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Power Peak Shaving:

How to Schedule Charging of Electric Vehicles and Organize Mutually Beneficial Vehicle to Grid (V2G)

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Industrial Economics

Abstract

This thesis contributes to a project by the Norwegian University of Life Sciences (NMBU) featuring a pilot Vehicle to Grid (V2G) park at Oslo Gardermoen Airport. The goal of the project is two-fold. On one hand, the goal is to provide the airport, a large power consumer who pays power tariffs, with viable measures to shave power peaks and thereby reduce costs. On the other hand, the example of an airport is used to illustrate how V2G can be implemented in a feasible way for EV owners. If successful, this would be advantageous both to power grid operators, to EV owners, and to large power consumers who facilitate EV charging.

The thesis approaches power peak shaving by utilizing electric vehicles (EVs) from two angles: Load shifting by scheduling EV charging, and EVs as alternative power supply through vehicle to grid (V2G). EVs with one-way charging capability can be utilized for the first approach, while EVs with two-way charging capability (currently not many) can be utilized for both.

In a setting where a large power consumer facilitates long term parking and charging of EVs on its property, both approaches in combination can contribute to reducing power tariffs for the large power consumer. Before V2G is ready for full scale implementation, scheduling the charging is a step in the right direction, and can be seen as ground work for V2G. This thesis presents a Python program demonstrating a method based on scheduling theory, adjusted to minimize simultaneous power demand from EVs, and schedule it outside of expected power peaks. To this author's knowledge, the theory has not been used for this purpose before.

While V2G is most commonly regarded from a grid operation perspective, the focus of this thesis is to organize V2G as a mutually beneficial cooperation between representatives of grid interests and the owners of EVs. The technical process that occurs during V2G can be described in very different business terms, depending on perspective. While control based V2G contracts are most commonly considered, stemming from the perspective that the grid operator takes control over (rents) the EV battery to use for V2G, this thesis explores contract designs that regard EV owners as electricity traders, who own the electricity in their battery until they decide to sell it. This leaves more control in the hands of EV owners. Different demand response mechanisms are explored to trigger electricity sale under different circumstances.

The thesis concludes with a volume based V2G contract design for the case at Oslo Gardermoen Airport, where EV owners agree to sell a certain electricity volume during a predefined time frame, that the airport may extract when it suits their purposes. Elements from a price based contract, where EV owners define a sales price that triggers a sale when matched by the market price, is also included for certain circumstances. An approach to design V2G contracts for different circumstances can be derived from the discussion.

Sammendrag

Denne oppgaven bidrar til et prosjekt i regi av Norges Miljø- og Biovitenskapelige Universitet (NMBU), som omhandler et V2G-pilotprosjekt ved Oslo Lufthavn, Gardermoen. Prosjektets mål er todelt. På den ene siden er målet å tilby flyplassen, en stor strømkunde som betaler effekttariffer, virkemidler for å jevne ut effekttopper og dermed redusere kostnader. På den annen side brukes flyplassen som et eksempel på hvordan V2G kan innføres på en gangbar måte for elbileiere. Hvis dette lykkes, vil det komme både nettoperatører, elbileiere og store strømkunder som fasiliterer elbillading, til gode.

Oppgaven tilnærmer seg effekttopputjevning ved hjelp av elbiler fra to ulike vinkler: Lastforflytning gjennom tidsplanlegging av elbillading, og elbiler som alternativ kraftforsyning gjennom *vehicle to grid* (V2G). Elbiler med batterier som kan lades én vei kan brukes til den første tilnærmingen, og elbiler som kan lade to veier (foreløpig ikke mange) kan brukes til begge deler.

I tilfeller der en stor strømkunde fasiliterer langtidsparkering og lading av elbiler på eiendommen sin, kan en kombinasjon av begge tilnærmingene bidra til å redusere effekttariffer for strømkunden. Før V2G er modent for innføring i full skala, er tidsplanlegging av ladingen et steg i riktig retning, og kan ses på som forarbeid for V2G. Denne oppgaven presenterer et Python-program som demonstrerer en metode bygget på *scheduling*-teori, tilpasset til å sikre at minst mulig effekt trekkes samtidig til lading av elbiler, i tillegg til å planlegge det utenfor forventede effekttopper. Såvidt denne forfatteren vet er ikke teorien blitt brukt til dette formålet tidligere.

V2G er er oftest diskutert sett fra en nettoperatørs perspektiv. Denne oppgaven fokuserer på å organisere V2G som et samarbeid mellom representater for kraftnettets interesser og elbileiere, til gjensidig nytte for begge. Den tekniske prosessen som skjer ved V2G kan beskrives på flere måter i forretningsøyemed, avhengig av perspektiv. V2G er vanligvis diskutert som en kontrollbasert kontrakt, sprunget ut av et perspektiv der nettoperatøren tar kontroll over (leier) elbilbatteriet til V2G-bruk. Oppgaven utforsker kontraktsutforminger som springer ut av et perspektiv der elbileieren anses som en krafthandler, som eier elektrisiteten i sitt eget batteri, og kan velge å selge den. Dette gir elbileieren mer kontroll. Forskjellige etterspørselsrespons-mekanismer utforskes for å utløse salg av elektrisitet under ulike omstendigheter.

Oppgaven konkluderer med en volumbasert kontraktsutforming til case-studien ved Oslo Lufthavn, Gardermoen, der elbileiere forplikter seg til å selge et visst elektrisitetsvolum ila. en forhåndsdefinert tilkoblingsperiode. Flyplassen kan kan kjøpe dette volumet på tidspunkt som passer deres formål innenfor den avtalte perioden. Elementer fra en prisbasert kontrakt, der en forhåndsdefinert salgspris utløser et elektrisitetssalg idet markedsprisen matcher den, er også inkludert for visse tilfeller. En tilnærming til V2G-kontraktsutforming til forskjellige sammenhenger kan utledes fra diskusjonen.

1 Acknowledgements

With this thesis I end my masters degree in Industrial Economics at the Norwegian University of Life Sciences (NMBU).

I would like to thank my supervisors, Heidi S. Nygård and Olvar Bergland, for valuable suggestions and for asking the right questions.

I also thank my partner Pål, for nutritious meals and other support during this time.

Ingrid Maria Mørch 30.04.2022

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2 Abbreviations

EV: Electric vehicle
FCEV: Fuel cell electric vehicle (hydrogen vehicle)
V2G: Vehicle to grid
V2H: Vehicle to home
PoC: Proof of concept
TSO: Transmission system operator
DSO: Distribution system operator
LRPT: Longest remaining processing time

3 Important Words and Concepts

Energy:
The capacity for doing work. A quantity. May exist in several forms: Potential, kinetic, electric, among others.

Electricity:
Common term for electric energy.

Power:
Energy per time. A flow rate. Often apparently used interchangeably with energy, depending on context. Sometimes an amount of energy is discussed separately from a time aspect, and sometimes an amount of energy in the course of a time frame - an energy flow (power).

Power peak:
Expression that stems from the graphic representation of power demand. When the x axis represents time and the y axis represent power, the "peak" of the graph represents the largest power that was demanded simultaneously during the course of the time period shown.

Power peak shaving:
Visual expression that represents the concept of decreasing the maximum power that is demanded simultaneously.

Load shifting:
Load is the electro-technical term for demand from the power grid. Load shifting moves electricity consumption from one time period to another, for example in the interest of power peak shaving.

Vehicle to Grid (V2G):
The concept of utilizing batteries in electric vehicles (EVs) to store excess energy from the power grid, and extract needed energy back to the grid at opportune times. Only possible for EVs with a battery capable of two-way charging.

4 Introduction

4.1 Background

Reducing energy related costs by better timing your demand for power is a concept rapidly growing in the consciousness of the general population in Norway. A new system for electricity bills is about to be implemented, where the monthly peak of each consumer's demand defines a significant portion of the bill [1]. This can be regarded as differentiated rental of power transmission lines according to the portion each consumer occupies. It has long been a wish from the energy business to implement such a billing system in order to reduce power peaks in the grid, and thereby delay the need for expanding the transmission capacity. With the green shift and the electrification of the transport sector in particular, this is increasingly urgent.

Large power consumers, such as airports, are well acquainted with the objective of evening out power demand, as they already pay power tariffs for the large portion of the transmission lines that needs to be reserved for them. This portion is defined by their peak power demand during a month, the same principle that guides the new billing system for regular consumers [2].

Unusually high energy prices due to a series of factors, some of which are temporary while others are not, has further incentivized adjusting power consumption habits to the variations in the electricity spot price [3]. Many in Norway have argued that we should stop building transmission lines to other countries, even stop exporting so much power through the ones we already have, because it renders Norwegian energy prices vulnerable to price developments on the continent [4]. Norwegian electricity consumers are historically accustomed to very low prices because of our abundance of water power, and are reluctant to let go of that good. It also weakens the competitive advantage of power consuming industry, which is a significant argument for protectionism.

However, with the recent development regarding Russia's invasion of Ukraine, the political will in Europe to gain independence from Russian gas is strong [5]. This will likely make a protectionist energy policy in Norway increasingly difficult to defend. Norway was already under pressure from the EU to further join the ongoing merging of European energy markets, which resulted in the much debated ACER law and the current level of electricity export [6]. Now, energy policy has also become security policy, which will likely further increase that pressure. The pressure can prove hard to resist as following the invasion of Ukraine, the trend in Europe, including Norway, is solidarity.

The European effort to become independent from Russian gas also accelerates the rate at which European countries will convert their energy consumption to renewable energy sources [5], most of which produce at unpredictable (at least unmanageable) times, due to fluctuations in wind and sun. The influx of power from renewable energy sources has long been a predicted driver for greater variations in energy prices, and this development will now be significant even sooner than anticipated.

Regardless of what one believes should be the case, it is likely that the current policy of energy trading with Europe will continue, if not increase, which connects Norway's energy prices to theirs [7]. It is also likely that the energy prices in Europe will remain high, and increasingly fluctuate, in the foreseeable future. This strengthens the incentive for large power consumers, such as airports, to implement cost reduction measures. It also makes it likely that Norwegian power consumers, perhaps particularly EV owners, will continue to educate themselves on the possible economical advantages by adjusting their power demand to fluctuating prices, and distribute their demand more evenly in time. This is connected - the price is low when demand is low, and the price is high when demand is high (relative to supply).

Systems for smart charging and other money saving measures are already marketed to EV owners [8]. As two-way charging capability of the EV batteries become more common, it is likely that EV owners will be offered opportunities to earn money as well, by charging their EV while the energy price is low, and extracting the energy from the car battery for use in their home when the price is high - or selling it back to the grid.

The research question for this thesis is as follows:

> "How can a pool of EVs parked at the property of a large power consumer be utilized to shave power peaks? How can this be organized in a way that benefits both the large power consumer and the EV owners?
>
> Can a case study at an airport serve as a general example of mutually beneficial cooperation between EV owners and the power grid?"

4.2 Case Study at Oslo Gardermoen Airport

Oslo Gardermoen Airport in Norway is the location of a V2G research project by NMBU in cooperation with the airport owner, Avinor.

V2G utilizes two-way charging capability of the batteries in EVs to store excess energy from the power grid in the car battery, and releasing the energy back to the grid when needed.

Oslo Gardermoen Airport, owned by Avinor, is an example of a large power consumer that pays power tariffs. They are hosting NMBU's research project hoping that organizing the pool of EVs in their parking houses into a V2G park, can reduce their power tariffs. The idea is for the airport to use the EVs as storage for cheap energy when demand is low, and extract power from battery storage when demand from the grid is high.

NMBU uses the example of an airport to illustrate how the concept of V2G can be implemented to be both advantageous to the power grid, and eligible for EV owners.

4.3 Contribution of this Thesis

There are easier and cheaper measures to reduce power tariffs for the airport, or any large power consumer that hosts a pool of EVs, than implementing V2G. A natural first step is load shifting, accomplished by organizing the timing of the charging of the EVs. Today, charging starts as soon as the EV is parked and connected, which may imply buying electricity when the price is high. It may also imply adding power demand at peak hours, which needlessly adds to the power peaks of the airport.

Building on scheduling theory from industrial production, this thesis proposes a system that schedules the charging of each EV in the EV pool such that all charging is restricted to nighttime if possible, on the assumption that power peaks rarely, if ever, occur during nighttime. (If this assumption does not hold, the method can easily be adjusted provided there is a pattern of a daily time interval where power peaks rarely or never occur). No EVs are charged before they must in order to finish in time, which increases the chance of fitting all charging hours into the defined interval. It is also ensured that no more EVs than necessary charge simultaneously, which will spread out the power demand used to charge the EVs, and will therefore contribute to power peak shaving. In this author's opinion, this should be an integrated part of the organization of a V2G park with long term parking, and can therefore be considered "ground work" before a V2G park is implemented. This measure also does not require two-way charging capability in EVs, which most EVs on Norwegian roads currently lack [9].

To this author's knowledge, this optimization measure requires no additional equipment, and can be integrated into the existing systems at the parking houses. The program demonstrated in this thesis is a proof of concept (PoC) for EV charging schedules, not a simulation of the specific circumstances at Oslo Airport.

Implementing V2G requires two-way charging capability in the EVs' batteries, which only one manufacturer (Nissan with the models Leaf and eNV200) on the Norwegian market currently offers in Norway [9]. From Avinor it requires investing in additional equipment in the form of two-way chargers, because regular chargers can only supply the EV batteries with electricity - not receive electricity back. However, given these requirements being met, V2G has the potential to decrease power peaks of the airport even further. Another master's thesis connected to the project [10] has established that the batteries in the EVs parked at Oslo Gardermoen Airport represent a substantial unused potential for flexibility (and thereby power peak shaving) for the airport. However, there is uncertainty regarding how V2G should be organized such that EV owners will agree to make their EVs available for this use.

This thesis addresses that problem by analyzing each party's interests, defining what the required services from each party are, and formalize them in the form of a contract between EV owner and Avinor.

EV owners' interests and their importance for participation willingness are identified through the results of a Dutch survey from 2019, published in 2021 [11], which among other things highlights the importance of contract design. The contract designs considered in the thesis are inspired by an article published in 2018 [12], one of the co-authors of which also contributed to the Dutch survey. The article analyzes the outcomes of different contract designs through agent based models. Based on those outcomes, it offers some suggestions for which designs are fitting for various V2G circumstances.

Since the purpose of this thesis is to propose a contract design for a very specific context, the thesis expands on the article's analysis of correspondence between technical circumstances and contract design. The contractual roles of the parties involved (Avinor and the EV owners) are analyzed, as are their implicit negotiating positions - similar to how the standard electricity price is settled at Nord Pool through an implicit auction. This culminates in a proposed contract design in terms of parameters included and how they are formed.

4.4 Structure of the Thesis

The thesis is organized as follows: Section 5 relays an overview of the Norwegian power grid and power market, as far as it relates to this thesis. It then explains the scheduling theory used for charging schedules, as well as V2G technology (briefly), in context of the power grid and power market. The section concludes by explaining V2G contract designs from relevant literature.

Section 6 elaborates on the technological and societal context that the V2G pilot project at Oslo Gardermoen Airport and this thesis should be seen in relation to. It also elaborates on the pilot project and the circumstances of its V2G setup, which is important for the proposed contract design.

