. Tonne-km are the distance covered times the trucks payload, as aforementioned. Granted that the distance covered is constant, then the unique possibility for the augmentation is an increase of the truck's payload. Otherwise, for LDVs the outcome for both graphs are the opposite. Tonne-km stood more or less constant overtime, while vehicle-km increased. Consequently, the number of light vehicles has increased.

Another outcome from the performance of the Swiss freight transport is that HDVs have higher distance routes on average than LDVs. In Switzerland, the amount of business days is around 300 (this number has been calculated by not counting Sundays neither Swiss holidays). By looking at the data, the amount of vehicle-km done by the Swiss transport is 6.8 billion v-km in 2018, as aforementioned. Thereby, having stated before that v-km are equal to the number of vehicles times the distance covered by them, it can be known the average values for the distance that is being covered in a normal business day by each type of the presented freight transportation vehicles. See Table 3.1.

	% of total v-km	Swiss active fleet	Distance covered per vehicle per year (km)	Distance covered per day (km)
HDVs	33	52804	41663.5	139
LDVs	67	387991	11856	40

Table 3 1: Average distance covered by HDVs and LDVs in a business day

From a different source, a HDV covers almost 35000 v-km (Çabukoglu et al., 2018). This means that instead of having a distance covered per day of 139 km, it is of 117 km. Further on, it is this value the one considered for the evaluation. Basically, it is the one taken into account for the calculation of the extra demand needed for electrification of HDVs. And this estimation is used in the evaluation too.

An explanation for the behaviours aforementioned in why the payload of HDVs has increased without increasing the number of vehicles, or why the number of LDVs have increased may be the following. First of all, a delivering company has mainly a specific number of customers to provide its services. This translates in having repetitive routes for their delivering trucks fleet. Therefore, the routes are easier to be planned, scheduled and optimized for certain dates (Hall & Lutsey, 2019). For instance, a food truck delivers from point A to point B every week on Tuesday. Therefore, the HDVs share of the freight sector is suitable to be optimized. In other words, there has been an improvement in the efficiency of freight logistics such as load-matching and maximizing the capacity.

Second of all, LDVs transport goods from point B, aforementioned, directly to end-customers. “The majority of LDVs are involved in collections and deliveries that require short distances between stopping points” (Browne et al., 2010). The growth of home delivery sales and the number of households are partly responsible for the growth in the LDVs fleet and vehicle-km travelled by them. Both arguments keep growing stronger. In 2016 there was an increase of 8.3% in the amount of CHF spent via online shopping (Swissinfo, 2017). Altogether make routes and goods transported different every time. In addition, this part of the freight sector highly depends in the number of goods available to be delivered too. For instance, a LDV has the zone A assigned, hence depending on the amount of goods that needs to be delivered on day X, the vehicle will be more or less loaded. Therefore, because of the variety in type and number of goods delivered, the LDVs division of the freight sector is difficult to be optimized. Both statements presented above may be the reason for the behaviours shown in Figure 1.3.

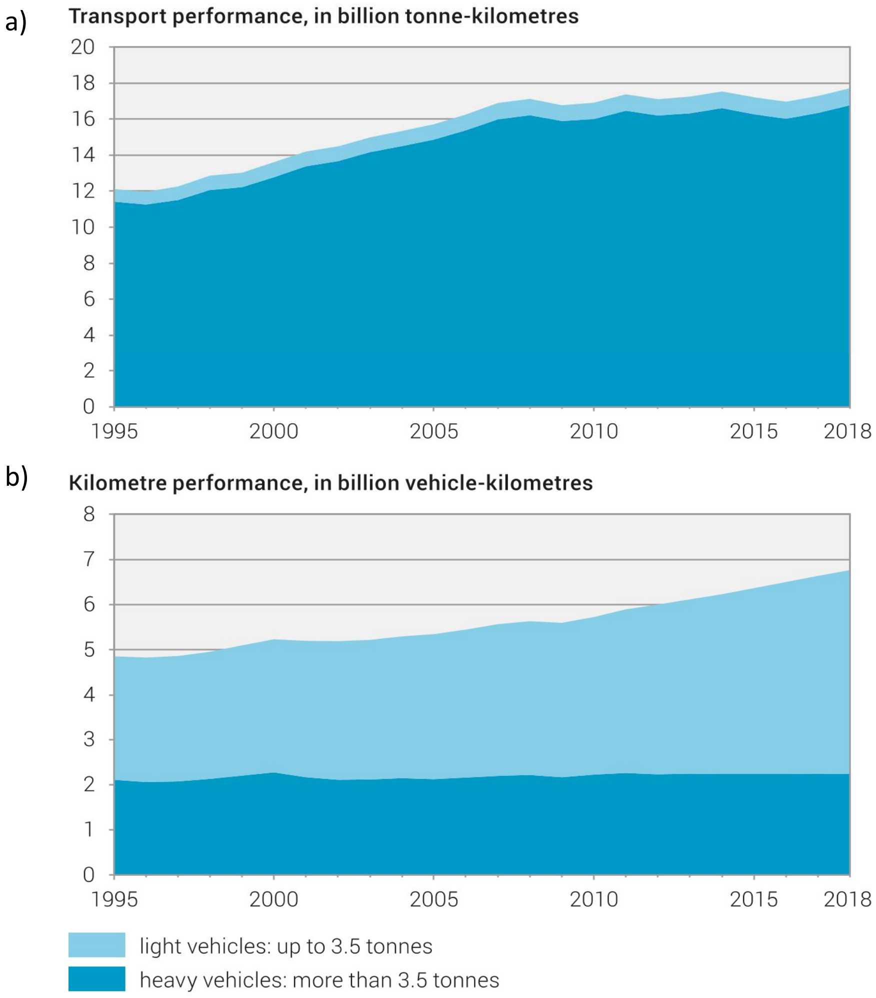
For private mobility, the arguments before commented are not valid. Both transport and kilometre performance have increased. Hence, the reasons for the continuous increase seen in Figure 3.6 may be a growth in the number of vehicles in the roads, the number of persons transporting, the distances covered or a combination of them. However, the vehicle stock has kept rising, as aforementioned. Therefore, along with all the considerations exposed, it can be considered that the number of vehicles in the roads have increased.

As a side note, for the freight sector, transport performance is a suitable measure unit for emissions quantification. Truck payload has to be considered when talking about emissions. An unloaded truck does not emit as much as a loaded truck. Road freight emissions depend on travelled distance and payload, among other factors. Tonne-km measure unit represents the previous consideration. On the contrary, for the vehicle-km measure unit the vehicles considered have variations. Each type of vehicle has its own amount of emissions. Therefore, it could be known the real emissions caused by the freight sector, because it considers every vehicle transporting goods. However, it is more homogenous comparing a tonne of goods transported by a type of vehicle, than comparing the emissions that two different loaded trucks have. The kilometre performance might be used to talk about the infrastructure capacity, road congestion or intensity of vehicles use (BFS, 2019b, 2019c).

Consequently, as the HDVs are more loaded, the number of LDVs and private mobility vehicles are increasing regularly, it can be said that the GHG emissions are increasing too. Given that the transport fleet grows in a faster pace than the technology to reduce emissions. Besides the previous statement, there are a couple more factors to be considered. According to the Swiss Federal Office of Energy (BFE), the rise in emissions is also assisted by a shift away of diesel engines because of the bad reputation gained with the high NOx emissions that produce and the growing number of owners of 4x4 vehicles, mainly in private transportation. As for the aim of this research, in the freight transport sector “97.9% of all medium and heavy trucks sold in the EU ran on diesel, 0.1% ran on petrol, 1.7% ran on natural gas, 0.2% were electrically-chargeable and 0.1% were hybrid electric” (European Automobile Manufacturers Association, 2020). Diesel is still the dominant fuel type (Partners, 2016). Simultaneously with the particularity of a HDV of being continuously on the road, the freight transportation is one of the most capable sectors in causing a great reduction of the total GHG emissions by transferring the fleet to a total electrified sector. The electrification of road transportation has the potential of offering zero tailpipe emissions.

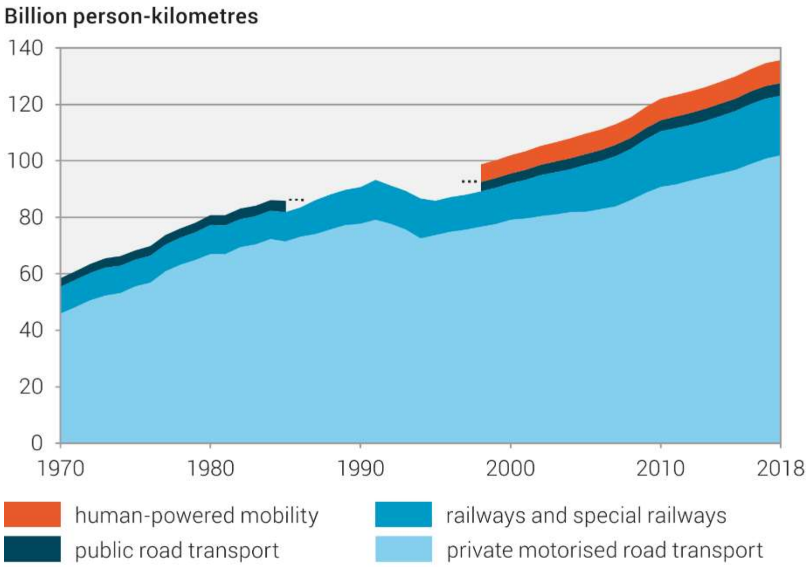
As seen in Figures 3.5 and 3.6, passenger and freight transportation demand have been increasing for the past decades. This translates into a growing vehicle fleet and more kilometres travelled by those vehicles. Thus, the transportation sector is the only sector that has not reduced GHG emissions in recent years. Between 1990 and 2016, total Swiss GHG emissions were reduced by 10%, while emissions from the transportation sector were increased by a 4.5% (Thalmann & Vielle, 2019). A long-haul diesel tractor trailer produces an amount of emissions around 1700 gCO2/km (ICCT, 2018), compared to the EU average car emissions of 120 gCO2/km. Nonetheless, cars in Switzerland have a slightly higher average emissions than in Europe, 135 gCO2/km (Thalmann & Vielle, 2019), being amongst the highest in Europe.

Data shows that drastic measures have to be adopted in order to accomplish the objective from the Federal Council. “A key element in reducing GHG emissions will be the shift to less environmentally strenuous sources of power for the road freight sector” (Partners, 2016). Primarily, improvements of vehicle designs and fuel technologies may reduce emissions, however, these are not long-term solutions. One of the most promising alternatives are battery electric (BE) trucks. They have a higher potential to save emissions per vehicle than any other vehicle to date (IQPC, 2018b), because the emissions per kilometre of trucks are more than ten times higher than cars.



Source: FSO – Goods transport statistics (GTS) © FSO 2019

Figure 3 5: Goods transport by road (Performance by type of vehicle)



Sources: FSO – Passenger transport performance (PV-L), public transport statistics (TP) © FSO 2019

Figure 3 6: Passenger transport performance

Nowadays, the cost for a BE truck are much higher than a diesel truck (IQPC, 2018a), mainly due to the batteries used to store the energy. “Batteries account for a major part of the vehicle cost” (Schulte & Ny, 2018). However, once technological advancements are made, costs will substantially decrease, and BE trucks will be able to outcompete all other heavy-duty trucks. In addition, it has been proved that “advances in the electric motor and power electronics components have resulted in significant gains in energy efficiency offering impressive improvements in range per charge” (IQPC, 2018a). Once these barriers are managed, and as long as the electricity needed to charge the electric vehicles is generated from a non-pollutant source, i.e., clean renewable sources, the target could be achieved.

For every electric vehicle added to the fleet, there is a direct impact in the load on the Swiss electric power system, i.e., an increase in the electricity demand. Electricity that will be mainly used to charge the electric batteries. Moreover, indirect energy consumptions are the extra processes needed to build the electric vehicles and the charging stations required. Both direct and indirect actions have to be supply from renewable energy plants, in order to maintain the net-zero emissions.

d. Road network

The Swiss road network is divided in three type of roads. The network is known as Autobahn/Autoroute network. First of all, motorways (or in German known as “Autobahn”) are characterized by a strictly separation with the oncoming traffic, and at least a couple of lines each way. The maximum velocity is 120 km/h. The Swiss motorway network is about 1800 km long (BFS, 2020c). See Figure 3.7. Motorways are named according to the following patter: a letter A followed by a number. In order to be able to travel using the motorways a fee of 40 chf has to be paid (EZV, 2020b). This fee applies for vehicles with a MPLW lower than 3.5 tonnes. As for the HDVs (that have a MPLW higher than 3.5 tonnes), the so-called LSVA is applied to them, in order to be able to use the Swiss motorway network. This HDV tax “depends on the total weight, emissions level, and kilometres driven in Switzerland and the principality of Liechtenstein” (EZV, 2020a).

Second of all, there are roads known as expressways or highways (known in German as “Autostrasse”), where the two directions share the same road. The standard velocity in them is 100 km/h. The amount of travel distance for this type of road in the network is around the 25% of the whole road system (around 18000 km). Third of all, the rest of the roads: the communal roads. These include roads inside the cities/towns, roads connecting highways to other highways, or connecting to cities, etc. The distance covered by these roads is the greatest of all. These involve around 70% of the total network (Martin Ruesch, 2006). Therefore, motorways are equivalent to 5% of the total.

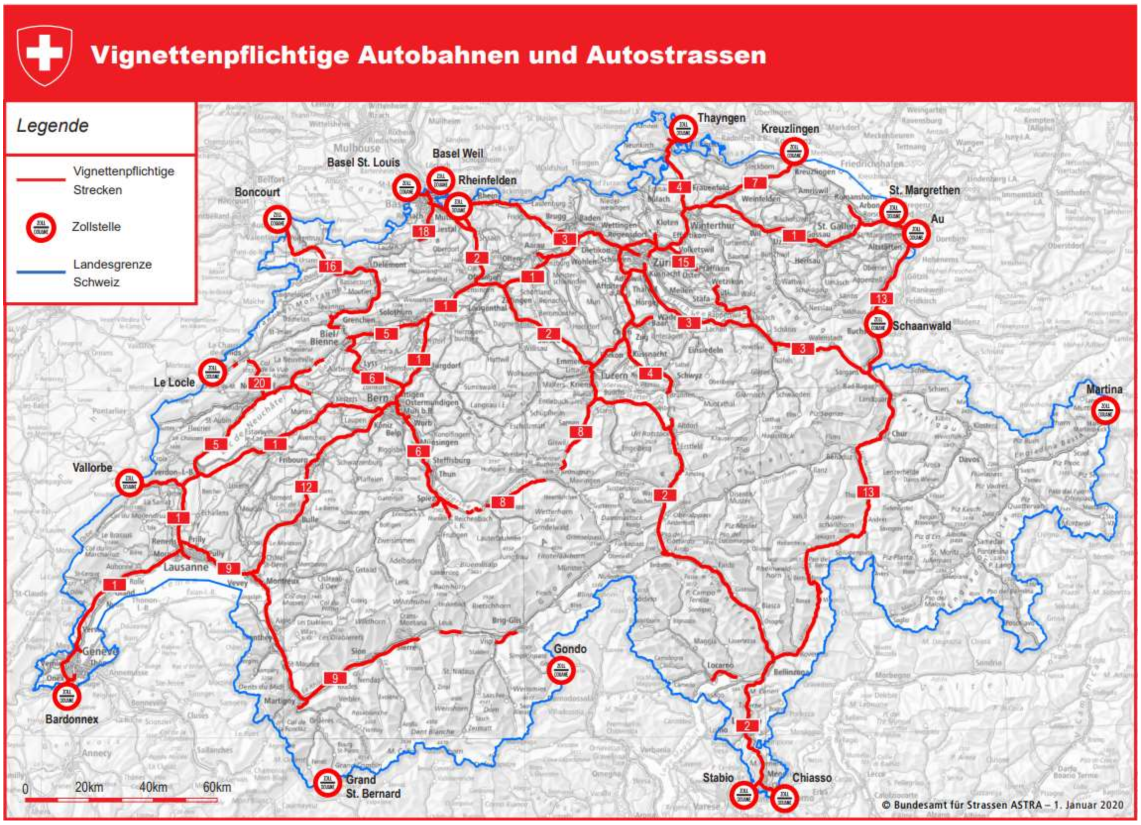


Figure 3 7: Motorways and highways where the Vignette/LSVA tax applies (EZV, 2020b)

e. Electric vehicle market

Nowadays, there are automobile companies already manufacturing electric vehicles. Here in Switzerland, the company E-Force One AG was founded in 2012. Their objective was to smooth the way to the electrification of the heavy freight transport. It was in 2013 when they first launched the world's first series-produced all battery electric powered 18-tonne truck (E-FORCE One AG, 2020). Moreover, Coop Switzerland has in operation this truck since 2014 in the region of Zurich (Wikipedia, 2020). Today, a total of four eco-efficient HDV models are being manufactured by E-Force (EF18, EF18 SZM, EF26 and EF26 KSF), in addition to technological equipment such as batteries. However, the innovative technology for the drivetrain and battery for the trucks stays mostly the same in all the models. Therefore, the body of the model chosen depends on the applications and requirements that the truck must meet. Basically, models EF18 weighs 18 tonnes, and the EF26 weighs 26 tonnes. Both of them have a permitted gross vehicle weight rating (GVWR) up to 44 tonnes. They have stated that the features of the electric devices may vary depending in the driving profile, and the type of performance the trucks are used for. Moreover, it is accurate to say that more electric power is needed to pull a 26-tonne truck, than an 18 tonne one. Therefore, the characteristics values given in Table 3.2 may differ from what has been stated, or they are given in a range of values.

Another example for a company manufacturing electric trucks is BYD. "BYD is a high-tech company devoted to technological innovations for a better life. BYD is dedicated to providing zero-emission energy solutions. BYD is listed in the Hong Kong and Shenzhen Stock Exchanges, with revenue and market capitalization each exceeding RMB 100 billion" (BYD, 2018). The conversion from the Chinese Yuan Renminbi to Swiss francs on the 12 August 2020 is 1 RMB equal to 0.13 CHF. This relation has maintained similar for the last 8 years (XE, 2020). They offer a variety of technological products, such us passenger vehicles, batteries, rail transit infrastructure equipment, electronics, commercial vehicles, etc. Among those commercial vehicles there are vehicles intended for freight transportation. This Asian company has been selected just for the purpose to do a comparison with E-Force technology available in Switzerland.

The third example for electric trucks that is going to be presented is not from a specific company that assemblies them, but from a research paper from the United States where three models of trucks are presented. They represent the freight transportation sector in the US. The models of trucks correspond to three different applications. First of all, long-haul tractor-trailer. They have delivering routes that involve multi-day shifts rather than frequent returns to the starting base. They are the trucks with the highest GCWR out in the roads, and account for the highest share of fuel consumption and GHG emissions. Therefore, their electrification would have a great impact. Second of all, the drayage trucks. They carry shipping containers within and around ports. They have short routes, low speed travels and frequent stops. Therefore, they are a very good opportunity to have an early electrification. As it has been mentioned, adding in the logistic facilities charging points could solve most of the battery capacity and range limitations. And third of all, delivery trucks. These are the ones in charge of the last kilometres freight. They supply to commercial, industrial and residential addresses, and then they return to the depot base. HDVs that carry out this application have a certain resemblance to drayage trucks. Therefore, the electric infrastructure needed is similar (Hall & Lutsey, 2019). The specifications for each of the three applications mentioned are seen in Table 3.4.

The previous examples for electric truck models have been presented to get an overview of the current technology available in different markets for freight transportation. The technology used for the E-Force trucks, four different trucks manufactured by BYD, and three truck models for three different applications have been selected. The specifications for each of the models are presented in Tables 3.2, 3.3 and 3.4, respectively. For example, it can be noticed that the model T3 is a LDV, whereas the rest of the vehicles belong to the HDVs part of the sector, according to the division made by BFS.

E-FORCE		EF18/EF26
GCWR		up to 44 ton
Maximum range		350 km
Supported charging output		up to 500 kW
Battery capacity		170-340 kWh
Charging capacity		AC 44 kW (up to 8 hours)
		DC 350 kW (less than 1 hour)
Consumption	Urban	80-120 kWh/100 km
	Highway	130-180 kWh/100 km

Table 3 2: E-Force electric truck model specifications (E-FORCE One AG, 2020b)

BYD	T3	T5	T7	T9SJ
GCWR	6100 lbs (2.767 ton)	7.26 ton	10.6 ton	28 ton
Range	155 miles (250 km)	250 km	200 km	200 km
Battery capacity	43 kWh	150 kWh	175 kWh	217 kWh
Charging capacity	AC 40kW	AC 100 kW DC 150 kW	AC 100 kW DC 150 kW	DC 150 kW
Charging time (hours)	1 hour	AC 1.5 hours DC 1 hour	AC 1.8 hours DC 1.2 hours	2 hours
Source	[1]			[2]

Table 3 3: BYD electric trucks models specifications (1 mile = 1.61 km; 1 lbs = 0.45 kg)

[1]: (BYD, 2019); [2]: (BYD, 2017)

Applications	Long-haul truck	Drayage truck	Delivery truck
GCVWR (kg)	36300	27500	11600
Tare weight (kg)	15030	9330	4800
Battery size (kWh)	600	500	300
Range (no trailer/empty)	400	340	277
Range fully loaded (km)	306	282	264
Average distance route (km)	1850	90	50

Table 3 4: Electric truck models specifications considered for three different applications (Hall & Lutsey, 2019)

However, for the scope of this thesis, the model that is considered for the calculation of the investment are the drayage trucks. The main reasons for this choice are the following. First, a Swiss HDV has an average route of 117 km per day. Compared to the one for a drayage truck of 90 km (it is the closest one). Second, the ICCT paper provides specific data on infrastructure needs and costs for each of the applications presented. Therefore, the estimation for the investment needed is much more accurate. Even tough, it is still going to be an approximation due to differences between the Swiss freight sector and the describe for drayage trucks (average distances covered, speeds, payload, etc.).

4. Power grid

a. Swiss transmission grid

The Swiss transmission grid is a 50 Hz AC system owned by Swissgrid. The grid is more than 6700 km long and transports electrical energy at a voltage of 380 and 220 kilovolts (kV), in three-phase systems. The transmission grid includes all the lines in charge of electricity circulation and distribution, as well as a total of 141 substations (Swissgrid, 2020a). Substations are part of an electrical generation, transmission and distribution system. They are connected to the 220 kV and/or 380 kV grid lines. One of the most important function of a substation is to transform voltage from high to low, or the reverse, via transformers. Therefore, between the electricity generation station and the end user consumers, electric power may flow through several substations at different voltage levels.

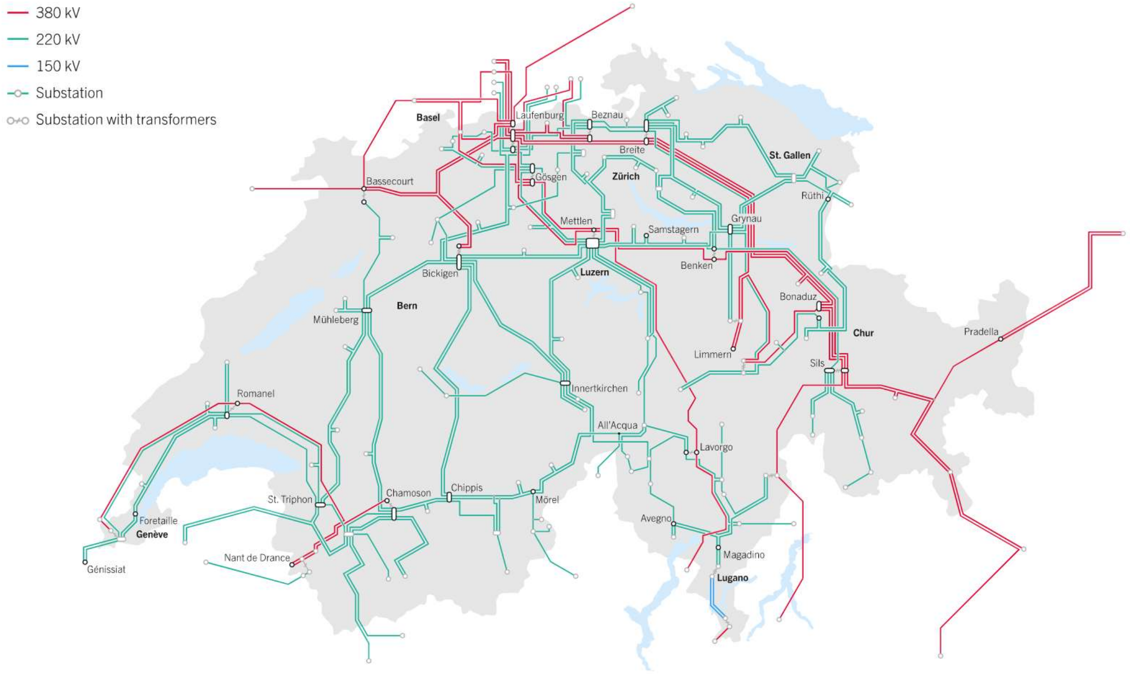


Figure 4 1: Swiss transmission grid (Swissgrid, 2020a)

The higher the voltage a line has, the higher amount of electricity can be transported over great distances with minimal losses. End consumers use a voltage either of 400 or 230 volts. Electricity has to circulate through a total of 7 levels in order to be converted to the required voltage as an end consumer. The first level is electricity flowing into the transmission grid from the power generation plants at a voltage of 380 or 220 kV. Level three, voltage is reduced until it reaches between 36 kV to 150 kV. Level five, the electricity circulating in the grid has a voltage between 1 kV and 36 kV. Lastly, in the seventh level, voltage is reduced to suitable voltage values for end user consumers, i.e., 400 or 230 V, as aforementioned. Levels 2,4 and 6 are equivalent to the substations that electricity has to go through in order to drop the voltage to the required levels of the following line (Swissgrid, 2020a).

Thereby, Swissgrid has mainly two functions. First, it makes sure that the transformation of the voltages is taking place under secure conditions and complying with the right values. Second, it has to make sure that production and consumption levels must always be in equilibrium, having just enough electricity in the grid at any time. Moreover, maintaining the equilibrium between energy generation and consumption ensures that the frequency of 50 Hz in the system remains at a stable level. Otherwise, electrical devices and generator may be damaged (Swissgrid, 2020b).

b. Transformers

An electrical substation is made of a large variety of components, such us conductors, circuit breakers, isolators, or busbar systems. However, one of the most important components are transformers. A transformer converts an alternating current from one voltage value to another, as aforementioned. A transformer consists mainly of two coils of wire, commonly known as primary and secondary windings. These two coils are not directly in contact but are instead wrapped around a common closed magnetic iron circuit, having a mutual induction. This circuit is called the core, and it makes the coils to be magnetically connected allowing electrical power to be transferred from one coil to the other (*Transformer basics*, n.d.). Applying an alternating voltage to the primary winding, creates an alternating flux in the core, i.e., the core is magnetized. The alternating flux induces an electromagnetic force in both coils. This force in the secondary winding causes a current, hence a voltage is induced. Although the voltage levels are different, the frequency of input and output power is the same. The voltage difference in a transformer depends directly on the ratio between the number of turns of the two coils.

The costs of the transformers are mainly given by the amount of raw materials used for their design. However, operating and maintenance costs have to be taken into account too. These costs can be many times transformers initial price (*Transformer Life-Cycle Cost: Total Owning Cost*, n.d.). Copper is the fundamental material used in a transformer (*What Determines The Cost Of Power Transformers?*, n.d.). The characteristics of a transformer can be personalized depending in the buyer's requirements. For instance, magnetic materials, level of magnetic induction, or ratio between copper and steel. However, varying the characteristics of the transformers alters the electrical behaviour of them. "A transformer with more iron and less copper, tends to have higher iron losses, and one with more copper and less iron will have higher copper losses" (Csanyi, 2011). Therefore, the initial price of a transformer varies depending in their characteristics. Swiss transformers costs for the different voltage levels and different levels of apparent power (i.e., this value depends on the electrical load of the system) are shown in Table 4.1.

U1/U2 [kV]	Sn [MVA]	Standard costs per Trafo [TCHF]
380/HS	400	14300
220/HS	400	7100
	125	4400
	100	3800
	80	3100
	40	2900

Table 4 1: Standard costs for different voltages values in Switzerland (Wiederkehr et al., 2007)

Over the territory of Switzerland there are a total of 17 extra high voltage transformers. These substations transform voltage from 380kV to 220 kV, or the reverse. The transformers can be numbered and located in Figure 4.2.

