Impact of Plug-in Hybrid Electric Vehicles on the Electricity System

Kristien CLEMENT-NYNS

Jury:	
Prof. dr. ir. H. Neuckermans, voorzitter	Proefschrift voorgedragen
Prof. dr. ir. J. Driesen, promotor	tot het behalen van de
Prof. dr. ir. R. Belmans	graad van Doctor in de
Prof. dr. ir. G. Deconinck	Ingenieurswetenschappen
Prof. dr. ir. W. Kling	door
(Technical University of Eindhoven	Kristien CLEMENT-NYNS
and Delft, The Netherlands)	
Prof. dr. ir. J. Peças Lopes	
(University of Porto, Portugal)	
Prof. dr. ir. E. Van den Bulck	

Oktober 2010

Kasteelpark Arenberg10 bus 2445, B-3001 Leuven (Belgium)

D/2010/7515/89
ISBN 978-94-6018-250-1

Voorwoord

Dit boekje is het tastbare resultaat van een meer dan vier jaar durende (intense) zoektocht. De weg naar dit resultaat was minstens even belangrijk als het boekje zelf. Gelukkig heb ik deze weg niet alleen moeten afleggen en kreeg ik steun van velen. Steun betekent niet alleen effectieve hulp, maar ook een goede discussie, een luisterend oor, een bemoedigend woord samengaand met een goede portie humor. Dit heeft het mogelijk gemaakt om door te zetten en dit werk tot een goed einde te brengen. Hoewel het onmogelijk is om iedereen op te noemen, wil ik toch enkelen expliciet bedanken.

Allereerst wil ik mijn promotor Prof. dr. ir. Johan Driesen bedanken om mij dit fantastisch onderwerp aan te bieden. Plug-in hybride elektrische voertuigen stonden vier jaar geleden nog in de kinderschoenen. Gedurende mijn onderzoeksjaren heb ik een hele evolutie mogen meemaken waardoor elektrische voertuigen en smart grids nu een hot item geworden zijn. Bedankt om mij een kans te hebben gegeven om in een zo vroeg stadium een bescheiden bijdrage te mogen leveren tot dit onderzoek. Natuurlijk was de weg niet altijd even evident en daarom gaf u mij op het juiste moment de gepaste hulp en aanwijzingen. Ook bedankt om mij bij te staan bij alle ombudsproblemen.

In tweede instantie wil ik de leden van mijn doctoraatsjury Prof. dr. ir. Ronnie Belmans, Prof. dr. ir. Geert Deconinck, Prof. dr. ir. Wil Kling, Prof. dr. ir. Eric Van den Bulck en Prof. dr. ir. João Peças Lopes bedanken voor hun opbouwende kritiek en het aandachtig nalezen van mijn doctoraatstekst. Prof. dr. ir. Herman Neuckermans wens ik te bedanken om het voorzitterschapschap van deze jury op zich te nemen.

Een bijzonder woord van dank gaat uit naar alle mensen die dit onderzoek financieel mogelijk hebben gemaakt. Ik ben ook verheugd te zien dat mijn onderzoek wordt voortgezet en dat het deel uitmaakt van het Linear-project over Smart Grids dat tot stand is gekomen met de steun van Minister Ingrid Lieten.

Vooral de goede werksfeer heeft er voor gezorgd dat ik iedere dag graag kwam werken bij Electa. Die leuke omgeving is vooral te danken aan alle toffe collega's. Hoewel ik zelf geen koffiedrinker ben, waren de koffiepauzes toch altijd leuk om te vertoeven, ook als je dan maar een glaasje water drinkt. Bovendien zal ik heel goede herinneringen overhouden aan al de leuke uitstappen die regelmatig georganiseerd werden.

Er zijn enkele collega's aan wie ik expliciet een woordje van dank wil richten. Peter Tant en Kristof Engelen, jullie hebben ervoor gezorgd dat er in onze bureau altijd een fijne sfeer was en dat er veel gelachen werd. Kristof, bedankt voor de leuke praatjes, je gevatte antwoorden en je kritische blik. Peter, bedankt voor de vele tips en je nuchtere kijk op de zaak. Draag goed zorg voor de plant! Sven De Breucker was de voorbije jaren een partner in crime als het over elektrische voertuigen gaat. Ik vond het ontzettend leuk dat je mijn tekst tot in het kleinste detail hebt willen nalezen! Daarnaast wil ik Edwin Haesen bedanken om mij wegwijs te maken in de optimalisatiewereld. De pauzes in de zon op de trappen voor ons gebouw samen met Reinhilde D'Hulst waren een goede en fijne ontspanning tussen al het programmeren door. Nathalie Belmans wil ik ook nog bedanken voor het ontwerpen van mijn voorblad en mijn idee goed weer te geven. Bedankt aan het secretariaat van Electa voor alle hulp en de leuke babbels aan de toog.

Buiten mijn werk heb ik natuurlijk ook veel steun gekregen. In het speciaal wil ik mijn 'vriendinnekes' van Diest hier vermelden. Annelies, Ans, Bieke, Griet, Liesbet, Lieselotte, Marijke en Sarah: bedankt voor de leuke etentjes, weekendjes, brunches en zoveel meer! Ik heb vaak op onze blog gekeken om te lezen welke zotte dingen jullie weer allemaal hadden meegemaakt. Daarnaast wil ik natuurlijk ook alle andere vrienden en vriendinnen van Leuven en van buiten Leuven bedanken voor alle leuke ontspannende momenten, bezoekjes aan de Oude Markt, spelletjesavonden en andere...

Deze laatste paragrafen zijn natuurlijk gereserveerd voor de belangrijkste personen voor mij. Een grote dank gaat uit naar mijn familie. Roeland en Klaudie, bedankt voor alle leuke momenten en voor de gezellige weekends thuis. Ik heb heel veel te danken aan mijn ouders. Niet alleen omdat ze me de kans hebben gegeven om te studeren, maar vooral ook hun onvoorwaardelijke steun. Papa, bedankt voor je interesse in mijn onderzoek, de vele krantenknipsels over elektrische voertuigen en je goed advies. Mama, bedankt voor al je geduld, je luisterend oor en je vertrouwen in mij.

Liefste Valentijn, je hier bedanken in een paar woorden is niet gemakkelijk. Toch wil ik je speciaal bedanken om er altijd te zijn voor mij, voor het nalezen van mijn tekst, voor al je begrip, omdat je me altijd aan het lachen brengt en voor zoveel meer ...

Kristien
Augustus 2010.

Abstract

Plug-in hybrid electric vehicles, are rapidly gaining interest. Batteries of plug-in hybrid electric vehicles are charged by either plugging into electric outlets or by an on-board generator. For grid charging, these batteries are supplied by power from the grid at home from a standard outlet or on a corporate car park. The extra electrical load, from charging the batteries, has an impact on the electricity system in general and more specifically on the distribution grid and the electricity generation system. The impact of such vehicles on the distribution grid is analyzed in terms of power losses and voltage deviations. The impact on the electricity generation system is investigated in terms of available generation capacity.

Uncoordinated charging of plug-in hybrid electric vehicles may cause local grid problems. These grid problems can be avoided by coordinated charging. The aim is to determine the optimal charging profile for each vehicle and to minimize the impact on the electricity system. For the coordination, the linear or quadratic programming technique is found to be the most efficient and is applied for this optimization problem.

Plug-in hybrid electric vehicles cannot only charge when connected to the grid, but also discharge and thus inject power. In that way, electric vehicles may offer grid services to support the grid. It is not clear whether offering grid services is economic for these vehicles. A voltage controller could be easily implemented in the charger and the grid services may be enabled. Such a controller avoids large voltage deviations at the household level.

The vehicles may also be matched with distributed generation units such as combined heat and power units, small-scale wind turbines and photovoltaic panels. If there is power or energy produced by these units, the batteries of the vehicle could be charged with this energy and their curtailment due to grid congestion is avoided.

Charging of plug-in hybrid electric vehicles also has an impact on the electricity generation system. When the penetration level of these vehicles is high, charging during the evening peak must be avoided since not enough generation capacity is available. Therefore, the charging must be shifted in time.

From the perspective of the distribution grid, the management or coordination of charging plug-in hybrid electric vehicles allows for grid reinforcements to be postponed. On the other hand, the introduction of smart chargers or meters is inevitable for the coordination of the charging of plug-in hybrid electric vehicles.

Samenvatting

Nieuwe voertuigconcepten, zoals plug-in hybride elektrische voertuigen, krijgen meer en meer aandacht. Hun batterijen kunnen opgeladen worden vanuit het net door ze in te pluggen in een (standaard) elektrisch stopcontact of door generatie aan boord van het voertuig. Het opladen door ze bijvoorbeeld in te pluggen in een stopcontact kan thuis plaatsvinden maar ook op een parking. Deze extra belasting voor het net heeft een significante impact op het elektriciteitssysteem en meer in het bijzonder op het distributienet en op de opwekking van elektriciteit. De impact op het distributienet is geanalyseerd in termen van lijnverliezen en spanningsafwijkingen. De impact op het generatiesysteem is onderzocht in termen van beschikbare capaciteit.

Ongecoördineerd opladen van deze voertuigen veroorzaakt lokale netproblemen die kunnen vermeden worden door het opladen van de voertuigen te coördineren. Dit optimalisatieprogramma bepaalt het optimaal oplaadprofiel voor ieder voertuig en minimaliseert de impact op het elektriciteitssysteem. De lineaire of kwadratische programmeertechnieken zijn de meest efficiënte oplossingsstrategieën voor dit optimalisatieprobleem.

Plug-in hybride elektrische voertuigen kunnen niet alleen opladen wanneer ze verbonden zijn met het net maar kunnen ook ontladen en op die manier energie injecteren in het net. Deze elektrische voertuigen hebben dus de mogelijkheid om netdiensten te leveren. Het is niet duidelijk of deze diensten economisch haalbaar zullen zijn. Een spanningscontrole ingebouwd in de lader is wel realistisch omdat deze controle eenvoudig te implementeren is. Deze netdienst zorgt ervoor dat de spanning op lokaal niveau noch te laag noch te hoog is door respectievelijk te ont- of opladen.

Deze voertuigen kunnen ook gecombineerd worden met gedistribueerde productie-eenheden zoals warmte-krachtkoppelinginstallaties, kleinschalige windturbines en zonnepanelen. Als deze eenheden meer energie produceren dan lokaal verbruikt,

kunnen de voertuigen opgeladen worden met het overschot. Zo wordt een beperking van de output van de productie-eenheden als gevolg van lokale netoverbelasting vermeden.

Het opladen van plug-in hybride elektrische voertuigen heeft ook een impact op de opwekking van elektriciteit. Wanneer een significant aandeel van de voertuigen plug-in hybride elektrische voertuigen zijn, moet opladen tijdens de avondpiek vermeden worden als er onvoldoende of te dure productiecapaciteit voorhanden is.

Vanuit perspectief van het distributienet, kan het management of de coördinatie van het opladen van de batterijen van plug-in hybride elektrische voertuigen netversterkingen uitstellen. De implementatie van slimme meters is anderzijds noodzakelijk voor de coördinatie van het opladen van plug-in hybride elektrische voertuigen.

List of symbols and abbreviations

List of symbols

symbol	explanation	unit
$\mathbf{A}_{\mathrm{eq}}$	matrix of the equality constraint	
$\mathbf{A}_{\mathrm{ineq}}$	matrix of the inequality constraint	
$\mathbf{b}_{\mathrm{eq}}$	vector of the equality constraint	
$\mathbf{b}_{\mathrm{ineq,l}}$	vector of the lower bounds of the inequality constraint	
$\mathbf{b}_{\mathrm{ineq,u}}$	vector of the upper bounds of the inequality constraint	
$\mathbf{C}$	nodal current summation matrix	
$\mathrm{C}_{\mathrm{day}}$	electricity tariff during the day	[€/kWh]
$\mathrm{C}_{\mathrm{max}}$	maximum capacity of the battery	[Wh]
$\mathrm{C}_{\mathrm{min}}$	minimum capacity of the battery	[Wh]
$\mathrm{C}_{\mathrm{night}}$	electricity tariff overnight	[€/kWh]
$\mathbf{C}_{\mathrm{n,t}}$	battery capacity at node n at time step t	[Wh]
$E\left(x\right)$	mean value of the stochastic variable x	
$\mathbf{F}_{\mathrm{LP}}$	vector of the objective function of linear programming	
$\mathbf{F}_{\mathrm{QP}}$	vector of the objective function of quadratic programming	
$\hat{f_N}$	a sample-average approximation of the objective of the stochastic programming problem	
f_{t}	optimal power losses from period t to the last time stage	[W]
$\mathrm{f}_{\mathrm{QP,t}}$	part of matrix $\mathbf{F}_{\mathrm{QP}}$ at time step t	
$\mathrm{g}_{\mathrm{error}}$	error function used in convergence criteria	

$\mathbf{H}$	matrix of the objective function of quadratic programming	
h_t	part of matrix $\mathbf{H}$ at time step t	
$\mathbf{I}_{\mathrm{line}}$	vector of line currents	[A]
$\mathbf{I}_{\mathrm{line,i}}$	line current in segment i	[A]
$\mathbf{I}_{\mathrm{line,i,t}}$	line current in segment i at time step t	[A]
$\mathbf{I}_{\mathrm{node}}$	nodal current injections vector	[A]
$\mathbf{I}_{\mathrm{node,t}}$	nodal current injections vector at time step t	[A]
$\mathrm{L}_{\mathrm{N,M}}$	unbiased estimator $E\left(\hat{\nu}_n\right)$	
$\mathbf{l}_{\mathrm{b}}$	vector with the lower bounds of the candidate solution	
$\mathbf{P}_{\mathrm{DG}}$	vector of nodal DG power injections	[W]
$\mathrm{P}_{\mathrm{loss,t}}$	line losses at time step t	[W]
$\mathbf{P}_{\mathrm{PHEV}}$	vector of nodal PHEV power injections	[W]
$\mathrm{P}_{\mathrm{PHEV,max}}$	maximum charger power	[W]
$\mathrm{P}_{\mathrm{PHEV,min}}$	minimum charger power	[W]
$\mathrm{P}_{\mathrm{PHEV,n}}$	power of the charger at node n	[W]
$\mathrm{P}_{\mathrm{PHEV,n,t}}$	power of the charger at node n at time step t	[W]
$\mathrm{P}_{\mathrm{PHEV,t}}$	vector of nodal PHEV power injections at time step t	[W]
P_{t}	power losses during period t	[W]
$\mathbf{R}$	matrix of line resistance	[Ω]
$\mathbf{R}_{\mathrm{l}}$	element of matrix R	[Ω]
R_s	possible storage levels of dynamic programming	
$\mathbf{S}_{\mathrm{h}}$	vector of the apparent power injections of households	[VA]
$\mathbf{S}_{\mathrm{h,t}}$	vector of the apparent power injections of households at time step t	[VA]
$\mathbf{S}_{\mathrm{node}}$	vector of nodal apparent power injections	[VA]
$\mathbf{S}_{\mathrm{t,i}}$	battery content of the i^{th} vehicle at time stage t for dynamic programming	[Wh]
$\mathbf{T}$	incidence matrix	
$\mathrm{U}_{\mathrm{grid}}$	rated voltage at the secondary of a distribution transformer	[V]
$\mathbf{U}_{\mathrm{lower\ limit}}$	vector of the lower voltage limits in a distribution grid	[V]
$\mathrm{U}_{\mathrm{max,n,t}}$	upper voltage limit at a node n at time step t	[V]
$\mathrm{U}_{\mathrm{min,n,t}}$	lower voltage limit at a node n at time step t	[V]
$\mathbf{U}_{\mathrm{node}}$	vector of nodal bus voltages	[V]
$U_{\mathrm{n,t}}$	nodal voltage at node n at time step t	[V]
$\mathbf{U}_{\mathrm{upper\ limit}}$	vector of the upper voltage limits in a distribution grid	[V]
U_{VD}	voltage constant	

$\mathbf{u}_\mathrm{b}$	vector with the upper bounds of the candidate solution	
X	line reactance	[Ω]
$\mathbf{x}$	candidate solution of the coordination problem for the charger of the PHEV	[W]
$\mathbf{x}_\mathrm{n}$	no PHEV: 0; PHEV:1	
$\mathbf{Z}$	impedance matrix	[Ω]
$\mathrm{Z}_{i,j}$	impedance of the feeder segment if it is situated between nodes i and j	[Ω]
$\Delta\eta_i$	efficiency loss for the i^{th} sample	[%]
Δ t	time interval	[s]
$\Delta U_{n,t}$	voltage difference between U_{grid} and node n at time step t	[V]
ϵ	error measure used in convergence criteria	
μ	mean value	
$\hat{\nu}_n$	sampled-average approximation based on n objective function samples	
ν^*	real optimal value of the stochastic problem	
$\rho(X,Y)$	correlation coefficient between X and Y	
σ	standard deviation	
ω^j	random input variable of the stochastic programming problem	

List of abbreviations

abbreviation	explanation
AA	Availability Analysis
AC	Alternating Current
ACEA	European Automobile Manufacturers Association
BEV	Battery Electric Vehicle
CD	Charging Depleting Mode
CHP	Combined Heat and Power
CIM	Current Injection Method
CNG	Compressed Natural Gas
CS	Charge Sustaining Mode
CV	Conventional Vehicle
DC	Direct Current
DDDP	Discrete Differential Dynamic Programming
DG	Distributed Generation
DP	Dynamic Programming
DPSA	Dynamic Programming Successive Approximation
DSO	Distribution System Operator

ENTSO-E	European Network of Transmission System Operators of Electricity
EREV	Extended Range Electric Vehicle
EU-27	European Union
FCEV	Fuel Cell Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IDP	Incremental Dynamic Programming
IEEE	Institute of Electrical and Electronics Engineers
Li-ion	Lithium-ion
LP	Linear Programming
LPG	Liquified Petroleum Gas
Ni-MH	Nickel-Metal Hydride
PHEV	Plug-in Hybrid Electric Vehicle
P(H)EV	Plug-in (Hybrid) Electric Vehicle
PSD	Power Split Device
PV	Photovoltaic
QP	Quadratic Programming
RFID	Radio Frequency Identification
SME	Small and Medium Enterprise
SOC	State Of Charge
TML	Transport and Mobility Leuven
TSO	Transmission System Operator
UCTE	Union for the Coordination of Transmission of Electricity (since July 2009 integrated in ENTSO-E
VREG	Vlaamse Reguleringsinstantie voor Elektriciteits- en Gasmarkt (Regulator for gas and electricity of the Flemish region)
V2G	Vehicle-to-Grid operation
ZEV	Zero-Emission Vehicle

Contents

1

Transition to electric vehicles

1.1 Introduction

Nowadays, most vehicles have an internal combustion engine (ICE) in which the combustion of petrol or diesel (derivatives of petroleum or oil) occurs. Therefore, 95% of the road transport sector depends on oil [1]. When neglecting bio-fuels, oil is a finite resource and will eventually run short in future. The global peak oil consumption will probably occur somewhere in the next decade [2]. Furthermore, a large part of the oil reserves are located in politically unstable countries. In general, the oil prices are increasing. Because of the economic crisis, they temporarily dropped in 2009 with respect to the level of 2008. Nevertheless, it is to be expected that the oil prices will be soaring again after the crisis [3]. The dependence on oil is one of the main economic motives for the development of new vehicle concepts making the transport sector less oil dependent.

Another essential motive in the development of new vehicle concepts is an increasing concern in limiting the emission of greenhouse gases such as CO_2 to reduce global warming and to meet the Kyoto restrictions. CO_2 is one of the most important greenhouse gases and transport is a major source. Nowadays, the transport sector emits 23% of the energy-related CO_2 emissions and its share will probably rise in future [4]. Under the Kyoto protocol of the United Nations, Belgium commits itself to a greenhouse gas emission reduction of 7.5% compared to the level of 1990 by 2008-2012 [5]. Moreover, the European 20-20-20 measure requires a 20% reduction of energy consumption, a 20% reduction of the greenhouse gases and a 20% share of renewable energy by 2020 [6] compared to 1990 levels.

The European Automobile Manufacturers Association (ACEA) and the European Commission have established a voluntary agreement to limit the amount of CO_2 emissions for new passenger cars sold in Europe. The target of the agreement is to achieve an average level of 120 gram CO_2 per km by 2012. Unfortunately, the automobile manufacturers are not reducing CO_2 emissions fast enough. Since the ACEA is not achieving these goals within the proposed period, a legislation on CO_2 emissions from passenger cars is officially published in 2009 in the form of a regulation [7] to reduce CO_2 emissions from light-duty vehicles. The European emission standards for newly sold vehicles in the European Union members describe the limits for exhaust emissions. In 2014, European emission standards for passenger cars will be the EURO 6-standard [8]. This standard prescribes that the nitrogen oxide emissions of diesel vehicles must be halved with respect to the level of the Euro 5-standard. Vehicles that do not satisfy this standard will be rejected for sale. To meet these measures and restrictions, alternative vehicle concepts, which may be more energy efficient, must be developed. Although conventional vehicles will also be more efficient and cleaner to a certain point, these vehicles have already improved a lot over the past decades, leaving not much room for further improvements.

Electric vehicles become attractive. The main motives for this development are described in this section. Beside electric vehicles, some other types types are distinguished in section 1.2. Electric vehicles can be divided by type and topology as analyzed in section 1.3. The batteries remain a critical issue. The disadvantages and advantages of the most common batteries for electric vehicles are discussed in section 1.4. The rate of charging mostly depends on the charging point. Fast charging mostly occurs at charging stations and slow charging can take place at home as mentioned in section 1.5 and 1.6. Several business models of the main concerns of electric vehicles are discussed in section 1.7.

1.2 Alternative vehicles

To achieve more independence of oil and to make the vehicles more efficient and cleaner, several alternative vehicle concepts are developed. An alternative vehicle is defined as a vehicle operating on other energy sources than petroleum fuel, i.e. diesel or petrol. Examples are bio-fuels, hydrogen, compressed natural gas, liquified petroleum gas and electricity. This list is not limited. Exotic alternatives such as compressed air and solar energy are not considered in here. Some vehicle concepts will use multiple energy sources, for instance a combination of petroleum fuel and electricity or hydrogen. These vehicles are defined as hybrid vehicles. Hydrogen and electricity can be produced by sustainable energy sources such as wind and solar energy or by the regular power plants. Therefore, vehicles based on electricity or hydrogen can (partially) break the link between oil and transport [9].

1.2.1 Compressed natural gas and liquified petroleum gas

Compressed natural gas (CNG) and liquified petroleum gas (LPG) are fossil fuels. LPG and CNG engines can work with leaner mixtures improving energy efficiency. They also offer better combustion characteristics and have low emissions in dedicated spark-ignition engines. Safety issues are important and proper handling is required [1]. The dependency on fossil fuels remains.

1.2.2 Bio-fuels

Biodiesel is typically derived from rapeseed oil or other vegetable oils such as sunflower, coconut oil or palm oil. Bio-ethanol is currently produced from sugar beets, maize, etc. A disadvantage is the large area needed to grow these crops [1] which gives problems with food crops and bio-diversity [10]. However, newer generations of bio-fuels are supposed to give less problems. Bio-fuels can use the current petrol and diesel infrastructure and can be used in existing engines, in its pure form or blended with conventional diesel fuel if appropriate modifications are carried out. These fuels are probably a good alternative at the short term, but not in the long run due to the disadvantages mentioned above.

1.2.3 Electricity

For the electric drive based vehicles, a distinction must be made between vehicles which charge by plugging into an electrical outlet and those generating electricity on-board from liquid fuels. A hybrid electric vehicle combines an internal combustion engine and an electric motor. The electricity is generated on-board by the combustion engine. Because of the optimal and decoupled control of the combustion engine and the electric motor, this vehicle is more energy efficient than a conventional vehicle and emissions are reduced. If the batteries can be charged by the electricity grid, sustainable energy such as renewable energy resources and clean fossil fuels, which can be handled centrally, can be used. The energy needed to charge the batteries is produced centrally and so are the emissions. Therefore, when the vehicle is driving in full electric mode, the emissions are shifted in time and from local to central generation where they can be treated better. This would improve the air quality in city environments. Electricity infrastructure is fully developed in Belgium. It may be possible that the current infrastructure has to be reinforced when a considerable amount of vehicles charge from the grid. The electrification of bicycles, scooters, motorcycles and mopeds could also be of interest. The largest barrier for electric vehicles is the battery technology. Batteries have a low energy density compared to diesel or petrol and the vehicles need a large and expensive battery pack to achieve a reasonable range [9].

1.2.4 Hydrogen

Hydrogen can be used in an internal combustion engine or in a fuel cell in combination with an electric motor. The latter, defined as a fuel cell electric vehicle (FCEV), is more efficient than using hydrogen in an internal combustion engine. Hydrogen can for instance be produced by electrolysis using electricity from the grid. In a FCEV, the chemical energy of the hydrogen, stored in a tank, is converted in electric power in the fuel cell supplying the electric motor. The energy density of hydrogen storage is higher than batteries but does not achieve the same level as conventional fuels. Hydrogen generation, distribution and refueling infrastructure are required for these vehicles. If the current infrastructure for natural gas can be used is depending on the vol% of the mixture of natural gas and hydrogen. For mixtures containing up to 17% of hydrogen the existing infrastructure should be sufficient [11]. The hydrogen well-to-wheel pathway is less efficient than the electrical pathway for electric vehicles. But the range of these vehicles is significantly larger. Hydrogen can be stored in liquid or in gas form. The former has a poor energy efficiency [9], [12].

1.3 Types of electric vehicles

An electric vehicle in this text is a vehicle using at least one electric motor for propulsion purposes. This includes battery electric vehicles as well as (plug-in) hybrid electric vehicles. Different types of electric vehicles can be distinguished depending on their topology and design. An electric motor, converting electricity into mechanical propulsion with an efficiency on top of 90% [13], is more energy efficient than an internal combustion engine. Conventional vehicles (CVs) have an internal combustion engine running on diesel or petrol. These vehicles have bad efficiency characteristics, especially at partial load. The engine size is determined by the required peak power. Therefore, the size or maximum power of the engine is for most of the time too large and this peak power is only needed for acceleration. For a hybrid electric vehicle, the combustion engine is dimensioned on the nominal power required by the vehicle and the electric motor is taking care of the peak power.

1.3.1 History of electric vehicles

Electric vehicles were the most promising drive technology at the end of 19^{th} century. The first vehicle that exceeded 100 km/h was the “Jamais Contente” in 1899. In 1911, the start motor was invented, making the starting of petrol vehicles much easier. These engines became more powerful and the electric vehicles disappeared in the early 1900s. Meanwhile, the model T of Ford, which is a conventional vehicle, became very cheap due to improvements in mass production. The drop of the fuel prices because of the discovery of many oil wells encouraged the breakthrough of these vehicles. In the second half of the twentieth century, the theoretical interest in electric vehicles started to revive again, partially due to the oil crisis of the early 1970s. Considering the tremendous improvements in power electronics in 80-ties and 90-ties, the electric motor could be driven more efficiently. The last two decades, tendency towards more energy efficient vehicles is observed. This encourages the further development of electric vehicles. For the moment, most of the automotive manufacturers have electric vehicles as prototype or even in production [14], [15].

1.3.2 Battery electric vehicles

A battery electric vehicle (BEV) uses an electric motor for propulsion and no internal combustion engine is implemented. The electrical energy required for the electric motor is coming from the batteries or supercaps. The batteries are charged by plugging into an electric outlet. Regenerative braking is also implemented and the kinetic energy is converted during braking into electrical energy and stored in the batteries of the BEV. They have a limited range. Therefore, BEV owners may suffer from so-called range anxiety. The battery electric vehicle is often referred to as a zero-emission vehicle (ZEV), but this is misleading . The entire energy cycle, including power plants or other generation units needed to produce electrical energy, must be considered to determine the emissions.

1.3.3 Hybrid electric vehicles

A hybrid electric vehicle (HEV) combines a conventional internal combustion engine and an electric motor. The downsizing of the internal combustion engine is possible without lowering performance, because the electric motor has the potential for a power boost. Internal combustion engines are the most inefficient when their output is low, i.e during idle or slow driving. In this case, the internal combustion engine can be switched off and the vehicle can rely on its electric motor only. The combustion engine provides the steady or average power and the electric motor the dynamics [1], [16], [17]. As a result, the HEV operates always near its optimal working point. Under-utilization of the too large internal combustion engine is avoided and a better fuel economy is achieved compared to conventional vehicles. HEVs are divided, based on topology, into series, parallel and mixed series-parallel hybrid electric vehicles, a technical classification.

For series hybrid electric vehicles, the wheels are driven by an electric motor. The energy can be either derived from the batteries or from the internal combustion engine driving a generator as shown in Fig. 1.1. The internal combustion engine is not directly linked to the wheels which simplifies speed control. The ICE takes care of the average power and the batteries are stored with the excess of energy and provide energy when needed. There are several advantages: the combustion engine works at optimum efficiency and at minimal fuel consumption and emissions, the battery can provide the extra power boost when needed, the internal combustion engine is downsized and structure and drivetrain of the topology is simple. However, the energy of the combustion engine must be converted twice (from mechanical by the combustion engine to electrical and then from electrical back to mechanical through the traction motor) due to the series topology of the components. As a result, the reliability of the system is reduced. Furthermore, the traction motor must be large since the wheels cannot be driven by the internal combustion engine [17].

Fig. 1.2 shows the drivetrain for parallel hybrids. The driving power to the wheels is provided via two parallel paths, i.e. mechanical and electrical. The ICE works jointly with the electric motor to deliver power to the wheels. The same advantage is also valid here: the internal combustion engine works at optimal efficiency, thus achieving minimal fuel consumption and emission. Parallel HEVs also have a downsized internal combustion engine. Although, the same performance as a series HEV can be achieved with a smaller internal combustion and electrical engine. The energy losses are smaller as no double energy conversion occurs. The components are not in a series topology and therefore, the system is more reliable. A disadvantage is that the mechanical coupling between ICE, electric motor and wheels is rather complex. The electric motor is also not available when the batteries are charging since this motor is working in generator mode [1], [17].

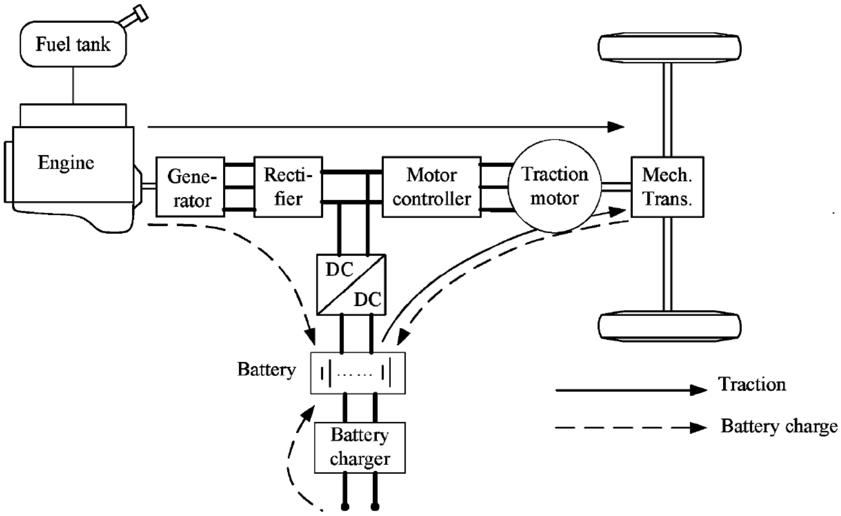

Fig. 1.1: Series hybrid electric drivetrain [17].

The current Toyota Prius is using a mixed series-parallel topology with a special power split device (PSD) or a planetary gear unit as shown in Fig. 1.3. This vehicle uses two electric machines. The smallest electric machine is mostly used for generating energy for either the larger electric machine (which functions as a motor driving the wheels) or to charge the batteries or for both simultaneously. The internal combustion engine also works at optimal efficiency. The battery is now a buffer between electrical and mechanical transmission contrary to the parallel HEV, where the electrical motor works as generator or motor. The internal combustion engine and the electric motor are working complementary. In the city, the vehicle behaves more as a series hybrid, driving as an electric vehicle if the battery is sufficiently charged and the speed is low. On the highway, the vehicle behaves as parallel hybrid, i.e. the combustion engine provides the propulsion energy but the electric motor still takes care of accelerations. This mixed series-parallel configuration has the advantages of both drivetrains. However, in this configuration, the HEV needs two electric motors and requires one or more complex PSD systems. Consequently, the control system is more complicated. This complexity increases the purchase price [17], [18].

These vehicles can also be categorized by different engine architectures depending on the size of the combustion engine and electric motor, depending on the electric

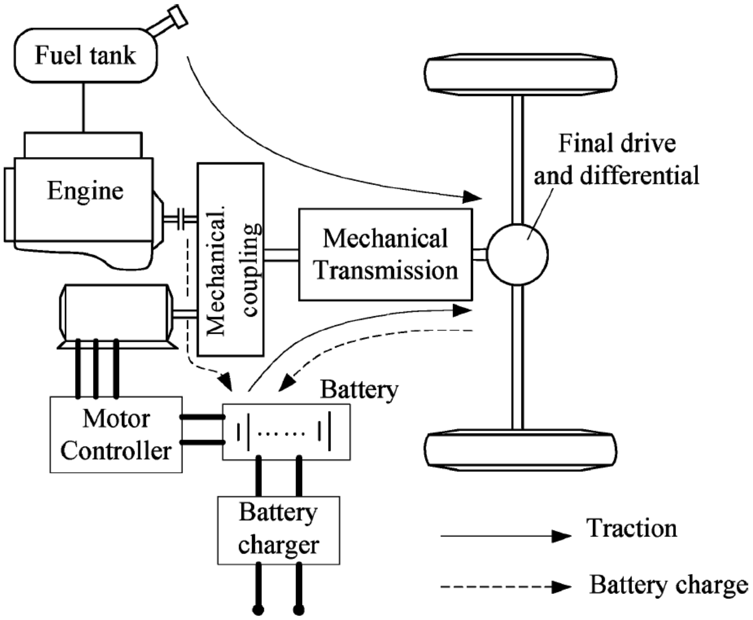

Fig. 1.2: Parallel hybrid electric drivetrain [17].

driving possibilities. Therefore, the HEVs can be divided based on their use, i.e a function classification. Light or micro HEVs have an internal combustion engine with a starter/generator of a few kilowatts designed to shut off the internal combustion engine during stops or idling to save fuel. This combination is rather considered as an improvement of the internal combustion engine than a powertrain on its own and is not really considered as a HEV. Mild HEVs have an electric motor of 10-20 kW which permits an additional power boost to the internal combustion engine. The system is also able to recuperate energy during braking. These HEVs have a larger battery pack increasing the weight and the purchase price but are not able to drive in full electric mode. Full HEVs are capable of driving in full electric mode for a limited range. Therefore, a larger energy storage system is required [19], [20]. An overview is given in Table 1.1.

1.3.4 Plug-in hybrid electric vehicles

Plug-in hybrid electric vehicles (PHEVs) are hybrid electric vehicles that can be charged with energy from the electricity grid by plugging into a standard electric outlet next to an on-board electricity generation. Therefore, PHEVs offer essential fuel flexibility. These vehicles are full hybrid electric vehicles as they can drive in

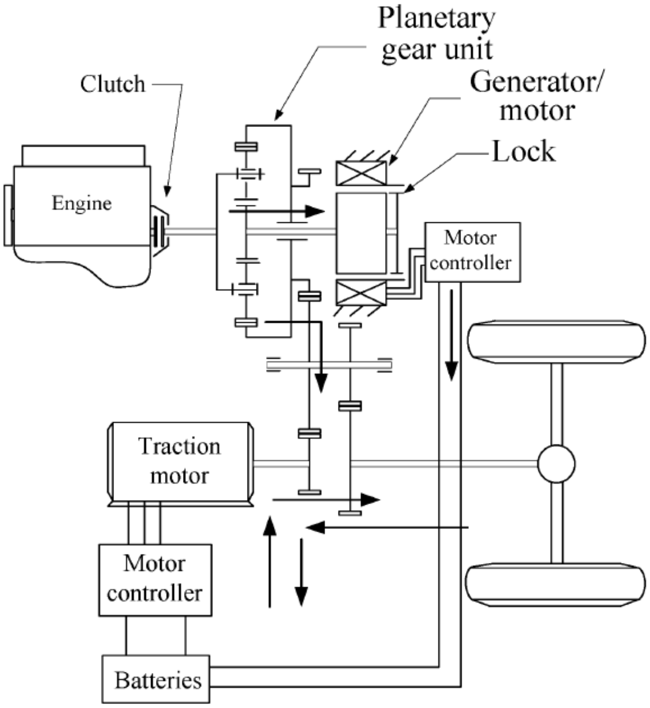

Fig. 1.3: Series - parallel hybrid drivetrain by using a planetary gear unit [17].

	Micro	**Mild**	**Full**
Electric motor power [kW]	<5	10-20	>20
Voltage [V]	14 or 42	42-144	150-450
Function	start-stop	start-stop & power boost	full electric mode

Table 1.1: Types of hybrid electric vehicles [19].

full electric mode. Although they may have a larger battery compared to hybrid electric vehicles, their electric range is rather limited compared to conventional vehicles. A PHEV is defined by [21] as any hybrid electric vehicle which contains at least:

- a battery storage system of 4 kWh or more used to power the motion of the vehicle,
- a means of recharging that battery system from an external source of electricity,
- the ability to drive at least 10 miles (16 km) in all electric mode consuming no petrol or diesel.

PHEVs can drive in full electric mode until the batteries are fully depleted, defined as the charge depleting (CD) mode. If the batteries are empty, PHEVs behave as HEVs and the state of charge (SOC) of the battery remains stable, called the charge sustaining (CS) mode. In CS mode, PHEVs have the same efficiency as HEVs [20], [22].

Plug-in hybrid electric vehicles are considered as the most promising approach of introducing grid supplied electricity as energy source for transportation. The electricity of the grid used for charging the batteries substitutes a part of the regular fuel. PHEVs combine the advantages of HEVs and BEVs. Compared to HEVs, PHEVs rely less on petroleum. Compared to BEVs, PHEVs have an extended range because they need a small internal combustion engine for longer distances and a lower purchase price since the battery pack is the most expensive part of electric vehicles. The larger battery pack of BEVs is more expensive and demands a longer charging time [23]. The x in PHEVx indicates that the vehicle can drive x miles in electric mode. For instance, a PHEV60 can drive 60 miles or about 100 kilometers in full electric mode.

PHEVs can also be divided into parallel and mixed series-parallel hybrids. An example of another configuration is the extended range electric vehicle (EREV), a plug-in hybrid electric vehicle with a small internal combustion engine. This vehicle normally drives in full electric mode, using its small combustion engine in emergency cases, for instance when charging not occurs when needed, or for long distances. In that way, the range anxiety of BEV owners is reduced.

1.3.5 Barriers for successful commercialization

Battery electric vehicles have two major drawbacks. The maximum electric range of electric vehicles is rather limited and the required battery pack is large and expensive. Fast charging could help to solve this disadvantage, however, for this purpose batteries are not yet fully developed. Nowadays, the charging time is rather long. In future, charging should become as easy as filling a petrol tank of a conventional vehicle. It is uncertain if you could plug-in your vehicle at work or at home. From a grid manager's point of view, the ideal situation is to plug-in wherever you can, so vehicle owners can charge where a connection is available. Next to the batteries, there is a need for standardization of charging stations, electrical outlets and plugs.

(Plug-in) hybrid electric vehicles (P)HEVs have also two major drawbacks. First, (P)HEVs need two propulsion systems, making them more expensive. Second, the batteries for electric vehicles are expensive and the size of the batteries is rather large. The limited electric range for (P)HEVs is less important since they can still rely on their internal combustion engine if needed [10].

In this research, the focus lies on plug-in (hybrid) electric vehicles P(H)EVs, i.e. vehicles plugged into an electric outlet to charge the batteries. As a result, these vehicles together with BEVs will have the largest impact on the electricity system.

1.4 Charging of electric vehicles

The performance of batteries is essential for electric vehicles. This section describes the available types of batteries and a comparison is made. The ideal battery for a PHEV has a high energy density and a high power capability. The battery price has a major impact on the vehicle price. Therefore, the battery lifetime should be the same as the vehicle lifetime. Furthermore, the batteries must also be produced as cheap as possible. The safety of the batteries is an important issue to guarantee the safety of the occupants. The batteries of PHEVs are subjected to both shallow and deep discharge cycles especially when driving in hybrid and full electric mode respectively. Contrary, the batteries of BEVs are only subjected to repeated deep discharge cycles. These cycles differ a lot from the discharge cycles in HEVs, which are shallow discharges. Deep discharges are more demanding for the batteries, which must be improved in future in this area [24]. Batteries are not fully discharged, mostly up to 20% of the state of charge in order to extend battery life time. Sometimes, supercaps are also used in electric vehicles. The recycling of the batteries is important for the environment. Batteries are also an important element for the life cycle assessment of greenhouse gas emissions from PHEVs. The production and recycling of the battery count for 2-5% of life cycle emissions from PHEVs [25].

1.4.1 Charging profile

Charging is more or less the same for all types of batteries and can be divided into stages as shown in Fig. 1.4 for a lead-acid battery. In the first stage, at t=1, the battery is charged with a constant current until the increasing voltage level reaches the upper-voltage cutoff. Thereafter, at t=3, batteries are charged at a constant voltage level, while the current decreases until it is 3-5% of the rated value. As a result, the power of the charger decreases at the end of the charging period. The third stage, at t=6, is a float charge and the battery is charged to compensate for self-discharging [26], [27].

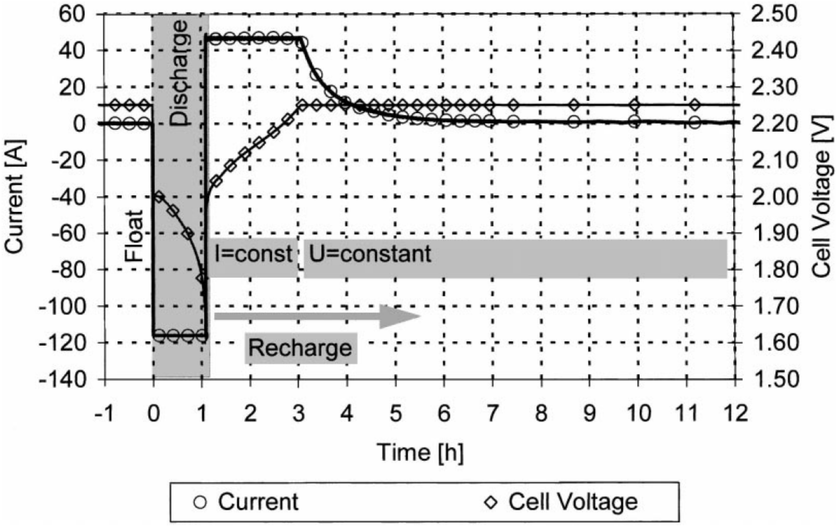

Fig. 1.4: Charging stages for a lead-acid battery [28].