Section 8 relays the methods used in the thesis. It begins by describing the process of applying scheduling theory to optimal charging of an EV pool with respect to power peaks, for which there is no blueprint in existing literature that this author is aware of. The method for modeling an abstract number of machines, which is developed by the author of this thesis, is explained. Section 8 concludes with a rendition of the course of the V2G literature research.

Section 9 presents and discusses the results. Examples of charging schedules are shown, as well as a discussion of approach to mutually beneficial V2G organizing, and finally a proposed contract design for a context such as the case at Oslo Airport Gardermoen. The applicability of the results to other cases is also discussed.

Section 10 is the conclusion of the thesis.

5 Related Literature and Theoretical Focus

5.1 The Norwegian Power Grid

The power grid in Norway is organised into three levels, from top to bottom: The transmission grid, the regional grid and the distribution grid. While the distribution grid is operated by various local distribution system operators (DSOs), the transmission grid in Norway is operated by Statnett, a state-owned transmission system operator (TSO). The TSO ensures reliable distribution of power nationwide [13]. The transmission grid connects the major power producers and consumers both nationwide and to international transmission grids.

In the power grid, supply and demand need to be in balance at all times. Generally, this means that electricity must be used as soon as it is produced, because it is difficult to store. The less flexible one side is (supply or demand), the more the other side needs to be adjusted in order to keep the balance. The TSO, Statnett, is in charge of this. The DSOs manage local balance in smaller scale.

The management of demand in the service of this objective is called demand response. It typically involves incentivizing shifts in electricity consumption among consumers [14], also called load shifts. Load is the electro-technical term for power demand.

Figure 1 illustrates the concept of load shifting, using the load related to EV charging as an example. The load on the grid (i.e. the power demand) is typically higher during daytime than nighttime, hence the valley and peak in the figure. The size dimensions are purely illustrative, as is the stylized / simplified load line.

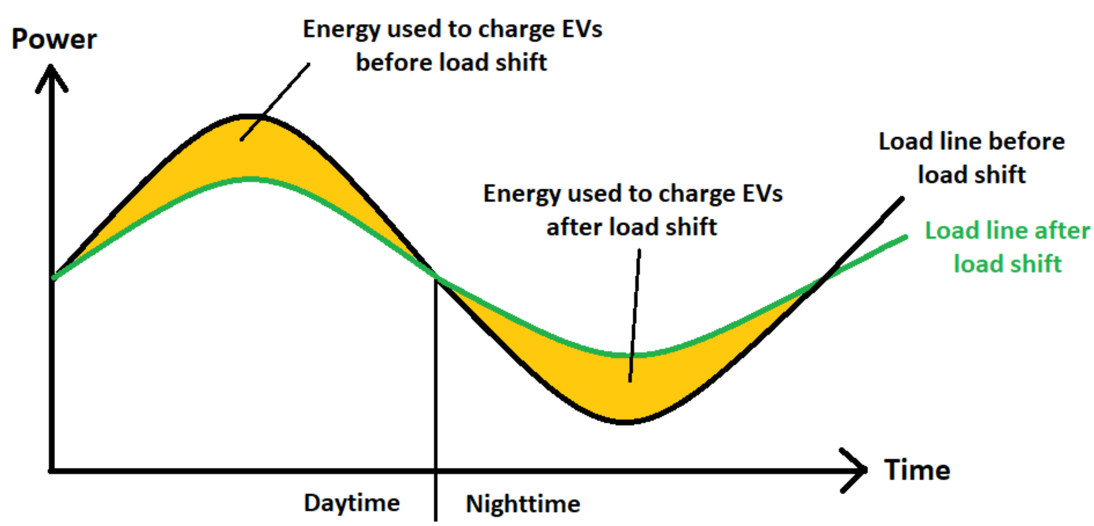

Figure 1: The concept of load shifting, here exemplified by moving the charging of EVs from daytime to nighttime. Simplified illustration of load line tendencies during daytime and nighttime; a real load line is more nuanced.

In Norway, the water magazines provide a coveted control of the supply side that cannot be replicated with most other energy sources, especially not other renewable ones. The greater the influx of other, unpredictable renewable energy sources, the more flexible the demand side has to become, which increases the relevance of demand response. The adjustment can happen in the form of change in consumption habits, or energy storage. In addition to indirect financial incentives, the TSO typically has special agreements with large energy consumers such as factories, where they agree to adjust their power consuming production, e.g. their demand, to times that serve the balancing needs of the grid.

Demand response is also relevant for another objective of the power grid, namely the shaving of power peaks. The transmission capacity of the grid needs to be dimensioned for the peak power demand, that is, the largest power that is consumed simultaneously during the course of a year. The lower the peaks are, i.e. the less power that is demanded simultaneously, the less transmission capacity is needed in the grid.

Figure 2 illustrates the concept of peak shaving, using as an example the utilization of EV batteries as an alternative power source to the grid during peak hours, which results in reduced demand from the grid. The size dimensions are purely illustrative. Additionally, in reality the power grid is dimensioned after the peak power demand over the course of a year, with a buffer margin added. It is exactly aligned in the figure for concept illustration.

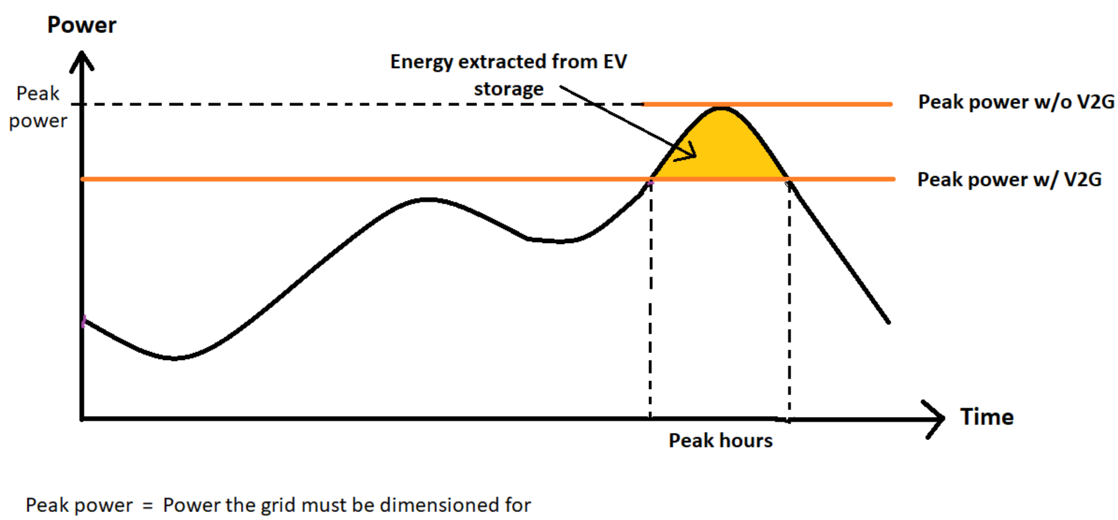

Figure 2: The concept of peak shaving, here exemplified by using the stored electricity in EV batteries as an alternative power source to the grid during peak hours.

The purpose of demand response in this case is not to balance out an unexpected surge or delay in supply, but rather for the demand to be as evenly distributed in time as possible. The power tariffs that Avinor pay for their power demand at Oslo Gardermoen Airport is an example of a financial incentive designed to trigger this kind of demand response. The effect is that the party who has to pay the power tariffs will reduce their power peaks to the best of their ability.

5.2 Scheduling Theory

For a large power consumer that hosts a pool of EVs on its property, like Oslo Gardermoen Airport, scheduling theory can be used as a form of smart charging in the service of load shifting, to shave power peaks, as shown in figure 1.

Since the charging of EVs on Oslo Gardermoen Airport's property contributes to their power demand, charging of EVs during power peaks should be avoided. Assuming that the power peaks, which are defined hourly, take place during day time, the simplest and most effective measure is to delay all EV charging to nighttime. In addition to shaving power peaks, the electricity costs will be lower, since electricity prices normally are lower during nighttime than daytime. However, there is a cap on how much power the EV pool can draw simultaneously before a security shutdown occurs (according to the airport employee who guided participants in the project on site). For this reason, all EVs may not be able to charge simultaneously on the first night after their arrival.

Creating a charging schedule with scheduling theory ensures that no EVs are charged before they have to in order to be finished by their due date. This increases the chance of fitting all charging time into the hours with lowest demand and lowest energy prices. It also ensures that the charging is not delayed beyond the time the EV owner wants to collect their EV. Generally, it ensures that the needs of the EV owners are not infringed upon in favor of peak shaving purposes for the airport. It also ensures that peak shaving purposes for the airport are met as well as they can be without affecting the EV owners.

Scheduling theory has been used for decision making in industrial manufacturing and service industries since the beginning of the last century [15]. In later years it has appeared in industrial engineering and operations research literature. The book used for the charging scheduling in this thesis, "Scheduling - Theory, Algorithms and Systems" by Michael Piledo [15], is the result of courses in scheduling theory and applications at Columbia University.

Although the theory is also used in the service industry, the theory primarily describes scenarios where there is one or more machines that can perform a set of jobs with certain completion times. The goal is often to find a schedule for the machines to process the jobs so that the entire set of jobs are completed as soon as possible, and so that the production capacity of the machines is used to the fullest.

The chargers in the parking house at Oslo Airport Gardermoen can be regarded as machines, while the full charging of one EV can be regarded as one job.

This thesis has employed the scheduling theory in a Python script that yields example schedules. The following sections give a general summary of the theory and its application in this thesis, while section 8.1 elaborates on the considerations and choices that resulted in the triplet used to describe the charging scheduling problem. Section 8.1 also elaborates on the construction of the Python program and the abstract modeling of the number of machines.

5.2.1 General Theory

The following is an overview of the concepts from the book [15] used for the development of charging schedules in this thesis:

A scheduling problem is described by a triplet:

$$\boldsymbol{\alpha}|\boldsymbol{\beta}|\boldsymbol{\gamma} \tag{1}$$

- α: Describes the machine environment
- β: Provides details of processing characteristics and constraints
- γ: Describes the objective to be minimized

Machine Environment (α)
Many different machine environments are defined in the theory. The two considered for describing the chargers in the parking house at Oslo Gardermoen Airport were:

- P_m: m identical machines in parallel
- Q_m: m machines in parallel with different speeds

Processing Characteristics & Constraints (β)
The theory defines many different processing characteristics and constraints. The ones that were considered for the charging environment are:

- r_j: Release date of job number j. If this characteristic is present in the β field of the triplet, job number j cannot start before its release date.
- $prmp$: Preemptions permitted. This means that jobs do not need to run continuously from start until completion. They can be paused and restarted at will.

Objectives to be Minimized (γ)
There are several objectives to minimized defined in the theory. The most relevant to the charging problem are:

- C_{max}: Maximum makespan (makespan is the time it takes to complete the job)
- L_{max}: Maximum lateness (lateness is the time between the job's due date and its actual completion date)

5.2.2 The Charging Problem Described as a Triplet

The author of this thesis arrived at the following triplet to describe the charging scheduling problem:

$$\boldsymbol{P_m|prmp|L_{max}} \tag{2}$$

- P_m: Parallell machine environment consisting of m machines
- $prmp$: Preemptions allowed
- L_{max}: Maximum lateness must be minimized

Parallel Machine Environment (P_m)
It is most intuitive to let each machine represent one physical charger, which would make m equal to the number of chargers. However, following the conventions of scheduling theory, that would lead to a schedule where as many chargers as possible are in use at all times. That is the opposite of what is wanted for power peaks shaving. The number of machines, m is therefore kept flexible in this case.

In order to fulfill the goal of power peak shaving, no more chargers than necessary should be in use simultaneously. The chargers are therefore modeled as a minimized number of machines. Section 8.1 will elaborate on how this was solved, as the author of this thesis could find no prior example of this in the theory. Maximizing machine idleness is perhaps not an objective that arises in many industries.

Preemptions Allowed ($prmp$)
The EVs do not need to be charged continuously. The charging processes of each EV can be stopped and restarted automatically, with no harmful effect to the battery.

Maximum Lateness (L_{max})
The maximum lateness is set as the objective to be minimized. It is defined as due date plus lateness, $d_j + z$. The due date is really the time (in this thesis: number of days) until the due date of a job, and lateness is the number of days of accepted delay relative to the due date. For the purposes of the charging problem, z is not only minimized, but specifically set to zero. It is a hard constraint that all EVs must be fully charged (or charged to the agreed-upon minimum battery level) upon the EV owners' return. It is unlikely that the EV owners will accept the possibility of delays.

5.2.3 Solution to the Charging Triplet: LRPT

There are many existing algorithms that yield schedules that uphold the requirements defined by many triplet combinations. Not all problem description triplets are easy to solve. Fortunately, the triplet that can be used to describe the charging scheduling problem in this thesis has a deterministic solution.

Pinedo's Scheduling book [15] contained one solution for the charging problem triplet, triplet (2), which according to Pinedo is one of the few due date objective related problems that are solvable in polynomial time: Longest Remaining Processing Time first (LRPT). The LRPT principle is simply to always prioritize the job that has the longest remaining processing time. When a job is processed enough that a different job has more processing time left, the machine switches to that job, which initially had the second longest remaining processing time. This goes on until no jobs have any processing time left.

Triplet (2) is not directly solvable by LRPT. For LRPT to be applicable to the problem in this thesis, the timeline must be reversed. This operation converts the due dates (d_j) of the jobs to release dates (r_j), and converts the zero lateness-objective (L_{max}, $z = 0$) to a maximum makespan (C_{max}) objective. Then the latest due date in the job set is considered the starting point, and the LRPT rule is applied backwards. If all the jobs are finished by time zero after following the LRPT principle, the schedule is feasible. If not, it would normally lead to lateness greater than zero. Pinedo states that the accepted lateness (z) must be increased until a feasible schedule is reached [15].

However, since this thesis has modeled the number of machines as a soft constraint for the charging scheduling problem, the number of machines is simply increased until a feasible schedule is reached. One more machine means that the amount of jobs that can be processed simultaneously increases by one. For the charging schedule, this means that the number of EVs allowed to charge simultaneously is increased by one. This way, it is ensured that the practical interests of the EV owners take priority over ideal charging patterns in terms of power peak shaving. If this is implemented in a real setting, a site-specific capacity related cap on number of machines should be added, triggering an expansion of the permitted charging time interval.

The triplet for the charging problem on a reversed timeline, which is solvable by LRPT, is

$$\boldsymbol{P_m|prmp, r_j|C_{max}} \tag{3}$$

- P_m: Parallell machine environment consisting of m machines
- $prmp$: Preemptions allowed
- r_j: Release dates (restricting when jobs can start)
- C_{max}: Maximum makespan must be minimized

Figure 3 illustrates the method. The timeline is here illustrated from start in time zero to end on the furthest due date, and the LRPT principle is employed backwards, from right to left. The number of machines is modeled after the highest number of jobs that must at one point be run simultaneously for the schedule to be feasible (instead of increasing lateness, z, which the original theory requires). In this figure, it is apparent that the schedule is feasible because no processes "spill over" further to the left from time zero. The jobs in this example have different processing times, which is why some jobs are processed for longer than others.

