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Technical-economic Analysis of Fast Chargers for Plug-in Electric Vehicles in Distribution Networks

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Master of Science in Energy and Environment
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Problem Description

Lyse is the regional utility company in Rogaland, Norway. They have built three filling stations for bio gas and are planning to combine filling stations with fast charging stations for electric vehicles. The location of the first combined filling and fast charging station is Luravika in Sandnes. The installation starts in autumn 2010. The main load at the filling station is a compressor rated 120kW. The load is connected to the 400V low voltage grid.

Task:

1. Give an overview of fast charging technologies and their characteristics based on literature studies
2. Establish load flow models suited for the given case representing Lyse s supply area
3. Evaluate possible consequences for the grid from the case studies using technical-economic analysis based on appropriate analysis criteria
4. Evaluate the fulfilment of the Norwegian power quality code

Assignment given: 22. January 2010
Supervisor: Kjell Sand, ELKRAFT

Preface

I would like to thank Lyse Neo AS and Audun Aspelund for giving me the opportunity to work on a current problem. It has been very inspiring to know that my analyses will be useful and put to life. Audun was very helpful and enthusiastic about my work during my visit at Lyse in February. I would also like to thank the Hana family for a nice stay during my few days in Sandnes and Stavanger.

I wish thanks to my supervisor Kjell Sand and Sintef Energy AS. They have provided me with a large office and all tools needed to do the necessary analysis. Kjell has long experience on network planning and quality of supply which has come in handy. He has given me good advice on the overall structure and goals of my project. I thank Sintef Energy for giving me great opportunities and hiring me as an Energy Trainee. Starting in August, I will spend the next two years in three different companies. First stop is Sintef Energy in Trondheim, then Lyse in Stavanger and Statnett in Oslo as the final stay.

I would also like to thank all those who have answered all my detailed questions, especially Reidar Ognedal in Powel AS.

Trondheim, June 2010

Nina Wahl Gunderson

Contents

1 Summary

This project focuses on finding the optimal grid connection of fast charging stations for electric vehicles. The project was carried out in cooperation with Lyse, which is the regional utility company in Rogaland, Norway. Lyse is developing combined filling stations for gas vehicles and fast chargers for electric vehicles. The first combined station will be built close to an existing petrol station in Luravika, Sandnes. There is space for four fast chargers at the site. The distance to the closest distribution substation is 200m along the road. There are both a gas pipe and a 22kV cable close to the site. The area is in an urban environment and the distribution grid consists of underground cables and pipes.

Different load cases were studied using Powel Netbas for load flow simulations and a simulation tool called Dynko for economic analysis. Each load case included a certain power rating on the EV charging station. To achieve short charging times, the power rating should be high. Power ratings spanning from 125kW to 500kW were analysed for the charging station. Two solutions for grid connection were evaluated. One involved using the existing distribution substation. The other involved installing a new substation close to the new load. The optimal dimensioning of cables and transformers were analysed. The quality of supply and fulfilment of the Norwegian PQ code were evaluated.

The economic results showed that it is optimal to use the existing distribution substation as long as the total maximum load at the combined filling and charging station is less than 263kVA. For larger loads, a new substation should be built close to the new load. Replacing the transformer in the existing substation is not an optimal solution for any of the load cases. The cables should be chosen so that the loading is close to 30%. The average optimal transformer loading was around 75%, but the results had a large variance.

The quality of supply was investigated for the worst case scenario. All values concerning voltage variations and harmonics were well within the limits of the Norwegian PQ code. The loading of the high voltage distribution grid was considered acceptable. No adjustments are needed in the 22kV grid.

2 List of Acronyms

BEV – Battery Electric Vehicle
capex – Capital cost
CENS – Cost of Energy Not Supplied
DOD – Depth of Discharge
ENS – Energy Not Supplied
EV – Electric Vehicle
EVSE – Electric Vehicle Supply Equipment
GIS – Geographical Information System
HEV – Hybrid Electric Vehicle
ICE – Internal Combustion Engine
LCA – Life Cycle Assessment
NIS – Network Information System
opex – Operating cost
PHEV – Plug-in Hybrid Electric Vehicle
PQ code – Power Quality code
SLI – Start, Lightning, Ignition
SOC – State Of Charge

3 Introduction

The first electric vehicles were built the 1830s. In the early 20th century, commercial electric automobiles were commonplace and had the majority of the car market. Several countries were lacking natural resources of fossil fuel, which lead to development of electric transport. Electric rail transport was developed and first used in coal mines and trams. In the 1920s, gasoline became cheaper and more available. The engine starter was invented and the technology of the combustion engine was improved. Since then, the internal combustion engine (ICE) has totally dominated the car market. Electric vehicles have been used for specialist roles such as forklift trucks, golf carts and airport ground service equipment [7].

Since the 1990s, the electric car has regained popularity. Currently, all major automobile manufacturers are either producing or developing electric vehicles (EV) or plug-in hybrid electric vehicles (PHEV). Start-up car companies that develop and commercialise plug-in vehicles are increasing in numbers and size [4].

Currently, there are many factors driving commercial production of plug-in vehicles for the highway. National and international agreements aim to reduce emission of green house gasses and other pollutants. Vehicle tail-pipe emissions are a major source of pollutants, and there is great potential to cut emissions in the sector. There is a growing public awareness of climate changes which promotes clean products. Fuel prices are rising and we acknowledge that there is limited supply of petroleum. The battery technology is driven by demand for laptops computers and mobile phones. The battery electric vehicle (BEV) marketplace benefits from this development [3].

EVs have many advantages to the ICE vehicle. There are no local emissions and little noise. The energy efficiency is higher, even if the electricity is made from fossil fuels [3]. Electricity may be produced from a variety of energy sources including both fossil fuel and renewables. This makes electric transport less dependent on oil prices than ICE vehicles. The Norwegian electricity mix consists of mostly hydro power, which makes EVs in Norway low carbon emitters. Biofuel is another net CO_2 neutral technology, which may play an important role to reduce green house gas emissions in the transport sector [3].

The energy efficiency in ICE vehicles is still improving. This development is expected to flatten out [3]. At the same time, the number of cars on the road is increasing. The total emission from road transport is increasing. EU has set a goal to reduce emissions from new cars to 120 g CO_2/km by 2012 and 95 g CO_2/km by 2020. To reduce emissions from road transport, zero emission vehicles have to gain a substantial market share [3].

In Norway, there are many incentives promoting EVs. They have no taxes or annual fees. Toll roads, ferries and parking are fee, and you can drive in the bus lane. Currently, there are about 2850 EVs in Norway, which is about 1‰ of the road vehicles [14]. The amount of EVs and PHEVs is expected to be 5% by 2020 [8].

The Norwegian report *Klimakur 2020* suggests measures to reach the climate goals set by the parliament [8]. The annual emission from the Norwegian road sector is 17 million tons CO_2, and this number is expected to increase to 21 million tons in a business as usual scenario. The report concludes that the emissions from the transport sector can be reduced by 3-4.5 million tons CO_2-equivalents. The price is less than 1500 NOK/ton CO_2 for most of the means evaluated.

The main means to reduce emissions in the transport sector introduced in *Klimakur 2020* is a large introduction of biofuel. Other means are to improve the existing ICE technology, invest more in public transport and introduce economic incentives to promote research and environmentally friendly transport. There is a great uncertainty as to which technology that will break through, and the report does not favour any technology over the others.

The ICE technology has been developed for more than 100 years. Conventional vehicles perform very well: they are comfortable and roomy, have a long range, you can tank anywhere and the speed and performance are high. The vehicles are mass produced, and the price is low. The customers have high expectations to vehicles. To get mass appeal for EVs, they have to reach the performance of ICE vehicles.

The key customer concern regarding EVs is the limited range and the fear of being stranded, called *range anxiety*. This leads to a demand for fast charging. A study from Japan illustrates the concept [1]. The driving pattern for EV delivery trucks in Tokyo was studied before and after installation of fast chargers at various locations in the city. Before the installation, the state of charge at the end of the day was 50-80%, and average mileage was 203 km/month. After the installation, the state of charge was 15-45% and average mileage was more than seven times higher. When fast chargers are available, the fear of being stranded disappears. This raises the acceptance of EVs as an adequate alternative to an ICE vehicle.

This report will look into an actual problem given by Lyse Neo AS which is a part of the Lyse Corporation, the regional utility company in Rogaland, Norway. Lyse delivers electricity, gas, district heating, broadband and security systems. The gas system contains of both natural gas and biogas. Lyse is building filling stations for gas vehicles. So far they have three stations in operation, and they are planning to build in total 10-15 stations over the next few years. Fast chargers for electric vehicles will be installed at the same locations. This will be a part of their profile for more environmentally friendly road transport. Starting autumn 2010, a combined gas filling station and fast charging station for electric vehicles will be built in Luravika in Sandnes close to Stavanger. At the gas filling station, the dominating load is a compressor of 120 kW.

This project aims to answer the following:

1. Give an overview of fast charging technologies and their characteristics based on literature studies
2. Establish load flow models suited for the given case representing Lyse's supply area

3. Evaluate possible consequences for the grid from the case studies using technical-economic analyses based on appropriate analysis criteria
4. Evaluate the fulfilment of the Norwegian power quality code

The project focuses on finding the minimum cost grid connection for the new load that is within the restrictions. The different solutions for grid connection will be ranked according to cost and the relative cost difference between the solutions will be evaluated. One goal is to develop general dimensioning guidelines based on loading of components at maximum load. The total cost calculated for each solution is not accurate. In this analysis, only the difference in cost between the solutions is of interest. Cost elements like Cost of Energy Not Supplied (CENS) and operating costs (opex) are not included.

The first section contains the literature study which gives an overview of technologies related to plug-in vehicles. The second section contains theory which is needed for the analysis. The main part contains the results from the analyses. There are results from theoretical calculations, technical-economic analyses and power quality analysis. The last section contains discussion, conclusion and further work.

4 Literature

This chapter is intended to give an introduction to electric vehicles and charging technologies. Extensive literature studies vehicle technology, batteries and charging technologies are not a part of this project. The literature section contains an overview of technologies on plug-in vehicles, batteries and charging.

4.1 Plug-in Electric Vehicle Technology

This section is a summary of a Canadian report on guidelines for EV infrastructure in British Colombia [4]. The section describes the basic technology of Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV). Electric vehicles are common for applications like golf carts, forklifts and airport ground support. The project focuses on vehicles registered for public roads. Plug-in electric vehicles span from low speed city vehicles and bicycles to highway speed vehicles and buses.

4.1.1 Battery Electric Vehicle (BEV)

BEVs use on-board battery energy storage as its only power for propulsion. Energy is supplied by connecting the battery charger to the grid. Most BEVs have regenerative braking that recaptures energy to the battery during breaking and down-hill driving. The charger works as a rectifier to deliver DC power to the battery.

The basic technology of the vehicle is displayed below. The battery is the only energy source and has to have large energy and power abilities to meet the demands of the vehicle.

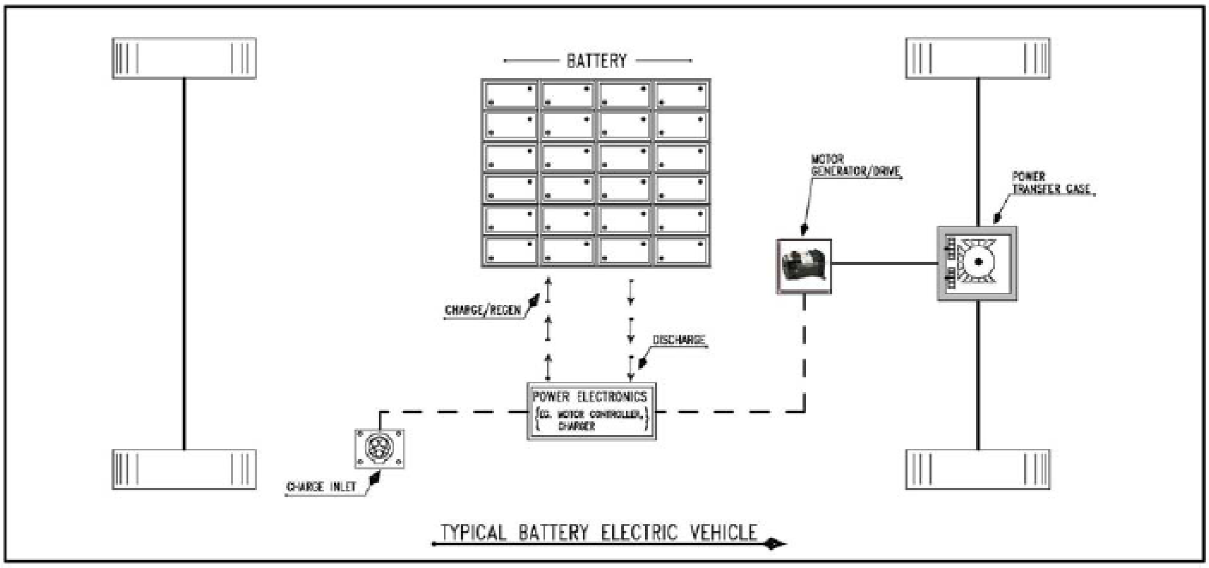

Figure 1: Battery Electric Vehicle Configuration [4]

4.1.2 Plug-in Hybrid Electric Vehicle (PHEV)

PHEVs are powered by both an internal combustion engine (ICE) and an electric motor. There are two energy sources on-board the vehicle: a battery and a liquid or gas fuel like petrol, diesel, ethanol, hydrogen or biogas. There are two main technology designs for hybrid electric propulsion: series and parallel hybrids.

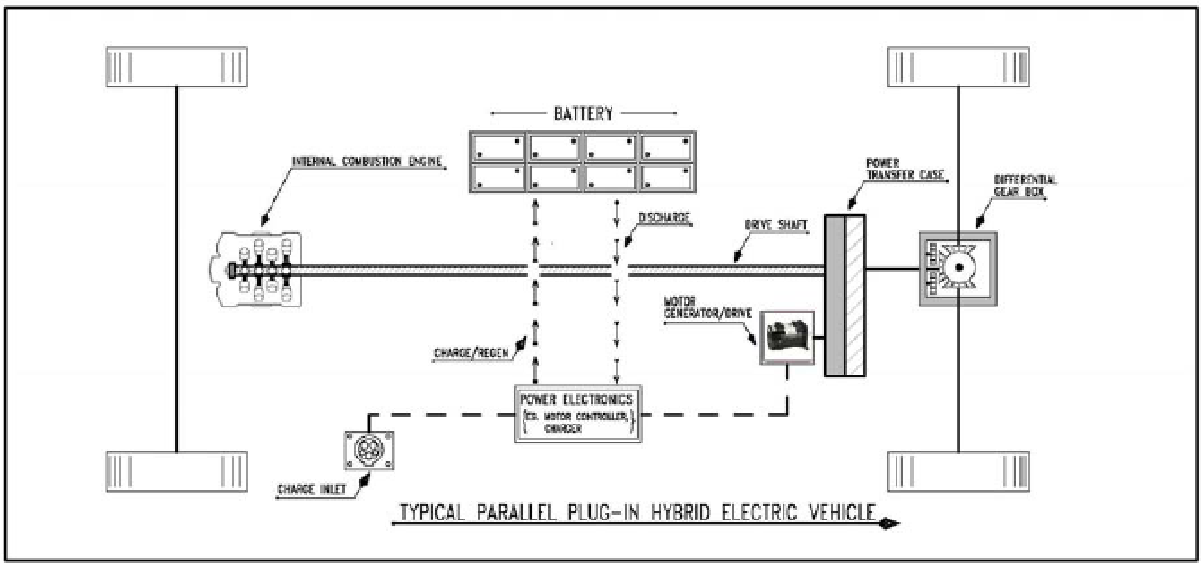

Figure 2: Parallel Plug-in Hybrid Electric Vehicle Configuration [4]

The figure above displays the design of a parallel plug-in hybrid. The shaft is propelled by both the ICE and the electric motor. The two energy sources are coupled mechanically through a differential gear. Energy is recaptured through regenerative breaking. This technology is the most common hybrid design at the present.

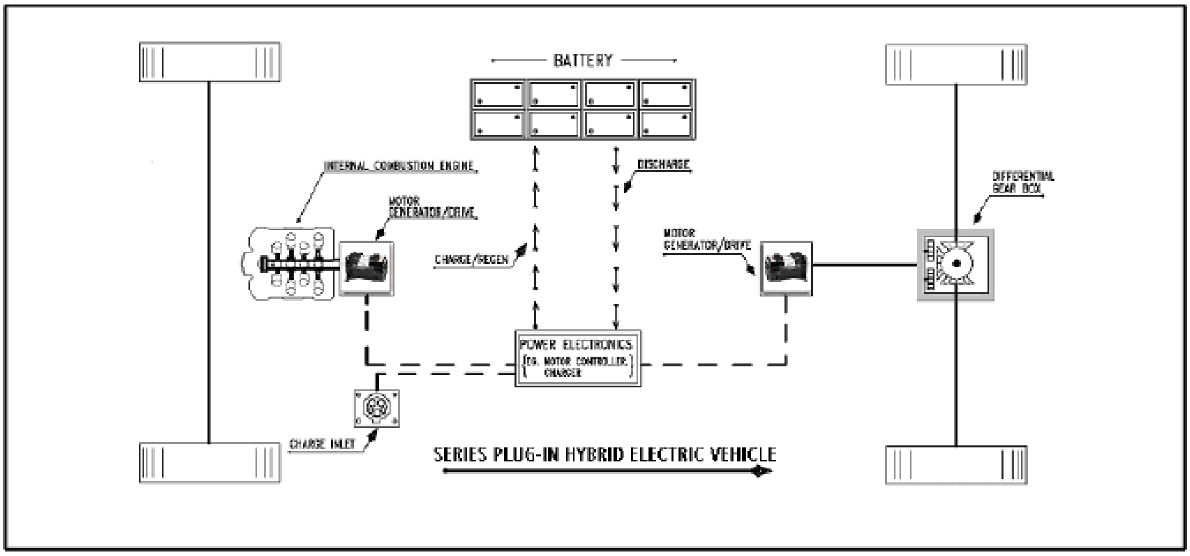

Figure 3: Series Plug-in Hybrid Electric Vehicle Configuration [4]

The figure above displays the design of a series hybrid. This configuration is also called a range-extended electric vehicle. The ICE runs as a generator and delivers energy to the battery through the power electronics to extend the range of the vehicle. The ICE may run at its best set-point to reach higher efficiency. The electric drive system propels the vehicle. The electric motor provides high efficiency and torque over a wide speed range. The motor may be coupled directly to the shaft without a gear box. The electric motor works as a generator during regenerative breaking. This design is already used in ships and locomotives. The design gives a much higher efficiency than the parallel design. The battery pack needs to be larger and provide more power than for a parallel hybrid.

4.2 Battery Technologies

This section is a summary of a Belgian study that performed a life cycle assessment on batteries used in vehicles [15]. The technology of batteries is advancing. Highway electric vehicles require batteries that contain a large amount of energy and can provide high power for acceleration. The weight and volume should to be low. This section gives an overview of the different technologies. The table below gives a summary of the properties of the different battery technologies.

Table 1: Specific Energy and Power of Battery Technologies [15]

	Pb-acid	NiCd	NiMH	Li-ion	Zebra
Specific Energy (Wh/kg)	30-35	50-60	60-70	60-150	125
Specific Power (W/kg)	80-300	200-500	200-1500	80-2000	150

4.2.1 Lead-acid (Pb-acid)

Lead acid is the oldest technology on the market. It dominates the market of start, light ignition (SLI) batteries and is also used in fork lifts, golf carts, small EVs and other industrial applications. The cost is low, and so is the specific energy which is about 30Wh/kg. Lead is toxic, and the batteries may explode during overcharging. Hydrogen gas is emitted during charging and ventilation is required when the battery is charged indoors.

4.2.2 Nickel-Cadmium (NiCd)

The specific energy is higher than for lead acid, around 50Wh/kg and the specific power is good. The cost is quite high, but the battery is still widely used in EVs today. NiCd batteries suffer from memory effect. The batteries gradually lose their maximum energy capacity if they are repeatedly recharged after being only partially discharged. Cadmium is a toxic heavy metal, and needs to be handled carefully during recycling.

4.2.3 Nickel-Metal-Hydride (NiMH)

This battery has many similarities to the NiCd battery, but the performance is better. The battery has high specific power and is well suited for hybrid electric vehicles. The battery is used in many EVs and PHEVs. However, the battery is affected by high self-discharge when not in use.

4.2.4 Lithium-ion (Li-ion)

Lithium-ion batteries are of many considered to be the next generation in EV battery technology. The specific energy and power are very high. It has no memory effect and little self-discharge. The resources of material in the battery are generally considered abundant and non-hazardous. Damage can be made to the battery if it experiences deep discharge, and the battery has poor working life time. Li-ion batteries are widely used in electronics like computers and mobile phones. The current challenge is scaling up the size of the batteries while lowering the cost.

4.2.5 Sodium-Nickel-Chloride (Zebra)

The Zebra battery uses a molten electrode and requires a high temperature around 300°C. The specific energy is high. The battery is placed in an insulated container, and the battery needs energy supply during standstill to for heating.

4.2.6 Life Cycle Assessment

Life Cycle Assessment (LCA) is a cradle-to-grave analysis of products or services to determine their environmental impact. Raw materials production, manufacture, distribution, use, disposal and transportation are taken into account. The environmental stressors from each process are identified. Each stressor contributes to one or more impact categories such as global warming or human toxicity. The assessment gives an overview of how the different stages of the product's life contributes to the different impact categories. The product may be given a total score that indicates the total environmental impact of the product. The score makes it possible to compare the environmental impact of similar products or services. Assessment tools and commercial databases are used to carry out the analysis. There are ISO standards that give requirements and guidelines for the assessment.