Fig. 1.5 shows simplified charging profiles as a function of time for several voltage and current levels. The power output is constant and the reduction of the power output of the charger at the end of the charging period is approximated by charging at significantly lower constant power for the last hour. Higher voltages or currents reduce the charging time. In this work, the power output of the charger without any intelligence is taken as a flat profile. The power is not reduced for the final hour because only the maximum impact on the electricity grid is investigated. Although the charging profile in Fig. 1.5 is typical for the United States [29], the same assumptions hold for Europe. The voltage and current levels differs, but a flat charging profile can still be assumed.

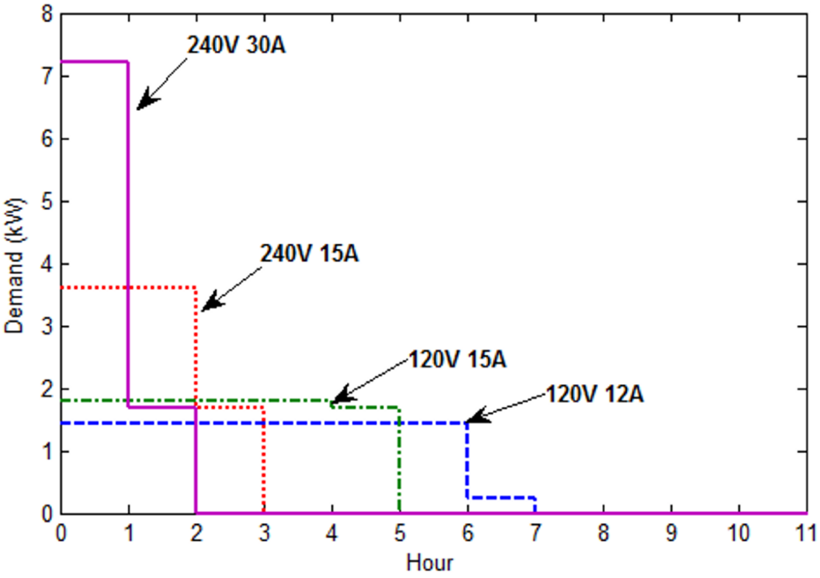

Fig. 1.5: Charging profiles [29].

1.4.2 Battery types

Electric vehicles require an electric storage device. Batteries are most commonly used for this purpose and are implemented in these vehicles. Nowadays, the performance of the batteries is still not satisfying the requirements wished by the vehicle developers. However, batteries have been improved over the last decades.

This paragraph gives an overview of the main types of battery technology that can be considered for use in electric vehicles, i.e. lead-acid , nickel-metal-hydride and lithium-ion batteries [30] as represented in Table 1.2.

	Pb-Ac	**Ni-MH**	**Li-ion**
Energy Density [Wh/kg]	30-50	60-70	70-160
Power Density [W/kg]	300-80	1500-200	2000-650
Cycle Life (80% DOD)	200-300	300-500	>1000
Fast Charge Time	8-16h	2-4h	1h or less
Overcharge Tolerance	high	low	low
Self-discharge/Month	5%	30%	<10%
Cost	low	high	very high

Table 1.2: Types of batteries [27],[31],[32].

Lead-acid batteries

Lead-acid (Pb-Ac) batteries have the most mature battery technology and are the cheapest. This battery type is often used in conventional vehicles to deliver power to the start motor. The low energy density makes this technology inadequate for an optimal use in electric vehicles. The limited cycle life is also a major disadvantage since batteries in electric vehicles require frequent charging and discharging. After the second phase of charging, a float charge is necessary at a voltage lower than the voltage of the second phase to compensate for the self-discharge [27]. These batteries were used for instance in the first generation EV1 of General Motors in 1996 [33] and in many other electric vehicles.

Nickel-metal-hydride batteries

Nickel-metal-hydride (Ni-MH) batteries have a larger energy density and the cycle life is larger than for Pb-Ac batteries. The batteries are fully developed and safe and have almost no potential for cost reduction and increase in energy density anymore. They have a high self-discharge and can lose up to 30% of their energy capacity within a month. The cells of the Ni-MH battery pack are placed in series to achieve a sufficiently high voltage level. Individual cells could have a lower capacity than the others cells connected in series due to production variability. If the battery pack is further discharged, the cells overdischarge and polarity reversal occurs. This phenomena damages the cells. Therefore, the dept of discharge (DOD) for a battery pack is much stricter than for individual cells to protect them and the individual cells have a low available capacity. For instance, the state of charge of a Toyota Prius is kept between 45% and 75%. Nowadays, Ni-MH batteries are the most common batteries used in electric vehicles and the sales will rise up to 2012 compared to the current sales [34]. The cycle efficiency is low and therefore, this is not a sustainable solution for PHEVs and BEVs [35]. In future, Li-type batteries will probably take over their leadership.

Lithium-type batteries

Lithium ion (Li-ion) batteries combine a high energy density, due to higher terminal voltage, with a higher cycle life. Table 1.2 shows a cycle life of more than 1000 cycles which can be increased up to 5000 or more. These advantages allow for reduced weight, increased range and improved cycle life compared to Ni-MH batteries, making them very suitable for electric vehicles. Li-ion cells are stable and have a low self-discharge, so the third charging stage is not necessary. There is no maintenance required and no memory effect occurs. Unfortunately, these batteries are very expensive at the moment. Only mass production can reduce the cost. Unfortunately, even with Li-ion batteries, problems remain with limited cycle life, large recharge time and low power delivery for small batteries [35].

Recent developments in nano-technology-based lithium batteries have focused on high power batteries suitable for electric vehicles by replacing graphite in conventional Li-ion batteries with nano-titanate materials. These batteries have a longer life, up to 9000 charge and discharge cycles, are able to recharge in minutes and are inherently safe [36]. It is unclear whether these batteries can be produced at low cost. On the other hand, lithium metal polymer have a flexible form factor and an improved safety. Lithium metal polymer, however, is not proven to be suitable for electric vehicles [20].

It is uncertain if the supply of Lithium will be sufficient to provide each future electric vehicle with Li-ion batteries [37]. Old batteries should be collected and lithium could also be recycled. It is uncertain to which percentage, cost and quality this can be achieved [38]. Another possibility is to reuse the batteries in a ”second life” for stationary storage, such as in households, if they are no longer suited for the utilization in PHEVs.

ZEBRA batteries

ZEBRA batteries or Sodium-Nickel-Chloride (NaNiCl) are suffering from a modest power density and therefore, these batteries are mostly excluded for BEVs and PHEVs applications, except for some smart EVs and busses [39].

Summary

A summary of the requirements for the batteries for each vehicle type is shown in Fig. 1.6 in terms of energy and power density. Batteries, developed for high power densities, have lower energy densities and vice versa. The larger the energy density, the more efficient the electric vehicles become. However, electric vehicles need both power and energy density. The relationship between power and energy density is defined as the Ragone characteristics. If the performance domain of a vehicle type is below and at the left of a Ragone characteristic, this battery type will satisfy the battery requirements of that vehicle type. This figure affirms that Li-ion batteries are the most promising technology [39].

Micro or light HEVs have only a starter/generator and will therefore use Pb-Ac batteries because of the low purchase cost and the low requirements in terms of energy and power density. Ni-MH batteries have a higher energy density and will be used in mild and full HEVs. (P)HEVs will use also Ni-MH batteries nowadays and Li-ion batteries in future providing a higher power and energy density and reducing the weight of the batteries. The weight of the batteries will be of increasing interest; otherwise they will become too large to achieve a sufficient electric range [31].

If fast charging is applied, the first stage of Fig. 1.4 is shortened, but the second prolongs. Fast charging is not just increasing the current during the constant current phase. Potential damage due to overvoltages increase and charging time does not decrease considerably. Fast charging reduces the cycle life of the battery significantly and its use should be restricted to 5% of the total number of charging cycles [40]. Otherwise, fast charging requires a new battery technology [41].

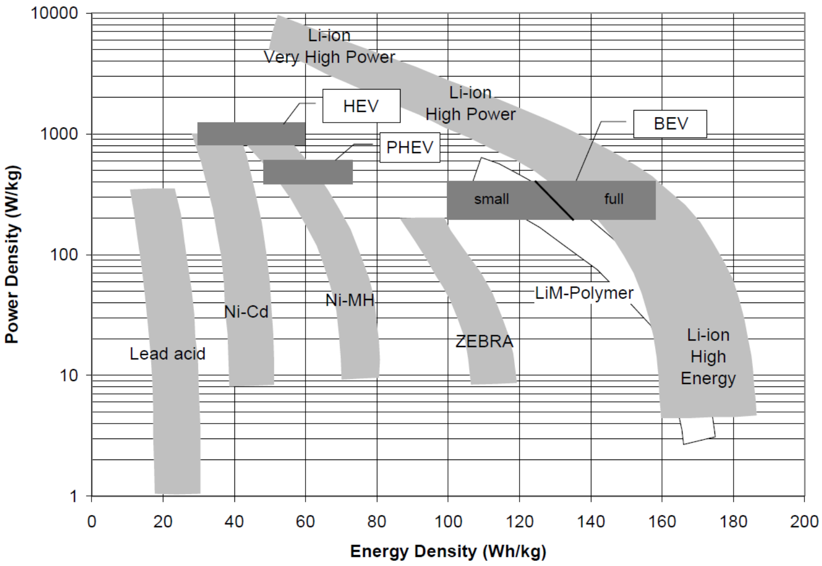

Fig. 1.6: Battery Technology for HEVs, PHEVs and BEVs [39].

1.4.3 Supercapacitors

Supercapacitors cannot store much energy per unit, as required for electric vehicles, compared to batteries but they have a high power density. The combination of a battery and supercapacitor could be useful for acceleration or regeneration of the braking energy. The current batteries have higher power densities and therefore, supercapacitors are no longer used in combination with batteries in electric vehicles.

1.5 Charging methods

The batteries of P(H)EVs can be charged from the electricity grid by plugging into an electric outlet. An infrastructure is needed to charge these vehicles. In general, before a new technology is introduced, the infrastructure should be available [42]. Fortunately, the current grid infrastructure can partly be used depending on the required charging rate. However, extra investments will probably be necessary, certainly when fast charging is applied or when the penetration level is large.

Two different charging techniques are currently available: i.e. conductive and inductive charging. Inductive charging uses magnetic field for the coupling without a direct contact. There are a few problems with inductive charging. The charger needs a high frequency resonant inverter and a high power low leakage inductive coupler which makes the charging system more complicated [43]. A bidirectional power flow, needed to provide vehicle-to-grid operation, which is described in chapter 4, is also more difficult to implement. In conductive charging, the power is transferred by a direct electrical contact of charger and battery. Conductive charging is more popular than inductive [44]. Several conductive charging methods can be distinguished depending on the connection and charging rate.

1.5.1 Slow charging

Batteries of P(H)EVs can be slowly charged. Slow charging means charging at low power rating which is at low voltage and current. The charging rate, determined by the connection constraints, and the battery capacity determines the charging time. This type of charging mostly takes place at home or at a parking lot. Vehicles are plugged into a standard electric outlet. The vehicles are connected to the low-voltage grid which is part of the distribution grid. At home, the vehicles are charged when they are parked at the garage, which is mainly during the evening and overnight. Slow charging could also occur in small and medium enterprises (SMEs) or at the parking lot of a large company during the day. Generally, no special equipment must be installed for charging these vehicles.

Within the slow charging method, three charging levels exist which can be installed at home whether or not with adaptations. A standard domestic outlet, single-phase in Belgium, has a voltage level of 230 V and a maximum current of 20 A, limiting the maximum output to 4.6 kW. Most households have a heavy single-phase electric outlet for an electric cooker with a maximum current of 32 A and thus a maximum power output of 7.4 kW. Of course, this electric outlet is not available in most garages, so adaptations in the domestic infrastructure are necessary. Some households are equipped with a three-phase connection. Depending on the grid infrastructure, the three phase connection has a line voltage of 230 V or 400 V. The 230 V connection has a rating of 32 A and 12.7 kW and the 400 V connection has a rating of 20 A and 13.8 kW. This allows a higher charging level with unaltered domestic consumption.

1.5.2 Fast charging

One of the main disadvantages of electric vehicles is the limited electric driving range and the large charging time. Fast charging is defined as charging batteries of P(H)EVs with a charging rate larger than 20 kW by increasing the charge current. In that way, vehicles can be charged up to 80% in half an hour. Increasing the power of the charger reduces the charging time. This partially solves the disadvantages [40]. Unfortunately, the larger charging current causes a strong heating of the battery pack reducing lifetime and efficiency significantly [35]. Therefore, better cooling of the batteries is necessary. The batteries can handle a larger discharge than charge current.

This high power rating cannot be delivered at home. Instead, special charging points must be provided to allow fast charging. For charging a battery pack of 15 kWh in 5 minutes, a charging power of 180 kW is required. A charging station of 15 cars requires a connection of maximum 2.7 MW. When a battery pack of 15 kWh must be charged in 30 minutes, a charging rate of 30 kW is required. A charging station of 15 vehicles requires a connection of 450 kW. Possibly, these charging stations will be directly connected to the medium-voltage level. Therefore, this connection requires large investments and a heavy infrastructure and it could mean a disaster for the electricity grid. Fast charging will be a necessity for many types of fleet drivers, for instance taxis. On the other hand, fast charging has a psychological advantage for possible vehicle owners regarding range anxiety. The current conventional vehicles have a driving range of about 600 km or more. A P(H)EV will have an electric driving range from 30 up to 200 km. Fast charging will lower the barrier to purchase a P(H)EV. However, PHEVs will still have a small internal combustion engine and fuel tank to drive longer distances which make them more attractive for the moment.

1.5.3 Battery swapping

Battery swapping is defined as switching a depleted battery by a fully charged one in an exchange station. For the moment, there is little experience in battery swapping techniques. This technique has one major advantage, i.e. switching batteries can be faster than charging batteries. However, this methodology has some large disadvantages. First, the weight of a battery pack cannot be underestimated and will range from 100 up to 200 kg. Therefore, the exchange will have to be fully automated, requiring an expensive infrastructure. Frequent swapping could damage the batteries. The battery pack and the electric vehicles must be standardized and accessible from the outside to achieve full compatibility. It is also unclear who will have the ownership of the batteries [35]. For each electric vehicle, almost three battery packs must be available. One battery pack will be in the vehicle, the second battery pack is charging and the third battery pack will be ready for switching. This number could be reduced if the logistics are optimized. Charging of the batteries can be managed and planned well in advance. Therefore, the grid impact will be small. Since the battery is the largest cost of an electric vehicle, this method will increase the cost enormously. Moreover, the battery must be one package and cannot be positioned anywhere in the vehicle. Therefore the space in the vehicle is not optimally used. Nevertheless, there may be niche markets where this technology is preferred. For instance, batteries could be switched during loading and unloading of delivery vans.

1.6 Charging points

The methods for charging, as described in the previous section, can be applied at several locations where charging could be made available as shown in Table 1.3. This list is of course not limited but gives an overview of possible charging points in future.

For home charging, a distinction must be made for P(H)EV owners with and without a garage. Vehicle owners with a garage or carport have the possibility to slowly charge their electric vehicles overnight. If necessary, this can be completed by charging at work during the day. In large companies, slow or fast charging can be applied depending on the work connection and whether the vehicle is used during the day for work purposes. SMEs will probably only offer slow charging. According to [45], home charging will be inadequate due to a lack of private garages. Vehicle owners with no possibility for home charging are obliged to charge somewhere else. Charging points may be installed in streets in urban areas close to homes. In that way, the vehicles may be slowly charged during the night. Otherwise, if possible, these vehicles can also be charged at work. If these vehicle owners do not have these possibilities, charging stations can offer a solution. Only fast charging and battery swapping will be offered at charging stations, because the time that vehicles are parked must be minimized. Studies have shown that fast charging will only be used occasionally, e.g. for larger trips [44]. Slow and fast charging is possible at parking lots and the charging rate could depend on the time the vehicles are parked. Delivery companies have a large fleet of delivery vans and the daily distance of these vehicles does usually not exceed 100 or 200 km. Therefore, such vans are ideally suited for hybridization or electrification. These vehicles can be slowly charged during the night, when they are not used, or fast charged during the day while the vehicles are unloaded or loaded. As mentioned before, the vehicles are also suitable for battery swapping. In the cities, there will probably be fewer charging stations compared to the current number of filling stations, because charging at home is also possible. The fast charging stations, placed along motorways, are going to be larger than the filling stations because it takes more time to charge the vehicle, even fast. For battery exchange stations, the stations are larger because of the capacity required to store the extra batteries.

Needs inhabitants	**Slow charging**	**Fast charging**	**Battery swapping**
House with garage or carport	night	/	/
Town house without garage	/	day	day
SME	day	/	/
Large companies	day	day	/
Public parking	day	day	/
Charge stations	/	day	day
Delivery companies captive fleets	night	day	day

Table 1.3: Possible charging points and moments.

Table 1.3 indicates that the point in time when the charging method is applied, will differ. Therefore, each charging method will have another impact on the electricity grid, depending on the point in time when charging occurs, the connection level and the number of people that are simultaneously charging. The charging method and point in time that will be most favorable will strongly depend on several parameters, of which the most are uncertain for now. First, if fast charging is very expensive and if the battery lifetime is reduced significantly, fast charging will only occur in case of ”emergency”, such as larger trips. It must be observed that 65% of the vehicle owners drive less than 50 km per day in Germany [35]. In Belgium, the average distance per day is about 40 km [46]. 50% of the trips in Europe are less than 10 km and 80% less than 25 km [24]. Thus, for some vehicle owners, it will not be necessary to charge multiple times per day. The importance of electric driving with respect to the daily distance will depend on the fuel and electricity price. For the moment, fuel and electricity have different taxes and levies. It is not inconceivable that taxes will be augmented for electricity, otherwise the government will lose a significant amount of income from fuel taxes, money that should be used to build and maintain roads, etc. As can be seen, it is difficult to predict which methods and charging points will be superior to others in future.

1.7 Business models

Nowadays, electric vehicles are more expensive than conventional ones. The batteries are still taking a major part of the purchase price. The large purchase price of electric vehicles is partly caused by the small-scale production. A lot of questions arise about the ownership of the batteries, the payment for the charging and the infrastructure. Therefore, the main elements of the business models are described in this section to give an overview of the possibilities.

1.7.1 Choice of an electric vehicle

The choice between a PHEV and a BEV depends on several elements. A distinction must be made between households with two vehicles and with only one. For the latter, the type of vehicle depends on the daily distance. If only short distances are covered every day, a small electric vehicle is sufficient. Sharing or renting could offer a solution for the occasional long distances. If the daily distance is rather large, the purchase of a PHEV would be well-considered. For a household with two vehicles, the situations differ a little bit. A BEV could be combined with a PHEV or HEV for the long distances. Possibly, PHEVs with different electric ranges could also be combined [10].

1.7.2 Battery

To accelerate the introduction of electric vehicles, the purchase price of these vehicles must be reduced. However, the battery cost will remain a large part of the total price. There are also other disadvantages linked to these batteries, such as cycle life.

The cost of the batteries can be spread over several years by for instance monthly payments. In that case the vehicle owner has also the ownership of the batteries but he or she will not pay the battery immediately when the vehicle is purchased. Via a leasing contract he or she will pay the monthly financial contribution for the batteries, the charging infrastructure and the electricity for charging. The charging infrastructure can include home charging and charging at public locations, maybe supplemented with fast charging or battery swapping. The companies who deliver these contracts are responsible for the availability of the battery charging and swapping infrastructure. The electricity for charging could be centrally purchased in the charging stations.

The ownership of the battery and the vehicle could also be separated. The electric vehicle is the property of the vehicle owner and the batteries are owned by a company. This system has several advantages. The purchase price of electric vehicles is lowered. Because the batteries can be switched, there is no uncertainty that the battery lifetime will be shorter than the vehicle lifetime and new battery technology can be installed in vehicles which are already in use. These leasing contracts can be compared with leasing contracts of cell phones [47].

1.7.3 Company cars

Most of the owners of a company car have a card for refueling, provided by the company. An electric vehicle, provided by the company, could probably charge at work. However, extra charging moments could be needed. It is unclear where the vehicles must be charged and who will pay for the charging. If home charging is applied, a separated meter for the electric vehicle is necessary, if the company is paying for this energy.

1.7.4 Incentives

Strategic planning will be very important for the economies of scale. The strategy would be to concentrate the electric vehicles and the infrastructure in cities or areas to gain economies of scales. The more vehicles that are produced and purchased, the more the price will be reduced. The same is valid for the infrastructure and for the batteries [24].

For improving air quality in densely populated cities, electric vehicles could receive a preferential treatment. For instance in London, electric vehicle owners do not have to pay a congestion charge. Another incentive could be to reduce the parking cost of electric vehicles. These vehicles could also profit from a tax benefit. The insurance of electric vehicles could be made profitable for electric vehicles compared to conventional vehicles. Such incentives could accelerate the penetration level of electric vehicles.

1.7.5 Electrical contract

The price for charging depends on the electricity price based on the concluded contract. This is especially important if vehicles charge everywhere. It is possible that vehicles charge at home or at homes of other people, having another electricity contract and thus electricity price. An extensive ICT infrastructure is essential.

1.7.6 Payment of charging

A charging cost must be paid for charging batteries of electric vehicles. There are several methods to determine this. The method will also depend on the charging method. The fuel cost can be determined by the consumed energy, the time the vehicle is plugged in or a fixed fee. If home charging is applied, the charging cost will be determined by the consumed energy as this is the normal settlement. It may be possible in future that for charging vehicles a separate meter will be necessary because a tax must be applied. For charging at public charging points, the payment is more difficult. If the charging cost is determined using the consumed energy, the vehicle owner will pay only the energy stored in his battery augmented with the charging losses. This could be a good incentive for more efficient vehicles. A meter is necessary for measuring the consumed energy, unless the vehicles measurements can be communicated to the charging point. A disadvantage is that the cost of the infrastructure is also not negligible. The charging point will stay unavailable, even when the charging is stopped, until the vehicle is removed. To reduce the time vehicles are plugged in without charging, the vehicle owner could be charged for the time the vehicle is plugged in. This avoids the use of energy meters and the parking costs are included in the charging cost. Of course, no difference is made between a vehicle arriving with almost a fully depleted battery and a vehicle with an almost full battery. For the latter, the parking cost will be high. The use of a standard parking meter lowers the infrastructure costs. All vehicles will be charged for the same amount if the parking time is the same, regardless of their energy consumption. No special billing equipment is necessary, which reduces the cost of the charging infrastructure. Smart meters are necessary for the communication between the vehicles and the network. Radio frequency identification (RFID) tags can be used to collect information from the PHEVs. An internet connection could also be essential for the communication between the electric vehicles and the network to settle the payment of the charging of the vehicles.

1.8 Objectives of the work

The main objective of this work is to indicate that charging plug-in hybrid electric vehicles has an impact on the electricity system in general and more specifically on the distribution grid and the electricity generation system. The emphasis lies on the distribution grid as these vehicles are mainly connected to the low-voltage grid to charge their batteries.

The impact of uncoordinated charging on the distribution grid is investigated. The improvements that can be achieved by the coordination or management of the charging are demonstrated. It is not the goal to reach a solution for all cases and scenarios, but it will be demonstrated that the coordination improves the grid quality and efficiency compared to uncoordinated charging. Different objective functions are considered to optimize this grid charging. The linear and quadratic programming techniques are used. It is not the aim to develop a new distribution grid, but to adapt an already existing distribution grid which may be reinforced. Thus no design standards for distribution grids are taken into consideration. However, power quality standards are investigated to improve the reliability and stability of the distribution grid.

These vehicles can also discharge and thus inject power back into the grid. In that way, these vehicles may support the grid. This is the vehicle-to-grid operation. The possible grid services are discussed and some scenarios are described in which plug-in hybrid electric vehicles can deliver ancillary services. The aim is to indicate the percentage of PHEVs required to support the grid. These PHEVs can also be combined with distributed generation units, such as photovoltaic panels, small-scale wind turbines and combined heat and power units. The opportunities of charging at work are also investigated.

Not only the impact of plug-in hybrid electric vehicles on the distribution grid is studied, also the impact on the electricity generation system will be investigated. The question that arises is whether there is enough capacity to generate the extra energy required to charge PHEVs.

1.9 Outline of the thesis

The dissertation is organized as follows:

- In chapter 2, the evolution of the Belgian vehicle fleet is described. The electrical energy required for charging plug-in hybrid electric vehicles is compared to the total electricity consumption in Belgium. The conceivable impacts on the electricity systems are discussed. A model is constructed for the examination of the impact of plug-in hybrid electric vehicles on the distribution grid. The well-considered assumptions are explained.

- Chapter 3 describes the methodologies applied to determine the impact in terms of grid parameters. Methodologies for both uncoordinated and coordinated charging are interpreted. Both deterministic and stochastic models are investigated. One other method for coordinated charging is suggested, i.e. dynamic programming. A general overview of the impact of plug-in hybrid electric vehicles on a small distribution grid is investigated for both uncoordinated and coordinated charging.

- In chapter 4, the vehicle-to-grid operation is studied. A bidirectional power flow of the charger is considered in terms of voltage control implemented in the charger. The impacts of three objective functions are compared.

- Chapter 5 describes some applications of the vehicle-to-grid operation. An entire day is simulated to give a global assessment of the impact of plug-in hybrid electric vehicles. Distributed generation units are also considered. These units are matched with plug-in hybrid electric vehicles to achieve an optimal match. The impact of a connection at work is also studied.

- The impact of plug-in hybrid electric vehicles on the electricity generation system is described in chapter 6. The E-simulate model is used to calculate the impact of the PHEV loads on the generation system and to evaluate whether sufficient capacity is available to generate the extra energy required for charging a fleet of PHEVs.

- Chapter 7 summarizes the conclusions of this work and some suggestion for further work are given.

2

Development of the model

This chapter starts with an evolution model of the Belgian vehicle fleet in section 2.1. The topics in the field of the impact of plug-in hybrid electric vehicles on the electricity system, that are not yet fully understood, are highlighted in section 2.2. In section 2.3, a model is constructed to examine the impact of charging PHEVs on the distribution grid and assumptions are made for further studies and modelling.

2.1 Fleet evolution towards 2030

Electric vehicles will gain more market share within the next decades. This section describes the trends to 2030 in the evolution of the light duty vehicle fleet, the fuel economy and the CO_2 emissions.

2.1.1 Belgian vehicle fleet

A study made by Transport and Mobility Leuven (TML) [48] forecasts the vehicle fleet size, the transport volumes and the emissions from road transport in Belgium. This study is based on the TREMOVE model [49] which is a policy assessment model. The European Commission uses this TREMOVE model to support its environmental transport policy. Originally, 21 European countries were modelled, but this model can also be used for an individual country. The model consists of a vehicle stock module, an emission module, a life cycle module and a welfare module.

TML has forecasted the evolution of the composition of the Belgian fleet of light duty vehicles for the period 2005-2030 based on a simulation for the "business as usual scenario" as shown in Fig. 2.1. According to this model, the market share of diesel CVs will be slightly larger than of petrol CVs in 2010. For new technologies, such as hybrid electric vehicles, it takes time to penetrate the market. By 2030, the number of compressed natural gas vehicles is expected to be 190 000 and the number of HEVs will be 1 800 000 vehicles, for diesel and petrol HEVs together [48].

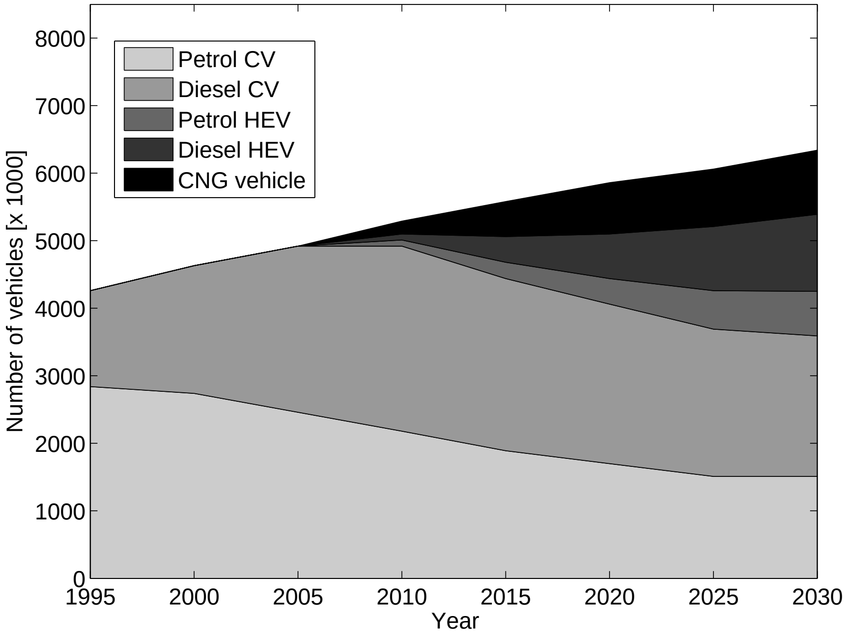

Fig. 2.1: Vehicle fleet in Belgium [48].

These predictions can be compared with the number of vehicles in 2009 [50], when there were about 5 163 000 passenger vehicles in Belgium. The number of vehicles in 2009 is 2.5% smaller than the level predicted for 2010. The number of petrol vehicles is 2 092 000 and the number of diesel vehicles is 3 039 000, i.e. larger than forecasted. The market share of HEVs is currently not as large as predicted. The economic crisis of 2009 obviously had an impact on the vehicles sales. This crisis is of course not taken into account in the forecasts of TML and TREMOVE.

In 2015, the amount of diesel and petrol HEVs is equal and contains both 90 000 vehicles. The fleet of both diesel and petrol HEVs will increase substantially by 2030 up to respectively 1 140 000 and 660 000, which is 35% of the diesel vehicles and 30% of the petrol vehicles. In general, HEVs should take over about 7% of the market by 2010 and about 30% by 2030 as represented in Fig. 2.2. For 2010, this number is not realistic anymore. The CNG vehicles will have a share of 15% by 2030. Fuel cell electric vehicles are not taken into account in this study due to the uncertainty about production cost and availability of hydrogen. All HEVs are assumed to be plug-in hybrid electric vehicles. In [26], it is assumed that PHEVs will cover 25% of the market by 2020. According to [51], PHEVs will represent 50% of the newly launched vehicle market share by 2030. In the Netherlands, a 60 up to 75% penetration level of PHEVs is assumed in 2050. A study concerning Portugal predicts a maximum penetration level of 20% by 2020 [52]. These studies indicate that the replacement of all HEVs by PHEVs in the study of TML is realistic and acceptable. Accordingly, only vehicles that can be charged by the electricity grid are assumed in this work.

2.1.2 Fuel economy of vehicles

The fuel economy of both conventional and hybrid electric vehicles will improve in future. Generally, HEVs are more efficient compared to CVs as shown in Table 2.1 and Table 2.2. The fuel economy of PHEVs in hybrid mode is similar to that of HEVs. The types of hybrid electric vehicles are described in section 1.3.

Table 2.1 shows that the fuel consumption of conventional vehicles will decrease for the period 2003-2050 [1]. Generally, diesel vehicles consume less fuel than petrol vehicles. In the first period, i.e. 2003-2015, diesel vehicles are equipped with a second generation common-rail fuel injection. There is also an increased use of variable-valve timing and direct injection in the petrol vehicles. In the second and third period, the turbocharged diesel engine will be downsized. The particle filter and NO_x trap will be more commonly applied. In petrol vehicles, direct injection and variable-valve timing will be more frequently used.

The fuel consumption of HEVs must be compared with ICE CVs. Table 2.2 gives an idea of the efficiency of HEVs. The introduction of starter-alternator systems

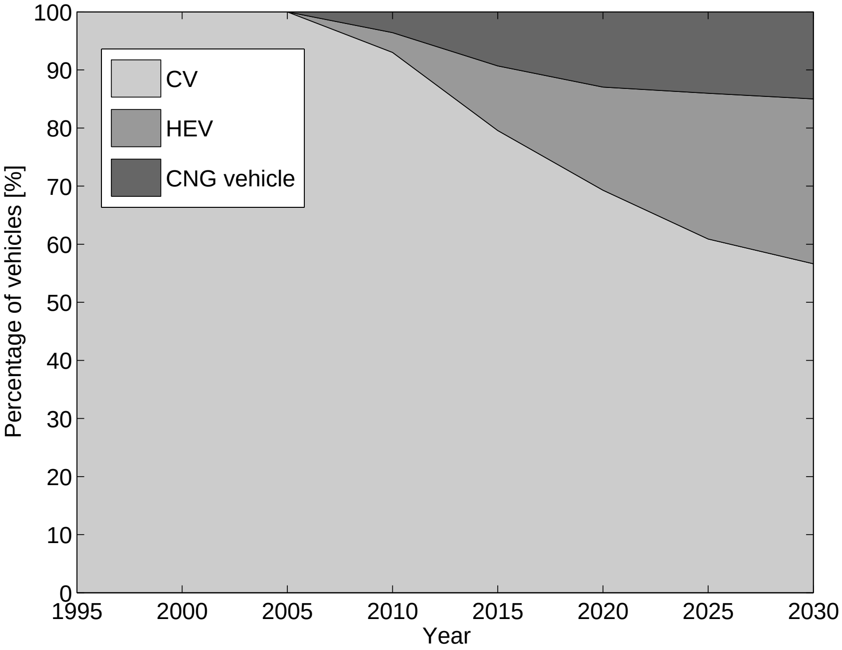

Fig. 2.2: Vehicle fleet in Belgium [48].

	2003-2015	**2015-2030**	**2030-2050**
Diesel ICE vehicles	4.2-7.5	4.1-7.3	4-7.1
Petrol ICE vehicles	5.4-9.7	5.1-9.1	4.7-8.4

Table 2.1: Fuel economy of CVs [Liters of petrol equivalent/100 km] [1].

is expected in the period of 2003-2015. Some HEVs will be micro hybrids and large HEVs (from segment D) will mainly be full hybrids. The next fifteen years are characterized by a higher penetration of micro hybrids even on small vehicles (segment A and B) and the wide diffusion of full hybrids on large vehicles. Diesel HEVs are more efficient compared to petrol HEVs, but the fuel reduction will also be smaller in future.

	2003-2015	**2015-2030**	**2030-2050**
Petrol full hybrids	4.1-7.4	3.9-7	3.7-6.6
Petrol mild hybrids	4.5-8	4.1-7.4	3.9-7
Petrol micro hybrids	4.9-8.8	4.6-8.3	4.3-7.7
Diesel full hybrids	3.2-5.7	3.1-5.5	3-5.4
Diesel mild hybrids	3.4-6	3.2-5.8	3.1-5.5
Diesel micro hybrids	3.7-6.7	3.6-6.5	3.5-6.3

Table 2.2: Fuel economy of HEVs [Liters of petrol equivalent/100 km] [1].

Similar results can be found in [19], [51], [53] and [54]. The study of McKinsey [19] starts from a consumption of 7.6 l/100 km for petrol ICE vehicles and 6.1 l/100 km for petrol HEVs for the year 2005. For 2020, the consumption of ICE vehicles will fall down to 6.0 l/100 km and for hybrid vehicles to 5.1 l/100 km. An electrical consumption of about 175 Wh/km for a PHEV is assumed in [51]. In [53], the electrical consumption of a PHEV is assumed to be 123 Wh/km. The Chevrolet Volt has a total and useful battery capacity of respectively 16 kWh and 8.8 kWh and an electric range of 64 km. This gives an electric fuel consumption of 7.3 km/kWh or 138 Wh/km [54]. The electricity consumption depends on the weight of the vehicle, the size of the electric motor and other properties. The electricity consumption has of course an impact on the electric range as a better efficiency improves the electric distance in full electric mode given the same battery capacity.

2.1.3 Transport volumes per vehicle type

Not only the fuel consumption, but also the distance travelled or the vehicle-kilometers are essential for the global overview. In the study of TML, the vehicle-kilometers per year and per vehicle type have been predicted for Belgium, as shown in Fig. 2.3. The total vehicle-kilometers for diesel vehicles are significantly increasing in contrast with petrol vehicles. The total vehicle-kilometers per year by diesel vehicles increase from 61 000 up to 70 000 million kilometers. In contrast, the vehicle-kilometers per year by petrol vehicles decrease slightly from 25 000 to 23 000 million kilometers.

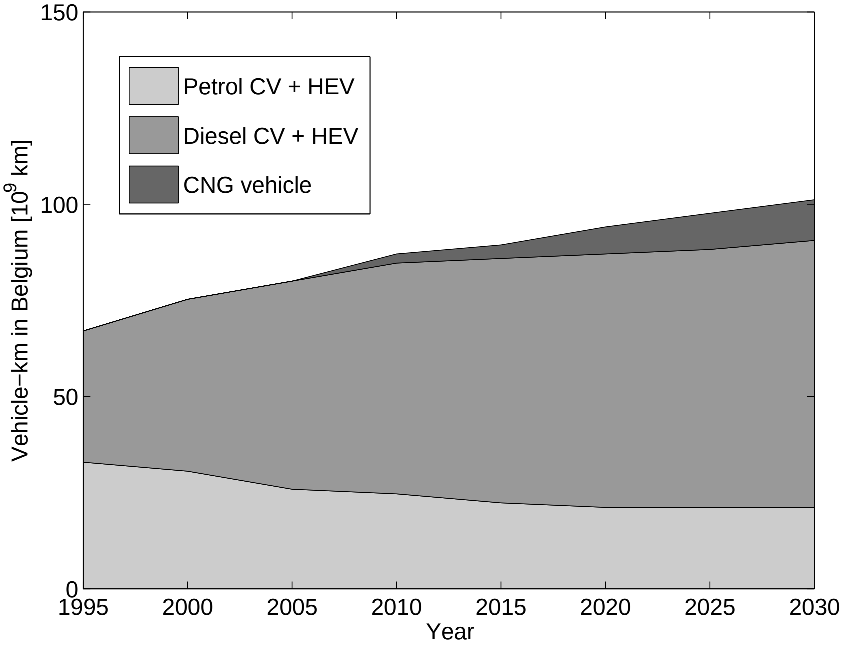

Fig. 2.3: Vehicle-kilometers in Belgium [48].

2.1.4 Emissions of vehicles

The greenhouse gas emissions of vehicles are important. A better fuel economy is directly linked to a decrease in the vehicle emissions. Air pollutants, such as ozone, particulate matter, carbon monoxide, nitrogen oxides, sulfur dioxide and lead [55], can also be reduced by improving filters, catalysts and fuel quality. Both conventional and hybrid electric vehicles are getting cleaner in future. Table 2.3 gives an idea of the expected CO_2 emissions from conventional vehicles for the period 2002-2050. Diesel vehicles are still emitting less CO_2 compared to petrol. The improvements will be larger for petrol vehicles than for diesel.

	2003-2015	**2015-2030**	**2030-2050**
Petrol ICE vehicles	151-270	141-253	131-235
Diesel ICE vehicles	125-223	121-218	118-212

Table 2.3: CO_2 emissions, well-to-wheel, for CVs [g/km] [1].

Table 2.4 gives the CO_2 emissions for HEVs for the period 2003-2050. Because of the direct link between fuel economy and CO_2, diesel vehicles are emitting less CO_2 compared to petrol vehicles. Generally, HEVs have significantly lower CO_2 emissions compared to conventional vehicles.

	2003-2015	**2015-2030**	**2030-2050**
Petrol full hybrids	115-206	109-195	103-184
Petrol mild hybrids	125-224	115-205	108-194
Petrol micro hybrids	138-247	128-230	119-214
Diesel full hybrids	95-171	90-165	89-159
Diesel mild hybrids	100-179	96-172	92-165
Diesel micro hybrids	111-199	108-193	105-188

Table 2.4: CO_2 emissions, well-to-wheel, for HEVs [g/km] [1].

2.1.5 Electrical consumption

Not all electrical energy for charging the battery of a PHEV is generated on-board by converting petrol or diesel. The batteries of PHEVs can also be charged from the grid. This amount of electrical energy is determined and compared with the total electricity consumption in Belgium. The period of 2010-2030 is examined.

The aim of this paragraph is to determine the amount of electrical energy from the electricity grid needed to charge the battery to partially fulfil the daily distance travelled by electric driving. The other part of the distance travelled is done in hybrid mode. Electric driving can reduce fuel consumption and emissions. The capacity of the battery determines the maximum amount of energy the battery can store.

It is difficult to predict the proportion of electric driving, using grid-charged electricity, and the proportion of driving on diesel or petrol for a PHEV as it depends on the type of vehicle and trip. The utility factor predicts the fraction of driving that is performed by electricity for a PHEV [51]. The utility factors for a PHEV10, PHEV20 and PHEV40 are shown in Fig. 2.4. This factor depends on the type of PHEV and thus on the electric range. For the calculations, a PHEV60 is also considered by extrapolation. The utility factors will not change during the time period.

The average driven kilometers per vehicle per year are calculated. Petrol and diesel vehicles are taken together and averaged. There is no reason to assume that PHEVs will drive fewer or more kilometers compared to conventional vehicles. The average driven kilometers per year per vehicle are not changing significantly from 2010 to 2030 and the mean value of this time period is determined. The electric distance is calculated for four PHEV types by multiplying the utility factor of the according PHEV type by the average distance travelled per vehicle. The mean values over the considered time period of the annual electric distance per vehicle are represented in Table 2.5 for the four PHEV types. For each type, the electric distance is also more or less constant in time because average kilometers per year and per vehicle do not change significantly. Obviously, the electric distance increases when the electric range of the PHEV type also increases.

PHEV10	**PHEV20**	**PHEV40**	**PHEV60**
2859	8626	11450	13638

Table 2.5: Mean annual electric distance per vehicle [km].