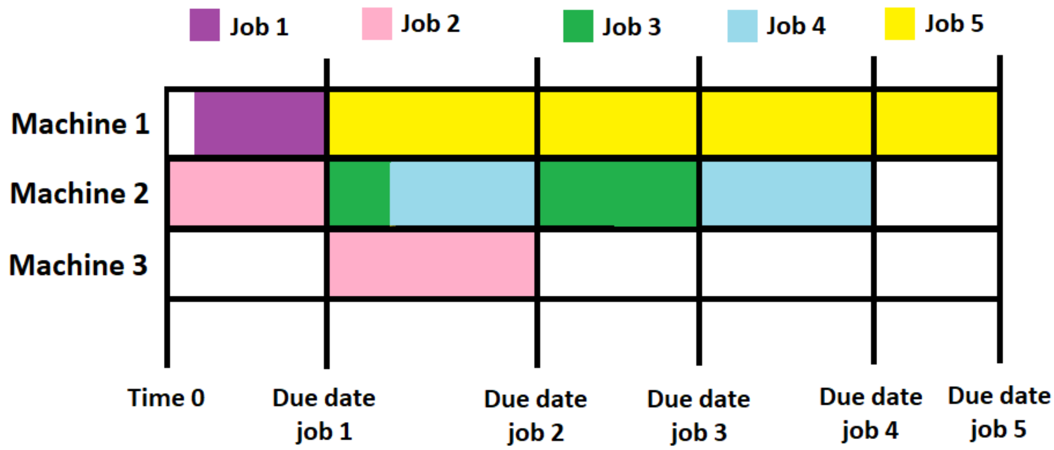

Figure 3: The LRPT principle employed backwards, from latest due date to the right until time zero to the left. The backwards LRPT treats the due dates of the jobs as release dates.

5.3 The Norwegian Power Market

5.3.1 Organization of the Power Market

Section 5.1 describes grid operations, i.e. power transmission and distribution, which in Norway is considered a natural monopoly. That is why Norway has one state-owned TSO, Statnett. However, electricity production and trading is market based, to ensure efficient resource allocation as well as reasonable prices on electric energy. A market based price formation minimizes the cost at which society meets its electricity needs [16].

The rest of this section describes the Norwegian power market following closely excerpts from the exposition in [16].

The electricity is traded on a platform called Nord Pool, a communal trading platform for the Nordic and Baltic regions. On this platform, electricity producers and consumers from the entire region make bids on electricity quantities they want to sell or purchase, to prices of their preference. The sum of all the bids make up an implicit auction, that culminates in a price settlement calculated by Nord Pool's algorithm. This happens once a day.

The bidders in the Nord Pool exchange participate in the wholesale market, which may be differentiated from the end-user market. The wholesale market deals in large quantities of electricity, and among the "consumers" in the wholesale market are power supplier companies. These are the market agents that small and medium-sized end users, such as private households and small businesses, purchase their electricity from. The prices that end users meet have local variations, in part because the standard price settled at Nord Pool is adjusted for local differences in transmission capacity and bottlenecks in transmission lines between areas. They also differ due to different contract designs.

Figure 4 illustrates the agents in the power market and their interconnections, differentiating between wholesale and end user market.

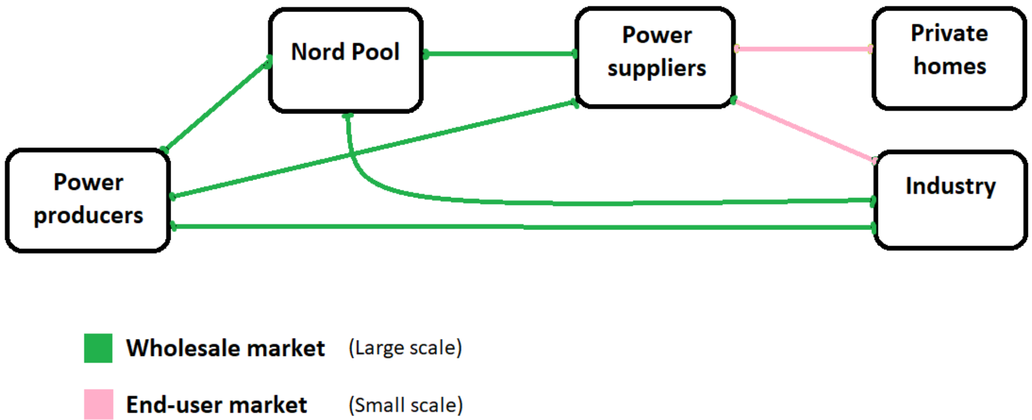

Figure 4: The agents in the Norwegian power market and their interconnections. The interconnections that make up the end-user market are differentiated from those of the wholesale market.

It is important to note that market mechanisms reflect the physical possibilities and limitations of power flow. This is why it is convenient to have a merged market for the Nordic and Baltic regions; because their transmission lines are well integrated with each other, which physically allows the energy to flow relatively freely across national borders in the region. It is also why the increasing linkage of the Nord Pool region with other European markets, which the transmission cables from Norway to the UK and Germany are examples of, affect Norwegian electricity prices. Norwegian power supply companies can respond to higher purchase bids from other regions, because they are physically accessible. The Nord Pool region has to some degree been integrated with the UK and Germany, and there is a system for price coupling with these regions, as well as the rest of Europe.

The wholesale market consists of the day-ahead and intraday markets, which together largely ensures the physical balance between supply and demand in the power grid. However, there are bound to be unforeseen events. This calls for an additional market: the balancing market. This is operated by the TSO as a grid operation task. The TSO coordinates bids for emergency supply and demand that are made specifically to cater to the balancing needs of the grid. V2G is considered a potentially valuable addition to this market, since EVs with two-way charging capacity can serve as both emergency supply and emergency demand.

5.3.2 End User Contracts

Different power supply companies, who purchase power at Nord Pool, compete for the end users, who purchase the power for their own consumption. Since electricity is a homogeneous product, the power suppliers compete in offering the most advantageous contracts to the end users. Currently, there are three main types [16]:

- Fixed-price
- Standard variable price
- Spot price

These are based on market prices, but have a mark-up for cost coverage. The contract with a fixed price sets the price relatively high, because it is in part an insurance against very high prices. With a spot price contract the price follows the fluctuations of the market price, with the risks and possible rewards that entails compared to a fixed-price contract. A standard variable price contract is something in between.

Table 1: Parameters of an electricity bill for a small to medium sized consumer

Parameter	Description
Grid rental	Fixed price for usage of the transmission, regional and distribution grid. Will soon become a variable price defined by the consumer's individual peak power demand
Electricity payment	Consumed amount of electricity multiplied with electricity price (variable). Electricity price depends on the contract types listed above.
Taxes and fees	Electricity consumption tax and various fees, hereunder green certificates (fixed)

Large power consumers also pay a power tariff as an addition to the first part, because a substantial portion of the transmission grid must be reserved for them. The tariff rate is set by the size of power demand the consumer is technically equipped to draw. The tariff for each month is then defined by the hour of peak demand over the course of the month [2].

Following the installment of AMS meters in all power consuming residences, including private homes, their hourly consumption can be measured as well. This enables the grid rental to be more aligned with each users actual grid occupancy, as is already the case for larger consumers. This is the change in billing for private consumers that is referenced in the introduction and in table 1. Although, a recent compromise resulted in the peak not being defined by peak hour, but a slightly broader time interval yet to be clearly defined [17]

5.4 Vehicle to Grid (V2G)

5.4.1 Purpose

As mentioned in the introduction, V2G is the concept of utilizing two-way charging capability in EVs by keeping the EV's battery as a power bank. The battery can serve as extra demand by taking in excessive power from the grid, and provide needed supply at a different time.

V2G can thus be regarded as a sub category of demand response, as well as at-will supply, like the water power that can be extracted from the magazines at any time. From a TSO or DSO's point of view, who has to maintain the balance between supply and demand at all times, the EVs provide flexibility to the grid. They also provide the opportunity to delay the need for grid capacity expansion by shaving power peaks.

EVs can shave power peaks simply by charging at times when demand from the grid is low, such as nighttime. This is purely demand response / load shifting. But by participating in V2G, they can also alleviate some of the demand from the grid during peak hours by serving as an alternative energy source outside of the grid, given they are capable of two-way charging. This can be done for instance by connecting the EV in a micro grid to a large power consumer, so that the large power consumer can demand a smaller amount from the grid at peak hours. This obviously serves both the grid and the large power consumer, who will pay lower power tariffs when they reduce their peak demand.

From an EV owner's point of view, V2G provides an opportunity to earn some extra money from their vehicle, with an alternative cost of 0, since it will not be otherwise occupied while it is parked.

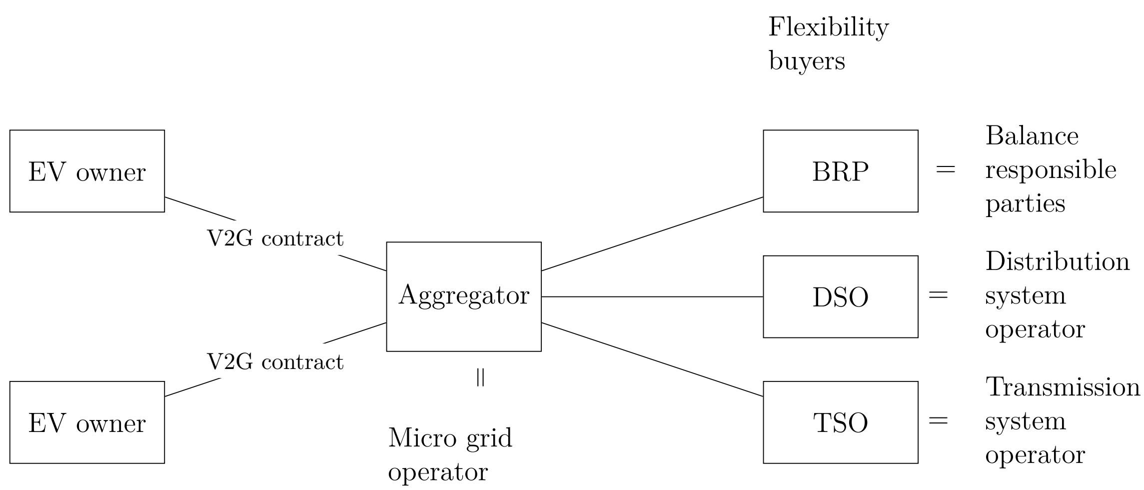

Figure 5: Relationships of actors in the V2G value chain, adapted from the figure in [12]. Micro grid operator is added as a subcategory of aggregator, since this is relevant to the case at Oslo Gardermoen Airport.

Figure 5 is adapted from the previously mentioned 2018 contract design article [12] and shows the relationships of the actors in the V2G value chain. Flexibility buyers is here a blanket term for actors in need of power from V2G. Because the EV's flexible supply and demand is their most important characteristic in the market, flexibility is seen as their most relevant service in V2G.

The aggregator is the control center who communicates with all the actors, and manages the recharging and discharging cycles. Each EV owner has a contract with the aggregator, while flexibility buyers purchase V2G services from the aggregator, not directly from the EV owners. A flexibility buyer can purchase an amount of electricity that comes from several different EVs, while dealing with only one actor: The aggregator.

In the case at Oslo Airport Gardermoen, the airport is the operator of a micro grid, where they are both the aggregator and a flexibility buyer. This setup is expanded on in section 7.

5.4.2 Organizing V2G: Contract Designs

Since demand response is an important part of the desired service from the EV owners, demand response literature can be used in the design of the contract between EV owner and Avinor. The contract can be designed to trigger the desired behavior from the EV owners. However, literature on how to organize remuneration and other important interests for the EV owners is limited [12].

In existing literature, the most common way to think of V2G is that the EV owner temporarily secedes control of their vehicle to the grid operator [12], probably the DSO because of the small scale, to use for balancing purposes in the grid. In a sense, the EV owner rents out their car battery as a power bank, and has no control or knowledge of how much their battery is recharged and discharged during the rental time. This line of thinking corresponds to a ***control based contract***, a term that originates from demand response literature, and is used in V2G context by an article from 2018 called "Conceptualization of Vehicle-to-Grid Contract Types and Their Formalization in Agent-Based Models" by Lukszo et. al. [12].

The article [12] proposes two more advanced contract types that regard V2G a little differently in terms of the service transactions that take place. These contract designs also draw on concepts from demand response literature, and thus incentivize desireable behavior from the EV owners.

The V2G contract designs from the article [12] are designed for fuel cell EVs (FCEVs), also known as hydrogen vehicles. They therefore contain fuel level as a parameter. For the purposes of this thesis, fuel level is switched with battery level. The unspecific term "energy" is also switched with electricity, since that is the only energy form being traded with regular EVs. Adjusted to suit regular EVs, and with some paraphrased / elaborated descriptions, the three contract designs from the article [12] are as follows:

5.4.2.1 Control Based Contract

Table 2: Parameters of a control based contract

Parameter	Description
Time interval	Plug-in time, voluntary or precommitted
V2G remuneration	Electricity and capacity remuneration
Guaranteed battery level	Minimum percentage of the battery guaranteed to be charged after operation, requested by driver

The control based contract design, as shown in table 2, is the least complex alternative. The aggregator temporarily seizes control of the EV, and stores and withdraws energy to serve grid purposes. The EV owner agrees to a certain plug-in time, where they essentially rent out their battery as storage capacity. They are typically compensated for the service by fixed-price remuneration derived from plug-in time or length of contract period. They are guaranteed a minimum battery level upon return.

5.4.2.2 Price Based Contract

Table 3: Parameters of a price based contract

Parameter	Description
Minimum V2G price	Minimum price for activation, defined by driver
V2G remuneration	Remuneration for electricity supply, for example market price (>= Min. V2G price) multiplied with amount of electricity
Guaranteed battery level	Minimum percentage of the battery guaranteed to be charged after operation

With a price based contract the EV owner stays in control of their vehicle, in that they decide the terms for V2G activation. Rather than renting out their car battery for storage of someone else's electricity, the electricity belongs to the EV owner as soon it enters their battery. The aggregator must purchase the electricity from the EV owner when they want to use it, to a price the EV owner is willing to accept. As shown in table 3, the EV owner decides on a sales price (Minimum V2G price) in advance, and a sale is triggered by the offered price (for example the market spot price) reaching the sales price. In demand response terms, this is an indirect sales activation mechanism.

The remuneration for the EV owner is whatever revenue is accumulated at the end of the plug-in time. The electricity volume sold is implicitly decided by the market price development relative to the sell price the EV owner has set, and is not known in advance.

The article [12] mentions that the price based contract design might be best suited for a V2G setup where the EV owner sells to the wholesale market, here-under the balancing market.

5.4.2.3 Volume Based Contract

With a volume based contract the EV owner also stays in control of their vehicle, and has ownership of the electricity entering their property - but the sales activation mechanism is different. Instead of deciding a price they are willing to sell to, they commit to selling a certain electricity volume during a certain plug-in period, as shown in table 4. In demand response terms, this is called an explicit sales activation mechanism.