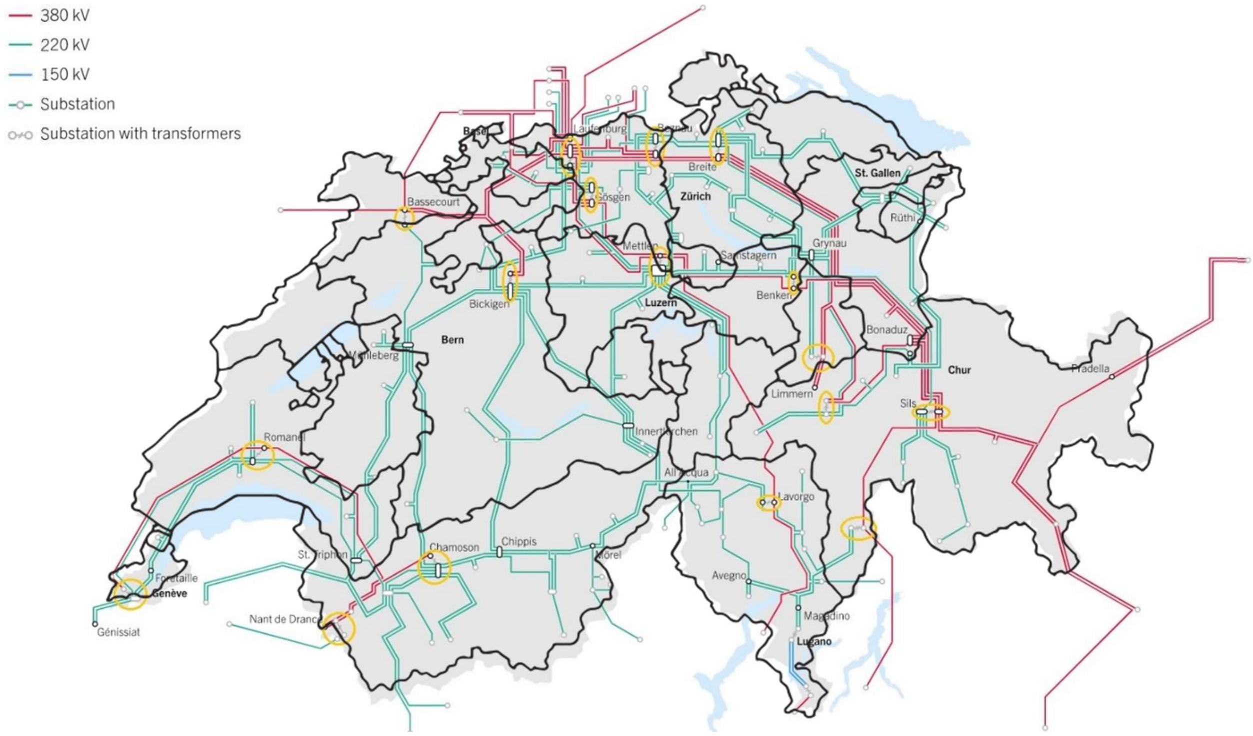


Figure 4 2: Number of extra high voltage transformers per cantons

c. Current electricity demand

Data of the Swiss energy statistics are divided into single cantons or groups of cantons. These divisions are stablished by the data provider. In this case, the data comes from Swissgrid. The data shows values of energy production and consumption during 2019 in intervals of 15 minutes. Each of the groups from Swissgrid's data have a specific number of the extra high voltage transformers aforementioned. See Table 4.2. This table also shows the highest energy production and consumption values achieved in an interval of 15 minutes in 2019. Therefore, it is certain to say that the system is at least capable of distributing those amounts.

In order to make a general analysis of the Swiss electricity demand, three different energy behaviours have been chosen. First of all, the region of Bern and Jura, where yearly production and consumption energy values are similar: 7800 GWh aprox (12% of the total energy produced and consumed in Switzerland). Second of all, another type of behaviour happens in Schaffhausen and Zurich. They have a yearly energy production of 948 GWh (1.5% of the total energy produced in Switzerland), although a yearly energy consumption of 9259 GWh (15% of the total energy consumed in Switzerland). This region can be classified as an import area, i.e., more energy than the energy produced is needed. Therefore, surrounding areas/cantons have to export energy to areas like Zurich in order to fulfil the demand in the area. Those areas characterize the last of the behaviours exposed. Third of all, an area that produces more energy than it consumes. The remaining energy is exported to other regions. For instance, Aargau has a yearly energy production value of 15268 GWh (24% of the total energy produced in Switzerland) and a yearly energy consumption value of 4872 GWh (8% of the total energy consumed in Switzerland). A possible reason for this behaviour is the type of land available in a region. For instance, if Aargau has more possible locations to install a hydraulic plant than in Zurich, the energy produced in this area by hydropower would be higher and therefore the total energy of the region too.

Areas		No. Trafos	Max. energy produced in 2019 (MWh)	Max. energy consumed in 2019 (MWh)
AG	Aargau	2	588.106	200.229
FR	Fribourg	0	79.642	113.982
GL	Glarus	1	152.082	56.620
GR	Graubünden	3	596.348	142.334
LU	Luzern	1	43.788	150.095
NE	Neuchatel	0	3.424	28.617
SO	Solothurn	1	284.344	89.089
SG	St. Gallen	1	111.620	168.642
TI	Ticino	1	289.384	132.898
TG	Thurgau	0	22.020	77.606
VS	Valais	2	861.059	150.567
AI,AR	Appenzell Ausserrhoden and Innerrhoden	0	7.467	24.036
BL,BS	Basel Landschaft, Basel Stadt	0	43.688	139.293
BE,JU	Bern, Jura	2	434.735	337.139
SZ,ZG	Schwyz, Zug	0	32.936	73.754
OW,NW,UR	Obwalden, Nidwalden, Uri	0	94.167	40.444
GE,VD	Geneva, Vaud	2	206.028	350.785
SH,ZH	Schaffhausen, Zürich	1	55.950	393.829

Table 4 2: Energy peak of production and consumption achieved per area

If the same approach made above, but this time, with the average energy produced/consumed in intervals of 15 minutes (as the data was given) instead of comparing total yearly energy values, the characteristic behaviours remains the same: Aargau is an export area, and Schaffhausen and Zurich is an import area. The values for the averages of each of the areas are shown in Table 4.3.

	Production (MWh)	Consumption (MWh)
Aargau	435.736	139.058
Schaffhausen and Zürich	27.064	264.244
Bern and Jura	222.426	224.304

Table 4 3: Average values for different types of areas in Switzerland

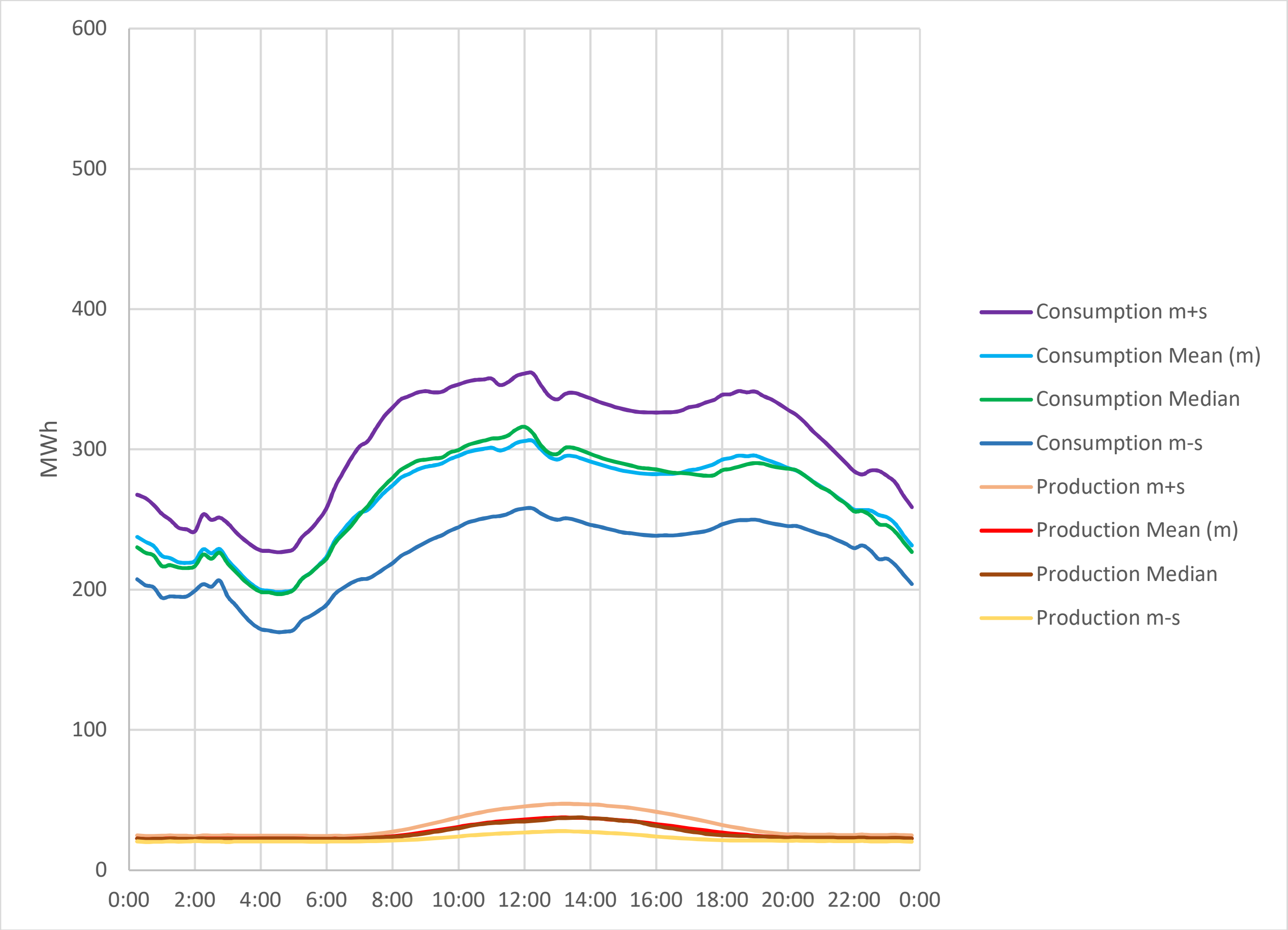


Figure 4 4: Consumption and production curves in Zurich and Schaffhausen (2019)

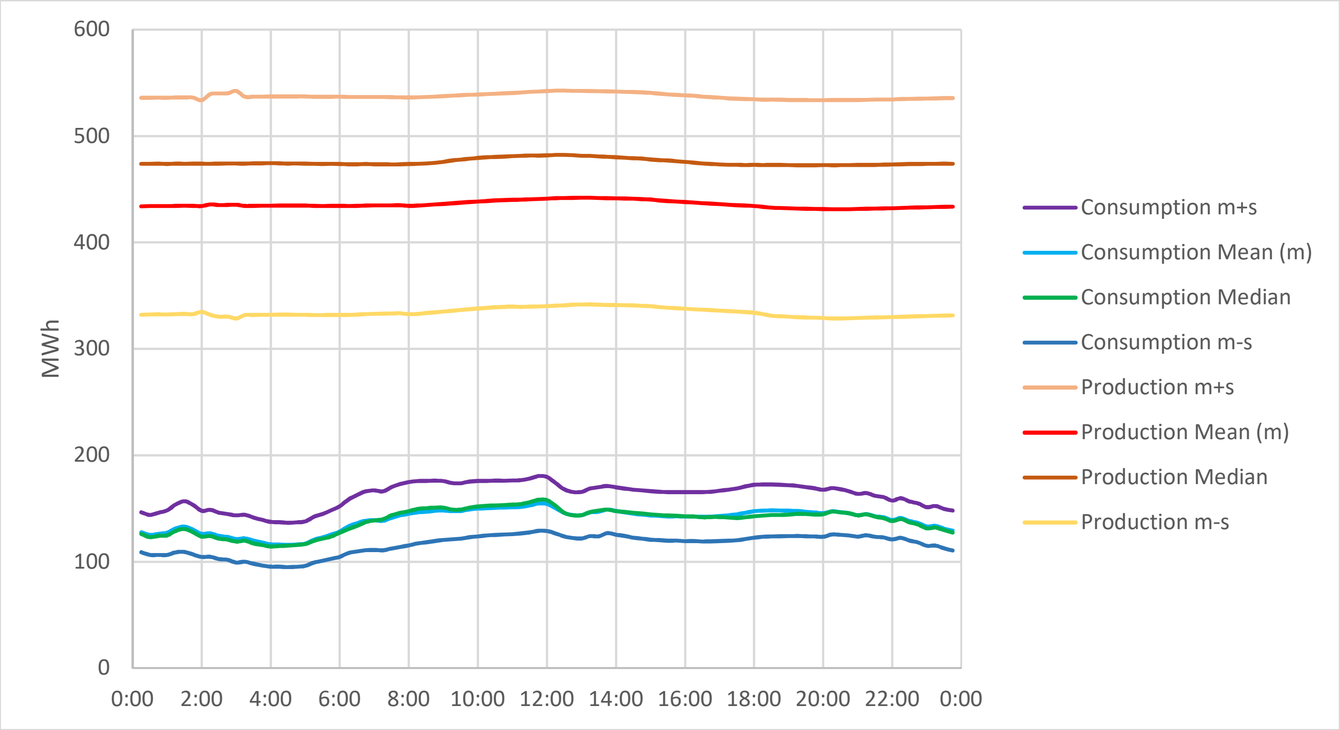


Figure 4 3: Consumption and production curves in Aargau (2019)

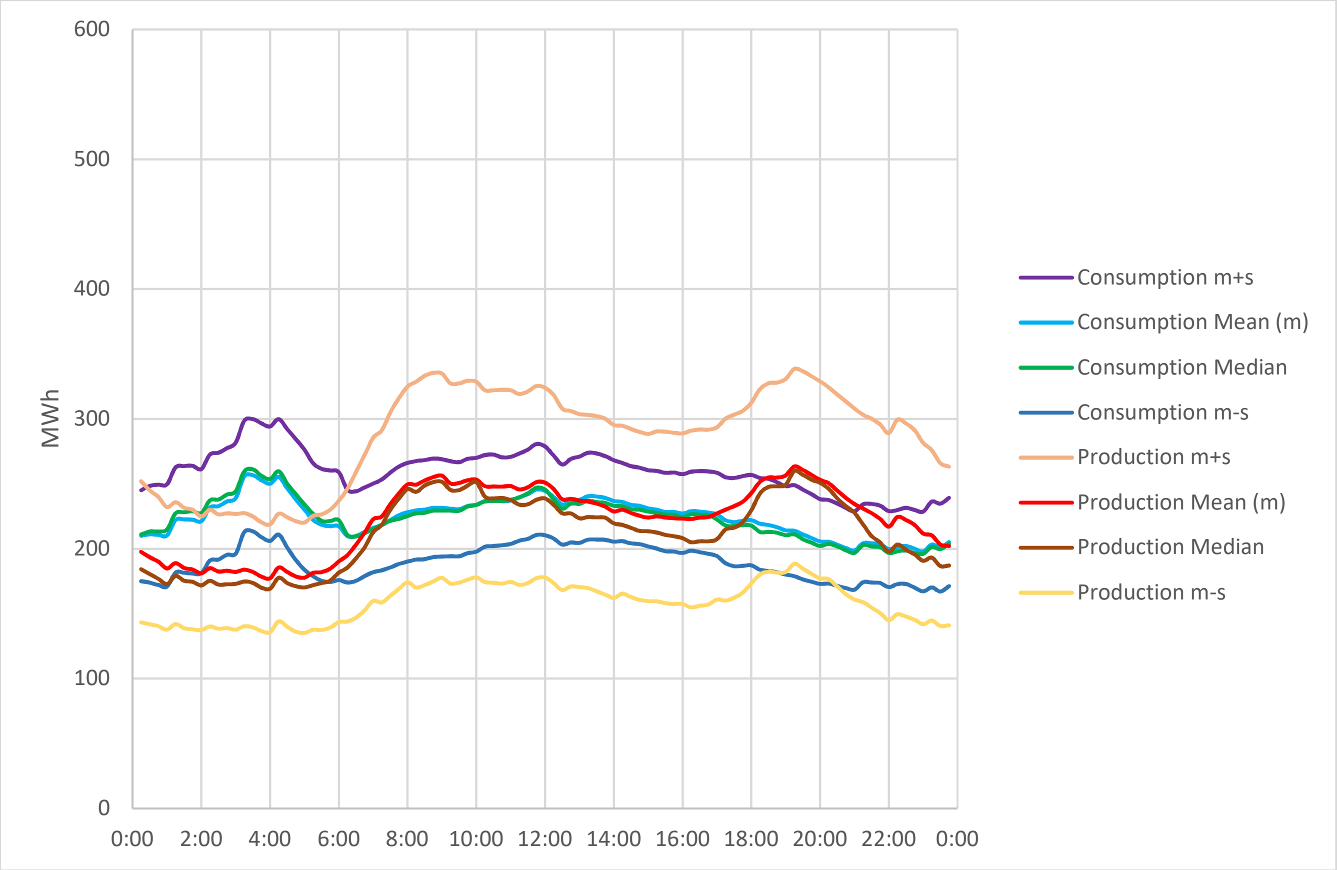


Figure 4 5: Consumption and production curves in Bern and Jura (2019)

Figures 4.3, 4.4 and 4.5 show the demand and production curves for the following areas: Aargau; Schaffhausen and Zurich; and Bern and Jura. They represent three different energy schemes: import, export, and similar energy consumption and production values, respectively. These curves are built using the maximum value consumed or produced in each of the intervals of 15 minutes in the complete year 2019, as aforementioned. The shape in Zurich demand curve, as well as its characteristic behaviour aforementioned, makes sense. Zürich is a region where residential and commercial locations are important (lifestyle, job opportunities, etc.) and therefore significant. The previous characteristic may be the main reason for having one of the highest shares of consumption in Switzerland. Furthermore, the higher the commercial and residential addresses, the lower the amount of available land to install a power generation plant. It is not likely to see them next to a residential area (mainly due to visual pollution standards). This type of infrastructure tends to be located separated from populated areas.

Most of the energy is consumed during the day. One interesting fact is that in Figures 4.3 and 4.4, the peak demand happens at approximate 12pm, although in Figure 4.5, the peak demand is around 4am. Possible reasons for the type behaviour of Bern and Jura:

- Industrial activity at night
- High number of pumped storage hydro power plants (at night-time when electricity price is lower than during the day, these plants take the opportunity to pump the water back into the reservoir)

In the area of Glarus, the demand peak happens also during the night, as it does in Bern and Jura. The rest of the curves for each of the areas of Switzerland may be seen in the appendix 2 (Figure A.2.1 to Figure A.2.19).

Swissgrid’s data is going to be treated by following these steps. First of all, the maximum peak value achieved in 2019 are chosen for each of the divisions’ production and consumption energy data. The grid is capable of transmitting those values, as far as it is known. Second of all, a relationship is stablished between the number of transformers per region and the energy data in that same region.

In Figures 4.6 and 4.7 scatter plots are represented. These figures describe a relationship between energy and installed transformers. A scatter plot has a particular characteristic: it is possible to both deduct the correlation between two data sets and quantify the strength of the relationship. In both figures, equations of a line are indicated. These lines are called regression lines. They express the correlation aforementioned, i.e., these lines predict how the model behaves based on current data. Therefore, in case of an increase of the electricity demand, an estimation of new required transformers in the grid could be made. For instance, the supposed electrification of the road that is going to happen in the future will lead to an increase in the energy demand. Thus, required changes to the current transmission grid are estimated in order to be capable of supplying this new demand.

On the one hand, in order to quantify the correlation between the number of transformers installed and the energy distributed in a region, there exists the parameter knows as Pearson correlation coefficient (r). Its absolute value varies between 0 and 1. An r=0 means no correlation at all, and r=1 means a total linear correlation. On the other hand, the previous coefficient explained squared (known as coefficient of determination) expresses how accurate are the regression predictions, i.e., the closer the points in the plot are to the regression line, the closer the value of r^2 is to 1.

Figure 4.6 has a value of $r^2 = 0.659$, and therefore a value of r = 0.812. Thereby, in the energy production chart, it can be said that the correlation between the number of transformers per area and the energy generated is quite high, as the r value is quite close to the unit. However, there is a slightly lack in the predictions set by the regression line, as the r squared value is closer to 0.5, although an estimation for the number of transformers needed for a certain energy value produced could be stablished.

For Figure 4.7, the values of r-squared and r are a little worse. They are 0.309 and 0.556, respectively. The fact that these values are further away from the unit is partly due to the area of Zürich and Schaffhausen, where the energy consumed is the highest of the country. The possible reasons for this uniqueness are explained further below. This specific data point in the graph is considered as an anomaly, i.e., as if the data from that area is not used for the calculation of the regression line and the coefficient of determination. This consideration would mean that the new set of data would have a value of $r^2 = 0.435$. The value is improved by 40% compared to the previous calculation.

Another approach to the analysis of the correlation in Figures 4.6 and 4.7 is by carrying a statistical hypothesis test. Considering that the regression line has the following shape:

$$y = \beta_1 x + \beta_0$$

The hypothesis stablished are:

$$H_0 : \beta_1 = 0$$

$$H_1 : \beta_1 \neq 0$$

A brief explanation for this approach is that the null hypothesis states that no relation between y and x exists. It would mean that the relationship that appears to be in the graphs is just a coincidence. Basically, if the null hypothesis cannot be rejected, the relation that was trying to be proved does not happen. Contrarily, the alternative hypothesis represents the rest of the cases, i.e., the two variables (MWh and number of transformers) have an effect on each other, and therefore there exists a sufficient significant relationship in order to use the model as an estimation model for future changes in the Swiss electricity sector. As for the analysis in Figures 4.6 and 4.7, it is sought to reject the null hypothesis as stated above, and thus be able to use the regression lines in the figures as an estimation model for necessary transformer installations depending in variations on electricity consumed.

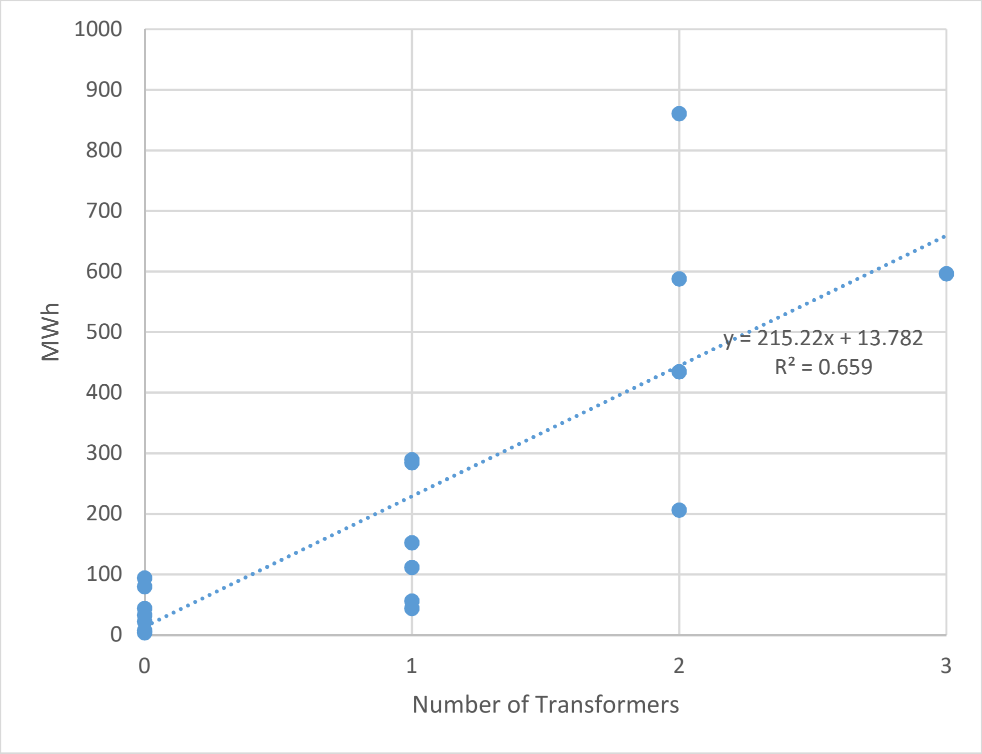


Figure 4 6: Energy production and number of transformers per area in 2019

This statistical significance is expressed through the so-called p-value. “The smaller the p-value, the stronger the evidence that you should reject the null hypothesis. A p-value less than 0.05 (typically ≤ 0.05) is statistically significant. It indicates strong evidence against the null hypothesis, as there is less than a 5% probability the null is correct (and the results are random). Therefore, we reject the null hypothesis, and accept the alternative hypothesis” (McLeod, 2019). However, this would not mean that H_1 is 100% true, there is still a slightly probability that the relationship occurred by chance and thus H_0 is correct.

The following steps shows the calculations made in order to get the p-value for the energy consumption data. First of all, we calculated the averages for each of the samples. The number of data points (n) is 18.

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} = 148.33\ MWh$$

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} = 0.94444\ transformers$$

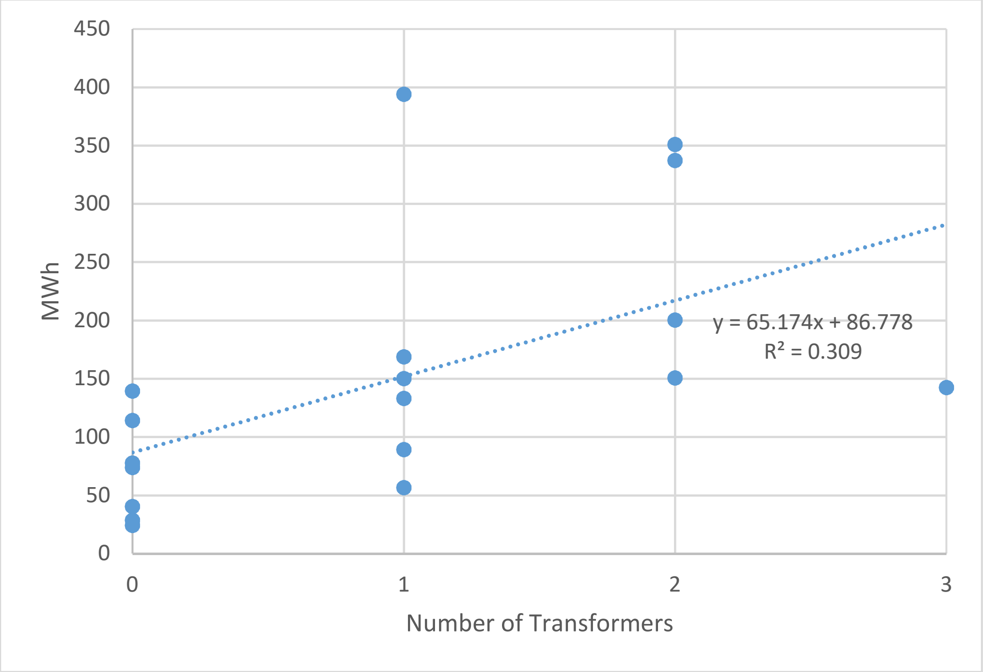


Figure 4 7: Energy consumption and number of transformers per area in 2019

Second of all, unbiased estimators for the parameters of the regression line β_1 and β_0, are calculated. These parameters ($\widehat{\beta_1}$ and $\widehat{\beta_0}$) are based on the sample and therefore, they are not the true values, but an estimation, as aforementioned. Obviously, the objective is to obtain unbiased estimators as close as possible to the true values.

$$\widehat{\beta_1} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} = 65.17385$$

$$\widehat{\beta_0} = \bar{y} - \widehat{\beta_1}\bar{x} = 86.77829$$

Third of all, in order to obtain the closer unbiased estimators of β_1 and β_0, the strategy is to minimize the so-called residual sum of squares (RSS), by the method of least squares.

$$\hat{y} = \widehat{\beta_0} + \widehat{\beta_1}x$$

$$RSS = \sum_{i=1}^{n}(y_i - \widehat{y_i})^2 = 141981.2847$$

Fourth of all, the following parameters indicate how the unbiased estimators differ from the true values. They are known as standard error (SE).

$$SE(\widehat{\beta_0})^2 = \sigma^2 * \left[\frac{1}{n} + \frac{\bar{x}^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}\right]$$

$$SE(\widehat{\beta_1})^2 = \left[\frac{\sigma^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}\right]$$

where σ^2 represents the variance of the error ε, which is unknown, so it is necessary to estimate it from the sample data. This estimation is known as residual standard error (RSE), and it has the following formula.

$$RSE = \sqrt{\frac{RSS}{n-2}}$$

The estimated value given by this parameter is not the variance of the error, but the standard deviation of it. In other words, RSE is an estimation of σ. Once RSE is calculated, it is possible to get SE for each of the regression line unbiased parameters.

$$SE\left(\widehat{\beta_0}\right)^2 = 1022.635$$

$$SE(\widehat{\beta_1})^2 = 593.788$$

Moreover, these two values are part of the confidence interval of both estimators.

$$\widehat{\beta_0} \pm t_{df}^{\alpha/2} * SE\left(\widehat{\beta_0}\right)$$

$$\widehat{\beta_1} \pm t_{df}^{\alpha/2} * SE\left(\widehat{\beta_1}\right)$$

Fifth of all, the last step to calculate the p-value is to carry out the statistical hypothesis test. As they were established at the beginning of this explanation, the hypotheses are:

$H_0: \beta_1 = 0$ → There is no correlation between x and y

$H_1: \beta_1 \neq 0$ → There is some correlation between x and y

A similar type of hypotheses could be established for β_0, although they are not as representative of the goodness of fit that it is being tried to demonstrate among the variables in the model. In order to check the null hypothesis, it is necessary to determine if $\widehat{\beta_1}$ is far enough away from 0. This difference depends on the $SE\left(\widehat{\beta_1}\right)$. The first thing to do is a t-test, in which t represents the number of standard deviations that estimators $\widehat{\beta_1}$ and $\widehat{\beta_0}$ are away from 0. t is also known as test statistic. Once the t value is known, it is possible to calculate the p-value, that depending on the statistical significance (α) established, it indicates whether the null hypothesis is rejected or accepted, i.e. if there is a relationship between the number of transformers and the amount of MWh consumed.

$$t = \frac{\widehat{\beta_1} - 0}{SE\left(\widehat{\beta_1}\right)} = \frac{65.17385}{\sqrt{593.788}} = 2.6746$$

An α value equal to 0.05 is set, to reach the conclusion of the exposed hypothesis test. However, as the test carried out is a two-tailed test, i.e., both endings of the normal distribution curve are considered, p-value is compared to $\frac{\alpha}{2} = 0.025$.

$$p - value(t = 2.6746, degrees\ of\ freedom = n - 1 = 17) = 0.0084 < \frac{\alpha}{2}$$

In conclusion, the p-value is lower than 0.025, and therefore the null hypothesis is rejected. It can be said that the model presented above is significant to predict future modifications to the transmission grid.