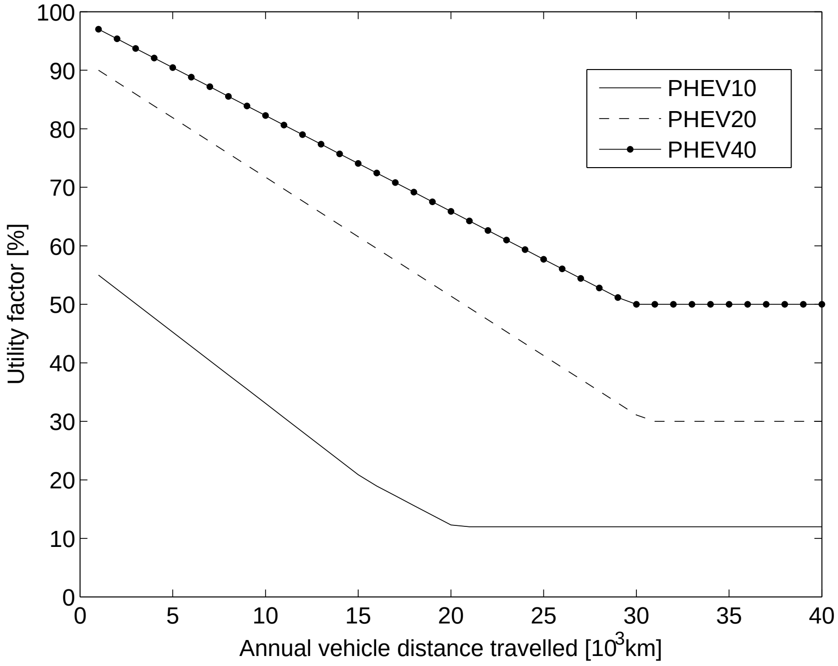

Fig. 2.4: PHEV utility factor assuming nightly home charging [51].

Fig 2.5 represents the average annual electrical energy consumed by an individual PHEV, assuming that the battery of a PHEV is performing only one full charging cycle per day. The electrical consumption of a PHEV is varied between 200 and 300 Wh/km. These consumptions are larger than given in the previous paragraph. The reason is that larger vehicles are also taken into account. The annual electrical consumption does not vary a lot during the time period because the vehicle-kilometers are more or less constant over this period. The electrical consumption of the vehicles will be reduced by 2030 and therefore, the electrical energy required to charge the vehicles will also be reduced. The average annual electrical energy does not equal the amount of energy the electricity grid has to deliver to charge a PHEV, because a conversion efficiency, i.e. the charging efficiency which is about 88% [51], must be taken into account. However, the consumed electrical energy depends on the electrical consumption and the electric range and thus the ratio of electric driving to the total driven kilometers. Obviously, a PHEV10 consumes less electrical energy compared to a PHEV40 because the latter is supposed to have a larger electric distance. The energy stored in a PHEV is not increasing in future because the annual distance per vehicle will remain more or less the same, as mentioned above. It is important to know that a household has an average electricity consumption of 3500 kWh per year [56]. If a PHEV with a battery capacity of 10 kWh is recharged every night from the grid, this will also give a total consumption for charging of 3500 kWh per year, neglecting losses in the charger. So electric vehicles will double the household consumption if they are charged at home in future. The figures of Fig. 2.5 can be compared with the amount of generated electricity in Belgium to give an idea of the proportion of the yearly consumed electrical energy that is dedicated to charging PHEVs. If the battery is recharged from empty to fully charged several times per day, the electrical charging energy will increase.

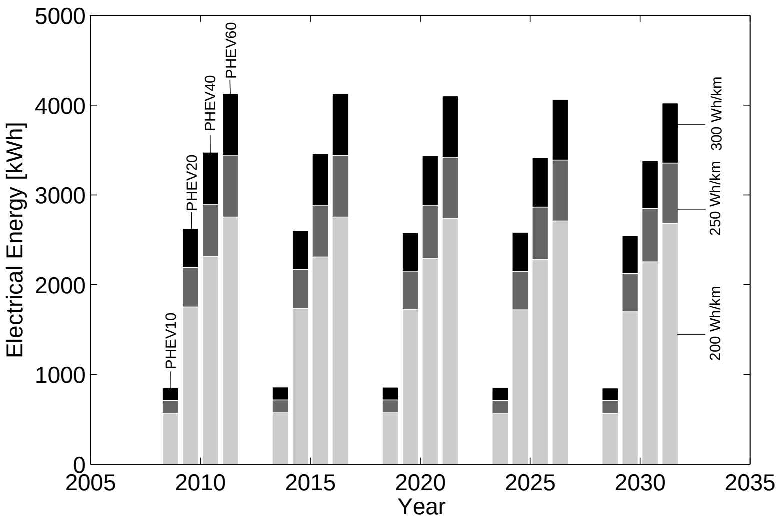

Fig. 2.5: Electrical consumption per vehicle per year.

The total battery capacity will, on average, range from 2.5 kWh for a PHEV10 up to 15 kWh for a PHEV60. Only 80% of the battery capacity can be used for optimizing the life expectancy. For instance, the Toyota Prius has a battery capacity of 1.3 kWh, but converting kits for the PHEV30 and PHEV50 have respectively battery capacities ranging from 5 to 12 kWh [57] and the prototype of the Daimler Chrysler Sprinter has a capacity of 14.4 kWh, using Lithium-ion batteries [58].

The Commission on Energy 2030 [59] predicts an annual electricity consumption for Belgium for three scenarios which are given in the Table 2.6. The first scenario is the baseline scenario where there is no post-Kyoto reduction limit and where a decommissioning of nuclear plants takes place. In the Bpk15 scenario, Belgium reduces its energy CO_2 emissions by 15% in 2030 compared to the 1990 level and the decommissioning of nuclear plants takes place. Energy CO_2 emissions are reduced by 15% in 2030 compared to the 1990 level in the Bpk15n scenario. There is a lifetime extension of existing nuclear plants and the possibility to have one new nuclear unit of 1700 MW after 2020. The electricity generation according to the Bpk15 and Bpk15n scenarios are respectively 0.2% and 9.6% higher in 2030 compared to the baseline scenario. The Bpk15 scenario is equated with the baseline scenario for the electrical consumption because the differences are not significant.

	Electrical consumption (baseline scenario) [TWh]	**Electrical consumption (Bpk15) [TWh]**	**Electrical consumption (Bpk15n) [TWh]**
2000	80	80	80
2005	85	85	86.8
2010	90	90.1	93.5
2015	95	95.1	100.3
2020	100	100.2	107
2025	105	105.2	113.8
2030	110	110.2	120.6

Table 2.6: The total electrical consumption per year in Belgium [59].

This information gives prospects to determine the proportion of the electrical consumption for charging the fleet of PHEVs to the total electrical consumption in Belgium. There is assumed that the battery will be charged with an efficiency of 88% [51]. The absolute values are shown in Fig. 2.6 for the entire PHEV fleet in Belgium. The amount of energy needed to charge the PHEVs will increase in future because the market share of PHEVs increases.

The ratio of the electrical energy for charging PHEVs and the generated electrical energy in Belgium for the baseline scenario and the Bpk15n scenario are

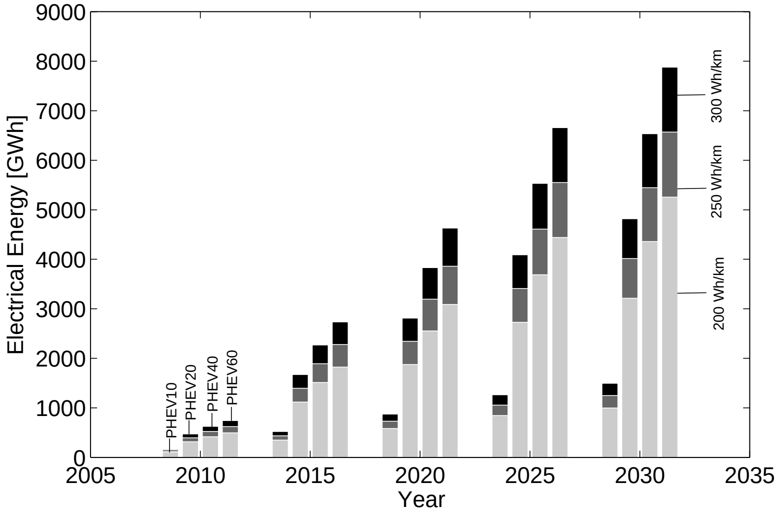

Fig. 2.6: Total electrical consumption for charging PHEVs in Belgium.

respectively shown in Fig. 2.7 and Fig. 2.8. The electrical consumption for charging PHEVs corresponds to about 8% of the total electrical consumption in Belgium in the worst case. In a study for the Netherlands, this proportion is 10% [10]. It is more likely that the vehicle market will consist of a mix of PHEVs with a large variety of electrical ranges. BEVs are not assumed in this investigation. BEVs will have larger battery capacities and thus the proportion of charging P(H)EVs to the total generated electricity will be larger if BEVs are also taken into account.

2.2 Impact of charging P(H)EVs on the electricity system

The electrification of the road transport will increase the loads on the existing transmission and distribution grid. The generation system must also produce more energy to charge P(H)EVs. Infrastructure investments could be reinforced [60]. Although, at first sight, the electrical energy needed to charge these vehicles is only a few percentages, there are some important remarks. First, this energy will be taken of the low-voltage grid, for instance at the electric outlet in the garage because a large part of P(H)EVs may charge at home. Second, the point in time and the duration the P(H)EVs charge, is also crucial. Charging during peak hours, when the grid and the power plants are already heavily loaded, must be avoided.

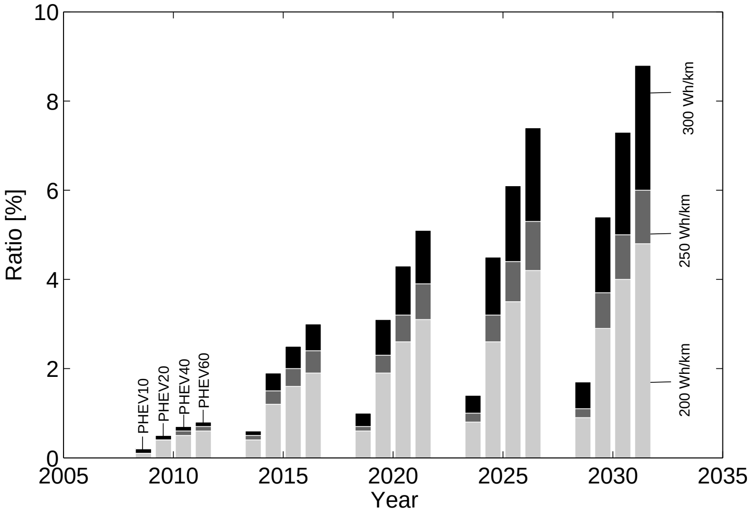

Fig. 2.7: Ratio of electrical energy for charging PHEVs in Belgium for baseline scenario.

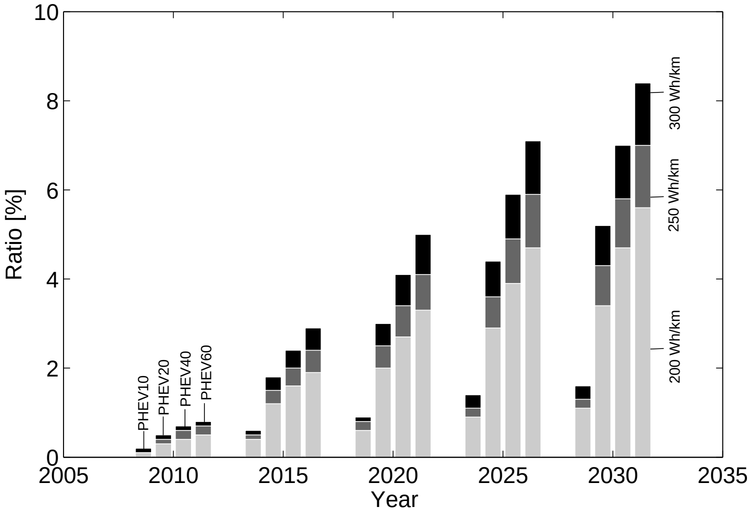

Fig. 2.8: Ratio of electrical energy for charging PHEVs in Belgium for Bpk15n scenario.

2.2.1 Impact on electricity generation

The extra energy required for charging P(H)EVs must be generated by the generation system which consisting mainly of a mix of base and peak load power plants and large wind farms. There is little storage available in the power grid nowadays, so the demand and generation must be matched instantaneously and continuously managed [61].

The power plants are not always working in their optimal operating point, decreasing their global efficiency, because of the daily variation in demand. Therefore, a “valley-fill” algorithm is applied to find the most economic way for charging the P(H)EVs, by smoothing through charging in periods of low demand [23], [62]. The technical potential is determined as the margin between the normal load and the total installed base load capacity, taking into account maintenance, primary and secondary reserves and other unavailabilities. Charging of P(H)EVs can be maximized during off-peak and minimized during peak hours. Therefore, P(H)EVs can be seen as dispatchable loads to decrease cycling of power plants to achieve a more constant power output. Balancing of wind turbines may become even more difficult because of their intermittent power output. A fleet of P(H)EVs can help to level out this fluctuating power. These actions are determined as load shifting or management [45]. For this method, there is a perfect forecast of the normal loads and the additional energy demand needed [23]. It does not introduce new peaks for the system load and the lows during the night are becoming nearly flat. With the valley-fill method, a large part of the current vehicle fleet could be charged by the current power plants. But these power plants will be heavily loaded each day for a significant part of the day. The increased time during which these power plants are working at full power, will increase the operation costs [26]. The scheduled maintenance will increase which could reduce the system reliability [62]. P(H)EVs will be able to reduce the number of times the power plants must be shut down. During the night, the extra energy is mainly produced by the baseload units. Although, there is expected that additional generation capacity will be necessary for evening charging, especially by 2030. Evening charging can reduce the available reserve capacity [26]. P(H)EVs can be combined from renewable energy such as wind and solar energy and can be charged with the overcapacity of these resources (5). This could reduce the number of standby power plants [63] as shown in chapter 6.

The location and point in time that P(H)EVs charge will determine the power plants which provide the additional energy. The emissions, caused by charging P(H)EVs, are also related to the power plants generating the electricity and thus to the point in time of charging. The emission reductions of P(H)EVs are the largest in areas with power plants with low carbon fuels or with a large proportion of renewable energy. The emission reduction is much smaller or non existing if the main power plants are coal-based, although, it is much easier to handle the emissions on a central source than at the tailpipe of each vehicle [26]. In general, the installed capacity will not be large enough if the charging of P(H)EVs is not coordinated. More details are described in chapter 5.

2.2.2 Impact on transmission grid

Nowadays, the transmission grid is designed to satisfy peak demand, but the rest of the time, the system is under-utilized. Questions arise on grid stability and increased transmission capacity needed for the additional energy for charging P(H)EVs [23]. By using the valley-fill method of the previous paragraph, the utilization of the transmission grid is also augmented. This will increase the efficient use of the assets of the transmission grid because nowadays this grid is under-utilized for many hours. The effects of flattening the daily load curve are investigated, based on system equipment and oil-cooled substation transformers. Some of the components of the grid, such as the oil-cooled transformer, are designed for peak/off-peak utilization. If this transformer is overloaded for too many hours, its lifetime of this component will significantly reduce [64]. Therefore, charging P(H)EVs can impose constraints on the grid to ensure its reliability [52].

It is generally assumed that the grid impact will be low and that the transmission and generation capacity is sufficient to charge P(H)EVs during off-peak hours as described above. This argumentation does not consider that P(H)EV owners will plug in their vehicle when convenient for them instead of the most profitable moment for the grid, when no incentives are given to these owners [26]. A key question is at which moment vehicle owners want to charge the batteries. In reality, it may be difficult to motivate a P(H)EV owner to charge their vehicles at a specific moment in time. From the viewpoint of the grid operator, this is during the night, from the customers viewpoint, this is from the moment they have access to a charging point to connect and plug in [52]. The owner also wants to keep the batteries sufficiently charged as soon as possible in case he needs the vehicle sooner, for instance in case of an emergency. Incentives should be given by the grid operator or electricity suppliers to shift the charging of PHEVs to off-peak hours. The grid operator wants to avoid that the grid stability is not guaranteed during peak hours. The electricity suppliers want to ensure that the generation capacity is sufficient. These incentives could be time-of-use prices, real-time prices or charge management reimbursements. If charging is coordinated automatically, smart meters are necessary.

2.2.3 Impact on distribution grid

As indicated in the previous paragraph, the point in time and the place where P(H)EVs are plugged in are very essential. These vehicles could add local or regional constraints to the grid. The low-voltage grid is not capable of handling situations where everyone is charging simultaneously. Local problems may arise in some critical areas. Local demand profiles will change significantly because of charging. The household profiles at distribution level, i.e. at a substation or at local feeders are less aggregated compared to the transmission level. Therefore, the demand is more sensitive to the demand profile of each customer. If many P(H)EV-owners charge their vehicle simultaneously in a district, it will have a major impact on local infrastructure and local peak demand [63]. It is important to know from which penetration level of P(H)EVs, devices such as feeders, substations and transformers, become overloaded. Overloading of the transformer does not immediately result in device failure, but reduces its lifespan. Transformers can be investigated individually, but for the analysis of the voltage levels and imbalances, the whole network must be evaluated. The study of [29] and [65] concludes that P(H)EVs will influence the distribution grid for certain. The extent of the impact depends on the penetration level of the PHEVs and the charging behaviour.

Most of the grid infrastructure is installed during the 1960s and the 1970s. The technical and economic lifetime of the assets is 40-50 years, so the replacement will occur in the near future [66]. Nowadays, the distribution grid is a passive grid, with annual increasing electricity demands. At the start, distribution grids were overdimensioned. But because of increasing demand, distribution grids operate closer to their maximum capacity. The distribution system operator wants to overcome overloading [10]. Therefore, the current grid has to be used more efficiently. There is a trend towards a transition to an active grid with active elements wherein P(H)EVs will play an important role [60], [67]. P(H)EVs can be seen as active loads and charging can be coordinated to use the distribution infrastructure more efficiently. At some moments of the day, a large part of the capacity of distribution feeders is still available to transport the extra loads for charging P(H)EVs. Part of this capacity can be used for active loads such as charging P(H)EVs in a quasi-automatic and dependable way. Time of charging must be shifted to a more convenient point in time for the optimal use of the grid infrastructure. Load management gives the possibility to use the grid more efficiently and to transport more energy, using the same feeders [68]. For instance, this can be done by using a smart meter.

Developments lead to a more complex design and operation of the grid. For instance, more distributed generation units will be connected making the demand for capacity highly uncertain [69].

The impact on distribution systems is only briefly mentioned in a few papers, although the impact will be the largest on that part of the electricity grid. Therefore, this work mainly focusses on the impact of charging P(H)EVs on the distribution grid. The impact on the transmission grid is not handled in this work.

2.3 General model and considerations

For the investigation of the impact of charging PHEVs on the distribution grid, a general model has to be built to benchmark the results. For the construction of this model, several data and topologies such as the residential grid, the household load profiles and the charging periods must be chosen well-considered.

2.3.1 Specifications of PHEVs

Only PHEVs are considered in this research because these vehicles are the most promising in near future. The specifications of these PHEVs are described in this paragraph. For the moment, PHEVs are not widely commercially available, so assumptions must be made about their characteristics. The specifications depend on the type of PHEV. The impact of these specifications on the results is considered in the next chapter. It is assumed that a PHEV has a battery with a maximum capacity of 11 kWh [23], [70]. Only 80% of this capacity can be used in order to optimize life expectancy, i.e. an available capacity of 8.8 kWh. In a full charging cycle, 10 kWh is required from the grid, assuming an 88% energy conversion efficiency from AC energy absorbed from the utility grid to DC energy stored in the battery of the vehicle [51]. PHEVs can support the grid and thus deliver grid services by injecting energy into the grid. This is defined as the vehicle-to-grid operation which is explained in chapter 4. Therefore, the energy flow can be bidirectional, meaning that the batteries can charge and discharge. The power of the charger is always active. The charger has a maximum output power of 4 kW because the maximum power output of a standard single-phase 230 V outlet, with a maximum continuous current of 20 A, is 4.6 kW. 4 kW is measured at the grid side. Thus only 3.5 kW is measured at the battery or vehicle side, taking into account the charge efficiency. Therefore, this is the largest charger that can be used for a standard outlet at home without reinforcing the wiring. For an electric cooker, a connection of 32 A is provided in households. The maximum power of the charger for this electric outlet would be 7.4 kW. This is the largest single-phase connection possible in a household. Fast charging is not considered because it requires a higher power rating which is not available at standard electrical outlets in houses. For fast charging, three-phase connections at a higher voltage level are indispensable. A higher voltage connection could be installed at charging stations or public parking lots.

2.3.2 Grid topology

The distribution grid is typically a radial network with a rated voltage of 230 V, 400 V wye connection, for the residential connections. In a radial grid, there is only one path from the substation to the customer. This rather simple structure makes this type of grid the least expensive. Therefore, 80% of the current distribution grids and 90% of the new constructions in distribution grids are radial. The major disadvantage of a radial grid is the reliability. If an interruption on a feeder occurs, all customers downstream of this feeder are disconnected [71]. There are large differences in the practical layout of the Belgian distribution networks and the radial network used for this analysis is the IEEE 34 node test feeder [72], shown in Fig 2.9, which represents an average model of a distribution grid. The layout of the grid is described in Appendix B. The rated voltage of this IEEE grid is down-scaled to 230 V so this grid topology represents a residential radial network. The line impedances are adapted to achieve tolerable voltage deviations and power losses. Each node represents a residential connection with a household load profile linked to it. Some of the randomly chosen nodes, will have a PHEV charging.

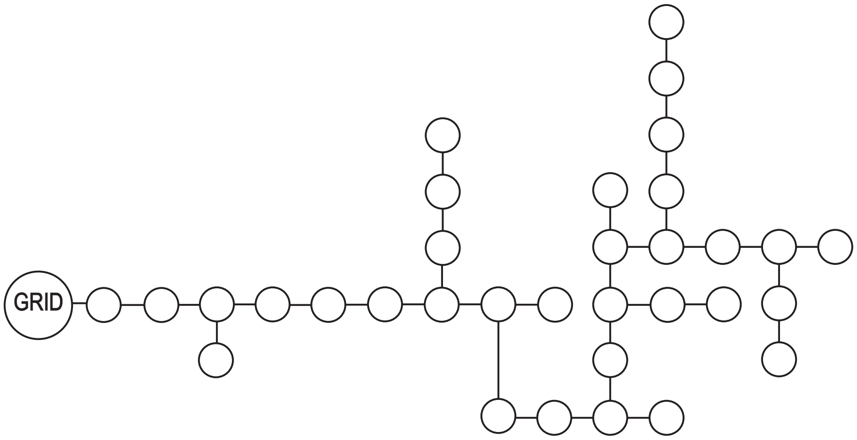

Fig. 2.9: IEEE 34 node test feeder [72].

2.3.3 Load scenarios

The impact on the distribution grid can only be investigated if household loads are also known. The Flemish Regulation Entity for the Electricity and Gas market (VREG) [73] provides synthetic residential load profiles. These load profiles are scaled to obtain a total yearly consumption of 3500 kWh. From this available set of residential load profiles, two large groups of daily winter and summer load profiles are selected. The load profiles cover 24 hours and the instantaneous power consumption is given on a 15 minute time base as shown in Fig. 2.10 for an arbitrary day during winter. The same trend of household load profiles can be found in [60], where the average residential load profile in the EU-27 member states is represented.

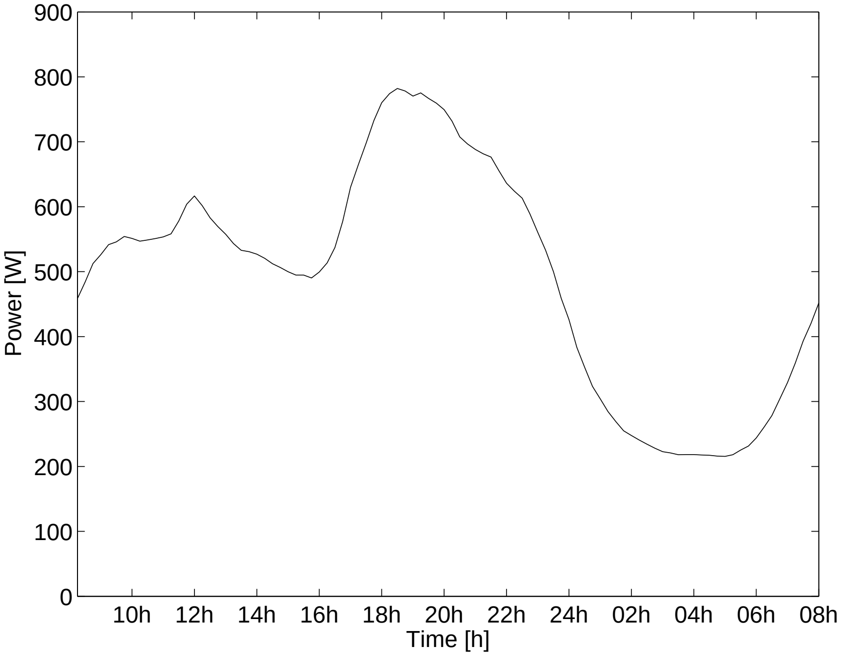

Fig. 2.10: Household load profile during winter [73].

2.3.4 Charging periods

There could be periods of the day when it is more likely that PHEVs are charged. Depending on the business model, as described in section 1.7, it is not realistic to assume that PHEVs could charge anywhere a standard outlet is present. Therefore, as a first assumption, the batteries of the vehicles are assumed to charge at home in residential distribution grids. Fig. 2.11 represents the starting hours of all the daily trips by vehicle. At that moment, PHEVs are not available for charging. Because the focus lies on home charging, it is not always true that a vehicle can charge when it is not driving. However, based on this figure, three important charging periods are proposed. The first charging period is during the evening and night. Most of the vehicles are at home from 21h00 until 06h00 in the morning. Some PHEVs are immediately plugged in upon return from work in order to be ready to use throughout the evening. Thus the second charging period takes place between 18h00 and 21h00. This charging period starts at 18h00 because most of the full-time employees are arrived from work at that moment. Charging during the evening coincides with the evening peak load. The number of vehicles charged during this period will probably be smaller. One other charging period is considered, i.e. charging during the day between 10h00 and 16h00. This charging will, for instance, occur on the parking lots of small offices in urban areas. It is assumed that only one vehicle per household or office can charge. The charging of multiple vehicles at a household or office is not considered because it is not feasible to reflect all possible scenarios. However, the proposed methods are also valid for other periods and scenarios. In this work, the focus lies on charging at home, in weaker distribution grids.

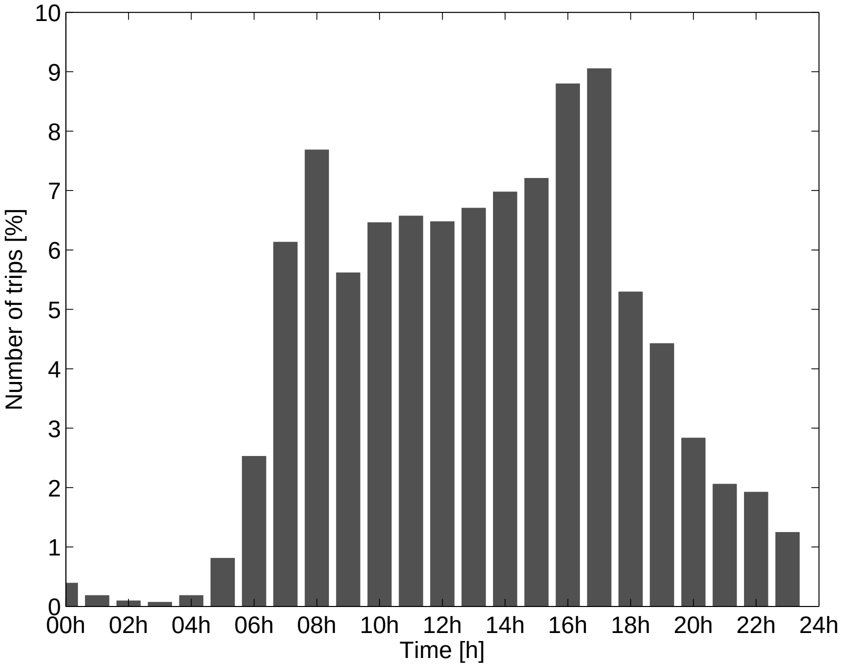

Fig. 2.11: Distribution of the starting hours of all the daily trips [74].

2.3.5 Availability analysis

The charging period in the previous section is determined as a fixed part of the day by determining the point in time when vehicles will most likely be at home. These charging periods will be extended to charging between 00h00 and 23h45, i.e. an entire day. For the simulation of an entire day, the time slots vehicles are present for connecting into the grid must be exactly known. A simulation of an entire day could include more information about the behaviour of PHEV owners.

The main function of a fleet of PHEVs is transport. To fulfil this function, the vehicles must be charged and they could also offer grid services as will be explained in chapter 4. Therefore, it is essential to have an idea when these vehicles will be available for charging or grid services. The knowledge of the amount of energy left in the battery and the presence of a network connection for charging are important. If vehicles are available for charging, the energy content left in the battery indicates the amount of energy needed to fully charge the battery. If discharging is implemented, the vehicles that have energy left in their battery when they arrive during the evening could support the grid during peak hours. The behaviour of PHEV owners is modelled in the availability analysis based on stochastic data representing the vehicles leaving and arriving at different instances in time. This gives prospectives for a more accurate assessment of the possibilities of a fleet of PHEVs.

The availability analysis used in this work is based on a model developed in the master thesis of Eric De Caluwé [75]. This analysis is mostly based on data of the Netherlands due to inadequate or non-existing data of Belgium. The transport behaviour of the Dutch people is assumed to be more or less the same as the behaviour of the Belgian people. In a mobility research in the Netherlands [76], there is asked at people to keep track of their journey behaviour, i.e. the type of transport, the reason for the trip, the point in time, the travelled distance etc. The study of [74] gives the vehicle use on an hourly basis for a day. This data is completed with the data of FPS Economy, SMEs, Self-employed and Energy [46]. Only weekdays are considered because these days are the most demanding and they have a repetitive pattern.

For the sake of convenience, it is assumed that the vehicle owner is a full-time employee and the trips to or from work are represented in Fig. 2.12. This is of course not realistic, but it is not the aim of this work to give a complete availability analysis. There is assumed that there is at the most one PHEV at each household. Some households could also have a conventional vehicle, not having an impact on the distribution grid. The probability that the vehicle owner leaves to work is the highest in the morning between 06h00 and 08h00. The probability that the vehicle owner arrives from work is the highest in the evening between 15h00 and 18h00. For each vehicle, the length of the trip and the point in time of leaving to and arriving from work is determined based on probability distributions of the duration of a trip. These distributions of probability are adapted for specific trips to work. It is also possible that a vehicle performs another trip during the day or

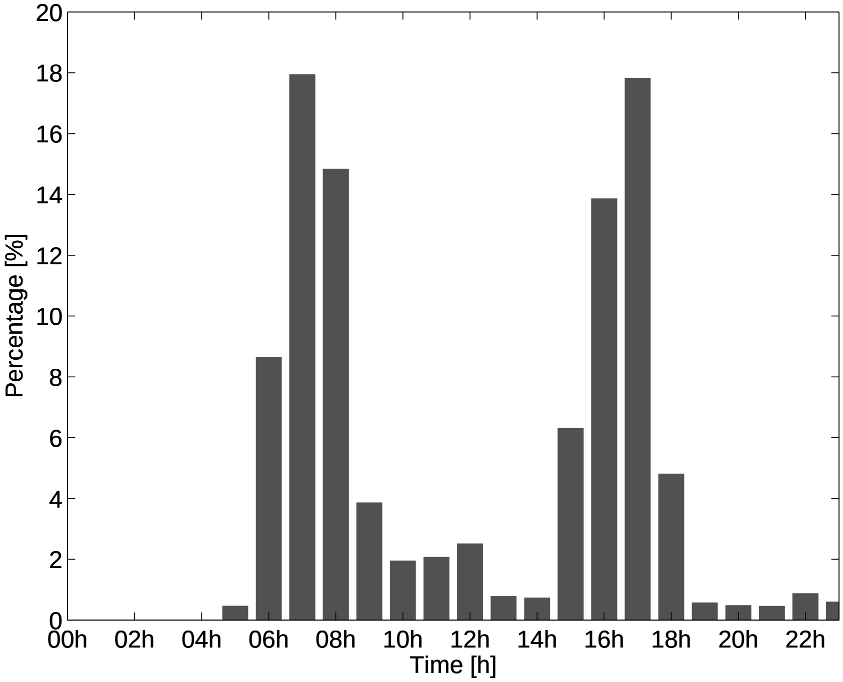

Fig. 2.12: Distribution of the starting hours of the daily trips for full-time employee [75].

evening, e.g. for a family visit, shopping, education etc. The average number of trips is 2.23 per day based upon the model.

At first instance, the vehicles are charged at home. One sample of the availability analysis gives information on one vehicle during a full day on a 15 minute base as shown in Fig. 2.13. For an entire day, it is determined when the vehicle is driving, when the vehicle is at home and when home charging can be applied. A distinction is made between being at work and being absent in the case that charging at work could be possible. The number of trips and the consumption per trip can be deduced from the sample. A database of 1000 samples is collected. If the PHEV consumes more than available in the battery, the vehicle uses its combustion engine to complete the trip. This will not have an impact on the results, because the battery is just assumed to be empty on that moment.

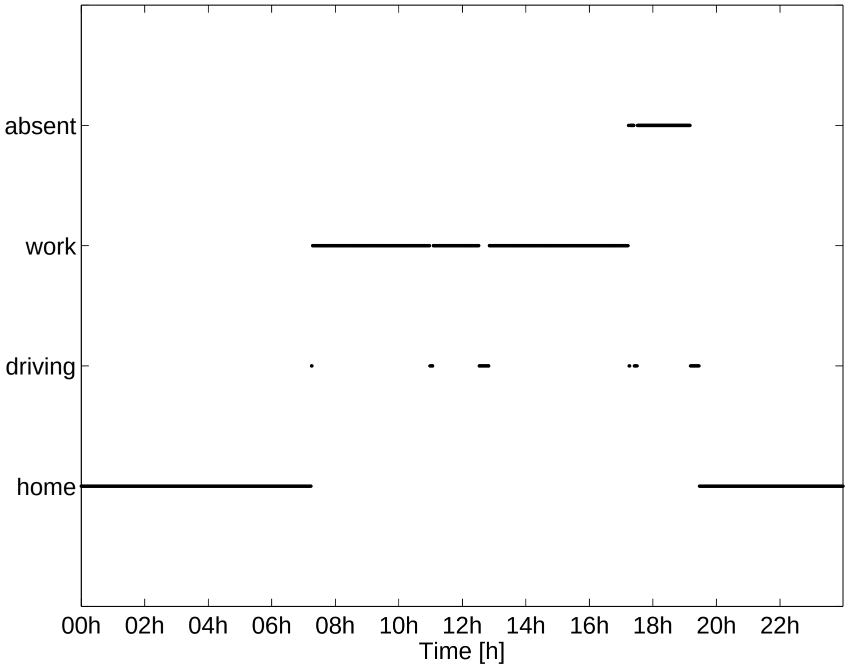

Fig. 2.13: Sample of the availability analysis.

2.3.6 Assumptions

The exact advantage of coordinated charging depends on the assumptions made in this section. The household load profiles are typical for Belgium. Other regions may have other load profiles because of different weather conditions, such as an air conditioning peak in the afternoon. Some regions will also have other grid voltages, such as 110 V in the United States. The IEEE grid is an example for a distribution grid, so the obtained results are only valid for this grid. It is assumed that this grid is a typical radial distribution grid. The radial distribution grid has of course an impact on the obtained results. This is described in section 3.6. The maximum power of the charger is determined by the maximum power of a standard electric outlet in Belgium. Other parameters which may have an impact on the distribution grid are amongst others, incentives and the use of smart meters. The results of the availability analysis are only valid for full-time employees.

2.4 Conclusions

The evolution of the Belgian light duty vehicle fleet is found in literature and an overview is given in this chapter. In the second part, a detailed description of the development, the characteristics and the constraints of the model is given.

In future, electric vehicles will constitute a part of the Belgian light duty vehicle fleet. The electrical energy needed to charge a PHEV fleet in Belgium is calculated and will be a few percentage of the total consumed electrical energy. This extra demand must be covered by the current power plants and transported by the electricity grid. Still, the point in time PHEVs will charge is very important.

If PHEVs charge during peak hours, this could give capacity problems for the generation of the electrical energy as described in literature. Moreover, it is possible that there will not be enough generation capacity when PHEVs are charged at these moments. Peak load power plants will be responsible to provide the electrical energy and these power plants are usually more expensive.

PHEVs are mostly connected to the low-voltage grid. The impact on the distribution grid will probably be even larger because the individual charging profiles will have a significant impact on the general load profile. The extra energy must be transported by the sometimes already heavily loaded grid. The impact on the distribution grid is also rarely studied in the literature. Therefore, the impact on the distribution grid, in terms of voltage deviations, power losses, feeder and transformer overloads etc., is the main goal of this work. Coordinated charging will partially solve the generation and distribution problem.

A model for this work is developed to simulate the grid impact of charging PHEVs. Some specifications of the PHEV, such as battery capacity, maximum power rating of the charger, charge efficiency etc., are determined. For the grid topology, an IEEE 34 node test feeder is considered as a radial residential distribution grid as this grid is already used for research about the optimal use of distribution grids. For the household loads, synthetic load profiles are used and are scaled to achieve an average yearly consumption of a Belgian household. The charging periods of the PHEVs are determined. An existing model, based on an availability analysis, defining when vehicles are at home, driving, at work or absent, is used. Because of the early stage of development of these new technologies, such as PHEVs and active grids, some well-considered assumptions were made.

3

Management of charging of PHEVs

Charging plug-in hybrid electric vehicles is likely to have a considerable impact on the distribution grid. The impact is indicated in terms of power losses, voltage deviations, overloading of transformers and feeders etc. A key question that comes up is whether demand-side-management techniques, such as load shifting, may significantly reduce the impact of charging a PHEV fleet on the distribution grid. Load shifting involves that the energy use of the peak hours is shifted to the off-peak hours. This load management can be achieved by the coordination of charging PHEVs. Charging is shifted in time and the power rating of the charger can also be adapted. If coordinated charging is applied, an optimal charging profile for each PHEV is determined. Different methods for determining this optimal charging profile are proposed and compared. The model and assumptions introduced in chapter 2 are used. The methodologies proposed in this work are based on the work of Edwin Haesen [77] and are only valid for a radial grid.

The implementation of the coordination of charging PHEVs assumes a smart metering system. Smart meters will be installed at households. PHEVs can take advantage of this intelligent meter for instance when a real-time or flexible pricing system is available.

In section 3.1, the methodology used to perform a load flow analysis is described. The next section describes the methods and results of uncoordinated charging. There are several methods to determine the optimal charging profile for plug-in hybrid electric vehicles. The quadratic programming technique is interpreted in section 3.3. Both the deterministic and stochastic model are investigated. The dynamic programming technique is explained in section 3.4. The impact on a small distribution grid is considered in section 3.5 to give a more general overview. For this investigation, a lot of assumptions are made. Therefore, a sensitivity analysis is performed in section 3.6 to study the impact on the results.

3.1 Load flow analysis

A load flow analysis is performed to assess the voltage deviations and the power losses of the representative distribution grid of Fig. 2.9. For the calculation of the grid parameters of a radial distribution grid, several methods are suggested, such as the backward-forward sweep, the network reduction and the fast-decoupled method [77]. The use of the backward-forward sweep method is the most common because it is rather straightforward, rapid and easy to handle. Heavily loaded grids can have convergence problems. Therefore other methods can be implemented such as Current Injection Method (CIM) using the full Newton method [78]. Only the backward-forward sweep method is considered in this work and no convergence problems are encountered.

The load flow analysis, based on the backward-forward sweep method, is applied to calculate the nodal currents, line currents and nodal voltages [79], [80]. For the first iteration, a flat voltage profile of 230 V is presumed at each node as shown in (3.1). In reality, not a flat voltage profile but an already decreasing voltage profile to the end nodes could be taken into consideration because this voltage profile will be closer to the real voltage profile. Next, the backward-forward sweep method consists of three stages as presented in (3.2).

$$\mathbf{U}_{\text{node}}: \text{ flat profile} \tag{3.1}$$

$$\text{while } \epsilon > \epsilon_{max}$$

$$do\begin{cases} \mathbf{I}_{\text{node}} &= f(\mathbf{S}_{\text{node}}, \mathbf{P}_{\text{PHEV}}, \mathbf{U}_{\text{node}}) \\ &= (\frac{\mathbf{S}_{\text{node}}}{\mathbf{U}_{\text{node}}})^* = (\frac{\mathbf{S}_{\text{h}} + \mathbf{P}_{\text{PHEV}}}{\mathbf{U}_{\text{node}}})^* \\ \mathbf{I}_{\text{line}} &= \mathbf{C} \cdot \mathbf{I}_{\text{node}} \\ \mathbf{U}_{\text{node}} &= U_{\text{grid}} - \mathbf{Z} \cdot \mathbf{I}_{\text{line}} \\ \epsilon &= g_{\text{error}}(\mathbf{S}_{\text{node}}, \mathbf{I}_{\text{node}}, \mathbf{U}_{\text{node}}) \end{cases} \tag{3.2}$$

The nodal and line currents are calculated in the backward step based on the voltages of the previous iteration. The current in each node, $\mathbf{I}_{\text{node}}$, is calculated based on the apparent power in each node, $\mathbf{S}_{\text{node}}$, and the voltage in each node, $\mathbf{U}_{\text{node}}$. $\mathbf{S}_{\text{node}}$ equals the sum of the household load, $\mathbf{S}_{\text{h}}$, and the power of the charger of the PHEV, $\mathbf{P}_{\text{PHEV}}$. A constant power load model is used at all connections at each time step. Other load models are the constant impedance, the constant current, the polynomial load and exponential load model [81]. In the second step of the backward sweep, the line currents, $\mathbf{I}_{\text{line}}$, are determined, defined as the current in a feeder segment. This step is rather simple because of the radial structure of the grid as shown in (3.3).

$$\begin{aligned} \mathbf{I}_{\text{node}} &= \mathbf{T}^T \cdot \mathbf{I}_{\text{line}} \\ \mathbf{I}_{\text{line}} &= (\mathbf{T}^T)^{-1} \cdot \mathbf{I}_{\text{node}} \\ &= \mathbf{C} \cdot \mathbf{I}_{\text{node}} \end{aligned} \tag{3.3}$$

$\mathbf{T}$ is the incidence matrix. Each row of this matrix represents a line between two nodes and each column a node. A radial grid of z nodes has z-1 lines. A line between two nodes is represented by -1 and 1 for respectively the start and end node as represented in Table 3.1. The rest of the row elements are zero. An extra row in the incidence matrix $\mathbf{T}$, i.e. the first row, is added to represent the fictitious line between the substation which is the grid node, and the first node to obtain a square matrix.