Table 4: Parameters of a volume based contract

Parameter	Description
Time interval	Plug-in time, voluntary or precommitted
Maximum volume	Maximum electricity volume usable for V2G, for example in kWh or number of charging cycles, decided by the driver
V2G remuneration	Electricity and capacity remuneration
Guaranteed battery level	Minimum percentage of the battery guaranteed to be charged after operation
Minimum battery level required at plug-in	Calculated level of electricity required in the vehicle before plug-in

Since the EV owner agrees to a certain sales volume beforehand, no matter the market price development, and the aggregator controls the time of sale according to the needs of the grid; the revenue from electricity sale alone might not be enough to make the trade worth it in the eyes of the EV owner. However, the service required from the EV owner in this contract design is not only the energy itself, but the availability of their battery's capacity. For this reason, the remuneration in this contract design includes a fixed portion that is payment for capacity, in addition to the revenue from electricity sales. This is similar to the parameters of a regular electricity bill that consumers currently pay to a power supplier, as described in section 5.3.2, where the transmission grid rental is a fixed payment for capacity.

The last parameter, Minimum battery level required at plug-in, is in the article [12] explained to be calculated from the sales volume and the guaranteed battery level upon the driver's return. It is calculated on the premise that the battery can not be recharged during plug-in time, stemming from the fact that these contracts are originally designed for FCEVs (the parameter was originally min. fuel level). With regular EVs, this parameter should rather be calculated based on whether the plug-in time leaves enough time for recharging before or after a sale occurs.

This contract design can be seen as a compromise between the interests of each party involved in V2G. The article [12] suggests that a volume based contract might be attractive for EV owners with a very predictable schedule. It could also be better suited for a micro grid setup, where the most important purpose of the EVs is balancing local energy supply and demand, or emergency capacity. The remuneration could be designed to reward availability.

6 Societal Context of the Case Study at Oslo Gardermoen Airport

6.1 Current Status of V2G. The Need for Power Peak Shaving in the Grid

V2G is currently not well known in the Nordic region, even among experts [18]. It is often conflated with smart charging (load shifting) of EVs, which is what the charging schedules are an example of. V2G technology is at an early stage, and is not currently in use other than in pilot projects [18]. However, the difficulties are not technical, but rather related to organizing, particularly managing incentives for the relevant parties [11]. This includes grid operators, EV manufacturers and especially EV owners. Currently, only one EV manufacturer on the Norwegian market provides two-way charging capability: Nissan with the models Leaf and eNV200 [9].

Since Norway already has a great amount of flexibility in the power grid due to easily regulated water power, as mentioned in 5.1, V2G is viewed as less relevant here than in places with less flexible power sources [18]. This can be interpreted as an indication that V2G is primarily seen as a provider of balancing services to the wholesale market. This is also apparent in the fact that most recommendations from experts to promote V2G focus on policy makers, seen purely from a grid operator perspective [18]. There are very few consumer (EV owner) oriented suggestions [18].

However, as explained in section 5.4, V2G can also be used to shave power peaks. This is highly relevant in Norway, seeing as the current power grid is not dimensioned for the anticipated increase in power peaks stemming from greater influx of renewable energy sources other than hydro power, as well as the decarbonization and following electrification of society [19]. The transmission capacity in the power grid will need to be expanded in order to meet this great increase in demand, but that will take time. Both because of the time it takes to build, but also regulation and political and local resistance to the construction of new transmission lines.

Power peak shaving through adjustment of consumer habits can therefore serve as an important delay of the inevitable need for grid capacity expansion, and enable more electrification before the grid capacity is expanded. The electrification of the transport sector entails a significant portion of the increased demand, which makes smart management of EVs particularly relevant. The charging of EVs entail great surges in demand at specific times, especially the more similar people's daily routines are. Their toll on the power grid can be reduced both by smart charging, i.e. load shifting, and with V2G, which is both load shifting and flexible supply. With the objective of power peak shaving in mind, it is relevant to also consider V2G from the EV owner's point of view. When participating in V2G, EV owners are no longer merely consumers in the electricity market, but also small scale producers. V2G cannot work unless EV owners decide to participate.

6.2 EV Owners' Perspective. V2G as an Opportunity to EV Owners

Even though V2G is rarely considered from the EV owners' perspective [11, 18], products related to money-saving load shifting are already being marketed to private power consumers [8]. Examples of this are smart home systems, including smart chargers that ensure charging of EVs during nighttime, when the electricity price is typically lower due to lower demand.

There are signals from the EV manufacturing business [20] that capability for two-way charging - that is, an EV's ability to not only charge the battery up, but also transfer the energy out of the battery again, will become a standard feature in EVs. If / when this happens, a natural development in the smart home systems would be to include so-called "Vehicle to Home" (V2H) [20] [9] where the EV owner can charge their car battery at a time when the price is low, and store it there for later use in their home when the price is high - provided they are not planning to drive at that time. In that way, the EV owner can buy less expensive electricity from the market during power peaks in daytime. With the pending billing system for private consumers with capacity payment similar to power tariffs, this would also reduce the part of the EV owner's bill that is defined by peak demand.

The concept of V2H is obviously related to V2G. V2H is a more mature technology than V2G, and is likely to precede V2G in widespread implementation [20]. The more technically easy something is to implement, and the less complicated to organize in terms of conflicting interests, the more likely it is to be implemented. As for V2G, there is still much to organize from the grid operations side [20]. But from an EV owner's perspective, a simple addition in the V2H system could allow the EV owner to sell the energy stored in the battery back to the grid when the price is high, if they do not need it in the home at that time. In this author's opinion, V2G is likely to first be implemented in contexts where it is easiest to organize, such as an extension of a V2H system.

The more common smart home systems and V2H becomes, the less foreign the idea of V2G should be to the regular consumer - given that it is presented as an advantageous offer to them, rather than just a favor to the grid. The documented scepticism to V2G [11] should be considered with that in mind. There is ample opportunity to organize V2G in a manner that is guided by shared value (expanded on in section 9.2) for the EV owners and the grid.

The article "Are electric vehicle drivers willing to participate in vehicle-to-grid contracts? A context-dependent stated choice experiment" from 2021 by Bing Huang et. al. [11] presents a survey of V2G participation willingness among EV owners done in the Netherlands in 2019. Judging by the percentage of respondents who knew of V2G before taking the survey (almost half), it is reasonable to assume that V2G is more commonly known in the Netherlands than in Norway, where it is relatively unknown even among experts [18]. Lacking a Norwegian survey, this thesis assumes that the Dutch population will be representative of the Norwegian population when V2G becomes more known, since the inherent conflicts of interests between the EV owners and the grid operators are the same. On that note, it should be mentioned that the Dutch survey's respondents are predominantly well educated males with high income, presumably because this group is over represented among EV owners in the Netherlands.

Some important take-aways from the article [11] regarding V2G participation willingness are:

- Around half of the Dutch respondents were willing to participate under present day circumstances
- Guaranteed minimum battery level upon return: Strong positive effect on participation willingness
- The lower the guaranteed minimum battery level; the higher remuneration required
- The higher the (fixed) remuneration; the higher the participation willingness
- But: Remuneration has low effect on willingness to extra plug-in time
- General dislike for long plug-in time
- Discharging cycles: The contract attribute of most concern. The more discharging cycles in the contract, the lower willingness to participate.

The survey shows that almost half of the respondents were reluctant to participate in V2G under current technical circumstances, but that only one third would decline given a hypothetical recharging time of only five minutes. This can be assumed to be related to "range anxiety", the worry that there is insufficient energy in the battery to get the EV as far as it needs to go. This indicates that willingness among EV owners to participate in V2G increases with reduction of perceived risk that their own interests will be encroached upon. The survey showed that remuneration has limited mitigating effect if V2G participation becomes inconvenient.

Another important interest for the EV owner that the survey uncovered, is the issue of battery degradation. It was shown that the more discharging cycles the contract specified that the EV would undergo in the service of V2G, the less willing they were to participate.

The actual degradation to the battery per charging cycle is minimal. The article [11] estimates the monetary devaluation of a Nissan Leaf battery of 50 kWh to €1,8 per cycle, based on the method for quantifying value degradation developed in the article "The economics of using plug-in hybrid electric vehicle battery packs for grid storage" from 2010 [21]. In stark contrast to this arguably negligible degradation, the EV owners' expectations of remuneration per extra charging cycle during V2G plug-in is estimated to €7 per cycle sold, inferred from some of the responses. This indicates a significantly exaggerated concern for battery degradation among EV owners, but they are the ones who decide whether to participate in V2G.

In this author's opinion, this highlights the importance of a contract design that is built on a thorough analysis of each party's interests, in pursuit of ensuring EV owner participation in V2G. It also indicates that it is wise to introduce V2G as a concept in contexts where it is technically easy to accommodate EV owners' interests.

7 Case: V2G Pilot Project at Oslo Gardermoen Airport

7.1 About

Oslo Gardermoen Airport, owned by Avinor, is located in the vicinity of Oslo, the capital of Norway, shown in figure 6.

Figure 6: The location of Oslo Gardermoen Airport. [22]

Avinor is hosting a V2G pilot project at Oslo Gardermoen Airport, hoping that they can use the EVs parked in their long term parking house, P10, as a way to reduce their peak power demand from the grid, and thereby reduce the power tariffs they pay. This would be accomplished by utilizing the EV pool as energy storage to be filled up during low demand hours, and as an alternative power source during peak hours - much like the EV owner from the V2H example would use their own EV in their garage. In addition to shaving power peaks, this use of the EV pool would also reduce costs for electricity purchase, since electricity is cheaper during low demand.

NMBU is conducting the pilot project hoping to gather experience with V2G that can further the implementation of the technology.

There are several reasons why an airport is a suitable location for a V2G pilot project. Besides the obvious incentive for the airport to shave power peaks, there are characteristics specific to this context that alleviate important barriers for V2G participation by EV owners: The EV owners usually know when they will be back to collect their EV, because they have a return flight. That way, the airport, can plan to have the EV fully recharged by the indicated return date. This should greatly alleviate range anxiety.

Another important characteristic of parking at an airport is that long plug-in time is a natural effect of the EV owners' own schedule, because their EV is parked while they are away traveling. Long plug-in time, which is an unpopular V2G contract parameter in other contexts [11] is therefor not inconvenient to EV owners in this context.

Additionally, the pool of EVs parked at an airport will not consist of the same EVs for any length of time. Most people do not fly that often. It can thus be argued that the battery degradation of each EV due to V2G participation will be negligible. However, since this is a concern for EV owners that can not be entirely eliminated, V2G participation may rely on a contract design that gives the EV owners a sense of overview and control over the extent of the use of their battery. This claim is substantiated by the aforementioned Dutch survey [11].

7.2 A Micro Grid V2G Setup

The case at Oslo Gardermoen Airport can be regarded as a micro grid. The airport wishes to use the EV pool in their parking house much like an EV owner would use their EV in their home in a V2H setup. V2H is an example of a very small micro grid, consisting of two entities: The EV and the home.

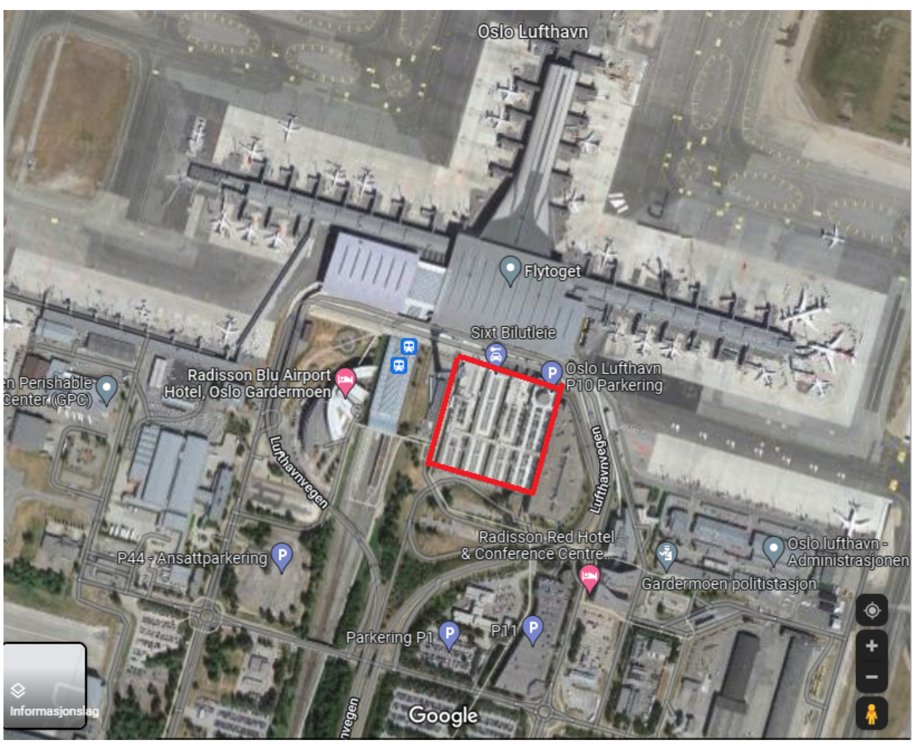

Figure 7: The location of the parking house P10 at Oslo Gardermoen Airport, outlined in red. As one can see, the parking house is located adjacent to the airport. [23]

An airport with a parking house full of two-way capable chargers and two-way capable EVs could use those EVs in the same manner as the V2H home owner. This case could also be considered a micro grid, with more entities: The airport, and the two-way charging capable EVs.

There is currently no infrastructure that allows excess energy from the P10 parking house, shown in figure 7, to be used at different locations of the airport. There is a dedicated AMS meter for the P10 parking house. The airport's demand for power from the EVs is therefore restricted to the needs of the P10 parking house, presumably for electric heating, most notably the heating cables in the ground that prevents icing. This information was relayed during a guided tour of the airport by Avinor for the researchers in the pilot project.

The close proximity of the P10 parking house to the rest of the airport makes for a lucrative opportunity to include the rest of the airport in the micro grid in the future, provided that the infrastructure can be adjusted so that they can be connected to the same AMS meter, and the power supplier accepts this.

Figure 8 illustrates what can be regarded as a microgrid: the EVs and the P10 parking house where they are parked, and its connection to the power grid as well as the rest of the airport. The P10 parking house and the rest of the airport are connected in the sense that their collective peak demand defines the power tariffs that Avinor must pay. The power grid is here a blanket term for the flexibility buyer agents illustrated in figure 5. Their distinction is not relevant for the analysis of this case study.