Furthermore, continuing with mathematical demonstrations, the value of the determination coefficient (r^2) is given by the following expressions.

$$TSS = \sum_{i=1}^{n} (y_i - \bar{y})^2 = 205459.676$$

$$r^2 = \frac{TSS - RSS}{TSS} = 0.3089$$

The closer the points in the plot are to the regression line, the closer the value of r^2 is to 1, as aforementioned. In a simple linear regression, the value of the determination coefficient is equal to the Pearson correlation coefficient.

The same process presented above for the energy consumption data is made for the energy production data. The p-value obtained is less than 0.0005. It is lower than $\alpha/2$. For this reason, the null hypothesis for this model is rejected too, and it is possible to state that there is a significant relation between x and y in energy production too.

Every calculation needed in every step can be seen in tables A.3.1 to A.3.4 (see Appendix 3). The information regarding these calculation has been obtained from a working paper called "Regression Lineal Simple" (Cristina Gil Martínez, 2018).

The aim of this thesis concerns demand levels in Switzerland. Therefore, for the grid evaluation, the consumption scatter plot is the one that is used to calculate possible changes in the network. In the regression line equation, the so-called intercept of the equation tells the minimum demand increase that leads to the need of installing an additional transformer in the grid (intercept = β_0= 86.778 MWh). Therefore, if the increase due to freight transport electrification is lower than the intercept, the distribution system is supposedly capable of supplying that extra amount without installing additional transformers. It needs to be considered that the scatter plot is made with the maximum registered consumption values in each area. Thereby, the plot comes into play when demand peaks are produced (by looking at the graphs in Appendix 2, the average peak value in the areas and in Switzerland as a whole, produces at 12pm). As long as the new energy demand is below the maximum registered point, the network is capable of distributing it, because a higher value has been distributed before.

In most of the areas the energy produced and consumed are different. A reasoned explanation for this behaviour is that energy is not only consumed locally, i.e., near the power plant where the energy is produced, but also distributed to peripheral areas, or even further away. It is in this case where the transmission grid is being used for its main purpose. This difference can be perfectly seen by looking at the figures 4.6 and 4.7. Each of the figures have a different regression line's equation, as the data points are different.

Depending on the demand of energy required in a specific area, and the production available in that area, energy is distributed from and to other areas. This situation causes the transmission grid to take a shape that suits the needs of Swiss market consumers. For instance, in the area of Zürich and Schaffhausen, the energy consumed in a year is around ten times bigger than the energy produced in that same area. Consequently, energy from other areas has to be supplied to this region. Power generation plants tend to be in unpopulated sites. This type of infrastructures has a significant visual impact, as well as occupying large portions of land. Likewise, Switzerland main form of generating electricity is via hydro power. This type of energy generation plants can be installed in places where certain conditions are fulfilled, i.e., basically, places where water flows. Therefore, those areas where is more suitable to have a higher amount of hydro power plants, more electricity is produced. However, in areas where the land characteristics are inadequate to build a power plant, less electricity will be produced, and more electricity have to be distributed to these areas. This could be one of the explanations for areas consuming more than energy produced. Furthermore, it may be also an explanation for the shape of the transmission grid nowadays. The difference between the yearly energy generated and consumed for each of the areas stablished can be seen in Figure 4.8.

By having an energy consumption much higher than the generated in the region of Zurich, means that much more amount of electricity must be directed to this region, therefore: "Why is there only one transformer in this region?". It is accurate to say that the region of Zurich possesses only one transformer by looking at Figure 4.2, although three more transformers are near around the borders of the canton. Thus, energy can enter Zurich from different points/regions, being able to face the required demand. A region (Zurich and Schaffhausen) where the consumption of energy is the highest among the others. This consideration translates in a singularity in Figure 4.4, where the dot corresponding to ZH and SH is way above the regression line. This is why the data for this region should not be taken into account when generating the scatter plot, since it is a simple peculiarity of the system, as aforementioned.

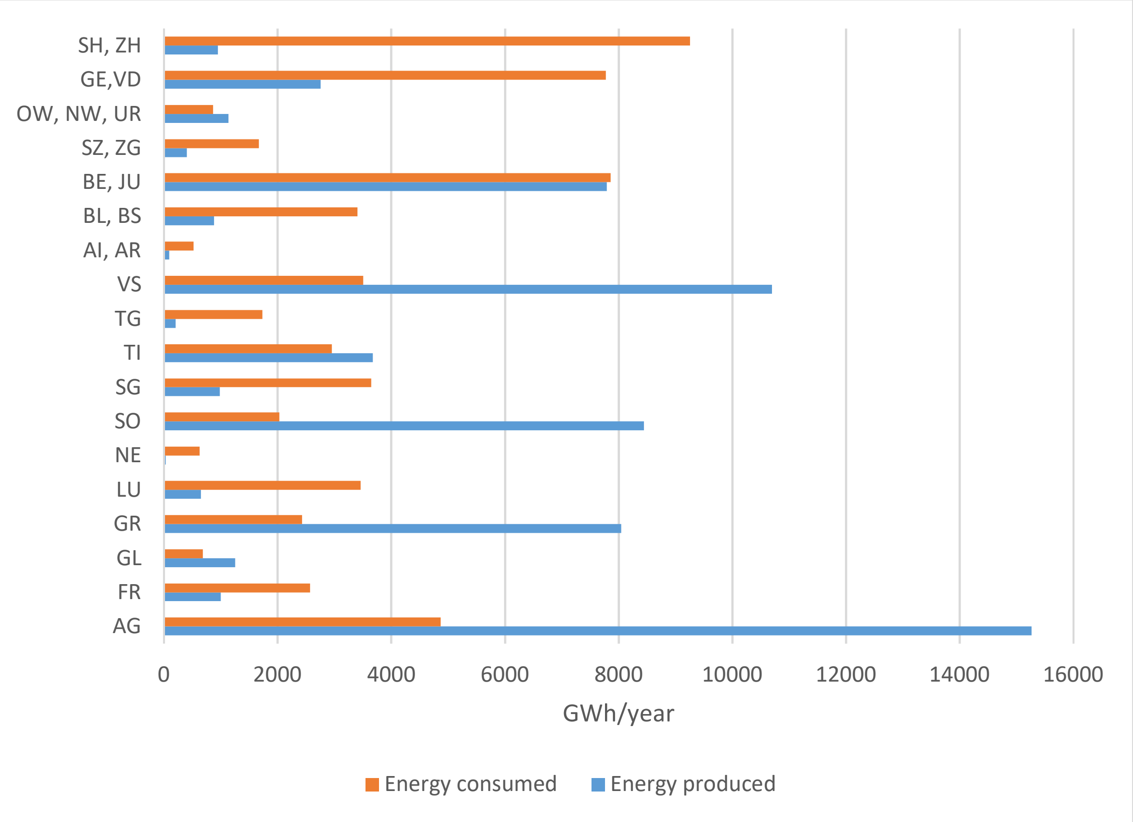


Figure 4 8: Yearly energy production and consumption per canton in 2019

As Figure 4.9 shows, energy generation in Switzerland is higher than the energy consumed. Switzerland is capable of supplying their own energy and therefore it can export the rest.

However, this consideration is made under a year-round average. In fact, Switzerland is able to export the energy in the summer season, while in winter it needs to import electricity to comply with the demand (Axpo, 2018).

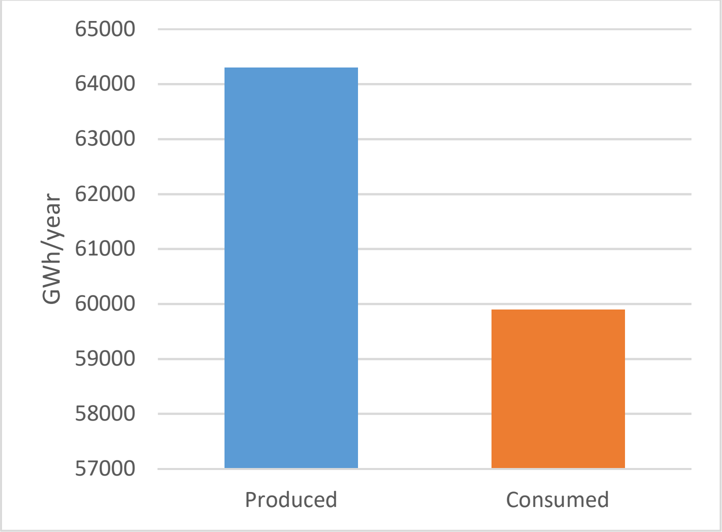


Figure 4 9: Yearly energy produced and consumed in Switzerland (2019)

d. Charging stations

A deep decarbonisation of the freight transport has to be achieved in order to reduce significantly transport GHG emissions. A very attractive option is the electrification of the transport, as aforementioned. Although, the electrification of freight transport has to be implemented at the same time as the technologies for charging electric batteries are being improved.

i. Type of charging processes

Nowadays, there are a few charging infrastructure processes available in the market: battery swapping, inductive power transfer charging and conductive charging being the technologies that have made an impact to the charging industry (Mckinsey & Company, 2012).

First of all, battery swapping is the fastest process of all the above. A vehicle enters the station and a robot replaces the drained battery with a fully charged one. In just a few minutes, the vehicle is ready with an entire range capacity. However, projects to promote this technology in the past have failed mainly due to the lack of standardized battery models. In the end, each brand has its own battery with characteristics and shapes that may be different from those of other brands (Bradley Berman, 2020). In fact, this situation has been reflected in companies like Tesla and Better Place. They gave up on this business idea. Moreover, the idea of USA of proceeding with a production in mass-scale of swappable batteries did not happen in the end, because of the previous reasons. Nevertheless, China is considering it. The government is stablishing a common industry-wide standard for battery packs where customers could swap batteries in a three-minute period (Bradley Berman, 2020).

Tesla did not have enough consumers to make the investment profitable, so it was decided to stop developing it. Tesla has an alternative charging technology called "Superchargers", free of charge. This device charges the vehicles' battery up to 80% of its full capacity within 40 minutes. Tesla customers would prioritize this process instead of paying $60-$80 for battery replacement (although a battery replacement was only a 90 seconds process) (Benjamin Zhang, 2015).

As for the idea behind Shai Agassi, founder and CEO of Better Place when it still existed, was to replace the internal combustion engine of a common car, with a 70-kW electric motor. The range of the electric battery was only around 80 miles. As a result, the company had installed hundreds of public stations all over Israel (where the company started their business) where a robot would swap the battery. Although, money from investors stopped coming and there were not enough costumers. The company went bankrupt (Max Chafkin, 2014).

Second of all, inductive power transfer (IPT) is a very promising technique. The idea of wireless charging, with no cables needed that cannot be damaged by weather conditions, is attractive to drivers. It has been in used for over 25 years in places such as entertainment systems in airplanes, clean rooms for semiconductor fabrication, etc. Basically, the IPT system is composed of two LC circuits close to each other. One of the circuits is the road charging unit (primary circuit), and the other one is the vehicle charging unit (pick-up circuit) (Nicolaides et al., 2018). See Figure 4.10.

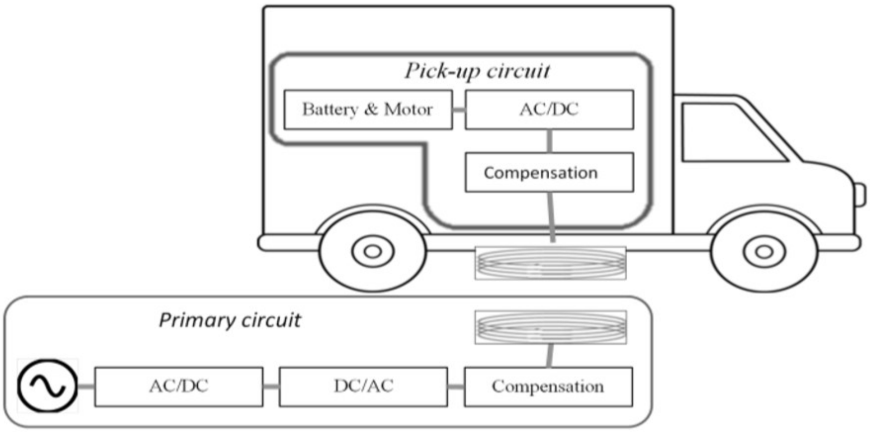


Figure 4 10: Example of an IPT system for EFVs power delivery (Nicolaides et al., 2018)

"The primary circuit is supplied with AC power at a suitable operating frequency. The transmitting coil is energised and the resulting magnetic flux is captured by the vehicle charging unit, inducing an AC voltage which can be rectified to produce a stable DC power source for the electric motor, the batteries and other loads on board" (Nicolaides et al., 2018). This type of charging method enables the so-called charge-on-the-road (CoM) or dynamic inductive charging. The advantage of this technique is that reduces the necessity of installing batteries with a big power capacity. This improvement translates into a reduction of both the weight of the vehicle and its cost. In addition, with an ITP charging technique installed, the phenomena called range anxiety disappears.

It was estimated in the motorways of Great Britain that having a road network of CoM would have a cost of £3m per mile of road (2.175million CHF per km of road). Considering that one mile of train track is around £2-4m, it was concluded that IPT is a feasible technology to implement in the roads (Nicolaides et al., 2018).

Moreover, IPT systems could be used in a charge-on-the-stop (CoS) or static inductive charging too. This method would be useful for those vehicles that have pre-determined the locations where they go through, e.g., buses, LDVs that recharge the battery at depots and delivery points, etc. (Nicolaides et al., 2018). Furthermore, vehicles that remain stationary could be charge using this technology too, instead of the plug-in charging stations, that are presented below. A feasible configuration for each of the techniques is shown in Figures 4.11 and 4.12, respectively.

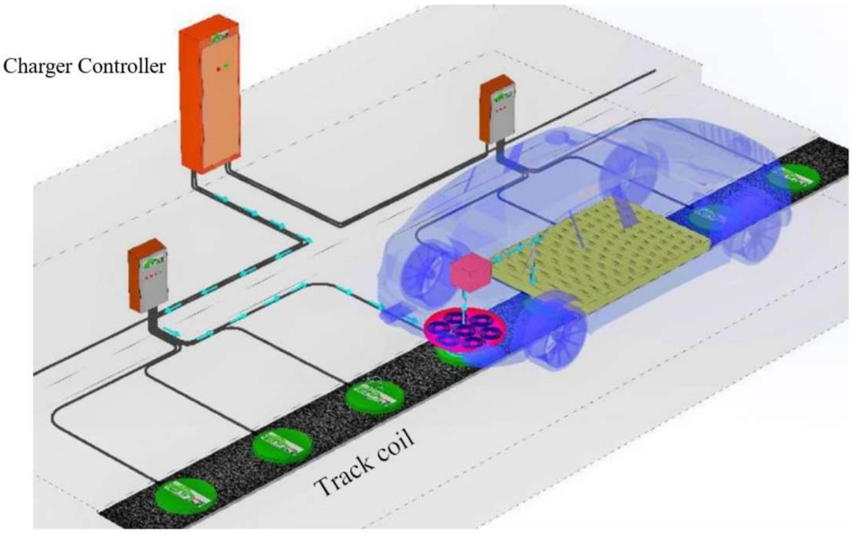


Figure 4 11: the concept of dynamic inductive charging (Ahmad et al., 2018)

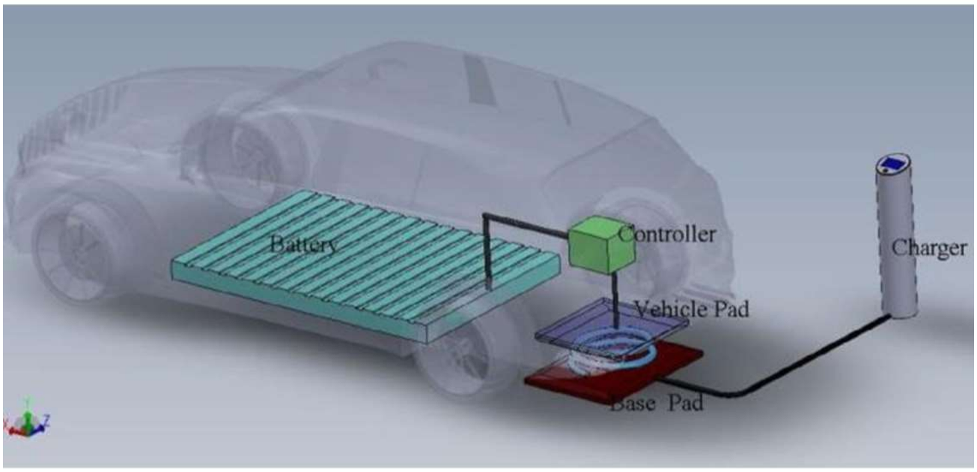


Figure 4 12: the concept of static inductive charging (Ahmad et al., 2018)

Third of all, in a conductive charging process a static EV charging station is used. It is an infrastructure that supplies electric energy directly to the battery of a plug-in electric vehicle. This technique is much alike static inductive charging, but instead of having a wireless battery charging, there is a cable and a plug involved. This type of infrastructure may be found in public or private areas (residential and business areas). Public stations should be located in high traffic areas to get the most out of them. Places where people spend a particular time interval (approximately 1 hour), for the vehicle to be effectively recharged, such as supermarkets, offices, public parking garage, etc. Commercial stations have a downside, the level of complexity is higher than in a residential station due to the higher electric energy demand (*New to the Electric Vehicle Industry?*, n.d.). The main reason for the complexity is that in a public station the charging method has to be quick, efficient and safe. For what has already been stated, customers who use a public charger have parked their vehicle while carrying out tasks in which it is rarely stopped for more than two hours. Compared to a private station where a vehicle may be stationed for over 6 hours.

For each of the divisions of the road freight sector made by Doros Nicolaides, David Cebon, and John Miles in the Freight Transportation section, one of the charging methods presented above is more convenient than the rest. For long haul trucking that use the national trucks networks, the best option is the CoM with an IPT system. This technology would be installed across the network; thus the trucks would only need a small battery capacity to use it outside of it, e.g., going in and out to load and unload the truck in depots.

As for urban deliveries, trucks could be BEVs that charge their batteries while in depots, i.e., CoS with a conductive charging technology or even with static inductive charging. Home deliveries are similar to urban deliveries, in which BEVs could carry out the process at the different delivery points until the capacity of the battery withstands. Then, a recharge process would be necessary. Finally, in auxiliary services the most suitable charging process would be the CoS. The technologies chosen before are based on using the smallest battery capacity possible for each of the divisions. By applying this method, it would allow the trucks to have more payload space, as well as reduce the gross weight, cost and rolling resistance of the vehicle (Nicolaides et al., 2018).

Nowadays, the most common technology to charge BEVs is the conductive charging. Therefore, it is the technology that will be considered further below to calculate the investment needed for the electrification of the freight transport.

ii. Conductive charging parameters

In the process of charging a vehicle through a plug-in station there are four parameters that have to be taken into account in order to have a correct and safe electric load. These parameters are power level, electrical current, type of plug and the vehicle's battery size.

Power level is measured in kW. It is defined by voltage (V) and current (A). Power level is the parameter that determines the amount of time in which the battery is charged. The values of this parameter vary between 3.3 kW (slow charge) to 50 kW (fast charge) and higher. Although, Tesla Superchargers can provide a power of up to 120 kW (Mckinsey & Company, 2012). As the power is lower, the amount of charging time increases. Thereby, low power charging source are intended for residential charging (private charging).

Batteries store energy in DC. Although, electricity is supplied by the grid in AC. Therefore, a converter is necessary. This converter may be implemented on-board in the vehicle or in the charging station. The second option is the most common one (Mckinsey & Company, 2012).

The third component that has to be taken into account when charging an EV in a plug-in charging station is the type of the plug. There are an enormous variety of sockets and plugs used for EV charging. For instance, for slow charging, a European standard plug has been established: Type 2 "Mennekes".

Finally, the capacity of the battery also plays an important role in selecting where and for how long to load the vehicle. The size is expressed with kWh. Depending the capacity of the battery, the power and the current are determined.

iii. Conductive charging modes

As it is mentioned above, the power level of a charging station mainly varies between 3 and 50 kW. At the rate of 3-7 kW the charger is a single phase AC classified as slow. Between a range of 7-22 kW, it is a tri-phase AC charging type process. The following categories are above 50 kW. Nowadays, not too many people own a vehicle capable of withstanding this level of power. Firstly, fast DC chargers have a power supply between 50-100 kW. Secondly, ultra-fast DC chargers, with a power supply above 100 kW (Mathieu & Poscanova, 2020). For instance, the Tesla Model S has a battery with a capacity between 75-100 kWh. If an ultra-fast charger were used, the time needed to fully charge the battery would be about 1 hour. However, the classification between slow or fast chargers is set by the manufacturer. This thesis' focus, i.e., freight transportation, for instance, a slow charger would be 50 kW. Conveniently, electric trucks are going to have much bigger battery capacities than a passenger car. Consequently, the classification in charging power level may vary.

According to Electrosuisse, there are four charging modes. Mode 1 refers to AC charging using a standard domestic or CEE industrial socket-outlet. Communication between the power output and the vehicle does not happen. In basic terms, having communication means that safety is being controlled while the process is taking place. For instance, controlling the amperage between power output and vehicle. There are more features that communication could bring to the charging process, such us user information, identification, billing data, etc. Mode 2 stays under the same terms as mode 1, although an in-cable control box (ICCB) is added to the configuration. This device allows charging an electric vehicle that would have to be charged in mode 3, through a standard or CEE socket-outlet. Therefore, mode 3 is the process in which EV are charged with 1- or 3-phase AC. Charging is possible by installing a type 2/type 3 socket-outlet or the permanently installed mode 3 charging cable. Finally, mode 4 refers to the fast charging infrastructure. It uses direct current (DC). Just as in mode 1 there is no communication, in modes 2, 3 and 4 there is (e'mobile; VSE AES; electro SUISSE, 2015).

The charging time of the electric battery depends primarily on the power level of the charging station and the capacity of the battery. The simultaneous charging of a high number of vehicles will result in power consumption peaks. Swiss utilities have to attend this change in demand and carry the necessary changes and upgrades to the grid, as well as the technology for energy generation.

As it is mentioned above, a very important component when charging an EV via conductive charging is the plug used. For modes 1,2 and 3, the cable needed to charge the vehicle is given by the vehicle manufacturer, and therefore is implemented in the vehicle (mode 3 has a different type of charging cable than mode 1 and 2). The consumer just needs to arrive to the charging station and connect the cable to the respective socket. However, for fast charging mode 4, the charging cable is implemented in the charging station (e'mobile; VSE AES; electro SUISSE, 2015).

iv. Current charging infrastructure

Nowadays, there are a total of 6520 electric charging stations all over Switzerland (European Alternative Fuels Observatory, 2020). 55 of those stations are the so-called ultra-rapid charging (Mathieu & Poscanova, 2020). It is classified as ultra-fast charging when the power level is equal or higher than 100 kW. In Figure 4.13 can be seen the number of filling stations for each of the alternative fuels (AF) available in the market (electricity, hydrogen, LPG and natural gas). Electric charging stations predominate the AF charging infrastructure.

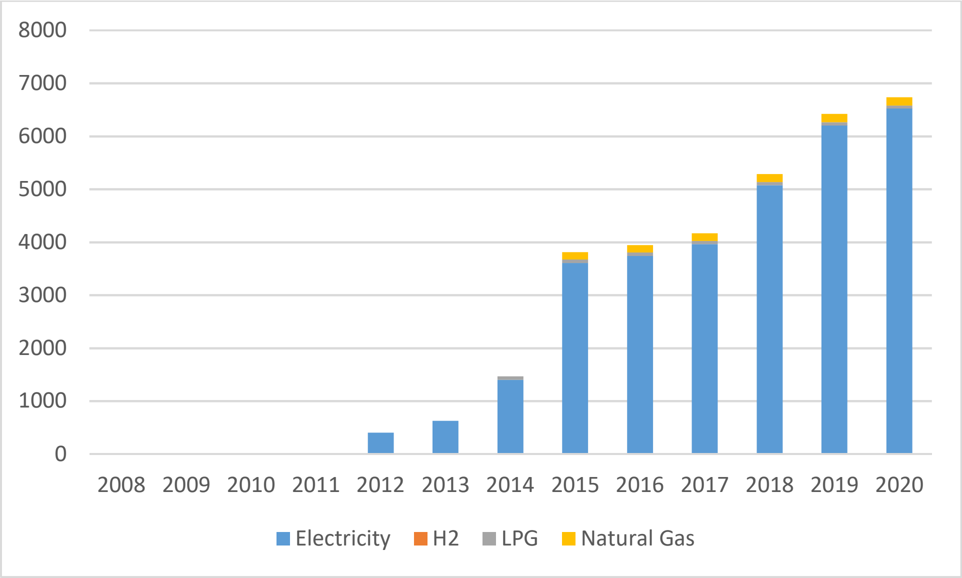


Figure 4 13: Total number of AF Infrastructure in Switzerland (European Alternative Fuels Observatory, 2020)

A comparison between the Swiss charging stations infrastructure and the infrastructure in the countries belonging to the European Union is made. It shows that Switzerland is ahead. The ratio of charging stations per number of electric vehicles and the ratio of fast charging stations (>= 22kW) per 100km of highway are both higher in Switzerland than the ratio in the European Union countries (European Alternative Fuels Observatory, 2020). A recommended ratio of the number of EV per public charging point is set in the current Directive on Alternative Fuels Infrastructure (DAFI) in the European Commission. This ratio is set to be 10 EVs per public charging point (Mathieu & Poscanova, 2020). Figures 4.14 and 4.15 represent the differences over the years between Switzerland and the European Union as a whole aforementioned, i.e., it takes into account the total number of BEVs and the total number of charging points throughout their territory. The ratios characterizing the European Union may be seen as an average value of all the countries belonging to it. As an interesting fact, Norway is the European country with the best ratios basically because the number of BEVs registered is the 4% of the total vehicles registered (European Alternative Fuels Observatory, 2020; Stoll, 2019). This percentage is much higher than the 0.6% belonging to Switzerland, as mentioned in the Swiss road transport situation section. Norway is in a very good pace towards the electrification.

Moreover, it can be seen in Figure 4.14 that the ratios of EV per public charge points is slight below the recommended ratio set by the European Commission aforementioned. Then, according to this recommendation, the number of charging stations installed is more than sufficient for the existing number of EVs on the streets today.