The nodal voltages, $\mathbf{U}_{\text{node}}$, are calculated in the forward step based on the voltage at the root node, U_{grid}, which is assumed to have a constant rated value of 230 V and the voltage drops between the nodes, based on the line currents and the

T	1	2	···	z
0	1	0	···	0
1	-1	1	···	0
2	0	-1	···	0
⋮	⋮	⋮	⋱	⋮
z-2	0	0	···	1
z-1	0	0	···	-1

Table 3.1: Incidence matrix **T**.

impedances, **Z**, of the lines as shown in (3.2). Each element $Z_{i,j}$ of the matrix **Z** gives the line impedance between node i and node j if there is a connection between those two nodes. The currents and voltages are updated iteratively until the stopping criterion $\epsilon \leq \epsilon_{max}$, based on node voltages, is reached. The voltage at the grid node, calculated with the line currents and impedances, must be equal to 230 V. Other stopping criteria are also possible. The load consumption is proposed as a positive value of the apparent power and an injection in the distribution grid is proposed as a negative value of the apparent power. The three phases of the load flow analysis are handled as matrix multiplications.

3.2 Uncoordinated charging

Uncoordinated charging indicates that the batteries of the vehicles either start to charge immediately when plugged in, or after a user-adjustable fixed start delay. Currently, the vehicle owners do not have the incentive nor the essential information to schedule charging of the batteries to optimize grid utilization or other parameters. A fixed start delay is introduced to give the vehicle owner the possibility to start charging using off-peak electricity tariffs. To avoid that all vehicles will start to charge at the beginning of the off-peak electricity tariffs and causing an extra peak at that moment, the vehicles start randomly within a specific period of time such that the vehicles are still fully charged at the end of the charging period.

3.2.1 Determination of charging profile

At the start of a charging period as defined in section 2.3.4, a daily profile is arbitrarily selected from the available set belonging to a specific scenario (winter, summer) and assigned at each node. The PHEVs are randomly placed. It is assumed that the batteries of the vehicles are depleted at the start of the charging period. The profile for charging a PHEV is kept straightforward. The vehicles are charged at full power, i.e. at 4 kW, until they are fully charged. For every quarter of an hour, the backward-forward sweep method is repeated to compute the line and nodal current and the nodal voltage. In that way, the power losses and the voltage deviations can be calculated for each time step and thus for the entire charging period.

In 2008, there were about 4 600 000 households [82] and 5 200 000 passenger vehicles. On average, each household has 1.13 vehicles in Belgium. In that way, a grid of 33 nodes would have about 37 vehicles. It is assumed that only one vehicle can charge per node or household. Therefore, the maximum number of PHEVs is considered to be 33. The other vehicles would be CVs or HEVs which do not need to be charged by the grid. For each charging period with a specified season (winter or summer), six cases depending on the penetration level are selected. The first case, with no PHEVs, is taken as a reference case. The next cases have a PHEV penetration level of respectively 10%, 20%, 30%, 40% and 50% representing the proportion of nodes with a PHEV present. Although, the maximum penetration level is forecasted to be 30%, a penetration level of 40 and 50% is also considered to give a more global overview.

For each scenario, consisting of a specified charging period, season and penetration level, 1000 separated runs are performed, creating 1000 samples. For each separate run, a daily load profile is selected from the available set of residential load profiles of the winter or summer season.

3.2.2 Results

The impact of uncoordinated charging on the distribution grid is illustrated by computing the power losses and the maximum voltage deviation for the different charging periods, seasons and penetration levels. The power losses are the ratio of the power losses to the total load and these power losses are calculated for an entire charging period for each sample. For each scenario, the average of the power losses of the 1000 samples is taken. For each sample, the maximum voltage deviation of an entire charging period is determined. For each scenario, the average of the maximum voltage deviations of the 1000 samples is calculated. The number of 1000 samples is large enough to achieve an accurate average per scenario. Taking more samples does not change the results significantly.

Table 3.2 depicts the ratio of the power losses to the total load. The total load includes the normal household loads and the charging of PHEVs, if present. In all cases, the power losses are larger in the winter season than in the summer season due to the larger household loads. The increase of the number of PHEVs leads to a significant increase in power losses and the increase of the power losses is the largest for evening charging.

Charging period	**Penetration level**	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**
21h00-06h00	**Summer**	1.1	1.4	1.9	2.2	2.6	3.1
	Winter	1.4	1.6	2.1	2.4	2.8	3.3
18h00-21h00	**Summer**	1.5	2.4	3.8	5.0	6.3	8.1
	Winter	2.4	3.4	4.8	6.0	7.4	9.5
10h00-16h00	**Summer**	1.3	1.8	2.6	3.2	3.9	4.8
	Winter	1.7	2.2	3.0	3.6	4.2	5.2

Table 3.2: Average of the ratio of power losses to total power [%] in case of uncoordinated charging.

Not only the power losses, but also the voltage deviations of the grid voltage (230 V), represented in Table 3.3, are important for the distribution system operator (DSO) for reasons of grid reliability. The maximum voltage deviation for each sample is determined and is averaged over all samples. An increase in the number of PHEVs leads to a substantial increase in voltage deviations. They are larger in winter compared to summer due to larger household loads. The maximum voltage deviations increase when the number of PHEVs increases, being the largest for evening charging. According to the mandatory EN50160 standard [83], voltage deviations up to 10% in low-voltage grids, for 95% of the time, are acceptable. Table 3.3 shows that for a penetration of 30%, voltage deviations are about 10%, especially during the evening peak. For a penetration level of 40 and 50%, voltage problems may occur during evening and day charging. Of course, this table does not reflect the amount of time that the voltage deviations are larger than 10%.

The amount of time that the voltage deviations are exceeding 10% of the grid voltage is also important and is represented in Table 3.4. This percentage may not be larger than 5% to satisfy the EN50160 standard. During the evening peak in winter, for a penetration level of 30%, the EN50160 standard is not achieved because for about 16.6% of the time, the nodal voltages are lower than 90% of the grid voltage. If the penetration level is 40 or 50%, problems occur during evening

Charging period	**Penetration level**	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**
21h00-06h00	**Summer**	3.1	3.5	4.4	5.0	5.8	6.7
	Winter	4.2	4.4	4.9	5.5	6.2	7.1
18h00-21h00	**Summer**	3.0	4.4	6.5	8.1	9.9	12.5*
	Winter	4.8	6.3	8.5	10.3*	12.2*	15.1*
10h00-16h00	**Summer**	3.0	4.1	5.6	6.9	8.1	9.9
	Winter	3.7	4.9	6.4	7.7	8.9	10.8*

Table 3.3: Average of the maximum voltage deviations [%] in case of uncoordinated charging.
*: Excessive voltage deviations.

peak and day charging. For evening charging during summer and a penetration level of 40%, the average of the maximum voltage deviation is lower than 10%. However, the number of excessive voltage deviations is larger than 5%. The reason is that the values of Table 3.3 provide mean values. At first sight, no problems occur in this scenario, although, when the number of excessive voltage deviations is taken into account, the EN50160 standard is not satisfied.

The power losses and the voltage deviations are the largest while charging during the evening peak, between 18h00 and 21h00. The reasons are twofold. First, this charging period, wherein the batteries must be fully charged, is rather short, only 3 hours. Therefore, more vehicles are charged simultaneously, due to the correlated behaviour. Secondly, the household load during the evening is the largest of the whole day, as shown in Fig. 2.10, and the output power of the charger is added to it. Charging during the day is a little more demanding for the grid compared to charging overnight.

Fig. 3.1 depicts the voltage profile at a node of the distribution grid for a penetration level of 0% and 30% during a winter night. This figure shows two charging examples and is not the average of several samples. Clearly, there is a voltage decrease in the presence of PHEVs during the charging period between

Charging period	Penetration level	0%	10%	20%	30%	40%	50%
21h00-06h00	**Summer**	0.0	0.0	0.0	0.0	0.0	0.0
	Winter	0.0	0.0	0.0	0.0	0.0	0.0
18h00-21h00	**Summer**	0.0	0.0	0.0	0.1	11.0*	39.0*
	Winter	0.0	0.0	0.1	16.6*	37.5*	60.0*
10h00-16h00	**Summer**	0.0	0.0	0.0	0.0	0.0	2.0
	Winter	0.0	0.0	0.0	0.0	0.5	5.3*

Table 3.4: Total amount of time the average of the maximum voltage deviations exceeds 10% [%] for uncoordinated charging.
*: Excessive voltage deviations for more than 5% of the time (EN50160 standard).

21h00 and 06h00. Between 23h00 and 04h00, a large number of vehicles charge, the voltage drop is the largest and deviates the most from the 0% PHEV voltage profile. The power needed for charging these vehicles is significantly larger compared to the household loads during the night. This voltage profile is not smooth, because the vehicles randomly charge at 4 kW. The small difference in voltage deviations during the rest of the day is caused by the different load profiles selected for both cases.

Fig. 3.2 illustrates the power consumption for a small distribution grid of 33 nodes for a penetration level of 30%. The consumption of the grid is averaged over 1000 samples. The power consumption of the household and the PHEVs are represented separately. The largest power consumption of the vehicles is about 15 kW. During the night, this is larger than the consumption of the households. The sum of the household loads and the load of the charging PHEVs is also represented. This sum is substantially increased compared to the household loads only. The vehicles are also charging when the household loads are still large.

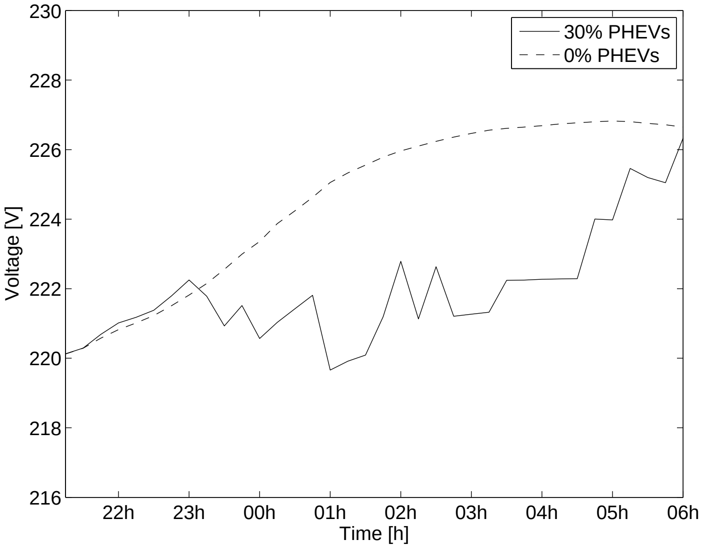

Fig. 3.1: Voltage profile at a node of a grid with 30% PHEVs compared to the voltage profile with 0% PHEV.

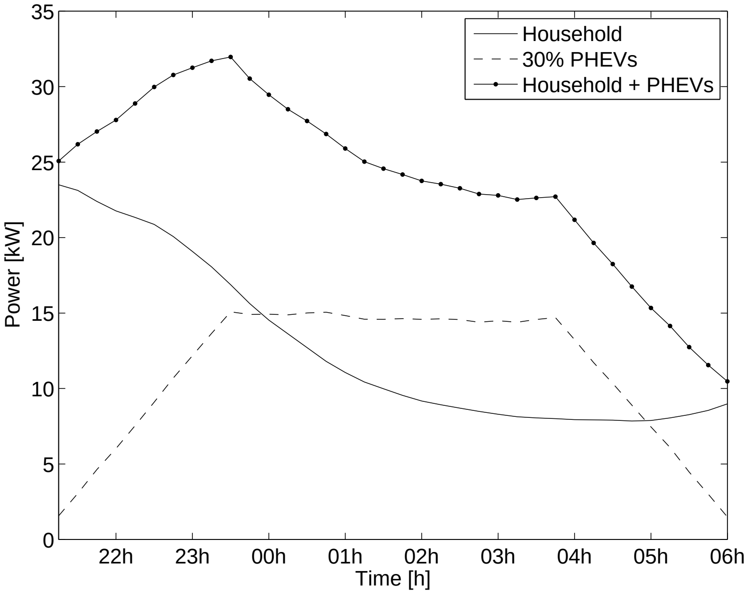

Fig. 3.2: Average power consumption for the total grid per time step for uncoordinated charging for a penetration level of 30%.

3.3 Coordinated charging: quadratic programming technique

In the previous section, charging batteries of PHEVs starts randomly, either immediately when they are plugged in, or after a fixed start delay. The idea of this section is to achieve optimal charging and grid utilization. A direct coordination of charging can be done by smart metering and by sending signals to the individual vehicles. The methods used for coordinated charging and the results are described in this section. Coordinated charging leads to an optimization problem in which an objective function, i.e. the power losses, must be minimized while satisfying several constraints. Other objective functions are described in section 4.5. The result of the optimization problem is an optimal charging profile for each individual vehicle.

3.3.1 Objectives and algorithms

The (optimal) charging profiles for a PHEV fleet are determined by the optimization programming technique. An objective function, f(x), must be optimized (i.e. minimized or maximized) and is subjected to constraints. The optimization algorithm determines an optimal charging profile minimizing the objective function and satisfying all constraints. There are several possible objective functions.

If the objective function is linear in the variable $\mathbf{x}$ as shown in (3.4) and this function is subjected to linear equality and inequality constraints as represented in (3.5), the linear programming (LP) technique can be used for the optimization problem.

$$\min\left(\mathbf{F}_{\mathrm{LP}}^{T}\mathbf{x}\right) \tag{3.4}$$

$$s.t. \begin{cases} \mathbf{b}_{\mathrm{ineq,l}} \leq \mathbf{A}_{\mathrm{ineq}}\mathbf{x} \leq \mathbf{b}_{\mathrm{ineq,u}} \\ \mathbf{A}_{\mathrm{eq}}\mathbf{x} = \mathbf{b}_{\mathrm{eq}} \\ \mathbf{l}_{\mathrm{b}} \leq \mathbf{x} \leq \mathbf{u}_{\mathrm{b}} \end{cases} \tag{3.5}$$

The feasible region of this problem is a polyhedron, defined by the linear constraints. Each local optimum of the linear problem is also a global optimum and the global optimum is always attained at one of the vertices of the polyhedron. In that way, it is also possible to achieve a set of optimal solutions covering an edge or face of the polyhedron. The first numerical solvers for solving linear problems were developed in 1947 by Dantzig and is the simplex algorithm. This algorithm starts at an admissible solution at a vertex of the polyhedron and searches for vertices with higher values for the objective function by moving along the edges of the polyhedron as long as the value of the objective function can be raised and until the optimum is reached. The interior point method is introduced in 1984 by Karmarkar and contrary to the simplex algorithm, this algorithm traverses the interior of the feasible region. The major advantage of this method is the extension to non-linear convex problems. The problem is transformed into minimizing a linear function over a convex feasible set which is encoded by using a barrier function. The number of iterations is to be bounded by a polynomial of accuracy and problem dimensions [84]. An example of a linear objective function is a cost function [85].

A quadratic objective function subjected to linear equalities and inequalities requires the quadratic programming (QP) technique. The algorithm is also the interior point method for solving such optimization problems. The general formula for the objective function and constraints is respectively given in (3.6) and the (3.7). If the matrix **H** is a positive semidefinite matrix, the quadratic objective function is convex. Therefore, the local optimum of the optimization problem is also a global optimum. An example of a quadratic objective function is the minimization of power losses. In that case, the matrix **H** is positive semidefinite, power losses are a convex function. The optimal charging profile is a global optimum [84]. In this work, the variable x represents the power of the charger of a PHEV.

$$\min\left(\frac{1}{2}\mathbf{x}^T\mathbf{H}\mathbf{x} + \mathbf{F}_{\mathrm{QP}}^T\mathbf{x}\right) \tag{3.6}$$

$$s.t.\begin{cases} \mathbf{b}_{\mathrm{ineq,l}} \leq \mathbf{A}_{\mathrm{ineq}}\mathbf{x} \leq \mathbf{b}_{\mathrm{ineq,u}} \\ \mathbf{A}_{\mathrm{eq}}\mathbf{x} = \mathbf{b}_{\mathrm{eq}} \\ \mathbf{l}_{\mathrm{b}} \leq \mathbf{x} \leq \mathbf{u}_{\mathrm{b}} \end{cases} \tag{3.7}$$

The TOMLAB® toolbox in MATLAB® with the CPLEX solver is used for implementing the linear and quadratic problems [86], [87], [88]. The CPLEX solver is an optimization software package that contains the interior point method and is developed by Bixby. It can solve linear and quadratic programming problems.

3.3.2 Objective function: power losses

Only power losses, which are a quadratic function, are considered as objective function in this chapter. In the next chapter, other (linear) objective functions are investigated. The distribution system operator may prefer to maximize the grid efficiency. This efficiency can be improved by minimizing losses to avoid transformer and feeder overload. These losses are an economic concern. The objective is to minimize the power losses which are treated as a reformulation of the non-linear power flow equations. This non-linear minimization problem can be tackled as a sequential quadratic optimization problem, thus the quadratic programming technique is applied [89]. The power losses are represented in (3.8).

$$\min \sum_{t=1}^{t_{max}} \sum_{l=1}^{lines} R_l \cdot I_{line,l,t}^2 \tag{3.8}$$

The quadratic programming technique optimizes the objective function and determines the corresponding optimal charging profiles. The variable in the objective function is the power of the charger, $\mathbf{P}_{\mathrm{PHEV}}$. The (optimal) charging profile is a vector with the power rating of the charger for each node and each time step as shown in (3.9).

$$\mathbf{P}_{\mathrm{PHEV}} = \begin{bmatrix} P_{PHEV,1,1} \\ P_{PHEV,2,1} \\ \cdots \\ P_{PHEV,z,1} \\ P_{PHEV,1,2} \\ P_{PHEV,2,2} \\ \cdots \\ P_{PHEV,z,2} \\ \cdots \\ P_{PHEV,1,T} \\ P_{PHEV,2,T} \\ \cdots \\ P_{PHEV,z,T} \end{bmatrix} \tag{3.9}$$

The power losses for one time step can be handled by rewriting (3.8) by

$$
\begin{aligned}
P_{loss}(P_{PHEV,t}) &= I_{line,t}^{T}\begin{bmatrix} R_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & R_{n-1} \end{bmatrix} I_{line,t} \\
&\quad \text{with} \quad R = \begin{bmatrix} R_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & R_{n-1} \end{bmatrix} \\
&= (C \cdot I_{node,t})^{T} R (C \cdot I_{node,t}) \\
&= \left(C \left(\frac{S_{node,t}}{U_{node,t}} \right)^{*} \right)^{T} R \left(C \left(\frac{S_{node,t}}{U_{node,t}} \right)^{*} \right) \\
&= \left(C \left(\frac{S_{h,t}+P_{PHEV,t}}{U_{node,t}} \right)^{*} \right)^{T} R \left(C \left(\frac{S_{h,t}+P_{PHEV,t}}{U_{node,t}} \right)^{*} \right) \\
&= (\tfrac{1}{2} P_{PHEV,t}^{T} h_t P_{PHEV,t} + f_{QP,t}^{T} P_{PHEV,t} + constant).
\end{aligned}
\tag{3.10}
$$

The subscript t indicates the sample time t at which the variable is evaluated for all nodes in the grid. The apparent power, $\mathbf{S}_{\mathrm{node}}$, consists of the household load, $\mathbf{S}_{\mathrm{h}}$, and the load of the PHEVs, $\mathbf{P}_{\mathrm{PHEV}}$. h_t and $\mathrm{f}_{QP,t}$ are parts of respectively the matrix $\mathbf{H}$ and $\mathbf{F}_{\mathrm{QP}}$. A constant appears because the household loads are assumed known and are not a variable. A flat voltage profile is assumed for the first iteration step for the voltage at node n, $\mathbf{U}_{\mathrm{node,t}}$. For the next iteration steps, these voltages are calculated with the backward-forward sweep method. Therefore, the voltage at each node is known in the formula of the power losses. The power losses must be summed over all time steps of the charging period as given in (3.11).

$$
\begin{aligned}
P_{loss,total}(\mathbf{P}_{\mathrm{PHEV}}) &= P_{loss,t=1}(P_{PHEV,t=1}) + \cdots + P_{loss,t=T}(P_{PHEV,t=T}) \\
&= (\tfrac{1}{2}\mathbf{P}_{\mathrm{PHEV}}^{T}\mathbf{H}\mathbf{P}_{\mathrm{PHEV}} + \mathbf{F}_{\mathrm{QP}}^{T}\mathbf{P}_{\mathrm{PHEV}} + \mathrm{constant})
\end{aligned}
\tag{3.11}
$$

Matrices $\mathbf{H}$ and $\mathbf{F}_{\mathrm{QP}}$ are a function of the nodal voltages and thus the optimization problem is non-linear. If the nodal voltages are assumed constant, the problem would just be a quadratic optimization problem. These voltages change when the charging profile of the vehicles change, the problem is iteratively solved. This is the sequential quadratic programming technique. It could also be possible to take the nodal voltages in the optimization problem, however, this is not considered in this work.

3.3.3 Constraints

The constraints of this optimization problem are linear equality and inequality constraints. The constraints of the coordination of charging a fleet of PHEVs are represented in (3.12). These constraints must be rewritten in a general form to apply the quadratic programming technique.

$$s.t. \begin{cases} \forall t, \forall n \ \epsilon \ \{nodes\} : 0 \leq P_{PHEV,n,t} \leq P_{PHEV,\max} \\ \forall n \ \epsilon \ \{nodes\} : \sum_{t=1}^{t_{max}} P_{PHEV,n,t} \cdot \triangle t \cdot x_n = C_{max} \\ \forall t, \forall n \ \epsilon \ \{nodes\} : 0 \leq C_{n,t} \leq C_{\max} \\ x_n \epsilon \ \{0,1\} \end{cases} \tag{3.12}$$

The first constraint of (3.12) defines the upper and lower limit for the variable which is the power output of the charger. The general form is given in (3.13). $P_{PHEV,n,t}$ is the power rating of the charger at node n at time step t. In the case of a standard domestic outlet, the maximum charger power output, $\mathrm{P}_{\mathrm{PHEV,max}}$, is 4 kW. At first instance, the output power of the charger cannot be negative, meaning that the vehicle cannot discharge. The lower and upper limit are represented respectively in (3.14) and (3.15).

$$\mathbf{l}_{\mathrm{b}} \leq \mathbf{P}_{\mathrm{PHEV}} \leq \mathbf{u}_{\mathrm{b}} \tag{3.13}$$

$$\mathbf{l}_{\mathrm{b}} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{3.14}$$

$$\mathbf{u}_{\mathrm{b}} = \begin{bmatrix} P_{PHEV,max,1,1} \\ P_{PHEV,max,2,1} \\ \vdots \\ P_{PHEV,max,z,1} \\ \vdots \\ P_{PHEV,max,1,T} \\ P_{PHEV,max,2,T} \\ \vdots \\ P_{PHEV,max,z,T} \end{bmatrix} \tag{3.15}$$

The second constraint of (3.12) is the equality constraint. The general form of the equality constraint is given in (3.16). $\mathrm{x_n}$ is zero if no PHEV is present at node n and is one if there is a PHEV present at node n and thus $\mathrm{x_n}$ is no variable. This constraint is used to ensure that the batteries must be fully charged at the end of the charging period. $\mathbf{A}_{\mathrm{eq}}$ is represented in (3.17). The vector $\mathbf{b}_{\mathrm{eq}}$ shows the maximum battery capacity for each vehicle at node n, $C_{max,n}$, as shown in (3.18). The maximum useful battery capacity is 8.8 kWh. If no vehicles are connected, $\mathbf{b}_{\mathrm{eq}}$ will be put to zero.

$$\mathbf{A}_{\mathrm{eq}}\mathbf{P}_{\mathrm{PHEV}} = \mathbf{b}_{\mathrm{eq}} \tag{3.16}$$

$$\mathbf{A}_{\mathrm{eq}} = \begin{bmatrix} 1 & 0 & \cdots & 0 & \cdots & 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 & \cdots & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \cdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & \cdots & 0 & 0 & \cdots & 1 \end{bmatrix} \tag{3.17}$$

$$\mathbf{b}_{\mathrm{eq}} = \begin{bmatrix} C_{max,1} \\ C_{max,2} \\ \vdots \\ C_{max,z} \end{bmatrix} \tag{3.18}$$

The third constraint of (3.12) sets that the energy content of the battery at node n for time step t, $\mathrm{C}_{n,t}$, may not be larger than the maximum battery capacity, $\mathrm{C}_{\mathrm{max},n}$. The general form of this constraints is given in (3.19). The matrix $\mathbf{A}_{\mathrm{eq}}$ is used to built up matrix $\mathbf{A}_{\text{ineq}}$, now for each time step. $\mathbf{A}_{\text{ineq}}$ is computed in (3.20) and $\mathbf{b}_{\text{ineq,l}}$ and $\mathbf{b}_{\text{ineq,u}}$ in respectively (3.21) and (3.22).

$$\mathbf{b}_{\text{ineq,l}} \leq \mathbf{A}_{\text{ineq}}\mathbf{P}_{\text{PHEV}} \leq \mathbf{b}_{\text{ineq,u}} \tag{3.19}$$

$$\mathbf{A}_{\text{ineq}} = \begin{bmatrix} 1 & 0 & \cdots & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \cdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & \cdots & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & \cdots & 0 & \cdots & 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 & \cdots & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \cdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & \cdots & 0 & 0 & \cdots & 1 \end{bmatrix} \tag{3.20}$$

$$\mathbf{b}_{\text{ineq,l}} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{3.21}$$

$$\mathbf{b}_{\text{ineq,u}} = \begin{bmatrix} C_{max,1,1} \\ C_{max,2,1} \\ \vdots \\ C_{max,z,1} \\ \vdots \\ C_{max,1,T} \\ C_{max,2,T} \\ \vdots \\ C_{max,z,T} \end{bmatrix} \tag{3.22}$$

The current limits in each branch of the grid are not taken into account as restrictions. For the implementation of the current limits, a perfect knowledge of characteristics of the feeders is required which is not available for the IEEE 34 node test feeder.

3.3.4 Deterministic model

The quadratic programming technique and the deterministic model are applied to handle deterministic household load profiles. By minimizing the power losses, the owners of PHEVs are no longer able to control the charging profile. The only degree of freedom left for the owners is to indicate the point in time when the batteries must be fully charged. For the sake of convenience, the end of the indicated charging period is taken as the point in time when the vehicles must be fully charged. The power rating of the charger varies between zero and maximum and is no longer constant. The coordinated charging is analyzed for the same charging periods as described in the previous section. The range of the PHEV penetration levels remains the same. The same test grid is used. For each charging period and season, the power losses and voltage deviations are calculated and compared with the results of uncoordinated charging.

An overview of the method used to determine the optimal charging profile is shown in Fig 3.3. At each node of the test grid, a household load is assumed. The vehicles are randomly placed and the number of vehicles depends on the penetration level. Hence some of the nodes have a PHEV connected. At first instance, a flat voltage profile is assumed at each node. Since the optimal charging profile is not known at this moment, no charging profile is considered and the voltage and current in the nodes and the line currents are calculated with the backward-forward sweep method [79] in the case of no PHEVs. Next, the charging profile is determined by the quadratic programming technique. The backward-forward step is performed again, now with the charging profile taken into account. This process is repeated until convergence is reached. At that moment, the optimal charging profile is determined. The backward-forward sweep method has no convergence problems when the grid is not heavily loaded. The quadratic programming technique reaches a solution when a feasible region can be found. Switching between two solutions which give more or less the same results for the objective function, must be avoided.

1000 separate runs are performed for the same scenarios as for uncoordinated charging. The vehicles are not placed at the same nodes as for uncoordinated charging but are randomly placed. For each separate run, a daily load profile is selected from the available set of residential load profiles of the winter or summer season, depending on the scenario.

This paragraph describes the results of coordinated charging to illustrate the impact on the distribution grid. Table 3.5 and Table 3.6 represent respectively the power losses and the maximum voltage deviations for coordinated charging during different charging periods. For each scenario, the power losses are the average of the power losses calculated for each of the 1000 samples. The voltage deviations are the average of the maximum voltage deviation of each of the 1000 samples.

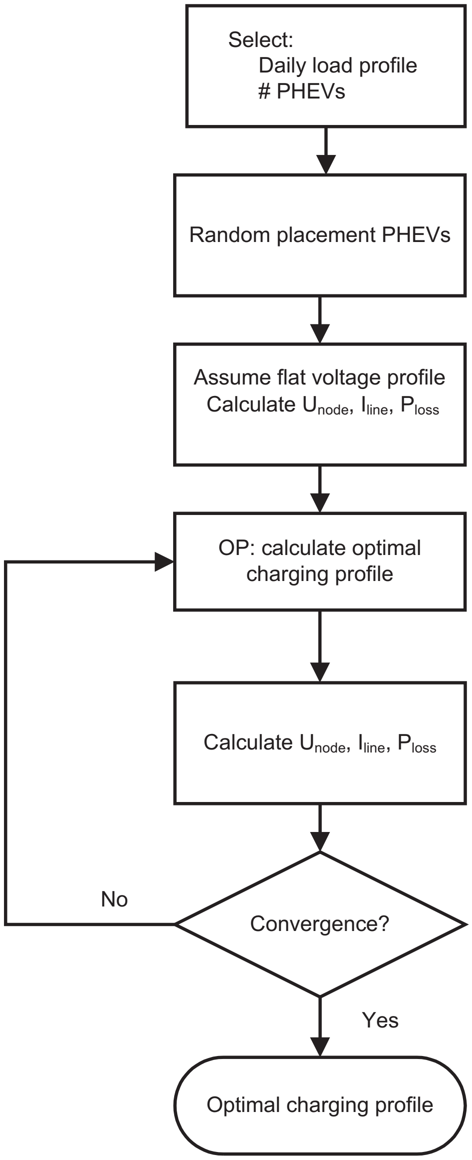

Fig. 3.3: Algorithm of coordinated charging.

These results must be compared to Table 3.2 and Table 3.3. For all scenarios, the power losses are significantly reduced when coordinated charging is applied. The decrease of the power losses is larger when the number of PHEVs is increased. The largest reduction of the power losses is achieved for evening charging, however the power losses for that charging period remain large compared to day or night charging.

Charging period	**Penetration level**	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**
21h00-06h00	**Summer**	1.1	1.3	1.7	1.9	2.3	2.7
	Winter	1.4	1.5	1.8	2.1	2.4	2.8
18h00-21h00	**Summer**	1.5	2.3	3.7	4.7	5.8	7.4
	Winter	2.4	3.3	4.7	5.8	6.9	8.7
10h00-16h00	**Summer**	1.3	1.7	2.3	2.8	3.3	4.0
	Winter	1.7	2.1	2.7	3.2	3.7	4.4

Table 3.5: Average of the ratio of power losses to total power [%] in case of coordinated charging.

If the number of PHEVs is increased, the voltage deviations are larger for charging during the evening than during a night or day, as expected. The reduction of the maximum voltage deviation increases when the number of PHEVs increases. The maximum voltage deviations for charging during the evening remain the highest. However, they are reduced compared to uncoordinated charging. The maximum voltage deviation for a penetration level of 30% is now well below 10%. For a penetration level of 40 and 50%, the maximum voltage deviation exceeds the limit during evening charging, but is significantly reduced compared to uncoordinated charging. The charging period during the evening is rather short, which makes it more difficult to optimize the charging profile because less variation is possible compared to night or day charging, which are longer charging periods.

Table 3.7 illustrates the total amount of time that the voltage deviation exceeds the limit set by the standard. For a penetration level up to 30%, no problem occurs. The evening charging remains a problem for a penetration level of 40 and 50%. The amount of time voltage deviations exceed 10% of the grid voltage is

Charging period	**Penetration level**	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**
21h00-06h00	**Summer**	3.1	3.1	3.3	3.7	4.1	4.7
	Winter	4.2	4.2	4.2	4.3	4.8	5.3
18h00-21h00	**Summer**	3.0	4.1	5.8	7.2	8.6	10.6*
	Winter	4.8	6.0	7.8	9.1	10.6*	12.8*
10h00-16h00	**Summer**	3.0	3.3	4.1	4.7	5.4	6.2
	Winter	3.7	4.0	4.9	5.5	6.2	7.1

Table 3.6: Average of the maximum voltage deviations [%] in case of coordinated charging.
*: Excessive voltage deviations.

slightly decreased compared to uncoordinated charging, but is still significantly larger than 5%. The maximum voltage deviations, averaged over all samples, is lower than 10% for evening charging during winter and a penetration level of 40%. No voltage problems occur in this case. However, this is an average value and some of the 1000 samples may have a maximum voltage deviation larger than 10%. The number of excessive voltage deviations is much larger than 5% and the EN50160 standard is not met.

Fig. 3.4 shows that the maximum voltage deviation during overnight charging when no PHEVs are involved occurs at the beginning of the charging period when the household loads are still high. A penetration level of 10% gives the same voltage deviations during peak hours, meaning that the vehicles are not charged when the household load peak occurs. The vehicles cause an extra load during the off-peak hours to obtain the objective to minimize power losses. Voltage deviations during these off-peak hours are smaller compared to these voltage deviations due to the household loads during the evening peak. For a vehicle penetration level of 30%, charging is more distributed. Some vehicles charge during peak hours increasing the voltage deviation and thus lowering the voltage level.

Fig. 3.5 shows the charging profiles of the nodes 1 and 33 of the grid of Fig. 2.9 with a penetration level of 30% for the charging period from 21h00 until 06h00

Charging period	**Penetration level**	**0%**	**10%**	**20%**	**30%**	**40%**	**50%**
21h00-06h00	**Summer**	0.0	0.0	0.0	0.0	0.0	0.0
	Winter	0.0	0.0	0.0	0.0	0.0	0.0
18h00-21h00	**Summer**	0.0	0.0	0.0	0.0	0.4	33.7*
	Winter	0.0	0.0	0.0	2.6	35.9*	58.2*
10h00-16h00	**Summer**	0.0	0.0	0.0	0.0	0.0	0.0
	Winter	0.0	0.0	0.0	0.0	0.0	0.0

Table 3.7: Total amount of time the average of the maximum voltage deviations exceeds 10% [%] for coordinated charging.
*: Excessive voltage deviations for more than 5% of the time (EN50160 standard).

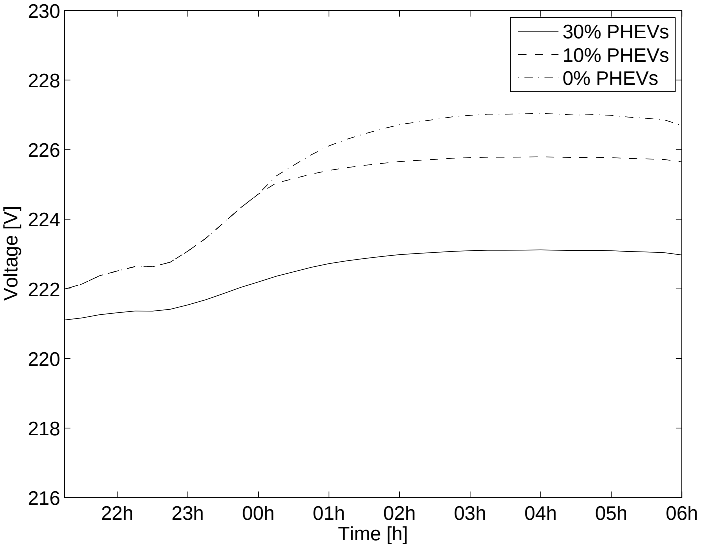

Fig. 3.4: Voltage profile at a node with 30% and 10% PHEVs compared to the voltage profile with 0% PHEV for coordinated charging.

during winter. The nodes are chosen at the beginning and end point of the grid. Clearly, the power output of the charger is not constantly 4 kW, but varies. The vehicles are not charging or charging at low power when the household load is large, i.e at the beginning of the charging period. The power of the charger is the largest during the off-peak hours.

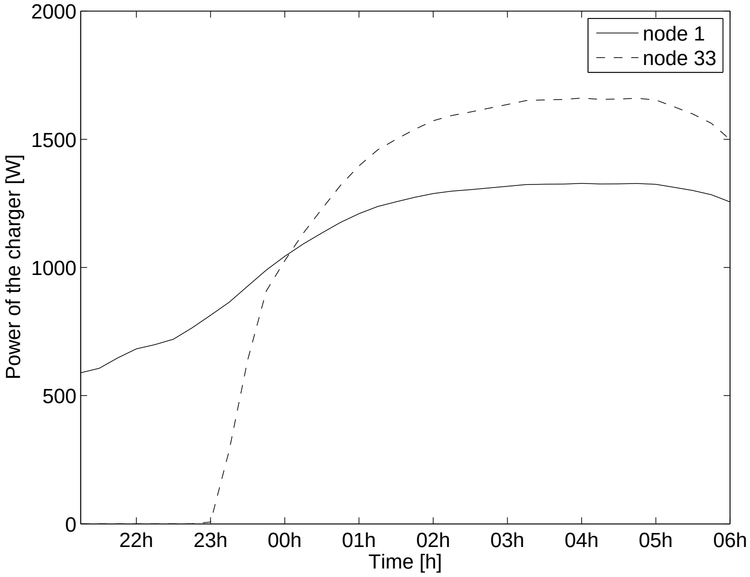

Fig. 3.5: Load profiles of the 4 kW charger for the charging period from 21h00 until 06h00 during winter.

Fig. 3.6 depicts the power consumption in the total grid for overnight charging. The consumption of the households and the PHEVs are represented separately. The PHEVs almost do not charge when the household loads are large and the power of the PHEVs increases when the household loads decrease. Therefore, the total consumption during night is more or less flat. As a result, the power consumption of the small distribution grid as seen at the substation is an almost flat demand during the entire night.

3.3.5 Stochastic model

The previous results are based on deterministic or historical data for the daily load profiles: essential input parameters are fixed. For this model, a sufficient number of measured data must be available. Most of the time, however, these measurements are not adequate to perform a perfect forecasting of the data. A stochastic model in which an error in the forecasting of the daily load profiles is

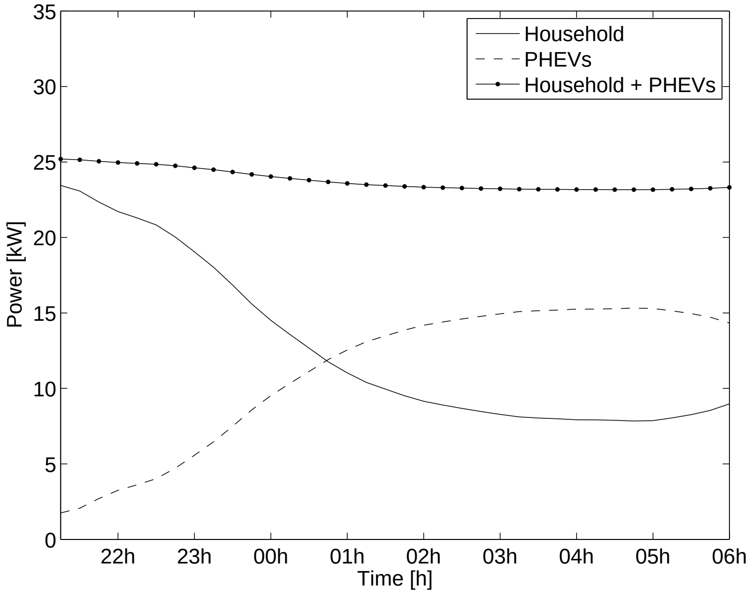

Fig. 3.6: Power consumption of the total grid per time step for coordinated charging.

considered, is therefore more realistic. In this quantitative analysis, the probability of the optimal charging profile and the power losses are examined.

The daily load profiles are key input parameters. Their uncertainties can be described in terms of probability density functions. In that way, the fixed input parameters are converted into random input variables with normal distributions assumed at each node. Thus, the fixed values are changed with small random variations at each time step. If the input variables are normally distributed, due to the linearization of the power flow equations, the output variables have a similar distribution as well. However, errors do occur. The correlation coefficient between the variables X and Y is defined in [90] as

$$\rho(X,Y) = \frac{\mathrm{cov}(X,Y)}{\sigma_X \sigma_Y}. \tag{3.23}$$

The correlation coefficient ρ is 1 in the case of a positive linear relationship, -1 in the case of a negative linear relationship. Values in between -1 and 1 indicate the degree of linear dependence between variables. At each point in time, on a

15 minute basis, a normal distribution of the variation of the household loads is assumed. A positive correlation between the time steps is implemented, thus each point in time is positively correlated with other points in time.

A Monte Carlo simulation is used to identify the impact on the optimal charging profile by taking into account the uncertainties of the household load profiles. A set of input samples, i.e. household load profiles, is applied to the deterministic model to achieve a final result, i.e. one optimal charging profile. Most of the time, the results of Monte Carlo simulations are represented using histograms. N independent samples of the random input variable ω^j, the daily load profile, are selected. One household load profile is selected and 2000 normally distributed variations are applied on that household profile. Equation (3.24) gives an estimate for the stochastic optimum $\hat{\nu}_n$. The function $g\left(P_{PHEV,n,t}, \omega^j\right)$ gives the power losses and $P_{PHEV,n,t}$ is the power rating of the charger for a PHEV at node n and time step t. $\hat{f_N}$ is a sample-average approximation of the objective of the stochastic programming problem.

$$\hat{\nu}_n = \min\left\{\hat{f_N}\left(P_{PHEV,n,t}\right) \equiv \frac{1}{N}\sum_{j=1}^{N} g\left(P_{PHEV,n,t}, \omega^j\right)\right\} \tag{3.24}$$

The mean value of the power losses, $E\left(\hat{\nu}_n\right)$, sets a lower bound for the real optimal value of the stochastic programming problem, ν^*, as shown in (3.25) [91].

$$E\left(\hat{\nu}_n\right) \leq \nu^* \tag{3.25}$$

$E\left(\hat{\nu}_n\right)$ can be estimated by generating M independent samples $\omega^{i,j}$ of the random input variable each of size N. M optimization runs are performed in which the non-linear power flow equations are solved using the backward-forward sweep method. According to (3.26), $\hat{\nu}_n^j$ is the mean optimal value of the problem for each of the M samples. The optimal values of the M samples constitute a normal distribution.

$$\hat{\nu}_n^j = \min\left\{\hat{f_N}^j\left(P_{PHEV,n,t}\right) := \frac{1}{N}\sum_{i=1}^{N} g\left(P_{PHEV,n,t}, \omega^{i,j}\right)\right\}, j = 1...M \tag{3.26}$$

In equation (3.27), $L_{N,M}$ is an unbiased estimator of $E\left(\hat{\nu}_n\right)$. Simulations indicate that in this type of problem, the lower bound converges to the real optimal value when N is sufficiently high, i.e. when the number of daily load profiles is sufficiently high.

$$\hat{E}(\hat{\nu}_n) = L_{N,M} = \frac{1}{M}\sum_{j=1}^{M} \hat{\nu}_N^j \tag{3.27}$$

The variance can be estimated as

$$\hat{\sigma^2}(\hat{\nu}_n) = \frac{1}{M-1}\sum_{j=1}^{M} \left[\hat{\nu}_N^j - \hat{E}(\hat{\nu}_n)\right]^2 . \tag{3.28}$$

A forecasting model for the daily load profile for the next day or charging period is required. The load on each point in time is varied by a normal distribution function. The standard deviation σ of this normal distribution function is determined in such a way that 99.7% of the samples vary at maximum 5% or 25% of the average μ of the daily load profiles.