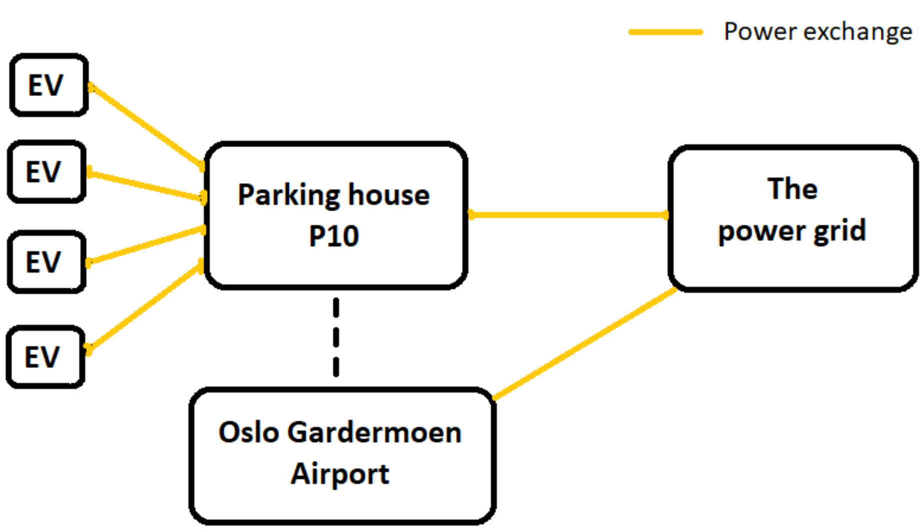

Figure 8: Illustration of the micro grid at Oslo Gardermoen Airport, consisting of the EVs and the P10 parking house, and their connection to the power grid.

7.3 Requirements From a Contract Design

The airport case's key difference from V2H, of course, is that the airport does not own the EVs. The EVs are just standing on their property. If they want to use the EVs in this way, they need to negotiate terms with the EV owners. As for the EVs, they are technically capable of providing power both to the airport for their internal use, and out to the grid, through the airport's equipment. How this reality corresponds to a contract in terms of commitments and remuneration, is less obvious than say, when an EV is connected to a public charger in the city.

An important challenge is to design the V2G contract in a way that is sufficiently advantageous for EV owners that they will participate in the project - while also not making it unsustainable for Avinor. As mentioned earlier, this should be done by analyzing the roles each party plays, and what their interests are in the relevant scenario.

The EV owners in this scenario are consumers, because they require energy to recharge their EVs. They are also producers, because they provide two products: Energy, that can be sold both to the airport and to the grid, and capacity, which is required by the airport. The airport in this scenario is both consumer, producer, and aggregator. Consumer because they require energy and capacity from the EVs, and aggregator because of their role of coordinating V2G and participating in the market on behalf of EV owners. Agents that are both consumers and producers are typically called "prosumers". So both the EV owners and the airport are prosumers, while the airport additionally is the aggregator.

8 Method

8.1 Scheduling Theory and Python Simulation

This section expands on the process of applying the scheduling theory relayed in section 5.2 to a load shift and peak shaving motivated scheduling problem for EV charging. Since the author could find no previous examples of this, the basic building stones of the theory were assessed to explore the possibility of combining them into a useful model of the problem.

The section begins by reiterating the considerations in formulating the problem, and continues by describing how the problem was solved with a Python program. The program builds partly on the LRPT principle that was found in Pinedo's book [15] to be a solution to part of the problem, and partly on this author's own idea of modeling an abstract number of machines to fully solve the problem. The logic of the program is explained insofar as it contributes to explain the solution to the problem. The code in its entirety as added as an attachment to the thesis.

8.1.1 Formulating the Scheduling Problem

Given the tools provided by the scheduling theory described in section 8.1, the triplet (2) was constructed to describe the charging scheduling problem. The construction was built on the following considerations:

8.1.1.1 Choice of machine environment (α)

The chargers are here regarded as machines, of which there are several that can operate simultaneously; thus the machine environment in this case makes it a parallel machine problem (P_m). For reasons that will be expanded on, all chargers are regarded as normal speed chargers with the same characteristics; therefore P_m and not Q_m.

8.1.1.2 Choice of processing characteristics (β)

A full charging of one EV is regarded as one job. Since charging processes can be stopped and restarted without difficulty, preemptions are allowed.

It was considered to add r_j, release dates of the jobs, to the processing characteristics. All EVs in need of charging do not arrive at the same time. However, even though it can be assumed that new EVs arrive every day, it is not known when, how many, or anything about their characteristics, like their charging needs and due dates.

This author decided to only include what is known in the triplet, which in this case is by nature a snapshot in time, since the circumstances change daily. It is only known which EVs with their respective charging needs and due dates are parked right now. It is not known how the picture will look tomorrow. It was chosen to disregard the possibility of EV owners notifying ahead of time that they are coming, because that only alleviates the problem to a small degree: That the future is not known.

To account for the daily changes in the collections of parked EVs, it was concluded that each charging schedule should be regarded as just that, a snapshot in time - a sensible charging plan based on the currently parked EVs - that is updated once per day, taking into account the new EVs that arrived during the day. Since it makes sense both power peak wise and electricity price wise to only charge during nighttime if possible, the schedule only needs to be updated once per day, in the evening, before the nightly charging starts.

8.1.1.3 Choice of Objective to be Minimized (γ)

The case really has two objectives to be minimized: Maximum lateness (L_{max}), because the charging must be finished by the EV owner returns; and number of EVs that are charged simultaneously, for minimizing power peaks.

The latter, which can be regarded as maximum idleness of the machines, is not a defined objective function in Pinedo's book [15] that can be set in for γ in the triplet. The author of this thesis opted instead to solve it by adding a feature to the Python program that minimizes the number of machines; the m in P_m in the triplet.

The chosen objective to be minimized is thus maximum lateness (L_{max}). It must not only be minimized; the accepted lateness, z, must be set to zero. No tardiness can be allowed, because the driver must be guaranteed that their vehicle is ready for them upon return. Allowing delays would be a serious downgrade of the service that is offered them today. L_{max} with zero tardiness is therefore a hard constraint, which takes priority over the minimization of modeled machines, a soft constraint.

8.1.1.4 How the Number of Machines (m) is Modeled

Instead of letting one machine represent one physical charger, the collection of chargers is modeled as a minimized number of "machines". The number of machines determines how many jobs can be processed simultaneously. Thus, minimizing the number of "machines" will minimize the amount of EVs charging at the same time. This is why it was chosen to disregard the potential for fast chargers to complete jobs faster: If the chargers can be regarded as homogeneous, they can be modeled as one machine. For scheduling purposes, it does not matter which physical charger the respective EVs are actually connected to. If there are fast chargers in the parking house, the only negative impact of the simplification is that their fast charging potential will not be utilized. They will be scheduled to work as though they need the same time to complete a charging cycle as a regular charger.

To achieve minimization of the number of machines, i.e. minimization of EVs simultaneously charging, the Python program starts by solving the problem as a single machine problem; setting m equal to 1. If the resulting schedule is proven feasible, it concludes that the collection of chargers can be modeled as one machine - meaning that all EVs can be fully charged by their due dates inside the defined permitted charging hours, while allowing only one EV to charge at a time. If the resulting schedule is not proven feasible, the program makes a new attempt with two machines modeled instead, and so on. It continues to add one machine until a feasible schedule can be found.

The theoretical maximum for the number of machines is the number of EVs parked. If this happens, it means that all the EVs need to be allowed to charge at the same time in order for all EVs to be ready by their due dates. Failing a feasible schedule with the maximum number of machines, the parameters for permitted charging hours (ideally set to the eight hours of the night with lowest demand and electricity price [24]) must be altered in the program. If implemented in a real setting, a capacity related cap shoud be put on the permitted number of machines, if the electrical system is not dimensioned for all chargers to draw power simultaneously. However, the scenario of the number of machines reaching the theoretical maximum is unlikely in the airport case, since that would imply that the due date of all the EVs is the following day.

8.1.2 Creating the Schedule in Python

As for the actual creation of the schedule, Pinedos book [15] was consulted for the formulated charging problem triplet, triplet (2). It was found that it is one of the few parallel machine problems with a due date related objective that is solvable in polynomial time. As previously explained in section 8.1, this is done by reversing the timeline in the problem, and apply the LRPT rule to the resulting triplet, triplet (3).

In a single machine problem, only one job can be processed at a time. In a double machine problem, two jobs can overlap partially or fully, and so on. As explained in section 8.1, with preemptions allowed, a job does not need to continue until completion once started. It can be paused and restarted any number of times, as long as it is finished within the defined constraints. On the reversed timeline, where the LRPT process goes backwards in time starting at the furthest due date, and the due dates are regarded as release dates, the "due date" for all jobs is time 0. As long as all the jobs can be completed between their respective release dates and time 0, the schedule is feasible.

The Python program checks whether the schedule is feasible by simulating the LRPT charging process within the defined constraints, which is the release dates of the jobs, the attempted modeled number of machines, and the permitted charging hours. When the process finishes at time 0, it checks whether the remaining processing time (RPT) of all EVs is 0. If this is not the case, it means that not all EVs will be fully charged by their due dates on the currently modeled number of machines. In that case, the process is reiterated with one more machine, until a feasible schedule is reached.

The program then finishes, and yields an output consisting of which number of machines was modeled, plus the feasible charging schedule.

To summarize, the program takes information about a pool of parked EVs as input, and gives a charging schedule as output, examples of which are presented in section 9.1. For the purposes of this thesis, the program is a PoC, not a simulation of actual EVs at Oslo Gardermoen Airport. The input is therefore set by the author of this thesis or simulated by the program.

8.1.3 Possible Extensions of the Scheduling Program

8.1.3.1 V2G Functionality

The charging scheduling program can be extended to accommodate V2G functionality. Currently, it facilitates load shifting / smart charging of EVs. In an EV pool where a portion of the EVs participate in V2G, the schedule can account for EVs that sell electricity during certain days, and thus be in need of charging several times during the time it is parked. In the program, this can be accomplished simply by resetting the remaining processing time (RPT) to maximum after an amount of energy equal to a charging cycle is sold.

The program can also be extended to keep track of how much energy is bought (to charge the battery) and how much is sold by each EV, and calculate the revenue according to the proposed contract design.

8.1.3.2 Daily Updates of the Charging Schedule

Currently, the program yields one schedule based on the EVs that are parked in the parking house at a certain point in time. The program can be extended to update the EV pool once for each day simulated. EVs that reach their due date will be discharged, and new EVs will arrive. The new EVs' respective due dates and charging needs may affect the schedule, and demand an update to the schedule. Since charging will primarily happen during nighttime, the update should happen once every evening, after the new EVs of the day have arrived, and right before the charging starts.

With this extension, one could simulate for instance five operational days at the parking house, and receive five schedules - the four latter being updated iterations of the first.

For a version of the scheduling program to work with real world input, such updating functionality is obviously a necessary feature.

8.2 V2G Literature Research

The primary question related to V2G in this thesis is how to organize it to be eligible to EV owners. The original idea was to compare two different ways to regard V2G: The grid operator renting the EV battery (most common view [12]), or the EV owner participating in energy trade. The hypothesis was that the latter would be more eligible, and could be formalized in a contract design.

The research started broadly about V2G, both with regards to how far the technology has come, examples of setups, and social reception. After finding a recent study (published in 2021) from the Netherlands [11] indicating specific concerns for EV owners and how they may be alleviated, it became clear that contract design was indeed an important factor in participation willingness among EV owners.

After specifying "contract types" in the V2G literature research, the author of this thesis came across one article on the subject (in addition to the Dutch study [11]), published in 2018: "Conceptualization of Vehicle-to-Grid Contract Types and Their Formalization in Agent-Based Models" by Lukszo et. al. [12]. The article had formalized three contract designs, two of which corresponded to the concepts this author had originally planned to compare (control based and price based contracts). However, the third contract design in the article (volume based) appeared to be an even better fit for the case study at Oslo Airport Gardermoen.

This thesis therefore utilizes the concepts from the article [12] as basis for its analysis of an EV friendly contract design. Since the thesis is a contribution to the case study at Oslo Gardermoen Airport, the main focus is to arrive at a contract design suitable for that context.

A survey of how such a contract design would be received by Norwegian EV drivers may be a prudent next step for future work in the project. This is further discussed in section 9.2.

9 Results and Discussion

9.1 Charging Scheduling. A PoC Simulation

This smart charging method employs the scheduling theory described in section 5.2, and tailors it to the specific objectives of charging a park of EVs, as explained in further detail in section 8.

The following example schedules are yielded by the Python program attached to this thesis. The program is a PoC simulation, where certain parameters are set by the user depending on which scenario they want to explore.

Directly above the schedule the modeled number of machines is relayed. This is different every time, because it depends on the number of EVs, their due dates and their charging needs. The row on top of the schedules represents each EV in the EV pool. The column to the far left represent time, in hours.

For simplicity, the charging needs of all EVs is set to 6 hours. For scheduling purposes, it is more relevant to define charging need by hours than by kWh. The due dates (or rather, number of days until due dates) are randomly generated numbers inside a specified interval. For these examples, the interval is set between one and three, to avoid unnecessarily long example schedules. The concept is also best demonstrated with a hypothetical low number of EVs, to avoid unnecessarily wide schedules.

Charging is restricted to the eight hour time span between 2200 and 0600 hours, because these are typically the hours with lowest demand and lowest electricity price in Norway [24]. Individual users of the method can define the permitted charging interval according to fit their own circumstances.

Since there are eight charging hours per day in the simulation, and each row represents one hour, the number of rows in the schedules equals the number of days until the furthest due date in the EV pool multiplied with eight.

9.1.1 Example Schedule 1

Figure 9 shows a charging schedule made by the Python program from this thesis.

Relevant parameters:

- **Charging hours per night:** 8
- **EVs:** 6
- **RPT (remaining prosessing time, hours):** 6
- **Days until due date of each EV:** 1, 1, 1, 1, 1, 2

Since the furthest due date in the EV pool is two days from now, the number of hours shown in the schedule is 16 (counting from 0 to 15). Since the due date of five of the six EVs is the following day, all five must be charged on the first night. Given that they each need to charge for six hours during a time span of eight hours, four EVs must be allowed to charge simultaneously at the most. This results in the chargers being modeled as four machines.

As one can see, EV-2, with due date two days from now, does not start to charge before it has to in order to finish by its due date.

Number of machines modeled: 4

	EV-1	EV-2	EV-3	EV-4	EV-5	EV-6
0						
1	charge		charge			
2	charge			charge	charge	charge
3			charge	charge	charge	charge
4			charge	charge	charge	charge
5	charge			charge	charge	charge
6	charge		charge		charge	charge
7	charge		charge	charge		charge
8	charge		charge	charge	charge	
9						
10		charge				
11		charge				
12		charge				
13		charge				
14		charge				
15		charge				

Figure 9: Example schedule 1

9.1.2 Example Schedule 2

Figure 10 shows another example schedule generated from the same input. The randomized due dates landed differently this time, resulting in a different schedule.

Relevant parameters:

- **Charging hours per night:** 8
- **EVs:** 6
- **RPT (remaining prosessing time, hours):** 6
- **Days until due date of each EV:** 1, 2, 2, 1, 3, 2

Number of machines modeled: 2

	EV-1	EV-2	EV-3	EV-4	EV-5	EV-6
0						
1						
2			charge			charge
3	charge			charge		
4	charge			charge		
5	charge			charge		
6	charge			charge		
7	charge			charge		
8	charge			charge		
9		charge				charge
10		charge	charge			
11		charge	charge			
12		charge				charge
13			charge			charge
14			charge			charge
15		charge				charge
16		charge	charge			
17						
18					charge	
19					charge	
20					charge	
21					charge	
22					charge	
23					charge	

Figure 10: Example schedule 2

Since the furthest due date in the EV pool is three days from now, the number of hours shown in the schedule is 24 (counting from 0 to 23). One of the EVs having a further due date than in the previous example leads to only two EVs needing to be charged simultaneously this time.