However, the number of stations installed is expected to increase more, as the number of EV increases. At present, the European Union, the EFTA countries and Turkey together have a total of 248849 EV charging stations (European Alternative Fuels Observatory, 2020). 61% of those public stations are tri-phase AC chargers, around 4% are fast charge points and 0.25% are ultra-fast chargers (Mathieu & Poscanova, 2020), i.e., the majority of the installed stations have a power supply between 7-22 kW. Therefore, it can be noticed that today there is a preference for slow AC chargers.

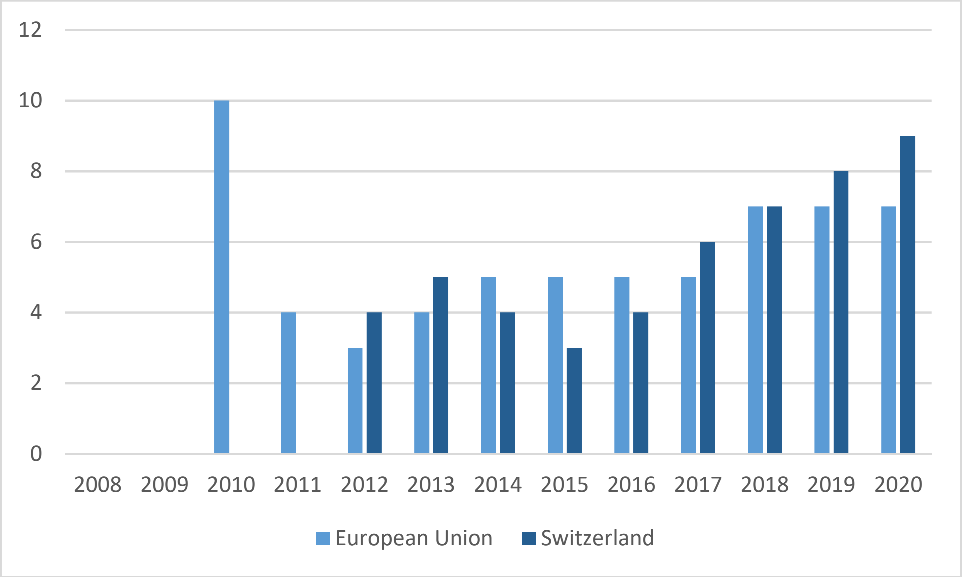


Figure 4 14: Plug-in electric vehicles per public charging point in Switzerland and in the European Union (European Alternative Fuels Observatory, 2020)

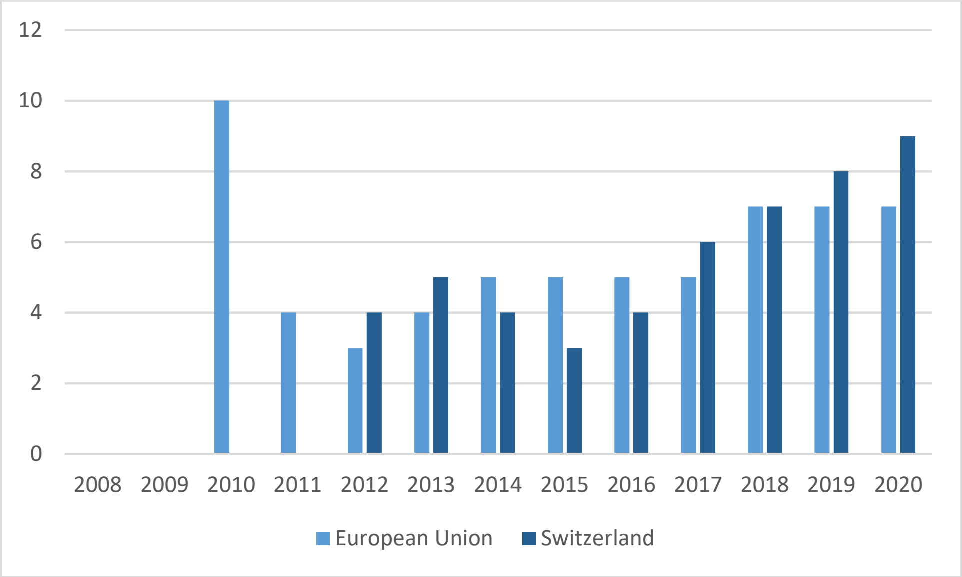


Figure 4 15: Fast public charging points per 100 km highway in Switzerland and in the European Union (European Alternative Fuels Observatory, 2020)

According to a study made by Transport & Environment, by 2025, the number of installed public charging stations in Europe will be necessary to be 1.3 million and 2.9 million by 2030, in order to serve with the growing number of EV and comply with the zero-emission road transport target by 2050. In addition, under this zero-emission scenario, the expected number of EVs in 2025 is about 14 million, and 44 million by 2030. It is estimated that an investment of 80 billion euros is necessary by 2030 for the roll out of public and private charging infrastructure (Mathieu & Poscanova, 2020).

It was conducted an interview to Robert Schürch, head of corporate development, sales and energy management at WWZ Enegie AG. It is mentioned in the interview (Robert Schürch, Email, Zürich, 30.06.2020, see Appendix 1) that WWZ Energie AG operates 50 charging stations with a rapidly increasing trend. These stations are sited in the canton of Zug. Most of them are residential with 11 kW, some public with 22 kW (always AC), one 50 kW DC and one 100 kW DC. The residential stations are located mainly in underground garages. As for public stations, ideally, they should be located in "commercial properties such as large shops, leisure and sports facilities with parking facilities, as well as petrol stations" (Mathieu & Poscanova, 2020). In WWZ Enegie AG case, the 22 kW and 50 kW chargers have been installed in public places, it was not specified the type of places. The costs for each station type presented and owned by the utility are shown in Table 4.4, among others.

The previous power level stations are mainly aimed to private individuals, who use the service provided by the utility either at home, work, while shopping or they are just transients that are just passing through the area. That is the reason why the charging stations possessed by WWZ Energie AG are installed in underground garages or public places, where the number of available customers is more likely, as aforementioned. Nevertheless, the ultra-fast station is located in a motorway junction. This is one of the best locations for this type of station, because in these sites, short stops are made, and customers seek to recharge the highest percentage of battery in the least amount of time.

As battery and charging technology advances, both small and fast stations will improve their efficiency and charging capacity, as well as increasing the number of charging points available. Fast charging stations will become the norm in public places, trying to make a battery recharge as similar as possible to a current fuel tank refilling.

Bearing in mind that the battery capacity needed by a truck is much greater than in a car, both the type of chargers and the way to charge those batteries must be approached differently. "In terms of charging infrastructure, long-haul BE tractors, whose routes involve multi-day intercity travel, need extensive charging infrastructure along the motorway network. Charging can be done either overnight or through high-power charging points" (Fournols et al., 2020). The charging capacity of a HDV has to be higher than the stations already presented. The less time a truck sits idle, the more profitable and beneficial it is. So, the charging process should be as fast as possible, or charged in those places where stopping is inevitable.

For a battery with a capacity of 1200 kWh and a battery-to-wheel consumption of 1.43 kWh/km, the following power levels may be convenient for the charging requirements presented above. On the one hand, there exists the so-called mega charger with a power supply of 1.2 MW. This type of charger costs 420000 € with operational expenses per year of 4200 €. It would be classified as an ultra-rapid charger. In an amount of time of 30 minutes, a BEV would have a range of 400 km. A charger with this power level may have several charging outlets. More than one user can charge simultaneously. On the other hand, a residential charger of 150 kW for a period of charging time of 8 hours, the vehicle is capable of doing up to 800 km. This type of overnight charger costs 80000 € as initial cost, with operational expenses per year of 800 €. Considering that the service life of these charging stations is around 15 years, the total cost for each type (Fournols et al., 2020) are also shown in Table 4.4. Lifetime costs is the sum of the costs of the purchase of the equipment, installation costs, maintenance costs during the expected life of the infrastructure and the dismantling of it.

A third source for charging stations is presented in Table 4.4, in order to get an overview of the different possibilities available in today's market. As aforementioned, in the ICCT research paper exposed in the Electric vehicle market section, three types of trucks for three different applications are studied. The costs and needs of the infrastructure for their electrification is presented. In those costs are included both the installation and grid connection costs, as well as the fixed costs for the charging units. It can be noticed that costs are pretty consistent across sources when corresponding to same power levels, even from different sources.

Type of charger	Lifetime costs (TCHF)	Sources
Slow 11 kW	2.5	[1]
Public AC 22 kW	15	
Fast 50 kW	30	
Ultra-fast 100 kW	80	
Overnight charger 150 kW	98	[2]
Mega charger 1.2 MW	514	
Slow 50 kW	25	[3]
Ultra-fast 350+ kW	191	

Table 4 4: Cost of different types of charging stations; [1]: (Robert Schürch, Email, Zürich, 30.06.2020, see Appendix 1); [2]: (Fournols et al., 2020); [3]: (Hall & Lutsey, 2019)

The locations for these big chargers (more than 50 kW) aimed for the freight sector should be sited in points where freight vehicles routes go through. First of all, chargers could be placed in service areas where trucks drivers refuel/rest/spend the night, i.e., a charge overnight would take place. Second of all, in logistic facilities. It is mentioned that the transport chain for goods consists in the combination of many processes, from the origin where raw materials are worked on, to the final product delivered to the customer. Thereby, it is in those different points in the journey in which the goods pass, where the trucks in charge of the transport between them could be recharge. And third of all, a very promising system is the charging infrastructure on the move, such us the IPT or overhead catenary systems, as aforementioned. It is very impractical, heavy and expensive to install sufficient battery capacity in a truck (Nicolaides et al., 2018). However, the technology needs to be more mature in order to be implemented on a national level.

For the time being, research in this thesis is focused on the first and second options, i.e., BEVs CoS, since the necessary technology for them is already developed as well as the electricity distribution system. Nonetheless, technology is always improving, and maybe in a few years there are other feasible options for electric charging.

The amount of new electric infrastructure connected to the grid needed for the electrification of the road, specially the two chargers from [2] and [1] in Table 4.4, would cause significant additional power demands and perhaps, the need of reinforcements in the transmission grid.

As aforementioned, in the ICCT paper, the costs for installation, and charging units are included. It is stated that as higher the power installed in a specific location, the lower the costs (see Figure 4.16). Therefore, it is preferable to build more stations in a few sites, rather than spreading them across many sites. The change applied in order to get the fixed values for the charging units of 50 and 350+ kW is the following. 1 US Dollar is equal to 0.91 Swiss francs (16th August 2020). For the past 8 years, the exchange rate has maintained between a minimum of 0.89 and a maximum of 1.01 Swiss francs (Macrotrends, 2020).

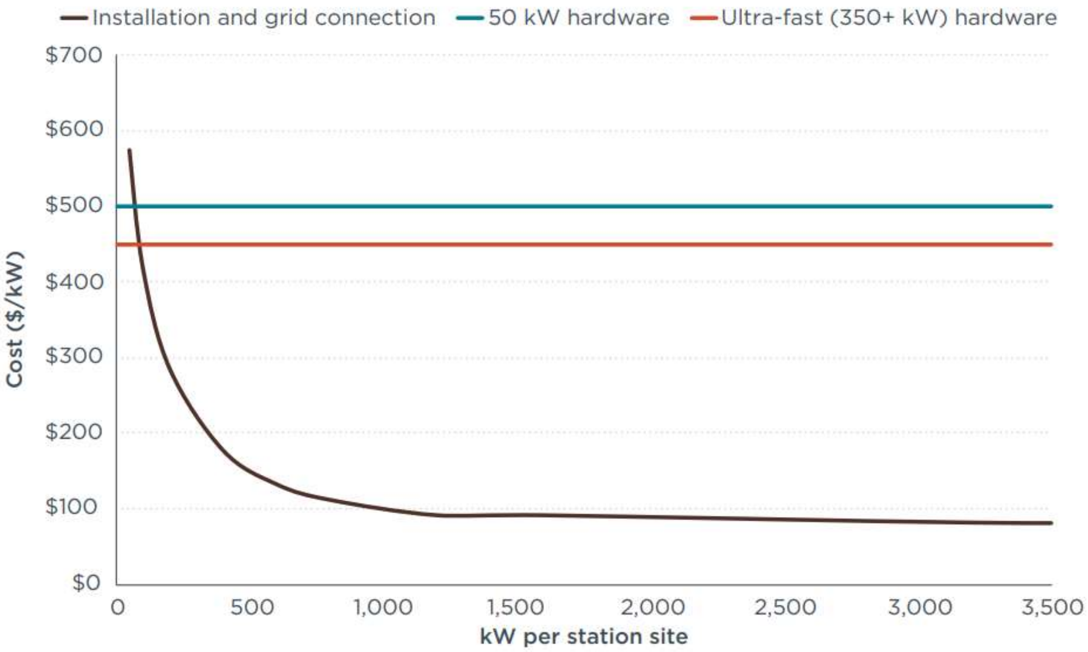


Figure 4 16: Estimated charging infrastructure hardware and installation costs, shown in dollars per kilowatt (Hall & Lutsey, 2019)

HDVs travel longer distances per day in average than LDVs, as mentioned in the Swiss transport performance section. HDVs cover more distance from point A to point B of delivery, and therefore they preferably make use of longer, safer, easier, faster roads, i.e., motorways and highways. The traveling velocity is higher, and the vehicle is mostly going straight, so it is more efficient the transportation in these roads. Thereby, HDVs spend more time in highways.

The range for an electric HDV is one of the most important points, whether in LDVs, it is important too, but the number of stops is higher and distance from point A to B, lower. Thus, they have more chances to charge the vehicles, and there is no need for a significant capacity of the battery if a charging network is installed accordingly to their type of freight transportation. This means that whether there is a type of recharging process in every delivery stop, in the logistics centre where they operate, or a mix of both. A very good alternative for now, is to install these charging stations in petrol stations that already exist. The network available for fuel stations has already been design and well thought, so every vehicle user has access to it. Specially in the type of delivery of a LDV, where every day the routes of these vehicles may vary, so it is laborious to find a good combination that fits to every LDV.

v. Service stations

Besides installing charging units in logistic facilities where HDVs and LDVs need to spend a significant part of their time, they might need to charge the battery during the route to the delivery point. As aforementioned, a possible solution for this condition is by installing charging units in petrol stations too.

Nowadays, petrol stations are intended for refuelling ICE vehicles tanks. They are already incorporated to the road network and available to all vehicle users. There are more than 3400 brand-name petrol stations all over Switzerland (Avenergy Suisse, 2018). Avenergy Suisse provides the exact location for each of the stations. Among those fuel stations, there are the stations that belong to the Swiss motorways network. They are also referred as service stations, because normally offer other services such as restoration, hotel, leisure time, etc. This type of roads tends to be apart from agglomerations due to acoustic and visual pollution. That is why more options than just tank refuelling are available. The total number of service areas in the Swiss motorways is 40 (Motorways of Switzerland, 2018). A great part of them are seen in Figure 4.17.

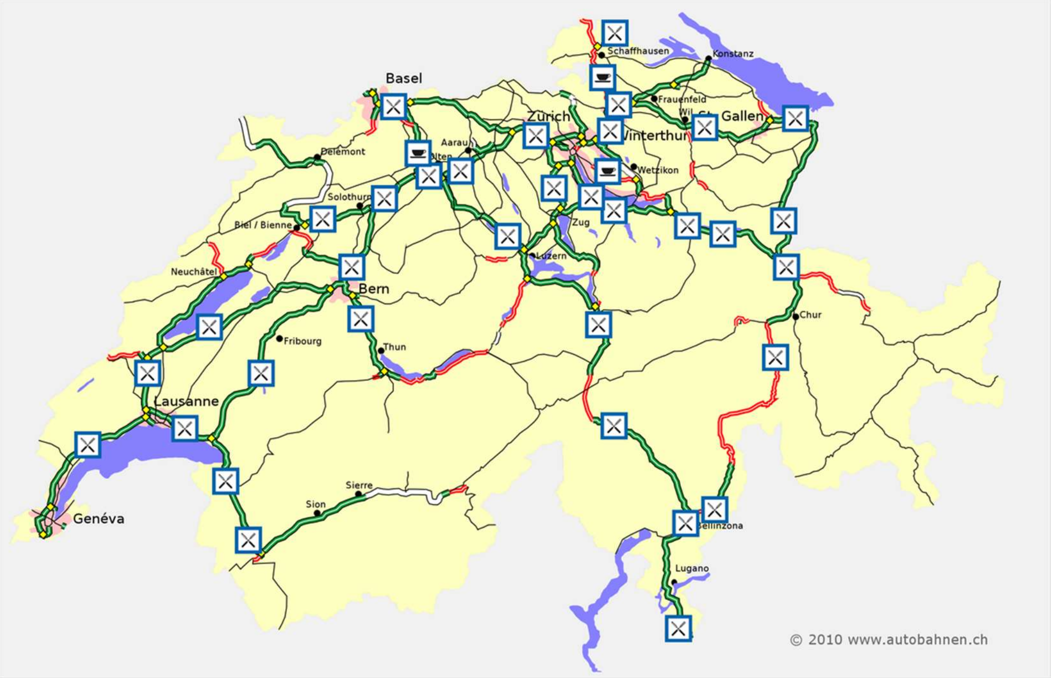


Figure 4 17: Service areas in the motorways of Switzerland (Motorways of Switzerland, 2018)

Therefore, having this service along the road network, the charging process may be done in other sites rather than having to go back to base to recharge the truck. On the one hand, it could be charged overnight in one of these stations and continue the journey the next day. On the other hand, charging may happen during the day, taking advantage that these stations may be nearer than going back to base depot to recharge and then continue the work shift. Basically, it would bring a bigger charging infrastructure, where the truck driver is capable of choosing which charging point is the most convenient depending on the type of delivery they are carrying out. Furthermore, the charging capacity installed in each of the logistic facilities and service stations will be different. As a result, another reason to choose one charging option or another is not only because of the distance to it, but the user's willingness to charge a certain amount of the battery capacity (depending on available time and charging power offered).

However, for the purpose of this thesis, the location of the charging points is not a matter of it. It is just presented to get a basic idea of what the different places for installing charging stations might be. If this were the case, modelling the Swiss road network would be necessary, considering the points where the freight transport vehicles drive through most often during their delivering routes, as well as battery and charging capacities of each of the vehicles in the sector.

e. Road electrification demand

According to a study made by the Aerothermochemistry and Combustion Engines Laboratory in ETH Zürich, HDVs "full electrification increased the total Swiss electricity demand by about 5% over its current level". In terms of vehicle stock, HDVs division accounts for the 12% of the total freight transport sector, as aforementioned. The full electrification would mean that the whole HDVs fleet of 52804 active vehicles is converted/substitute by electric trucks, assuming that the available space for payload in each of the trucks stays the same (Çabukoglu et al., 2018). This assumption is important because if an electric truck with the same dimensions and range as a diesel truck is considered, the space occupied by the electric components (drivetrain and batteries) is greater than that occupied by the components in an internal combustion diesel engine. Thus, there is less space for payload in the electric truck. Therefore, with this assumption the number of HDVs active fleet stays the same, because the freight needs are already covered.

A different approach to calculate the extra electricity demand due to the electrification of the freight transport is to add electric truck's battery energy capacities and compare it with the actual demand levels. In other words, the Swiss representative model HDV's battery capacity is considered as the impact it has on the grid's electricity demand. This representative model is a truck used for port freight transportation applications, i.e., the drayage truck, as aforementioned. The characteristics of this model are presented in Table 4.5. Considering that every Swiss HDV is equipped and characterized with the values from the table, there will be a total of 52804 times 500 kWh travelling on the Swiss roads. If those trucks are fully loaded, the range is lower than having the trailer empty (see Table 4.5). 500 kWh translates in 282 km covered without recharging. That range accounts for more than two days of work for the Swiss HDV average route distance (i.e., 117 km per vehicle per day). That means that on average, every truck will have to be fully charged every two days. Or once a day, but just half of the capacity, i.e., 250 kWh (assuming there are no losses and the 500 kWh are equally distributed for the entire capacity).

Application	Drayage truck
GCVWR (kg)	27500
Tare weight (kg)	9330
Battery size (kWh)	500
Range (no trailer/empty)	340
Range fully loaded (km)	282
Average distance route (km)	90

Table 4 5: Truck model characteristics for a drayage truck application (Hall & Lutsey, 2019)

As seen in Appendix 2, most of the peak demands in Switzerland as a whole, and for the different Swiss regions, happen around noon (12pm). In a scenario assuming that every truck is charged at the same time, it would increase the demand in 13.2 GWh a that specific time (250 kWh times the HDVs active fleet). By looking at Figure A.2.1 (see Appendix 2), whether the charging occurs overnight or during the day, it is not known if the grid is capable of distributing that new amount. Since the new demand is much higher that he actual one and that amount has never been distributed.

However, this is a scenario unlikely to happen. And for that reason, in further calculations, the extra demand considered is 5% over the current electricity consumption level of Switzerland, as stated in the Aerothermochemistry and Combustion Engines Laboratory at ETH's research paper, previously presented.

5. Methodology

The procedure followed to estimate the required investment to achieve heavy-duty freight transportation full electrification is presented in this section. As it is mentioned throughout the thesis, the active fleet of HDVs in Switzerland accounts for 52804 vehicles. The gran majority of them, i.e., 99% of the total, are diesel powered. This division of the sector represents only a 3% of the total Swiss vehicle fleet. However, they account for 25% of road transportation's emissions. These values give an idea of the positive consequences that electrifying HDVs would bring. Basically, the method used to estimate the investment required considers the impact of an average HDV model for the whole Swiss active fleet in the road and electric networks as well as the electric charging infrastructure costs associated to it.

First, section 2 gives an overview of the Swiss energy generation sector, the different ways of generating electricity, and their corresponding emissions and costs per kWh. With this analysis we get an outlook on which are the different technologies to produce electricity and we can decide the best option in case energy generation requires an increase.

Second, section 3 exposes the road transportation sector. In this part of the thesis, it is presented the principal characteristics of the sector, other alternatives to BEVs that are out on the roads in Switzerland. An explanation also on how the freight transportation sector is organized, as well as how are the two divisions of this sector (i.e., HDVs and LDVs) performing nowadays in Switzerland in comparison to previous years. Finally, a brief presentation of the electric freight vehicles' current market is done. This section gives an overview of the sector's most important points in order to understand, design and estimate a better electrical distribution network for electric truck charging.

By the end of this section we get the following outcomes used to get to the final estimation of the investment. Over the years, HDV's t-km have kept rising, while v-km have stayed constant. It means that the responsible for t-km rise is the increase of payload carried by these freight vehicles. The optimization of this sector's division have made possible to keep the same number of freight vehicles on the road for higher amounts of goods delivered each year. Thus, it is assumed that HDVs travel fully loaded, and therefore the range achieved with an electric battery is lower than if the truck is empty.

In this section, several truck models are presented as aforementioned. From those presented, the model chose to represent the average Swiss HDV is the truck used for port applications, i.e., the drayage truck. It is the closest model to Swiss HDV type of deliveries and average distance routes. Drayage trucks do an average distance of 90 km per delivery, whereas a HDV in the Swiss freight sector does 117 km per day. Obviously, this distance does not mean that they are involved in only one delivery process of 117 km, but they can do several ones that sum up that amount. However, at the end of the day, the approximation can be applied stating that one drayage truck's delivery accounts for almost one Swiss HDV's day of work.

Third, in order to better understand the electrical distribution in Switzerland, section 4 provides an analysis of the Swiss transmission grid. Its principal characteristics are given. It is formed by transmission lines and substations. Part of this substations are the so-called transformers that convert alternating current from one voltage to another. In our case, the transformers considered work from 380 to 220 kV, and vice versa. There are a total of 17 of these transformers connected to the grid.

Energy generation and consumption values are also given in this section. This data helps to characterize each of the regions in Switzerland. There are regions producing more than consuming, others consuming more than producing, and a couple of regions that consume and produce in similar amounts. The power grid is designed to be capable of supplying the electricity demand all over the territory, e.g., those areas where production is lower than consumption, energy from other parts is required to be distributed to comply with the energy demand.

The implementation of electric transportation will bring an increase in electricity demand. Mainly due to electric battery charging. The grid needs to be prepared to supply the new demand. The following steps have been carried out in order to have an estimation of the grid's required enhancement due to road transport's electrification.

First of all, both maximum production and consumption values in intervals of 15 minutes during 2019 for each of the regions are selected (although for this thesis' scope we will focus just in the consumption values). This data states what the grid is capable to distribute as far as it is known. Second of all, the number of transformers installed in each of those regions are counted. Finally, using a scatter plot, a relation between the number of transformers installed and the maximum energy values is stablished. Now, when energy consumption values are above the maximums considered, we can use this plot to estimate the number of new transformers required to comply with the new energy demand. A linear regression analysis as well as a hypothesis test were carried to this plot. We wanted to know if the relationship was usable and not something that happened randomly. It was concluded that the model is significant to predict future modifications to the transmission grid.

The focus of this thesis is the evaluation of electrifying HDV's sector, as aforementioned. As stated in the Aerothermochemistry and Combustion Engines Laboratory's study, the full electrification of HDVs increases the total Swiss electricity demand by about 5% over its current level. Let us assume that the increase may happen equally distributed during the year and the days, i.e., the impact of charging trucks during the night is equal to the impact of charging the trucks during the day, when the peak demand happens. Two different electric charging scenarios are considered.

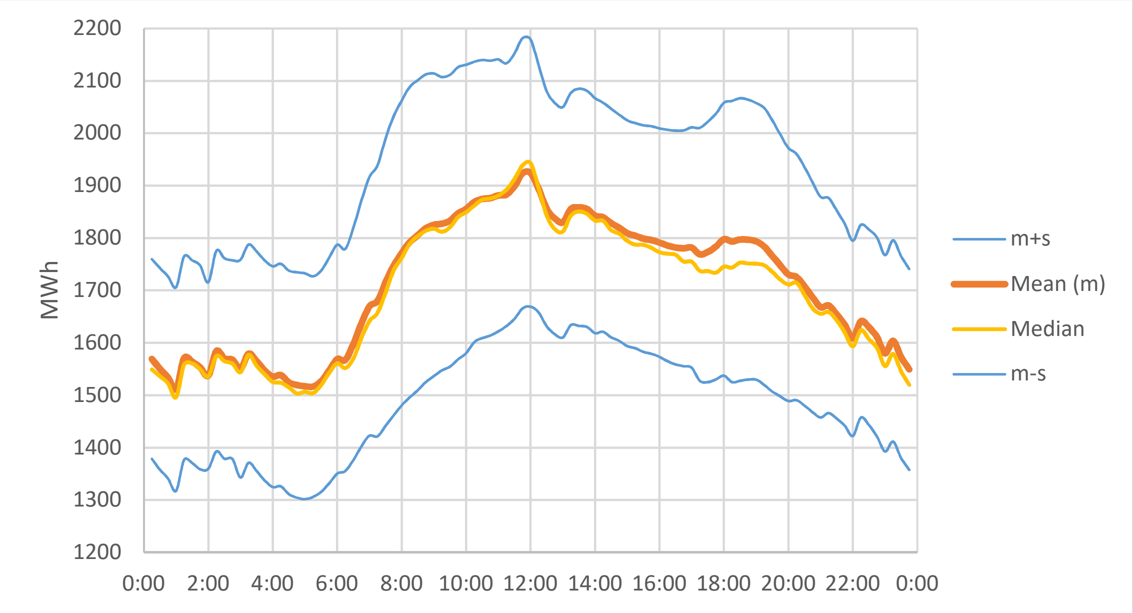


Figure 5 1: Consumption demand curve for Switzerland (2019)

Scenario 1 - electric HDVs are charged overnight. By looking at Figure 5.1, and under average values (i.e., looking at the mean demand curve of the graph), the electricity demand during the night is around 1600 MWh. The electrification of the freight sector implies a 5% increase. And as far as we know, the grid is capable of distributing at least the amount of energy set by the peak. It is possible to say that the grid is good enough to supply the extra energy demand due to the electrification, i.e., the increase on the demand stays lower than the one set by the peak.

Scenario 2 – charging during the day. Furthermore, let us consider that charging happens right when the demand peak strikes (i.e., at noon and at the knowable point of the electric network's maximum capabilities). In this case, having an increase in the electricity demand involves being in a situation of uncertainty, because it is not possible to know if the grid is capable or not of distributing it. Hence, it is assumed that the grid needs an enhancement. Therefore, by making use of the scatter plot mentioned above (see Figure 4.7), it is possible to make an approximation whether it is necessary the installation of a higher amount of high voltage transformers in the grid or not due to the electricity demand increase. The relationship between number of transformers and energy values is characterized by the following regression line's expression:

$$y = 65.174x + 86.778$$

where the y represents the energy demand increase, and the x, the estimated number of transformers needed for that amount of energy. In this case, under average values, the peak demand corresponds to an energy amount around 1950 MWh (see Figure 5.1). By determining the 5% for that current peak, it is possible to know the corresponding number of new transformers required in addition to the current distributing network. It is worth to mention that one extra high voltage transformer has a standard cost of 14300 TCHF. In case more transformers are required, this is going to be the cost considered for grid enhancements.