For 2000 independent samples of the daily household load profile, one optimal charging profile is calculated. This optimal charging profile is used to determine the power losses for the 2000 individual household load profiles. This is the stochastic optimum. For each of these 2000 load profiles, the optimal charging profile and the corresponding power losses are also computed, which is the deterministic optimum.

The power losses of the deterministic optimum are subtracted from the power losses of the stochastic optimum and divided by the deterministic optimum, defined as the efficiency loss $\Delta\eta$. The efficiency loss for the ith sample is shown in (3.29).

$$\Delta\eta_i = \left(P_{loss,\, stoch,i} - P_{loss,\, det}\right) / P_{loss,\, det,i} \tag{3.29}$$

This efficiency loss is shown for a variation of the household loads of 5 and 25% respectively in Fig. 3.7 and 3.8. The value of this difference is always positive. The forecasting of the daily load profiles introduces this efficiency loss because the charging profiles of the PHEVs are not optimal for this specific daily load profile. If the standard deviation of the normal distribution and thus the variation of the household load is reduced, the 2000 charging profiles of the deterministic optimum converge to the optimal charging profile. The efficiency loss will go down by a factor 25 if the standard deviation is reduced from 25% to 5% as shown in

Fig. 3.7 compared to Fig. 3.8. This can be explained because there is a quadratic relation between the power losses and the current in the grid and thus also between the power losses and the loads of the grid.

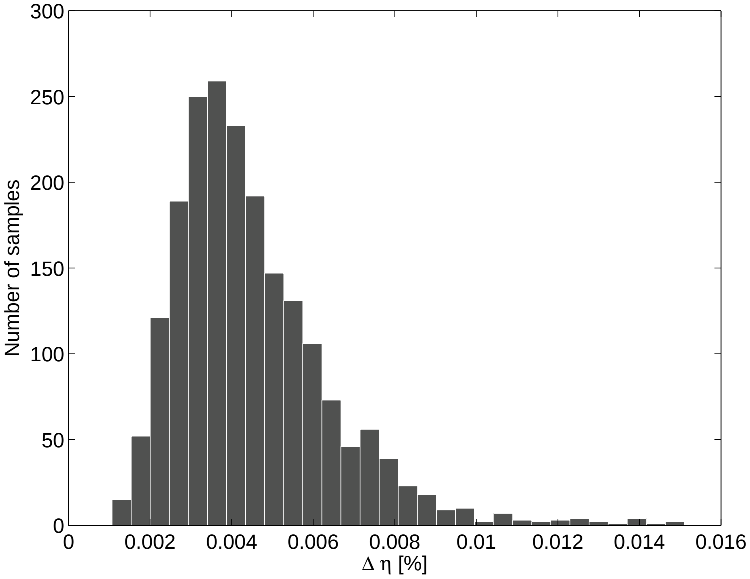

Fig. 3.7: Histogram of the efficiency loss of an arbitrary day during winter for a variation of 5%.

In general, the difference between the power losses of the stochastic and the deterministic optimum is very small. Clearly, the error in forecasting does not have a major impact on the power losses in this case. 2000 variations of a daily household load profile are generated. Each load profile of this set shows the same trend resulting in an optimal charging profile resembling the deterministic charging profile of a specific day as shown in Fig. 3.9 for the last node of the test grid. Therefore, the contrast in terms of power losses between the deterministic and stochastic optimum is small.

The daily household load profiles during winter show the same trend each day as shown in Fig. 3.10. 2000 random household load profiles are displayed in this figure. It is observed that the efficiency loss is small if a specific day is replaced by a random one. However, the difference between uncoordinated and coordinated charging is much larger because the charging profiles are more different. The uncoordinated charging has a constant charging profile, at a higher power level, for a specific amount of time.

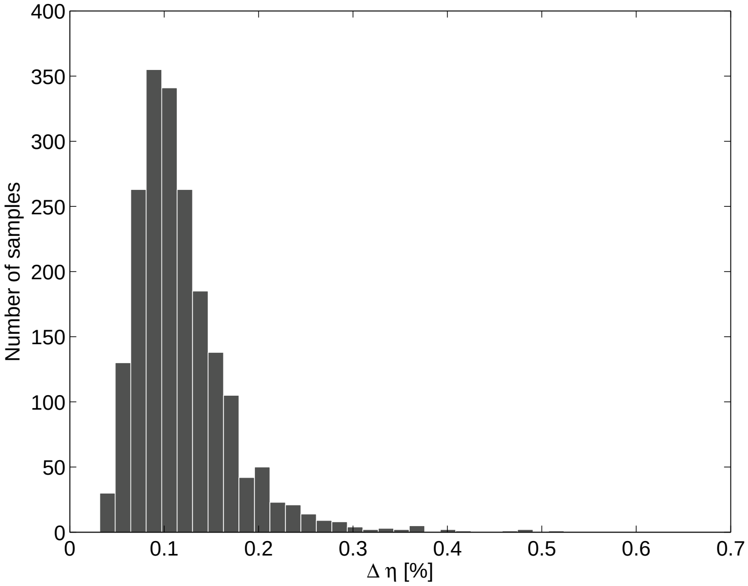

Fig. 3.8: Histogram of the the efficiency loss of an arbitrary day during winter for a variation of 25%.

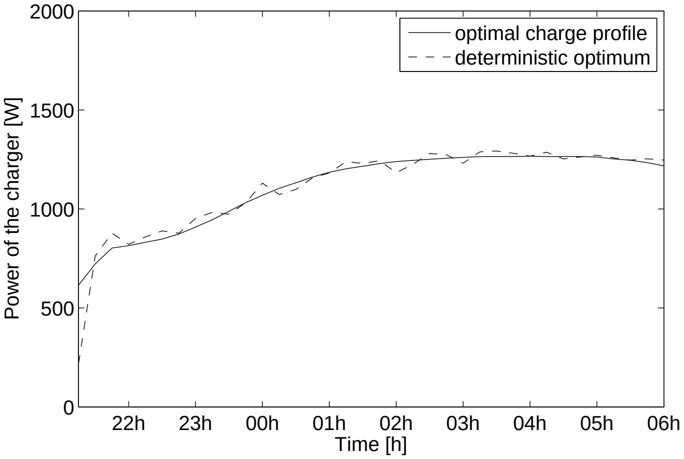

Fig. 3.9: The deterministic optimum and optimal charger profile for node 33.

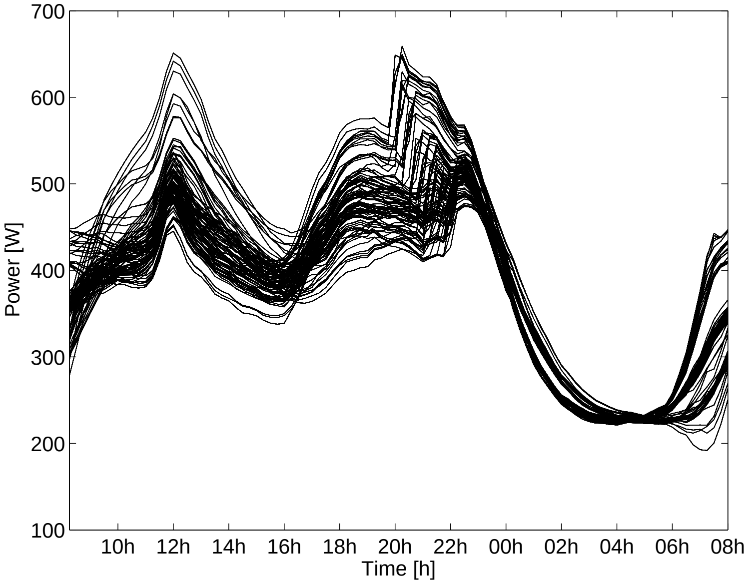

Fig. 3.10: A set of 2000 random household load profiles of the winter season.

In Fig. 3.7 and 3.8, a specific household load profile is assumed which is varied according to a normal distribution function. In Fig. 3.11, the load profiles are randomly selected from a database of measured household load profiles. This database contains profiles that differ more each day and are more peaked increasing the efficiency losses. The difference between the deterministic and stochastic models is larger. This indicates that the shape of the household profile or the moment of time of the peak load is essential to avoid efficiency losses. These losses are caused by the implementation of not optimal charging profiles for PHEVs and can easily increase up to 3% or more.

3.4 Coordinated charging: dynamic programming technique

The optimal coordination of charging PHEVs can also be tackled by the dynamic programming (DP) technique. The QP and DP techniques are compared with respect to results, storage requirements and computational time. The DP technique decomposes the original optimization problem into a sequence of subproblems, solved backwards over each stage. A classical implementation of the DP technique is the shortest path problem.

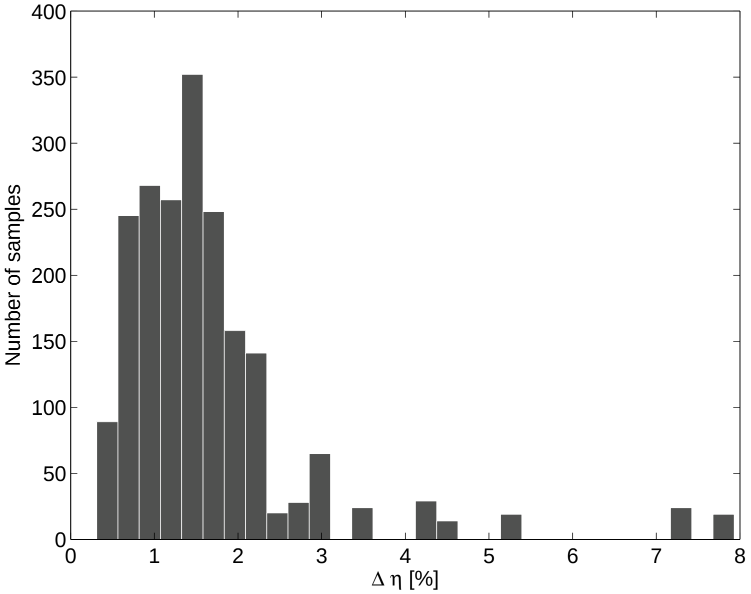

Fig. 3.11: Histogram of the efficiency loss of an arbitrary day during winter for a set of household profiles.

3.4.1 Methodology

There are Q vehicles with batteries charging and the maximum value of Q corresponds with a penetration level of 30%. The battery content of these Q vehicles at each stage is the state variable, $S_{t,i}$. The number of stages T, is the number of hours of the charging period multiplied by four because the household loads are available on a 15 minute time base.

The backward recursive equations for the conventional dynamic programming technique are given in (3.30) and (3.31).

$$f_t = \min\left[P_t\left(S_t, P_{PHEV,t}\right) + f_{t+1}\left(S_{t+1}\right)\right] \quad t = T, T-1, ..., 2, 1 \tag{3.30}$$

$$S_{t,i} = S_{t+1,i} - P_{PHEV,t,i} \cdot \Delta t \ \ \forall i = 1, ..., Q \tag{3.31}$$

The function f_t represents the total optimal power losses from period t to the last period T. The vector S_t is a of the R_s possible storage levels and the Q vehicles at time t. P_t is the power loss during period t and $S_{t,i}$ the battery content of the i^{th} vehicle at time stage t. The power of the chargers is represented by $P_{PHEV,t}$ and is also a vector. So the first component of this vector gives the power of the charger for the first PHEV. The output of the charger is not continuous, but has a step size of 400 W. This is relatively large, but smaller step sizes would lead to too much computational time, proportional to R_s^T [92]. As such, the battery content is also discrete. The constraints of the problem remain the same and are shown in (3.32), (3.33) and (3.34).

$$0 \leq P_{PHEV,t,i} \leq P_{PHEV,max} \tag{3.32}$$

$$S_{T,i} = C_{max} \quad \forall i = 1, ..., Q \tag{3.33}$$

$$0 \leq S_{t,i} \leq C_{max} \tag{3.34}$$

The power losses are still the objective function to be minimized. The storage vector S_t is a matrix of Q vehicles and thus ”the curse of dimensionality” [93] arises which is handled by modifying the original dynamic programming technique. Three modification arises:

- Coarse grid/interpolation techniques,
- Dynamic programming successive approximation (DPSA),
- Incremental dynamic programming (IDP) or discrete differential dynamic programming (DDDP).

The coarse grid/interpolation technique reduces the computational time and storage requirements by using larger discretization intervals and thus decreasing the number of discretization levels N. Accurate results are attained by interpolation over the coarser grid [92]. This method is not used because the profile of the household loads is on a 15 minute base, which is already reasonable coarse. By making the profile more coarse, more information about peak loads which is essential for determining the charging profile, would be lost.

The IDP and DDDP techniques handle the dimensionality problem by limiting the number of discretization levels N. A good overview is given in [94] and [95]. The

IDP technique allows only three storage states (corridor) for the whole problem horizon. The optimal charging profile of the previous iteration procedure is the center of the corridor of the next iteration and the process continues until convergence is obtained. The computational time is reduced to 3^T, but an iteration procedure is indispensable. For the DDDP technique, the procedure is the same, but the discretization levels are not limited to three but can be increased. The IDP and DDDP technique are both not implemented because the results of these techniques are not accurate enough.

The dynamic programming technique successive approximation (DPSA) decomposes the multidimensional problem in a sequence of one-dimensional problems, being much easier to handle [96]. The optimizations occur one variable at a time while holding the other variables constant. All variables are evaluated that way. This technique converges to an optimum for convex problems. This method is used for the deterministic and stochastic model. The deterministic model uses fixed values for household loads while the stochastic model uses normally distributed values.

3.4.2 Deterministic model

A daily load profile of the selected season is chosen and the vehicles are randomly placed. The DPSA technique needs initial values of the state variables to start the iteration. These values are generated by calculating the optimal charge trajectory for each PHEV separately without considering the other PHEVs. These optimal trajectories are put together into one temporary optimal trajectory and thus one state vector. All components of the state vector are kept constant, except the first one. The optimal charge trajectory for the first component of the state variable is calculated. The new value is ascribed to the first component and the procedure continues until the last component of the state vector is optimized. This procedure is repeated until convergence is obtained. The problem is switched from a multidimensional problem to a sequence of one-dimensional problems. The algorithm of dynamic programming successive approximation is represented in Fig. 3.12.

3.4.3 Stochastic model

The uncertainties of the household loads must also be implemented in the DP technique. 2000 stochastic household load profiles are generated and the mean power losses of these loads are used to determine the total power losses f_t as

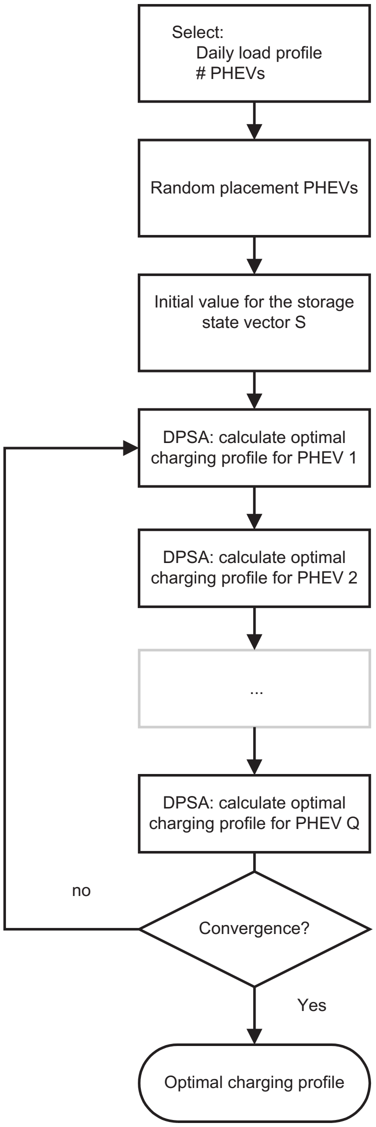

Fig. 3.12: Algorithm of DPSA charging.

presented in (3.35).

$$f_t = \min \left[E \left(P_t \left(S_t, P_{PHEV,t} \right) \right) + f_{t+1} \left(S_{t+1} \right) \right] \quad t = 1, 2, ..., T \tag{3.35}$$

The same stochastic household load profiles as generated in the stochastic programming of the QP technique are applied to make the comparison more relevant. One optimal charging profile is generated for these 2000 stochastic household loads with the DPSA technique. The power losses are calculated separately for the 2000 household load profiles and the single optimal charging profile, the stochastic optimum. For the deterministic optimum, the optimal charging profile and power losses are determined for each of the 2000 stochastic household load profiles, giving 2000 optimal charging profiles. The power losses of the deterministic optimum are subtracted from the power losses of the stochastic optimum and divided by the deterministic optimum for a variation of the household loads of 5% and 25% as defined in (3.29).

3.4.4 Results

In Fig. 3.13, the charging profiles for the QP and DP technique are compared. In general, the difference between the results of the DP and QP techniques is negligible, although the QP technique gives more accurate results as the values of the charging profile are continuous in that case. The DP technique, where a step size of 400 W is introduced for the power of the charger, gives a discrete charging profile. Reducing the step to an infinitesimally small value would give the same result as the QP technique. This step size is taken rather large in order to reduce the number of levels and thus computational time and storage requirements. The storage requirements are heavier for the DP technique compared to the QP technique as every possible path over each stage must be stored. Since this leads to very large matrices and increased computational time, the DP technique is slower. Therefore, the dynamic programming technique is not further considered in this work.

3.5 Impact on a small distribution grid

Uncoordinated charging of the batteries of PHEVs has a non-negligible impact on the performance of the distribution grid in terms of power losses and power quality for the IEEE 34 node test feeder during winter for a penetration level of 30%. Both power quality and power losses are represented in Table 3.8 and Table 3.9 for three cases: without PHEVs, uncoordinated and coordinated overnight charging. For

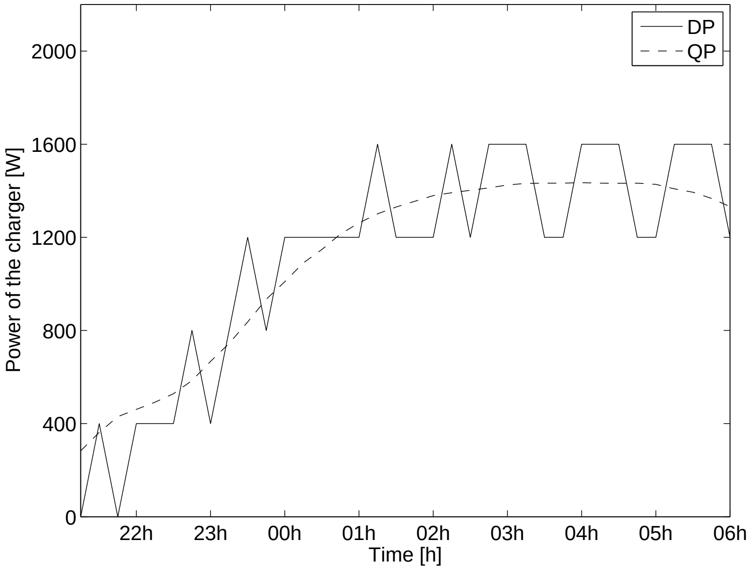

Fig. 3.13: Charging profile for node 1 for the QP and the DP program technique.

each of the 1000 samples and for each time step of the charging period, the total load, the line current at the substation or grid node and the minimum voltage of the grid is determined. The ratio of the power losses is defined as the ratio of the power losses to the total load and these losses are determined for the entire charging period. For each time step, the average value of the 1000 samples is calculated for the total load of the grid, the line current at the grid node and the minimum nodal voltage of the grid. These values are averaged again over the points in time of the charging period. The power losses are averaged over the 1000 samples. These results are represented in Table 3.8. The total load, on average, of uncoordinated charging and coordinated charging remains the same as expected because the consumed energy in both charging scenarios is the same. Obviously, the total load increases if vehicles charge uncoordinated or coordinated. The line current also increases while vehicles charge. Coordinated charging decreases the average line current slightly. The minimum voltage decreases if vehicles charge. The power losses of the coordinated charging scenario are between these of the scenario without PHEVs and the uncoordinated charging scenario. Of course, they are only average values and do not take into account the extremes.

To take into account the extreme values, the peak values are represented in Table 3.9. The maximum value of the total load of the grid and the line current at the grid node and the minimum value of the voltage of the grid of the 1000 samples

Parameters	Without PHEVs	Uncoordinated charging	Coordinated charging
Total load [kVA]	13	23	23
Line current [A]	56	105	104
Nodal voltage [V]	225	222	222
Power losses [%]	1.4	2.4	2.1

Table 3.8: Mean values of power quality and losses for the test grid with a 30% PHEV penetration level.

is determined for each time step of the charging period. Then, out of these maxima, the maximum value of the line current and total load is calculated over the entire charging period. In the same way, the minimum value is determined for the voltage. The maximum of the power losses of the 1000 samples is determined. With respect to uncoordinated charging, the coordination of the charging reduces power losses, total load, line current and minimum nodal voltage. Power quality is improved to a level which is similar to the case where no PHEVs are present. Because the extra loads for charging PHEVs remain in the case of coordinated charging, additional losses are still higher compared to the scenario without PHEVs.

The extreme values of Table 3.9 are not indicating which amount of time such high values occur. The distribution grid may only be overloaded for a small period, which is less harmful than continuously overloading. Therefore, a duration curve is set up. All data, i.e. each time step of the 1000 samples of the charging period, is ordered in descending order and not chronological. This curve indicates the amount of time of the charging period that a minimum amount of, for instance peak load, must be delivered. The minimum value of the total load must be delivered for the entire charging period, i.e. 100% of the time. The maximum of the total load must only be delivered for a small time period. The duration curve is plotted for three variables of Table 3.9, i.e. total load, line current and power losses. It is impossible to represent the nodal voltages in this way.

Fig 3.14 shows the total load duration curve. Uncoordinated charging increases the total load significantly, especially at the left of the curve with respect to the

Parameters	**Without PHEVs**	**Uncoordinated charging**	**Coordinated charging**
Total load [kVA]	26	52	29
Line current [A]	119	242	129
Nodal voltage [V]	219	211	218
Power losses [%]	1.7	3.5	2.7

Table 3.9: Extreme values of power quality and power losses for the test grid with a 30% PHEV penetration level.

reference case, which is the scenario without PHEVs. The maximum of the total load, at the left of the figure, is increased from 26 kVA when no PHEVs are present to 52 kVA when these vehicles charge uncoordinated. The coordination of charging reduces the maximum of the peak load to 29 kVA. If coordinated charging is applied, the total load is flattened over the charging period and is almost constant, except for a small amount of time, where there is still a small peak load. For almost 60% of the time of the charging period, the total load of the uncoordinated charging is higher compared to coordinated charging.

Fig 3.15 shows the line current duration curve at the grid node. If the charging is not coordinated, the line current increases significantly. The maximum of the line current is increased from 119 A when no PHEVs are present to 242 A when the vehicles charge uncoordinated. When coordinated charging is applied, the maximum line current decreases to 130 A. In the first half of the curve, there is almost a constant offset between the scenario without PHEVs and the uncoordinated charging. If coordinated charging is applied, the line current is more flat and a peak is also avoided.

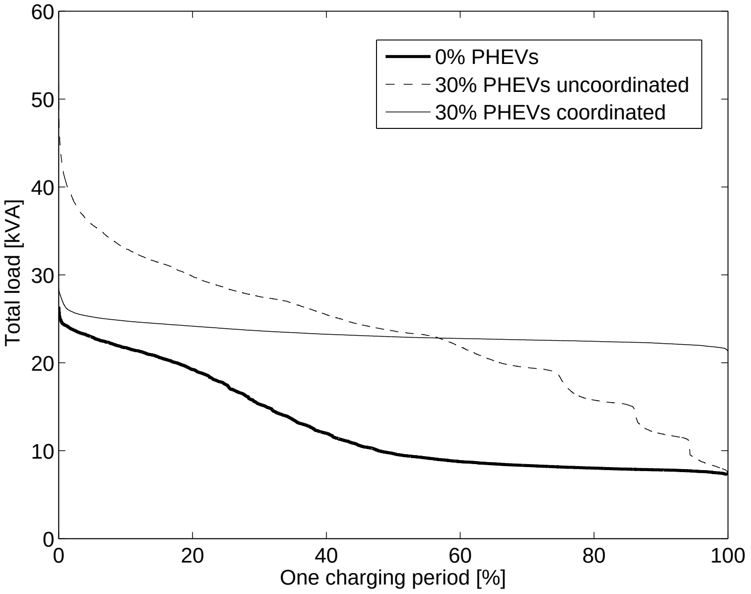

Fig. 3.14: Peak load duration curve of the charging period.

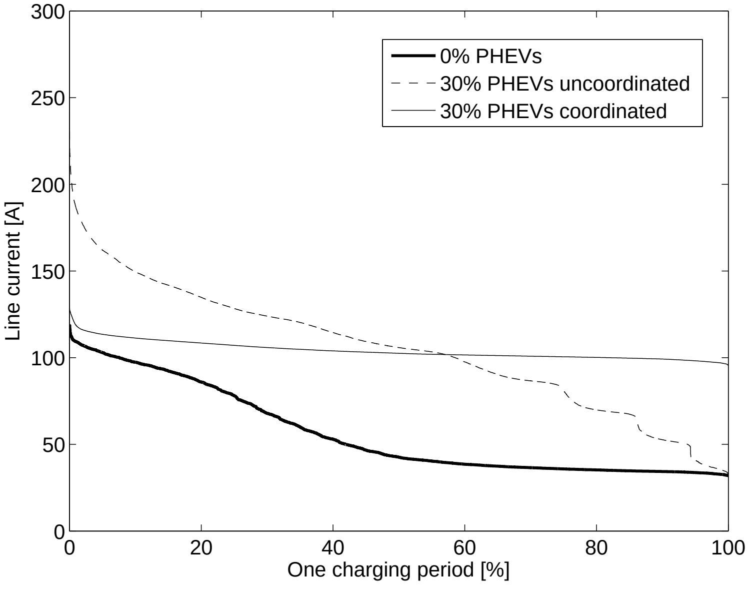

Fig. 3.15: Line current duration curve of the charging period.

Fig 3.16 shows the power losses duration curve. In the reference scenario, the power losses are the lowest. If coordinated charging is applied, the power losses are significantly reduced with respect to uncoordinated charging. Obviously, the level of the reference case cannot be achieved as the energy consumption is much larger. The power losses are also almost flat over the entire charging period except in the beginning of the curve, where there is still a small peak for a small amount of time. The maximum of the power losses is increased from 1.7 % for the scenario without PHEVs to 3.5 % for the scenario when uncoordinated charging is applied. The coordination of the charging reduces the peak of the power losses to 2.7 %.

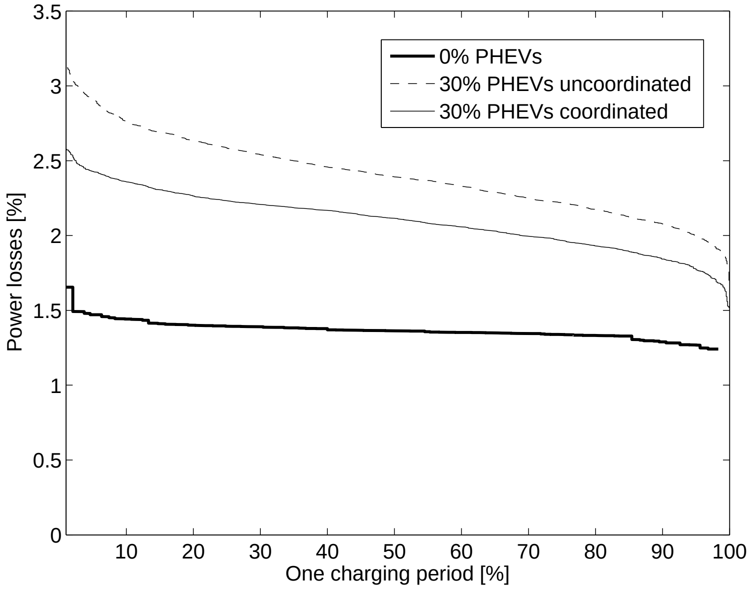

Fig. 3.16: Power losses duration curve of the charging period.

Coordinated charging can be done by a smart metering system. The distribution grid must be reinforced to cope with the increased loads and voltage drops caused by charging PHEVs if this coordination system is not applied. Both scenarios will introduce extra costs for the distribution system operator and eventually the customers. A global estimate is performed in order to indicate the level of upgrading needed for a small distribution grid. The design of the grid is based on the peak values. For the argumentation, the IEEE 34 node test feeder is connected to each phase of a three phase transformer of 100 kVA, forming a global grid of 100 nodes. The system exists of three independent single-phase systems. If a three-phase system is considered, load unbalances between the phases can lead to increased power losses. These load unbalances can be minimized by the three-phase management of the charging [97]. This is not taken into account in this work.

When no PHEVs are present, the maximum load for the three phases together is 78 kVA. Considering no PHEVs in future, the transformer has enough reserve capacity for this global grid to meet additional peak load and load growth for the next 10 years, assumed to be a few percent per year. A 4x50 mm^2 aluminium underground conductor of 400 V, indicated as conductor 1, is the standard. The maximum capacity of these conductors is about 160 A [98]. For each time step of the entire charging period, the average and maximum of the 1000 samples of the line current are plotted in Fig 3.17 together with the maximum current of the conductor. For the case without PHEVs, the standard underground conductor would be sufficient.

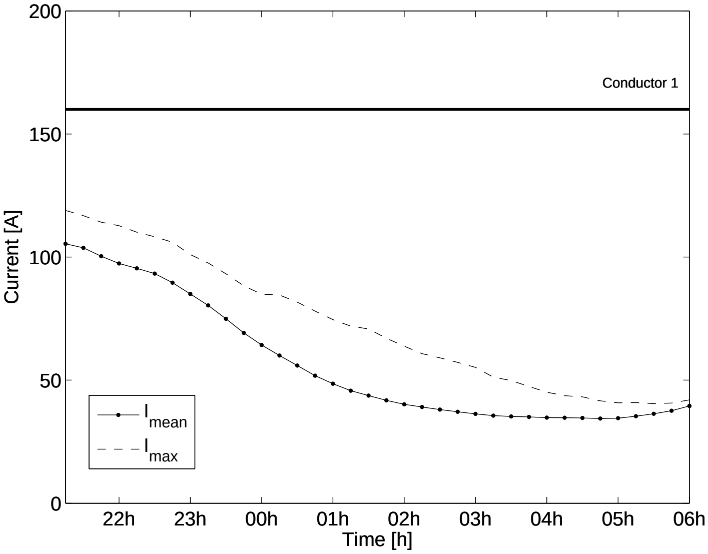

Fig. 3.17: Line current in the conductor without PHEVs.

If 30% PHEVs are introduced without a coordination system, the total load for the global grid increases to 156 kVA, which is out of range for the 100 kVA transformer. This transformer must be replaced by a standard transformer of 160 kVA or 250 kVA to deal with extra PHEVs, load growth and additional peak load. Due to the PHEVs, the line current increases to 242 A. The maximum capacity of the current conductor is not enough and must be replaced by a 4x120 mm^2 or 4x185 mm^2 aluminium underground conductor, indicated as conductor 2, with a capacity of respectively 250 A and 320 A as shown in Fig. 3.18, depending on the expected load growth.

If coordinated charging is applied, the conductor of the reference scenario could be used as shown in Fig. 3.19. The reserve capacity of this conductor is reduced

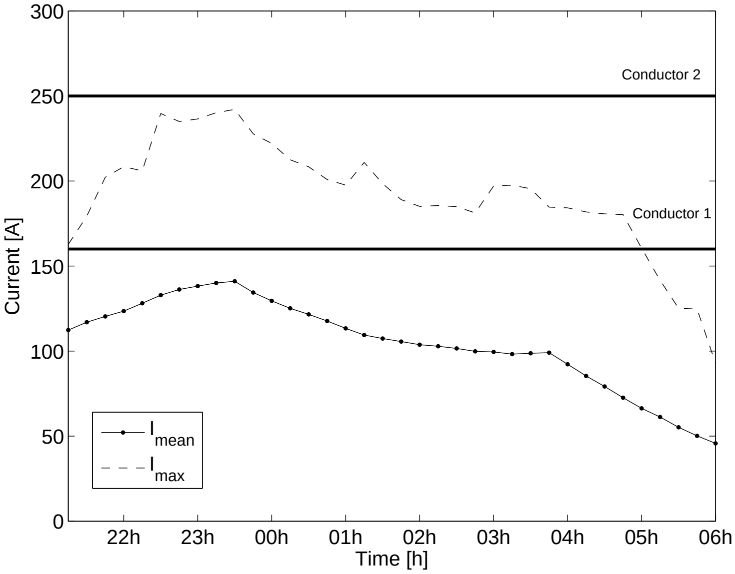

Fig. 3.18: Line current in the conductor with 30% PHEVS and uncoordinated charging.

because the line current is increased for the entire charging period. The line current is also more flat compared to the line current if uncoordinated charging is applied. The coordinated charging flattens the line current and avoids peaks.

Voltage deviations up to 10% in low-voltage grids are acceptable for 95% of the time according to the EN50160 standard which is mandatory in Belgium. In the case of uncoordinated charging, this limit has been reached for charging during the evening and action must be taken to reduce the voltage drop. This problem can be tackled by compensation techniques such as on a load tap changing transformer. Although the latter is not common at low voltages in Belgium, it may be necessary in future, especially for the vehicle-to-grid concept as described in chapter 4. This type of transformer can handle voltage variations of plus and minus 10% by adjusting among 32 tap settings built into the windings [71]. There is also another cost involved: the power losses. These losses increase significantly in the case of uncoordinated charging. The power losses and loads must also be generated and transported over the transmission and distribution lines which involve extra costs.

A smart metering system must be implemented in case of coordinated charging, to coordinate and communicate between the PHEVs individually, the distribution system operator and the transmission system operator (TSO). The vehicles could

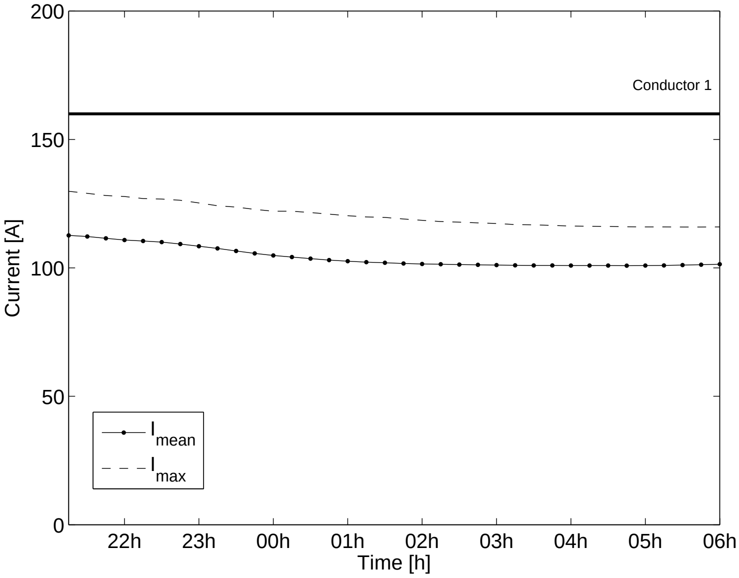

Fig. 3.19: Line current in the conductor with 30% PHEVS and coordinated charging.

also be grouped and represented by a fleet manager to communicate with the DSO and TSO. Smart metering will lead to opportunities to make PHEVs a controllable load, to apply the vehicle-to-grid concept and to combine PHEVs and renewable energy, as described in chapter 4 and 5. This technology is available for implementation, but investments by the utilities and maybe by the PHEV owners are necessary [99]. For the implementation of smart metering, also other incentives, such as real-time pricing and integration of renewable energy, are important.

If coordinated charging is applied, no reinforcements would be necessary in the near future. Of course, the reserve capacity is reduced and replacement will be more quickly enforced. The maximum load is lower for coordinated compared to uncoordinated charging, because the vehicles are not charging if the household loads are peaking. Therefore, the voltage drops, line currents and power losses are considerably reduced. The cost of upgrading the grid must be compared with the cost of the implementation of smart metering. The implementation of smart metering has more opportunities than only coordinated charging of PHEVs. Smart meters can help to achieve an efficient use of the electrical appliances at home. This also results in a more efficient use of the distribution grid.

3.6 Sensitivity analysis

Not all parameters of the model are known with adequate accuracy. Thus, the impact of charging PHEVs on the distribution grid is modelled in this work based on some assumptions. For the comparison of different scenarios, these parameters must be maintained. However, it is reasonable to assume that the change of some of the parameters of the model has an impact on the results. Therefore, the impact of these parameters is regarded in this section. To obtain a well-organized overview, only the results for winter are presented. The conclusions for summer remain the same as for winter. The results of summer are given in Appendix A. The power losses and voltage deviations are determined. The PHEV penetration level for all results is 30%. The same three charging periods, as in section 2.3.4, are considered. The reference scenario is the uncoordinated and coordinated charging as shown in Table 3.2, Table 3.3, Table 3.5 and Table 3.6 and the average of the power losses and the average of the maximum voltage deviation are calculated in the same way.

3.6.1 Placement of the PHEVs

For the calculations of the previous section, the vehicles are randomly placed, being the most obvious choice. The vehicles cannot be repositioned to another household in order to charge there for minimizing their impact on the distribution grid. However, it may be of interest to see the impact of an extreme placement of PHEVs, meaning that all vehicles are situated at the beginning or at the end of the grid. The power losses and voltage deviations of the placement at the begin and end of the grid are represented respectively in Table 3.10 and Table 3.11.

The power losses reduce if the vehicles are placed at the beginning of the grid and increase if the vehicles at the end of the grid. The line current at the grid node is for both scenarios more or less the same. If the vehicles are placed at the beginning of the grid, a large part of the current is injected in the begin nodes of the grid. The line current decreases rapidly in the beginning of the grid because of the large loads at these nodes. Therefore, only a smaller part of the line current flows to the end nodes of the grid. When the PHEVs are placed at the end of the grid, large line currents flow through a large part of the grid, increasing the power losses. The impact of the power losses during evening is larger compared to day and night charging with respect to the reference scenario for both uncoordinated and coordinated charging. The coordination of the charging still reduces power losses.

The voltage deviations of Table 3.11 are determined in the same way as in the reference scenario, i.e. as the average of the maximum voltage deviation of 1000

Scenario	**Charging period**	**30% PHEVs uncoordinated**	**30% PHEVs coordinated**
Beginning of the grid	**21h00-06h00**	1.6	1.4
	18h00-21h00	3.4	3.3
	10h00-16h00	2.2	2.1
End of the grid	**21h00-06h00**	3.2	2.8
	18h00-21h00	9.0	8.4
	10h00-16h00	4.9	4.2

Table 3.10: Placement of PHEVs: average of the ratio of power losses to total power [%].

samples. The voltage deviations reduce if the vehicles are placed at the beginning of the grid and increase if the vehicles are placed at the end. The impact on the voltage deviations is the largest during evening charging. However, these trends are less clear because the maximum voltage deviation is considered.

Normally, the voltage is the lowest at the end of the radial grid as shown in Fig. 3.20 for the scenario without PHEVs. The most left node is connected to the substation which is not displayed in the figure.

If the vehicles are placed at the beginning of the grid, the power consumption of the first nodes is large. Therefore, the voltage at the first nodes decreases compared to the scenario without PHEVs. The voltage of the nodes downstream the nodes with a PHEV, is lower. So the voltage decreases in the entire grid. This is shown in Fig. 3.21.

If the vehicles are placed at the end of the grid as shown in Fig. 3.22, the voltages of the end nodes with a PHEV substantially decrease. The nodes upstream of the end nodes with PHEVs also have a decreased nodal voltage compared to the scenario without PHEVs because large currents flow through a large part of the grid.

Scenario	**Charging period**	**30% PHEVs uncoordinated**	**30% PHEVs coordinated**
Beginning of the grid	**21h00-06h00**	4.5	4.2
	18h00-21h00	7.4	6.8
	10h00-16h00	5.5	4.5
End of the grid	**21h00-06h00**	6.5	4.9
	18h00-21h00	13.0*	11.2*
	10h00-16h00	9.6	6.4

Table 3.11: Placement of PHEVs: average of the maximum voltage deviations [%]. *: Excessive voltage deviations.

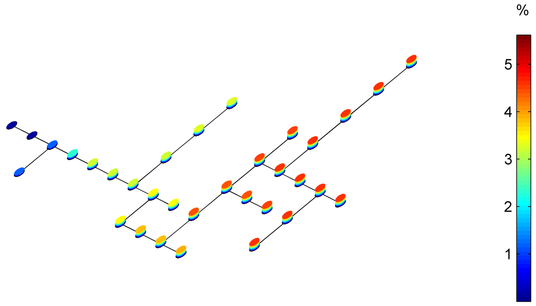

Fig. 3.20: Minimum of excessive voltage deviations of PHEVs for the scenario without PHEVs.

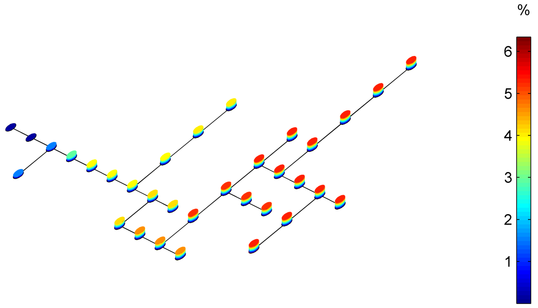

Fig. 3.21: Minimum of excessive voltage deviations of PHEVs at the beginning of the grid.