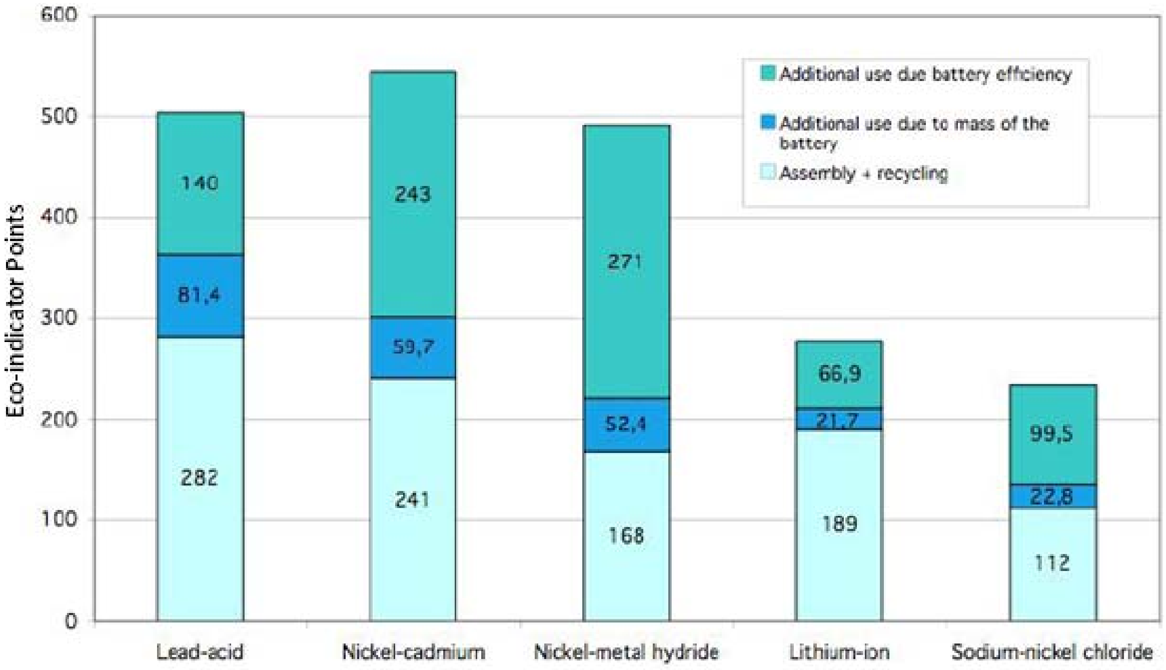

Figure 4: Environmental Impact of Batteries [15]

A Belgian assessment on battery technologies for EVs and HEVs was carried out [15]. The functional unit was a 60 km one-charge range. The European electricity mix was used and the recycling rate was set to 95%. Each battery technology was given eco-indicator points using *Eco-indicator 99*. The results are displayed in Figure 4.

It appears that the energy losses in the battery and losses due to the weight of the battery have a significant environmental impact. This impact depends strongly on the electricity mix. If the electricity mix contains more renewable energy than the European mix, the environmental impact will be significantly lower. The Norwegian electricity mix contains mostly hydro power. The environmental impact of vehicle use in Norway will be lower than the results displayed here. The results show that lithium-ion and sodium-nickel chloride batteries have lower environmental impact than the other three batteries assessed.

4.3 Charging Technologies

Charging technologies for electric vehicles are described in Society of Automotive Engineers (SAE) *Surface Vehicle Recommended Practice* J1772 [12]. The EV charging technologies are divided into three groups: Level 1, Level 2 and Level 3 charging. Level 1 charging is described in the figure below. The battery and charger is located on-board the vehicle. The conversion from AC to DC occurs in the charger. Power and information are delivered through the inlet, which is coupled to the off-board connector. The EV Supply Equipment (EVSE) is located off-board the vehicle and consists of all devices between the power grid and the connector.

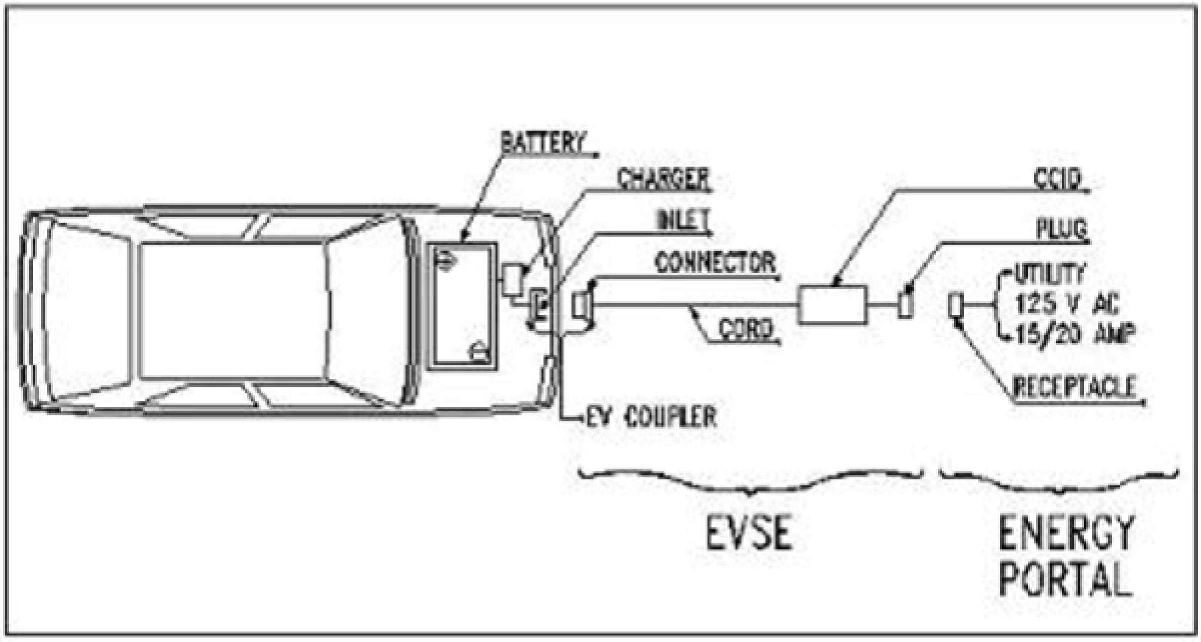

Figure 5: Level 1 Charging Diagram [4]

Level 1 charging uses a single phase 120V standard US socket-outlet (NEMA 5-15R/20R). The maximum rated current at the output is 15-20A, and the power is limited to about 1.4kW [4]. In Norway, the common low voltage output is 230V or 400V. Level 1 charging will therefore not be considered in this project.

Level 2 charging uses 240V single phase and requires dedicated supply equipment which is hard wired to the electric utility. The charger is on-board the vehicle. A charging diagram for level 2 is displayed in Figure 6. The SAE standard J1772 describes a charge coupler for electric vehicles [12]. The coupler allows currents up to 80A. However, current levels that high are not common and a more typical rating would be 16 or 32A. This provides 3.6kW or 7.6kW [4]. The vehicle is charged faster with level 2 charging than with level 1 charging. Most EV producers recommend level 2 charging as the primary charging method for EVs.

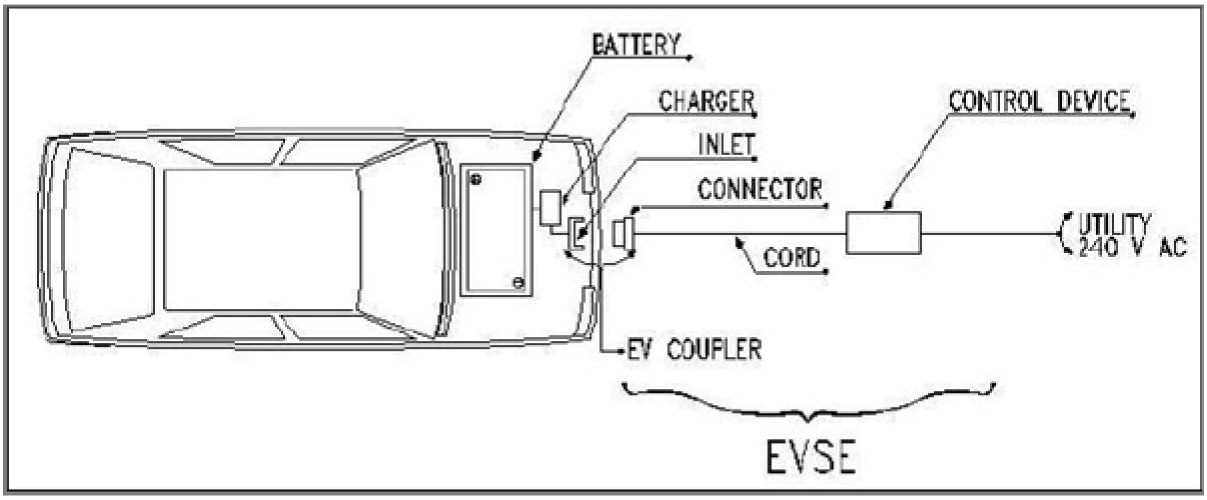

Figure 6: Level 2 Charging Diagram [4]

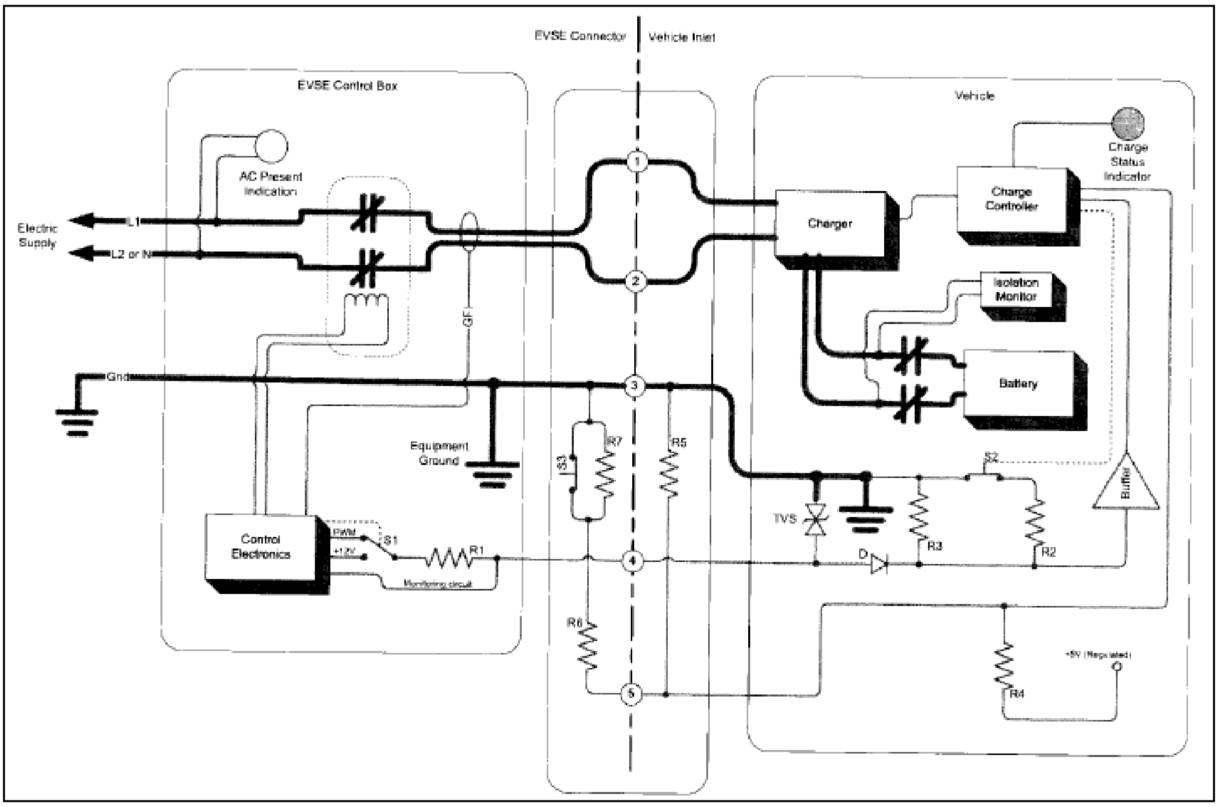

Figure 7: AC level 2 System Configuration [12]

A common coupler for level 1 and level 2 charging is described in the SAE standard. The system configuration is displayed in Figure 7. The connector has five pins. The functions of the connectors are listed below.

1. AC Power (L1) – Power for AC Level 1 and 2
2. AC Power (L2, N) – Power for AC Level 1 and 2
3. Ground – Connect EVSE equipment grounding conductor to EV/PHEV chassis ground during charging. This pole is the first to make contact and the last to break contact.
4. Control pilot – Primary control conductor
5. Proximity Detection – Allows vehicle to detect presence of charger connector

The control pilot performs five functions. For further details, see SAE J1772 [12].

1. Verification of vehicle connection. The pilot indicates that the vehicle is properly connected by sensing the resistance R3.
2. EVSE is ready to supply energy. The square wave oscillator in the control electronics of the EVSE is turned on to indicate that the EVSE is ready to supply energy.
3. EV is ready du accept energy. When the square wave is sensed, S2 is turned on to indicate that the vehicle is ready to accept energy.
4. Determination of indoor ventilation. Some batteries emit hazardous gasses during charging, and ventilation is needed if the charger is placed indoors. A specified dc voltage level on the control pilot indicates that ventilation is needed.
5. EVSE current capacity. The duty cycle of the square wave indicates the current capacity of the EVSE.
6. Verification of equipment grounding continuity. The ground connection is used as a return path for the control pilot current to insure a safe connection between the EV chassis ground and the EVSE equipment ground.

The proximity detection detects the presence of a connector. This is to prevent inadvertent disconnection or driving during charging. It may be coupled to the drive interlock in the vehicle. The proximity detection may also be used to reduce electrical arcing during disconnect. The switch S3 is mechanically linked to the connector latch release actuator. When the connector is decoupled, S3 opens and the charge control provides a controlled shutoff of charge power prior to disconnection.

Figure 8: SAE J1772 EV Charge Coupler [5]

Level 3 charging is also called *fast charging*. A recharge of 50% takes 10 to 15 minutes, and the charger is intended to perform similar to a petrol service station. The vehicle's on-board battery management system controls the off-board charger to deliver DC power directly to the battery. The configuration is displayed in the figure below.

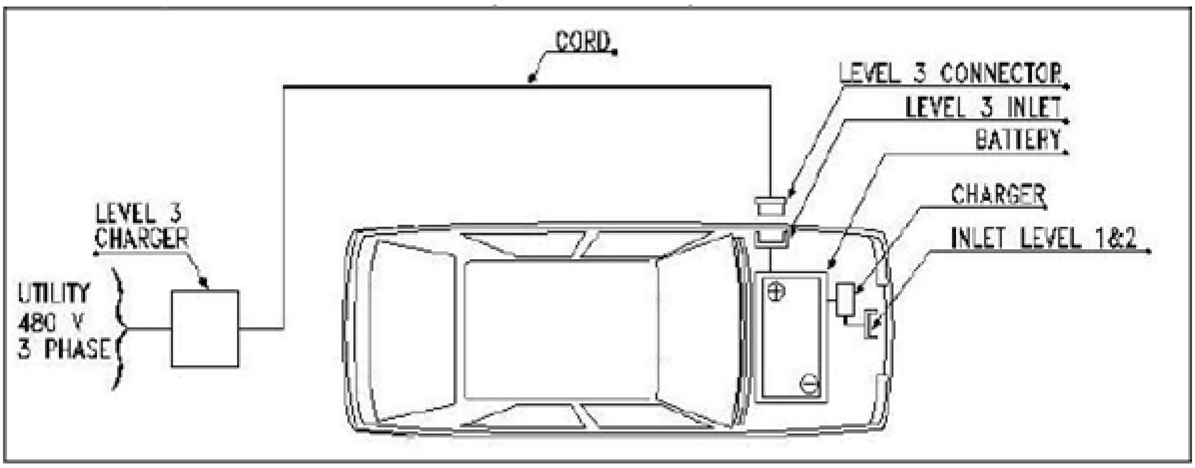

Figure 9: Level 3 Charging Diagram [4]

The charger is supplied with 3-phase 230VAC to 600VAC. A standard coupler is not developed yet. Even so, charging stations are available on the market. AeroVironment™ EV Solutions provide EV Fast-Fuel Charging Stations. They provide charging stations rated from 30 to 250kW. The configuration displayed in the figure above is used.

4.3.1 Charging Times

The charging time spans from many hours to a few minutes. This is caused by a large span in battery sizes and charging power. Plug-in hybrid vehicles normally have small batteries because the vehicles are powered by several fuel sources. Battery electric vehicles of the same size have much larger batteries because they are the only power source in the vehicle. The charging time also depends on the state of charge. Driving habits, hilliness of the terrain and weight of the vehicle and load affect the rate of depletion and the range of the vehicle.

Table 2: Minimum Charging Times 0-100% State of Charge [4]

Vehicle Type	Usable Battery Capacity (kWh)	Level 2 10A circuit (hrs)	Level 2 16A circuit (hrs)	Level 2 32A circuit (hrs)	Level 3 (min)	Level 3 (min)	Level 3 (min)	Level 3 (min)
		2kW	**3.5kW**	**7.5kW**	**30kW**	**60kW**	**125kW**	**250kW**
PHEV-10	4	2	1.1	0.5	8	4	1.9	1.0
PHEV-20	8	4	2.3	1.1	16	8	3.8	1.9
PHEV-40	16	8	4.6	2.1	32	16	7.7	3.8
City EV	20	10	5.7	2.7	40	20	9.6	4.8
BEV (mid-size)	35	17.5	10.0	4.7	70	35	16.8	8.4
BEV (large)	50	25	14.3	6.7	100	50	24.0	12.0
Hybrid Bus	40	20	11.4	5.3	80	40	19.2	9.6

The table above displays approximate charging times for different battery sizes. The battery pack is assumed to be fully depleted when the charging starts. Charging times for level 3 charging are longer than what the table suggests. Most batteries are not capable of receiving full power during the entire charging cycle. The charging power needs to be gradually increased at the beginning and decreased at the end of the charging cycle. The charging pattern is controlled by electronics in the vehicle so that the battery is not harmed during charging. Charging times will be different for every battery type and every car manufacturer.

5 Methodology

The elements described in this section are needed in the further calculations and analyses. The economic principals are basis for calculating the cost of losses. The section on network planning describes the overall method which is used when planning reinforcements or extensions in distribution networks. This is the basis for some of the analysis in this project. The cost functions which are used in further analysis are described. Some phenomena included in the Norwegian Power Quality (PQ) code are defined. Three of the phenomena are evaluated for specific load cases in the results section. One of the phenomena evaluated is harmonic voltage. The last part of this chapter includes the basis for calculating the harmonic voltage.

5.1 Economic Principals

The following principals are used in calculating the capitalised costs in Table 40 and Table 41. In network planning, investment costs occur at the beginning of the year, and running costs and payments occur at the end of the year. Power grid components normally have a long lifetime. The period of analysis should be long, in the range 15 to 30 years. Economic lifetime of a component is the expected time that the component will be useful.

5.1.1 Capitalised Value

The capitalised value represents today's value of a stream of fixed costs over a specified period of time in the future.

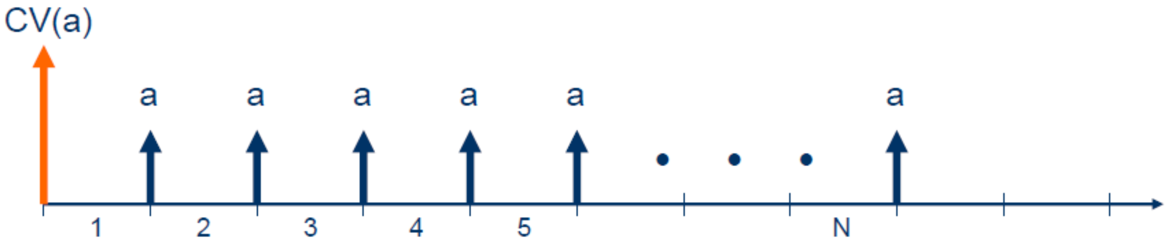

Figure 10: Capitalised Value [13]

$$CV(a) = a\left(\frac{1-(1+r)^{-N}}{r}\right) = a\lambda_{R,N} \tag{1}$$

Where

CV – Capitalised value
a – Annual investment
N – Period of analysis
R – Rate of interest (%p.a.)
$\lambda_{R,N}$ – Capitalisation factor

5.1.2 Annuity

The annuity is a stream of fixed costs over a specified period of time that represents an investment made today. It can be considered as the opposite of the capitalised value.

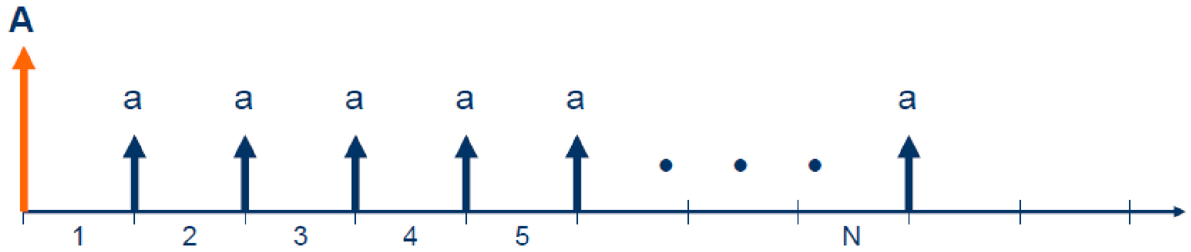

Figure 11: Annuity [13]

$$a(A) = \left(\frac{r}{1-(1+r)^{-N}}\right) = A\varepsilon_{R,N} \tag{2}$$

$$\varepsilon_{R,N} = \frac{1}{\lambda_{R,N}} \tag{3}$$

Where

$\varepsilon_{R,N}$ – Annuity factor

5.1.3 Present Value

The present value represents today's value of a future cost.