Again it is apparent that no charging startes before it needs to in order to reach its due date, within the constraint of the number of available machines, and the constraint of permitted charging hours. No more than two EVs charge simultaneously at any point.

The interrupts that occur due to the LRPT principle are also well exemplified. Keep in mind that LRPT is applied backwards, while the schedule shows the charging on a regular timeline.

9.1.3 Applicability of the Charging Schedules

As discussed under possible extensions of the program in section 8.1.3, the schedules are based on the EV pool as it is any given moment in time. The idea is that an update would happen every day, where new EVs arrive and cause adjustments. Each EV will gradually be replaced by new ones. This means that none of the schedules will realistically be followed exactly as they are. It is likely that the adjustments to the original schedule will cause some EVs to require charging outside of the defined permitted charging hours, due to for instance unforeseen charging needs of new arrivals with a short due date. How the daily adjustments would affect the effectiveness of the schedules in terms of peak shaving can be tested in future work. Either by implementation in a real setting, or by an extension of this simulation, as described in section 8.1.3, where input is given according to the circumstances one wants to examine.

The method can, as far as the author understood from a guided tour at Oslo Gardermoen Airport, be implemented with the equipment that is already installed at their P10 parking house. They need only adapt the algorithm in this thesis to their systems, with some aforementioned extensions The equipment is already capable of automatic interrupts and restarts due to safety measures, according to the employee who functioned as a guide on site.

In an EV park with 100 % V2G participation, this scheduling method will have limited (but not negligible) relevance. This is because if every EV will sell a full charging cycle every day, they all will be in need of charging the following night, and the number of modeled machines would be equal to the number of EVs, capacity restrictions notwithstanding. However, in the likely scenario where a significant percentage of the EVs in the V2G park are unable - or unwilling - to participate in V2G, scheduling their charging with the proposed method in this thesis would still be useful. And even in a scenario where this particular scheduling method is less effective, charging should still be scheduled to nighttime as much as possible.

9.1.4 Charging Schedules as an Optimization Measure

This optimization measure is relatively simple, compared to for instance machine learning algorithms that could take into account existing power peaks when timing the charging, and update continually instead of once a day. However, the charging schedule measure is a significant improvement from how it is done today, where the charging of a vehicle starts once it is connected to the charger (or at a time chosen by the owner in the app).

This author would also argue that charging scheduling has a comparatively good ratio between how much it costs to implement, and how much there is to gain from it. Power peak wise, much is already achieved simply by delaying the charging until nighttime, assuming that the power peaks occur during daytime (if not, the method works as long as there is an identifiable daily interval with low probability of power peaks occurring). It also reduces the direct charging costs because "nighttime" can easily be defined as the hours during the night with the typically lowest electricity price.

Ensuring that no more EVs than necessary are charged at the same time is perhaps already more complicated than it needs to be to sufficiently achieve the desired peak shaving goal - at least at the current scale of the EV pool. However, scheduling the charging such that no EVs charge before they have to in order to complete by their due date, increases the chance of fitting all the charging hours into the hours with lowest demand and lowest electricity price. This makes charging schedules a worth wile optimization measure in this author's opinion.

9.2 Approach to Mutually Beneficial V2G Organizing

9.2.1 Shared Value

For V2G to work in practice, EV owners must be willing to make their property available to service the power grid. The chosen approach of this thesis is to reformulate the premise. Instead of asking how to entice EV owners into accepting something that is inherently disadvantageous to them, this thesis approaches V2G from a perspective of shared value.

The term "shared vaule" was coined by Michael E. Porter and Mark R. Kramer in an article for the Harvard Business Review in 2011, in which they dispute the commonly held belief that there is an inherent contradiction between profitable business and the good of society, particularly in terms of environmental sustainability [25]. Critics argue that this is only true for certain cases. While that may be true, it does not negate the fact that before accepting a conflict of interest between stakeholders, much would be gained by looking for business solutions that generate shared value for all stakeholders.

In the case of V2G, which is in its infancy as a business model, the possibility of an implementation based on shared value should at least be considered. In this context, that would mean exploring V2G as primarily a mutually beneficial exchange between EV owners and the party who represents the interests of the grid. As opposed to exploring it as a concept that is advantageous to the grid and disadvantageous to the EV owners, and discussing EV owner participation primarily in terms of how much compensation is required in order for them to accept the inconvenience.

While there may be undeniable conditions that the EV owners will need to commit to for their EV to be useful for V2G, this is not necessarily inconvenient to the EV owner. That depends on the circumstances. With this in mind, the research of this thesis is focused on implementation of V2G under circumstances where inconvenience to the EV owners can be avoided (which the case study at Oslo Gardermoen Airport is a prime example of). That leaves room for organizing V2G in a manner that can be honestly represented as an advantageous opportunity for EV owners, as opposed to an inconvenience that must be compensated. The Dutch survey [11] discussed in section 6.2 uncovered the strong tendency that EV drivers would not accept the inconvenience of extra plug-in time after their preferred time to unplug the EV, even in exchange for additional financial compensation. Although, in this case it might be relevant to remember that the respondents of the survey were predominantly individuals with high income. This might make them less susceptible to financial incentives than EV owners in a future where EVs are the norm for people of all income classes. This development is at an advanced stage in Norway, where EV purchase and ownership has been subsidized for many years [26].

Even with the reservation regarding representative respondents, this strongly suggests that avoidance of inconvenience to the EV owners in the practical organization of V2G is necessary for participation willingness anyway, certainly more effective than even large increase in remuneration. In that case, shared value based V2G is not only a natural place to start, but possibly also the only realistic, financially sustainable model.

As mentioned in 6.2, in addition to practical inconvenience, battery degradation is among the circumstances around V2G organization that affect EV owners' willingness to participate. However, the results of the Dutch survey also suggests that addressing this in the design of the V2G contract can greatly affect participation willingness. This highlights the importance of contract design for EV owners' V2G participation willingness. But in any case, this author would argue that any sustainable business arrangement between different parties should be clearly defined by a contract, that takes into account all relevant interests of the respective parties.

For this reason, this thesis approaches the question of how to make V2G eligible for EV owners by analyzing the interests of each stakeholder, weighing them reasonably against their negotiating positions in the context of the case study at Oslo Gardermoen Airport, and allocating this analysis into a proposed contract design.

9.2.2 Future Work: Survey in Norway

Relevant future work could be a survey among Norwegian EV owners that put the proposed contract design of this thesis to the test. Modeled after the Dutch survey, the respondents should have several contract variations to choose from. Having templates for what to expect is perhaps especially important in a Norwegian context, since current EV owners have no frame of reference for what their service is worth. As mentioned earlier, there is reason to believe that most current Norwegian EV owners have never heard of V2G, at least not to the extent that they know what it entails. The Dutch survey included an educational video for those who did not know what V2G was. This would probably be a good idea to include in a Norwegian survey as well, even more important because V2G is less known here than in the Netherlands. For the answers to be representative of future EV owners, this author recommends that the respondents are educated about their stakes and interests, so that their answers may reflect informed opinions.

It is also worth noting that the average Norwegian EV owner today is likely not representative of EV owners who have made the conscious choice to purchase a vehicle with two-way charging capability, which will likely be the case for Norwegian EV owners for some time [9]. Neither are they likely to be representative of EV owners under the possible future circumstance where two-way charging capability is a standard feature in EVs - in which case they probably have experience utilizing that in various contexts such as V2H before they encounter the possibility of V2G. These EV owners will likely have some frame of reference for what they can expect to earn on utilizing their two-way charging capability. This makes it important to educate respondents in order to get representative answers, but it also suggests an advantage of V2G contract designs based on market mechanisms. This can contribute to the development of a standard frame of reference for interaction with the technology.

To summarize, this thesis focuses on providing an eligible contract design, and leaves it to future project contributors to put it to the test in a survey.

9.3 V2G Contract Design

9.3.1 Analyzing Negotiating Positions Between EV Owner and Aggregator

Similar to how the standard electricity price at Nord Pool is settled as a result of an implicit auction, any contract is the result of a negotiation, explicit or implicit. The contract must be an eligible compromise between the interests of each party, and these interests must be properly defined, sometimes quantified, in order to be taken into account. But which interests take priority and which interests must acquiesce, is determined by each party's negotiating positions.

First, there are different ways to regard what happens when an EV participates in V2G. Does the EV owner rent out their battery to the airport, who may store and collect their electricity there whenever and in such quantities that suits them? As long as the battery is fully charged when the EV owner returns? Or does the electricity belong to the EV owner as soon as it enters their property (the battery), and the airport must buy it back when it needs it, at terms that the EV owner will accept? How are those terms determined? Should the EV owner have a say in how much their vehicle is used for V2G in the relevant time interval, so they have control over how much battery degradation occurs due to this use?

These different perspectives are really what results in different types of contracts between the airport and the EV owner. Some perspectives are more advantageous to one party than the other. Since participation by all parties is a premise for the setup to work, perspectives that are a deal-breaker for one of the parties must be discarded. After that first elimination, the negotiating positions related to technical circumstances can be taken into consideration.

From a negotiation perspective, a V2G contract must also bee seen in context of what EV owners are likely to expect due to previous experience, for example with V2H via their smart home system. This currently requires some speculation, since only two EV models with two-way charging capability is currently available on the

Norwegian market [9].

A control based contract, where the grid operator seizes control over the EV during plug-in time and the EV owner essentially is remunerated for renting out their battery, is well suited for all technical setups, seen purely from a grid operator's perspective. It can also alleviate range anxiety and provide predictability by guaranteeing a minimal battery level upon the EV owner's return, provided the EV owner knows their return time. The remuneration can be simple and predictable, with a fixed price for the battery rental.

However, since a control based contract design leaves the EV owner without any control or even knowledge about the number of discharging cycles their EV undergoes during plug-in time, this contract form does not address the (perceived) important interest of battery degradation for the EV owner. The lack of overview is probably also a breach with the expectations EV owners may have from experience with smart home systems and V2H [8], where apps keep the users posted on everything. A control based contract might be a deal-breaker for participation for many EV owners. This thesis will instead explore contract designs born out of the perspective where EV owners participate in electricity trade.

In this perspective, the EV owner owns any electricity stored in their battery, and must be persuaded to sell it back when desired by the party representing the grid interests. What the grid interests are, depends on the technical circumstances surrounding the V2G setup. A V2G contract should be designed to trigger the wanted behaviour from the EV owners, which is what the contract design article referenced in section 5.4.2 employs principles from demand literature to achieve. At the same time, it should be an advantageous business opportunity for the EV owners, in accordance with the shared value principle.

9.3.2 Analysis of Technical Circumstances in Different V2G Setups

As explained in section 5.3, power market mechanisms are governed by technical circumstances. A V2G contract is a contract for electricity trade, and should similarly reflect the technical circumstances of the V2G setup it operates in. V2G can also serve different objectives in different setups, and implicit financial incentives in the contract should be designed to serve those context specific objectives.

9.3.2.1 V2G Balancing the Power Grid

The most straight-forward version of V2G is when an EV is connected to a charger, it will both receive and return electricity while it is parked. The grid can get rid of excessive power, and extract needed power. When power supply is excessive, the electricity price is low. When power supply is scarce, the price is high. Therefore, for the EV owner, this functionality can naturally translate to buying electricity when it is cheap, and selling it back when it is expensive. This description implies participation in the balancing market.

It corresponds naturally to a price based contract, which is explained in section 5.4.2, where the EV owner can predefine what price should trigger purchase, and what price should trigger sale. Obviously, the larger the gap between the two, the greater the revenue.

The contract design article [12] only specifically mentions setting a price for sale, since their price based contract is designed for FCEVs, which require hydrogen fuel. However, with fully electric EVs, there is no reason not to take the trade one step further, and let the EVs both buy and sell during the plug-in time. With this set-up, the time of the EV owner's return to pick up the EV does not even have to be known in advance, as long as the battery is never drained below the required minimum battery level.

It should be noted that for this to work, the purchase of electricity for recharging EVs must also be based on kWh, and not on plug-in time, which has previously been the norm in Norway and is still the case at Oslo Airport Gardermoen. However, kWh based charging is increasingly becoming the norm, to make it easier for EV owners to compare the offers of different suppliers [27].

9.3.2.2 V2G in a Micro Grid Setup

Another way to set up V2G is inside a micro grid. In the former example, the EV owner would transfer their electricity directly to the power grid, and sell to the wholesale market (probably the balancing market). In a micro grid, the electricity transmission happens internally in what to the power supply company is just one customer. Alternatively, it happens as an extra trade between a limited set of entities in parallel with the regular power market. An example of a micro grid could be a set of closely located houses in a village with solar panels on their roofs, who choose to share their collective production amongst themselves. Another example is a setup such as in the case study in this thesis, where a large power consumer hosts a pool of EVs in a parking house on their property.

As explained earlier, a large power consumer could reduce their peak demand from the grid if they have a pool of EVs organized in a micro grid on their property. In this V2G setup, the capacity / flexibility that the EVs provide is worth more than the electricity itself. Additionally, the market price stemming from circumstances in the grid might not reflect the local needs of the micro grid. That makes the price based contract design, where sale is triggered by electricity price, less suited to incentivize the desired outcome for the operator of a micro grid setup such as this.

The agent based models in the article "Conceptualization of Vehicle-to-Grid Contract Types and Their Formalization in Agent-Based Models" [12] suggest that with a price based contract, the EV owners will often set the sales price so high that an energy sale from EV to grid will often not take place. This defeats the purpose of the EVs functioning as extra capacity in a micro grid. For this reason, a volume based contract, in which the operator of the micro grid pays for the capacity provided through a committed sales volume, could be preferable for this setup.

9.3.3 The V2G Setup at Oslo Gardermoen Airport

As concluded in section 9.3.1, the premise for a contract design in this thesis is that the EV owners own any electricity that enters their car battery, and the terms must be eligible for them to sell it back.

As illustrated in figure 8, the airport is connected to the power grid, and the EVs are connected to the power grid through the airport. The airport is not just an aggregator between EV owners and flexibility buyers on the grid; they are also the facilitator of a micro grid, consisting of their own P10 parking house and the EVs parked there.

Important interests for the airport:

- Reduction of power tariffs –> EV participation in V2G microgrid
- Money saved / earned from V2G surpassing money spent by implementing V2G (profitability)

Important interests for the EV owners:

- Guaranteed minimum battery level upon return
- Battery degradation being considered
- Sense of control over their property
- Revenue / cost

From a negotiation perspective, the EV owners depend on the airport to be able to charge their vehicles, and to sell their services in V2G, whether they sell it to the micro grid (the airport) or to the power grid (the wholesale market). They must accept a contract that the airport as aggregator is willing to offer.

The airport, on the other hand, must offer a contract that seem fair enough to the EV owners that they choose to sell V2G services, rather than just pay for charging.

The following section proposes a contract design for this V2G setup. The design is a template for a contract, consisting of a list of suggested parameters. The content and formation of those parameters are discussed i varying detail.