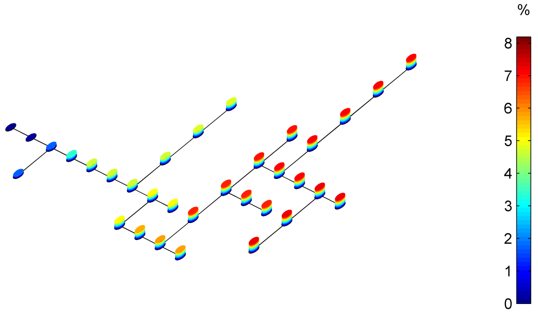

Fig. 3.22: Minimum of excessive voltage deviations of PHEVs at the end of the grid.

3.6.2 Length of the lines

The length of the lines between the nodes is varied and the impact on the power losses and voltage deviations are represented respectively in Table 3.12 and Table 3.13. If the length of the lines changes, the line impedances will also change. Two scenarios are investigated. In the first scenario, the length of the lines is halved, i.e. the ”Short” scenario. In the second scenario, the length of the lines is multiplied by 1.5, determined as the ”Long” scenario. However, in the reference scenario, the length of the lines is determined such that the power losses and the voltage deviations have acceptable values in the case that no PHEVs are present. The scenario without PHEVs is also recalculated with the adapted lengths, as this scenario also changes. If the lines are halved, the power losses decrease. The extension of the lines, increases the power losses as the product of the line currents squared and the resistance. An increase of the length of the lines, increases the impedance of the feeders and thus the power losses. The opposite is true if the length of the lines is shortened. These findings are valid for uncoordinated and coordinated charging. The coordination of the charging will reduce the power losses in the same extent compared with the reference scenario. The length of the lines are tripled for the ”Long” scenario compared to the ”Short” scenario. However, the power losses for the ”Long” scenario are larger than the triplicate of the power losses of the ”Short” scenario.

Scenario	**Charging period**	**0% PHEVs**	**30% PHEVs uncoordinated**	**30% PHEVs coordinated**
Short	**21h00-06h00**	0.7	1.2	1.0
	18h00-21h00	1.2	2.8	2.6
	10h00-16h00	0.8	1.7	1.5
Long	**21h00-06h00**	2.1	3.8	3.3
	18h00-21h00	3.8	10.4	9.7
	10h00-16h00	2.6	5.8	5.1

Table 3.12: Length of the lines of the grid: average of the ratio of power losses to total power [%].

If the line impedance is changed, the nodal voltages and thus maximum voltage deviations will also change. The voltage deviations increase in the ”Long” scenario and decrease in the "Short" scenario with respect to the reference scenario.

Scenario	**Charging period**	**0% PHEVs**	**30% PHEVs uncoordinated**	**30% PHEVs coordinated**
Short	**21h00-06h00**	2.0	2.7	2.1
	18h00-21h00	2.3	4.8	4.3
	10h00-16h00	1.8	3.6	2.7
Long	**21h00-06h00**	6.4	8.6	6.7
	18h00-21h00	7.4	17.0*	14.8*
	10h00-16h00	5.7	12.4*	8.6

Table 3.13: Length of lines of the grid: average of the maximum voltage deviations [%].
*: Excessive voltage deviations.

3.6.3 Battery capacity

In Table 3.14 and Table 3.15, the battery capacity is changed compared with the reference scenario. The battery capacity is, on the one hand reduced to 6 kWh and on the other hand increased to 16 kWh. The maximum power output of the charger is still 4 kW. The battery of 16 kWh cannot be fully charged during the evening because the charging period is too short and is therefore not considered in this scenario. The power losses of a charging period are the sum of the power losses of each time step. The power losses decrease if the battery capacity is decreased, because less energy must be transported. There are less time steps where vehicles charge or the vehicles can charge at a lower charger rate and still be fully charged at the end of the charging period. On the contrary, the power losses increase if the battery capacity is increased, because more energy must be transported and the vehicles have to be charged during a larger period or at full power to achieve a fully charged battery at the end of the charging period.

The voltage deviations are smaller if a smaller battery capacity is implemented in the vehicle because the charging period, required to fully charge a PHEV when uncoordinated charging is applied, is shorter. Therefore, there will be less vehicles charging simultaneously, increasing the nodal voltages. If coordinated charging is

Scenario	**Charging period**	**30% PHEVs uncoordinated**	**30% PHEVs coordinated**
6 kWh	**21h00-06h00**	2.0	1.7
	18h00-21h00	4.7	4.3
	10h00-16h00	2.8	2.5
16 kWh	**21h00-06h00**	3.2	2.8
	18h00-21h00	NA	NA
	10h00-16h00	4.8	4.2

Table 3.14: Battery capacity: average of the ratio of power losses to total power [%].

implemented, vehicles can charge at a lower power rating increasing the minimum voltage level of the grid. If the battery capacity is increased, more vehicles will be charged simultaneously at a power of 4 kW. The power is higher compared to the smaller battery if coordinated charging is applied in order to have a fully charged battery at the end of the charging period.

3.6.4 Power of the charger

The maximum power of the charger is also varied. If home charging is applied, the power could not be enlarged without adaptations of the electrical circuit in households, thus only smaller power values are considered. The power is halved, giving a charger of 2000 W. For the second scenario, the power rating is determined such that the battery can be fully charged during the evening. This gives a maximum power of 3333 W. The results are represented in Table 3.16 and Table 3.17 for respectively the power losses and voltage deviations.

For both chargers of 2000 W and 3333 W, the power losses are reduced for uncoordinated charging compared to the reference scenario with a maximum power of the charger of 4000 W. For uncoordinated charging, the vehicles always charge at maximum power. The lower power of the charger reduces the load at the nodes and therefore, the node and line currents. The power losses are a quadratic function of

Scenario	**Charging period**	**30% PHEVs uncoordinated**	**30% PHEVs coordinated**
6 kWh	**21h00-06h00**	5.0	4.2
	18h00-21h00	9.8	7.3
	10h00-16h00	6.2	4.7
16 kWh	**21h00-06h00**	6.4	5.2
	18h00-21h00	NA	NA
	10h00-16h00	9.0	6.8

Table 3.15: Battery capacity: average of the maximum voltage deviations [%].
*: Excessive voltage deviations.

the line current and thus the power losses will also decrease. On the other hand, the time a vehicle charges to be fully charged before the end of the charging period is reached, is enlarged. Therefore, more vehicles charge simultaneously increasing the power losses too. In general, the power losses are slightly decreased for both chargers of 2000 W and 3333 W compared to the reference scenario with a charger of 4000 W.

If coordinated charging is applied, the power losses are the same for both chargers with lower power as for the reference scenario. If the objective function is to minimize the power losses, the vehicles are charged with the lowest possible power. Probably, charging at a maximum power of 4000 W does almost not occur in the reference scenario. For the charger of 3333 W, the charging time equals the charging period for evening charging. All vehicles charge during the entire charging period. Therefore, there is no difference between uncoordinated and coordinated charging.

For uncoordinated charging the voltage deviations are smaller for the charger of 2000 W than 3333 W. The voltage deviations for the charger of 3333 W are smaller than for 4000 W. In both cases, the reduction of the power reduces the maximum voltage deviations. For coordinated charging, the voltage deviations are more or less the same as for the reference case with the charger of 4 kW because the vehicles charge at the lowest possible power rating to minimize the power losses.

Scenario	Charging period	30% PHEVs uncoordinated	30% PHEVs coordinated
2000 W	**21h00-06h00**	2.3	2.1
	18h00-21h00	NA	NA
	10h00-16h00	3.3	3.2
3333 W	**21h00-06h00**	2.4	2.1
	18h00-21h00	5.8	5.8
	10h00-16h00	3.5	3.2

Table 3.16: Power rating of the charger: average of the ratio of power losses to total power [%].

Scenario	Charging period	30% PHEVs uncoordinated	30% PHEVs coordinated
2000 W	**21h00-06h00**	4.9	4.4
	18h00-21h00	NA	NA
	10h00-16h00	6.2	5.5
3333 W	**21h00-06h00**	5.3	4.4
	18h00-21h00	9.3	9.3
	10h00-16h00	7.6	5.5

Table 3.17: Power rating of the charger: average of the maximum voltage deviations [%].
*: Excessive voltage deviations.

For both power losses and voltage deviations, the length of the lines has the largest impact on these grid parameters for all scenarios. The placement of the PHEVs has a also a large impact on these parameters. Both the battery capacity and the power rating of the charger has the smallest impact on the grid parameters.

3.7 Conclusions

The model of chapter 2 is applied to determine the impact on a residential distribution grid of charging a fleet of PHEVs in terms of voltage deviations, power losses, feeder and transformer overloads. Uncoordinated charging of these vehicles causes grid problems. The grid must be reinforced to cope with an increasing number of PHEVs. For a penetration level of 30% or more, voltage problems occur during the evening for the test grid used in this work. If evening charging is avoided, voltage problems occur for a penetration level of 50%. The choice of charging periods is rather arbitrary and the impact of the PHEV penetration level is large.

The methodology of coordinated charging is described. The optimization problem minimizes the power losses of the distribution grid by adapting the power of the chargers of the PHEVs. The power losses are a quadratic function and the constraints of the optimization problem are linear thus the quadratic programming technique can be used. The technique of linear and quadratic programming is found in literature for optimal use of distribution grids. However, this technique is not yet applied on the optimal charging of PHEVs in this grid. In general, coordinated charging of plug-in hybrid electric vehicles can lower power losses and voltage deviations by flattening peak power with respect to uncoordinated charging. A smart or intelligent meter must be implemented and thus the implementation of the coordinated charging comes at a cost. When coordinated charging is applied, the voltage problems during evening charging can be postponed to a penetration level of 40%. The voltage problems of overnight charging can be totally solved by coordination of charging.

In a first stage, historical data is used so there is a perfect knowledge of the load profiles. In a second stage, stochastic programming is introduced to represent an error in the forecasting of the household loads. This forecasting error increases the power losses causing an efficiency loss. This efficiency loss is rather small if the trend of the household load profiles is known and charging during the peak hours of the evening can be avoided.

These results are obtained with the quadratic programming technique, using the power losses as objective function. The dynamic programming technique is also implemented, but does not improve the computational time nor the achieved accuracy. The applied techniques and methods can be extended to other objective functions, such as voltage control by PHEVs, reactive power output control and grid balancing.

Charging PHEVs does not only have an impact on the grid parameters, but also on the feeders and the transformers. Therefore, a small distribution grid of 100 nodes is assumed. PHEVs can be considered as controllable loads. If a considerable amount of PHEVs is charged from the distribution grid, this obviously increases the average load of the grid. However, the management of charging PHEVs can postpone grid reinforcements, such as the replacement of transformers or feeders, but requires the implementation of smart meters. Of course, even when charging PHEVs is coordinated and no replacements of neither feeders nor transformers is required, the reserve capacity of these components is significantly reduced.

A sensitivity analysis is performed to evaluate the impact on the results of some parameters. The length of the lines and the placement of the PHEVs have the largest impact on the results for both winter and summer. The power of the charger and the battery capacity have a smaller impact.

4

Vehicle-to-grid

Plug-in hybrid and battery electric vehicles have an advantage compared to regular hybrid electric vehicles, i.e. the possibility to connect to the electric power grid, offering more opportunities. These vehicles cannot only charge by plugging into a standard electric outlet, but can also discharge and thus inject energy into the grid. In that way, PHEVs can support the grid. This is indicated as vehicle-to-grid (V2G) operation.

The idea of this chapter is to support the grid by using a bidirectional power flow which is realized by the charger of PHEVs. The possible ancillary services are described in section 4.2. The optimization problem is defined in section 4.3. The impact of a voltage control, implemented as a constraint in the optimization problem to increase the power quality of the grid by using coordinated charging and discharging, is explained in section 4.4. A smart meter or an embedded voltage controller in the charger are essential [100] for this use. Three objective functions are compared in section 4.5. The coordination of charging and discharging and the implementation of a voltage control may postpone reinforcements of the grid. Applications of the V2G operation are investigated in chapter 5.

4.1 Introduction

In practice, there is little storage available in the power grid so demand and generation must be matched and continuously managed to avoid frequency deviation and voltage instabilities. In the ideal case, the electricity consumption should perfectly match with renewable energy units and the generation from conventional power plants. Because of forecasting errors and the intermittent behavior of renewable resources, such as solar and wind power, imbalances occur and generation and demand do not perfectly match all the time.

The connection of the PHEVs to the electric power grid offers the possibilities for PHEVs to charge but also discharge and thus reinject energy in the grid. PHEV storage units can handle large and frequent power fluctuations because they are designed that way for driving needs [61]. Moreover, the wear of the batteries caused by frequently charging and discharging may not be neglected. The combustion engine can also deliver electricity during peak hours, though this is not realistic for several reasons. The emissions, emitted locally, rise in this case because of the local generation and the efficiency is lower compared to large power plants. There is also a cooling problem for vehicles which remain stationary while delivering significant amounts of power. Emptying their fuel tank will also reduce their driving range and increase the noise level. Therefore, this is not considered further on.

Vehicles can help to match consumption and generation by charging and discharging 'at the right moment'. However, vehicle owners need energy for driving at more or less predictable times and the grid operator needs power to match demand and consumption [101], so the management, i.e. dispatching of PHEVs, is inevitable. Communication is needed between the vehicles, the utility provider and the grid, by sending signals to request energy exchanges from the PHEVs [101]. One can say that there are three requirements for vehicle-to-grid operation:

- a power connection to the grid,
- a control connection for communication with the grid operator
- an on-board precision metering for knowing the battery capacity [102].

The vehicles can be addressed in three ways. First, the signal to control the chargers can be sent to each vehicle separately or, second, to a central controller supervising the PHEVs in a single facility, e.g. a parking lot. The third possibility is a third-party aggregator which is responsible for separately located vehicles.

It is unlikely that each vehicle will be contracted separately because the maximum power output of each vehicle is rather small. Although, a fleet manager or aggregator could conclude a contract for a fleet of PHEVs. The advantage of dealing with an aggregator or fleet manager is that a single party represents a more significant amount of power, i.e. the cumulative power of the vehicles in a fleet. Moreover, the availability profile of a larger group of vehicles is much smoother. A single vehicle owner could conclude a contract with the aggregator without being concerned about the interface with the electricity markets.

4.2 Ancillary services

PHEVs have an energy storage capacity which is rather small for each individual vehicle, but when the number of vehicles becomes large, a significant storage capacity is present. At any given time, at least 90% of the vehicles are theoretically available for V2G [21], [101]. These vehicles must be connected to the grid when idle. There must be enough vehicles plugged in during the day to provide grid services. Therefore, it could be beneficial to give incentives to vehicle owners to remain plugged in. Most of the weekdays, vehicles follow a schedule which does not vary much [102]. The electrical storage of PHEVs could provide grid services via V2G concept and add a surplus value to the vehicle owner [103] because PHEVs are at the moment still more expensive compared to conventional vehicles. In [101], it is concluded that selling energy could be beneficial for these vehicles. The most promising market for these vehicles is probably that of the ancillary grid services [21].

Possible services for V2G are: supply of peak power, supply of primary, secondary and tertiary control (for frequency regulation and balancing), load leveling or management and voltage regulation. PHEVs are able to respond quickly and thus serving for high value electrical services over a large geographical area.

4.2.1 Frequency regulation

One aspect of grid management is to provide power reserves to maintain frequency and to facilitate the efficient handling of imbalances or congestion. So it is essential to keep the frequency at appropriate levels, i.e. between 49.99 and 50.01 Hz according to the ENTSO-E, the former UCTE [104]. Frequency regulation has several levels of control: primary, secondary and tertiary control.

- The primary reserves regulate the frequency and stabilize the European grid to avoid blackouts. The frequency control is activated automatically and continually. Primary control can only be activated if primary reserves are available. The primary reserves are about 100 MW for Belgium. The response time is smaller than one second.

- Secondary reserves are allocated a day ahead to balance the grid and are continually adjusted by the TSO, both upward and downward on a 15 minute time base. If the frequency is lower than 50 Hz, the batteries could be discharged (regulation up) and if the frequency is above 50 Hz, the batteries could be charged (regulation down). On average, the regulation up and down are equal. The impact on the battery is a small discharge due to charge and discharge efficiency. The reaction time is a few seconds. These reserves are used for imbalances between nominated and measured power injections and to restore the frequency.
- There are two types of tertiary reserves: Tertiary production and tertiary offtake reserves. Tertiary production reserves contain the injection of additional power into the grid. Tertiary offtake reserves imply the reduction of the amount of power taken by the grid by the user. These reserves are used for major imbalances and congestions. In contrast to primary and secondary reserves, they are activated manually and only a few times per year. They must deliver their power within 15 minutes [105].

It is not clear which types of services for frequency regulation are economically profitable for PHEVs. According to [61], secondary and tertiary control are assumed to be competitive and primary control is supposed to be highly competitive for PHEVs. For these ancillary services, there is both an energy payment and a capacity payment. The capacity payment is for the maximum capacity contracted for the time duration. The capacity payment is lower for the secondary and tertiary control compared to the primary control. In Belgium, there is a capacity and energy payment for the secondary and tertiary control but there is only a capacity payment for the primary control. In [106], primary control is expected to have the highest value for V2G. The power that must be delivered by tertiary reserves would be too large and the duration too long for the vehicles [75]. As a result, only primary and secondary control could be of interest from a technological point of view.

4.2.2 Voltage regulation

In a low-voltage grid, cables are common and the resistance R is relatively large compared to reactance X. Adjusting the flow of active power in this grid influences the voltage. The voltage regulation maintains the voltage between the limits defined by the mandatory EN50160 standard [83]. This voltage control can be embedded in the charger. Charging of vehicles stops when the voltage at the grid connection becomes too low. In a further step, discharging of a unit of active power can also be taken into account to raise the grid voltage. The low voltage level could be caused by a large demand on a local scale. In the ideal case, the voltage regulation should be a combination of active and reactive power [107]. However, the control of reactive power is not considered in this work.

4.2.3 Load leveling and peak power

PHEVs could discharge during the daily peak loads, replacing the peak capacity generators which are only used during peak demand hours. If these vehicles want to discharge during the peak hours, they have to charge during off-peak hours. For load leveling, the demand is shifted from peak to off-peak hours. Therefore, dispatching is necessary. In the case that a part of the energy which is stored during off-peak hours, is released during peak hours to relieve congestion in the grid infrastructure, supplying peak power and load leveling are similar. Supplying peak power is possibly difficult for PHEVs because of the relatively long duration and the storage limitations. Thus, supplying peak power is generally not profitable as the largest cost is the wear of the batteries [75]. However, according to [108], peak power control could be the most economic solution in Japan. Load leveling is more likely because the vehicle does not necessary need to discharge during peak hours. The total electricity consumption will not be lowered but shifted to hours of low electricity consumption which are the off-peak hours to minimize the power losses and to increase grid efficiency. The implementation of smart meters or real-time pricing and coordinated charging (and discharging) is essential.

4.2.4 Opportunities for PHEVs

PHEVs have the potential to support a residential distribution grid but are technically and economically unsuitable for some kinds of ancillary services. These vehicles have a high cost per kWh of electrical energy and a low durability compared to large generators, making them unsuitable for base load power. They may be suitable for voltage regulation, primary and secondary reserves. There are several costs involved with the reserves and regulation. The profit is the capacity and energy payment. The costs are purchased energy, wear and capital cost [61]. The vehicles must also be connected to the grid to provide grid services. The vehicles are 96% of the time not driving, but a connection to plug in the grid may not always be available at that moment. Actually, the management of the charging of a fleet of PHEVs can be considered as a kind of ancillary service because it increases the grid stability and reliability.

Voltage regulation is the most obvious choice for local control of the grid since this can be easily implemented in chargers. In that way, voltage regulation can be controlled independently by each vehicle and a voltage controller can be embedded in the chargers of the PHEVs. Only voltage control is considered in this work. In combination with for instance photovoltaic panels, this control can become essential in future because the voltage at households will more and more deviate from the rated voltage level. The energy management system will bring an additional cost, in terms of battery wear, which could be outweighed by the revenues obtained by V2G. These revenues could reduce the payback times of PHEVs [103]. For an optimal implementation of V2G, the battery technology must be improved, especially the efficiency and lifetime. Battery wear is not considered here.

4.3 Optimization problem

The optimization problem of the previous chapter is extended. The plug-in hybrid electric vehicles are able to discharge to support the electricity grid. Both uncoordinated and coordinated charging and discharging are examined. The linear and quadratic programming technique are used to determine the grid parameters and the impact on the distribution grid. The same grid parameters as in chapter 3, i.e. the power losses and the voltage deviations, are evaluated. This methodology is used to indicate the significance of the coordination of charging and discharging. At first instance, the optimization problem minimizes the charging cost of a fleet of PHEVs. Other objective functions, i.e. minimization of power losses and voltage deviations, are evaluated in section 4.5. Voltage control is added as a first step in the direction of ancillary services provided by PHEVs. Only the deterministic model is investigated in this chapter, because the impact of the stochastic model is rather small. If a daily load profile of another day is used, the efficiency loss can amount to 3% or 4%.

4.3.1 Model and assumptions

The PHEVs still have a battery capacity of 11 kWh. Only 80% of the battery is used. This gives an available capacity of 8.8 kWh. An 88% energy conversion is assumed for both charging and discharging. The energy flow is now bidirectional, meaning that the batteries can charge and discharge. The maximum power output of the charger is 4000 W. The minimum power rating of the charger is assumed to be -3520 W, which 88% of 4000 W.

The IEEE 34 node test feeder, shown in Fig 2.9, is again used as an example for a radial distribution grid.

4.3.2 Uncoordinated charging

For uncoordinated charging, the methodology remains the same. When charging of PHEVs is not managed, the vehicles immediately start to charge at full power when they are plugged in and charge until they are fully charged or disconnected. The vehicle owners or their controllers do not have the incentives nor the essential information to schedule the charging of the batteries to optimize the grid stability. For that reason, these vehicles will not discharge. For the load flow analysis, the backward-forward sweep method of section 3.1 is used.

4.3.3 Coordinated charging and discharging

The general principles of coordinated charging, as described in Chapter 3, are retained. Therefore, the PHEV owners will not be able to change their charging profile at any time, meaning that the only realistic degrees of freedom left for the owners is to postulate a point in time when the vehicles must be fully charged or possibly a charging tariff. This charging tariff could define an upper limit of the electricity price which indicates when the charging must be stopped. Vehicles could be charged during peak hours if the vehicles owners are willing to pay a higher electricity price. The power output of the charger varies and can also be bidirectional, meaning that the vehicle can charge (consume energy) and discharge (inject energy into the grid). The penetration level varies between 0% and 75%.

However, the objective function is initially no longer a power losses function but is now a cost function which reflects the price of electricity. This function must be minimized as shown in (4.1). The cost function has only two constants: one represents the tariff during the day, C_{day}, and one is the tariff overnight, C_{night}. The ratio of the day to the night constant is estimated to be about 1.6 [109]. A night tariff is assumed to start between 21h00 and 23h00 and ends between 06h00 and 08h00. In this work, it is assumed that the night tariff starts at 22h00 and ends at 07h00. The constraints are shown in (4.2). The objective function and the constraints are linear, so the linear programming technique can be used. In this work, no difference is made between the electricity price for the charging cost and the injection revenues. Of course, this is not realistic but to take into account a different electricity price, a profound economic analysis must be performed.

$$\min \sum_{n=1}^{nodes} \left(\sum_{t=1}^{t_{night}} C_{day} \cdot P_{PHEV,n,t} + \sum_{t_{night}+1}^{t_{max}} C_{night} \cdot P_{PHEV,n,t} \right) \tag{4.1}$$

$$s.t. \begin{cases} \forall t, \forall n \; \epsilon \; \{nodes\} : P_{PHEV,\min} \leq P_{PHEV,n,t} \leq P_{PHEV,\max} \\ \forall n \; \epsilon \; \{nodes\} : \sum_{t=1}^{t_{max}} P_{PHEV,n,t} \cdot \triangle t \cdot x_n = C_{max} \\ \forall t, \forall n \; \epsilon \; \{nodes\} : 0 \leq C_{n,t} \leq C_{\max} \\ \forall t, \forall n \; \epsilon \; \{nodes\} : U_{min,n,t} \leq U_{n,t} \leq U_{max,n,t} \\ x_n \epsilon \; \{0, 1\} \end{cases} \tag{4.2}$$

The general form of the objective function is given in (4.3), in which (4.1) must be rewritten.

$$\min \left(\mathbf{F}_{\mathrm{LP}}^{T} \mathbf{x} \right) \tag{4.3}$$

The first constraint is changed with respect to the constraints shown in (3.12) of the coordinated charging discussed in chapter 3. The vehicles are now able to charge and discharge so the charger output varies between the minimum and maximum power rating. The general form of the first constraint is given in (4.4). $\mathbf{l}_{\mathrm{b}}$ is displayed in (4.5). However, $\mathbf{u}_{\mathrm{b}}$ remains the same, as shown in (4.6). $\mathrm{P}_{PHEV,min,n,t}$ and $\mathrm{P}_{PHEV,max,n,t}$ are respectively the minimum and the maximum power rating of the charger for node n and time step t. Nevertheless, the minimum and maximum values are constant. $\mathrm{P}_{PHEV,min,n,t}$ is negative, meaning that energy is injected into the grid.

$$\mathbf{l}_{\mathrm{b}} \leq \mathbf{P}_{\mathrm{PHEV}} \leq \mathbf{u}_{\mathrm{b}} \tag{4.4}$$

$$\mathbf{l}_{\mathrm{b}} = \begin{bmatrix} P_{PHEV,min,1,1} \\ P_{PHEV,min,2,1} \\ \vdots \\ P_{PHEV,min,z,1} \\ \vdots \\ P_{PHEV,min,1,T} \\ P_{PHEV,min,2,T} \\ \vdots \\ P_{PHEV,min,z,T} \end{bmatrix} \tag{4.5}$$

$$\mathbf{u}_{\mathrm{b}} = \begin{bmatrix} P_{PHEV,max,1,1} \\ P_{PHEV,max,2,1} \\ \vdots \\ P_{PHEV,max,z,1} \\ \vdots \\ P_{PHEV,max,1,T} \\ P_{PHEV,max,2,T} \\ \vdots \\ P_{PHEV,max,z,T} \end{bmatrix} \tag{4.6}$$

The constraints concerning the battery capacity remain the same. x_n still indicates whether a PHEV is connected or not and is not a variable. A voltage constraint is added. This is the last constraint of (4.2). The general form of the constraint is given in (4.7). The voltage must satisfy the EN50160 standard so the nodal voltages $U_{\mathrm{n,t}}$ at each time step must be higher than 90% and lower then 110% of 230 V, respectively $\mathbf{U}_{\text{lower limit}}$ and $\mathbf{U}_{\text{upper limit}}$, as shown respectively in (4.8) and (4.9). The vector $\mathbf{U}_{\text{node}}$ represents the nodal voltage for each time step. The amount of time that the voltage limit may be exceeded is not taken into account in this constraint. A flat voltage profile is assumed for the first iteration step for the voltage at node n, $\mathbf{U}_{\text{node,t}}$. For the next iteration steps, these voltages are calculated with the backward-forward sweep method. As a result, the voltage at each node is known. The same algorithm as in Fig. 3.3 is valid.

$$\mathbf{U}_{\text{lower limit}} \leq \mathbf{U}_{\text{node}} \leq \mathbf{U}_{\text{upper limit}} \tag{4.7}$$

$$\mathbf{U}_{\text{lower limit}} = \begin{bmatrix} U_{min,1,1} \\ U_{min,2,1} \\ \vdots \\ U_{min,z,1} \\ \vdots \\ U_{min,1,T} \\ U_{min,2,T} \\ \vdots \\ U_{min,z,T} \end{bmatrix} \tag{4.8}$$

$$\mathbf{U}_{\text{upper limit}} = \begin{bmatrix} U_{max,1,1} \\ U_{max,2,1} \\ \vdots \\ U_{max,z,1} \\ \vdots \\ U_{max,1,T} \\ U_{max,2,T} \\ \vdots \\ U_{max,z,T} \end{bmatrix} \tag{4.9}$$

4.4 Voltage control of PHEVs overnight

This section emphasizes the importance of the implementation of a voltage controller to support the grid. This support is a first step in the direction of supporting the grid by PHEVs. This voltage support, by injection of active power, can be embedded in the charger. It could even be made compulsory, as for photovoltaic panels, because grid reliability must be assured. The voltage constraints and the discharging are added separately to distinguish their impacts.

4.4.1 Charging period

The charging period is slightly changed compared to section 2.3.4. The computations are performed for charging during evening and night (between 19h00 and 06h00). For the sake of convenience, the vehicles must be fully charged at the end of the charging period. From an available set of residential load measurements, a weekday with large peak loads is selected. If this household load profile is connected to each node, no voltage deviations occur if no PHEVs are present in the IEEE test grid. Only one charging period is evaluated in this section. Nevertheless, the proposed methods are still valid for other periods and scenarios. It is not the aim of this section to give a global overview of the impact of charging and discharging on the distribution grid. It wants to indicate that for a heavily loaded day, a voltage control can help to improve grid quality and stability. The results of this section are also valid for other heavily loaded days with no voltage problems. When voltage problems already occur when no PHEVs charge, it is uncertain that PHEVs can solve the problem. The test grid is too small to evaluate this problem because a certain amount of PHEVs must be connected and must have energy left in their batteries to handle voltage problems. For a more global overview, a larger grid is required.

4.4.2 Results

The objective function of this optimization problem is the charging cost function which is minimized. In the first scenario, the vehicles are unable to discharge and no voltage constraint is implemented. The objective function is simplified and a single tariff is used, making no distinction between night and day. This is the worst case scenario and serves as a reference for the other scenarios. The vehicles have no incentive to discharge or avoid charging during evening peak. The minimum voltage of the grid and the cumulative power of the chargers for the entire grid are both plotted for each time step. The voltage profile is shown in Fig. 4.1 for three different penetration levels. Because no voltage constraint is implemented, the voltage goes frequently well below the voltage limit for a penetration level of 50% and more. Even during the evening peak for a penetration level of 10%, the nodal voltage can be too low. It must be stressed that this figure shows only the minimum voltage level for each time step and for one sample.

The cumulative charging profiles for the PHEVs are displayed in Fig. 4.2 for three penetration levels. A cumulative charging profile is defined as the sum of the charging profiles of the entire grid for each time step. This cumulative charging profile gives the power, augmented with appropriate losses, which must be provided at the substation to the distribution grid to charge the vehicles. For a penetration level of 10%, the PHEVs only charge during peak hours. For higher penetration levels, PHEVs charge during peak hours and night. The vehicles do not have any incentive to avoid charging during the evening peak and charge rather randomly. Obviously, the cumulative charge power increases when the number of PHEVs increases.

To avoid voltage problems, a voltage constraint is implemented. As shown in Fig. 4.3, the voltage stays well above the limit. So the implementation of a voltage

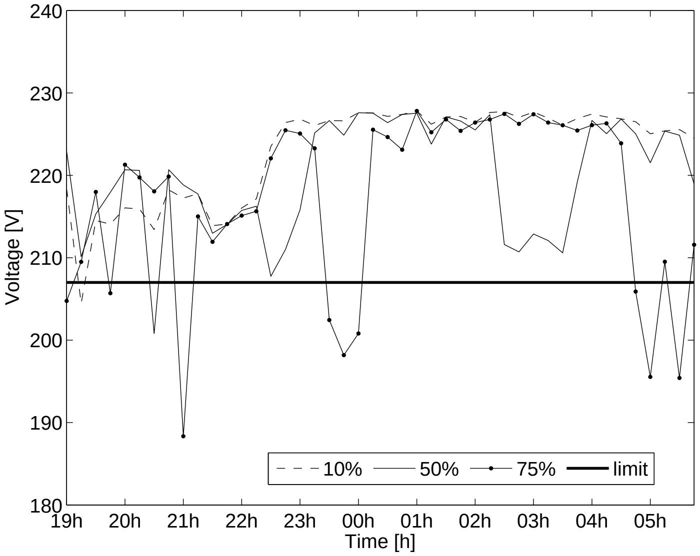

Fig. 4.1: Voltage profile for different penetration levels with a single tariff cost function and no voltage constraint.

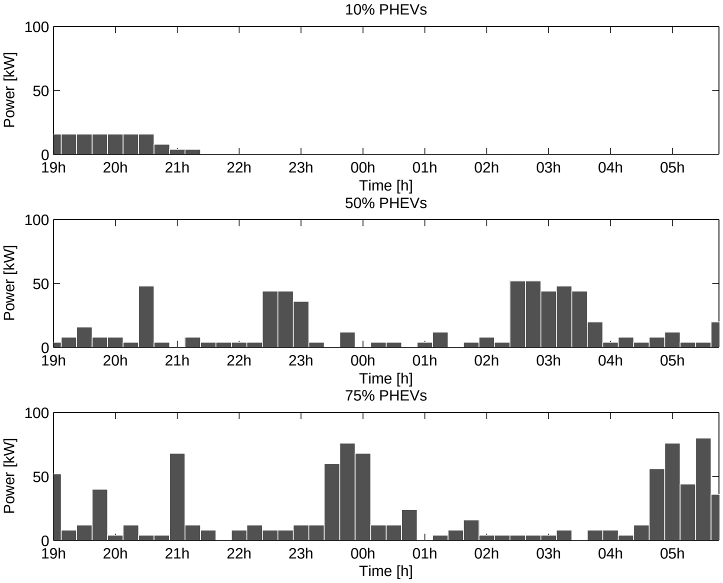

Fig. 4.2: Cumulative charging profile for different penetration levels and no voltage constraint and single tariff cost function.

constraint makes it possible to avoid voltage problems for this specific case. The voltage level is lower at the end of the charging period due to the constraint that the vehicles must be fully charged at the end of the charging period.

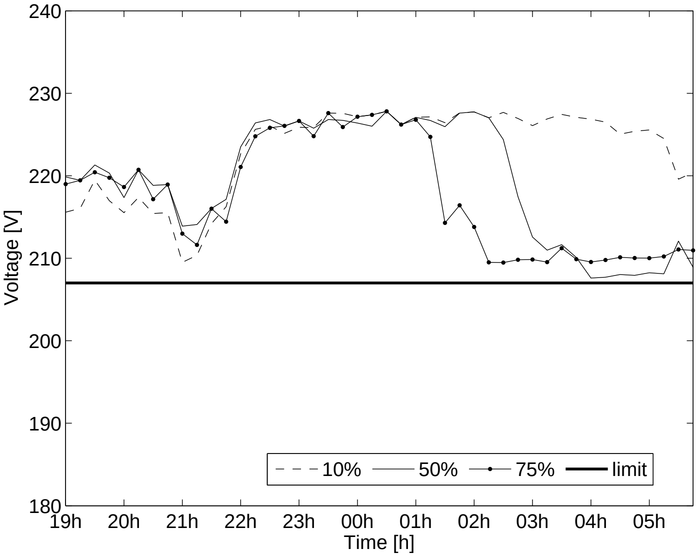

Fig. 4.3: Voltage profile for different penetration levels with voltage constraint and single tariff cost function.

The cumulative charging profile is shown in Fig. 4.4. The vehicles are not allowed to charge when the voltage is already low due to the household loads, especially when the penetration level is rather large. The cost function (single tariff) remains the same so the vehicles charge randomly between 19h00 and 06h00, satisfying an extra constraint, i.e. the voltage constraint.

For the next scenario, the discharging of the vehicles is implemented and the objective function has two tariffs. However, in this case the vehicles never discharge as can be seen in Fig. 4.5. The charging period starts at 19h00 and thus there is only a couple of hours left to discharge at peak tariff. This is not happening because the batteries of the PHEVs are assumed to be empty at the start of the charging period and charging and discharging at the same electricity price is not economic due to the charge and discharge efficiencies. Since there is no other objective function and there are only two electricity prices, the vehicles are further randomly charged at night tariff at 22h00. There is no incentive to reduce the power losses. No voltage problems occur considering the voltage constraint is still implemented.

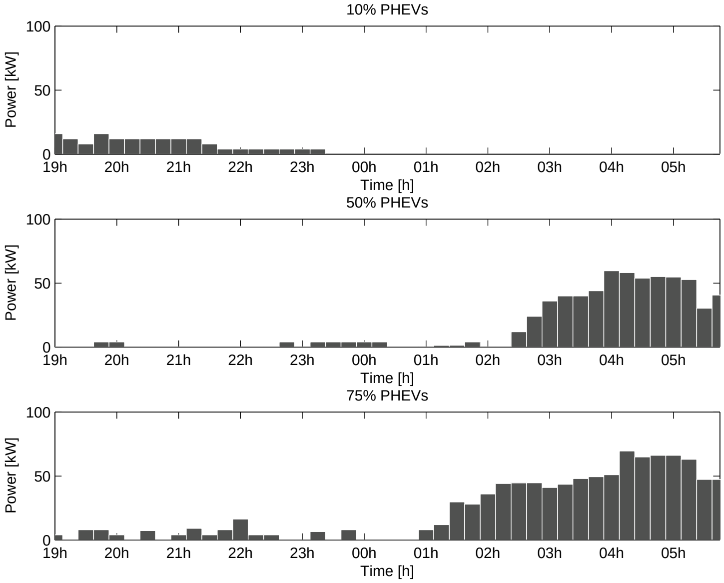

Fig. 4.4: Cumulative charging profile for different penetration levels with voltage constraint and single tariff cost function.

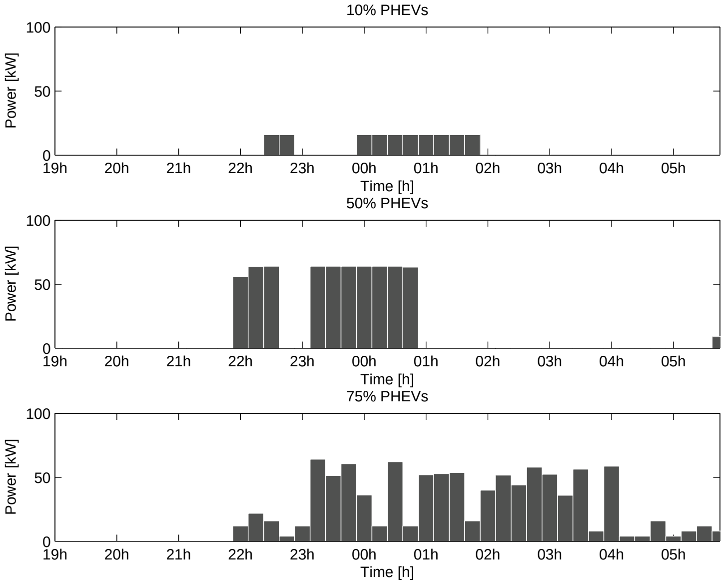

Fig. 4.5: Cumulative charging profile for different penetration levels for double tariff cost function and with a voltage constraint.

In the last scenario, there is still energy left in the batteries at the start of the charging period. This energy is determined stochastically based on a Gaussian distribution with an average of zero and a standard deviation, σ, of 1000 W. Only the positive values of this curve are used. This scenario still uses a double tariff function and a voltage constraint. Fig. 4.6 shows the cumulative charging profiles for different penetration levels. The night tariff starts at 22h00. Therefore the vehicles discharge between 19h00 and 22h00 depending on the energy left in the battery. The batteries must still be fully charged at the end of the period.

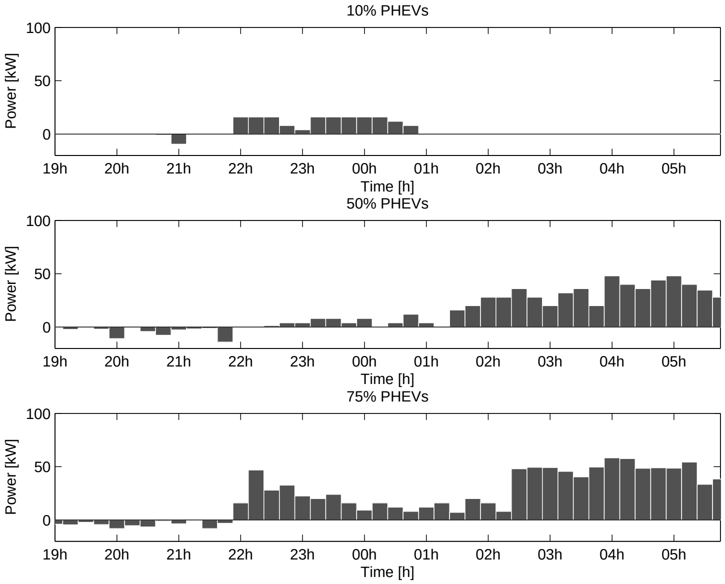

Fig. 4.6: Cumulative charging profile for remaining battery content different from zero for double tariff cost function and with a voltage constraint.

The impact of the energy left in the battery at the beginning of the charging period is shown in Fig. 4.7. The more energy left in the battery, the more the PHEVs discharge between 19h00 and 22h00, when the peak tariff is valid. The amount of discharging is directly related to the energy left in the battery. This is shown for a penetration level of 50%.

4.5 Evaluation of the objective functions

The impact of an objective function on the results in terms of grid parameters and optimal charging profiles is regarded in this section for an entire day. An entire day simulation is discussed in section 5.1. Four scenarios can be distinguished

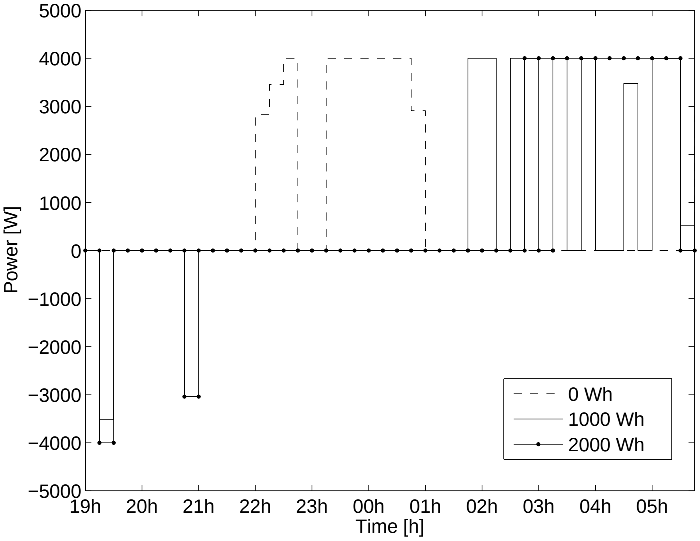

Fig. 4.7: Cumulative charging profile for different remaining battery contents at 19h for double tariff cost function and with a voltage constraint.

depending on the objective functions. The investigated objective functions are the power losses and the cost function which are already described in this chapter and chapter 3. The minimization of the voltage deviations is also added to this list. The voltage deviations and the power losses are not independent. The minimization of the power losses also reduce the voltage deviations and vice versa. The scenario with no objective function and no constraints is assigned as uncoordinated charging. Both charging and discharging are possible in these four scenarios. The power losses, voltage deviations, charging costs and optimal charging profiles are compared for each of the different scenarios. For each objective function, 700 runs are performed to achieve adequate and accurate results. The impact of discharging is also examined by disabling discharging for the scenarios.