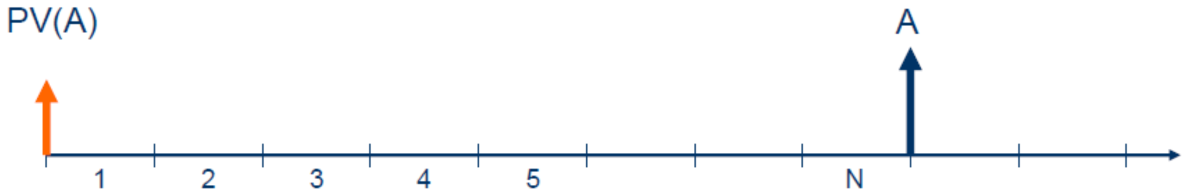

Figure 12: Present Value [13]

$$PV(A) = A(1+r)^{-N} = A\varepsilon_{R,T}\lambda_{R,N} \tag{4}$$

$$r = \frac{R}{100} \tag{5}$$

Where

PV – Present Value
A – Investment
T – Economic lifetime

5.2 Network Planning

This section contains selected information from *Planboka* [11]. Network planning consists of a variety of tasks. Both connecting a new load to the network and planning a maintenance plan for the regional grid are included in network planning. The utility companies are obliged to act in a socio-economic manner. Components in a power grid have long lifetimes, and period of analysis should be long. When planning a grid investment, the following cost elements needs to be included: investments (capex), operating and maintenance cost (opex), cost of losses, cost of energy not supplied (CENS) and bottleneck costs. The bottleneck costs are caused by low transfer capacity in the grid. These costs are not relevant for the distribution grid.

The calculation interest represents the cost of tying up capital and taking risk. The risk contains uncertainty concerning interest level, advance in prices, exchange and tax regulations. The calculation interest is set to 4.5% by the Norwegian Department of Energy, NVE. This interest does not include inflation.

The goal when planning an extension of the power grid is to minimise the expected socio-economic costs. In the distribution grid, a simplified analysis is used. The grid consists mostly of radials going from the distribution transformer to the end-user. CENS and opex can be neglected. The goal of the analysis is to minimise the investment cost and the capitalised cost of losses. The planning process can be split into four phases:

- Phase 1: Establishing data
    - The customer's needs
    - Electric grid data: Load flow of high voltage grid and electric data for components and low voltage grid
    - Data on existing loads in the network and new loads
    - Restrictions on electric quantities, quality of supply and environmental concerns
- Phase 2: Technical solutions
    - Evaluate different points of connection and dimensioning of components
    - Perform load flow simulations and evaluate restrictions
- Phase 3: Selecting the optimal solution
    - Calculate investment costs and capitalised cost of losses
    - Select the cheapest solution that meets the restrictions
- Phase 4: Control of cost absorption
    - Evaluate if the project is profitable
    - If not: charge the costumer for the connection

5.3 Utilisation Time

The utilisation time describes use pattern of the load. It is defined by the formula below.

$$T_u = \frac{W}{P_{max}} \tag{6}$$

Where

T_u – Utilization time
W – Energy consumption for the period (kWh)
P_{max} – Maximum power during the period (kW)

The annual duration curve in Figure 13 illustrates the concept. The curve represents the load for a year sorted from largest to smallest. The area $P_{max}T_u$ equals the time integral of the curve. T_u gives an indication for the variations in the load over a year.

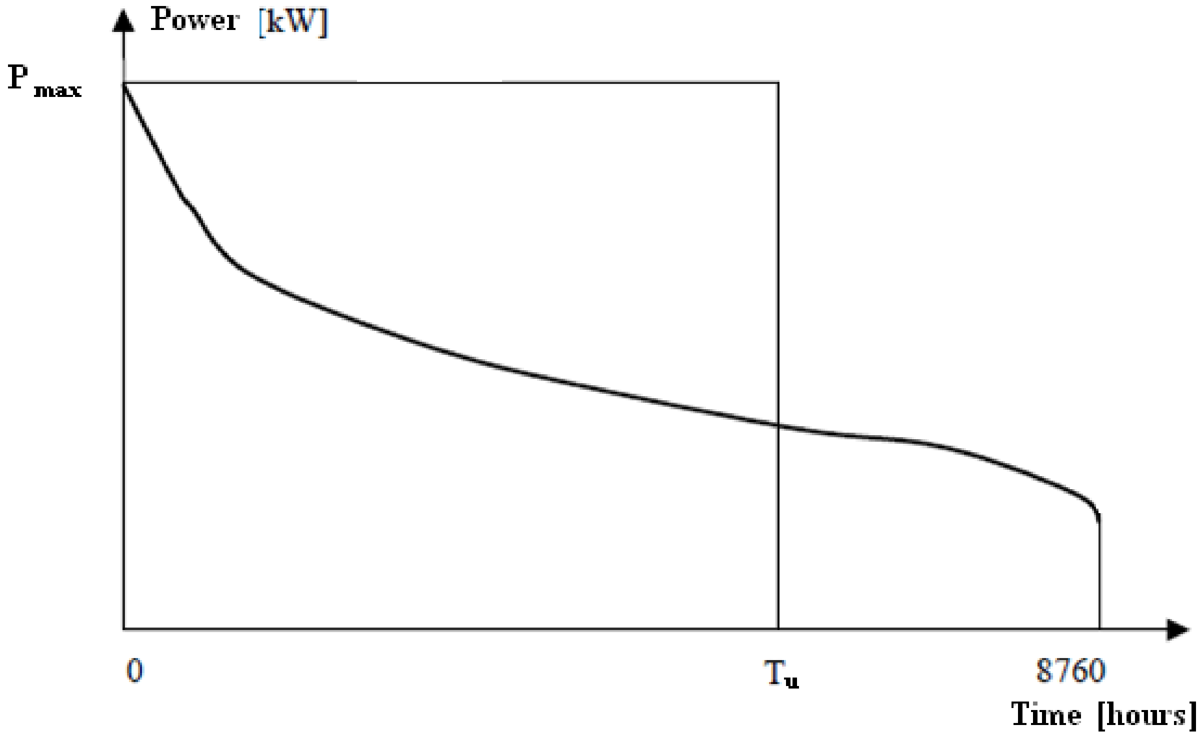

Figure 13: Annual Duration Curve [11]

The utilisation time of losses is defined in the same way as for the load.

$$T_{\Delta P} = \frac{\Delta W}{\Delta P_{max}} \quad \textbf{(7)}$$

Where

$T_{\Delta P}$ – Utilisation time of losses
ΔW – Energy losses
ΔP – Power losses

5.4 Cost of Losses

The cost of losses is an important factor when planning a power network. The energy losses are about 8% of the annual energy production and the power losses can be up to 15% of the power production. The cost of losses has to be included in the socio-economic analysis.

The specific cost of losses is given:

$$\begin{aligned} k_{\Delta P} &= k_p \Delta P_{max} + \Delta P_{max} k_w T_{\Delta P} \\ &= (k_p + k_w T_{\Delta P}) \Delta P_{max} \\ &= k_{pekv} \Delta P_{max} \end{aligned} \quad \textbf{(8)}$$

Where

$k_{\Delta P}$ – Cost of losses (NOK/year)
k_p – Power cost (NOK/kW)
ΔP_{max} – Maximum power losses (kW)
k_w – Average energy cost (NOK/kWh)

T_l – Utilisation time of losses (h/year)
K_{pekv} – Equivalent cost of losses (NOK/kW,year)

The power cost k_p is given in Table 39. Capitalised costs of losses are given in Table 40 and Table 41. A simplified, radial network is used to calculate the constants. There are different columns for different loading conditions. When analysing, the constants for the highest voltage level included in the analysis is to be used.

5.4.1 Cable Costs

The cable cost consists of two elements: investment and cost of losses. The investment costs are proportional to the length of the cable:

$$K_I = K_L L = (k_0 + k_{cs} A)L \tag{9}$$

The cost of losses:

$$\Delta P = 3RI^2 = 3R\left(\frac{P}{\sqrt{3}U_2 cos\varphi}\right)^2 = rL\left(\frac{P}{U_2 cos\varphi}\right)^2 \tag{10}$$

$$K_{\Delta P} = K_{pekv}\Delta P \tag{11}$$

Where

K_I – Total cost of investment (NOK)
K_L – Cost per length (NOK/m). Data is given in Table 36.
L – Length (m)
k_0 – Cross section independent cost (NOK/m)
k_{cs} – Cross section dependent cost (NOK/m,mm^2)
A – Cross section (mm^2)
ΔP – Power losses (kW)
I – Current (A)
R – Resistance (Ω)
P – Power of the load (kW)
U_2 – Voltage at the load (V)
cosϕ – Power factor of the load
r – Resistance per length (Ω/m). Data is given in Table 43.
$K_{\Delta P}$ – Cost of losses (NOK)
K_{pekv} – Capitalised cost of losses (NOK/kW). Data is given in Table 40.

5.4.2 Transformer Cost

The cost of a transformer consists of three elements: investment, copper losses and no-load losses. The copper losses are caused by the resistance in the windings of the transformer. These losses increase in pace with the loading of the transformer. The no-load losses are due to magnetising of the iron core. They are independent of the loading, and dominate when the loading is low.

$$\Delta P = P_k \left(\frac{S}{S_n}\right)^2 \tag{12}$$

$$K = K_{pekv}\Delta P + K_{Tekv}P_0 + I \tag{13}$$

ΔP – Copper losses (kW)
P_k – Losses at rated power (kW). Data is given in Table 44.
S – Load at transformer (kVA)
S_n – Transformer rating (kVA)
K – Total cost of transformer (NOK)
K_{pekv} – Capitalised cost of losses (NOK/kW). Data is given in Table 40.
K_{Tekv} – Capitalised cost of no-load losses (NOK/kW). Data is given in Table 41.
P_0 – No-load losses (kW). Data is given in Table 44.
I – Investment (NOK). Data is given in Table 38.

5.5 Quality of Supply

The Norwegian utility companies have to fulfil the regulations *European Standard EN50160* and the Norwegian PQ code given in *Forskrift om Leveringskvalitet* [2], [9]. The standards define the properties of the voltage at the point of delivery. The two regulations include the same phenomena, but the Norwegian PQ code is stricter than EN50160 on several of the phenomena included. The phenomena that are evaluated in this report are described in Table 3.

Table 3: Some Phenomena Included in the Norwegian PQ Code [2], [9]

Phenomenon	Definition	Requirements
Supply voltage variations	Increase or decrease of voltage.	U_n±10%
Rapid voltage changes	A single rapid variation of the r.m.s. value of a voltage between two consecutive levels which are sustained for definite but unspecified durations	ΔU_{stat}>3%: <24/day ΔU_{max}>5%: <24/day
Flicker	Impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time. **Flicker severity:** Intensity of flicker annoyance defined by the UIE-IEC flicker measurement method and evaluated by the following quantities: **Short term severity (P_{st}):** measured over a period of ten minutes. **Long term severity (P_{lt}):** calculated from a sequence of 12 P_{st}-values over a two hour interval, according to the following expression: $$P_{lt} = \sqrt[3]{\sum_{i=1}^{12} \frac{P_{st}^3}{12}}$$	P_{st}≤1.2 95% of the time P_{lt} ≤1.0 100% of the time Measured for one week
Supply voltage unbalance	Condition in a poly-phase system in which the r.m.s. values of the line-to-line voltages (fundamental component), or the phase angles between consecutive line voltages, are not all equal. The degree of inequality is calculated from the relation U_-/U_+, where U_- and U_+ are the negative and positive sequence voltage components.	U_-/U_+<2%
Harmonic voltage	Sinusoidal voltage with a frequency equal to an integer multiple of the fundamental frequency of the supply voltage. Harmonic voltages can be evaluated individually by their relative amplitude (U_h) which is the harmonic voltage related to the fundamental voltage U_1, where h is the order of the harmonics or globally, for example by the total harmonic distortion factor THD, calculated using the following expression: $$THD = \sqrt{\sum_{h=2}^{40} (U_h)^2}$$	THD≤8% measured with 10 minutes average. Table of individual values is in Table 46.
Inter-harmonic voltage	Sinusoidal voltage with a frequency not equal to an integer multiple of the fundamental	No specific requirements
Voltage dip	A temporary reduction of the voltage at a point in the electrical supply system between 90% and 1% of the reference voltage, with duration from 10ms to 60s.	Dips caused by load: <24/day Other causes: no requirements.

5.6 Harmonic Voltage

Harmonics are currents and voltages that have a frequency equal to an integer multiplied with the fundamental frequency. Components containing power electronics produce harmonic currents. The harmonic currents produce harmonic voltage given by:

$$U_h = (Z_{uh} + Z_{kh})I_h \tag{14}$$

Where

h – Indicates harmonic order at frequency h*50Hz
Z_{uh} – Local harmonic impedance at h*50Hz
Z_{kh} – Resulting harmonic impedance in the grid at h*50Hz
I_h – Harmonic current produced

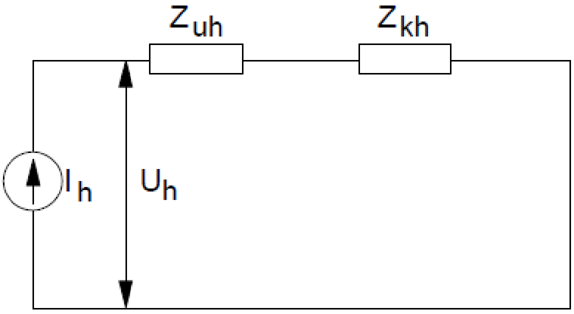

Figure 14: Harmonic Current Source [10]

The currents add up to the fundamental waveform and make a distortion of the voltage. Nonlinear appliances produce harmonic currents. The harmonic current I_h is given by:

$$I_h \leq \frac{I_1}{h} \tag{15}$$

The harmonic impedance is calculated for every component and every harmonic order h. The grid can be modelled by using the short circuit capacity Sk.

$$X_{kh} = hX_1 = h\frac{U^2}{S_k} \tag{16}$$

$$R_k = 0.1X_h \tag{17}$$

The harmonic voltage is calculated for every harmonic frequency h. There are restrictions on harmonic voltage of all orders up to 25 and the total harmonic distortion for harmonics up to 40.

6 Approach

This section covers phase 1 of the network planning method. A detailed description of the new load is given. The computer tools and network data which will be used are described. Load data and assumptions used in the analysis are given.

6.1 Load Description

The preferred charging method for EVs is level 2 charging at home or at work, while fast charging is a range extending measure for EV owners on long drives. The charging time needs to be low as low as 5-10 minutes for the EV to gain popularity [3]. Fast charging should be similar to filling a tank of petrol. Therefore, high power level 3 chargers rated 60kW or 125kW will be evaluated. At 125kW, the charging time for a mid-size BEV is minimum 17 minutes for a full charge. More charging times are displayed in Table 2.

A filling station for gas and fast chargers for electric vehicles (EVs) will be installed close to an existing petrol station at Luravika in Sandnes, Norway. A map of the area is displayed in Figure 15. The closest distribution substation is marked *N0520.* It contains a transformer rated 630kVA and a pump station that pumps surface water into the sewer. Technical specifications for the pump station are given at page 29. The local distribution grid consists of underground electric cables and gas pipes. The low voltage arrangement is a 400V TN-C network.

The main load at the gas filling station is a compressor from the Argentinean producer Galileo. The EV charging station is delivered by the Californian manufacturer of fast charging solutions AeroVironment Inc. Technical specifications for both components are given at page 29. The location of the compressor and the EV charging station are marked in the map.

This project aims to find the optimal grid connection for the load. Several solutions will be evaluated. One alternative is to connect the load to the existing substation. The connection will be made with PEX isolated 4x240mm^2 Al 400V cables. One or more cables will be installed for each of the two loads and connected directly to the substation. A trench will be dug along the existing 22kV-cable for the new low voltage cables. The cable lengths are 290m for the compressor and 200m for the EV chargers. The trench needs to cross the road. Underneath the road, there is a pipe with available space that can be used for drawing the cables. At the moment, the substation is only serving one load. The load is connected directly to the transformer. To serve more loads, a low voltage installation has to be made at the substation to connect the new cables.

Another solution is to build a new substation close to the new load. It can be connected to the existing high voltage cable which is marked in the map. The new substation will be installed close to the EV charging station by the green X in the map. A cable for the compressor station needs to be installed. The cable length is 90m. Technical specifications for the transformers used in the analysis are given in Table 45.

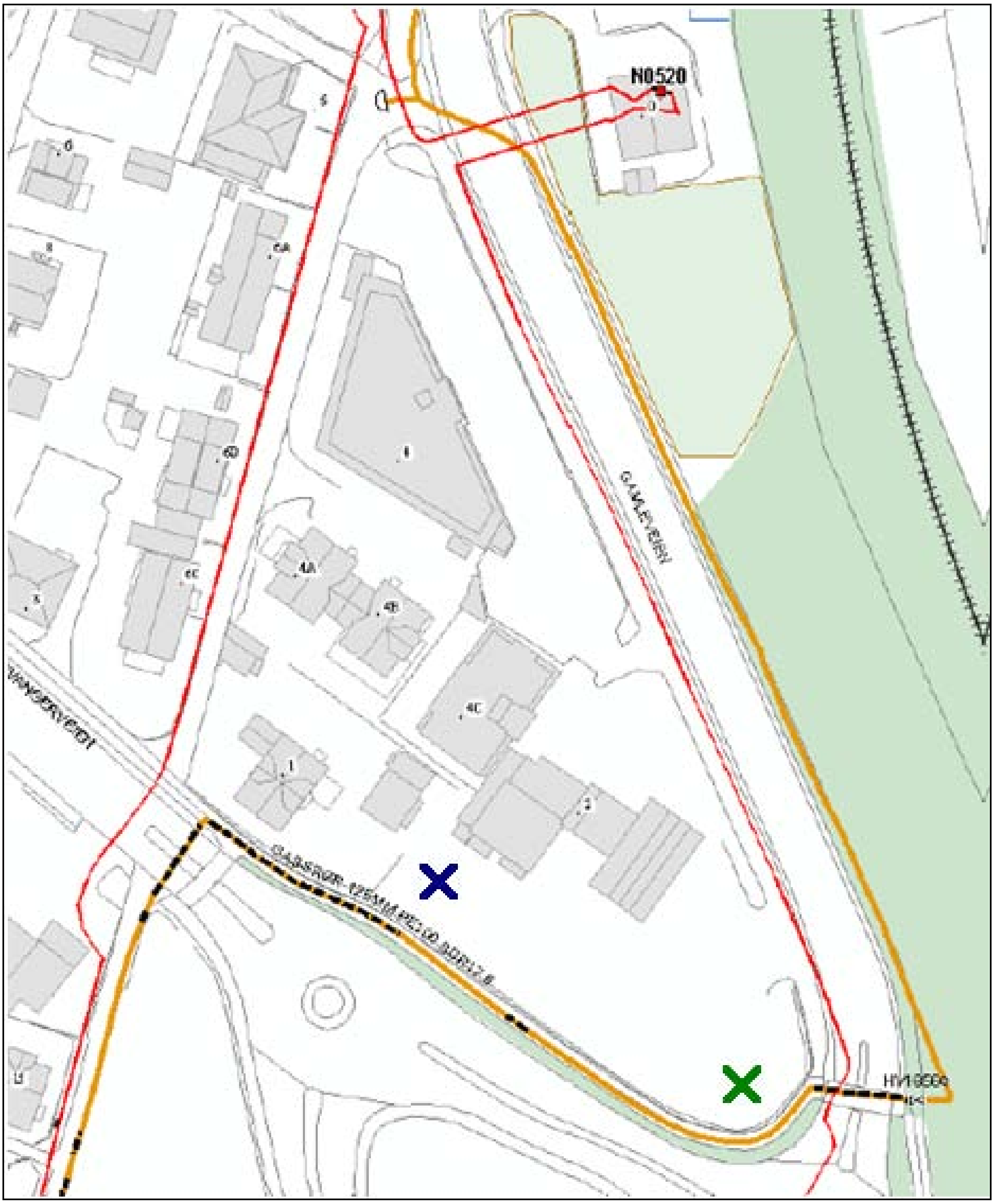

Figure 15: Map of Luravika. Red line: 22kV Cables. Yellow line: Gas Pipes. Blue X: Compressor. Green X: EV Charging Station.

6.2 Tools

Load flow simulations and economic calculations were carried out in this project. The computer tools that were used are described in this section.

6.2.1 Powel Netbas

Netbas is a network information system developed for distribution and transmission of electric energy. It is developed by the Norwegian company Powel. The system is suited for utility management and includes tools for planning, design, operations and maintenance of the network. The grid is represented in a graphical user interface that is easy to use. All the components in the grid are included containing position, technical specifications and connectivity. The system can be integrated with other systems which gives numerous opportunities to the utility companies.

In this project, Netbas was used for load flow. Lyse provided a mesh file that contains the 22kV distribution grid close to Lure transformer station in Sandnes. Detailed information about the low voltage grid was not included in the file. The network was modified to include the new load and different technical solutions were implemented. Load flow analyses were performed to get outputs like power losses, voltages, currents and more. Detailed simulations were made to simulate a whole year.

6.2.2 Dynko

Dynko is a program that was first developed in 1972 by EFI, which is called SINTEF today. The version used in the project was last modified in 1988. It is a cost minimising program for electric distribution grids. The program has a text based user interface. It is used when developing a new grid or when strengthening an existing grid. The program compares different technical solutions economically considering investments, cost of losses and energy not supplied over the period of analysis. The maximum period of analysis is 25 years. The cost of losses is calculated from peak power losses and k_{pekv}, which is given in Table 39. To include the no-load losses of the transformers, the capitalised value is calculated and added to the investment. The cost of no-load losses K_{Tekv} is given in Table 41. Cost elements can be entered with one decimal. Losses are entered in kW. The losses are given without decimals. This leads to inaccurate results. To give more accurate results, all data on costs and losses were scaled up by a factor of 10. Still the losses are given with only two or three valid digits.