A suggested price formation is outlined, and will vary from EV owner to EV owner depending on parameters in the contract. A benchmark for the size order of the fixed part of the price for V2G participation (paid to each EV owner) is discussed, but ultimately depends on many factors for Avinor to decide, as well as unknown factors in the future. It is possible that remuneration for participating in a pilot project should be differentiated from a fully operational, financially sustainable future V2G park made for profit. No concrete number is recommended in this thesis. Variations in remuneration should be included in a future survey in Norway, as proposed in section 9.2.2.

9.4 Proposed Contract Design Between EV Owners and Avinor

9.4.1 Practical implementation

This thesis suggests that V2G functionality is added to the existing app for EV charging at the airport, "Avinor" [28]. The charging of EVs is naturally connected to the V2G functionality, and this integration may lower the threshold for participation. The implicit question will be "Do you only want to pay for charging, or do you also want the opportunity to earn it back? Your vehicle can earn back the charging cost and more while you are away".

The EV owner, now called app user, will fill out a form with required information that corresponds with the parameters of the contract. Information from the same form can be used to generate charging schedules, since the parameter "plug-in time" is the same as the "due date" variable in the charging scheduling program.

After filling out the form, a proposed contract with terms for remuneration and practical agreement appears. The app user can accept this, or discard it. If they discard it, only the charging will be paid for at normal rates. This thesis suggests that charging without V2G participation is made kWh based, in accordance not only with the proposed V2G remuneration system, but with with the majority of EV charging suppliers in Norway [27].

In addition to lowering the threshold for V2G participation, the integration of V2G functionality with charging functionality inn the app allows for the payments to be integrated. This will be further explained in section 9.4.7.

9.4.2 Parameters

Table 5: Parameters of the proposed contract

Parameter	Description
Guaranteed minimum battery level	Minimum percentage of the battery guaranteed to be charged after operation
Time interval	Plug-in time, precommitted, in number of days. In many cases, the time that passes between a traveler's flight and return flight.
Minimum plug-in time	Minimum number of days parked, set to 1 counting from the start of the following day
Maximum volume	Maximum electricity volume usable for V2G, in number of charging cycles, decided by the EV owner
V2G remuneration	Remuneration for: * capacity (fixed) * electricity (variable) * compensation for battery degradation (fixed)

The proposed contract design in table 5 is a template for a volume based contract, building on the template from the contract design article [12], with some elements from a price based contract for certain cases. Some adjustments are made for the parameters to fit fully electric EVs, rather than FCEVs that the contract templates in the article are originally designed for. Other adjustments and elaborations are made to tailor the contract for the specific circumstances in the case study at Oslo Gardermoen Airport.

One sub-parameter, "battery compensation", is added by this thesis to the remuneration parameter for reasons expanded on in section 9.4.7.5. The remuneration parameter is significantly elaborated and tailored to the case.

9.4.3 Guaranteed Minimum Battery Level

The Dutch survey [11] showed that the lower minimum battery level was promised EV owners upon their return to collect their vehicle, the higher remuneration they required in order to participate. In the context of this case study, where the EV owners' and thus also the airport's schedule is so predictable, this author recommends guaranteeing a fully or nearly fully charged battery upon return, for instance 90 %. The charging is slower after 90 %.

Provided that the charging takes place at nighttime, this can be accomplished by not utilizing the EV for V2G on the day of the EV owner's return. Seeing as range anxiety is a common concern, the advertisement effect of guaranteeing a full or nearly full battery could outweigh the disadvantage of this restriction for the airport. Especially when there is a minimum plug-in time of one day, starting from midnight after plug-in. However, as discussed at the end of section 9.4.5, it is possible to give the EV owner / app user the opportunity to decrease minimum guaranteed battery level if they wish to increase their sales volume. EVs have been common in Norway for some time, and range anxiety might not be as prevalent here as in the Netherlands.

9.4.4 Time Interval

The time interval for V2G is defined by the plug-in time. From the airport's perspective, it is obviously very convenient to know during what time interval they can count on the EV to be available for their use. Since most EV owners who park at an airport know precisely when they will be back to collect their vehicle, committing to a time interval should not be inconvenient to them. This parameter would be submitted in the charging app by the EV owner upon connection to the charger.

9.4.5 Minimum Plug-in Time

The contract design article [12] listed minimum fuel level at plug-in as a necessary parameter in a volume based contract. This stems from the fact that the contracts in the article are designed for FCEVs, hydrogen cars. Hydrogen cannot be produced at a regular V2G site, which implies that electricity can only go one way: From the vehicle to the grid, and not from the grid to the vehicle. In section 5.4.2 this parameter was adjusted to the circumstances of a regular (fully electric) EV, and converted to minimum battery level required at plug-in. This would be a function of the amount of electricity the EV owner agree to sell, the minimum battery level they require upon return, and the plug-in time. The latter indicates whether there will be enough time to both sell the indicated electricity volume and recharge the battery to the desired minimum level.

However, in the context at Oslo Gardermoen Airport, this thesis suggests instead a minimum plug-in time for V2G participation, set to one day counted from midnight following the time of plug-in. This restricts the V2G eligible EV owner base to the long term parkers, and excludes the drivers who are only there for a short time, for instance to drop someone off. The charging schedules for load shifting must also exclude this part of the EV owner base, because their EVs must be allowed to charge during daytime so they can be collected later the same day. This can be accomplished by setting their due dates to 0, when they inform the app that they require the EV back the same day.

Perhaps the short term parkers can also be included in V2G in the future, especially as the fast charging technology advances. However, the circumstances for this group is so different from the long term parkers that it would require a different contract, given that the contract parameters are designed to trigger specific responses. This thesis focuses on the shared value that can be achieved between a micro grid operator and EV owners with a predictable schedule and plans that lead to a naturally long plug-in time.

It should be noted that even with a minimum plug-in time; plug-in time, sales volume and minimum battery level are still mutually dependent. Given that the first is fixed, the latter two must not be set to imply exceeding the first. If the standard is to guarantee a fully or nearly fully charged battery, which this thesis suggests in section 9.4.3, the sales volume is what must be restricted by the other two. However, providing an opportunity in the app to decrease minimum battery level in the interest of selling more volume is a possibility.

9.4.6 Maximum Volume

This parameter is the defining quality that makes this a volume based contract design.

Giving the EV owner control over how much their battery is used for V2G will distinguish between the EV owners with different degrees of concern about battery degradation. Those who would not participate under any circumstances will still not participate. But those who would on certain conditions regarding number of discharging cycles, can be willing to make a deal where those conditions are clearly defined. In this author's opinion, it can be inferred from the results of the Dutch survey [11] that this group would likely not participate without a parameter that addresses this concern. A price based contract would give them control in a different way, but as previously discussed, EV owner held control in terms of volume is better suited for a micro grid V2G setup like the one at Oslo Gardermoen Airport.

This thesis suggests maximum volume to be measured by charging cycles in the contract, with the condition that the EV owner must submit which EV model they have. Charging cycles is a more intuitive unit for the EV owner than for instance kWh, and the airport can derive the technical information they need from what EV model it is.

The maximum volume parameter is just a maximum volume permitted for extraction; it does not commit the airport to actually purchase the entire amount. They may not be able to use all of it inside the time frame of the EV's plug-in time. However, for predictability for the EV owners, this thesis suggests that they be permitted to sell the excess electricity to the wholesale market in such cases, with the airport acting as aggregator. In those cases, mechanisms from the price based contract design could be utilized.

9.4.7 V2G Remuneration

The contract design article [12] suggests that a volume based contract design defines remuneration for capacity as well as electricity, to reward the most desired service - which in the case at Oslo Gardermoen Airport is availability of the capacity, in order to shave power peaks.

Since a combination of capacity and electricity is what the electricity bill of an ordinary power consumer consists of, this thesis proposes that the remuneration resembles that setup, as shown in table 1 in section 5.3.2. This will presumably appear familiar to the EV owners. Additionally, this thesis proposes explicit remuneration for battery degradation, based on accurate monetary value of the degradation as described in section 6.2.

As of today, the remuneration for V2G participation in the pilot project, based on an agreement resembling a control based contract, is that the EV owner pays nothing for the charging of their vehicle. Results of this in terms of participation willingness have yet to be determined.

A benchmark for the size order of V2G remuneration in this thesis' proposed contract design should match the current setup: It should be guaranteed that the total V2G remuneration will be equal to or larger than the total price for charging.

9.4.7.1 Capacity Remuneration

Drawing on the setup of a regular electricity bill, the remuneration for capacity should be fixed, in the sense that it is decided before the contract is "signed" in the app. For availability to be rewarded, it should be a function of the plug-in time (time span available) and maximum number of charging cycles (electricity volume available). Since the plug-in time in this case is already "freely given" due to the EV owner's own traveling schedule, the emphasis should be on rewarding volume availability, as in how many charging cycles the EV owners are willing to sell.

This could be accomplished in the app by setting a benchmark capacity remuneration that is a function of the submitted plug-in time and one discharging cycle for sale. An easy menu is provided for the app user to increase the number of discharging cycles for sale, and see the capacity remuneration increase on the screen in real time for each cycle.

Technically, it would be most fair to differentiate between the volume of a charging cycle of a large battery from that of a small battery, in terms of capacity remuneration. However, that could be an unwise distinction between customer groups - at least in the early stages of V2G, where the main goal is to encourage participation, no matter the size or quality of their battery. Even if the EV owners with large batteries are not paid more for their capacity, they will still be paid more per discharging cycle due to remuneration for the electricity.

9.4.7.2 Size Order of Capacity Remuneration

As mentioned above, the capacity payment should be a function of plug-in time and the number of charging cycles for sale. Since available capacity is the most valuable service required from the EV owner, it should also be the largest part of the V2G remuneration, which is guaranteed beforehand, while the electricity remuneration is a variable bonus on top.

For the pilot project, a possible benchmark for the capacity remuneration is the current charging price in the P10 parking house [28]. Since the current rate is time based and not energy volume based, it would have to be adjusted to fit the EV in question. Then, the remuneration is differentiated based on plug-in time. This would be the default capacity remuneration the EV owner sees in the app, before it increases with the number of charging cycles.

Future Work:

For a V2G park such as the one in this case study to be sustainable long term, the benchmark rates for the capacity remuneration should be anchored in a profitability analysis by Avinor, or any other large power consumer who considers a V2G park with this setup. The investment cost for two-way chargers and the remuneration to EV owners should be compared to the savings in power tariffs.

Calculating how large the remuneration to EV owners can be for the investment to be profitable for Avinor is beyond the scope of this thesis. It depends on many unknown variables, such as how many two-way charging capable EVs can be expected to park there in the future, how many of them will participate in V2G, how will the prices on two-way chargers develop, etc. It also depends on how soon Avinor wishes the project to break even, how profitable they want the investment to be, and what they consider the discount rate to be. A template for arriving at a sustainable benchmark is suggested below.

In the suggested remuneration system in this thesis, the majority of the arbitration revenue from electricity trade (expanded on below) is paid to the EV owners, while the aggregator share reserved for Avinor is only supposed to be a small mark-up for use of the equipment. Therefore, only the revenue stemming from reduction of power tariffs, which is capacity related, is included in this suggested template for a profitability analysis. That is also why it is seen as a benchmark for the capacity remuneration, rather than the total remuneration.

Equation 4 describes the net present value of an investment in terms of future revenue and investment costs [29]:

$$NPV = -C_0 + \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} \tag{4}$$

where

- NPV = Net present value
- C_0 = Cash flow in time 0 (Investment costs for two-way chargers and other necessary preparation)
- C_t = Cash flow in time t (Reduction in power tariffs minus total capacity remuneration to EV owners)
- r = Discount rate (return that could be earned in alternative investments, adjusted for inflation)
- t = Wanted time frame for assessing the investment, for instance the life expectancy of the two-way chargers

The net present value (NPV) is the current value of the investment given expected future revenue. If NPV is equal to zero, the project breaks even. If negative, the project is financially unsustainable, and if positive, sustainable. The discount rate (r) discounts the future cash flows with respect to inflation, the alternative cost of committing the money to this investment, and general risk.

If the desired values for NPV, r and t are set in, as well asthe investment costs for C_0, and future cash flows (C_t) are defined as the total capacity remuneration paid to EV owners subtracted from money saved on reduced power tariffs due to V2G, the equation can be solved for the total capacity remuneration.

The total capacity remuneration can then be divided by an expected number of V2G participating EVs, which results in a benchmark for the average capacity remuneration that can be paid to each EV owner for the investment in the two-way chargers to be profitable. How to arrive at an expected number of V2G participating EVs, which will presumable develop for each year, is left to future work.

A benchmark arrived upon from a profitability standpoint must of course also be seen in context of what is acceptable to EV owners, which can be further investigated in a survey as discussed in section 9.2.2. If there is no eligible compromise, other factors must change before implementation of V2G is realistically profitable. Such factors are the price for two-way chargers, the power tariffs, or daily variations in electricity price. The latter will increase EV owners' electricity remuneration, which is further elaborated in the next section.

9.4.7.3 Electricity Remuneration

This thesis proposes that the electricity remuneration is variable, following the market price. The thesis also suggests that the charging price paid by the EV owner is incorporated into the variable electricity remuneration in the V2G contract. The EV owners pay market spot price (possibly with a mark-up) for the amount of electricity that enters their battery, and are paid market spot price (possibly a little lower) for the electricity that is extracted from their battery.

Since they recharge during nighttime and discharge during daytime (assuming that the charging scheduling method from this thesis is followed), they will (as a rule) profit from arbitration (the revenue stemming from low buy-price and high sell-price). If the electricity price is either added a mark-up for charging, or set slightly lower than spot-price when selling, or both; Avinor as an aggregator will get a small portion of the arbitration revenue, in addition to what they save in power tariffs on power peak shaving.

In addition to resembling an electricity bill (albeit from the producer side), a variable electricity remuneration may correspond with EV owners' experiences with smart charging and V2H, where purchasing cheap electricity during low demand and selling it during high demand are known mechanisms that they might expect to profit directly from in a V2G setup.

Additionally, if there are to be standard contracts for V2G in the future, it is good that the price mechanisms from different setups appear to follow a similar logic. A variable electricity price that follows the market price is akin to the remuneration mechanism in a price based contract, a design which may be more suitable in other cases.

The exact remuneration for electricity is not known beforehand; it depends on the development of the electricity price. It also depends on which hours of the day the airport purchases the agreed-upon volume. The total remuneration may appear as a receipt in the app after operation, with the possibility of inspecting the different posts in the remuneration, complete with explanations.

In the event that the airport does not need the full volume that the EV owner wants to sell, this thesis suggests that the EV owner is permitted to sell to the grid instead, to the wholesale market, for the same price that the airport would have paid. That is, market price or slightly lower. A slightly lower price leaves an aggregator revenue for Avinor, who will sell it to the wholesale market to market price.

If the airport concludes that they will not need the remaining volume in the remainder of the time frame, the sale to the grid can be set to occur at the highest occurring spot price within that time frame - provided it does not happen during an expected peak hour for the airport. It should be ensured that the pursuit of highest possible sales price for the EV owner does not defeat the purpose of power peak shaving for Avinor. Another possibility for such is that the app user defines a sales price they will sell to in the event that the airport does not need the entire volume, with a suggested default value to make it simple, and thus resembling a price based contract.