Another point presented in this section is the required conductive charging infrastructure for electric HDVs. It is considered that it consists in both ultra-fast charging units (350+ kW) as well as slower charging units (50 kW) that are used mainly overnight. Both types of charging units are suitable to be installed in logistic facilities too, i.e., while loading, unloading, maintaining, etc. Trucks would charge their battery through several charging processes for short periods of time, instead for a single long one, as it happens in overnight charging. For simplifying the explanation, the scenario 1 above presented, is fulfilled with 50 kW units, and scenario 2 is mainly fulfilled by installing fast charging units. The lifetime costs for each of these stations are seen in Table 5.1.

	Lifetime costs (TCHF)
Slow 50 kW	25
Ultra-fast 350+ kW	191

Table 5 1: Lifetime costs for the charging units considered in the evaluation (Hall & Lutsey, 2019)

The sector's electrification is presented as a process implemented in several steps, not all at once. Moreover, in the ICCT paper by Dale Hall and Nic Lutsey, three cases are presented: low, medium and high volume. These cases represent three different levels of electrification: 100, 1000 and 10000 electric trucks on the roads, respectively. Basically, this tells us that for a higher amount of electric trucks on the roads, the costs for the charging infrastructure decreases, not only because of technological improvements, but also because the lower costs when producing at higher scales, as well as the higher the charging points per site, the lower the cost for implementing them to the grid network. Furthermore, for a higher electric truck fleet, the ratio for number of charging points per electric truck also decreases. The following table shows these ratios and the infrastructure costs for each of those levels of electrification.

Application	Cases	Number of trucks	Ratio 50 kW charging points per truck	Ratio 350+ kW charging points per truck	Infrastructure cost per truck (TCHF)
Drayage trucks	Low volume	100	0.95	0.1	53
	Medium Volume	1000	0.78	0.05	35
	High volume	10000	0.7	0.03	25

Table 5 2: Charging units needed per electric HDV and the infrastructure costs associated for three levels of electrification (Hall & Lutsey, 2019)

The Swiss HDV's active fleet is around five time bigger than the high-volume presented case. Therefore, with the values presented on the table, three graphs have been plotted in order to predict those values at higher scales of HDVs' electrification (see graphs 5.2, 5.3 and 5.4). The reason to estimate the infrastructure costs by using a potential trend line is that the infrastructure costs data is compared with measurements that increase with a certain rate (i.e., the number of active electric HDVs).

In our case, the levels of HDVs' fleet electrification considered are 10, 20, 50 and 100% (i.e., full electrification of the sector). Using the previous figures, the following data is estimated:

Fleet electrification (%)	Number of electric HDV	Number of 50 kW points	Number of 350+ kW points	Infrastructure costs per HDV (TCHF)
10	5280	3723	166	27.425
20	10561	7393	317	24.494
50	26402	18401	772	21.096
100	52804	36748	1530	18.842

Table 5 3: Data used for the evaluation of the required investment for the Swiss case

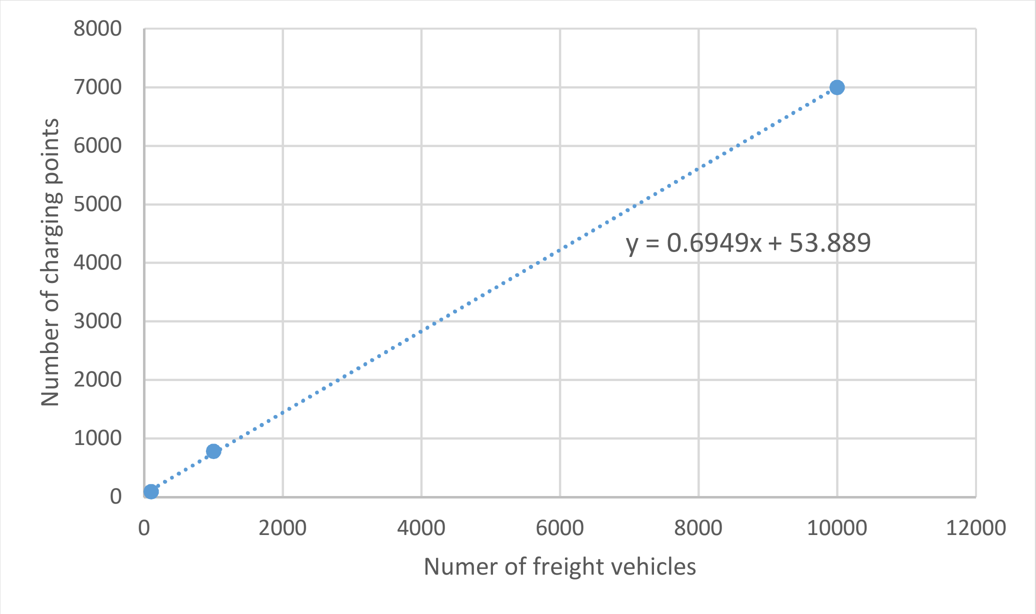


Figure 5 2: Number of 50 kW charging points required for different levels of electrification of the freight sector

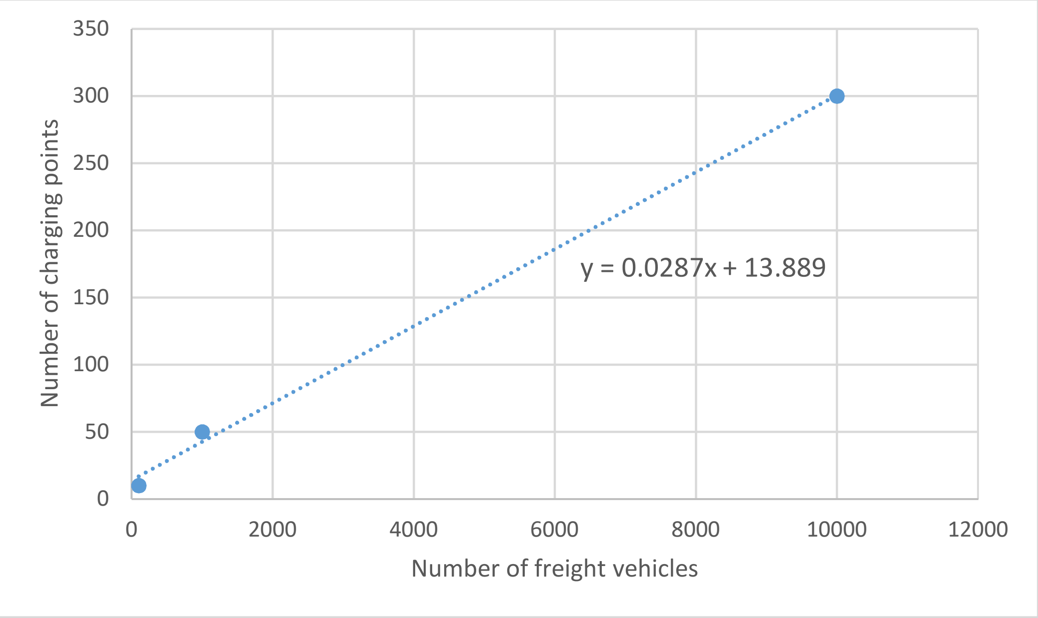


Figure 5 3: Number of 350+ kW charging points required for different levels of electrification of the freight sector

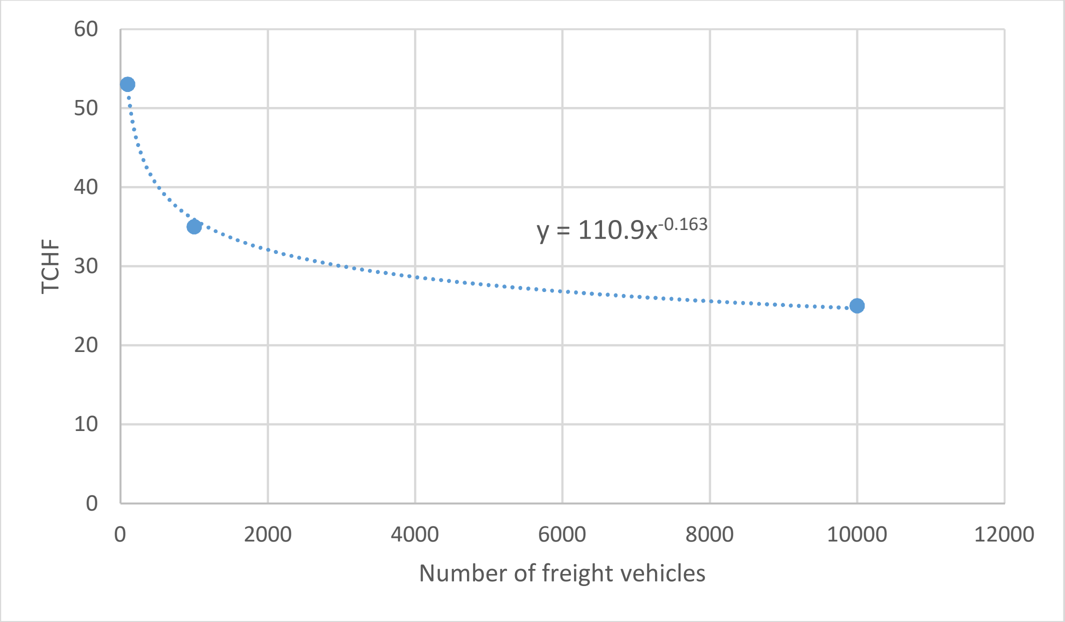


Figure 5 4: Associated infrastructure costs per electric freight vehicle for different levels of electrification

As a result of the previous data exposed, it is possible to have an estimation of the total infrastructure costs for the scenario where freight transportation is fully electrified (see Results and Discussion section).

6. Results and Discussion

The conclusions are presented in progressive steps.

First, the Swiss energy distribution system is estimated to require the installation of 1 extra transformer in order to supply the new demand due to HDVs full electrification.

As aforementioned, in a scenario where charging takes place during the night, the system is already capable of distributing higher energy demand values. Nevertheless, a scenario when charging is done during the peaks points of energy consumption, i.e., during the day; the system requires an enhancement. This enhancement comes with the installation of 1 high voltage transformer in the grid (its exact location on the network is outside the scope of this thesis).

In order to get to the previous conclusion, the steps presented in the methodology section have been followed. First, a 5% increase to the average peak value in Switzerland demand curve (by looking at the energy consumption Swissgrid datasheet, this point is equal to 1924 MWh, and it happens at 12pm), means an increment of 96.2 MWh to the current level. Second, adding this value to the regression line equation translates in the necessity of installing 0.145 transformers more, i.e., 1 more transformer is needed. It is noticeable that there is even more room for higher demands, hence it is not possible to install just a 15% of a transformer. For example, a new increase in the future demand could be due to a rise in the electric HDV fleet, caused by the estimated growth of the road freight in 33% until 2040.

Second, for the full electrification of HDV it is required to install charging units all over Switzerland with an infrastructure cost of 995 million Swiss francs.

The total investment is divided in several levels of electrification from 10%, 20%, 50% and 100% of electrification of the HDV Swiss freight sector. Infrastructure costs refer to the price of the hardware charging unit and the installation and connection costs of those units to the electric transmission grid. It can be noticed that the higher the amount of electric HDV fleet, the lower the infrastructure costs per vehicle. The decline explains as the power installed in one location increases, the costs of connection and construction can be amortized over more stations. Nevertheless, once the installed chargers in a single location are above two units, the hardware of the chargers represent most of the cost per site. The levels of electrification and the associated costs are included in the following table.

Fleet electrification (%)	Number of electric HDV	Infrastructure costs per HDV (TCHF)	Charging infrastructure costs (TCHF)
10	5280	27.425	144804
20	10561	24.494	258681
50	26402	21.096	556977
100	52804	18.842	994933

Third, the total investment including the grid upgrades, required to cope with the increase in the electricity demand is around one billion Swiss francs.

As it was stated in the first conclusion, the grid is estimated to need one extra high voltage transformer to the already 17 existing ones. The standard cost for one unit is 14.3 million Swiss francs. The price for a single transformer is considered as a fixed cost. That means that from the beginning of the transition to electrified HDVs, the transformer is installed in the grid, i.e., since day 1, the investment takes into account its cost. Therefore, adding to the infrastructure costs presented in the previous table the cost of the transformer, it gives the total investment for each of the electrification levels. However, the transformer needed has been calculated considering the full electrification of the HDV fleet. For lower levels of electrification, it may mean that no additional upgrades to the grid are necessary. The inflection point that decides whether the installation is required or not is estimated by the regression line of the scatter plot in Figure 4.7. The minimum increase in the demand in order to be required the installation of the transformer is 86.8 MWh. In our case, as the increase for the full electrification is just a little bit over that limit, i.e., 96.2 MWh, it is safe to say that for levels of electrification below 100%, the grid does not need an improvement. Nonetheless, as the addition to the grid will be necessary at one point in time, we assume the cost from the beginning of the transition to an electric fleet. The investment for each of the electrification levels considered are seen in the following table.

Fleet electrification (%)	Charging infrastructure costs (TCHF)	Grid improvements costs (TCHF)	Total costs (TCHF)
10	144804	14300	159104
20	258681		272981
50	556977		571277
100	994933		1009233

In conclusion, for the full electrification for the HDV division of the freight transportation sector a total investment of 1 billion Swiss francs is estimated. This implies the installation of 36748 slow chargers (50 kW) and 1530 ultra-fast chargers (350+ kW) all over Switzerland. The implementation of this investment is estimated to be enough for the preparation of both the grid as well as the road network to hold a full electrification of the sector.

7. Further research

Alternative charging processes

Technologies such as IPT systems and charging processes such as battery swapping are a very interesting alternative for the current conductive charging. First of all, IPT on the move means lower battery capacities in the vehicles, because while it is moving the battery is not consuming energy storage, but directly from the grid. Second of all, the standardization of batteries in the market could make possible the battery swapping option. This process would translate in a much faster recharge process than regular battery charging, making it pretty similar to refuelling a petrol tank, if not faster. However, the application of these techniques requires more research as they are in their early stages of development.

Smart charging

Using smart grid solutions would be helpful to not redesign the distribution network, and therefore no changes to it would be necessary. We need to take into consideration that not all EVs are going to be charged during the peak electricity demand values. An as mentioned through the thesis, they will not be charged all at once. Smart charging controls the timing for charging. It optimises the charging processes based on electricity demand. This technology can decrease power level of the charging station if the electric network saturates. At high penetration levels of EVs, some form of smart charging becomes unavoidable.

Furthermore, adding renewables energies to the system brings uncertainty (mainly solar and wind power). It is difficult to predict the energy that will be produced by these technologies as they depend on natural processes. Smart charging techniques would make EVs bring flexibility to the system. EVs are a future asset of energy storages. Therefore, they can be used as flexibility resources of the energy system. Energy could be sucked from the grid or reinjected back to the grid, depending of the grid needs, while getting the vehicle fully charged and ready to be used by the user. This measure could let produce more and more energy with renewable sources without comprising the actual energy system.

Alternative environmentally friendly powered vehicles

As it has been mentioned through the thesis, other alternative options for the full decarbonisation of the transport are electrofuels and hydrogen fuel cell vehicles. "Electrofuels are electricity based gaseous or liquid fuels which can be used in ICE" (Calvo Ambel, 2017). The most important barrier for these alternatives is that they need the production of hydrogen. Hydrogen can be obtained during electrolysis. An electricity source is applied to an oxygen sample, and hydrogen is produced. The electricity involved in the process must be generated from a zero-emission generation process. Later, if we want to produce electrofuel, the previous generated hydrogen is combined through synthesis processes with CO_2. How is this obtained? Or maybe it can be captured? This gas is a GHG. The tailpipe emissions are going to be lower than in an ICE vehicle, but there is still CO_2 being emitted to the atmosphere. Another important barrier for hydrogen fuel cell vehicles is that they would require a network of hydrogen suppliers. Whilst the electricity network is already available to all users. The same network used to distribute electricity to commercial/personal addressees, it is the one used for the electric charging units considered in this thesis. Therefore, the investment just includes the units and the installation of them, but not the distribution system. However, fuel cell vehicles have zero tailpipe emissions and the refilling time is like a petrol tank. Making it very attractive to vehicle users. Further research in alternative ways to achieve the full decarbonisation is very important.

Most likely, in the future, transportation sector would have available a variety of options, ones coexisting with each other (as gasoline and diesel do today). The user will be the responsible for choosing the best option that suits the best for them.

LDVs fleet

For further evaluations of the necessary investment, it is convenient to include the LDV fleet too. This division of the sector represents the 88% of the freight vehicles. Therefore, for the electrification of this sector, they would mean a significant increase in the demand. A quick calculation for their impact in the grid is the following. If the truck model for an electric LDV taken is the one provided by BYD, i.e., the T3. The battery capacity of one of these vehicles is around 50 kWh. Thant means that a LDV has approximately 10 times less impact that a HDV. Moreover, as the Swiss LDV fleet is around 388 thousand vehicles, all these vehicles electrified represent an approximate number of 39 thousand electric HDV. A similar value to the current HDV fleet. Therefore, the estimated impact of the entire freight sector in the yearly energy demand is then around 10% (double of the estimated by the ETH study). However, obviously this estimation is just a mere approximation, because both types of duty vehicles have different types of deliveries, weight, dimensions, etc.

Freights transported in the coming future

An increase of a 33% in the actual tonne kilometres in Switzerland until 2040 has been estimated. As aforementioned, tonne kilometres are the payload carried by the freight vehicles times the distance covered by them. The vehicle kilometres of the Swiss HDVs has stayed constant since more than the 2000s, i.e., both number of vehicles and distance covered have kept constant; whereas the amount of goods transported is increasing overtime. This has been possible due to both delivering routes' optimization as well as an improvement in the efficiency of freight logistics such as load-matching and maximizing the capacity. Therefore, we assume that the current trucks are fully loaded, hence an increase in the tonne-km would translate in a higher number of HDVs on the road to fulfil the new goods demand. For further research, it is important to have in mind the new hypothetical active truck fleet values and calculate the corresponding new charging points necessary to add to the existing network.

Where do I charge my vehicle?

A good way in order to have knowledge of the available charging points spread over the Swiss territory would be through an app. By knowing the location of the truck driver, the available time of the user, the battery limitations/conditions of the vehicle, and most importantly, the available chargers, the app would indicate the user the best option offered in the public charging network.

CO_2 sucking machines

Another alternative pretty interesting to have research on are CO_2 sucking machines directly from the atmosphere. They are an option to have a source of CO_2 too. Moreover, in 2017, a commercial plant for capturing CO_2 directly from the air was opened near Zürich by Climeworks AG. The carbon dioxide captured is then sold to costumers. This technology could be a very good alternative to accelerate the process of decarbonisation and reducing the amount of CO_2 in the air. Investigation should be put into this technology in order to know if it can truly make a significant difference in the polluted air, and if it is worth the investment.

Locations for transformers and charging stations

The location for the both estimations in number of transformers and charging stations added to the grid is a point outside this thesis. However, it is important to carry a research about it. First, modelling the grid considering that demand changes depending on the region. This will let us know which is the best location for the transformer. And second, modelling the delivering routes of the freight vehicles. Consequently, it will be known the most transit points by these vehicles and therefore knowing the best locations for charging stations.

Rise in energy production

In case of an increase on energy production, a decision in which are the best technologies to produce energy must be studied. The decision will be based in information already given in this thesis (emission and costs for each of the technologies), the willing on phasing out nuclear energy, and stop making use of non-renewable processes in order to achieve the objective of net-zero emissions. The new energy sector distribution would involve several technologies, if not all. For example, solar power is suitable for midday hours. Therefore, the modelling of the network is required, in order to know the most efficient combination of the processes. Obviously, every process has their own characteristics and specifications in energy generation. The model must include them.

External costs

For future research, it would be positive if external costs due to transportation and consequently vehicles fleet’s increase are considered. These costs refer to the consequences in social and environmental processes for carrying certain activities. In our case, road transportation. Emitting pollutants to the atmosphere have external costs such as health costs, forest damage costs, infrastructure surrounding road networks damage costs (i.e., dirty air might damage buildings), among others. Therefore, by carrying measures like electric transportation not only we are stopping the emissions to the atmosphere, but also stopping harming our belongings and ourselves.

8. Bibliography

ABB. (2011). Cuaderno de Aplicaciones Técnicas n° 10. Plantas fotovoltaicas. *Asea Brown Boveri, S.A.*, 114. https://doi.org/10.1016/S0927-0256(97)00022-0

Arcadia. (2017). *Greenhouse gas emissions - Natural vs manmade*. https://www.arcadia.com/energy-101/environmental-impact/greenhouse-gas-emissions-natural-vs-man-made/

Avenergy Suisse. (2018). *Petrol station network*. https://immer-in-bewegung.ch/xx/petrol-station-network/

Axpo. (2018). *Electricity market facts and figures*. https://www.axpo.com/ch/en/about-us/media-and-politics/power-market-switzerland.html

Bauer, C., Hirschberg, S., Bauerle, Y., Biollaz, S., Calbry-Muzyka, A., Cox, B., Heck, T., Lehnert, M., Meier, A., Prasser, H.-M., Schenler, W., Treyer, K., Vogel, F., Wieckert, H. C., Zhang, X., Zimmerman, M., Burg, V., Bowman, G., Erni, M., … Tran, M. Q. (2017). Potentials, costs and environmental assessment of electricity generation technologies. *Swiss Federal Energy Office*, 1–783. https://www.psi.ch/ta/PublicationTab/Final-Report-BFE-Project.pdf

Benjamin Zhang. (2015). *Tesla's battery-swapping plan has a mere shadow of the promise it once showed*. Business Insider. https://www.businessinsider.com/teslas-battery-swapping-plan-isnt-working-out-2015-6?r=US&IR=T

Betz, R., Geissmann, T., Hediger, W., Herter, M., Schillinger, M., Schuler, C., & Weigt, H. (2017). *The Future of Swiss Hydropower : Distributional Effects of Water Fee Reform Options - Interim Project Report*. *c*.

BFE. (2020). *Vehicles*. https://www.bfs.admin.ch/bfs/en/home/statistics/mobility-transport/transport-infrastructure-vehicles/vehicles.html

BFS. (2019a). *Energy*. BFS. https://www.bfs.admin.ch/bfs/en/home/statistics/energy.html

BFS. (2019b). *Goods transport by road*. https://www.bfs.admin.ch/bfs/en/home/statistics/mobility-transport/goods-transport/road.html

BFS. (2019c). *Passenger transport performance*. https://www.bfs.admin.ch/bfs/en/home/statistics/mobility-transport/passenger-transport/performance.html

BFS. (2020a). *Road vehicles - New registrations*. BFS. https://www.bfs.admin.ch/bfs/en/home/statistics/mobility-transport/transport-infrastructure-vehicles/vehicles/road-new-registrations.html

BFS. (2020b). *Road vehicles - Stock, level of motorisation*. https://www.bfs.admin.ch/bfs/en/home/statistics/mobility-transport/transport-infrastructure-vehicles/vehicles/road-vehicles-stock-level-motorisation.html

BFS. (2020c). *Transport infrastructure and vehicles*. https://www.bfs.admin.ch/bfs/en/home/statistics/mobility-transport/transport-infrastructure-vehicles.html

Bradley Berman. (2020). *EV battery swapping is dead in US, but China wants to make it happen*. Electrek. https://electrek.co/2020/01/17/ev-battery-swapping-is-dead-in-us-but-china-wants-to-make-it-happen/

Browne, M., Allen, J., Nemoto, T., & Visser, J. (2010). Light goods vehicles in urban areas. *Procedia - Social and Behavioral Sciences*, *2*(3), 5911–5919. https://doi.org/10.1016/j.sbspro.2010.04.006

BYD. (2018). *BYD*. https://www.byd.com/en/CompanyIntro.html?scroll=true

Çabukoglu, E., Georges, G., Küng, L., Pareschi, G., & Boulouchos, K. (2018). Battery electric propulsion: an option for heavy-duty vehicles? Results from a Swiss case-study. *Transportation Research Part C: Emerging Technologies*, *88*(January), 107–123. https://doi.org/10.1016/j.trc.2018.01.013

Calvo Ambel, C. (2017). Electrofuels - what role in EU transport decarbonisation? *Transport & Environment*. https://www.transportenvironment.org/sites/te/files/publications/2017_11_Briefing_electrofuels_final.pdf

Carey, F. A. (2008). *Chlorofluorocarbon - Chemical compound*. Encyclopedia Britannica. https://www.britannica.com/science/chlorofluorocarbon

Colby, J. J. (2019). *Wind Power: Onshore vs Offshore Wind Farms*. https://storymaps.arcgis.com/stories/b96f4db23c4449849deb60c0953b2509

Cristina Gil Martínez. (2018). *Regresión Lineal Simple*. RPubs. https://rpubs.com/Cristina_Gil/Regresion_Lineal_Simple

Csanyi, E. (2011). *Price of a transformer*. Electrical Engineering Portal. https://electrical-engineering-portal.com/price-of-a-transformer

Dones, R., Heck, T., & Hirschberg, S. (2004). Greenhouse Gas Emissions from Energy Systems, Comparison and Overview. In *Encyclopedia of Energy*. https://doi.org/10.1016/b0-12-176480-x/00397-1

E-FORCE One AG. (2020). *EFORCE Company*. https://www.eforce.ch/en/company/innovation

e'mobile; VSE AES; electro SUISSE. (2015). *Getting connected Electromobility and infrastructure*.

Economics of Nuclear Power. (2020). World Nuclear Association. https://www.world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx

European Alternative Fuels Observatory. (2020). *Electric vehicle charging infrastructure*. https://www.eafo.eu/countries/european-union/23640/summary/compare

European Automobile Manufacturers Association. (2020). Massive ramp-up of truck charging and re-fuelling infrastructure needed, new data reveals. *European Automobile Manufacturers Association (ACEA)*. https://www.acea.be/press-releases/article/massive-ramp-up-of-truck-charging-and-re-fuelling-infrastructure-needed-new

EZV. (2020a). *Heavy vehicle charges (performance-related and lump-sum)*. https://www.ezv.admin.ch/ezv/en/home/information-companies/transport--travel-documents--road-taxes/heavy-vehicle-charges--performance-related-and-lump-sum-.html

EZV. (2020b). *Vignette (Autobahngebühren)*. https://www.ezv.admin.ch/ezv/de/home/information-private/reisedokumente-und-strassenabgaben/vignette--autobahngebuehren-.html

Federal Department of Foreign Affairs. (2019). *Energy – Facts and Figures*. https://www.eda.admin.ch/aboutswitzerland/en/home/wirtschaft/energie/energie---fakten-und-zahlen.html

Flury, K., & Frischknecht, R. (2012). *Life Cycle Inventories of Hydroelectric Power Generation*. 51.

FOEN. (2013). *The Swiss hydrographic network*. https://www.bafu.admin.ch/bafu/en/home/topics/water/state/maps/the-swiss-hydrographic-network.html

FOEN. (2017). *Geography – Facts and Figures*. https://www.eda.admin.ch/aboutswitzerland/en/home/umwelt/geografie/geografie---fakten-und-zahlen.html

FOEN. (2019). *2050 climate target*. https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/climate-target2050.html

Fournols, P., Mathieu, L., Nix, J., Ambel, C. C., Unterlohner, F., Officer, I., Fournols, P., Freight, C., & Officer, P. (2020). How to descarbonise the French freight sector by 2050? *Transport & Environment*.

Freight transportation. (2020). Freight Center. https://www.freightcenter.com/freight-transportation

Grabski, F. (2014). Semi-Markov Processes: Applications in System Reliability and Maintenance. In *Semi-Markov Processes: Applications in System Reliability and Maintenance*. https://doi.org/10.1016/C2013-0-14260-2

Hall, D., & Lutsey, N. (2019). Estimating the infrastructure needs and Costs for the Launch of Zero-Emission Trucks. *The International Council On Clean Transportation*, *August*, 38. https://doi.org/10.13140/RG.2.2.17010.86724

Harris, M. (2017). Expansion of Switzerland's 480-MW FMHL pumped storage plant complete. *Hydro Review*. https://www.hydroreview.com/2017/05/11/expansion-of-switzerland-s-480-mw-fmhl-pumped-storage-plant-complete/#gref

Hou, E. (2008). Dirty Hydro: Dams and greenhouse gas emissions. *Rivers*, *NovembeR*.