The total cost during the period of analysis is calculated for each solution. The results are represented by ranking the solutions and giving each a score. The solution ranked 1 is the least costly solution. This is given score 100. The other solutions get a score greater than 100, which represent the total cost of the solution relative to the cost of the cheapest solution. An example of an output file is displayed from page 67.

6.2.3 GeoNIS

GeoNIS is a Geographical Network Information System. The system contains all of Lyse's infrastructure networks represented the same map. The networks included are electricity, telecommunication, street lights, gas and district heating. Information about all components is included, from the delivery point and up to 300kV. The placement of all components is available. Detailed information about the low voltage grid is represented in this system. The system is coupled to the customer database. Information about annual consumption and peak power is available for the loads. The background map is very detailed and contains all street addresses.

GeoNIS was used for planning the location of the installation, placement of cables and the cable lengths. Distances may be measured in the map. The system also contained useful information about the grid components and loads.

6.3 Load Data

The load data for the pump station, the compressor and the EV charging station was obtained. The data for the pump station was given by Odd Woster in IVAR. The data for the compressor was given by Audun Aspelund on behalf of Galileo S.A., Argentina. The information about the EV charging station was given by vice president Kirsten Helsel of AeroVironment Inc., California.

6.3.1 Water Pumps at Luravika

There are four pumps for surface water. The load is at maximum during wet seasons. At maximum load, three pumps run continuously. Otherwise there are 6-7 starts per hour.

Power rating: 132 kW
Voltage rating: 400 V
Rated current: 260 A. Measured value: 238 A
cosϕ: 0.82
Start-up cosϕ: 0.41
Start-up current: 1952 A at locked rotor.
Start-up type: direct start.

6.3.2 Compressor for Gas Filling Station

The expected daily load pattern is 20 start-ups per day; 3 per hour in hour 9 and 17, otherwise one per hour from 7 to 23. Each start lasts 15 minutes.

Type: Galileo Microbox
Power rating: 120 kW
Voltage rating: 400 V
cosϕ: 0.91

6.3.3 EV Charging Station

The daily load pattern is expected to be equal to the pattern for the compressor.

Type: AeroVironment™ EV Solutions DC charger
Output power rating: 30 / 60 / 125 / 250 kW

Input voltage: 400 V three phase at 50 Hz
Output voltage: 50-600 V DC
Output current: 50-550 A DC
cosϕ: 0.95
Efficiency: >90%

6.4 Assumptions

The restrictions are the same as was used a previous report on dimensioning of low voltage grids [5].

Period of analysis: 25 years
Economic lifetime components: 30 years
Calculation interest: 4.5%
Voltage level: 400V/22kV
Maximum allowed voltage drop in low voltage parts: 8%
Maximum allowed load at transformers: 130%
Load increase in period of analysis: 0%
Advance in prices in period of analysis: 0%
Energy not supplied: 0 kWh/year

7 Results

This chapter contains three sections. The first is a general dimensioning guide of cable cross sections and transformer power ratings. The second section contains network planning phases 2 and 3, which are described in the methodology chapter. Numerous technical solutions for connecting the load are analysed including two different points of connection. The dimensions of cables and transformers are investigated and load flow analyses are carried out. The costs of investments and losses are evaluated and the cheapest solution which meets the restrictions is chosen for each load case. The last section of this chapter looks at the fulfilment of the Norwegian PQ code.

7.1 Optimal Dimensioning

This section gives a general dimensioning guide for cable cross section and transformer power rating. It may be used when connecting new load to the network. The graphs are based on the formulas given in the section 5.4. The costs included are investments and capitalised cost of losses. Cost of Energy Not Supplied (CENS) and operating costs (opex) are not included.

7.1.1 Optimal Cross Section

By using the formulas (9), (10) and (11), graphs that show the cost of different cross sections for one load was made. Graphs are shown for 250kW and 500kW in Figure 16 and Figure 17. Table values for material costs and cost of losses are used, given in sections 12.1 and 12.2. The utilisation time of losses used in the tables is 2400h/year.

The largest available cross section for low voltage cables is 240mm^2. The cross sections used for low voltage in this project are different number of 240mm^2 cables in parallel. The optimal cross section is independent of the length of the cable. From Figure 16 one can see that the cost of 3, 4 or 5 cables in parallel is about the same for a 250kW load. The optimal cross section is 4x240mm^2. The graph is steep on the left side of the minimum, and quite even on the right side of the minimum. It is more expensive to make an underinvestment than to make an overinvestment. The cost increases little as the cross section increases by one step. The losses and heat generation decrease as the cross section goes up. High temperature causes damage to the isolation of cables and shortens the lifetime. By choosing a larger cross section than the optimal choice, the cable does not need to be changed if the load increases. In general, a larger cross section gives a more robust alternative.

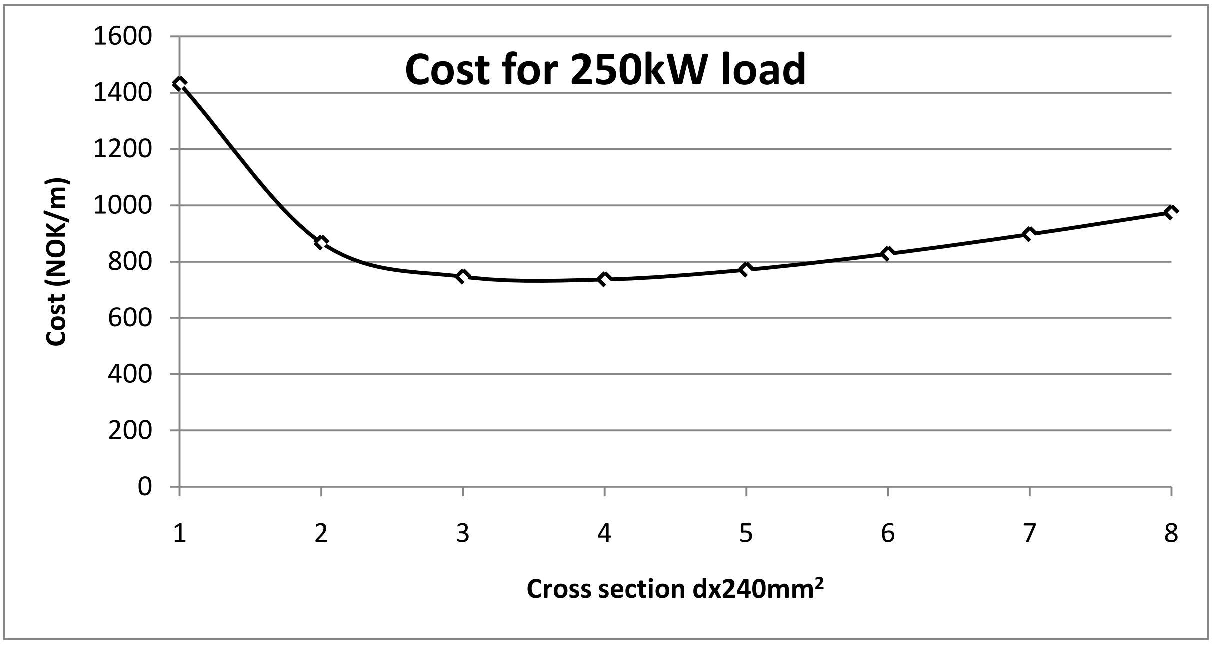

Figure 16: Cost of Cross Sections for 250kW Load

The graph in Figure 17 shows similar results for a 500kW load. The cost is about the same for 6, 7, 8 and 9 cables in parallel. The optimal cross section for 500kW load is 7x240mm^2. The cost increases little if the cable is upgraded to 8x240mm^2.

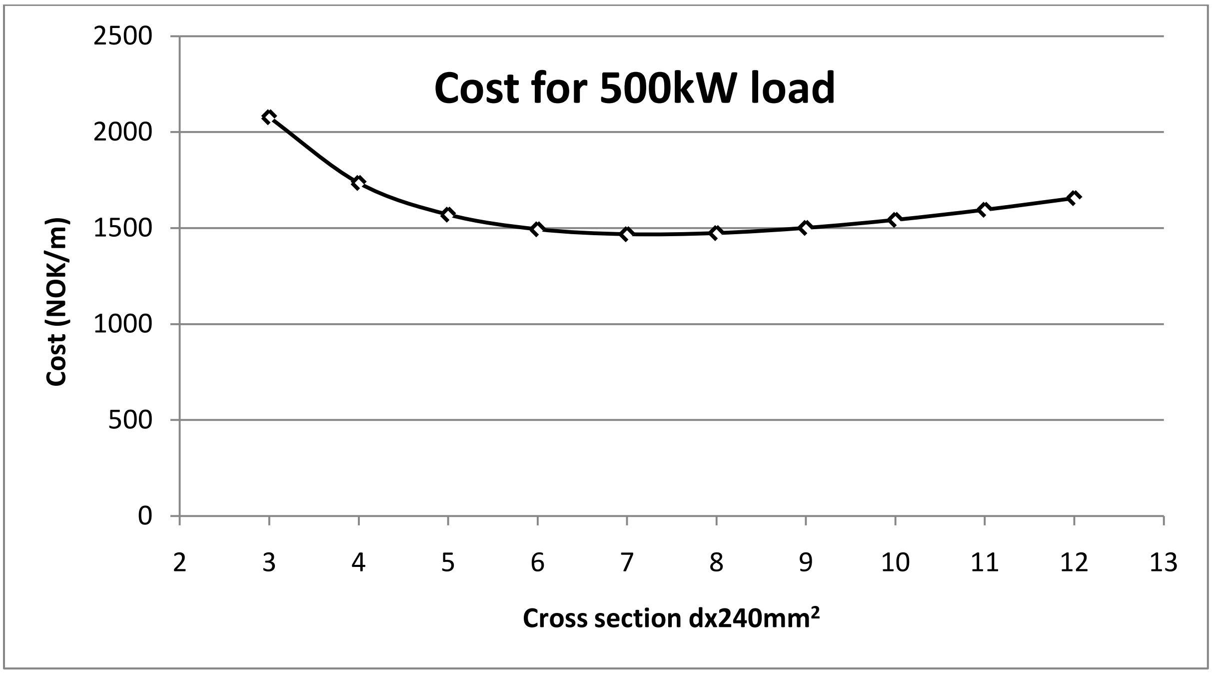

Figure 17: Cost of Cross Sections for 500kW Load

The optimal cross section is represented differently in Figure 18 and Figure 19. The graphs are based on formulas (9), (10) and (11). From Figure 18, one can see that the optimal cross section for a 250kW load is 4x240mm^2. The optimal cross section for a 125kW load is

2x240mm^2. From Figure 19 one can see that the optimal cross section for 500kW is 7x240mm^2. As the load increases, the cost varies little for a variety of cross sections. 6, 7 or 8 cables in parallel are almost equal in cost for a 470kW load.

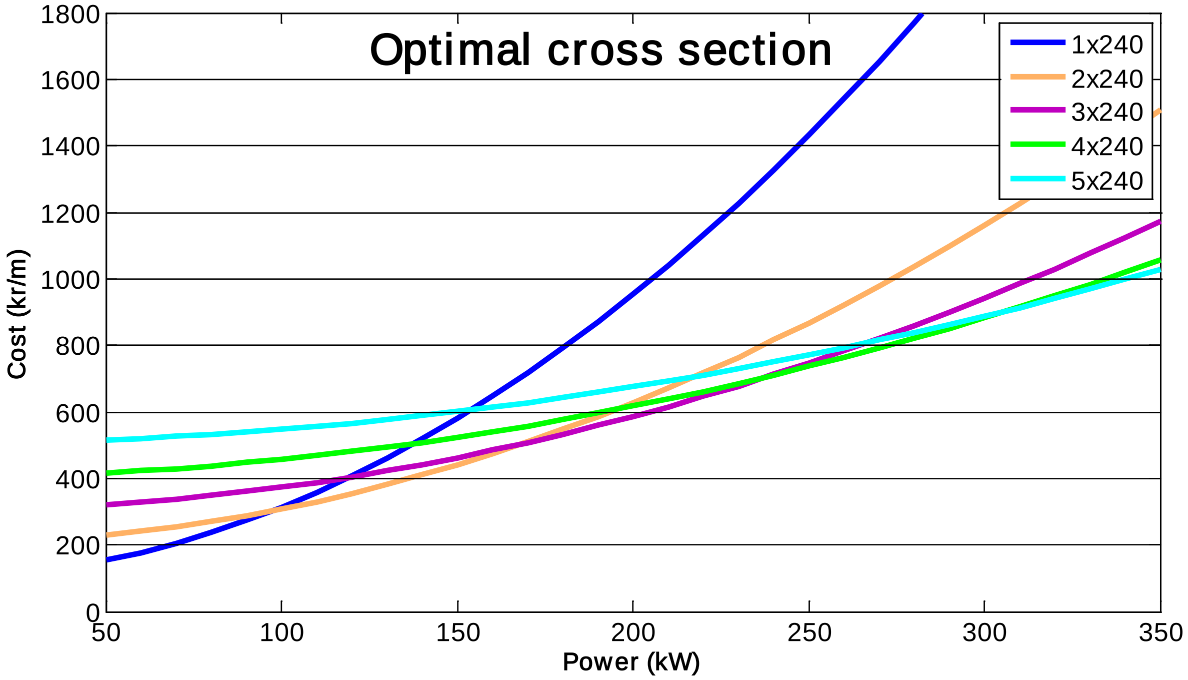

Figure 18: Cable Cost

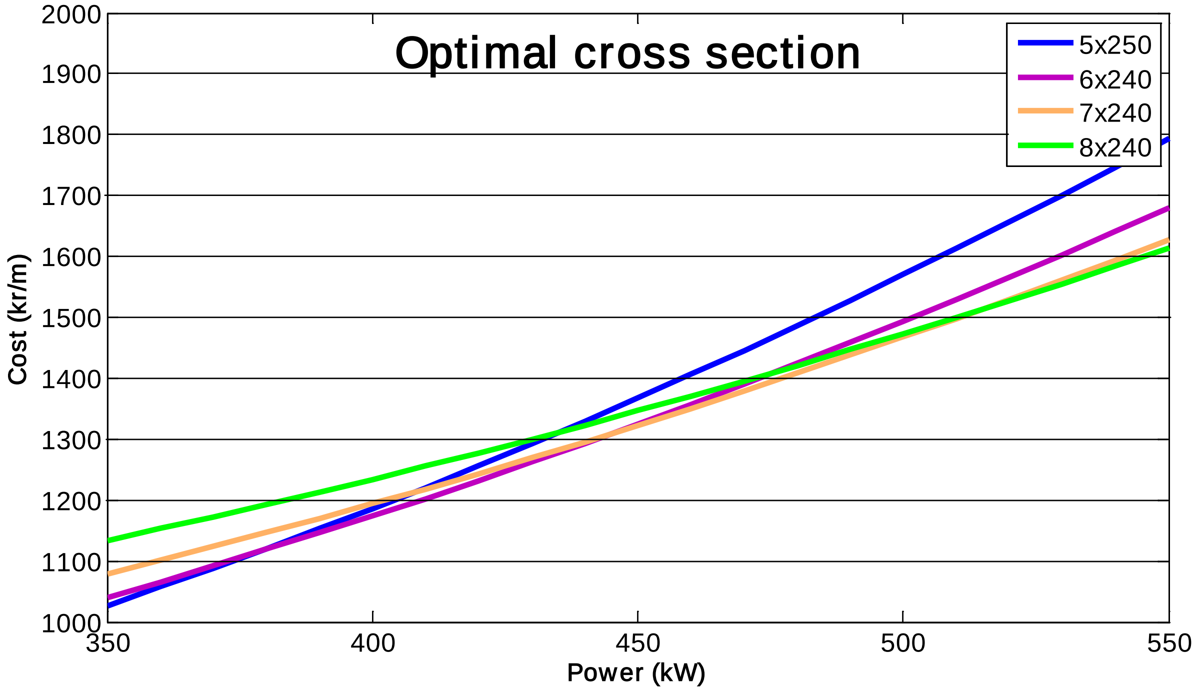

Figure 19: Cable Cost

7.1.2 Optimal Transformer Rating

The graphs below are based on formulas (12) and (13). The data used for the graphs are given in the appendices. The graphs show the total cost of a transformer for different loads. By studying the graphs, the optimal transformer for different loads can be decided. The results are given in the Table 4.

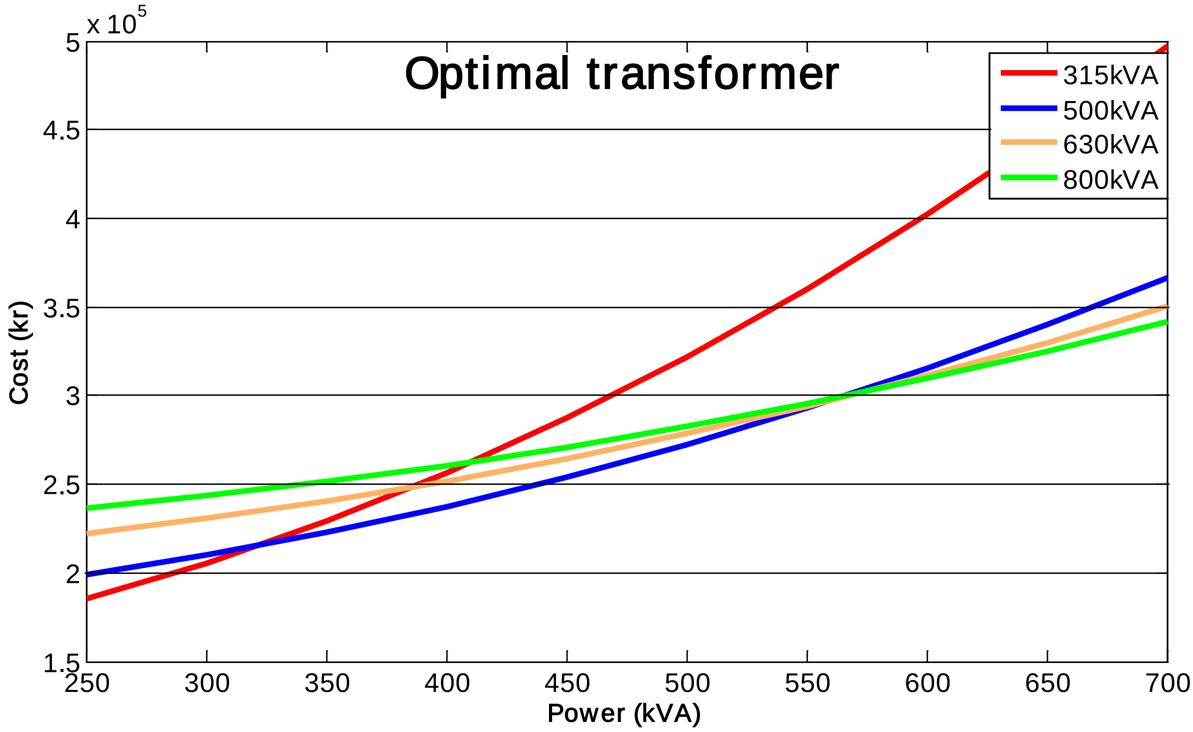

Figure 20: Transformer Cost

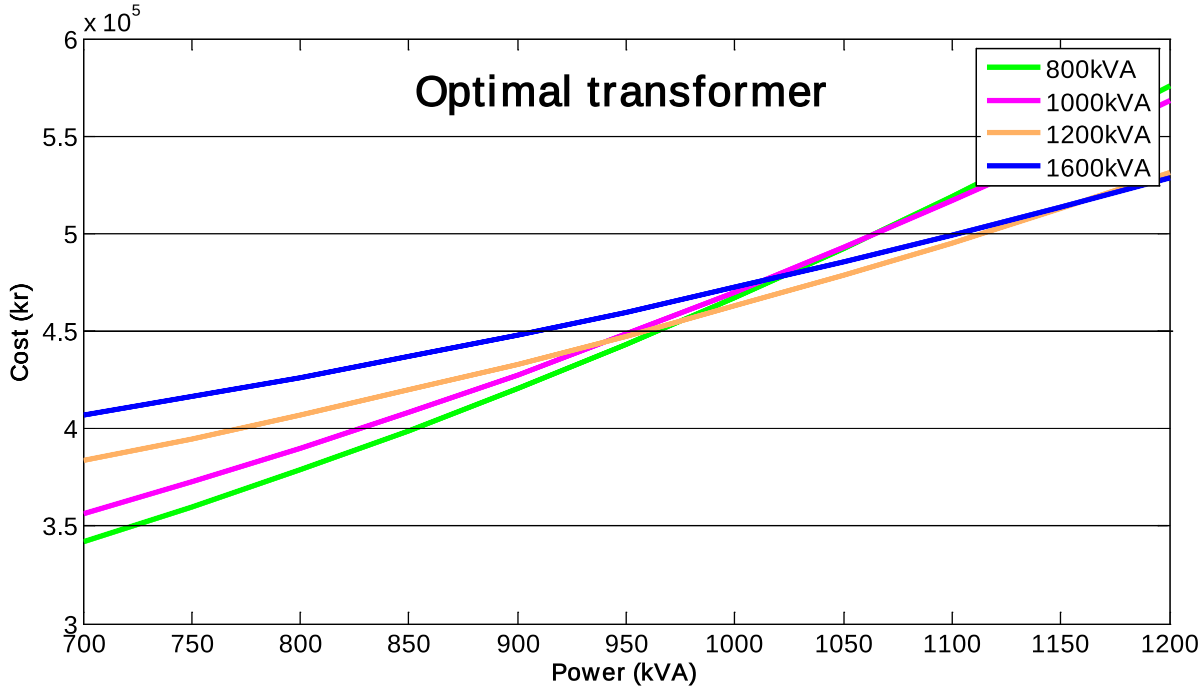

Figure 21: Transformer Cost

Table 4: Optimal Transformer Load

Transformer Rating (kVA)	Optimal Load (kVA)
315	<320
500	320-570
800	570-970
1250	970-1170
1600	>1170

The transformers rated 630kVA and 1000kVA are not included in the table. The reason for this is visible in the graphs. The pink line in Figure 21 displays the costs for the 1000kVA transformer. This line is never the bottom line. The 1000kVA transformer is not an optimal investment for any load. The same phenomenon occurs for the 630kVA transformer in Figure 20. The cost of the 630kVA transformer is marked with the orange line. The line is never at the bottom, so it is never an optimal investment.