4.5.1 Voltage deviations

From the distribution system operator point of view, the efficiency must be maximized. Large voltage deviations may cause grid instability. The proposed objective function minimizes the voltage deviations in the grid. A voltage deviation, $\Delta U_{n,t}$, is defined as the difference between the voltage at the substation, U_{grid}, and the voltage at a node n at time t, $U_{n,t}$. The minimization of the sum of the voltage deviations at all time steps and nodes gives a distorted view. Therefore, another method is applied. For each time step and node, the voltage deviation $\Delta U_{n,t}$ must be lower than a constant, $\mathrm{U_{VD}}$, as shown in (4.10). The minimization of the voltage deviations in (4.10) is added to the constraints of (4.2). The optimization program minimizes the constant $\mathrm{U_{VD}}$ as shown in (4.11), being obviously a linear objective function. The optimal charging profile is determined by the linear programming technique which minimizes $\mathrm{U_{VD}}$. The voltage deviations for all time steps and nodes are as small as possible which increases the grid quality and stability.

$$\begin{aligned} &\forall t, \forall n \,\epsilon\, \{nodes\} : \Delta U_{n,t} \leq U_{\mathrm{VD}} \\ &\qquad \Delta U_{n,t} = U_{\mathrm{grid}} - U_{n,t} \end{aligned} \tag{4.10}$$

$$\min\left(\mathrm{U_{VD}}\right) \tag{4.11}$$

The average of the maximum voltage deviation of each sample is determined and shown in Table 4.1 for the four scenarios. The scenario in which the voltage deviations are minimized gives the lowest voltage deviations. If the number of vehicles is increased, more vehicles discharge to raise the voltage level. Therefore, the maximum voltage deviation decreases when the number of vehicles increases. The scenario of minimizing the power losses gives results close to the results of the minimization of the voltage deviations. Discharging PHEVs when the household load is large, decreases the power losses. Therefore, the voltage levels also increase. The voltage deviations are within the voltage limit for both scenarios. The average voltage deviations of the double tariff scenario are only just within the voltage limits. The reason is that a voltage constraint is implemented which must be satisfied. The uncoordinated charging scenario does not have a voltage limit, so the voltage deviations exceed the voltage limit.

The sum of the cumulative charging profile and the household load for a penetration level of 10, 20 and 30% is displayed in Fig. 4.8. This sum is an indicator for the voltage deviations because large consumptions may cause large voltage deviations. The largest peak of the consumption occurs during the evening peak. For a penetration level of 10%, this peak is slightly smaller compared to the peaks for a higher penetration level. Therefore, the maximum voltage deviation is also slightly smaller for a penetration level of 10%. The differences between the largest peak of the consumption for the three penetration levels do not differ significantly.

Discharging vehicles has some disadvantages, such as it shortens the lifetime of the batteries considerably. The coordination system is also more complex if

	Uncoordinated	**Coordinated**		
PHEVs [%]		**double tariff**	**voltage deviations**	**power losses**
0	9.9	9.9	9.9	9.9
10	10.4*	9.5	8.5	8.4
20	11.4*	9.7	6.9	7.1
30	12.3*	9.6	6.5	6.9

Table 4.1: Average of the maximum voltage deviations with discharging [%]. *: Excessive voltage deviations.

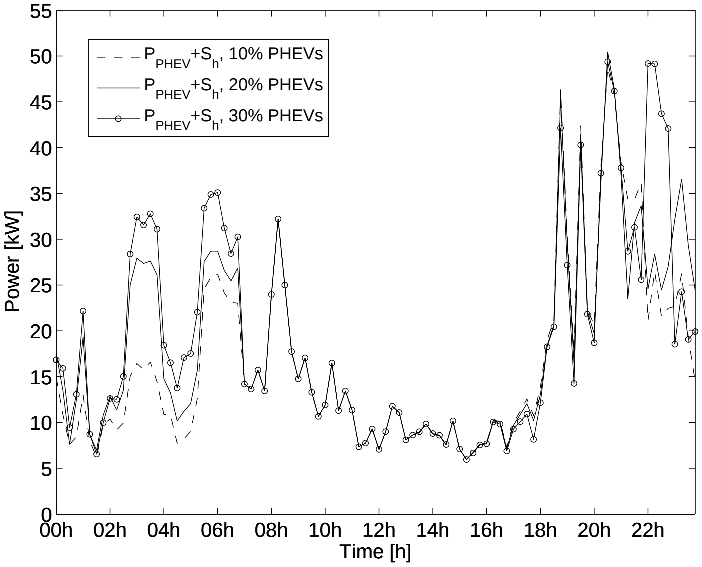

Fig. 4.8: Sum of cumulative charging profile and household load for coordinated charging and discharging for minimization of the voltage deviations for several penetration levels of PHEVs.

discharging would be made available and the management of the vehicles becomes complicated. Therefore, the situation wherein the vehicles are not able to discharge is also regarded. The same calculations are performed with discharging made unavailable. In the previous scenario, the voltage level raises during the peak hours, because the vehicles discharge at that moment. However, if the vehicles are no longer able to inject energy in the electricity grid, the voltage level cannot increase. Because of the voltage constraint, the voltage level may not exceed the voltage limit, so the vehicles are not charging during the peak hours. The average of the maximum voltage deviation is thus for each scenario and each penetration level the same, because this is the voltage level during the peak hours, as confirmed in Table 4.2. For uncoordinated charging, the voltage level is lower because no constraints are implemented and there are no incentives to avoid charging during peak hours.

	Uncoordinated	**Coordinated**		
PHEVs [%]		**double tariff**	**voltage deviations**	**power losses**
0	9.9	9.9	9.9	9.9
10	10.4*	9.9	9.9	9.9
20	11.4*	9.9	9.9	9.9
30	12.3*	9.9	9.9	9.9

Table 4.2: Average of the maximum voltage deviations [%] without discharging.
*: Excessive voltage deviations.

The cumulative charging profile for the entire grid is determined for each time step and averaged over 700 samples. These charging profiles are plotted in Fig. 4.9 for both uncoordinated and coordinated charging and discharging with a penetration level of 30% for the minimization of the voltage deviations. For the completeness, the cumulative household load profile and the sum of the coordinated charging profile and the household load are also displayed. Without the coordination of charging, the vehicles charge during peak hours, when the household load is already large. If coordinated charging and discharging is applied, the vehicles discharge when the household load is large, because the objective function is to minimize the voltage deviations. Moreover, the large voltage deviations during these peak hours caused by the household loads are reduced by discharging the vehicles. The negative values of the cumulative charging profile, meaning that the vehicles discharge, are compensating for the large household loads. The vehicles mostly charge overnight, in contrast with uncoordinated charging, where the vehicles are mainly charging during the evening peak when PHEV owners arrive at home. The vehicles almost do not charge during the day, due to the absence of a connection point because the drivers of the PHEVs are full-time employees as will be explained 5.

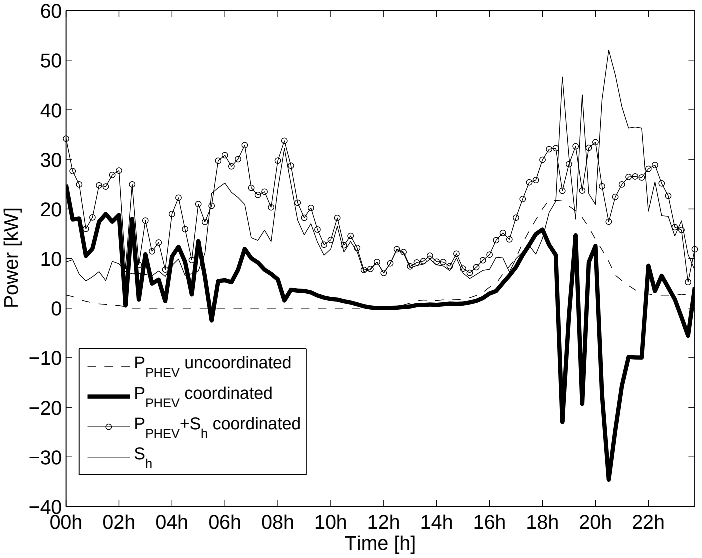

Fig. 4.9: Cumulative charging profile for uncoordinated and coordinated charging and discharging for minimization of the voltage deviations and for a penetration level of 30% PHEVs.

Fig. 4.10 shows the cumulative charging profiles for the same scenarios as mentioned above, only the vehicles are now not able to discharge. The uncoordinated charging profile remains the same. The vehicles cannot discharge during peak hours, as discharging during is not allowed. The vehicles mainly charge during the night.

The minimum voltage level for the entire grid is shown for each time step in Fig. 4.11. The minimum voltage level is also averaged over 700 samples. Without any coordination, the minimum voltage level goes well below the limit. This is avoided when coordinated charging and discharging is applied. The voltage level is just above the voltage limit during the peak hours due to the voltage constraint when coordinated charging without discharging is applied. The voltage deviations due to the peak in the household load are compensated during coordinated charging and discharging, resulting in a much smoother voltage profile.

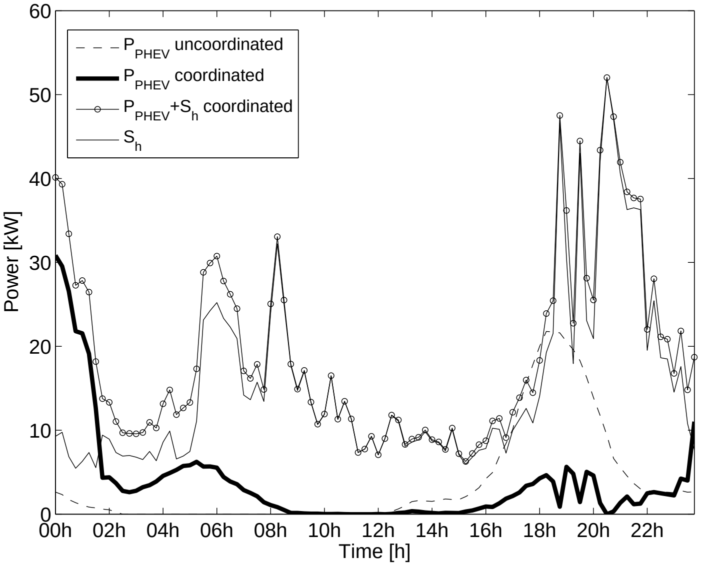

Fig. 4.10: Cumulative charging profile for uncoordinated and coordinated charging for minimization of the voltage deviations and for a penetration level of 30% PHEVs.

4.5.2 Power losses

The power losses as objective function are described in detail in chapter 3. They are determined for the four scenarios in Table 4.3. The power losses for each sample are calculated and averaged over 700 samples. The scenario which minimizes the power losses obviously gives the lowest power losses. Even though, the differences with the voltage deviation scenario are not significant. The scenario which minimizes the charging cost, gives larger power losses and uncoordinated charging gives the largest power losses. Obviously, the power losses increase if the penetration level of PHEVs is increased for all scenarios because more energy must be transported to charge the batteries of all vehicles.

When discharging is disabled, the power losses are slightly increased as displayed in Table 4.4. The total energy to be transported to charge the vehicles is less because the vehicles are not able to discharge. In this case, the vehicles cannot discharge during peak hours and therefore cannot reduce the substantial power losses at that moment. The power losses of each time step are summed to get the total power losses. The large power losses of the evening are taken into account in that sum. In any case, the coordination of the charging improves the power losses compared to uncoordinated charging because charging during peak hours is

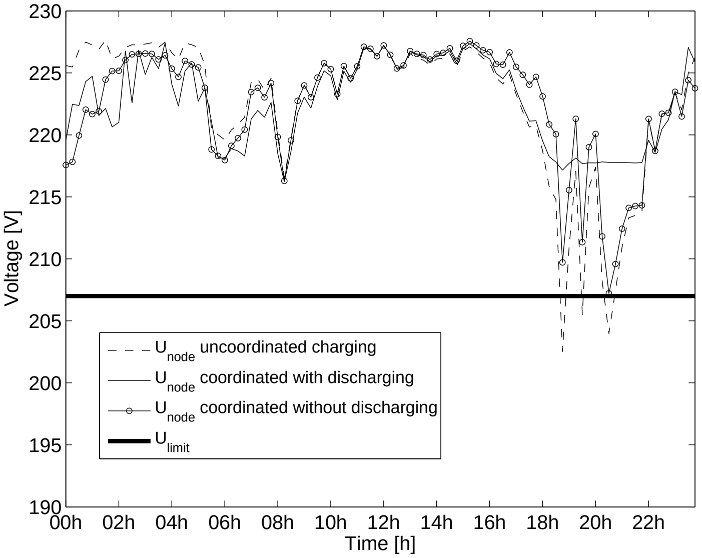

Fig. 4.11: Voltage profile for uncoordinated and coordinated charging and discharging for minimization of the voltage deviations and for a penetration level of 30% PHEVs.

	Uncoordinated	**Coordinated**		
PHEVs [%]		**double tariff**	**voltage deviations**	**power losses**
0	2.2	2.2	2.2	2.2
10	2.4	2.2	2.2	2.0
20	2.7	2.4	2.3	2.0
30	2.9	2.7	2.3	2.1

Table 4.3: Average of the ratio of power losses to total power with discharging [%].

avoided.

	Uncoordinated	**Coordinated**		
PHEVs [%]		**double tariff**	**voltage deviations**	**power losses**
0	2.2	2.2	2.2	2.2
10	2.4	2.2	2.2	2.2
20	2.7	2.4	2.4	2.2
30	2.9	2.6	2.5	2.3

Table 4.4: Average of the ratio of power losses to total power without discharging [%].

The cumulative charging profiles for the entire grid are determined for each time step. The uncoordinated and coordinated cumulative charging profiles are plotted in Fig. 4.12. For uncoordinated charging, this profile is still the same as in Fig. 4.9. For coordinated charging, the profile differs from the charging profile achieved by minimizing voltage deviations. The vehicles have a smaller rate of discharge during evening peak. The sum of the household load and the charging profiles is almost constant overnight. Thus, the total load of the grid is a flat profile overnight. The flat profile is preferable for the power plants. This means that the plants can deliver a constant power and do not have to vary their power. Moreover, power plants could operate in their optimal working point and achieve a better performance and efficiency. During the night, most of the vehicles are connected and the household load is already less peaked compared to during the day. During day and evening, a flat profile cannot be achieved because the household load has large peaks and the number of connected PHEVs is significantly lower.

The cumulative coordinated charging profile in Fig. 4.13 shows that the vehicles are not charging during the evening peak if discharging is disabled. The sum of the household loads and the charging profiles for coordinated charging almost equals the household loads. The vehicles cannot discharge and therefore, these peaks cannot be reduced. Overnight, the sum is a flat profile and the power consumption is almost constant. But the power consumption is less compared to Fig. 4.12. If vehicles are able to discharge, more energy is needed to fully charge the batteries and therefore, the power consumption overnight is larger. The uncoordinated cumulative charging profile is not changed.

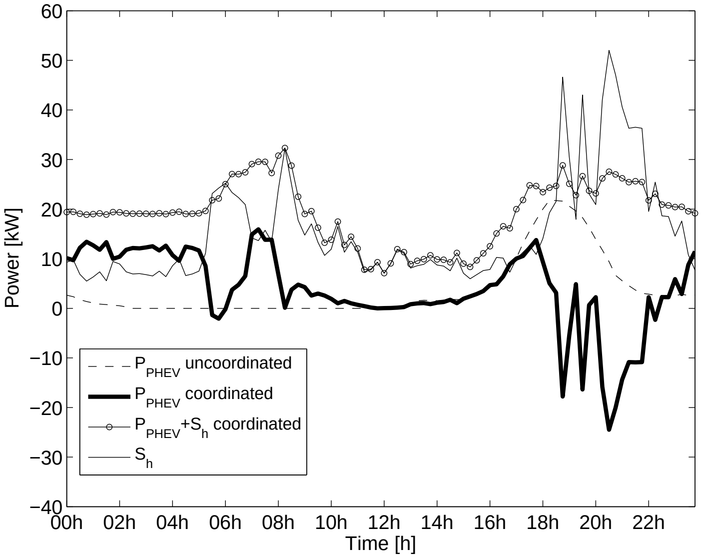

Fig. 4.12: Cumulative charging profile for uncoordinated and coordinated charging and discharging for minimization of the power losses and for a penetration level of 30% PHEVs.

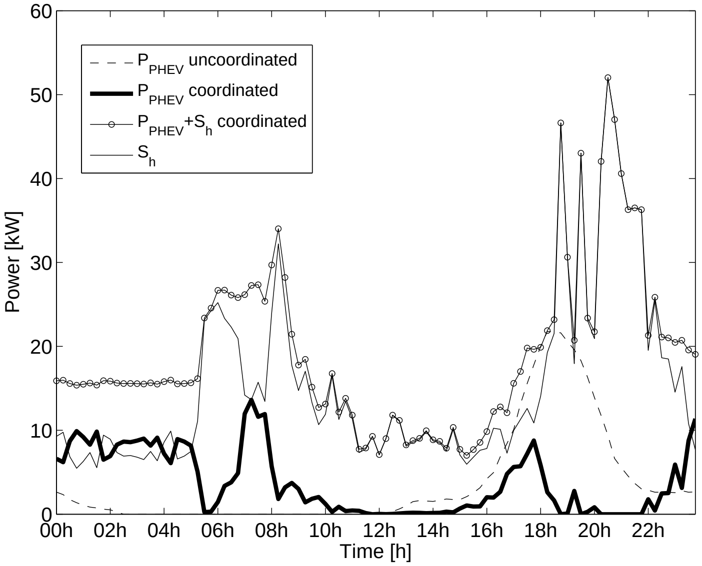

Fig. 4.13: Cumulative charging profile for uncoordinated and coordinated charging for minimization of the power losses and for a penetration level of 30% PHEVs.

The voltage profiles are displayed in Fig. 4.14. For uncoordinated charging, the voltage level is well below the voltage limit during the evening peak, because a lot of vehicles charge during the evening. If coordinated charging with discharging is applied, the voltage level is well above the limit and no problem occurs. The voltage level overnight is lower compared to uncoordinated charging because a large part of the vehicles charge overnight. For the scenario with coordinated charging without discharging, the voltage level during the evening peak hours is just within the limit. The voltage level overnight is high compared with coordinated charging with discharging because for the latter, more energy is required to fully charge the batteries. The cause for this is that the batteries are more depleted due to voltage support during the evening peak.

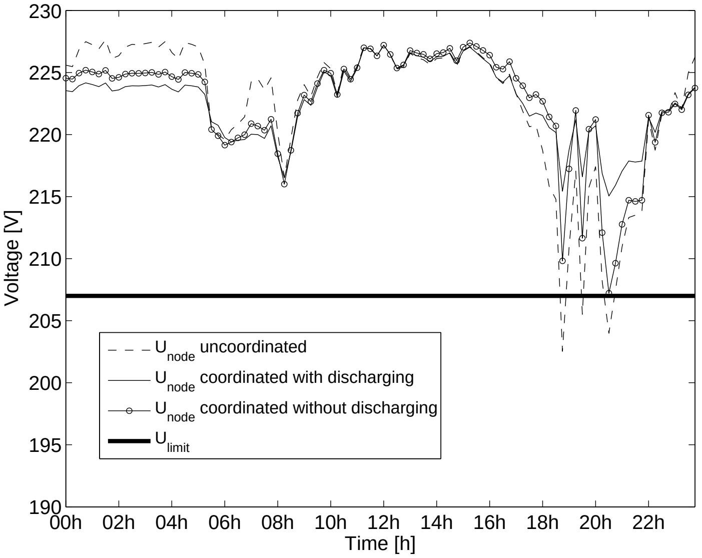

Fig. 4.14: Voltage profile for uncoordinated and coordinated charging and discharging for minimization of the power losses and for a penetration level of 30% PHEVs.

4.5.3 Cost function

The cost function with a double tariff is already represented in (4.1). The constraints are retained as in (4.2). The charging cost for each of the four scenarios is calculated in Table 4.5. For the scenario with the minimization of the charging cost using the double tariff function as objective function, the charging cost is obviously the lowest. The results for the scenarios in which the power losses and voltage deviations are minimized, are similar. The cost is lower compared to uncoordinated charging, but higher compared to the scenario with the minimization of the charging cost. The charging cost for PHEVs for the uncoordinated charging scenario is the most expensive.

	Uncoordinated	**Coordinated**		
PHEVs [%]		**double tariff**	**voltage deviations**	**power losses**
0	0.0	0.0	0.0	0.0
10	7.2	4.4	5.3	5.2
20	15.4	9.6	11.3	11.4
30	20.6	13.2	15.6	15.8

Table 4.5: Average of the ratio of charging cost to total energy cost for double tariff cost function with discharging [%].

The results for the same scenarios but without discharging are represented in Table 4.6. The vehicles charge when the electricity tariff is low. In general, charging cost is increased compared to the scenario wherein vehicles are able to discharge. Without discharging, the vehicles cannot discharge at the moment the tariff is high and thus cannot receive a reimbursement for injecting energy into the grid. Therefore, in general, the energy cost of charging PHEVs is lower if discharging is enabled. The total cost can be higher, depending on the depth of discharge and battery cost. However, this largely depends on the reimbursement received for injecting energy. It must be emphasized that discharging reduces the cycle life of the battery and the cost of wear is not taken into account in this investigation. This may have a major impact on the results.

The cumulative charging profiles for both uncoordinated and coordinated charging are represented in Fig. 4.15. Just before the night tariff starts, vehicles which are still having energy in their batteries, discharge to minimize the cost of charging. The vehicles charge overnight until 07h00 when the day tariff begins. During the day, charging of vehicles is minimal as they only charge when it cannot be avoided, for instance when the batteries must be charged before the next trip. The sum of the cumulative coordinated charging profile and the household load is also plotted. The profile is no longer flat overnight. Large peaks in this sum cannot be avoided. This objective function does not give an incentive to improve grid quality and stability.

	Uncoordinated	**Coordinated**		
PHEVs [%]		**double tariff**	**voltage deviations**	**power losses**
0	0.0	0.0	0.0	0.0
10	7.2	4.9	5.5	5.4
20	15.4	10.7	11.8	12.5
30	20.6	14.5	16.1	17.3

Table 4.6: Average of the ratio of charging cost to total energy cost for double tariff cost function without discharging [%].

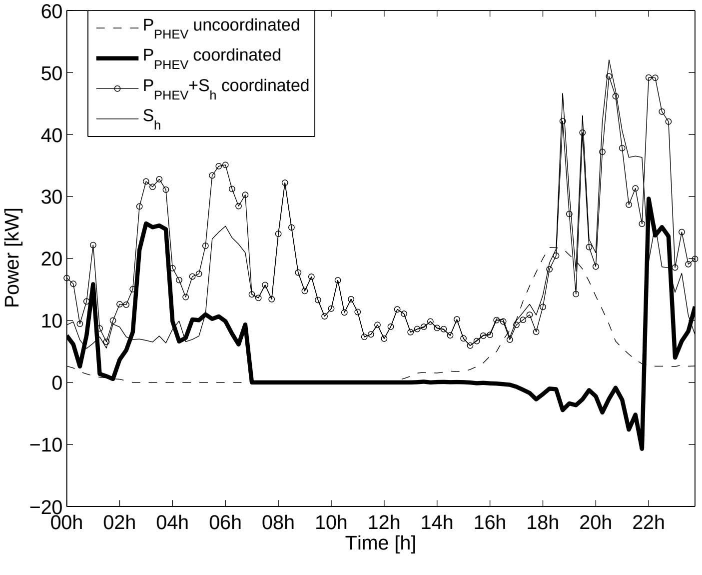

Fig. 4.15: Cumulative charging profile for uncoordinated and coordinated charging and discharging for the minimization of the charging cost and for a penetration level of 30% PHEVs.

The same charging results are plotted in Fig. 4.16 for the scenario without discharging. The vehicles are not charging until night tariff is valid. So the vehicles charge overnight until 07h00. The sum of the household loads and the coordinated cumulative charging profile still has large peaks for the same reason as mentioned above. For both cases, with and without discharging, the peak of charging is higher compared to uncoordinated, but occurs much later in time, at 22h00, at night tariff. But the sum of the household load and the charging profile is still large at that moment.

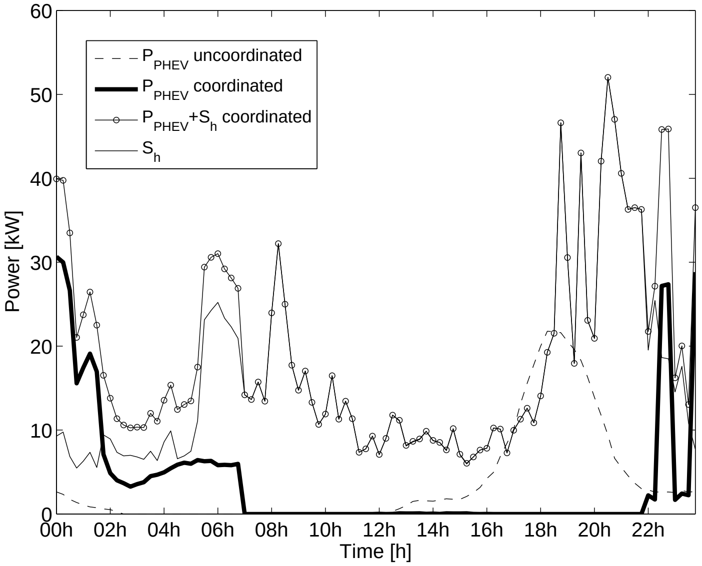

Fig. 4.16: Cumulative charging profile for uncoordinated and coordinated charging for the minimization of the charging cost and for a penetration level of 30% PHEVs.

The voltage profile is represented in Fig. 4.17. The uncoordinated charging profile remains, so the voltage problems still occur. Coordinated charging for both with and without discharging solves the voltage problems. The voltage profile is not flat during the night because the household load profile is not taken into account in the objective function of the optimization problem.

The selection of the objective function is essential for the impact on the grid parameters. The cost function does not take care of the household loads and improvement of the grid quality is not assured. Minimization of the voltage deviations reduces both power losses and voltage deviations. When the power losses are minimized, the voltage deviations are also reduced. If enough PHEVs are connected to the grid, the total electricity consumption of the grid has an

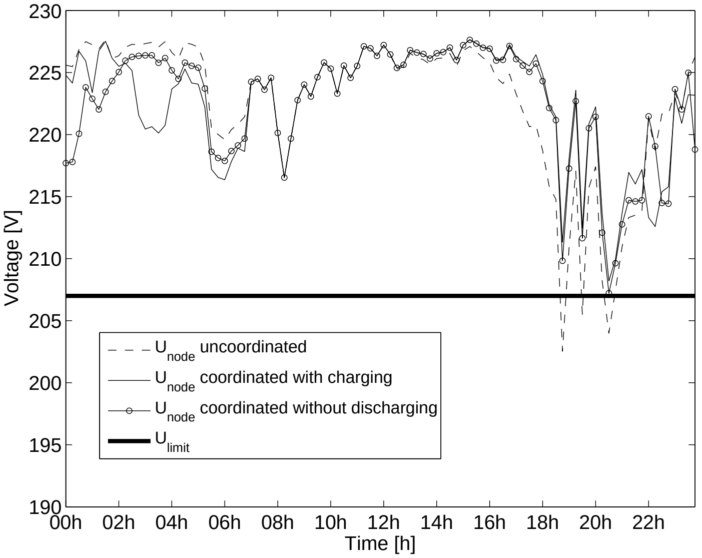

Fig. 4.17: Voltage profile for uncoordinated and coordinated charging and discharging for the minimization of the charging cost and for a penetration level of 30% PHEVs.

almost constant profile, which improves the performance and the efficiency of the power plants.

4.6 Conclusions

A PHEV connected to the distribution grid is able to charge its batteries, but can also discharge and inject energy into the grid to offer grid services. This concept is determined as the vehicle-to-grid operation. However, the management of the charging, described in the previous chapter, could also be considered as load leveling and thus as a grid service because it increases the grid efficiency and reliability. Not all grid services are feasible for PHEVs. A voltage control, implemented in the charger of a PHEV, is one of the grid services which is easy to achieve and is investigated in this chapter.

Uncoordinated charging leads to voltage problems for overnight charging. These voltage problems can be handled by including a voltage constraint in the optimization problem and making the power flow of the charger bidirectional. The optimization problem minimizes the charging cost which is a linear objective function. Therefore, the linear programming technique is used. Applying voltage control is a first step in the direction of supporting the grid by PHEVs. The implementation of a voltage controller embedded in the charger can solve the voltage problems partially.

Three objective functions are evaluated in terms of grid parameters and charging cost. The first objective function is the minimization of the charging cost. This function does not take into account grid parameters and therefore the grid is not optimally used. The minimization of the voltage deviations increases the minimum voltage level compared to the other scenarios and reduces the power losses, but the total load of the grid has still large peaks. Minimization of the power losses reduces also voltage deviations. The main advantage of this objective function is the flat profile, achieved for the total load of the grid. This is especially achieved during the night, because at that moment, a large part of the vehicles are connected. Because of this flat profile, the power plants can work at constant power during the night and in their optimal operating point to improve their global efficiency. If the vehicles are able to discharge, most vehicles discharge during peak hours to avoid large voltage deviations. More energy is transported on the distribution grid if vehicles discharge because the energy, injected in the grid, must also be stored in the battery again. The discharging of the vehicles enlarges the power losses.

5

Vehicle-to-grid: applications

The vehicle-to-grid concept, discussed in chapter 4, is applied to specific examples and scenarios. Up to now, the charging periods were described as well-defined parts of a day. To achieve a more global view of the impact of charging and discharging PHEVs on the distribution grid, an entire day is considered. The work fits in a more global context where also other new technologies, such as mini and micro combined heat and power systems and photovoltaic panels, are implemented in the distribution grid in combination with PHEVs. It may be possible to charge vehicles at work. In that case, the proportion of electric driving is increased, because the vehicles have more opportunities to charge. The batteries can be charged more than once per day. This can increase the impact of charging on the distribution grid. The optimal charging profile is determined based on the driving profile of the vehicle owner. Therefore, other driving profiles are investigated.

An entire day simulation is considered in section 5.1. The combination of PHEVs and distributed generation units is discussed in section 5.2. The impact of a connection at work and the driving profiles are investigated in respectively sections 5.3 and 5.4. The proposed methodology can help evaluating planned grid reinforcements versus PHEV ancillary services to achieve the most efficient grid operation. It allows to determine a maximum hosting capacity of the grid for PHEVs.

5.1 Simulations for 24 hours

For a more accurate assessment of the impact of charging a fleet of PHEVs on the distribution grid, an entire day of 24 hours is simulated, giving more information on the instances vehicles can connect and thus charge or discharge. The consumption of PHEVs is also taken into account thus the battery of a PHEV is not necessarily depleted when plugged in. At first instance, PHEVs are charged at home. In section 5.3, charging at work is also possible. In this section, the emphasis lies on voltage deviations. A heavily loaded weekday is selected from the available set. No voltage deviations occur when no PHEVs charge for that specific day.

5.1.1 Methodology

The optimization problem is extended because an entire day is considered. Grid parameters are evaluated on a 15 minute time basis, thus 96 time steps are examined for each of the 33 nodes. To reduce the computing time, the constraints are only implemented for the nodes having a PHEV connected.

The availability analysis of paragraph 2.3.5 is used to create 1000 profiles of full-time employees. These profiles are ascribed to the nodes with a connected PHEV. In case of overnight charging, it is assumed that the batteries of the vehicles are empty when they start to charge at 19h00 and that all the batteries must be fully charged at 06h00, at end of the charging period. In this analysis, the vehicles must be charged before the first trip in the morning. Not all vehicles must be fully charged at the same moment in the morning and not all vehicles will have a depleted battery at the end of the working day, depending on the daily distance travelled. At the start and end of the day, the battery capacity must be equal, i.e filled for one third, for continuity reasons and to obtain the same start values for each day.

For uncoordinated charging, the PHEVs charge whenever a connection is available until the battery is fully charged or the vehicle disconnects. For the management of the charging, the linear programming technique is used to solve the optimization problem. The objective function is the minimization of the cost function with a day and night tariff, which is described in section 4.3.

5.1.2 Uncoordinated charging

The impact of uncoordinated charging of a fleet of PHEVs on the distribution grid is studied in this paragraph for an entire day. 700 runs are performed for each penetration level. The results of the grid parameters (i.e voltage deviations and power losses) do not significantly change when more than 700 samples (runs) are executed. For each node, the number of times the voltage deviation exceeds 5% is determined for 96 time steps and 700 samples. The fraction of instances when the voltage deviation is too large per node compared with the total number of calculations (700 runs multiplied by 96 time steps), is determined. This fraction is indicated in this work by the term excessive voltage deviations. The maximum and average of the percentage of excessive voltage deviations of all nodes are plotted in Fig. 5.1. The number of voltage deviations increases if the number of vehicles does too. The amount of time that the excessive voltage deviations occur may not exceed 5% of the time according to the EN50160 standard. Problems occur from a penetration level between 40% and 45% for this specific day.

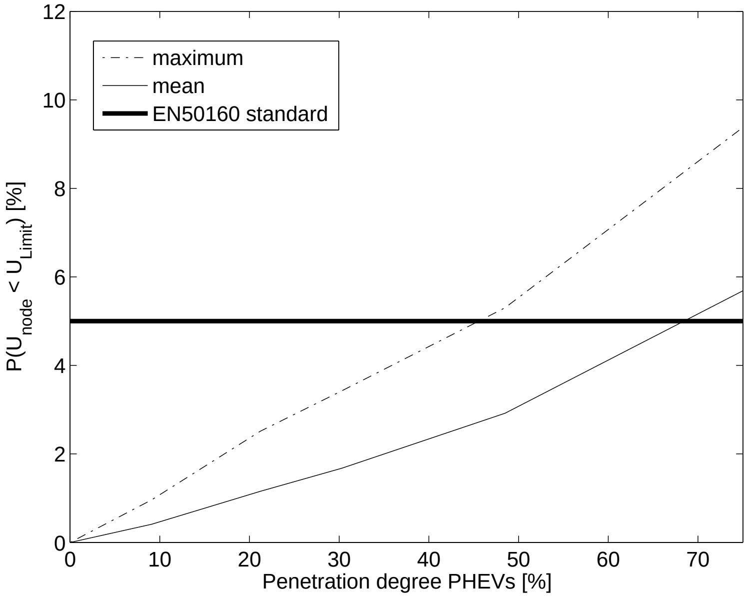

Fig. 5.1: Percentage of excessive voltage deviations.

The percentages of excessive voltage deviations are plotted in Fig. 5.2, 5.3 and 5.4 for a penetration level of respectively 10%, 30% and 50%. The substation of the grid is at the most left of the grid. The voltage deviations are large at the end of the feeder as expected. Near the medium-voltage substation, no voltage problems occur. The voltage levels decrease at the end of the grid and thus the number of excessive voltage deviations also increases.

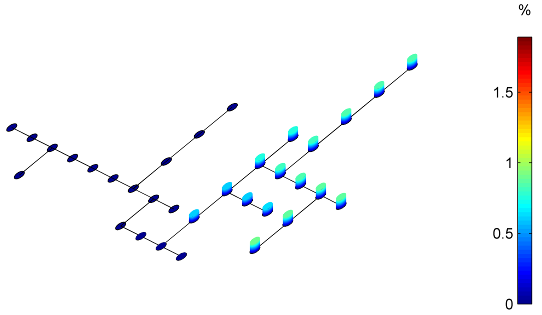

Fig. 5.2: Percentage of excessive voltage deviations for each node of the grid for uncoordinated charging and for a penetration level of 10% PHEVs.

5.1.3 Coordinated charging and discharging

Uncoordinated charging leads to excessive voltage deviations. This can be partly solved by management of charging and discharging. The objective function of this optimization problem is the same as in (4.1), i.e. the minimization of charging cost. The constraints remain the same as in (4.2) and thus the voltage deviations must stay within their limits.

The percentage of excessive voltage deviations for all penetration levels are practically zero, indicating that the problem is almost solved and the percentage of excessive voltage deviations are reduced to zero for 30% PHEVs. For 50% PHEVs or more, the percentage of excessive deviations is significantly reduced from almost 10% to 1.6%.

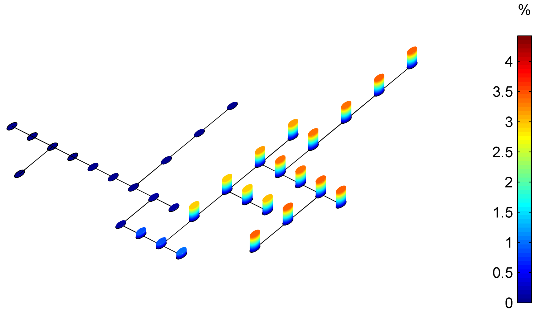

Fig. 5.3: Percentage of excessive voltage deviations for each node of the grid for uncoordinated charging for a penetration level of 30% PHEVs.

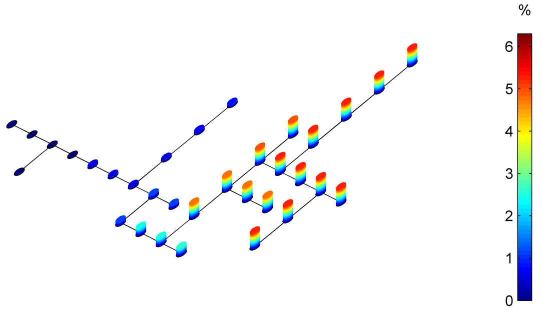

Fig. 5.4: Percentage of excessive voltage deviations for each node of the grid for uncoordinated charging for a penetration level of 50% PHEVs.

5.2 Renewable energy balancing

Distributed generation (DG) units are becoming more important. In [110], it is stated that if an essential amount of storage capacity is available in the grid, large amount of DG units can be connected to a isolated distribution grid. Three kinds of distributed generation units are considered. Photovoltaic (PV) panels, a combined heat and power (CHP) unit and a small-scale wind turbine. These units can be connected to households and therefore having a direct impact on the distribution grid. The generated electricity is injected locally in the distribution grid. The photovoltaic peak occurs a few hours before the peak hours of the households. Wind power is more complex and strongly intermittent. Photovoltaic and wind energy are considered as renewable. In the ideal case, the renewable energy and the generation by power plants should match the general consumption, being household and PHEV demand. If the locally injected energy is large, centralized power plants must decrease their electricity generation to restore the balance in the grid or the distributed generation units must be curtailed. Decreasing their output is not always efficient. A better approach is to charge the vehicles with this excess of energy instead of decreasing the power output of the power plants or the distributed generation units. Therefore, plug-in hybrid electric vehicles have the opportunity to be combined with renewable energy because they are dispatchable and the charging can be managed. Moreover, these vehicles will be a backup for the excess of renewable energy, if the number of connected PHEVs is large enough. This stored energy can be used for driving needs or to provide power at a later time [111].

5.2.1 Model and assumptions

Three kinds of distributed generation units are considered. First, a CHP with a power output of 1.2 kW is assumed [112]. The maximum power output of the PV panels is about 3 kW. The maximum power output of the small-scale wind turbine is 1.5 kW [113]. The wind velocity curve of Eindhoven is used [114]. The load of the DG units is shown in Fig. 5.5. The CHP profile is rather straightforward because it is calculated based on the electricity consumption of a single household. For this day during the month January, the wind turbine is only delivering a significant power output during the night and day except for the morning. Obvious, the PV panels are only generating energy during the day. The maximum power output of the PV panel during the day is about 200 W indicating a rather cloudy day.

It must be emphasized that this does not reflect a real situation and the calculations are only performed for a particular day of the winter season. The aim of this section is not to give a full comprehension of the combination of PHEVs and DG units, but has the intension to indicate that there are possibilities to combine DG units with dispatchable PHEVs. It is not the goal to indicate that PHEVs

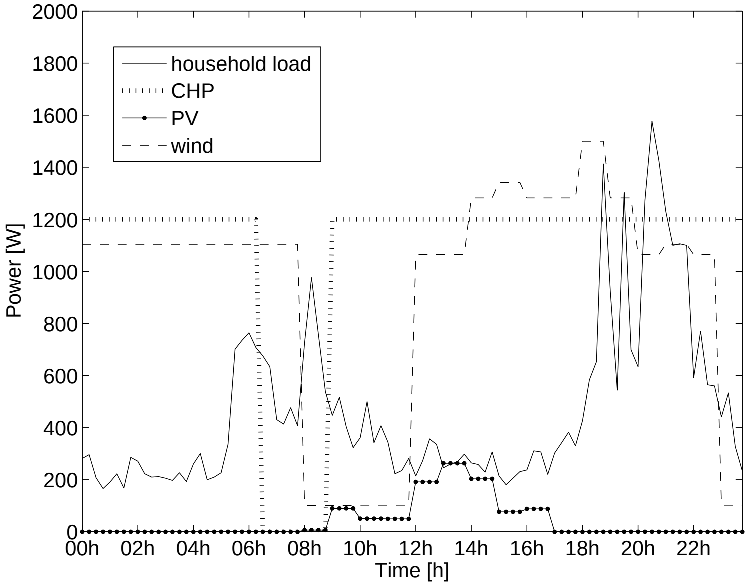

Fig. 5.5: Household load, CHP, wind and photovoltaic generation profiles.

and DG units are a good combination for all scenario and cases, but there will be established that a good combination is possible under certain circumstances. Therefore, it is presumable that a good combination could also be achieved for other scenarios. The availability analysis of paragraph 2.3.5 is used and these profiles are ascribed to the nodes with a connected PHEV.

5.2.2 Methodology

This investigation is still performed for an entire day and a full-time employee. The same methodology is employed for uncoordinated and coordinated charging and discharging. The linear and quadratic programming techniques are used to determine the optimal charging profile for each PHEV. The cost function and the power losses are considered as objective functions. The latter gives the best results as discussed in section 4.5. DG units are injecting energy into the grid, so the power of these units is negative. These DG units are placed randomly and the number of DG units depends on the penetration level. At most, one DG unit is assumed to be connected to a household or node. 700 runs are simulated. The constraints are only enforced for the nodes with a PHEV or DG unit connected to reduce computing time. Too large voltage levels, due to operation of DG units, are not considered in this grid and the curtailment of the DG units is not allowed.