ICCT. (2018). CO2 emissions and fuel consumption standards for heavy-duty vehicles in the European Union. *The International Council On Clean Transportation*, *May*. https://www.theicct.org/publications/co2-emissions-and-fuel-consumption-standards-heavy-duty-vehicles-european-union

IEA Wind TCP. (2017). IEA Wind Technolog y Collaboration Prog r a m m e 2017 Annual Report. *Annual Report*. https://community.ieawind.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=dd7c47c2-b19d-00bf-6c38-970494257e43&forceDialog=0

IQPC. (2018a). *Can advanced hybrid electric drive solutions cut heavy duty vehicle emissions?*

IQPC. (2018b). *Will heavy electric trucks bear the load?*

Lindsey, R. (2020). *Climate Change: Atmospheric Carbon Dioxide*. Climate.Gov. https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

Luigi Jorio. (2019). Why is solar power struggling to take off in Switzerland? *Swissinfo.Ch*. https://www.swissinfo.ch/eng/bright-future-_why-is-solar-power-struggling-to-take-off-in-switzerland--/45350090

Macrotrends. (2020). *US Dollar Swiss Franc Exchange rate - Historical chart*. https://www.macrotrends.net/2558/us-dollar-swiss-franc-exchange-rate-historical-chart

Mancera Sugranes, A. (2017). *Measuring Service Quality in Freight Transport Networks* (Issue 24444) [ETH Zurich]. https://doi.org/10.3929/ETHZ-B-000225616

Mann, M. E. (2019). *Greenhouse gas - Atmospheric Science*. Encyclopedia Britannica. https://www.britannica.com/science/greenhouse-gas

Martin Ruesch. (2006). *Solutions for freight transit transport through Switzerland*.

Mathieu, L., & Poscanova, J. (2020). *Recharge EU: how many charge points will Europe and its Member States need in the 2020s*. 68.

Max Chafkin. (2014). *A Broken Place: The Spectacular Failure Of The Startup That Was Going To Change The World*. Fast Company. https://www.fastcompany.com/3028159/a-broken-place-better-place

Mckinsey & Company. (2012). *Electric Vehicles in Europe: gearing up for a new phase?* https://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&uact=8&ved=0CC0QFjAB&url=http://www.mckinsey.com/~/media/McKinsey Offices/Netherlands/Latest thinking/PDFs/Electric-Vehicle-Report-EN_AS FINAL.ashx&ei=7MUWVf2zNcTeU42lg-AC&usg

McLeod, S. (2019). *What a p-value tells you about statistical significance*. Symply Psychology. https://www.simplypsychology.org/p-value.html#:~:text=The smaller the p-value,should reject the null hypothesis.&text=A p-value higher than,and reject the alternative hypothesis.

Motorways of Switzerland. (2018). *Service areas in Switzerland*. Motorways of Switzerland. https://www.autobahnen.ch/index.php?lg=001&page=018

Mühleberg plant to close in 2019. (2013). *Swissinfo.Ch*. https://www.swissinfo.ch/eng/nuclear-power_muehleberg-plant-to-close-in-2019/37223282

New to the Electric Vehicle Industry? (n.d.). SemaConnect. https://semaconnect.com/for-ev-drivers/charging-station-basics/

Nicolaides, D., Cebon, D., & Miles, J. (2018). Prospects for Electrification of Road Freight. *IEEE Systems Journal*, *12*(2), 1838–1849. https://doi.org/10.1109/JSYST.2017.2691408

Nuclear power in Switzerland. (2020). World Nuclear Association. https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/switzerland.aspx

OzonAction. (n.d.). *The Montreal Protocol*. UN Environment Programme. https://www.unenvironment.org/ozonaction/who-we-are/about-montreal-protocol

Partners, S. (2016). *Electrified Road Freight Transport*.

Ragheb, M. (2017). Economics of Wind Power Generation. *ScienceDirect*.

Schleup, J. (2008). *How Does Cogeneration Provide Heat and Power?* Scientific American. https://www.scientificamerican.com/article/how-does-cogeneration-provide-heat-power/

Schulte, J., & Ny, H. (2018). Electric road systems: Strategic stepping stone on the way towards sustainable freight transport? *Sustainability (Switzerland)*, *10*(4). https://doi.org/10.3390/su10041148

Sovacool, B. K. (2008). Valuing the greenhouse gas emissions from nuclear power: A critical survey. *Energy Policy*, *36*(8), 2950–2963. https://doi.org/10.1016/j.enpol.2008.04.017

Stoll, J. (2019). *Number of registered vehicles in Norway in 2018, by type*. Statista. https://www.statista.com/statistics/828602/number-of-registered-vehicles-in-norway-by-type/

Swissgrid. (2020a). *Power grid*. https://www.swissgrid.ch/en/home/operation/power-grid.html

Swissgrid. (2020b). *Regulation: Reliable and balanced around the clock*. https://www.swissgrid.ch/en/home/operation/regulation.html

Swissinfo. (2017). *Online shopping trend intensifies – especially cross-border*. https://www.swissinfo.ch/eng/retail-therapy_online-shopping-trend-intensifies-especially-cross-border/42996546

Swissinfo. (2019). *Record number of new e-cars on Swiss roads*. https://www.swissinfo.ch/eng/mobility_record-number-of-new-e-cars-on-swiss-roads/45409796

Tailpipe emissions. (n.d.). Climate Change Connection. https://climatechangeconnection.org/emissions/tailpipe-emissions/

Thalmann, P., & Vielle, M. (2019). Lowering CO2 emissions in the Swiss transport sector. *Swiss Journal of Economics and Statistics*, *155*(1). https://doi.org/10.1186/s41937-019-0037-3

Transformer basics. (n.d.). Electronics Tutorials. https://www.electronics-tutorials.ws/transformer/transformer-basics.html?utm_referrer=https%3A%2F%2Fwww.google.com%2F

Transformer Life-Cycle Cost: Total Owning Cost. (n.d.). Copper Development Association Inc. https://www.copper.org/environment/sustainable-energy/transformers/education/trans_life_cycle.html

Understanding Global Warming Potentials. (2017). United States Environmental Protection Agency. https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

United Nations. (2015). *Paris Agreement*.

What Determines The Cost Of Power Transformers? (n.d.). Miracle. https://www.miracle.net.in/blog/determines-cost-power-transformers/

Wiederkehr, B., Bachmann, P., Troxler, B., & Läderach, S. (2007). Einheitskosten. *Merkur Access II*.

Wikipedia. (2020). *Electric Truck*. https://en.wikipedia.org/wiki/Electric_truck#cite_note-42

Wood, J. (2019). *How each country's share of global CO2 emissions changes over time*. World Economic Forum. https://www.weforum.org/agenda/2019/01/how-each-country-s-share-of-global-co2-emissions-changes-over-time/

XE. (2020). *XE Currency stats: CHF to CNY*. https://www.xe.com/currencycharts/?from=CHF&to=CNY&view=10Y

YUE, X. L., & GAO, Q. X. (2018). Contributions of natural systems and human activity to greenhouse gas emissions. *Advances in Climate Change Research*, *9*(4), 243–252. https://doi.org/10.1016/j.accre.2018.12.003

Appendix

A.1. Interview made via e-mail to Robert Scürch, head of corporate development, sales and energy management at WWZ Enegie AG the 30th of June, 2020:

A.1.1. It has been estimated that transport electrification will lead to a 20% increase in electricity consumption. What type of infrastructure would be affected by this change in demand? What would be the investment needed in the infrastructure of WWE Energie's power generation plants?

This mainly affects the networks that charge electric cars with high power. The expansion of production in our grid can only be achieved via photovoltaics, which, however, only produces stochastically and usually not at the time of charging. Expansion in the rest of Switzerland will also be difficult.

A.1.2. What would be a list of the most common investments in electrical equipment in order to increase energy generation, as well as increase the distribution through the electricity grid? For instance, in order to generate more energy, one could invest in the expansion of the current plants owned, open new hydroelectric plants, or install a greater number of photovoltaic panels. On the other hand, to be able to distribute the new demand, new transformers could be installed, cables in the current network reinforced, Smart grids, investing in IT, etc.

As mentioned above, the expansion of production in Switzerland is very difficult, apart from photovoltaics. Both the expansion of hydroelectric power and the increase in wind power is prevented by the green side or by landscape protection. PV can only be expanded on existing roofs, which leads to high energy costs. The expansion of grids is relatively easy, especially if it is done under the ground. However, with stochastic production and variable loads (e-mobility and heat pumps), there is also flexibility in the grid, which can be used to avoid investments (peak shaving).

A.1.3. Is the price of both electrical equipment and electrical infrastructure expected to increase or decrease?

Constant to sinking.

Which are the reasons for basing an investment on one type of power generation or another? For example, environmental reasons, cost reasons, national agreements reasons to be met, etc.

Feasibility in the social and political framework, return on investment, security of supply, reasons of environmental protection

A.1.4. Currently, I have public data from Swissgrid on the energy production and consumption in kWh at a canton level in 15 minute intervals. Would it be possible to have access to data at a local level, from the areas that WWE Energie supplies? It does not have to be current data, it can be from past years, but it would be interesting to comment possible singularities or changes that are observed regarding the different areas within a canton.

In principle, this is possible. How long should the period be.

A.1.5. With regard to the charging stations, how many charging stations do you have under control, and what are their power level?

We operate about 50 stations with a rapidly increasing trend. Most of them are residential with 11 kW, some public with 22 kW (always AC), one 50 kW DC and one 100 kW DC.

A.1.6. Which are the locations of these charging stations installed and what are the reasons you have considered for this disposition?

The small stations are our products that we install for customers in underground garages. The others are located in public places and the fast charging station near a motorway junction.

A.1.7. What was the investment required to install these charging stations and throughout their lifetime?

The small stations cost around CHF 2500, the public AC around 15 TCHF, one 50 kW around 30 TCHF and one 100 kW around 80 TCHF.

A.1.8. What type of customer/consumer are the charging stations aimed at? Private cars, light, heavy duty vehicles, etc.

Mainly private individuals at home or at work, shoppers and transients.

A.1.9. The canton of Zug is the dominant canton with 1.4% of registered electric vehicles. As the number of electric vehicles increases, do you plan to install more charging stations? Will they be of the same power as the already installed ones, or more? What are the reasons for that? For example, shorter charging time, aimed at vehicles with larger battery capacities (such as trucks), etc.

We are mainly pushing the stations at home (underground car park) and at work, as most of the loading (90%) is done there. These are slow loaders (11 kW). We leave the fast loading network to national players.

A.1.10. Freight transport has a low share of vehicles in the road compared to the number of cars. However, the freight sector is the most pollutant of all the types of the transportation sector. Is WWE Energie considering the possibility of investing in charging processes aimed at the freight transport?

I think that H2 will prevail in freight transport. We have no intention of investing there.

A.1.11. Finally, in relation to question 5, if it were possible to have access to demand curves from previous years for both the charging stations and the areas supplied by WWE Energie, it would be pretty helpful.

Unfortunately, we do not have the charging stations in 15 minutes resolution, only the total consumption.

A.2. Consumption demand curves for each of the divisions commented in "Current electricity demand" section (Swissgrid)

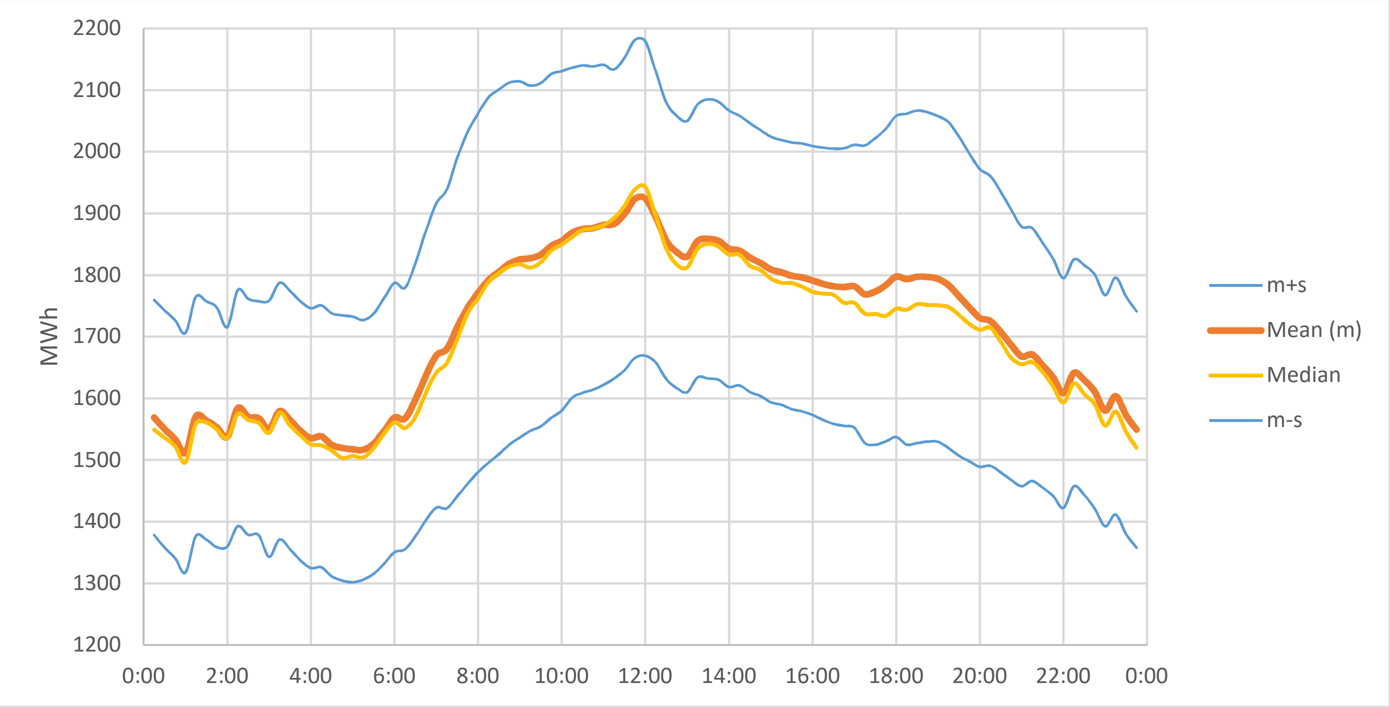


Figure A.2 1: Consumption demand curve for Switzerland (2019)

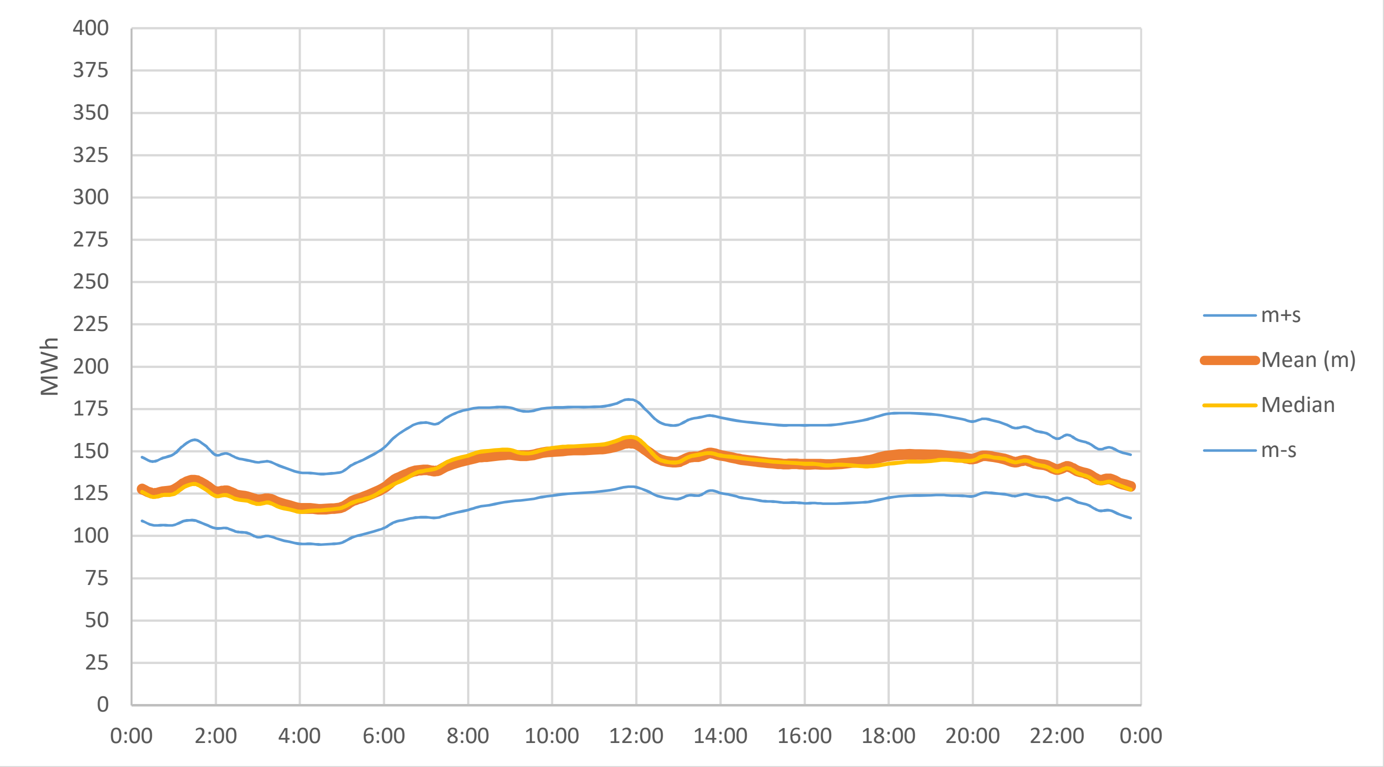


Figure A.2 2: Consumption demand curve for Aargau (2019)

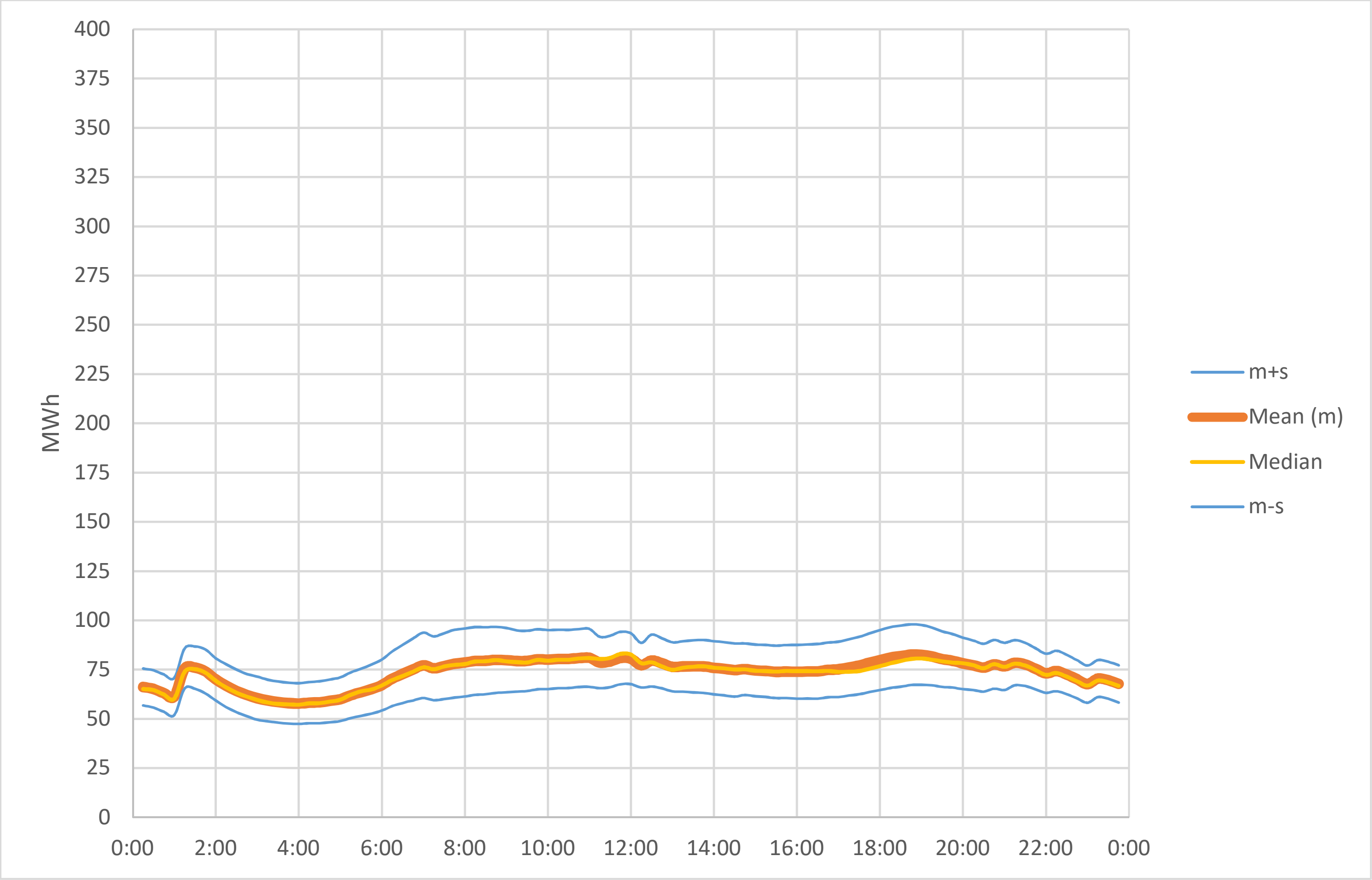


Figure A.2 3: Consumption demand curve for Fribourg (2019)

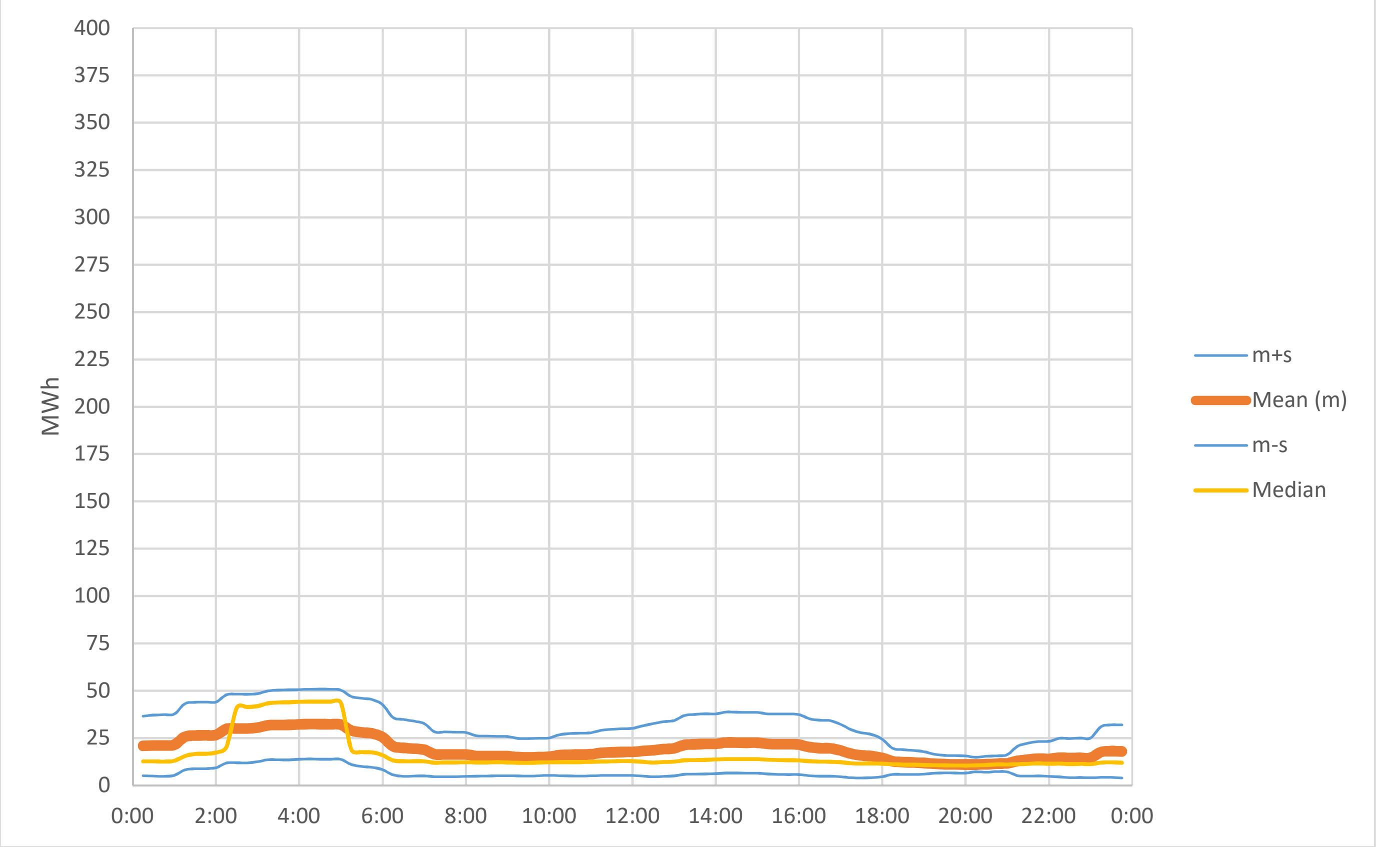


Figure A.2 4: Consumption demand curve for Glarus (2019)

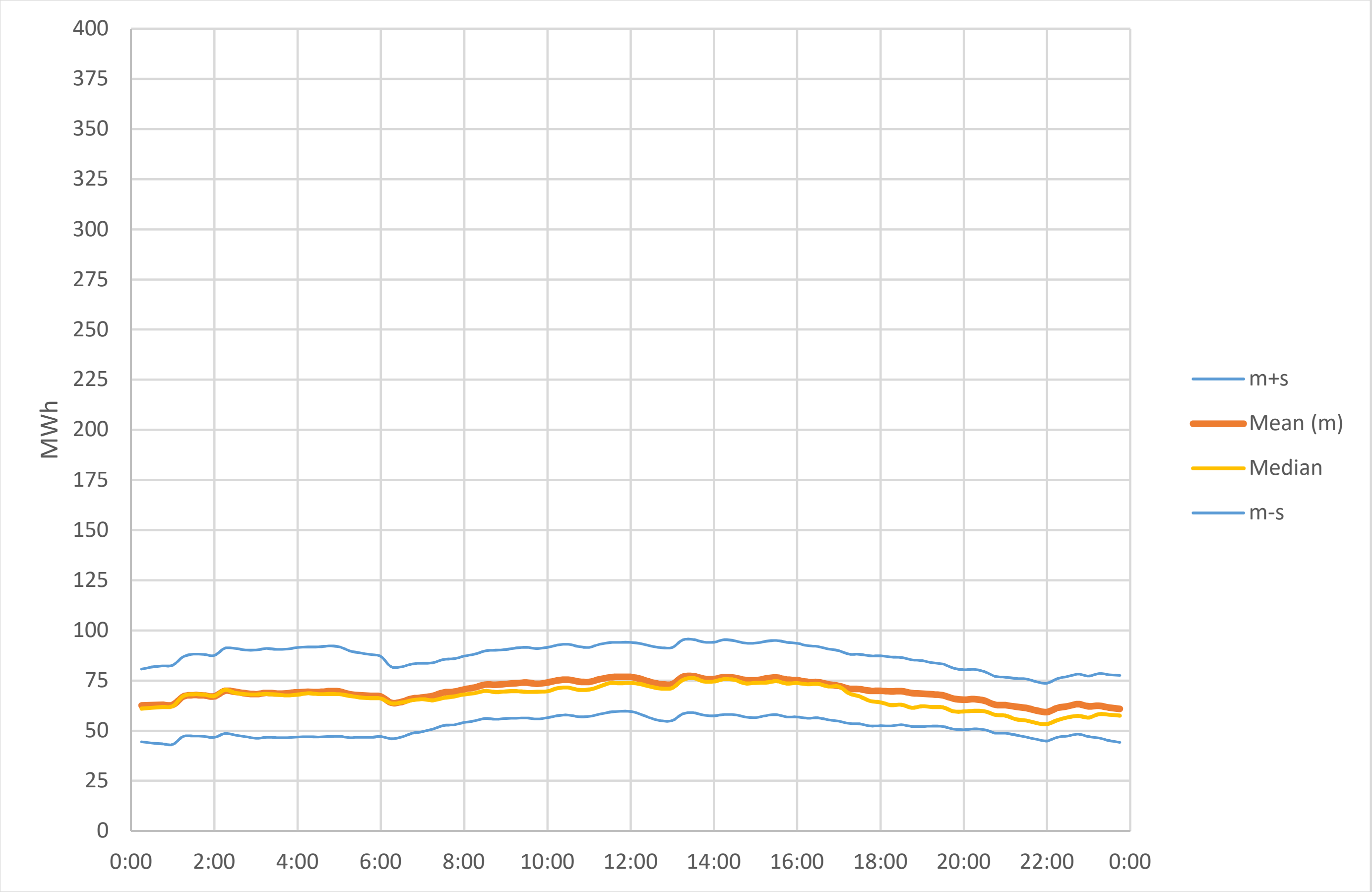


Figure A.2 5: Consumption demand curve for Graubünden (2019)