The cost of the different transformer is quite equal at many loads. When a new transformer is installed, one should consider increase of load in the future. By choosing a transformer with a higher power rating, the load may increase more before the transformer needs to be replaced.

7.2 Load Cases

At Luravika, there is space for maximum four charging outlets for EVs. They will be located at the green X in Figure 15. The compressor for gas filling will be located at the blue X. Three different load scenarios for the EV station will be evaluated. The three scenarios involve different power ratings of the EV charger. The compressor for the gas filling station will be equal in all scenarios. Different grid connections will be evaluated for each load scenario. There are several ways to connect the load to the grid. One way is to connect the cables to the nearest distribution substation, which is marked *N0520* in Figure 15. The cables for the compressor and the charging station will be placed in the same trench. Another solution is to build a new substation close to the EV charging station. There is a 22kV cable close to the site, as with a red line in the map. The new substation will serve both the compressor and the charging station.

Three load scenarios are investigated. Scenario 1 has a charging station rated 125kW. The load may be distributed on one outlet rated 125kW or two outlets rated 60kW each. The last alternative produce a total maximum load of 120kW, but the difference is considered so small that the alternatives are investigated as one scenario.

Scenario 2 has an EV charging station rated 250kW. The charging station can consist of four outlets rated 60kW or two outlets rated 125kW. Scenario 3 has an EV charging station rated 500kW. The load consists of four 125kW outlets.

Five load cases are studied. In case 1, 2 and 3 the maximum load occurs at the same time on all delivery points. Case 1 uses load scenario 1, case 2 uses scenario 2 and case 3 uses scenario 3. Case 4 and 5 includes load control. This control makes sure that the compressor is turned off when the EV charging station is at full load. The analysis is made with full load at the charging station and no load at the compressor. Case 4 uses load scenario 2, and case 5 uses load scenario 3.

Table 5: Overview of Load Cases

Case	Scenario			Load Control	Load at Transformer		
	1: 125kW EV Load	2: 250kW EV Load	3: 500kW EV Load		P (kW)	Q (kVAr)	S (kVA)
1	X			No	641	372	741
2		X		No	766	413	870
3			X	No	1016	495	1130
4		X		Yes	646	359	739
5			X	Yes	896	441	999

7.3 Load Flow Analysis

The load flow analysis was made in Powel Netbas. Lyse shared a mesh file containing the distribution grid close to Lura transformer station that was used in the analysis. Different load cases were established. They included different power ratings for the EV charger. For each load case many system solutions for grid connection were analysed. Different number of cables in parallel to the EV charging station and the compressor was investigated. The existing transformer rated 630kVA was used in the simplest solutions. Other solutions involved changing the transformer to another with higher power rating. Solutions that involved building a new distribution substation were included as well. Each solution consists of a unique combination of cable dimensions and transformer power rating.

A load flow was run for each solution. The results from each load flow involved voltage, losses and loading of each component. The tap changer position was adjusted so that the voltage at the low voltage bus bar was as close to 400V as possible. The solution was considered invalid if any of the values exceeded the restrictions given at page 30. The valid solutions for each case were compared economically. A program called Dynko was used for the economic analysis. Investment costs and cost of losses were included in the analysis. The economic data was collected from the network planning catalogue [11]. The technical and the economical analyses were carried out at the same time so that all relevant solutions were considered. The solutions that only use the existing distribution substation are described first. Later, solutions that investigate the opportunity of building a new distribution substation close to the EV charger will be investigated.

7.3.1 Solutions Using the Existing Distribution Substation

The solutions that are considered in this section all make use of the existing substation, which is marked *N0520* in Figure 15. The electric configuration is displayed in the figure below.

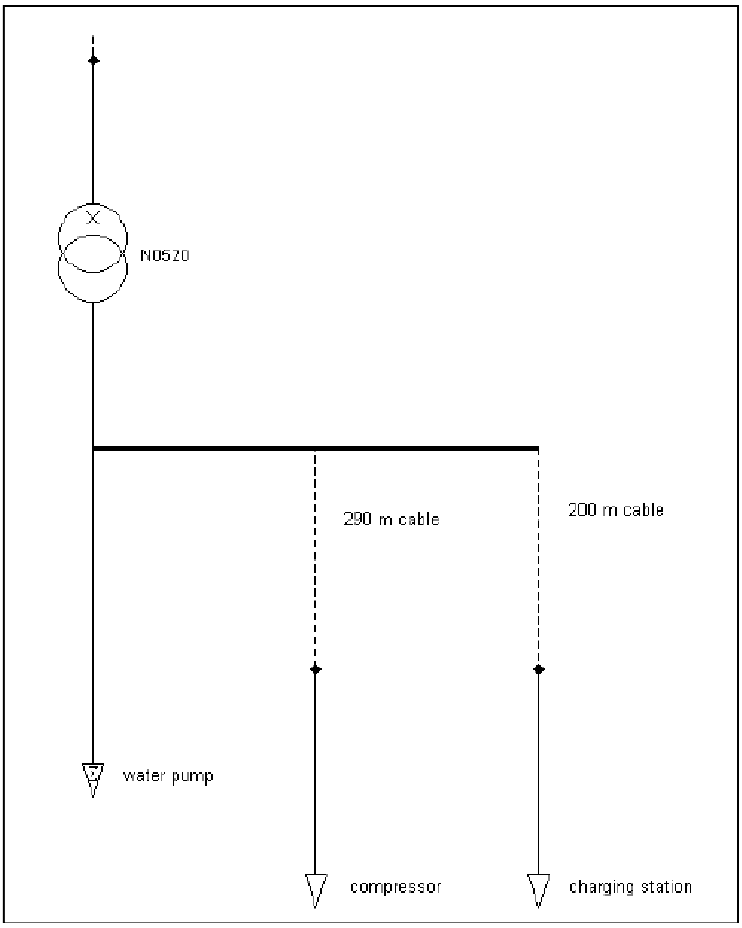

Figure 22: Electric Configuration

The cables for the compressor and the charging station will be placed in the same trench. The solutions contain different number of cables in parallel for the EV charging station and the compressor. Some solutions include the existing transformer rated 630kVA. In other solutions, the transformer is replaced by another with higher power rating. The water pump is the existing load at the transformer. It is connected directly to the low voltage side of the transformer. This load will be equal in all load scenarios.

The costs considered in the analysis are:

- 290m trench and cables for the compressor
- 200m cables for the EV charging station
- No-load losses for the transformer during the period of analysis
- Possible investment in new transformer

Prices are adjusted to 2010 price level using the consumer price index given in Table 42.

7.3.1.1 Load Case 1

This case contains the smallest EV charger that is considered in the analysis. The EV charger is rated 125kW. The maximum load on the transformer is 741kVA. The technical solutions that were considered are given in the table below.

Table 6: Load Flow Results for Case 1

Solution	Transformer Rating (kVA)	EV Cables	Compressor Cables	Transformer Loading (%)	EV Cable Loading (%)	Compressor Cable Loading (%)	Losses (kW)
1	630	1	2	124	52	26	14.04
2	630	2	2	124	26	26	12.52
3	630	3	2	124	17	26	12.04
4	630	2	1	124	26	53	14.81
5	630	2	3	124	26	17	11.79
6	800	2	2	96	25	26	10.55
7	1000	2	2	77	25	26	9.44
8	1250	2	2	61	25	26	7.82

Load flow analyses were carried out using Netbas. The results are displayed in the table above. The losses are the sum of losses in the transformer and the cables for the EV charger and the compressor. Several elements should draw the reader's attention. The loading of the transformer and the voltage is only dependent on the rating of the transformer. The number of cables for the loads does not matter. The loading of the cables is only dependent on the number of cables in parallel, not the transformer rating. Another element that should be noticed is the loading at the 630kVA transformer. The loading is 124%, which is close to the limit of 130%. This overloading might lead to overheating.

Economic analyses were carried out using Dynko. The program presents the results by ranking the solutions. The solution ranked as number 1 is the least costly solution, and is considered to be the economically optimal one. Each solution is given a score that represents the costs. The cost of each solution is compared to the cost of the optimal solution. The best solution gets score 100, and the other solutions get a score which is greater than 100.

The results from Dynko for case 1 are given in the in Figure 7. The economic analysis was only performed on a selection of the technical solutions. The least costly alternative is solution 2, which includes keeping the existing transformer and installing two cables in parallel to the EV charging station and the compressor. The second best alternative includes three cables in parallel to the EV chargers and two to the compressor. This gives a more robust solution at 1.9% higher costs.

Table 7: Economic Results for Case 1

Solution	Transformer Rating (kVA)	EV Cables	Compressor Cables	Ranking	Score
1	630	1	2	3	102.7
2	630	2	2	1	100.0
3	630	3	2	2	101.9
4	630	2	1	5	104.5
5	630	2	3	4	102.9
6	800	2	2	8	120.9
7	1000	2	2	7	117.6
8	1250	2	2	6	117.0

The optimal transformer rating is investigated in the table below. The existing transformer can still be used, which is the cheapest solution. If the transformer is to be replaced, a 1250kVA or a 1000kVA transformer is preferred. They are loaded 61% and 77% at maximum load. This will cost about 17% more over the period of analysis. The optimal transformer rating is displayed graphically in Figure 21. According to the graph, the optimal choice is an 800kVA transformer. The results from the two calculations are not consistent.

Table 8: Results on Transformers for Case 1

Transformer Rating (kVA)	Loading (%)	Score
630	124	100.0
800	96	120.9
1000	77	117.6
1250	61	117.0

Table 9 shows the solutions for the number of cables in parallel for the EV charger. The optimal number is two. The cables are loaded 26% at maximum load. Upgrading to a more robust solution with three cables in parallel will cost 2.8% more. The optimal cross section is displayed in Figure 18. The graphs give the same results as the simulation: 2x240mm^2 is the optimal cross section.

Table 9: Results on EV Cables for Case 1

EV Cables	Loading (%)	Score
1	52	102.7
2	26	100.0
3	17	101.9

Table 10: Results on Compressor Cables for Case 1

Compressor Cables	Loading (%)	Score
1	53	104.5
2	26	100.0
3	17	102.9

Table 10 shows the economic results for the number of cables in parallel to the compressor. The optimal number is two. The load at the compressor and the EV charging station are almost equal in this load case. The cable lengths are a little different. The optimal cross section is only dependent on the load, not the length of the cable. This results in an equal optimal cross section for the compressor and the EV charger in this load case. The loading at the optimal cross section is 26%, which is consistent with the results for the EV charging station and with the graph in Figure 18. In further analysis, the compressor will always be connected with two cables in parallel.

7.3.1.2 Load Case 2

This load case consists of is load scenario 2 with maximum load at all delivery points. The load at the transformer is 870kVA. The EV charging station is rated 250kW. Many different solutions were analysed. The results were used to draw general conclusions on the dimensioning of cables and transformers. The conclusions were useful when investigating the other load cases to limit the number of solutions. The results from the load flow analysis are displayed in the table below. Only a selection of the solutions is displayed here.

Table 11: Load Flow Results for Case 2

Solution	Transformer Rating (kVA)	EV Cables	Transformer Loading (%)	EV cable Loading	Voltage Drop (%)	Voltage (V)	Losses (kW)
1	630	1	148	108	6.29	394.7	27.06
2	630	3	147	36	2.86	394.9	18.28
3	630	5	146	21	2.20	394.9	16.67
4	800	3	114	34	1.39	400.7	15.39
5	1000	2	91	52	1.56	400.8	15.81
6	1000	3	91	34	1.38	400.8	13.83
7	1000	4	91	26	1.54	400.8	12.85
8	1250	2	72	52	2.10	401.1	13.31
9	1250	3	72	34	1.29	401.1	11.33
10	1250	4	72	26	0.89	401.1	10.39
11	1250	5	72	20	0.65	401.1	9.83
12	1600	3	56	34	1.23	402.3	11.06
13	1600	4	56	26	0.59	402.3	10.08

Several elements in the results are of interest. The existing transformer rated 630kVA is overloaded by more than 30%. A new transformer has to be installed. The solutions that involve the existing transformer will not be considered in the further analysis. The first solution includes only one cable for the EV charging station. The cable is overloaded by 8%. All solutions including one cable for the EV charging station are invalid and are not considered in the further analysis. Another important element is the voltage drop. The voltage drop is the difference between the system voltage and the voltage at the delivery point of the EV charging station. The largest voltage drop in Table 11 is 6.29%, which is lower than the limit of 8%. All other solutions have a smaller voltage drop and are well within the limits.

Table 12: Economic Results for Case 2

Solution	Transformer Rating (kVA)	EV Cables	Ranking	Score
4	800	3	10	106.2
5	1000	2	9	106.1
6	1000	3	4	102.6
7	1000	4	5	102.7
8	1250	2	6	103.5
9	1250	3	1	100.0
10	1250	4	2	100.1
11	1250	5	3	101.1
12	1600	3	8	104.0
13	1600	4	7	103.8

Only the valid solutions were analysed economically. The results are displayed in the table above. The least costly solution is number 9, which includes a transformer rated 1250kVA and three cables in parallel for the EV charging station. The second best solution is number 10, which includes the 1250kVA transformer and four cables in parallel for the EV charger. This solution costs 0.1% more, so the two solutions can be considered economically equal. Summaries of the results are given in the following tables.

Table 13: Results on Transformers for Case 2

Transformer Rating (kVA)	Loading (%)	Score
800	114	106.2
1000	91	102.6
1250	72	100.0
1600	56	104.0

The table above shows the results for the different transformer ratings. The optimal solution includes a 1250kVA transformer, which is loaded 72% at maximum load. The second best solution is a 1000kVA transformer, which will cost 2.6% more over the period of analysis.

According to the graph in Figure 21, the optimal transformer is an 800kVA transformer. The results from the two calculations are not consistent.

The table below displays the score for different number of EV cables. Three cables in parallel is the cheapest solution, followed closely by four cables. The other solutions are more expensive. Both cables are loaded around 30% at maximum load. The graph in Figure 18 shows that the optimal cross section for 250kW load is 4x240mm^2, while the simulation shows 3x240mm^2. The difference in cost between 3 and 4 cables in parallel is small in both the simulation results and the graph.

Table 14: Results on EV Cables for Case 2

EV Cables	Loading (%)	Score
2	52	103.5
3	34	100.0
4	26	100.1
5	20	101.1

7.3.1.3 Load Case 3

This case has the highest load which is investigated in this analysis. The EV charging station is rated 500kW. The load at the transformer is 1130kVA at maximum load. The results from the load flow analysis are given in the table below. Only a selection of the analysis performed is given here.

Table 15: Load Flow Results for Case 3

Solution	Transformer Rating (kVA)	EV Cables	Transformer Loading (%)	Cable Loading (%)	Losses (kW)
1	800	7	149	30	24.37
2	1000	2	121	107	40.05
3	1000	6	119	35	22.81
4	1000	7	119	30	21.66
5	1000	8	119	26	20.80
6	1250	5	94	41	19.75
7	1250	6	94	34	18.18
8	1250	7	94	30	17.03
9	1250	8	94	26	16.25
10	1250	9	94	23	15.59
11	1600	6	73	34	17.44
12	1600	7	73	29	16.36
13	1600	8	73	26	15.50

By looking at the load flow results it should be noticed that solution 1 and 2 are invalid. Solution 1 exceeds the limit for transformer loading, and solution 2 exceeds the limit for cable loading. The other solutions show that the loading at the transformer and the cables are independent.

Table 16: Economic Results for Case 3

Solution	Transformer Rating (%)	EV Cables	Ranking	Score
3	1000	6	11	109.3
4	1000	7	9	108.8
5	1000	8	10	108.8
6	1250	5	8	102.8
7	1250	6	3	100.8
8	1250	7	1	100.0
9	1250	8	2	100.6
10	1250	9	4	101.3
11	1600	6	7	102.7
12	1600	7	5	102.4
13	1600	8	6	102.5

The table above shows the results from Dynko for the technically valid solutions for case 3. The best solution is number 8, which includes the 1250kVA transformer and 7 cables in parallel for the EV charger. Solution 7 and 9 cost 0.6 and 0.8% more and can be considered equal to solution 7.

Table 17: Results on Transformer for Case 3

Transformer Rating (kVA)	Loading (%)	Score
1000	119	108.8
1250	94	100.0
1600	73	102.4

The table above shows the economic results for the transformers on case 3. The least costly solution includes the 1250kVA transformer, which is loaded 94%. The 1600kVA transformer is loaded 73% and the cost over the period of analysis is 2.4% higher that the 1250kVA transformer. The 1000kVA transformer is loaded 119% and the cost is 8.8% higher. The optimal transformer for 1130kVA load in Figure 21 is rated 1250kVA.

Table 18 compares the different cable alternatives for the EV charger. The least costly alternative is 7 cables in parallel. This cable is loaded 30%. The solutions that include 6 or 8 cables are almost equal in costs. These cables are loaded 34 or 26%. It seems that the optimal loading of cables is in the span 25-35%. The optimal cross section for a 500kW load is displayed in Figure 19. The results are consistent with the Dynko simulation.

Table 18: Results on EV Cables for Case 3

EV Cables	Loading (%)	Score
5	41	102.8
6	34	100.8
7	30	100.0
8	26	100.6
9	23	101.3

7.3.1.4 Load Case 4

This case includes load control. The control limits the maximum load. The compressor will not start if the EV charging station is at maximum load. The maximum load at the transformer in this load case is 739kVA. The charging station is expected to be little in use for the first 10 years after installation. The load control will most likely not bother the users of neither the gas filling station nor the EV charger. Case 4 is load scenario 2 with load control. The EV charger is rated 250kW.

Table 19: Load Flow Results for Case 4

Solution	Transformer Rating (kVA)	EV Cables	Transformer Loading (%)	EV Cable Loading (%)	Losses (kW)
1	630	3	124	34	12.75
2	630	4	123	26	11.78
3	630	5	123	21	11.21
4	800	4	96	25	9.83
5	1000	4	77	25	8.73
6	1250	4	61	25	7.13
7	1600	4	47	25	7.01

The table above shows the results from the load flow analysis on case 4. When load control is introduced, the existing transformer rated 630kVA does not need replacement. The transformer is loaded 123%, which is close to the overloading limit at 130%.

Table 20: Economic Results for Case 4

Solution	Transformer Rating (kVA)	EV Cables	Ranking	Score
1	630	3	2	100.5
2	630	4	1	100.0
3	630	5	3	101.8
4	800	4	6	126.0
5	1000	4	4	122.5
6	1250	4	5	123.2
7	1600	4	7	130.7

The economic results in Table 20 show that the optimal solution is to keep the existing transformer and install 4 cables in parallel to the EV charger. The second best solution includes 3 cables in parallel. The difference in cost between the two is small, only 0.5%. If the transformer is to be upgraded, the cost increases by almost 22.5%.

Table 21: Results on Transformers for Case 4

Transformer Rating (kVA)	Loading (%)	Score
630	123	100.0
800	96	126.0
1000	77	122.5
1250	61	123.2
1600	47	130.7

The table above shows a summary of the technical and economical results for different transformer ratings on case 4. It is technically possible to keep the existing transformer rated 630kVA. This solution has a significant lower cost than the other alternatives and is preferred. Out of the other solutions, the least costly one is the transformer rated 1000kVA. It is loaded 77% at maximum load. In the graphical representation in Figure 21, the optimal transformer at 740kVA load is rated 800kVA.

Table 22: Results on EV Cables for Case 4

EV Cables	Loading (%)	Score
3	34	100.5
4	26	100.0
5	21	101.8

The table above displays the alternatives for the number of cables in parallel to the EV charger. The least costly solution is four cables in parallel closely followed by three cables. Four cables in parallel are more robust than three cables and is the preferred solution. The cables are loaded 26%.

7.3.1.5 Load Case 5

This load case uses load scenario 3 with load control. The EV charging is rated 500kW. The maximum load at the transformer is 999kVA. The table below shows the results from the load flow analysis. The weakest solution includes an 800kVA transformer. This solution exceeds the limit of 130% overload and is invalid.

Table 23: Load Flow Results for Case 5

Solution	Transformer Rating (kVA)	EV Cables	Transformer Loading (%)	EV Cable Loading (%)	Losses (kW)
1	800	7	131	29	18.81
2	1000	7	105	29	16.74
3	1250	6	83	34	14.43
4	1250	7	83	29	13.34
5	1250	8	83	26	12.48
6	1600	7	64	29	12.83

Table 24: Economic Results for Case 5

Solution	Transformer Rating (kVA)	EV Cables	Ranking	Score
2	1000	7	5	105.5
3	1250	6	3	100.6
4	1250	7	1	100.0
5	1250	8	2	100.4
6	1600	7	4	103.0

The table above displays the results from the economic analysis of the valid solutions. The optimal solution includes a 1250kVA transformer and 7 cables in parallel for the EV charging station. The solutions that include the same transformer and 6 or 8 cables in parallel are almost equal in cost. The existing transformer has to be replaced. All the solutions that are considered are quite equal considering the costs.