From the EV owner's point of view, the guarantee that they will be able to sell the volume of electricity they agreed to, may be important for the contract to seem fair. To them, V2G is a business opportunity, and they should have some predictability around the trade when the deal is struck.

9.4.7.4 Size Order of Electricity Remuneration

The EV owners will recharge (purchase) more than they will discharge (sell), the difference being the amount of electricity that was lacking in their battery when they plugged in to reach the requested minimum battery level upon return. Depending on the number of discharging cycles they sell, as well as the day/night variations in the market price, and the mark-up the airport claims - the difference can be earned back by arbitration alone.

The post can also end up negative, if the battery is almost empty at plug-in and the EV owner requires an almost full battery upon return, and for instance only sells one charging cycle. However, the capacity remuneration should be set such that the total remuneration is always positive - as in, exceeds the cost of charging the vehicle.

To get a benchmark for how many charging cycles must be sold to earn back the entire charging cost on arbitration alone, the price variations in the price area of Oslo Gardermoen Airport in the last 14 days were investigated [30]. The calculations suggest that between three and four charging cycles must be sold for that to be achieved. This is provided the battery was empty at plug-in, which it presumably is not. However, losses are not accounted for. The calculations behind this can be found in the following GitHub repository: https://github.com/IngridMorch/Master-Thesis.

9.4.7.5 Battery Compensation

This thesis suggests that battery degradation also be addressed through a clearly defined compensation for battery degradation, that reflects the actual monetary value of the degradation. It is perhaps counter-intuitive to draw unwanted attention to this concern, but research clearly shows [11] that the concern is not only already present, but greatly exaggerated. Without knowledge of the size order of the degradation, the EV owners fear a much greater degradation than what is really the case.

This author's hypothesis is that having battery compensation as a separate sub-parameter under remuneration, with accurate monetary compensation, will implicitly educate EV owners on how small this concern ought to be. Compared with the remuneration they earn based on the service they provide, an accurate compensation for battery degradation as described in section 6.2 will be minuscule. It will thus be apparent how objectively advantageous the V2G deal is for EV owners. The transparency around the issue can also build trust, as opposed to the distrust that can arise by perceived attempts to distract from the issue.

9.4.7.6 Summary

The suggested remuneration system in this V2G contract design is separated into three parts: Capacity, electricity, and battery compensation.

Capacity remuneration is the largest post, and is a fixed price calculated before contract agreement. It is a function of plug-in time, which is predetermined by the app user, and number of charging cycles (electricity volume) made available for sale.

The latter is emphasized in the app to incentivize increasing the number of charging cycles.

Electricity remuneration is the variable revenue from arbitration minus the cost of charging from battery level at plug-in to minimum required battery level after operation. If the battery was almost empty at plug-in and the EV owner wants a full battery when they return, and they only sell one charging cycle, this post might turn out negative (but the total remuneration will always be positive). The more cycles are sold, the more this post will be a bonus on top of the capacity remuneration.

Technically accurate compensation for battery degradation is added as a small depreciation post, akin to depreciation when a car owner has used their vehicle for work purposes.

9.5 Applicability to Other Cases

The method for scheduling EV charging proposed in this thesis may be relevant to any actor who facilitates charging of a pool of long-term parked EVs on their property. It is most useful if a substantial portion of the EVs are parked for several days.

The method might be particularly relevant to large power consumers who pay power tariffs, but smart scheduling of EV charging will be relevant to smaller actors as well when the new billing system of power peak based transmission grid rental for everyone is implemented. It also saves electricity costs to charge when the price is low, regardless of peak demand.

Power tariffs and energy costs aside, scheduling the charging to demand no more simultaneous power than necessary could possibly expand the EV parking capacity of the facility, if internal power capacity were a defining constraint.

The V2G contract design tailored specifically to the case at Oslo Gardermoen Airport may be applicable to contexts that share the following characteristics:

- EV owners with predictable schedules
- Inherently long plug-in time (in accordance with the EV owner's plans)

It may be particularly well suited for micro grid setups where the main objective is balancing local supply and demand. Especially the remuneration parameter is designed specifically for this.

However, building on the electricity trade based templates for V2G contract designs, price based and volume based, the methodology for designing V2G contracts demonstrated in this thesis can be applied to various contexts.

Since the contract designs are intended to be an advantageous opportunity to EV owners as well as parties representing grid interests, they may also be of interest to actors who own a fleet of EVs as company vehicles. It might be possible for such actors to strike a bilateral deal with charging facilitators.

10 Conclusion

The thesis concludes that EVs parked on the property of a large power consumer can be utilized to shave power peaks by load shifting, and by V2G that is mutually beneficial for the power consumer and the EV owners.

Load shifting is the simplest measure to achieve power peak shaving. This thesis proposes a scheduling method to ensure that as much of the charging as possible can take place during low demand and low energy prices. Provided that the EV owner knows approximately when they will be back to collect their EV, this can be achieved without affecting the EV owners' interests. If the prices for charging are kWh based instead of time based, in accordance with the trend in Norway, charging at cheap hours may benefit EV owners.

Implementation of V2G can accomplish further power peak shaving by enabling alternative power supply, provided that EV owners agree to participate. V2G should be carefully organized to not infringe on the interests of EV owners, as a study from the Netherlands shows that financial compensation has limited effect on participation willingness compared to avoidance of practical inconveniences. Most importantly, the EV owners' original schedule should not be affected by V2G participation, and battery degradation should be kept minimal and under the EV owners' control. This thesis integrates these concerns into a mutually beneficial contract design template, with V2G price formation derived from demand response literature and the mechanisms of the power market. The proposed contract design is volume based, where the EV owner commits to selling a certain electricity volume, with remuneration consisting of three posts:

- Fixed price for the provided capacity, derived from plug-in time and number of charging cycles (electricity volume) for sale. Benchmark size order depends on circumstances
- Variable price for electricity remuneration, following the electricity market price. The cost for charging is integrated by also following the market price, and being subtracted from the revenue
- Fixed compensation for battery degradation, derived from characteristics of the battery and the number of charging cycles sold. Very small, in accordance with accurate depreciation

The conclusions of this thesis, regarding both charging scheduling and V2G organizing, are presumably applicable for other contexts that share key characteristics with the case study at Oslo Gardermoen Airport. The most important characteristics are long term parking, EV owners having a predictable schedule, and the EVs being hosted by a large power consumer who pays power tariffs.

The methodology for designing V2G contracts demonstrated in this thesis can be applied to organize mutually beneficial V2G in various contexts, possibly also those that do not share an airport's characteristics. Especially the price based template should be further investigated in future work.

11 Appendix

11.1 Code

Simulation.py

```
# -*- coding: utf-8 -*-

"""
This script contains functionality for simulating conditions at
the airport, which gives the necessary input to the classes and
class methods in the Oneway_charging script.

FUTURE ADDITION: Also gives input to a script called
Twoway_charging, which accommodates V2G functionality
"""

__author__ = 'Ingrid Maria Morch'
__email__ = 'ingrid.morch@gmail.com'


import Oneway_charging_1
# FUTURE ADDITION: import Twoway_charging

import random
from tabulate import tabulate


class Sim_1_way:
    """
    This class defines necessary variables and class methods to
create a charging schedule for EVs without V2G capability or
                                  willingness.
    """

    def __init__(self):

        """
        Variables of chosen size, can be changed to more feasible
  values. Could have made them inputs along with num_evs,
  but that would make for unnecessarily cumbersome
  simulations for the purposes of this thesis
        """

  # Cheap night night time spot price on energy:
        self.num_charging_hours = 8

        self.min_days_parked = 1
        self.max_days_parked = 5

  # As many hours as it takes to fully charged an empty
  # car battery of a chosen common size:
        self.max_rpt = 6

  # Container for EV objects:
```

```
        self.ev_pool = []

        self.schedule = None

 # Will be updated by the input when simulation function is called:
        self.num_days_sim = 0

 # Will be updated by the input when simulation function is called:
        self.num_evs_sim = 0

    def create_ev_pool(self, num_evs_sim):
        """
        Simulates EVs with relevant characteristics and places them
 in the empty list self.ev_pool
        """
        ev_pool = []
        num_evs = num_evs_sim
# rpt, remaining processing time, i.e. how depleted the battery is,
# should be simulated like this: random.randint(self.min_rpt,
# self.max_rpt). They are all set to max.rpt, i.e. same charging
# needs, for clearer example schedules in thesis

        for k in range(num_evs):
            ev = Oneway_charging_1.EV((k + 1), random.randint(self.
                                                  min_days_parked, self.
                                                  max_days_parked), self
                                                  .max_rpt)
            ev_pool.append(ev)

        return ev_pool

    def daily_cycle(self, schedule):
        """
        Creates a schedule based on the EVs currently present in the
 parking house
        """
        charging_schedule = Oneway_charging_1.Schedule.
                                            create_schedule(schedule)

        return charging_schedule

    def update_ev_pool(self):
        """
        FUTURE ADDITION:
            * EVs past their due date are removed from the ev pool
            * New EVs are added

            * Return: Updated self.ev_pool
        """

    def simulate(self, num_days_sim, num_evs_sim):
        self.num_days_sim = num_days_sim
        self.num_evs_sim = num_evs_sim
        self.ev_pool = self.create_ev_pool(num_evs_sim)
        schedule = Oneway_charging_1.Schedule(self.ev_pool)
```

```
        charging_schedule = self.daily_cycle(schedule)

        # FUTURE ADDITION: self.ev_pool = update_ev_pool()

        return print(tabulate(charging_schedule, headers = 'keys',
                                                  tablefmt = 'psql'))


class Sim_2_way:
    """
    FUTURE ADDITION:
        * Functionality from Sim_1_way class is replicated and
    extended to include two-way charging capability,
            i.e. V2G participation.
        * Notable extensions to EV characteristics:
            * charging cycles to sell (energy volume)

        * Notable changes to charging schedule:
            * Includes scheduling of energy sale during daytime
      (only which days the batteries are available)
            * Includes recharging of the same EV several times

        * Also possible to keep track of remuneration
    """


# Number of days must be 1 for now, before update_schedule is
                                  finished.
print(Sim_1_way.simulate(Sim_1_way(), 1, 6))

# NOTE: This means one schedule, based on one snapshot in time.
# Number of days scheduled is equal to the furthest due date of
# the EVs. Number of EVs can be set to anything, depending on
# what scenario one wants to explore. Here: 6
```

Oneway_charging_1.py

```
# -*- coding: utf-8 -*-

"""
This script contains functionality for creating EV objects and
Schedule objects. It takes input from the Simulation script.
"""

__author__ = 'Ingrid Maria Morch'
__email__ = 'ingrid.morch@gmail.com'


import pandas as pd


class EV:
    """
    This class contains the necessary characteristics for an EV
```

```
  object, representing an EV
    """

    def __init__(self, id, due_date, rpt):
  # To be able to sort the evs by identity:
        self.id = id

  # Number of days from admittance until due date /
  # number of days parked:
        self.due_date = due_date

  # Remaining Processing Time. Here, how many charging hours
  # are required before the EV is fully charged. (Assuming
  # constant charging speed. Uniform chargers and batteries):
        self.rpt = rpt

  # For tracking later:
        self.is_charged = False


class Schedule:
    """
    This class contains necessary variables and class methods to
  yield one schedule
    """

    def __init__(self, ev_pool):
        self.ev_pool = ev_pool

        self._num_charging_hours = 8

        # Containers / variables that will be updated by methods,
  # and are needed across several methods
        self._time_frame = 0
        self._num_machines = 0

    @property
    def time_frame(self):
        """
        The time frame of the charging schedule is equal to the
   number of days until the latest due date of the EVs
  that are currently parked.
        """
  # Sorts it by due date in descending order to
  # identify the time frame:
        self.ev_pool.sort(key=lambda x: x.due_date, reverse=True)

        self._time_frame = self.ev_pool[0].due_date

  # Sorts it back in original order:
        self.ev_pool.sort(key=lambda x: x.id)

        return self._time_frame

    def create_schedule(self):
        """
```

```
For each charging schedule, the chargers are modeled as
   a minimized number of 'machines' in order to maximize
  charger idleness, and thereby minimize power peaks.
"""

  # For recording when each ev is charged or not charged:
        charging_journal = {}
        rpts = []
        released_evs = []

   # Storing original rpts before operations
        for ev in self.ev_pool:
            rpts.append(ev.rpt)

  # The number of iterations the loop makes before breaking
  # defines the number of modeled machines.
        for m in range(len(self.ev_pool)):
            _clash = False       # Reset
            charging_journal.clear()    # Reset
            released_evs.clear()        # Reset

            for k in range(len(rpts)):          # Reset
                self.ev_pool[k].rpt = rpts[k]

            for k in range(len(self.ev_pool)):
                charging_journal["EV-" + str(k + 1)] = []

  # Makes for more efficient for loop:
            self.ev_pool.sort(key=lambda x: x.due_date, reverse=True
                                              )

# For each hour in the entire timeframe. Made it count from
  # 1, so k will match the due dates correctly
            for k in range(1, (self.time_frame * self.
                                              _num_charging_hours) +
                                               1):
                for ev in self.ev_pool:

  # Release date on reverse timeline, counted in hours:
                    if k >= (self.time_frame - ev.due_date) * self.
                                                      _num_charging_hours
                                                       and ev not in
                                                       released_evs:
  # Points to the original ev object in self.ev_pool:
                        released_evs.append(ev)

 # Sorting the released EVs, or rather their corresponding charging
# jobs, in descending order to see which one of them to charge
# "first" (on the reversed timeline) according to the LRPT rule

                released_evs.sort(key=lambda x: x.rpt, reverse=True)

# Attempt schedule as Pm problem, m = attempted number of machines
# (Not really, m start counting at 0, therefore m + 1 in code)

                if len(released_evs) < m + 1:
```

```
# Not + 1 because len starts at 1:
                h = len(released_evs)
            else:

# + 1 because the for loop starts m at 0
                h = m + 1

            for j in range(h):
                if released_evs[j].rpt > 0:
  # Charged for one hour --> one less
  # hour left to process:
                    released_evs[j].rpt -= 1
                    released_evs[j].is_charged = True

# Sorts it back in original order:
            self.ev_pool.sort(key=lambda x: x.id)

            for ev in self.ev_pool:

                if ev.is_charged:
                    charging_journal["EV-" + str(ev.id)].append(
                                                              'charge')
                    ev.is_charged = False  # Reset
                else:
                    charging_journal["EV-" + str(ev.id)].append(
                                                              ' ')

        for ev in self.ev_pool:
# Reversing the reversed timeline back for correct display
            charging_journal["EV-" + str(ev.id)].reverse()

# Schedule is feasible if all EVs are finished charging:
        for ev in self.ev_pool:

# when the reversed timeline reaches 0:
            if ev.rpt > 0:
# Otherwise, restart outer for loop with m = m + 1 (one more
                                  machine):
                _clash = True
                break

        if not _clash:
            self._num_machines = m + 1
            break

    if self._num_machines == 0:  # For debugging
# Charging hours must be expanded:
        print('No feasible schedule is possible within the
                                          specified parameters')

    print('Number of machines modeled: ' + str(self.
                                          _num_machines))

    return pd.DataFrame.from_dict(charging_journal)
```

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