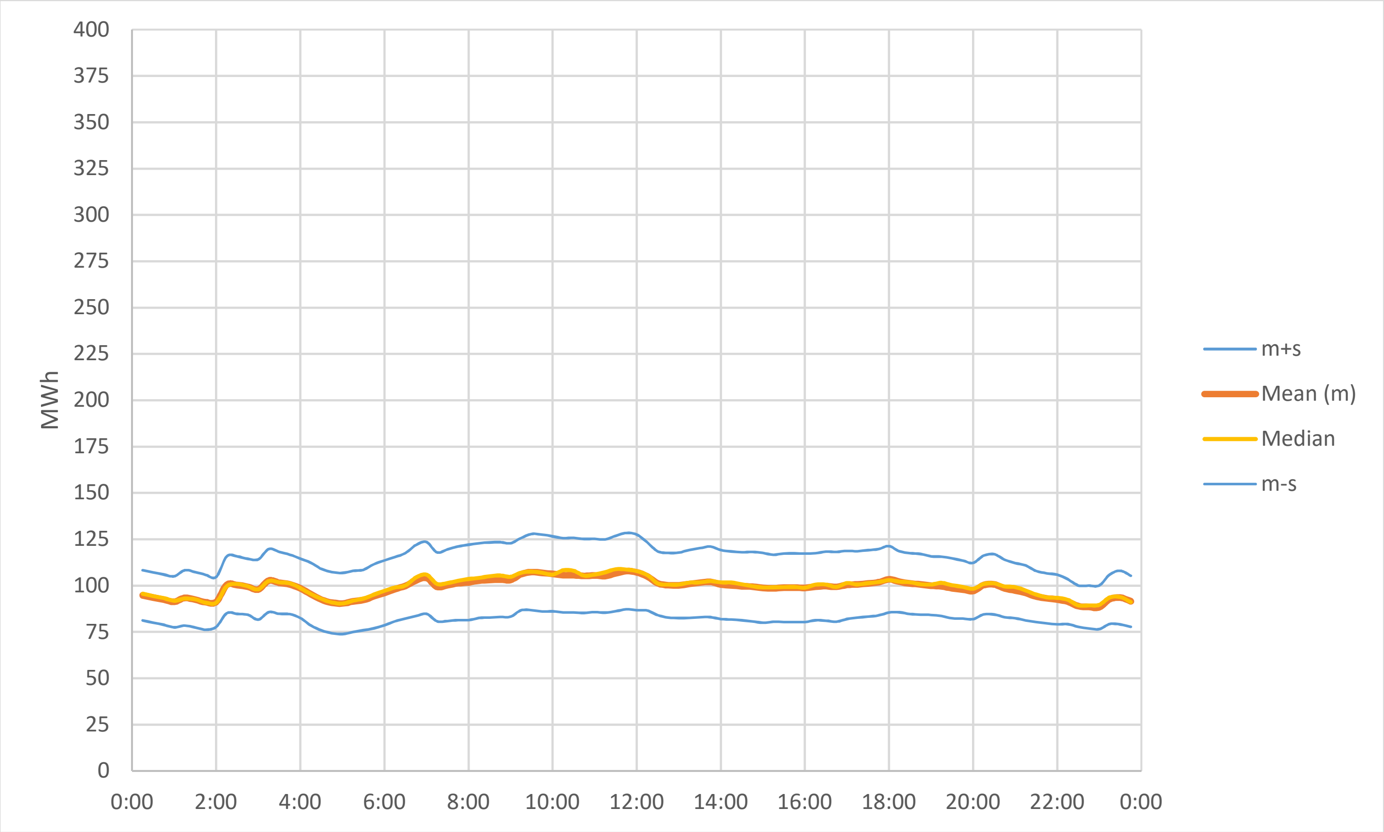


Figure A.2 6: Consumption demand curve for Luzern (2019)

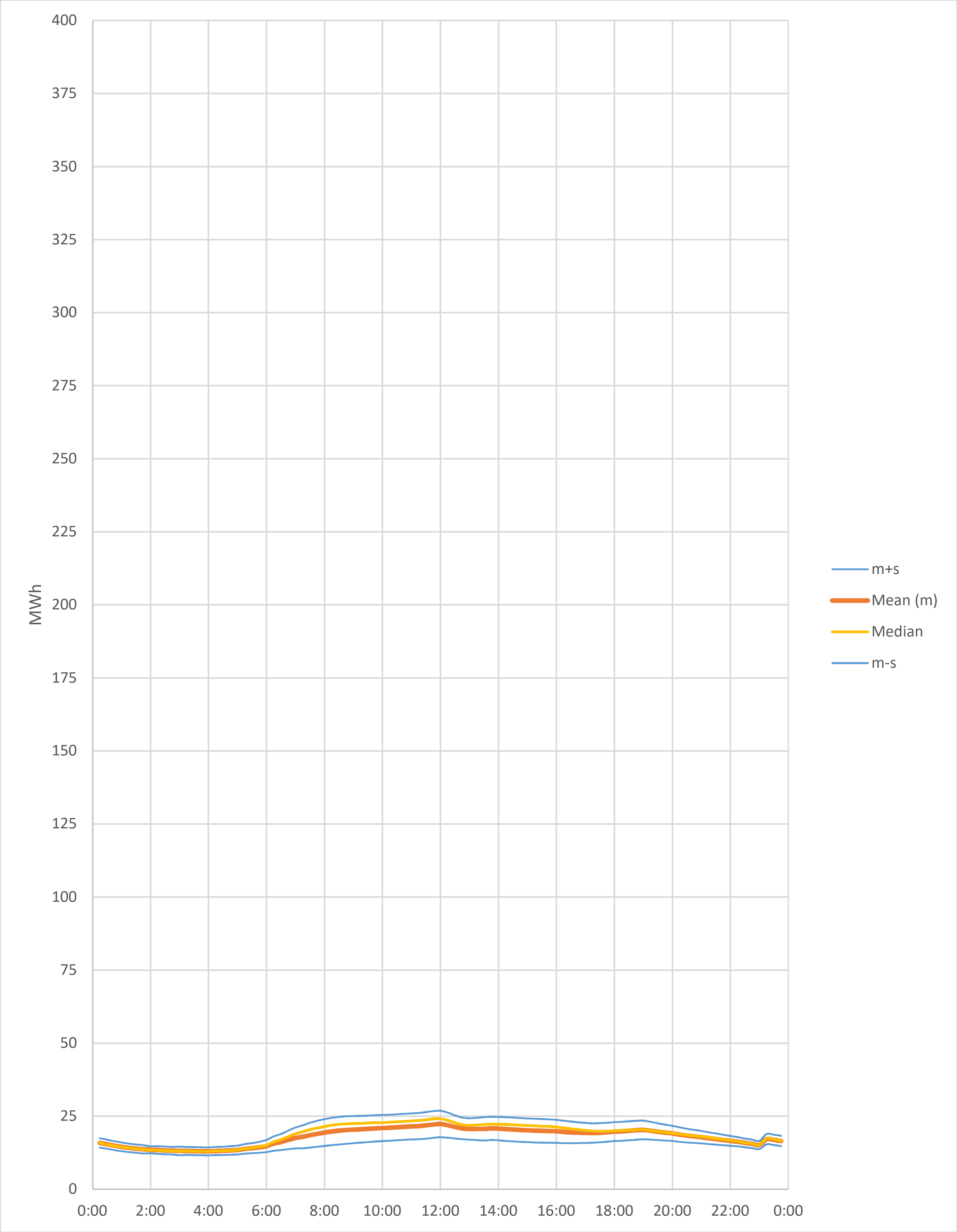


Figure A.2 7: Consumption demand curve for Neuchatel (2019)

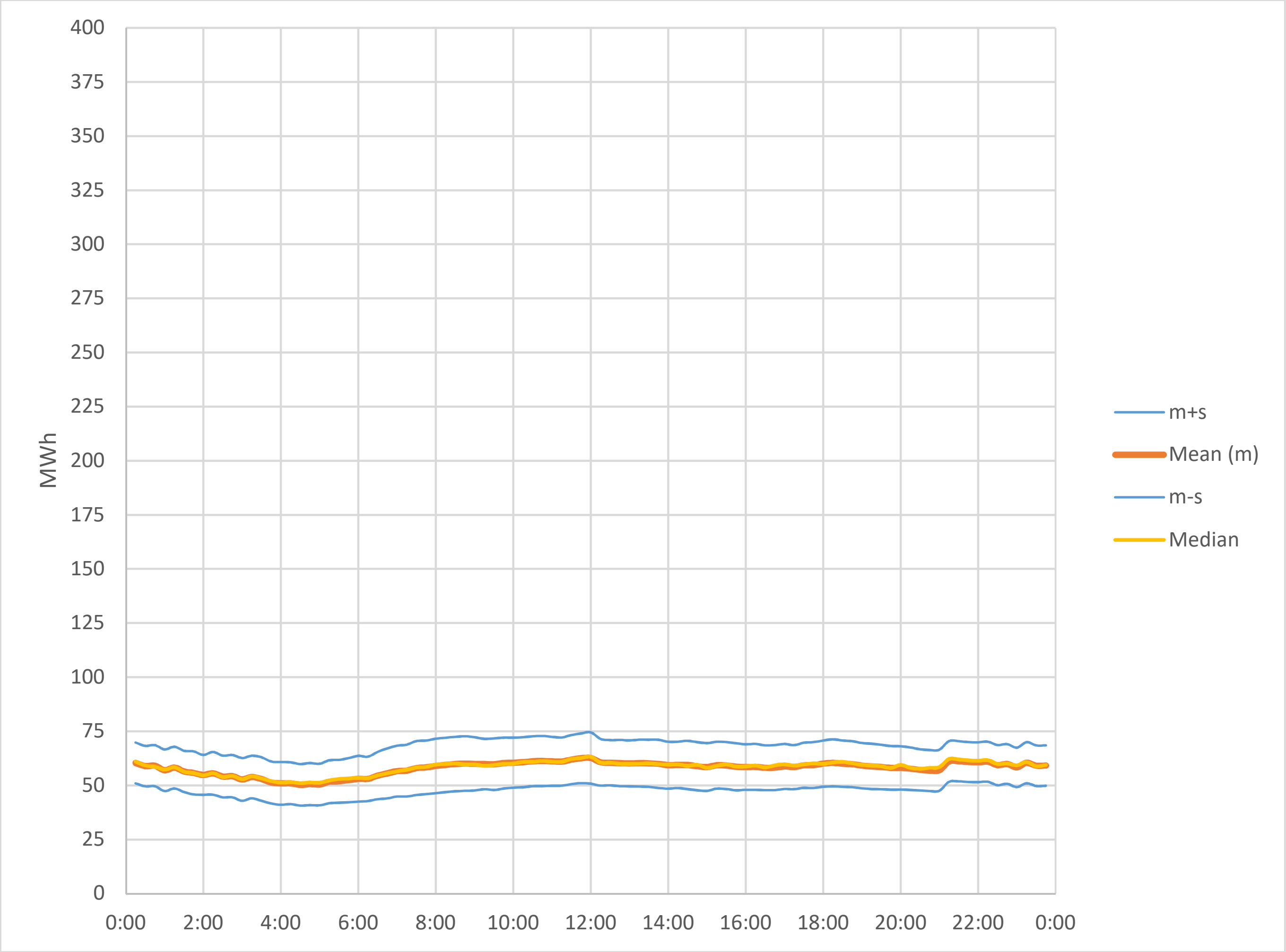


Figure A.2 8: Consumption demand curve for Solothurn (2019)

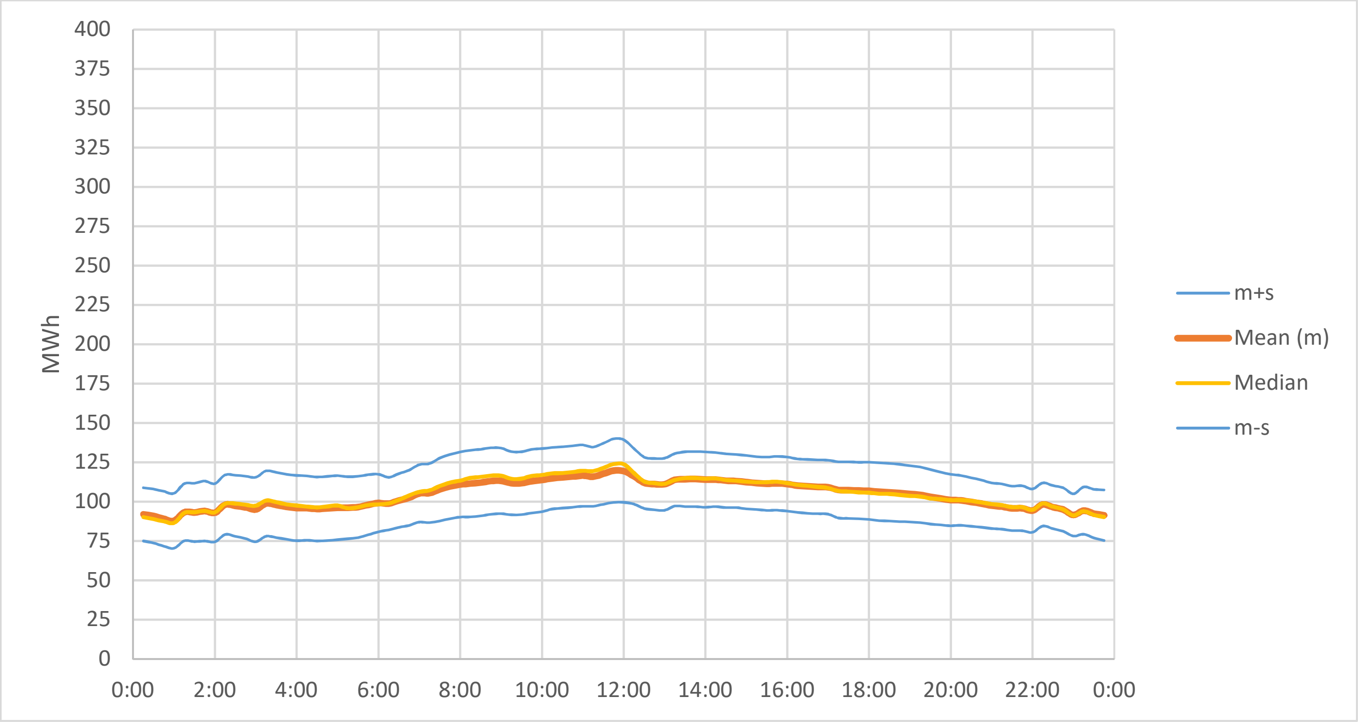


Figure A.2 9: Consumption demand curve for St. Gallen (2019)

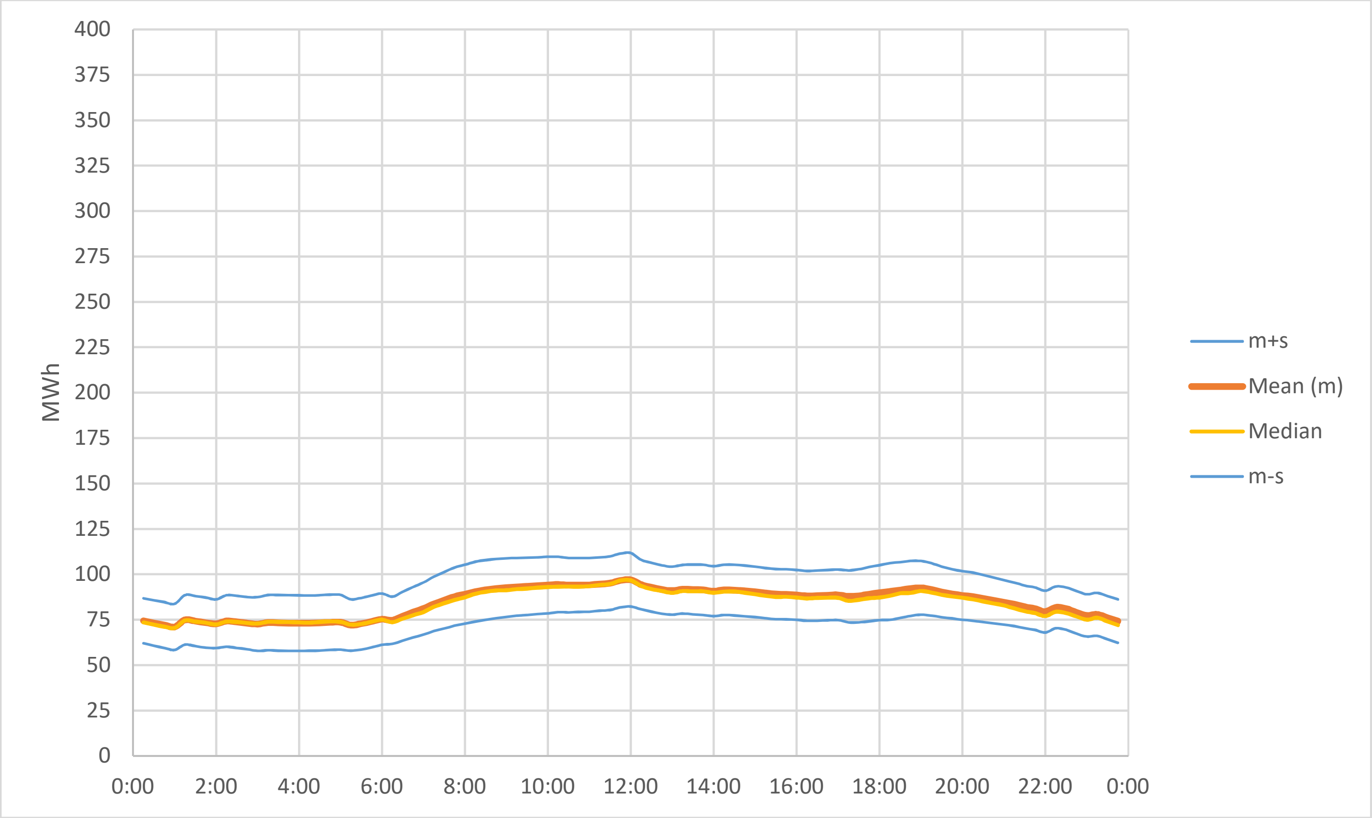


Figure A.2 10: Consumption demand curve for Ticino (2019)

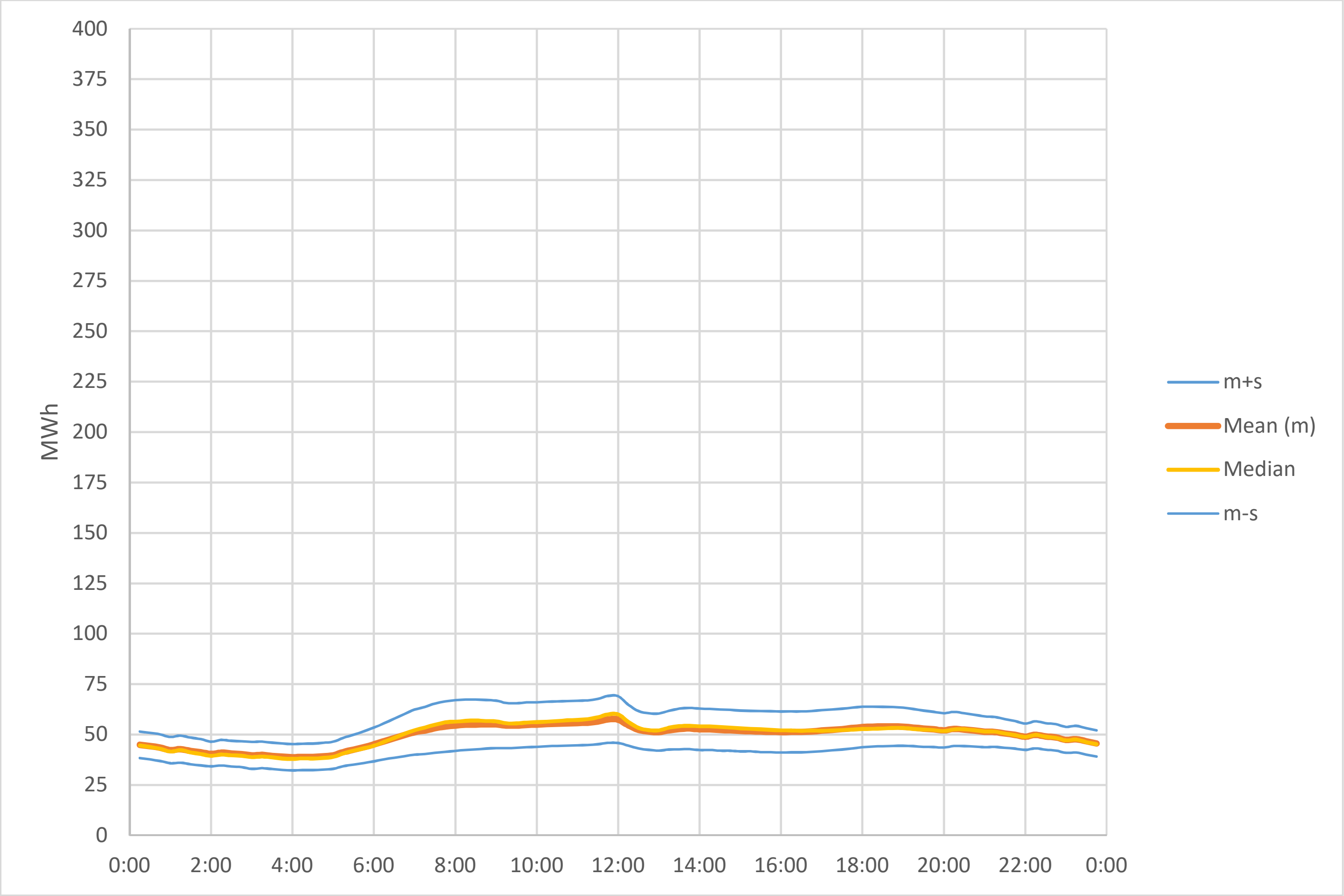


Figure A.2 11: Consumption demand curve for Thurgau (2019)

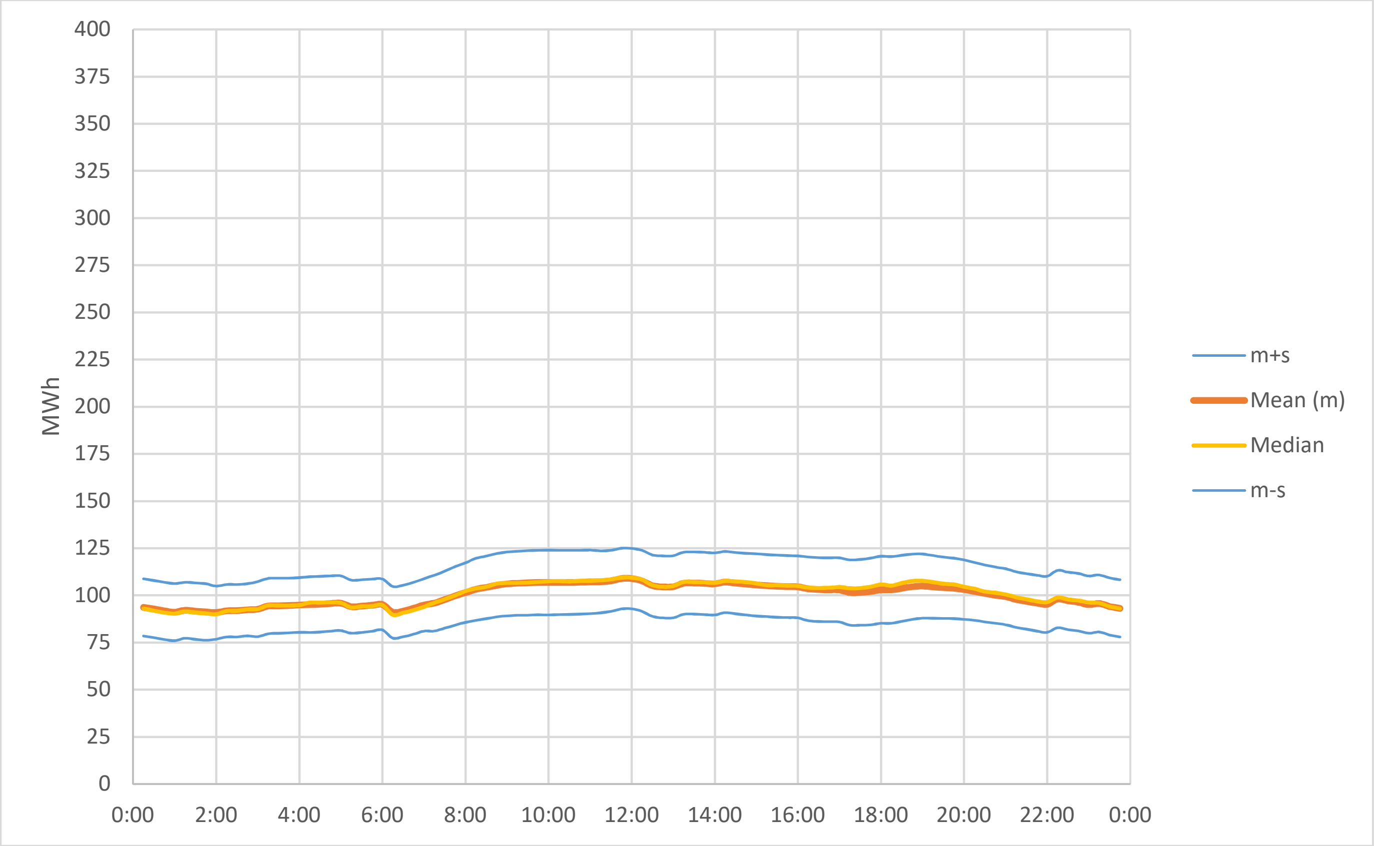


Figure A.2 12: Consumption demand curve for Valais (2019)

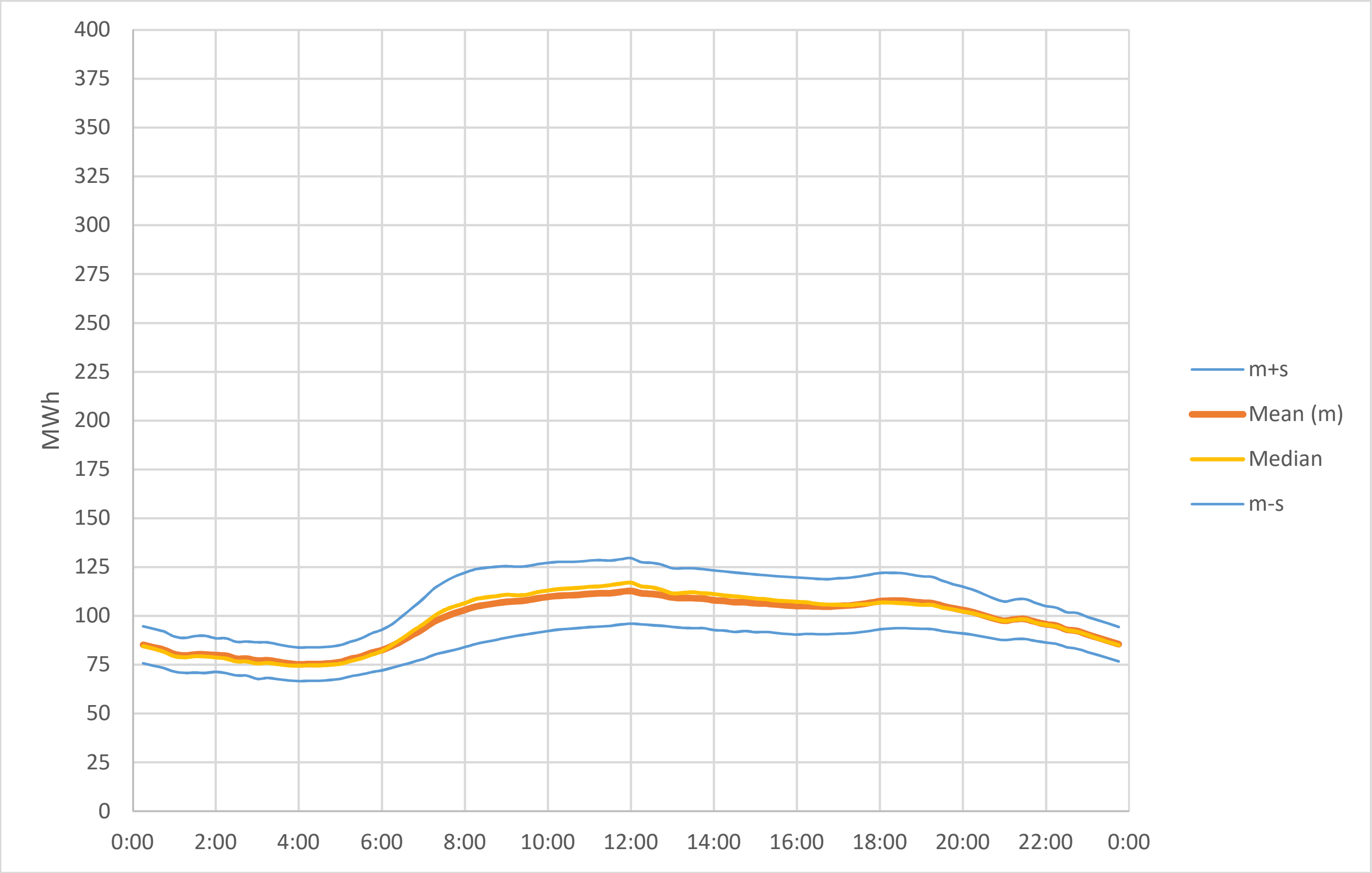


Figure A.2 13: Consumption demand curve for Basel-Landschaft and Basel-Stadt (2019)