Table 25: Results on Transformers for Case 5

Transformer Rating (kVA)	Loading (%)	Score
1000	105	105.5
1250	83	100.0
1600	64	103.0

The table above displays the different transformer alternatives for case 5. The preferred solution is a 1250kVA transformer, which is loaded 83%. A 1600kVA transformer will only cost 3% more over the period of analysis. This is a more robust alternative. The optimal loading of the transformer is 94% in this load case. The simulation results fit well with the graph in Figure 21. According to the graph, the optimal transformer for 1000kVA load is rated 1250kVA.

Table 26 shows the different cable alternatives for case 5. The preferred alternative is 7 cables in parallel. 6 or 8 cables give almost the same cost, 0.4 and 0.6% more. The preferred alternative is loaded 29%.

Table 26: Results on EV Cables for Case 5

EV Cables	Loading (%)	Score
6	34	100.6
7	29	100.0
8	26	100.4

7.3.1.6 Summary

Load case 1 to 5 is analysed both technically and economically in the previous sections. The economic analysis includes both investment costs and cost of losses over the period of analysis of 25 years. The connection between the loading of the components and the total cost in the period of analysis is investigated. The optimal number of 240mm^2 Al cables in parallel for the EV charger and the compressor was analysed. By comparing Table 9, Table 10, Table 14, Table 18, Table 22 and Table 26 it is evident that the optimal cable loading is in the range 26-34%. The solution where the cable loading is closest to 30% is the optimal solution. The results from the Dynko analysis are consistent with the theoretical optimal cross section displayed in Figure 18 and Figure 19.

The optimal transformer rating was investigated. The results for case 1 and 4 are given in Table 8 and Table 13. In these two cases it is technically possible to keep the existing transformer rated 630kVA. The investment costs of a new transformer are avoided, and this is the economically optimal solution. The results from case 2, 3 and 5 are displayed in Table 13, Table 17 and Table 25. The loading at the optimal transformer varies from 72% to 94%. In all the three cases, the cost of the second best transformer is less than 3% higher than the optimal solution. These solutions can be considered close to equal to the optimal solutions. The transformer loading at these six solutions varies from 64% to 94%, and the average is 79.5%.

In load case 3 and 5, the results of the analysis fits well with the graph displayed in Figure 21. In load case 1, 2 and 4, the results from the two analyses are not consistent. It seems as the analysis and the graph give the same results for the largest loads. The results from Dynko seem to favour the 1250kVA transformer, while the graphical representation favours the 800kVA transformer.

7.3.2 Solutions Including a New Distribution Substation

The option to build a new distribution substation close to the EV chargers was analysed. For each case, the best solution from the previous analysis was compared to different solutions that involved a new substation.

The new distribution substation will be installed close to the green X in Figure 15. The EV station and the compressor will be located at the same places as earlier. The substation will be connected to the existing 22kV cable, which is marked with a red line at the map. The substation is detached and air isolated. The trench from substation N0520 is then unnecessary. A 90m trench from the new substation to the compressor will be needed. The existing transformer in substation N0520 will stay unchanged. It's only load will be the water pumps, just as it is today. The new electric configuration is displayed in the figure below.

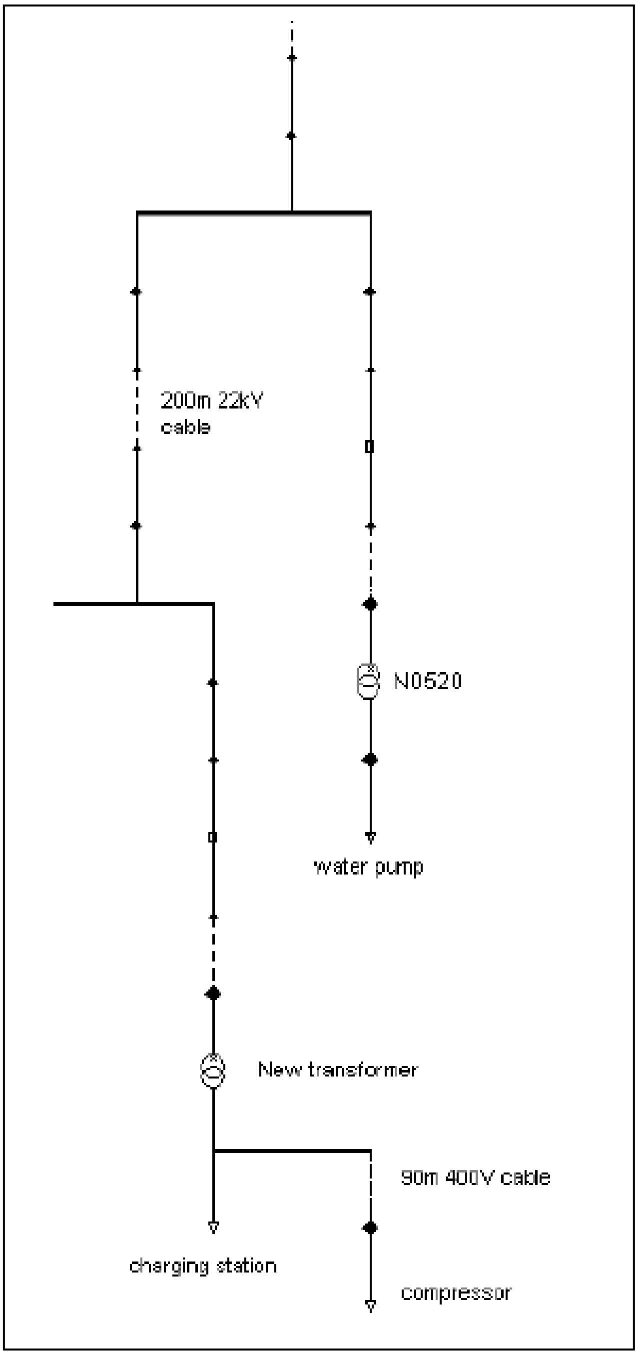

Figure 23: Electric configuration including a new distribution substation

The costs considered in solutions using the new substation are:

- Investment of new transformer. Given in Table 38.
- Investment and installation of the distribution substation. Given in Table 37.
- Connecting the new transformer to the existing 22kV cable. Costs NOK 35000.
- 90m trench and cables for the compressor. Given in Table 36.

Prices are adjusted to 2010 price level using the consumer price index given in Table 42.

7.3.2.1 Load Case 1

This load case uses load scenario 1, which includes a 125kW EV charger. The load at a transformer that only serves the EV charger and the compressor will be 263kVA.

Table 27: Load Flow Results for Case 1

Solution	New Substation?	Transformer Rating (%)	EV Cables	Compressor Cables	Transformer Loading (%)	Compressor Cable Loading (%)	Losses (kW)
1	No	630	2x200m	2x290m	124	26	12.52
2	Yes	315	-	2x90m	86	25	7.66
3	Yes	500	-	2x90m	54	25	6.79
4	Yes	630	-	2x90m	43	25	6.67

Table 28: Economic Results for Case 1

Solution	New Substation?	Transformer Rating (kVA)	EV Cables	Compressor Cables	Ranking	Score
1	No	630	2x200m	2x290m	1	100.0
2	Yes	315	-	2x90m	2	101.3
3	Yes	500	-	2x90m	3	104.6
4	Yes	630	-	2x90m	4	108.9

The optimal solution is to keep the existing transformer in the existing substation. The investment costs for this solution are low because no new transformer has to be purchased. However, the losses are almost double compared to the solutions that involve a new substation. The solution that includes a new 315kVA transformer costs only 1.3% more over the period of analysis of 25 years. Considering the large reduction in losses, this solution should be considered when building the charging station.

7.3.2.2 Load Case 2

This load case includes load scenario 2. At maximum load, a transformer serving the EV chargers and the compressor will be loaded with 395kVA.

Table 29: Load Flow Results for Case 2

Solution	New Substation?	Transformer Rating (kVA)	EV Cables	Compressor Cables	Transformer Loading (%)	Compressor Cable Loading (%)	Losses (kW)
1	No	1250	3x200m	2x290m	72	26	11.33
2	Yes	500	-	2x90m	81	25	8.23
3	Yes	630	-	2x90m	64	25	7.91
4	Yes	800	-	2x90m	50	25	7.48

Table 30: Economic Results for Case 2

Solution	New Substation?	Transformer Rating (kVA)	EV Cables	Compressor Cables	Ranking	Score
1	No	1250	3x200m	2x290m	4	131.3
2	Yes	500	-	2x90m	1	100.0
3	Yes	630	-	2x90m	2	103.0
4	Yes	800	-	2x90m	3	105.9

The optimal solution is to build a new substation close to the EV charging station. The solution that includes using the existing substation with a new transformer costs 31.3% more over the period of analysis. The new transformer should be rated 500kVA. The results from Dynko fit well with the graph in Figure 20.

7.3.2.3 Load Case 3

This load case uses load scenario 3, which gives it the largest load. The maximum load at a transformer serving only the EV charging station and the compressor is 658kVA.

Table 31: Load Flow Results for Case 3

Solution	New Substation?	Transformer Rating (kVA)	EV Cables	Compressor Cables	Transformer Loading (%)	Losses (kW)
1	No	1250	7x200	2x290m	94	17.03
2	Yes	630	-	2x90m	108	11.94
3	Yes	800	-	2x90m	84	10.40
4	Yes	1000	-	2x90m	67	9.60
5	Yes	1250	-	2x90m	54	8.59

The optimal solution is to build a new substation with a transformer rated 1000kVA. The solution that includes an 800kVA transformer costs about the same. In the graphical representation in Figure 20, the optimal transformer is rated 800kVA. If the existing substation is used, the costs over the period of analysis increase by 33%.

Table 32: Economic Results for Case 3

Solution	New Substation?	Transformer Rating (kVA)	EV Cables	Compressor Cables	Ranking	Score
1	No	1250	7x200	2x290m	5	133.0
2	Yes	630	-	2x90m	4	103.2
3	Yes	800	-	2x90m	2	101.2
4	Yes	1000	-	2x90m	1	100.0
5	Yes	1250	-	2x90m	3	101.8

7.3.2.4 Load Case 4

This load case is scenario 2 with load control. The control makes sure that the compressor is turned off when the EV charger is at full load. The load flow is made with the EV charger at full load and the compressor at no load. The load at the transformer at the new substation is 263kVA.

Table 33: Results for Case 4

Solution	New Sub-station?	Trans-former Rating (kVA)	EV Cables	Trans-former Loading (%)	Losses (kW)	Ranking	Score
1	No	630	4x200m	123	11.78	3	108.1
2	Yes	315	-	86	7.02	1	100.0
3	Yes	500	-	53	6.20	2	105.4

In the previous analysis, the optimal solution for case 4 was to keep the existing transformer rated 630kVA. From the table above one can see that the costs are lower if a new substation is built close to the EV charging station. If the existing transformer is used, the costs increase by 8.1%. The losses are almost double if the existing substation is used compared to the optimal solution. The optimal transformer is rated 315kVA. This corresponds to the optimal transformer in Figure 20.

7.3.2.5 Load Case 5

The load in this case is scenario 3 with load control. The load flow is run with full load at the EV charging station and no load at the compressor. The loading at the new transformer is 526kVA. Table 34 displays the results. In the pervious section, the optimal solution included a 1250kVA transformer and 7 cables for the EV charger. In this analysis, the optimal solution is to build a new substation with a transformer rated 500kVA. Several solutions are almost equal in costs. The results correspond to the graphical representation in Figure 20. The graph shows that the cost of transformers rated 500, 630 and 800kVA cost about the same at this load. The solution that involves using the existing substation has a 46.2% higher cost than the optimal solution.

Table 34: Results for Case 5

Solution	New Sub-station?	Trans-former Rating (kVA)	EV Cables	Trans-former Loading (%)	Losses (kW)	Ranking	Score
1	No	1250	7x200m	83	13.34	5	146.2
2	Yes	500	-	108	9.67	1	100.0
3	Yes	630	-	86	9.12	2	101.6
4	Yes	800	-	67	8.13	3	101.9
5	Yes	1000	-	54	7.63	4	101.9

7.3.2.6 Summary

The five load cases were investigated in this section. In four of the cases, the optimal solution involved installing a new substation close to the EV charging station. Compared to the results from the previous section, the losses were reduced by up to 50%. Solutions that involve lower losses are more energy efficient and can be considered the more environmentally friendly alternative.

The optimal loading of the transformer is close to the results from the previous section. The average loading of the transformer for the solutions that have a score lower than 103 at case 2, 3, 4 and 5 is 76%. The transformer loading of these solutions spreads from 54% to 108%. It seems that the transformer rating has little influence on the total costs over the period of analysis. The results from Dynko fit well with the graphical representation of transformer costs in Figure 20.

7.3.3 Other Charging Alternatives

EV chargers with lower power ratings will be evaluated. Level 2 chargers using singe phase 230V can be used. The power rating is less than 10kW. Small DC chargers with power rating around 30kW are also evaluated. There are many manufacturers that deliver chargers in this power range. The charging time will be significantly longer. The best location of public slow chargers is probably not at a petrol station, but rather shopping centres or other places where people are occupied while the vehicle charges.

The load case will be similar to case 1, with a smaller EV charger. The optimal solution in case 1 is to use the existing substation with the transformer rated 630kVA. When connecting an even smaller EV charging station, a new substation does not need to be built. The number of cables in parallel for the EV charging station should be chosen so that the maximum loading is around 30%.

7.3.4 High Voltage Distribution Grid

The 22kV cable going to Lura transformer station was investigated in load case 3. This load case has the largest load that was analysed in this project. Load flow analysis was made to look at the 22kV cable connection to Lura transformer station. At maximum load the cable is loaded 37% and carries 136A. The losses are 9.28kW, which is 0.18% of the power. Throughout the year, the losses are 21.658MWh, which is 0.094% of the energy consumed. The loading of the cable is acceptable. It is not necessary to do improvements in the high voltage distribution grid when connecting the new load.

7.3.5 Utilisation Time of Losses

The utilisation time of losses is set to 2400h/year in the Dynko analysis, which is the standard value used in Table 39. The utilisation time of losses was investigated for the optimal solution of case 1 and case 3 using Powel Netbas. The same load variation was used for the compressor and the EV charging station. The load was constant over the year and did not vary according to temperature. The daily load pattern is given in the table below.

Table 35: Daily Load Pattern for Charging Station and Compressor, Percentage of Maximum Load

Hour	Week-day	Week-end	Hour	Week-day	Week-end
1	0	25	**13**	25	50
2	0	25	**14**	25	50
3	0	0	**15**	25	50
4	0	0	**16**	25	50
5	0	0	**17**	100	25
6	0	0	**18**	25	25
7	0	0	**19**	25	25
8	25	0	**20**	25	25
9	100	0	**21**	25	25
10	25	25	**22**	25	25
11	25	25	**23**	25	25
12	25	25	**24**	0	25

For case 1, the utilisation time of load was 3966h/year, and the utilisation time of losses was 2438h/year. The value is close to the value used in the analysis, and no adjustments need to be made.

For case 3, the utilisation time of load was 3105h/year, and the utilisation time of losses was 3996h/year. The utilisation time is expected to be higher for the load than for the losses. The high value may be caused by the low loading of the transformer, which is 67% at maximum load. The no-load losses are dominating during low load conditions. The utilisation time of the no-load losses is close to 8760h/year. The daily load pattern which is used in the analysis is based on an expected use pattern, and the information is not certain. Considering the uncertainty, the standard utilisation time of losses is used in the analysis.

7.4 Quality of Supply

The power quality was investigated for the optimal solution of case 1 and case 3. Case 1 is the only load case where the optimal solution includes the existing substation and a long cable for the load. Case 3 has the largest load, and the load is connected close to the transformer. Three phenomena were investigated: supply voltage variations, rapid voltage changes and harmonic voltage. The phenomena are described in Table 3.

7.4.1 Supply Voltage Variations

For case 1, the voltage is 397.5V when the load is at maximum and 415.1V when there is no load. Both voltages have less than 10% deviation from the system voltage, which is 400V. For case 3, the maximum voltage is 409.5V and the minimum voltage is 404.5%. Both voltages are within the limits of ±10% of the system voltage. Neither of the cases exceeds the limits of supply voltage variations.

7.4.2 Rapid Voltage Changes

This phenomenon consists of rapid variations of the r.m.s. value of the voltage. Variations larger than 3% of the system voltage can not occur more often than 24 times a day. In the system analysed here, a rapid voltage change can be caused by a rapid load increase or decrease of the EV charging station. The voltage at the low voltage side of the transformer was investigated for different loads. The largest voltage change occurs when there is maximum load at all delivery points, and the EV charging station is turned off suddenly. For case 1, this change is 0.6%. For case 3, the change is 1.0%. The limits are not exceeded in any of the load cases.

7.4.3 Harmonic Voltage

No detailed information about the harmonic currents from the EV chargers was obtained. Approximation of the harmonic voltage was made through calculations. The equations are given in formulas (14) to (17). The worst case was considered to calculate the maximum harmonic voltage. It was assumed that the EV charger is a 6-pulse rectifier without filtering.

For case 1, the minimum short circuit capacity at the connection point of the EV charging station is 5.255MVA. The 5th and 7th harmonic voltage was calculated, which are the dominating harmonics from a 6-pulse rectifier. The current was calculated from formula (15). This gives the largest possible current. The first harmonic current is 97A in each cable. As there are two cables, the total fundamental current is 194A. Using formula (14), the harmonic voltage is calculated to 5.908V for both the 5th and the 7th harmonic. This is 1.48% of the system voltage. The limits given in Table 46 are 6% for the 5th harmonic and 5% for the 7th harmonic. The voltages are well within the limits.

For case 3, the minimum short circuit capacity is 11.006MVA at the connection point of the EV chargers. The fundamental current drawn by the chargers is 749A. The harmonic voltages for the 5th and the 7th harmonic are both 2.78% of the system voltage. The restrictions are fulfilled.

7.4.4 Summary

Three phenomena were investigated for load case 1 and 3. These two cases are expected to have the worst quality of supply out of the five load cases. The worst cases were considered. All values were within the regulations.

8 Discussion

The discussion addresses the three main topics of the analysis: optimal dimensioning of cables and transformers and fulfilment of Norwegian PQ regulations.

8.1 Optimal Cable Cross Section

In all load cases that were analysed, the optimal cable loading was in the range 26-34% at maximum load. The solution that includes cable loading closest to 30% is the optimal alternative. The results from the simulations fit well with the graphs in Figure 16 through Figure 19. The cost of upgrading the cross section is small in cases where the load is large. A larger cross section leads to lower current and lower losses. The temperature in the cables is reduced, which reduces the wear and tear of the isolation. A reduction of losses lowers the energy production, which gives less use of resources and minimises the environmental effects. A larger cross section is also favourable in cases where the load is expected to increase in the future.

The loading of the cable does only depend on the number of cables in parallel. The voltage and rating of the transformer have no impact in the analysis made in this project. The reason for this is that the voltage is very stiff at the point of connection.

The cable loading of the 22kV cable going to Lura transformer station is 37% at the heaviest load case. This is acceptable, and no adjustments need to be made on the high voltage distribution grid.

8.2 Optimal Transformer Power Rating

The loading on the transformer depends only on the load and of the rating of the transformer. The voltage variations for the different cable alternatives are too small to make an impact.

The first analysis does not consider the option to build a new distribution substation close to the load. The existing transformer fulfils the restrictions for the two cases with smallest power ratings. The overloading of the transformer is close to the limit of 30% and the losses are high. Still, it is economically optimal to keep the existing transformer. To install a larger transformer will increase the costs by around 20%.

In the other three load cases, the loading of the existing transformer exceeds the limit of overloading. The transformer is replaced by another with higher power rating. The loading at the optimal transformer varies from 72% to 94%. The difference in cost between the optimal and the second best transformer is low, less than 3% in all cases. When all solutions with a score lower or equal to 103 are included, the loading spans from 64% to 114%.

In the cost minimising program Dynko, there is a certain inaccuracy in the input data. Investments are entered in kNOK with one decimal while losses are entered in kW without decimals. To increase the accuracy, the input data was scaled up by a factor of 10. Still the losses are given with only two or three valid digits. This can be the source of the large variety in transformer loading of the optimal solutions. The variety of investment costs and losses are small for the different solutions. The inaccuracy in the program is possibly a reason for the variety in the results concerning the optimal transformer loading. Another limitation of the program is the period of analysis, which is set to maximum 25 years. The period of analysis used when making the general dimensioning graphs was 30 years.

The second analysis looked at the opportunity to build a new distribution substation close to the load. The optimal solution of the previous analysis was compared with different solutions for the new substation. This reduces the losses significantly. Especially for the large loads, a reduction of the losses improves the economy. Out of the five load cases that were analysed, only one case had an optimal solution that included using the existing substation. This case had the smallest load. Even for this case, the cost of installing a new substation was only 1.3% more expensive than to use the existing substation. Even if this solution costs a little bit more, it is the preferred solution. A new substation results in shorter cables and lower losses. The reduction in losses increases the efficiency and can be considered both a more robust alterative and better for the environment.

For the second smallest load case, the optimal solution is to build a new substation. The existing transformer does not exceed the loading limits, and may still be used. Even so, it is economically preferable to build a new substation. The investments are higher, but the losses are reduced significantly. For the last three load cases, it is preferable to build a new substation. The results from the analysis on transformer size fit well with the graph in Figure 20.

The size of a new distribution substation might be critical. There is limited space at the site. Dimensions of substations were not obtained in this project. Before choosing the solution for connection, the size and placement of a substation and the EV charging stations needs to be considered.

If the existing substation is used, a 290m long trench has to be dug to install the load. If the load is large, a new transformer with a higher power rating has to be purchased. When a new substation is built, the long trench is avoided. A new transformer has to be purchased, but it will be smaller and less costly than if a new transformer is installed in the existing substation. The investment costs might be larger when a new substation is built. However, the losses are much smaller. The reduced cost in losses compensate for the investment in the larger load cases.

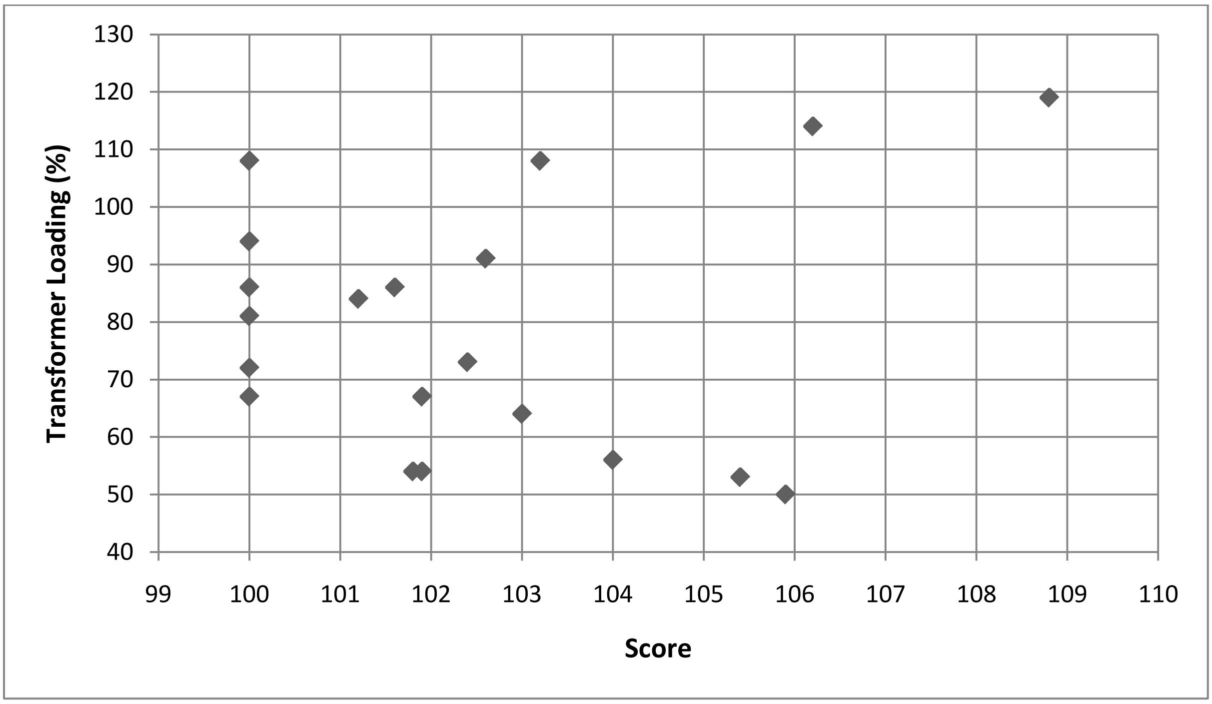

Figure 24: Variation in Optimal Transformer Loading

The scatter above describes the connection between the transformer loading and the economic score of the corresponding solution. The data included are from all load cases where a new transformer is installed. The loading of the optimal transformer spreads from 67 to 108%. The optimal transformer at different loads was also investigated in Figure 20 and Figure 21. The results from the analysis and the graphs correspond for loads less than 600kVA and larger than 900kVA. For loads between 600 and 900kVA, the results from Dynko suggest a larger transformer than the results displayed in the graphs. One difference between the two methods is the period of analysis. Dynko allows maximum 25 years in the period of analysis, while the graphs are based on capitalised values that use 30 years as the period of analysis.

8.3 Quality of Supply

An EV charging station is a large, nonlinear load. This might cause problems with the quality of supply. If the charger is suddenly turned on or off, it can cause rapid voltage variations. The nonlinear load can lead to harmonics in the network.

Three phenomena on quality of supply were investigated: supply voltage variations, rapid voltage variations and voltage harmonics. The two load cases that were expected to have the worst quality of supply were analysed. The voltage variations were investigated through load flow analysis. All values were within the limits given by the regulations. No detailed data was available for the EV charger, so the analysis was made with simple calculations. Simplifications were made so that the maximum harmonics were calculated. Still, the values were well within the limits of the regulations. The real harmonics are expected to be lower than what was calculated in this report.

The energy not supplied has not been investigated in this project. The network in the area around Luravika is mostly cables in the ground. These are well protected from elements like wind, birds and lightning. The energy not supplied is expected to be low.

9 Conclusions

A combined station for gas filling and vehicle charging will be built at Luravika in Sandnes. Two main solutions for grid connection were considered. The new load may be connected to the closest distribution substation or a new substation can be built close to the load. If the new load is less than 263kVA, the cheapest solution is to use to existing substation with the transformer rated 630kVA. Up to 290m long underground cables need to be installed. The losses are high and the installation is expensive. For larger loads, the cheapest alternative is to build a new distribution substation close to the new load. The long underground cables are avoided, and the losses are significantly lower.

When choosing cable cross section, investment and cost of losses need to be considered. The optimal choice is a cable which is loaded 30% at maximum load. The graphs in Figure 18 and Figure 19 may be used for dimensioning. The cost of overinvesting in cables is low. By choosing a larger cross section, the losses are reduced and the system gets more robust.

When deciding which transformer to install, investment and cost of copper losses and no-load losses need to be considered. Table 4 may be used for dimensioning. The table is based on the graphs in Figure 20 and Figure 21, and suggests transformer sizes for different loads. The results from the analysis correspond to the table when the load is smaller than 600kVA or larger than 900kVA. For loads in between 600 and 900kVA, the economic analysis suggests a larger transformer than what is suggested in the table. The results from the detailed analysis give a large variety in optimal transformer loading. The average maximum loading of the optimal transformer alternative is in the range 75% to 80%.

The quality of supply was investigated. The phenomena supply voltage variations, rapid voltage variations and voltage harmonics were analysed. No values were close to the limits given in the Norwegian PQ code [9]. The high voltage distribution grid close to the new load was investigated. The 22kV cable connecting the substation to Lura transformer station is loaded 37% at maximum load. This value is acceptable, and no improvements need to be made.

10 Further Work

The charging station in Luravika will be built in the autumn 2010. This report contains the necessary results to make decisions on technical solutions and dimensioning of the grid connection. This report does also suggest general guidelines for dimensioning of components when connecting new load. The dimensioning guide can be improved and expanded.

More detailed information on load characteristics should be obtained. The information is useful for further analysis on power quality issues. An EV charger is a large nonlinear load which emits current harmonics to the grid. This can disturb neighbour loads. Power quality is of particular interest if the load is installed in weak grids i.e. in rural areas. Benefits from intelligent load control and means to improve the reliability of supply should also be considered.

The previous analysis did not produce accurate cost estimates. Reliability of supply, CENS and maintenance costs were not included. The daily load pattern used in the analysis was not accurate. A more detailed pattern can be obtained by using data from other gas filling stations and EV chargers already installed in a similar environment. The data may be used for calculating utilisation time of load and losses. This information gives more accurate cost calculations.

11 References

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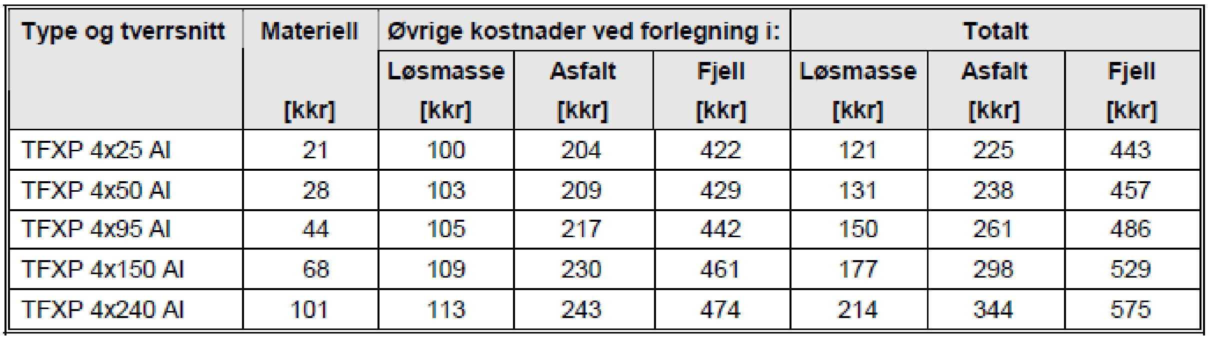
12 Appendices

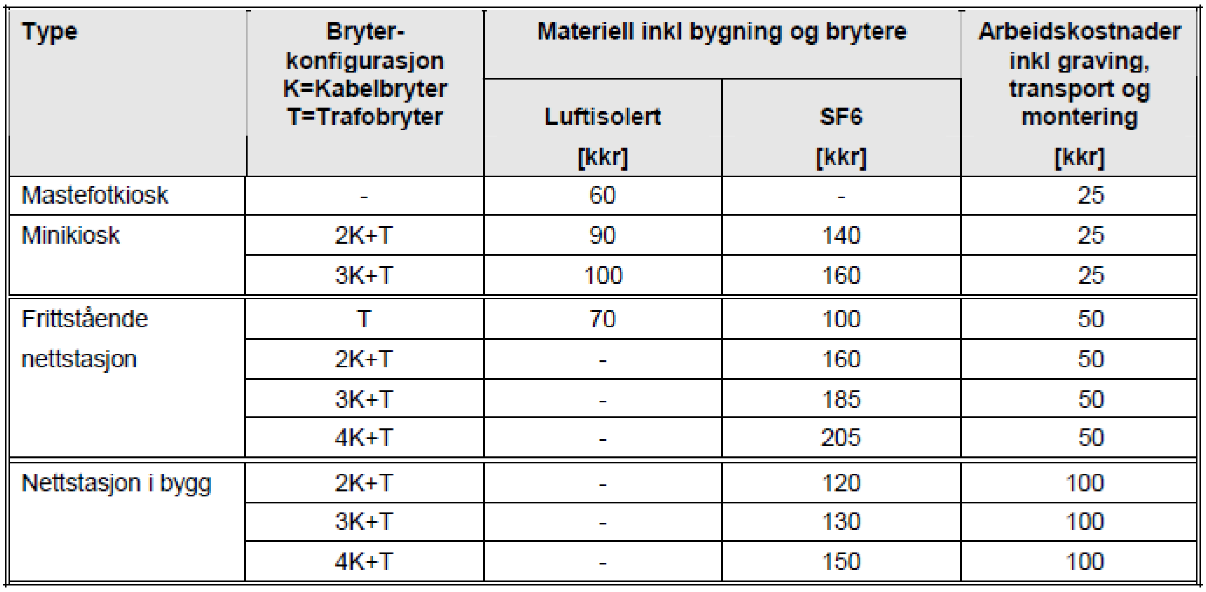
12.1 Cost Data for Components

Table 36: Cost for 1kV Earth Cable 4 Conductors without Screen per km [10]



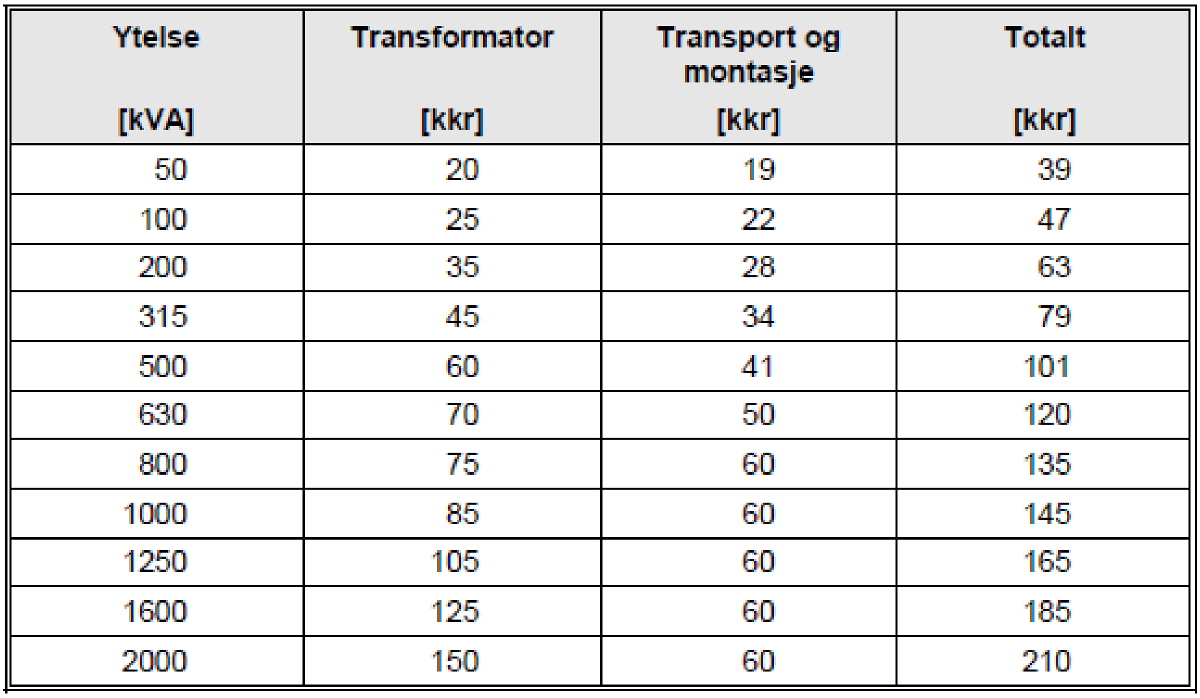
Type og tverrsnitt	Materiell	Øvrige kostnader ved forlegning i:			Totalt		
		Løsmasse	Asfalt	Fjell	Løsmasse	Asfalt	Fjell
	[kkr]	[kkr]	[kkr]	[kkr]	[kkr]	[kkr]	[kkr]
TFXP 4x25 Al	21	100	204	422	121	225	443
TFXP 4x50 Al	28	103	209	429	131	238	457
TFXP 4x95 Al	44	105	217	442	150	261	486
TFXP 4x150 Al	68	109	230	461	177	298	529
TFXP 4x240 Al	101	113	243	474	214	344	575

Table 37: Cost of Building Distribution Substations, Exclusive Transformer [10]



Type	Bryter-konfigurasjon K=Kabelbryter T=Trafobryter	Materiell inkl bygning og brytere		Arbeidskostnader inkl graving, transport og montering [kkr]
		Luftisolert [kkr]	SF6 [kkr]	
Mastefotkiosk	-	60	-	25
Minikiosk	2K+T	90	140	25
	3K+T	100	160	25
Frittstående nettstasjon	T	70	100	50
	2K+T	-	160	50
	3K+T	-	185	50
	4K+T	-	205	50
Nettstasjon i bygg	2K+T	-	120	100
	3K+T	-	130	100
	4K+T	-	150	100

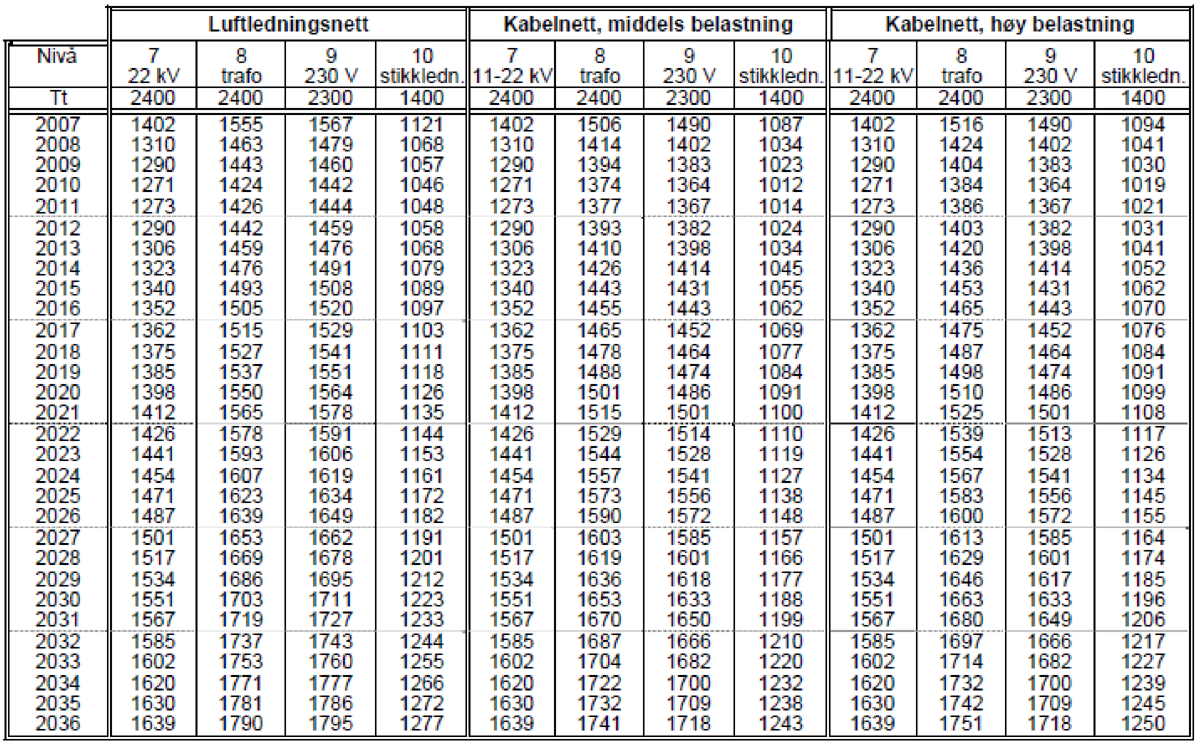
Table 38: Cost of Distribution Transformers and Installation [10]



Ytelse [kVA]	Transformator [kkr]	Transport og montasje [kkr]	Totalt [kkr]
50	20	19	39
100	25	22	47
200	35	28	63
315	45	34	79
500	60	41	101
630	70	50	120
800	75	60	135
1000	85	60	145
1250	105	60	165
1600	125	60	185
2000	150	60	210

12.2 Cost of Losses

Table 39: Equivalent Annual Cost of Losses k_{pekv} (NOK/kW,yr). 4.5% Calculation Interest. Cost Level 2006. [10]



	Luftledningsnett				Kabelnett, middels belastning				Kabelnett, høy belastning			
Nivå	7 22 kV	8 trafo	9 230 V	10 stikkledn.	7 11-22 kV	8 trafo	9 230 V	10 stikkledn.	7 11-22 kV	8 trafo	9 230 V	10 stikkledn.
Tt	2400	2400	2300	1400	2400	2400	2300	1400	2400	2400	2300	1400
2007	1402	1555	1567	1121	1402	1506	1490	1087	1402	1516	1490	1094
2008	1310	1463	1479	1068	1310	1414	1402	1034	1310	1424	1402	1041
2009	1290	1443	1460	1057	1290	1394	1383	1023	1290	1404	1383	1030
2010	1271	1424	1442	1046	1271	1374	1364	1012	1271	1384	1364	1019
2011	1273	1426	1444	1048	1273	1377	1367	1014	1273	1386	1367	1021
2012	1290	1442	1459	1058	1290	1393	1382	1024	1290	1403	1382	1031
2013	1306	1459	1476	1068	1306	1410	1398	1034	1306	1420	1398	1041
2014	1323	1476	1491	1079	1323	1426	1414	1045	1323	1436	1414	1052
2015	1340	1493	1508	1089	1340	1443	1431	1055	1340	1453	1431	1062
2016	1352	1505	1520	1097	1352	1455	1443	1062	1352	1465	1443	1070
2017	1362	1515	1529	1103	1362	1465	1452	1069	1362	1475	1452	1076
2018	1375	1527	1541	1111	1375	1478	1464	1077	1375	1487	1464	1084
2019	1385	1537	1551	1118	1385	1488	1474	1084	1385	1498	1474	1091
2020	1398	1550	1564	1126	1398	1501	1486	1091	1398	1510	1486	1099
2021	1412	1565	1578	1135	1412	1515	1501	1100	1412	1525	1501	1108
2022	1426	1578	1591	1144	1426	1529	1514	1110	1426	1539	1513	1117
2023	1441	1593	1606	1153	1441	1544	1528	1119	1441	1554	1528	1126
2024	1454	1607	1619	1161	1454	1557	1541	1127	1454	1567	1541	1134
2025	1471	1623	1634	1172	1471	1573	1556	1138	1471	1583	1556	1145
2026	1487	1639	1649	1182	1487	1590	1572	1148	1487	1600	1572	1155
2027	1501	1653	1662	1191	1501	1603	1585	1157	1501	1613	1585	1164
2028	1517	1669	1678	1201	1517	1619	1601	1166	1517	1629	1601	1174
2029	1534	1686	1695	1212	1534	1636	1618	1177	1534	1646	1617	1185
2030	1551	1703	1711	1223	1551	1653	1633	1188	1551	1663	1633	1196
2031	1567	1719	1727	1233	1567	1670	1650	1199	1567	1680	1649	1206
2032	1585	1737	1743	1244	1585	1687	1666	1210	1585	1697	1666	1217
2033	1602	1753	1760	1255	1602	1704	1682	1220	1602	1714	1682	1227
2034	1620	1771	1777	1266	1620	1722	1700	1232	1620	1732	1700	1239
2035	1630	1781	1786	1272	1630	1732	1709	1238	1630	1742	1709	1245
2036	1639	1790	1795	1277	1639	1741	1718	1243	1639	1751	1718	1250

Table 40: Capitalised Equivalent Cost of Losses K_{pekv} (NOK/kW). Period of Analysis 30 Years. 4.5% Calculation Interest. Cost Level 2006. [10]