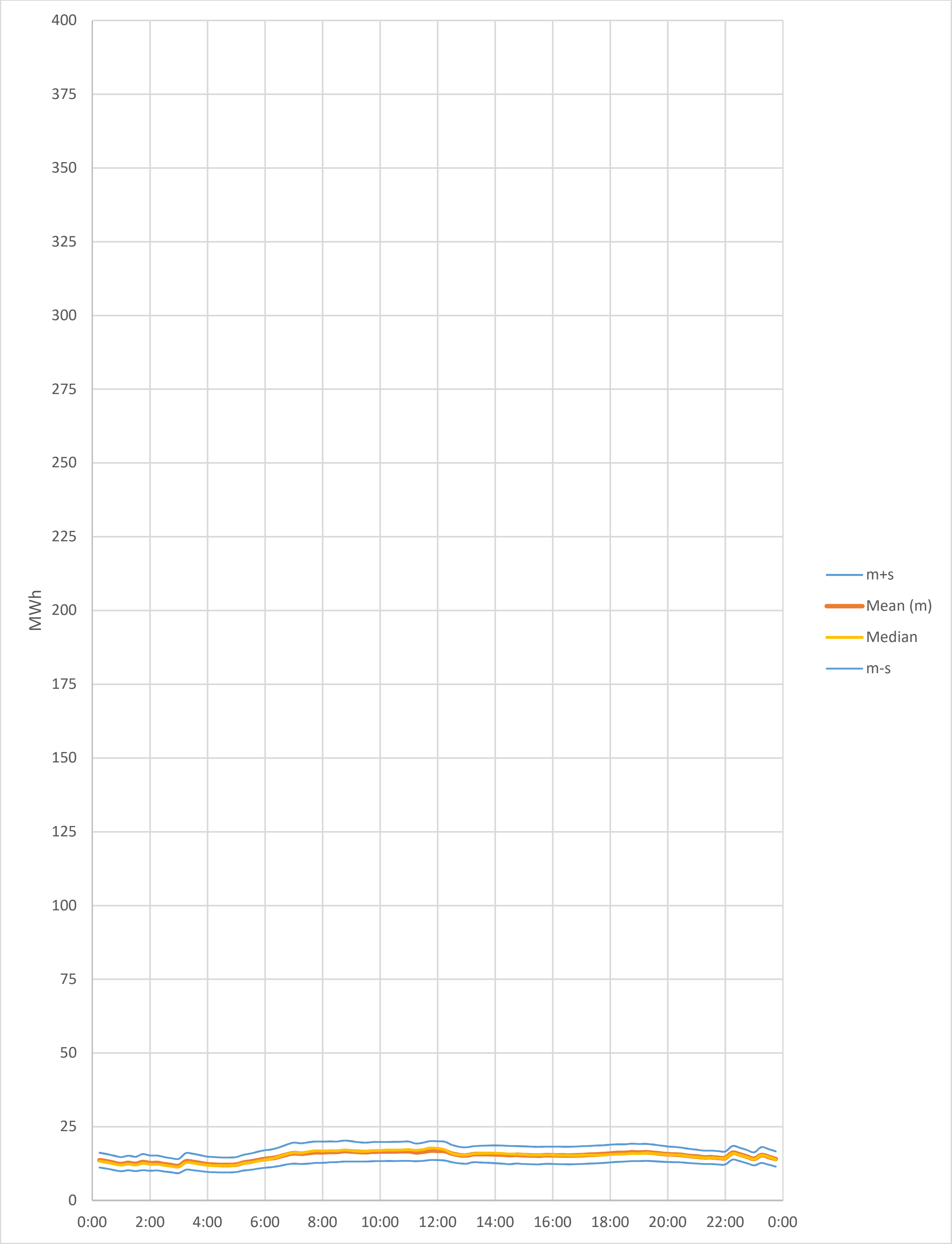


Figure A.2 14: Consumption demand curve for Appenzell Ausserrhoden and Appenzell Innerrhoden (2019)

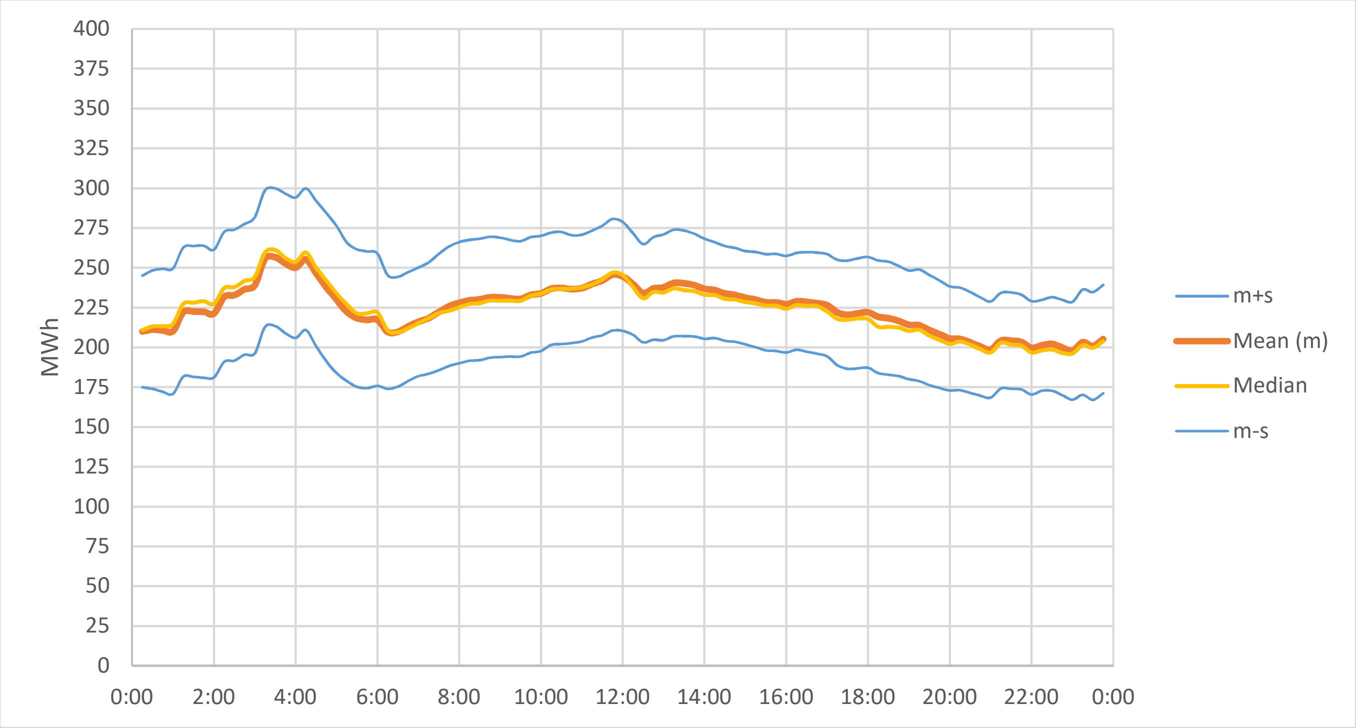


Figure A.2 15: Consumption demand curve for Bern and Jura (2019)

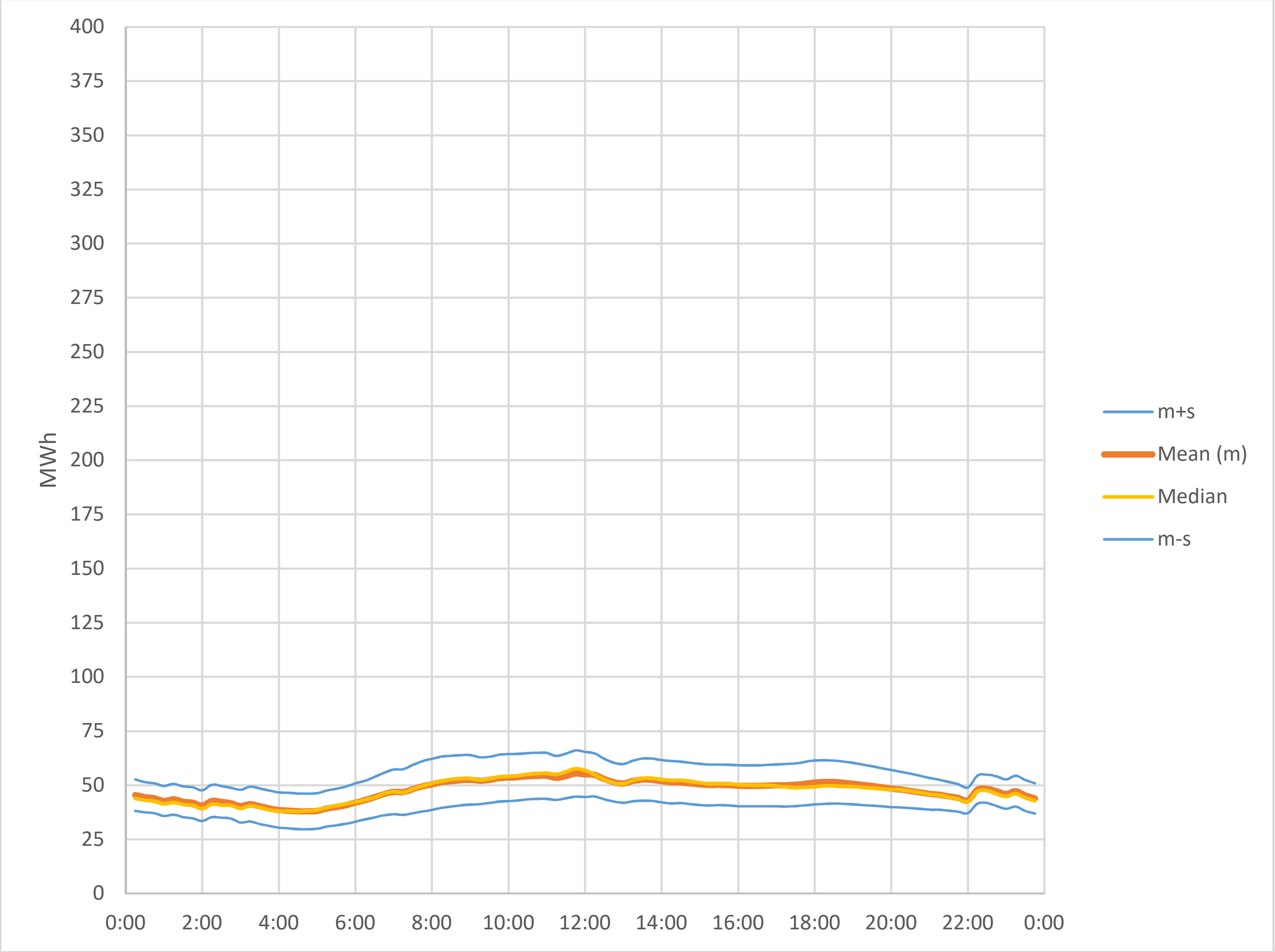


Figure A.2 16: Consumption demand curve for Schwyz and Zug (2019)

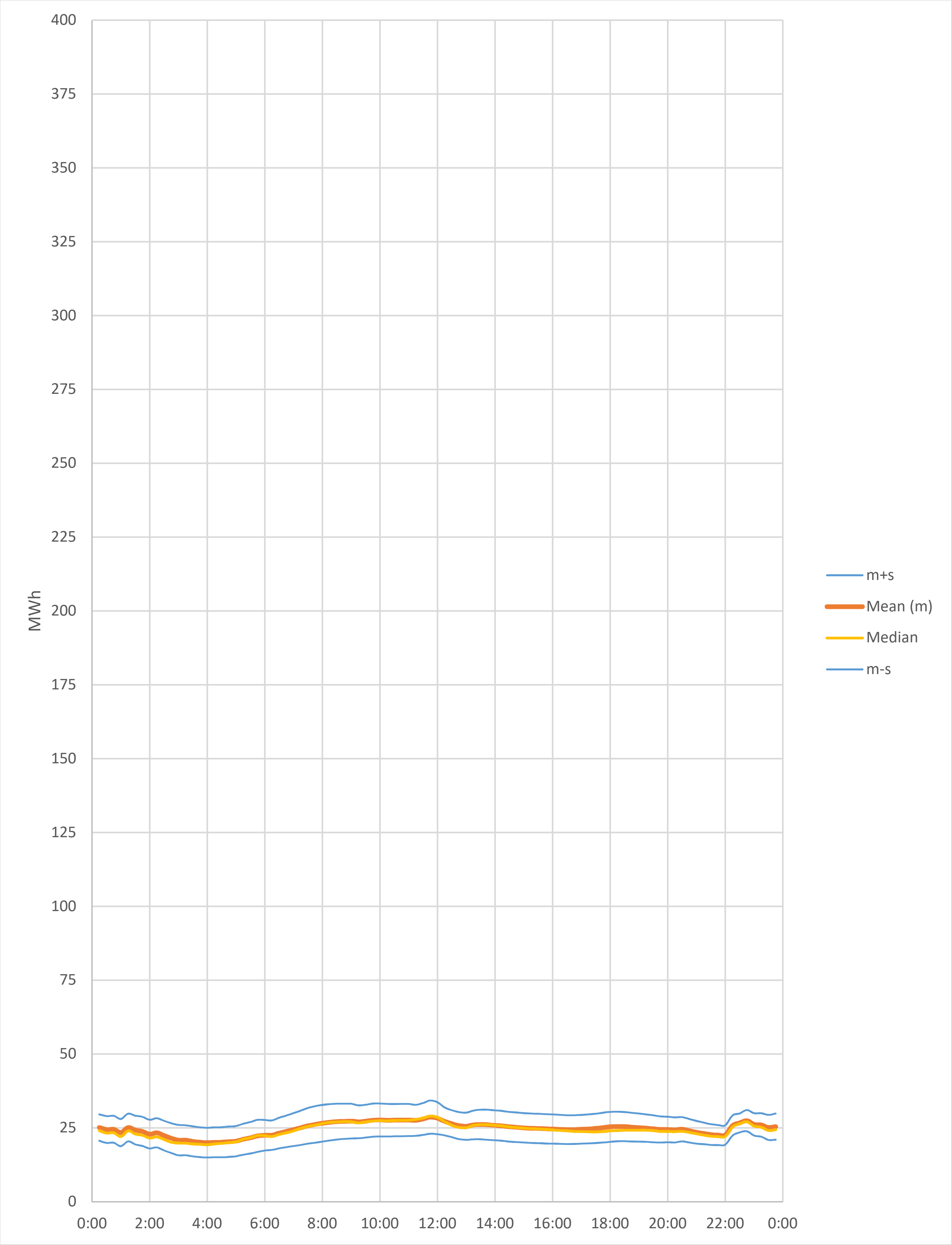


Figure A.2 17: Consumption demand curve for Obwalden, Nidwalden and Uri (2019)

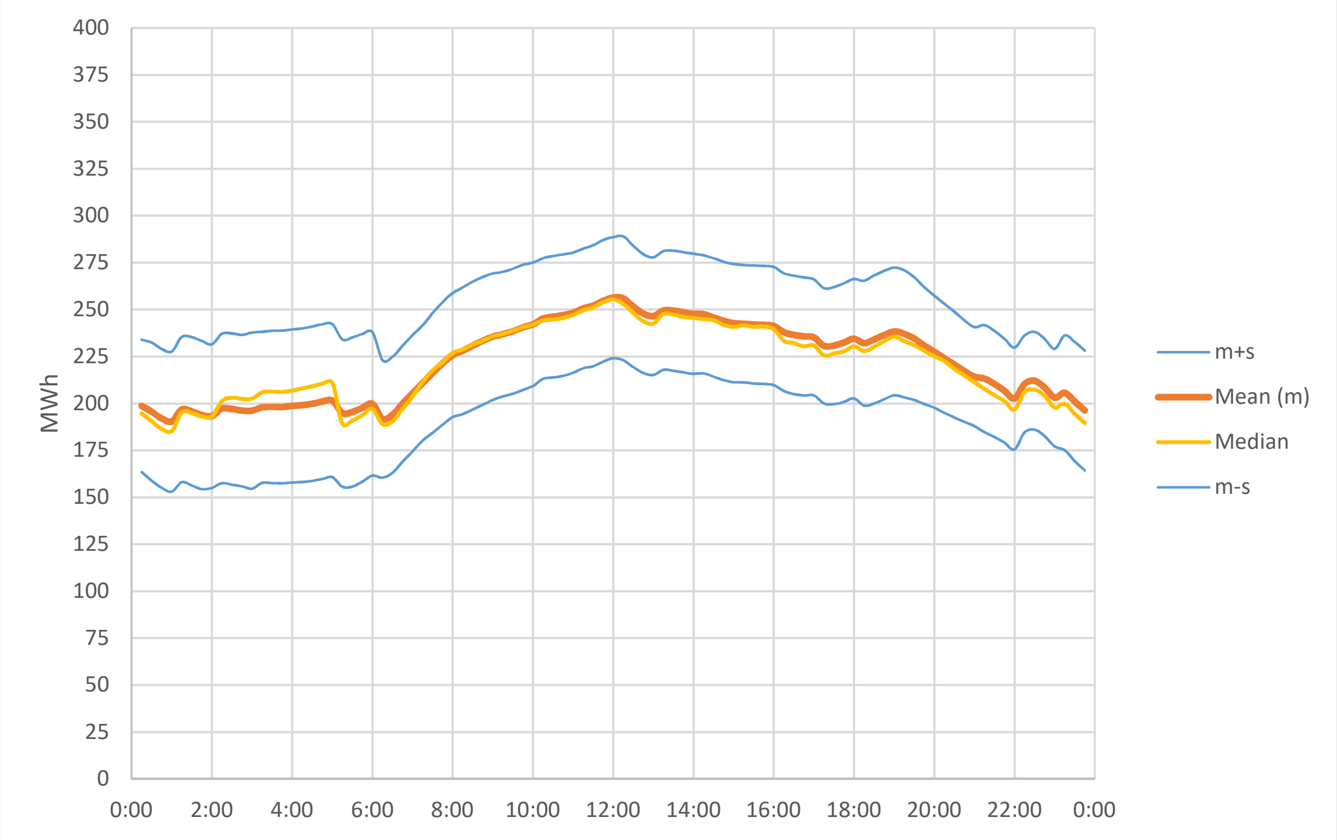


Figure A.2 18: Consumption demand curve for Geneva and Vaud (2019)

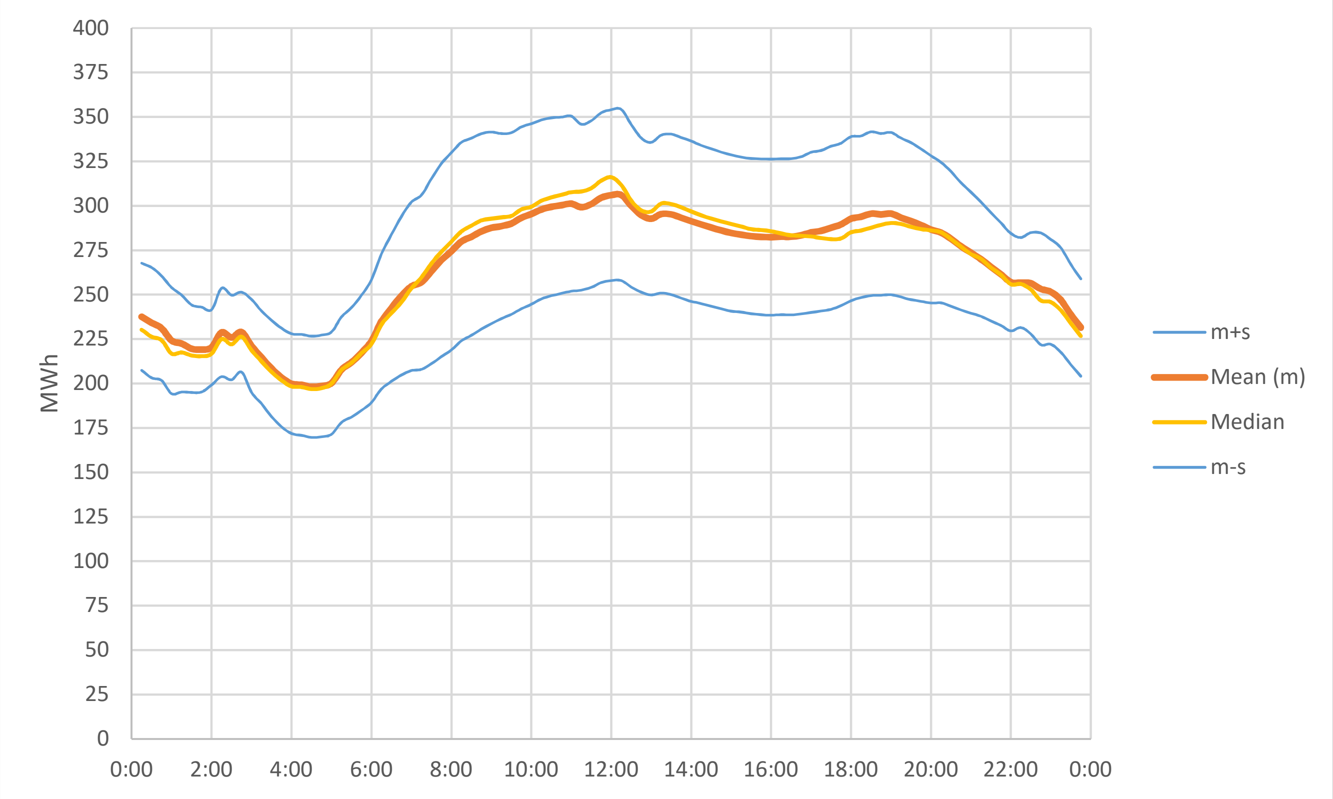


Figure A.2 19: Consumption demand curve for Schaffhausen and Zürich (2019)

A.3. Calculations carried out in the energy consumption and production models for p and r values

x	$y\ (MWh)$	$x_i - \bar{x}$	$y_i - \bar{y}$	$(x_i - \bar{x})$*$(y_i - \bar{y})$	$(x_i - \bar{x})^2$	$\hat{y}$	$y_i - \widehat{y_i}$	$(y_i - \widehat{y_i})^2$	$(y_i - \bar{y})^2$
2	200.229	1.056	51.898	54.782	1.114	217.126	-16.896	285.484	2693.435
0	113.982	-0.944	-34.349	32.441	0.892	86.778	27.204	740.045	1179.873
1	56.620	0.056	-91.711	-5.095	0.003	151.952	-95.332	9088.210	8410.969
3	142.334	2.056	-5.997	-12.328	4.225	282.299	-139.966	19590.403	35.968
1	150.095	0.056	1.764	0.098	0.003	151.952	-1.857	3.449	3.110
0	28.617	-0.944	-119.714	113.063	0.892	86.778	-58.161	3382.656	14331.356
1	89.089	0.056	-59.242	-3.291	0.003	151.952	-62.863	3951.736	3509.623
1	168.642	0.056	20.310	1.128	0.003	151.952	16.690	278.545	412.514
1	132.898	0.056	-15.433	-0.857	0.003	151.952	-19.054	363.060	238.189
0	77.606	-0.944	-70.725	66.796	0.892	86.778	-9.172	84.121	5001.995
2	150.567	1.056	2.236	2.360	1.114	217.126	-66.558	4430.011	5.001
0	24.036	-0.944	-124.295	117.389	0.892	86.778	-62.742	3936.508	15449.156
0	139.293	-0.944	-9.038	8.536	0.892	86.778	52.515	2757.832	81.685
2	337.139	1.056	188.808	199.297	1.114	217.126	120.013	14403.207	35648.435
0	73.754	-0.944	-74.577	70.434	0.892	86.778	-13.024	169.636	5561.800
0	40.444	-0.944	-107.887	101.893	0.892	86.778	-46.334	2146.817	11639.561
2	350.785	1.056	202.454	213.701	1.114	217.126	133.659	17864.821	40987.589
1	393.829	0.056	245.498	13.639	0.003	151.952	241.878	58504.744	60269.418

Table A.3 1: Calculations with energy consumption data (1)

$\widehat{\beta_1}$	65.1738
$\widehat{\beta_0}$	86.778
RSS	141981.285
RSE	94.20101005
$SE(\widehat{\beta_1})^2$	593.7879007
$SE(\widehat{\beta_0})^2$	1022.634718
TSS	205459.676

Table A.3 2: Calculations with energy consumption data (2)

x	$y\ (MWh)$	$x_i - \bar{x}$	$y_i - \bar{y}$	$(x_i - \bar{x})$*$(y_i - \bar{y})$	$(x_i - \bar{x})^2$	$\hat{y}$	$y_i - \widehat{y_i}$	$(y_i - \widehat{y_i})^2$	$(y_i - \bar{y})^2$
2	200.229	1.056	371.062	391.677	1.114	444.219	143.887	20703.416	137687.183
0	113.982	-0.944	-137.402	129.768	0.892	13.782	65.861	4337.615	18879.212
1	56.620	0.056	-64.961	-3.609	0.003	229.000	-76.918	5916.367	4219.974
3	142.334	2.056	379.304	779.681	4.225	659.438	-63.090	3980.328	143871.826
1	150.095	0.056	-173.255	-9.625	0.003	229.000	-185.212	34303.442	30017.393
0	28.617	-0.944	-213.620	201.752	0.892	13.782	-10.358	107.286	45633.547
1	89.089	0.056	67.301	3.739	0.003	229.000	55.344	3062.955	4529.366
1	168.642	0.056	-105.424	-5.857	0.003	229.000	-117.380	13778.089	11114.115
1	132.898	0.056	72.340	4.019	0.003	229.000	60.384	3646.173	5233.098
0	77.606	-0.944	-195.024	184.189	0.892	13.782	8.238	67.866	38034.412
2	150.567	1.056	644.015	679.794	1.114	444.219	416.840	173755.467	414755.679
0	24.036	-0.944	-209.577	197.934	0.892	13.782	-6.315	39.874	43922.452
0	139.293	-0.944	-173.356	163.725	0.892	13.782	29.906	894.374	30052.346
2	337.139	1.056	217.691	229.785	1.114	444.219	-9.485	89.958	47389.279
0	73.754	-0.944	-184.108	173.880	0.892	13.782	19.154	366.878	33895.815
0	40.444	-0.944	-122.877	116.050	0.892	13.782	80.385	6461.785	15098.754
2	350.785	1.056	-11.015	-11.627	1.114	444.219	-238.191	56734.869	121.339
1	393.829	0.056	-161.094	-8.950	0.003	229.000	-173.051	29946.480	25951.248

Table A.3 3: Calculations with energy production data (1)

$\widehat{\beta_1}$	215.218819
$\widehat{\beta_0}$	13.7815179
RSS	358193.2227
RSE	149.6231146
$SE(\widehat{\beta_1})^2$	1498.019983
$SE(\widehat{\beta_0})^2$	2579.923305
TSS	1050407.038

Table A.3 4: Calculations with energy production data (2)