	Luftledningsnett				Kabelnett, middels belastning				Kabelnett, høy belastning			
Nivå	7 22 kV	8 trafo	9 230 V	10 stikkledn.	7 11-22 kV	8 trafo	9 230 V	10 stikkledn.	7 11-22 kV	8 trafo	9 230 V	10 stikkledn.
Tt	2400	2400	2300	1400	2400	2400	2300	1400	2400	2400	2300	1400
2007	22750	25250	25450	18350	22750	24450	24200	17750	22750	24600	24200	17900
2008	22850	25300	25550	18400	22850	24500	24300	17800	22850	24650	24250	17950
2009	23000	25500	25700	18500	23000	24650	24450	17900	23000	24850	24450	18050
2010	23200	25650	25850	18600	23200	24850	24600	18050	23200	25000	24600	18150
2011	23400	25900	26100	18750	23400	25100	24800	18200	23400	25250	24800	18300
2012	23650	26100	26300	18900	23650	25300	25050	18350	23650	25450	25050	18450
2013	23850	26350	26500	19050	23850	25550	25250	18450	23850	25700	25250	18600
2014	24100	26550	26750	19150	24100	25750	25500	18600	24100	25900	25500	18750
2015	24300	26800	26950	19300	24300	26000	25700	18750	24300	26150	25700	18850
2016	24550	27000	27150	19450	24550	26200	25900	18900	24550	26350	25900	19000

Table 41: Capitalised Equivalent Cost of No-load Losses K_{Tekv} (NOK/kW). Period of Analysis 30 Years. 4.5% Calculation Interest. Cost Level 2006. [10]

	Luftledningsnett				Kabelnett, middels belastning				Kabelnett, høy belastning			
Nivå	7 22 kV	8 trafo	9 230 V	10 stikkledn.	7 11-22 kV	8 trafo	9 230 V	10 stikkledn.	7 11-22 kV	8 trafo	9 230 V	10 stikkledn.
Tt	8760	8760	8760	8760	8760	8760	8760	8760	8760	8760	8760	8760
2007	59500	62300	63600	65900	59500	61500	62300	65000	59500	61650	62300	65200
2008	59500	62300	63650	65900	59500	61500	62300	65000	59500	61650	62300	65200
2009	59850	62700	64000	66250	59850	61850	62650	65400	59850	62000	62650	65550
2010	60300	63150	64450	66750	60300	62350	63150	65850	60300	62500	63150	66050
2011	60900	63750	65050	67300	60900	62900	63700	66450	60900	63100	63750	66650
2012	61550	64400	65700	67950	61550	63550	64350	67100	61550	63700	64350	67250
2013	62150	65000	66300	68600	62150	64150	64950	67700	62150	64350	65000	67900
2014	62750	65600	66900	69200	62750	64800	65600	68300	62750	64950	65600	68500
2015	63350	66200	67500	69800	63350	65350	66200	68900	63350	65550	66200	69100
2016	63950	66800	68100	70350	63950	65950	66750	69500	63950	66100	66750	69700

12.3 Consumer Price Index

Table 42: Norwegian Consumer Price Index, 1998=100 [14]

	Jan.	Feb.	March	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Average
2010	127.1	128.7	129.3	129.6									
2009	124.0	125.0	125.1	125.4	125.7	126.4	125.7	125.4	126.4	126.2	126.6	126.9	125.7
2008	121.3	121.9	122.0	121.9	122.0	122.2	123.0	123.1	124.9	125.4	124.7	124.4	123.1
2007	117.0	117.5	118.2	118.2	118.3	118.2	117.9	117.8	118.6	118.9	120.8	121.8	118.6
2006	115.6	116.6	116.9	117.9	117.9	117.7	117.4	117.3	119.0	119.1	119.0	118.5	117.7
2005	113.6	113.7	114.2	114.8	115.2	115.3	114.9	115.1	116.0	116.0	116.0	115.9	115.1
2004	112.4	112.6	113.1	113.3	113.4	113.4	113.3	113.0	113.7	114.0	114.0	113.8	113.3
2003	114.5	114.6	113.8	112.9	112.3	112.0	111.6	111.9	112.5	112.4	112.6	112.6	112.8
2002	109.0	109.3	109.7	109.7	110.0	110.1	109.9	109.6	110.2	110.6	111.0	111.9	110.1
2001	107.6	108.4	108.6	109.1	109.6	109.7	108.2	108.1	108.7	108.6	108.7	108.9	108.7
2000	104.1	104.6	104.7	105.1	105.1	105.7	105.4	105.3	106.2	106.3	106.8	106.7	105.5

12.4 Technical Data of Components

Table 43: PEX Isolated 1kV Earth Cable 4 Conductors without Screen. [10]

Type og tverrsnitt	R	X	Cj	Cd	Ith	Ik 1 sek	Null-system imp,: Ro	Xo
	[ohm/km]		[µF/km]		[A]	[kA]	[ohm/km]	
TFXP 4x25 Al	1,200	0,082	0,42	0,82	125	2,2	4,800	0,374
TFXP 4x50 Al	0,641	0,079	0,53	1,08	180	4,5	2,564	0,358
TFXP 4x95 Al	0,320	0,076	0,57	1,10	260	8,5	1,280	0,358
TFXP 4x150 Al	0,206	0,072	0,60	1,19	335	13,5	0,824	0,334
TFXP 4x240 Al	0,125	0,072	0,64	1,26	435	21,6	0,500	0,334

Table 44: Distribution Transformers [10]

Ytelse [kVA]	PO [W]	P_k [W]	ek [%]	Oljev [kg]	Tot,vekt [kg]	B	L	H
31,5	125	520	2,5	105	370	560	835	1060
50	155	740	3,6	95	400	560	835	1060
100	240	1200	3,6	125	600	565	940	1150
200	465	1950	3,8	310	1160	710	1250	1400
315	615	2900	4,3	340	1360	700	1270	1430
500	880	3900	4,6	420	1890	740	1440	1740
630	1100	4750	4,9	475	2250	730	1510	1850
800	1220	6300	4,9	580	2650	910	1630	1900
1000	1320	8900	5,3	660	2910	1020	1690	2000
1250	1960	9700	5,7	790	3800	1060	1950	2020
1600	2150	13100	6,2	910	4375	1120	2040	2140

The values given in the table are related to the components in the figure below.

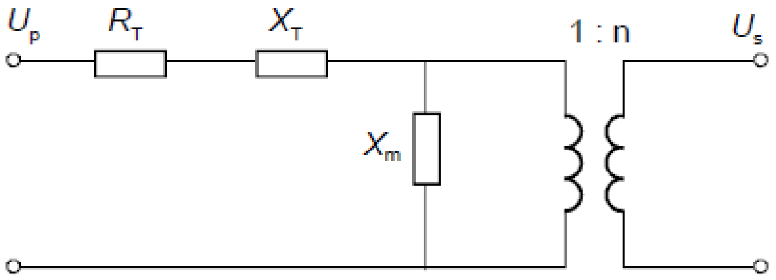


Figure 25: Electric Equivalent Circuit of Transformer [10]

In the figure above, the resistance R_T represents the resistance of the windings, while X_T represents the leakage inductance. Xm represents the magnetising inductance. The value is large and can be neglected. The resulting impedance is then:

$$Z_k = R_T + jX_T \tag{18}$$

The impedances are often given in per unit. The reference impedance Zn is given from the rated values of the transformer, and used to calculate the per unit values short circuit impedance e_k and its resistive part e_r and reactive part e_x. The copper losses in the transformer are given by P_k.

$$Z_n = \frac{U_n^2}{S_n} \tag{19}$$

$$e_k = \frac{Z_k}{Z_n} * 100\% \tag{20}$$

$$e_r = \frac{R_T}{Z_n} * 100\% \tag{21}$$

$$e_x = \frac{X_T}{Z_n} * 100\% \tag{22}$$

$$e_x = \sqrt{e_k^2 - e_r^2} \tag{23}$$

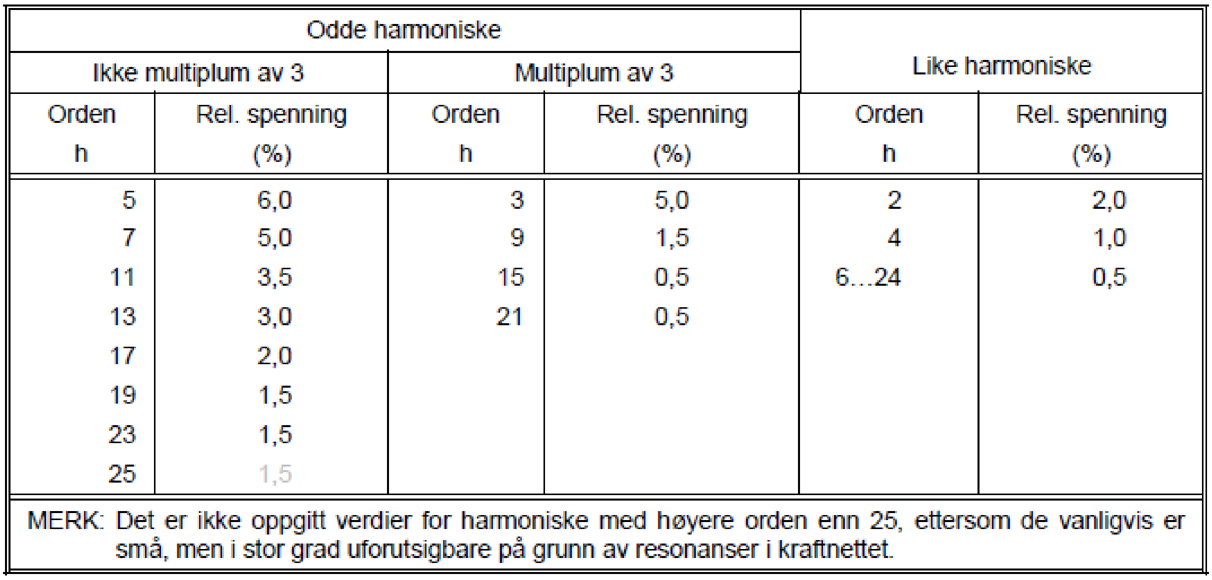
$$P_k = 3R_T I_n^2 = e_r S_n \tag{24}$$

Table 45: Transformers Used in Analysis

Power Rating (kVA)	e_r	e_x	Tap Change Position	Winding Type	No-load Losses (kW)
315	1.03	4.606	±2x2.5%	Dyn11	0.530
500	0.84	3.583	±2x2.5%	Dyn11	0.790
630	0.92	5.301	±2x3.67%	Dyn5	0.846
800	0.84	4.310	±2x2.5%	Dyn5	1.019
1000	0.86	5.685	±2x2.5%	Dyn11	1.036
1250	0.69	4.871	±2x2.5%	Dyn5	1.382
1600	0.78	5.330	±2x2.5%	Dyn11	1.609

12.5 Harmonic Voltages

Table 46: Limits for Harmonic Voltages Given in the Norwegian PQ Code [9]



Odde harmoniske				Like harmoniske	
Ikke multiplum av 3		Multiplum av 3			
Orden h	Rel. spenning (%)	Orden h	Rel. spenning (%)	Orden h	Rel. spenning (%)
5	6,0	3	5,0	2	2,0
7	5,0	9	1,5	4	1,0
11	3,5	15	0,5	6…24	0,5
13	3,0	21	0,5		
17	2,0				
19	1,5				
23	1,5				
25	1,5				

MERK: Det er ikke oppgitt verdier for harmoniske med høyere orden enn 25, ettersom de vanligvis er små, men i stor grad uforutsigbare på grunn av resonanser i kraftnettet.

12.6 Output File from Dynko

```
          *****************************************************
          *****************************************************

          Program              : D Y N K O
          EFI                  : 1991-02-15
          Versjon nr.          : 6
          Manual               : EFI-TR NR. 3531
          Program ansvarlig    : K.SAND
          *****************************************************


          DATAFIL :               lura500.dat



          BEGRENSNINGER :

          MAX. ANTALL SYSTEML\SNINGER              :  25
          MAX. ANTALL DELUTBYGGINGER               :  25
          MAX. ANTALL ]R I ANALYSEPERIODEN         :  25
          MAX. ANTALL ]R MED GITTE DRIFTSKOSTNADER :  25
          MAX. ANTALL PROGNOSEVARIANTER (EKSKL.0%) :   2
          MAX. ANTALL KALKYLRENTEVARIANTER         :   3
1

   ***  LURAVIKA 500kW elbillast



  1. KONTROLLDATA.


  1.1 BESKRIVELSE AV DELUTBYGGINGER OG UTBYGGINGSALTERNATIV

       DELUTBYGGINGER:


 NR.     TEKST                             TYPE  KOSTNAD  \KONOM.  L]NE-   AMORT.
                                                          LEVETID  RENTE   TID
                                                  (KKR.)   (]R)     (%)    (]R)
   1   ,1000kVA trafo                        1    2212.4    30      10.0     15
   2   ,1250kVA trafo                        1    2632.4    30      10.0     15
   3   ,1600kVA trafo                        1    2985.3    30      10.0     15
   4   ,5x240 kabel elbil                    1    1130.0    30      10.0     15
   5   ,6x240 kabel elbil                    1    1356.0    30      10.0     15
   6   ,7x240 kabel elbil                    1    1582.0    30      10.0     15
   7   ,8x240 kabel elbil                    1    1808.0    30      10.0     15
   8   ,9x240 kabel elbil                    1    2034.0    30      10.0     15



      UTBYGGINGSALTERNATIV


      UTSTR. I TID    NR.    DELUTBYGGINGSKODE
       FRA   TIL
                            1  2  3  4  5  6  7  8

      2010  2040       1    X           X
      2010  2040       2    X              X
      2010  2040       3    X                 X
      2010  2040       4       X        X
      2010  2040       5       X           X
      2010  2040       6       X              X
```

```
      2010  2040       7       X                 X
      2010  2040       8       X     X
      2010  2040       9          X     X
      2010  2040      10          X        X
      2010  2040      11          X           X
1
  1.2 OVERGANGSKOSTNADSMATRISE.    OVERGANGSKOSTNADER I KKR. REF. T=0.
      KOSTNADSELEMENTER AV TYPE 2 ER IKKE INKLUDERT.

  OVERG. TIL ALT.***
  FRA ALT.
   *
   *
       0    1    2    3    4    5    6    7    8    9   10   11


XXXX 3568 3794 4020 3988 4214 4440 4666 3762 4341 4567 4793
     XXXX
          XXXX
               XXXX
                    XXXX
                         XXXX
                              XXXX
                                   XXXX
                                        XXXX
                                             XXXX
                                                  XXXX
                                                       XXXX



1
  1.3 EKVIVALENTE \K. LEVETIDER REF. T=0
      BEREGNINGEN ER HER FORETATT VED KALKULASJONSRENTENIV] 4.50 % .
      KOSTNADSELEMENTER AV TYPE 2 ER IKKE INKLUDERT.

  OVERG. TIL ALT.***
  FRA ALT.
   *
   *
       0    1    2    3    4    5    6    7    8    9   10   11


XXXX   30   30   30   30   30   30   30   30   30   30   30
     XXXX
          XXXX
               XXXX
                    XXXX
                         XXXX
                              XXXX
                                   XXXX
                                        XXXX
                                             XXXX
                                                  XXXX
                                                       XXXX



1
  1.4 LEVETIDSDIAGRAM.   ]RLIGE MAKSIMALTAP I KW.

  1.4.1 AVVIK FRA OPPR. PROGNOSE:   .00 %


                    ]RLIGE MAKSIMALTAP I KW.
 ]R 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025
2026 2027 2028 2029 2030 2031 2032 2033 2034

 ALT.NR.
```

```
   1       228  228  228  228  228  228  228  228  228  228  228  228  228  228  228
228  228  228  228  228  228  228  228  228  22
   2       217  217  217  217  217  217  217  217  217  217  217  217  217  217  217
217  217  217  217  217  217  217  217  217  21
   3       208  208  208  208  208  208  208  208  208  208  208  208  208  208  208
208  208  208  208  208  208  208  208  208  20
   4       182  182  182  182  182  182  182  182  182  182  182  182  182  182  182
182  182  182  182  182  182  182  182  182  18
   5       170  170  170  170  170  170  170  170  170  170  170  170  170  170  170
170  170  170  170  170  170  170  170  170  17
   6       163  163  163  163  163  163  163  163  163  163  163  163  163  163  163
163  163  163  163  163  163  163  163  163  16
   7       156  156  156  156  156  156  156  156  156  156  156  156  156  156  156
156  156  156  156  156  156  156  156  156  15
   8       198  198  198  198  198  198  198  198  198  198  198  198  198  198  198
198  198  198  198  198  198  198  198  198  19
   9       174  174  174  174  174  174  174  174  174  174  174  174  174  174  174
174  174  174  174  174  174  174  174  174  17
  10       164  164  164  164  164  164  164  164  164  164  164  164  164  164  164
164  164  164  164  164  164  164  164  164  16
  11       155  155  155  155  155  155  155  155  155  155  155  155  155  155  155
155  155  155  155  155  155  155  155  155  15


                       ]RLIG IKKE LEVERT ENERGI I MWH.
 ]R 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025
2026 2027 2028 2029 2030 2031 2032 2033 2034

 ALT.NR.

   1
   2
   3
   4
   5
   6
   7
   8
   9
  10
  11


  1.5 UTGANGSPUNKT FOR BEREGNING AV TAP(SKOSTNADER).


      TAP VED DE GITTE STADIER. (OPPR. PROGN.):
      ]RLIGE MAKSIMALTAP I KW.





      TAP VED DE GITTE STADIER. (OPPR. PROGN.):
      ]RLIGE MAKSIMALTAP I KW.


      STADIUM: 2010   2020
      ALT. NR.
         1      228    228
         2      217    217
         3      208    208
         4      182    182
         5      170    170
         6      163    163
         7      156    156
         8      198    198
```

```
         9      174    174
        10      164    164
        11      155    155




      ]RLIG IKKE LEVERT ENERGI . (OPPR. PROGN.):
      GITT I MWH.


      STADIUM: 2010   2020
      ALT. NR.
         1        0      0
         2        0      0
         3        0      0
         4        0      0
         5        0      0
         6        0      0
         7        0      0
         8        0      0
         9        0      0
        10        0      0
        11        0      0

 TABELL 1.6 / 1.7

 SPESIFIKKE TAPS   OG AVBRUDDSKOSTNADER



      ]R      TAPSKOST.      AVBRUDDSKOST
              (KR/KW)          (KR/KWH)


    2010         1384               0
    2011         1386               0
    2012         1403               0
    2013         1420               0
    2014         1436               0
    2015         1453               0
    2016         1465               0
    2017         1475               0
    2018         1487               0
    2019         1498               0
    2020         1510               0
    2021         1525               0
    2022         1539               0
    2023         1554               0
    2024         1567               0
    2025         1583               0
    2026         1600               0
    2027         1613               0
    2028         1629               0
    2029         1646               0
    2030         1663               0
    2031         1680               0
    2032         1697               0
    2033         1714               0
    2034         1732               0
1

  2. RESULTATUTSKRIFT.
```

```
     BEREGNING NR.:  1


     ***  LURAVIKA 500kW elbillast



         FORUTSETNINGER.


         KALKULASJONSRENTE           :   4.50 %
         PRISSTIGN. FASTE KOSTN.     :    .00 %
         PRISSTIGN. DRIFTSKOSTN.     :    .00 %
         ANALYSEPERIODE              :     25 ]R
         AVVIK FRA OPPR. PROGNOSE    :    .00 %
         STARTALTERNATIV             :      0



                     OPTIMAL UTBYGGINGSPLAN

 NR.                 ]RSTALL
       10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34

  1     5  5  5  5  5  5  5  5  5  5  5  5  5  5  5  5  5  5  5  5  5  5  5  5  5
  2     6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6
  3     4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4
  4     7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7
  5    10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
  6    11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11
  7     9  9  9  9  9  9  9  9  9  9  9  9  9  9  9  9  9  9  9  9  9  9  9  9  9
  8     8  8  8  8  8  8  8  8  8  8  8  8  8  8  8  8  8  8  8  8  8  8  8  8  8
  9     2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
 10     3  3  3  3  3  3  3  3  3  3  3  3  3  3  3  3  3  3  3  3  3  3  3  3  3
 11     1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1


                     \KONOMISK OPPSUMMERING
        (NB. KUN DEN ANDEL AV KOSTNADENE SOM P]L\PER
INNENFOR ANALYSEPERIODEN INNG]R I KOSTNADSTALLENE)

 NR.   INVESTERINGS-  TAPS-       AVBRUDDS-   TOTALT     ANNUITET   RELATIV
       KOSTNADER      KOSTNADER   KOSTNADER                        VURDERING
         (KKR)         (KKR)       (KKR)       (KKR)     (KKR/]R)     (%)

  1       3836.5      3817.0          .0     7653.5        516.1     100.0
  2       4042.2      3659.8          .0     7702.0        519.4     100.6
  3       3630.7      4086.4          .0     7717.2        520.4     100.8
  4       4247.9      3502.7          .0     7750.6        522.7     101.3
  5       4157.7      3682.3          .0     7840.0        528.7     102.4
  6       4363.5      3480.2          .0     7843.7        529.0     102.5
  7       3952.0      3906.8          .0     7858.8        530.0     102.7
  8       3425.0      4445.7          .0     7870.7        530.8     102.8
  9       3454.1      4872.3          .0     8326.4        561.5     108.8
 10       3659.9      4670.2          .0     8330.1        561.8     108.8
 11       3248.4      5119.3          .0     8367.7        564.3     109.3



                    KONKLUSJON.

      F\LGENDE UTBYGGINGSPROGRAM GIR MINST SUM
      DISKONTERTE KOSTNADER I ANALYSEPERIODEN:

      ]RSTALL       UTBYGGING                                     INVEST.(KKR)
```

2010	-	1. ,1250kVA trafo	2632.4
	-	2. ,7x240 kabel elbil	1582.0