5.2.3 Uncoordinated charging

The combination of DG units and the uncoordinated charging of a fleet of PHEVs is investigated. The vehicles charge whenever they are at home and the battery is not yet fully charged. If DG units are producing energy, first the demand of the households is fulfilled. The excess of energy may be used for charging vehicles if connected and not yet fully charged. Power plants deliver less or no energy at that moment.

Fig. 5.6 shows the combination of several percentages of DG units and penetration levels of PHEVs. For each node of the grid, it is determined how many times the voltage level exceeds the lower voltage limit. The maximum and average of the number of excessive voltage deviations are calculated as described in section 5.1. If no DG units are present, the same results are achieved as in Fig. 5.1. An increase in the penetration level of DG units causes a decrease in the percentage of excessive voltages deviations. For a larger penetration level of DG units, more vehicles can be connected to the grid and therefore, the combination with DG units will be easier. In general, DG units take care of the problems of excessive voltage deviations. Nevertheless, the percentage of excessive voltage deviations is still high if the number of PHEVs is increased. If the DG units are producing energy and almost no PHEVs are connected to the grid, this energy is used to match the consumption of the household loads.

The cumulative power required to charge the vehicle fleet, the cumulative household power and the cumulative power produced by the DG units are calculated for each time step and for the entire grid. These values are averaged over 700 samples. The sum of these three parameters is plotted in Fig. 5.7 for a PHEV penetration level of 30%. The DG penetration level varies between 30% and 75%. For the completeness of the result, the sum of the power required to charge the vehicles and to match the household load and the power produced by the DG units for a DG penetration level of 50% are also plotted separately. The sum of the household and the power of the chargers is considered together, because this is the total consumption of the entire grid. If there are no DG units present at the grid, the power needed to charge the vehicles is positive. This energy must be produced by the power plants. The production of the DG units is also displayed to give an idea of the time moment the DG units are producing energy. From a penetration level of 50% or more for the DG units, the total consumption of the grid is not high enough to consume the energy injected by these units. Therefore, the sum of the power of the chargers, the household loads and the power of the DG units is negative during some parts of the day and night, meaning that there is an excess of energy. Clearly, DG units are producing during the day and the vehicles are not present at that moment. For uncoordinated charging, the vehicles are mainly charging during peak hours and the consumption during the night is

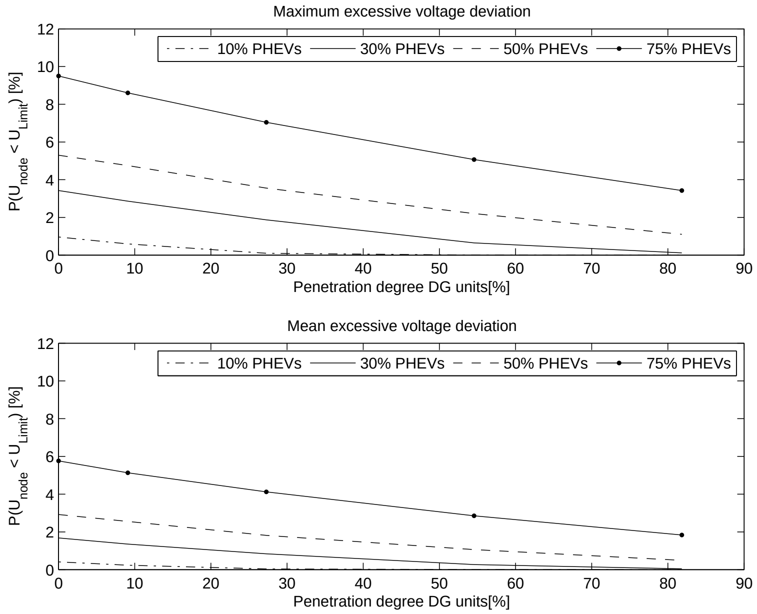

Fig. 5.6: Percentage of excessive voltage deviations for uncoordinated charging.

also small. Therefore, there is even an overcapacity of energy, produced by the DG units, overnight. This excess of energy could be transported to other distribution grids nearby, but adaptations at some components of the grid would be necessary. This is not further considered in this work. During the evening peak, the sum is positive, because the DG units are not producing enough energy and thus the power plants have to take care of the extra energy required to charge PHEVs. Therefore, if the vehicles are charged without any type of management, DG units and the charging of the PHEVs are not matched well.

5.2.4 Coordinated charging and discharging

Two objective functions are considered, i.e. the minimization of the charging cost and the power losses. The voltage constraint is still implemented to satisfy the mandatory EN50160 standard. Discharging is also implemented. Fig. 5.8 shows the percentage of the excessive voltage deviations for the minimization of the cost function. Both mean and maximum value are calculated. This percentage is significantly reduced for all penetration levels compared to uncoordinated charging. Only for a penetration level of PHEVs of 50 and 75%, a small percentage of excessive voltage deviations still occur. The number of excessive voltage deviations

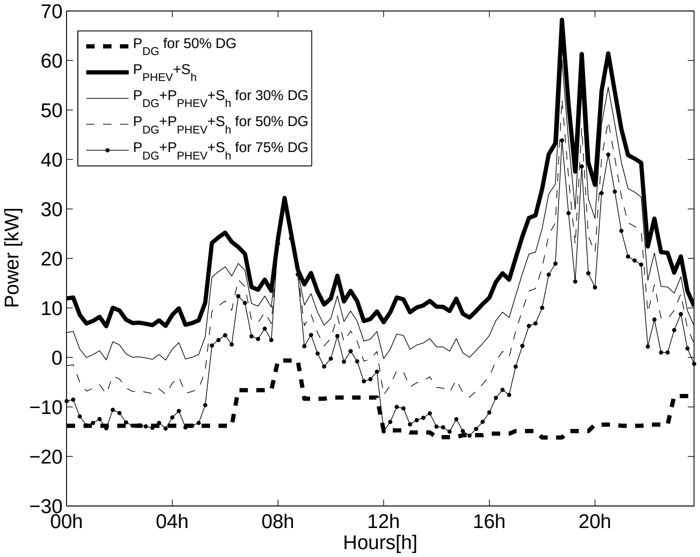

Fig. 5.7: Sum of power of PHEVs and DGs for a penetration level of 30% for PHEVs and several DG penetration levels for uncoordinated charging.

does not monotonically decrease because of small numerical rounding off errors. The cumulative power produced by the DG units for several penetration levels and the cumulative power of the chargers and the household loads are displayed in Fig. 5.9 for the minimization of the cost function. The charging peak, in the evening, is shifted to the moment the night tariff starts. This is an improvement because for uncoordinated charging, the peak power plants have to produce extra energy and these power plants are more expensive. Charging vehicles is also more distributed, especially during the night. The sum of the power produced by the DG units, the power of the chargers and the power of the household loads is still negative during the day, because vehicles are not connected to the grid. However, during the night, charging vehicles is more distributed and the amount of time that the power is negative, is reduced. Therefore, the power plants mainly have to produce additional energy during the night. However, it is clear that the minimization of the cost function does not give a good match with DG units. The vehicles are even discharging when the DG units also produce energy. Therefore, both PHEVs and DG units inject energy into the grid. The situation during the night and evening is slightly improved. During the day, almost no improvements are achieved. The reason is that the profile of the PHEV owner is a full-time employee who is mostly not at home during the day. Fig. 5.10 shows the cumulative power when minimization of the power losses is enforced. The sum of household loads, power of the chargers and the power produced by the DG units is

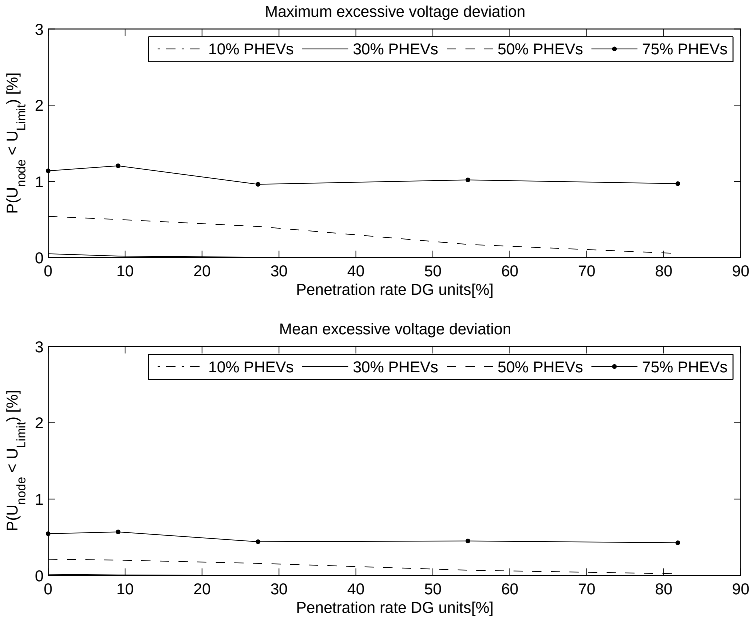

Fig. 5.8: Percentage of excessive voltage deviations for coordinated charging and discharging.

significantly reduced during the night. Even for a large DG penetration level, this sum is near to zero, meaning that the DG generation is almost perfectly matched by the consumption of the entire grid, thus almost no energy is injected into the grid overnight. The consumption during the night is also a flat profile. During the day, the problems are of course not solved because of the absence of PHEVs. No curtailment of the DG units is implemented, thus the grid could be instable during the day due to the production of the DG units. This objective function clearly is better than the cost function and uncoordinated charging. The optimization of the power losses prevents the unnecessary discharging of the batteries and lowers the peak consumption from 70 kW for uncoordinated charging to 50 kW for the scenario with the minimization of the charging cost to eventually 30 kW for the scenario with the minimization of the power losses It must be emphasized that it is not the aim of this work to state that a maximum penetration level of 30% of DG units is allowed to avoid that the units inject energy into the grid and that PHEVs are perfectly matched by these units. However, this section wants to indicate that it is possible to combine DG units and charging PHEVs. The choice of the objective function is essential to achieve a good match.

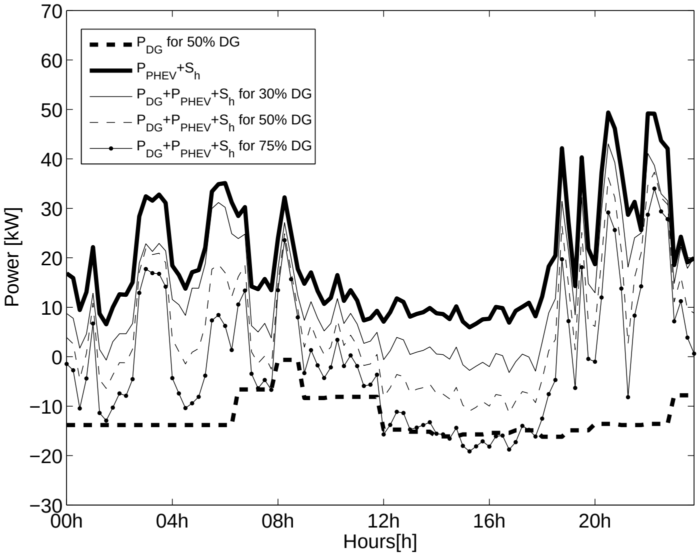

Fig. 5.9: Sum of power of PHEVs and DGs for a penetration level of 30% for PHEVs and several DG penetration levels for coordinated charging and discharging for minimization of charging cost.

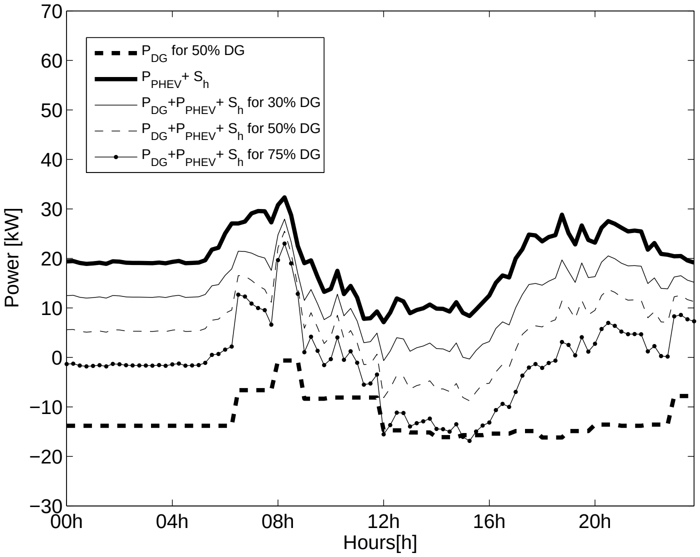

Fig. 5.10: Sum of power of PHEVs and DGs for a penetration level of 30% for PHEVs and several DG penetration levels for coordinated charging and discharging for minimization of power losses.

5.3 Charging and discharging at work

The impact on the distribution grid in case of a connection at work is considered in this section. In the availability analysis, the vehicles are now also able to charge and discharge when they are at work. The same strategy as for charging at home is considered. Only an extra charging possibility is added, i.e at work. Charging is supposed to occur in SMEs or offices in urban areas. It is assumed that only one vehicle per household or office can be charged. The charging of multiple vehicles at households or offices is not considered because it is not feasible to reflect all conceivable scenarios. The vehicles must not only be fully charged before the first trip in the morning, but also before returning home, which is made possible by the connection at work. Most of the time, this is the second (return) trip of the day. Some vehicles make a business trip during working hours. Then, the vehicles will be fully charged before the first business trip. For the next trips, the vehicles are not necessarily fully charged because no more requirements are enforced. An equality constraint is added to fulfil this extra requirement. Of course, the vehicles can only be fully charged between the first and the second trip if there is enough time to charge.

5.3.1 Uncoordinated charging

If uncoordinated charging is applied, the vehicles start to charge immediately when they are plugged in. For a 24 hours simulation, it is assumed that the vehicles are plugged in immediately when they have the opportunity. The connection at work enlarges the possible moments of charging, i.e at work and at home.

The mean and the maximum of the excessive voltage deviations of the grid are determined, as described in section 5.1. The percentage of excessive voltage deviations is shown in Fig. 5.11. This percentage increases if the number of vehicles increases. However, the percentage of excessive voltage deviations is lower compared to the scenario where the PHEVs are not able to charge at work. Without the possibility for charging at work, some vehicles do not have enough energy in the batteries to return home in full electric power mode. They need to use their internal combustion engine to drive home in the case of no connection at work. The battery of these vehicles are empty when they arrive at home. If charging at work is possible, these vehicles charge during the day and in that way, these vehicles can drive at home in full electric mode for their maximum electric range. For that reason, a larger part of the vehicle fleet arrives home with a battery content which is higher compared to the scenario without charging at work. Charging at work is of course more demanding for the distribution grid, because the vehicles can charge at least twice per day, i.e. at work and at home.

Therefore, the electric vehicles are driving more electrically. In that case, more energy must be produced and transported by the grid.

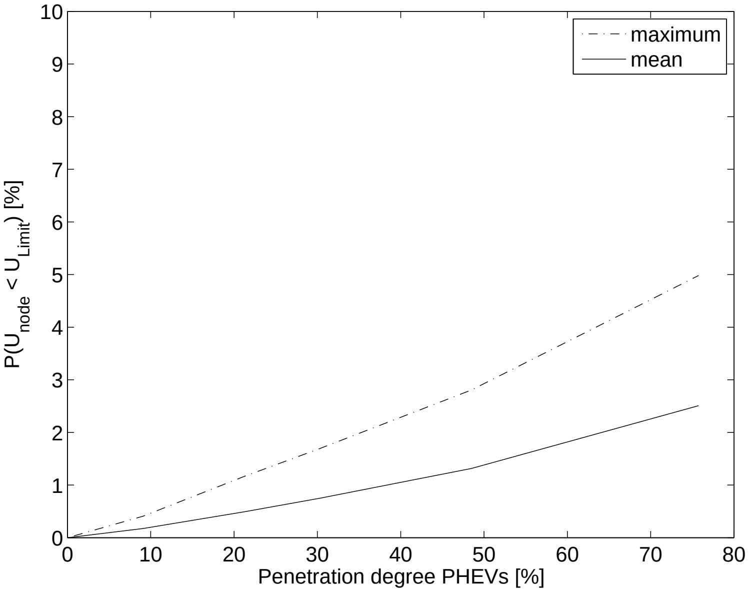

Fig. 5.11: Percentage of excessive voltage deviations for uncoordinated charging.

5.3.2 Coordinated charging and discharging

The percentages of the excessive voltage deviations of the grid, when coordinated charging and discharging is applied, are determined and are shown in Fig. 5.12 for the minimization of the power losses. The voltage deviations are lower compared to the scenario in which the vehicles can only charge at home. Until 30% PHEVs, the number of excessive voltage deviations is about zero. From 50% and more, the excessive voltage deviations increase, but they are reduced compared to uncoordinated charging. A more accurate assessment is to determine the number of voltage problems which could not be solved due to the overly stringent constraints, but this is not considered in this work.

5.4 Impact of driving profiles

For the determination of the optimal charging profile for each PHEV, it is assumed that the driving profile of each PHEV owner during the week is more or less

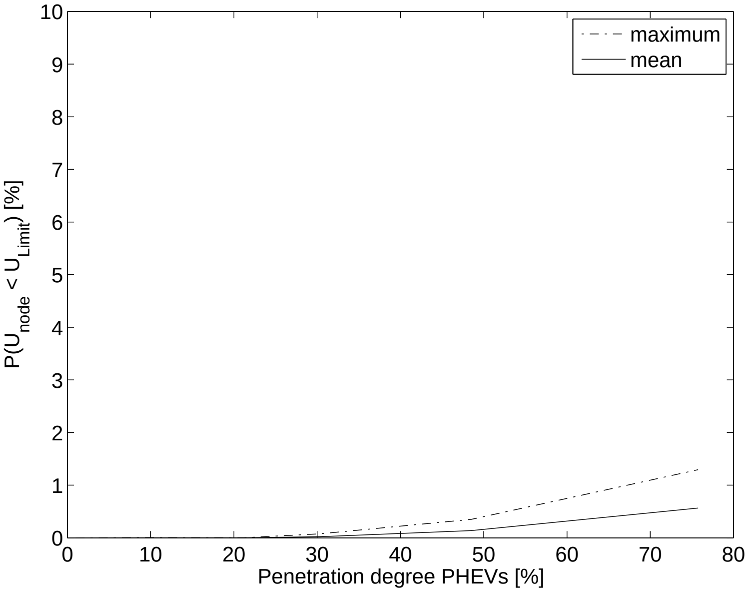

Fig. 5.12: Percentage of excessive voltage deviations for coordinated charging and discharging.

exactly known. For most of the weekdays, this is acceptable. The driving profiles generated by the model of the availability analysis are based on stochastic data of The Netherlands and Belgium, as described in section 2.3.5. This model predicts driving profiles for full-time employees. For the validation of this model, the optimal charge for PHEVs is also calculated with realistic driving profiles. These driving profiles are measured and logged for a BEV by the company AVL [115]. 10 drivers have tested a BEV for about a month in Germany. The start and end time are measured each day, together with the trip distance and the total energy consumption of each trip. With this information, several driving cycles per day are distinguished. The background of the test-drivers is not known, so probably, not all test-drivers are full-time employees. The energy consumption per trip is taken into account, in contrast with the availability analysis where a constant consumption is assumed. The aim of this section is to indicate that it is necessary to have a full assessment of the driving profiles of PHEV owners to achieve the most optimal charging profile.

5.4.1 Methodology

The simulations are performed for a set of daily household load profiles, the synthetic household load profiles as described in section 2.3.3. The calculations are not accomplished for a single heavily loaded weekday as in the previous sections.

The simulations for an entire weekday are performed for the real driving profiles of AVL and compared to the simulations with the driving cycles generated by the model based on the availability analysis, defined as the “AA driving profiles”. Both uncoordinated and coordinated charging and discharging are regarded in this section. The quadratic programming technique is used for minimizing power losses to investigate the grid parameters.

5.4.2 Uncoordinated charging

The results of the power losses and the voltage deviations are shown in Table 5.1 and Table 5.2 for respectively the AVL and the AA driving profiles. The maximum voltage deviation and the power losses are calculated as the average of 1000 samples. The power losses of the scenario with the AA driving profiles are slightly higher compared to the scenario with the AVL profiles. The voltage deviations are in both cases more or less the same. No significant differences can be distinguished. However, the voltage deviations are much larger compared to the results of section 3.2. Only the weekdays are considered here and in section 3.2 both week- and weekenddays are analyzed. During the weekdays, the maximum voltage deviations, which occur during the evening peak, are much larger.

Grid parameter	**0%**	**10%**	**20%**	**30%**
Power losses	1.9	1.9	2.0	2.1
Voltage deviations	6.2	6.5	6.7	6.9

Table 5.1: Average of the ratio of power losses to total power [%] and average voltage deviations for uncoordinated charging and AVL driving profiles.

The cumulative charging profile for the AA driving profiles is plotted in Fig. 5.13. Because a driving cycle of a full-time employee is considered, the vehicles are plugged in and mostly start to charge during the evening. If more vehicles are connected to the grid, the cumulative charging profile does not change, only the value of the power increases up to almost 24 kW as these driving patrons are based on probability density functions.

Grid parameter	**0%**	**10%**	**20%**	**30%**
Power losses	1.9	2.0	2.2	2.4
Voltage deviations	6.2	6.4	6.6	7.0

Table 5.2: Average of the ratio of power losses to total power [%] and average voltage deviations for uncoordinated charging and AA driving profiles.

The cumulative charging profile for the AVL driving profiles is displayed in Fig. 5.14. The cumulative charging profiles are more randomly compared to the cumulative charging profiles of the AA driving profiles. The AVL driving profiles are real profiles based on measurements and not generated by a model based on stochastic data and the number of driving profiles is much lower. It is still noted that most vehicles start to charge during the evening. However the charging profile is more flat and there is not really a maximum. Because of the flat cumulative charging profile, the maximum power, for charging a fleet of PHEVs, to be delivered by the grid, is less compared with the scenario with the AA profiles. For a penetration level of 30%, only about 8 kW is required.

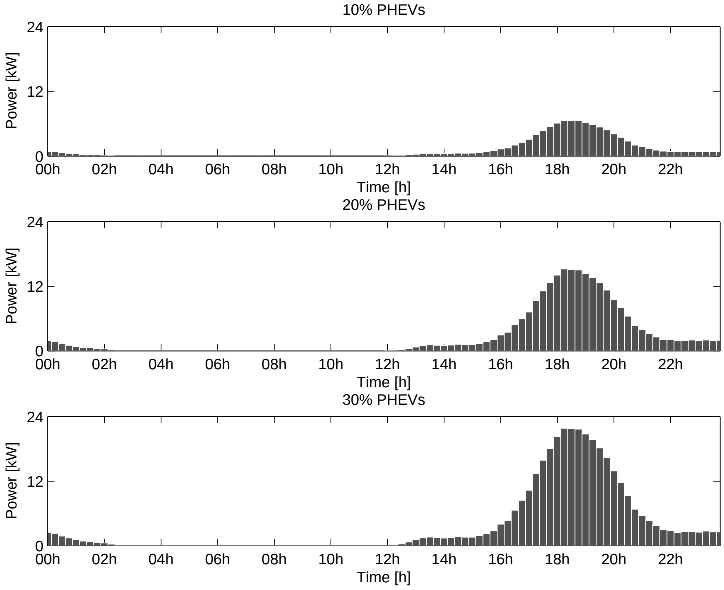

Fig. 5.13: Charging profile for uncoordinated charging and AA driving profiles.

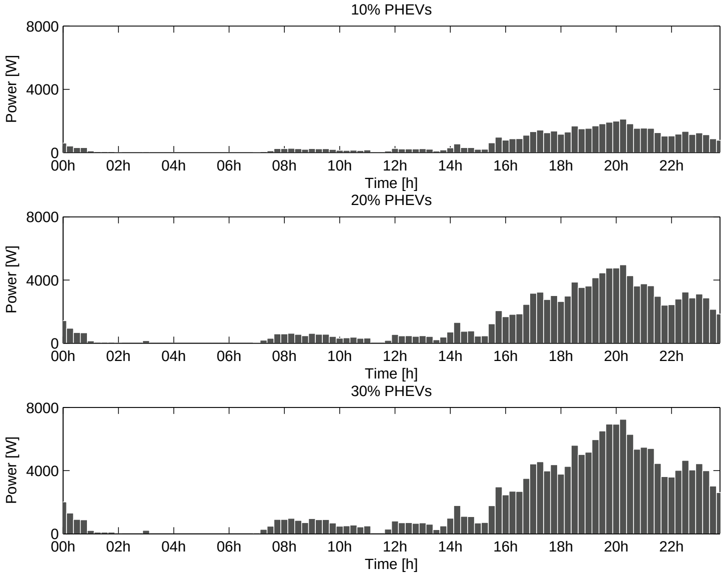

Fig. 5.14: Charging profile for uncoordinated charging and AVL driving profiles.

Fig. 5.15 shows the cumulative charging profile for both scenarios and the sum of the charging profiles and the household loads. Clearly, the maximum charging power needed for a fleet of PHEVs is much larger for the AA driving profiles compared to the AVL driving profiles. The maximum power is not only larger, also the energy required to charge the vehicles is larger. The charging energy is represented by the area under the curve in this figure. This required energy depends on the consumption of the vehicles during the day. The energy left in the batteries is also taken into account for the simulations. Thus, if the PHEVs are driving less kilometers or consuming less energy during the day, less energy is required from the grid to recharge PHEVs.

5.4.3 Coordinated charging and discharging: power losses

The impact of the coordination of the charging of a fleet of PHEVs is investigated for both driving profiles in terms of grid parameters and charging profiles. The results of the grid parameters are represented in Table 5.3 and Table 5.4 for respectively the AVL and the AA driving profiles. The power losses and the voltage deviations are reduced compared with uncoordinated charging for both driving profiles. The voltage deviations are larger in the case that the AA profiles are used. The power losses are the same for both AA and AVL driving profiles.

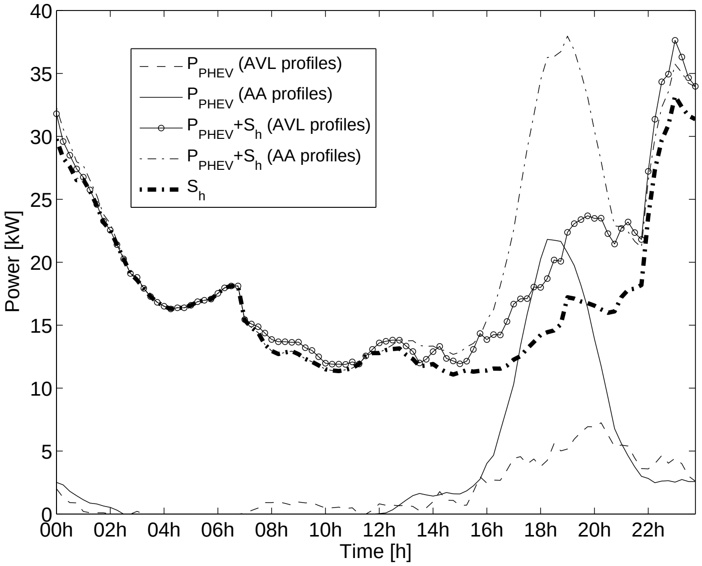

Fig. 5.15: Cumulative charging profile for uncoordinated charging and household loads.

Grid parameter	**0%**	**10%**	**20%**	**30%**
Power losses	1.9	1.8	1.9	2.0
Voltage deviations	6.2	5.1	5.1	5.3

Table 5.3: Average of the ratio of power losses to total power [%] and average voltage deviations for coordinated charging and discharging and AVL driving profiles.

Grid parameter	**0%**	**10%**	**20%**	**30%**
Power losses	1.9	1.9	2.0	2.2
Voltage deviations	6.2	5.1	5.4	6.1

Table 5.4: Average of the ratio of power losses to total power [%] and average voltage deviations for coordinated charging and discharging and AA driving profiles.

In Fig. 5.16, the cumulative charging profile, for AVL driving profiles, is shown for three penetration levels. The PHEVs are mainly charging during the evening if no coordination system is implemented. However, if coordinated charging and discharging is applied, the time of charging is shifted to the night. During the evening, the vehicles discharge to minimize the power losses. The vehicles also charge during the day.

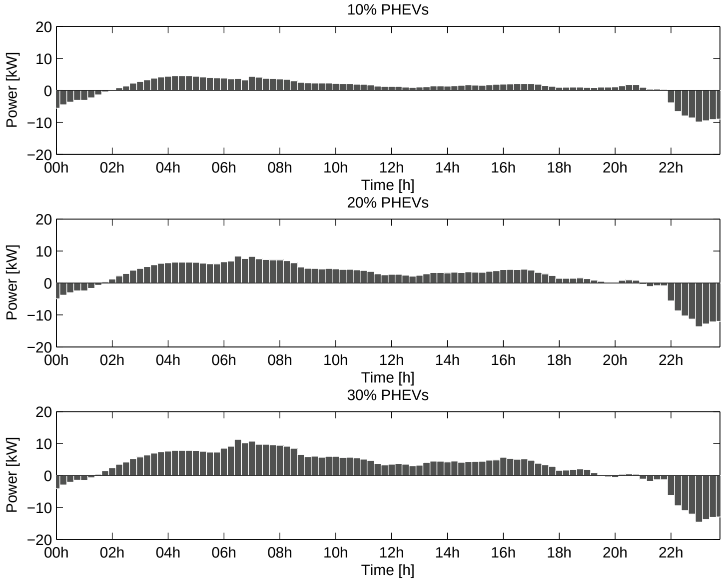

Fig. 5.16: Cumulative charging profile for coordinated charging and discharging and AVL driving profiles.

For the AA driving profiles, the results are displayed in Fig. 5.17. The vehicles also discharge during the evening. Charging occurs mainly overnight. The power of the charging profiles is only slightly higher for the AA driving profiles compared to the AVL driving profiles. The vehicles are almost not charging during the day because most vehicles are absent at that moment. The vehicles discharge less during the evening compared to the AVL driving profiles. Probably, less energy is left in the batteries when they arrive at home during the evening. Because the vehicles discharge during the peak hours, the maximum power of the charging profiles for both driving profiles is of the same magnitude during the night because the battery capacity is for both driving profiles the same.

The cumulative charging profiles for both driving profiles are represented in Fig. 5.18. These charging profiles are a lot more flat compared with uncoordinated charging. The peaks during the evening are eliminated for both driving profiles. For the AA profiles, the maximum power for charging is higher compared to the

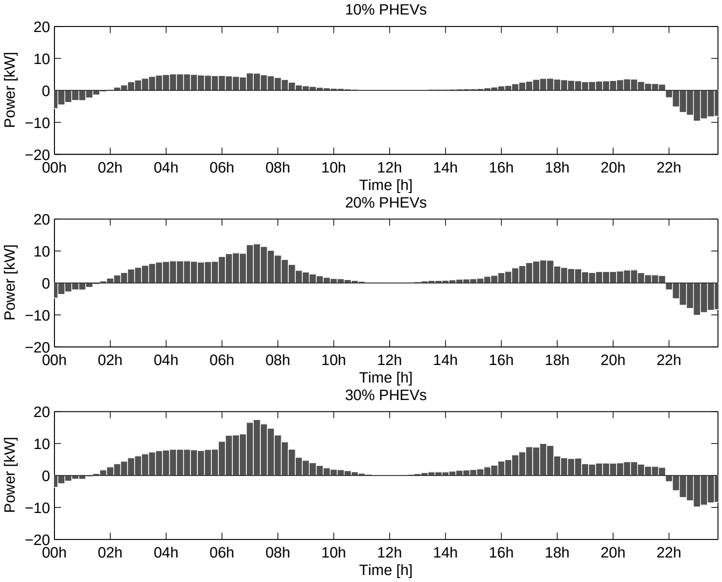

Fig. 5.17: Cumulative charging profile for coordinated charging and discharging and AA driving profiles.

AVL driving profiles. Two peaks occur, the first one in the morning before the first trip to work and the second during the evening, when arriving at home. During the day, the vehicles almost do not charge. The vehicles discharge when the household load is large.

When the AVL driving profiles are applied, the maximum power required for charging a fleet of PHEVs is smaller. The difference between the maximum of the charging profiles is significantly reduced compared to uncoordinated charging. The vehicles also charge during the day, indicating that part of the vehicle owners are leaving much later for work. Discharging during peak hours is smaller compared to the case with the AA driving profiles. The energy required to charge the vehicles overnight is more or less the same for both driving profiles because the PHEVs discharge during the peak hours and therefore, the batteries are almost depleted. Accordingly, the amount energy left in the battery after the last trip is not important. In general, the knowledge of the driving profiles is essential.

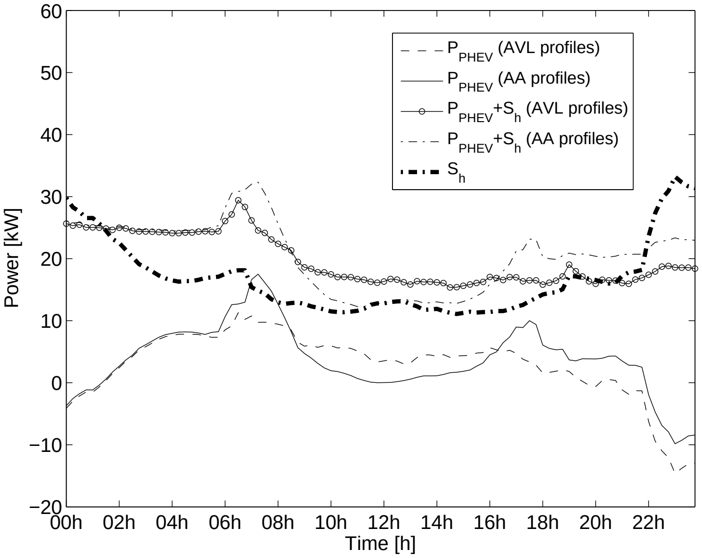

Fig. 5.18: Cumulative charging profile for coordinated charging and discharging and household loads.

5.5 Conclusions

The vehicle-to-grid operation and more specific, voltage control, is applied in some scenarios to investigate the impact of uncoordinated and coordinated charging and discharging. For an entire day simulation, the percentage of excessive voltage deviations is larger than 5% for a penetration level larger than 40% if the charging is not coordinated. Fortunately, these voltage problems can be solved by the coordination or the management of charging and discharging. These values are of course only valid for this model, i.e. the test grid, household loads and for the driving profiles of the availability analysis. However, the main issue is to indicate that the coordination of the charging can solve voltage problems.

PHEVs can be matched with distributed generation units to take care of excess of energy and store it in the batteries. This stored energy can be used for driving needs or can be injected in the distribution grid at a later time. It is indicated that the percentage of excessive voltage deviations increases when the number of DG units is increased if the charging is not coordinated. Coordination of charging reduces the number of excessive voltage deviations. A maximum penetration level of 30% of DG units is required to avoid these units to inject energy into the grid or must be curtailed if coordinated charging and discharging is applied. As mentioned above, these values and percentages are only valid for this model. To give a more accurate view of the intermittent properties of the DG units, a stochastic analysis has to be performed.

If a connection at work is available, the number of excessive voltage deviations is reduced compared to the case without a connection at work. If the vehicles charge at work, a larger part of the PHEVs still have energy left in the battery when they arrive at home. In that way, these PHEVs have more opportunities to support the grid. The proportion of electric driving may be increased.

The knowledge of the driving profiles is essential. Two types of driving profiles are compared, i.e. realistic driving profiles of the company AVL and the driving profiles generated with a model based on the availability analysis. It can be concluded that a forecasting is important because this predicts the amount of power required to charge the vehicles, the amount of energy that is left in the battery, etc.

6

Impact on electricity generation

The impact of charging a fleet of PHEVs on the residential distribution grid is discussed in the previous chapters. The extra energy required to charge these vehicles must not only be transported over the transmission and distribution grid but this extra energy must also be produced by the power plants. This chapter aims to investigate the impact of a fleet of PHEVs on the electricity generation system in Belgium. The impact of both uncoordinated and coordinated charging and discharging is examined. It is essential to know which power plants are producing this energy for cost and emission reasons.

In section 6.1, a study of literature is given about the impact of a fleet of PHEVs on the generation systems. The model and assumptions are explained in section 6.2 and the E-simulate model, used to determine the impact on the generation systems, is described in section 6.3. In section 6.4, the results are comprehensively discussed.

6.1 Introduction

The impact of a fleet of PHEVs on the electricity generation system is described in several articles. In [116], it is proposed that no additional generation capacity is required for a large penetration level of PHEVs when the vehicles charge during off-peak hours. In [117], the vehicles also charge when the power system load is low. The peak load is not increased and no extra generation is added for a penetration level of maximum 20%. The algorithm used to charge the vehicles when the load is low, is usually a valley filling method [62]. This method fills the valley in the load demand during the night to achieve a more flat profile. If a large number of PHEVs draw power from the electricity grid at night, the off-peak demand increases, the load factor increases and the daily load profile is more flat. Moreover, the utilization degree of the system increases [64] because the generation capacity of the country is idle during off-peak hours under normal conditions, i.e. without PHEVs. A large advantage for the generation system is that the infrastructure already exists and no extra investments are necessary when off-peak charging is applied. The emission reduction depends on the generation mix [118].

In reality, it may be very difficult to force consumers to charge their vehicles during some specific periods of time. They rather plug in their vehicles when convenient for themselves. For some scenarios, additional capacity is required during evening charging. Incentives and smart meters are necessary to shift demand to off-peak hours in a transparent way. An estimate of the demand is necessary to coordinate the charging according to [118].

6.2 Model and assumptions

The goal of this chapter is not to give a full assessment of the impact of PHEVs on the electricity generation systems, but to give an idea of the bottle-necks that can occur and of the opportunities that can be achieved by the coordination of charging a fleet of PHEVs. For the impact of charging and discharging PHEVs on the electricity generation system, the total consumption of PHEVs must be determined for Belgium. In the previous chapters, the cumulative charging profile for a distribution grid of 33 nodes is calculated. This charging profile is extended to achieve a charging profile for all the households in Belgium. In 2007, there were 4,5 million households in Belgium. So the total consumption can be determined for all the households in Belgium by assuming 4,5 million nodes. It is not achievable to simulate a distribution grid of 4,5 million nodes and therefore, the cumulative charging profile is just extrapolated to all the Belgian households. Obviously, this is not a realistic reproduction of the total consumption of PHEVs for charging and discharging. These simulations are performed for the same heavily loaded day as described in section 5.1.

6.3 Methodology

Both uncoordinated and coordinated charging and discharging are examined. For the coordination of the charging, three objective functions are investigated, i.e. power losses, voltage deviations and charging cost as described in chapter 4. The power losses and the voltage deviations are only considered in the distribution grid. At first instance, the vehicles are able to charge and discharge. Second, to investigate the impact of discharging on the generation systems, discharging is disabled. There is only a single connection at home available.

The E-simulate model, developed by Kris Voorspools [119] and modified by Eric Delarue [120], is a large-scale electricity generation simulation model. It simulates the electricity generation dispatch on a hourly basis over a daily cycle at power plant level. For this calculations, only the Belgian zone is considered. Four power plants are added representing the interconnection with the neighbouring countries. In that way, transfer among zones is available and a net import of energy in the Belgian zone is possible. The inputs of the model are the power plants within the considered zone and their technical characteristics, fuel and CO_2 prices, connection capacities. The load in this case exists of the load of the PHEVs, the residential and the industrial loads. PHEVs are added as extra load. This model generates as output the electricity generation of each power plant on an hourly basis and the corresponding CO_2 emissions. A heavily loaded day of the winter season is depicted.

6.4 Results

In this sections, the results of the analysis are described. The total load profile with and without PHEVs is determined to indicate the period of time the vehicles charge or discharge. It is examined which scenario could achieve a feasible solution. The type of fuel used to generate the extra energy to charge the vehicles is investigated as well as the generation cost and the CO_2 emissions.

6.4.1 Loads

The charging profiles for the Belgian zone are described for all scenarios in this paragraph for a penetration level of 10, 20 and 30%. These loads are added to the residential and industrial load of the E-simulate model and the sum is defined as total load. In Fig. 6.1 the total consumption in Belgium is represented for uncoordinated charging. Clearly, the vehicles are mainly charging during the evening hours. Therefore, the peak during these hours is enormously increased. For uncoordinated charging, the vehicles are only charging because no incentives are given to discharge the vehicles.

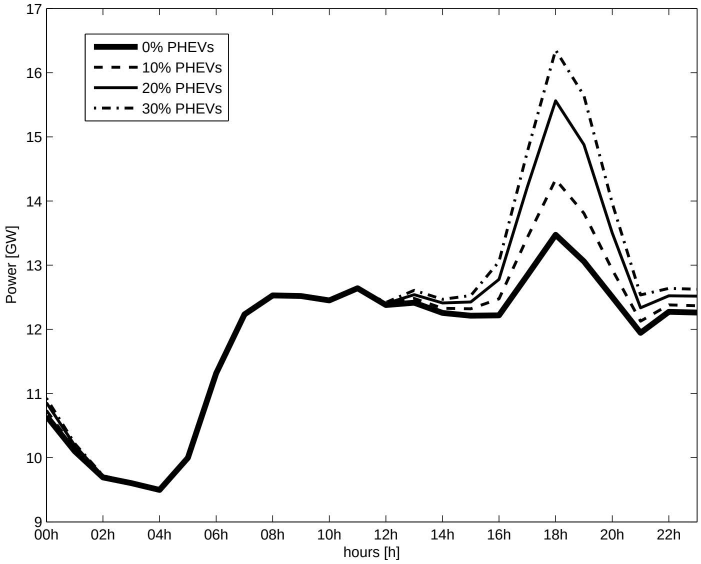

Fig. 6.1: Total load for uncoordinated charging.

In Fig. 6.2 - 6.4, both charging and discharging are possible. The total load for minimizing the charging cost is shown in Fig. 6.2. The night tariff starts at 22h00, so the vehicles discharge before 22h00 to avoid voltage problems and to minimize the charging cost, as shown in Fig. 4.15. At 22h00, a second peak in the evening occurs because the PHEVs start to charge. In case of a penetration level of 20 or 30%, the peak is even larger than the peak caused by residential and industrial loads. The vehicles are now charging overnight. However, the charging profile is not flat, because it has several smaller peaks during the night as mentioned in section 4.5.3.

In Fig. 6.3, the total load, i.e. the sum of the household, residential and PHEV loads, is displayed when power losses are minimized in the distribution grid. This objective function is already described in section 4.5.2. The sum of the industrial and residential loads has a peak at 18h00. This peak during the evening is enlarged because the electric vehicles charge at peak hours. The vehicles discharge when the industrial and residential loads are lower. This can be explained by comparing the

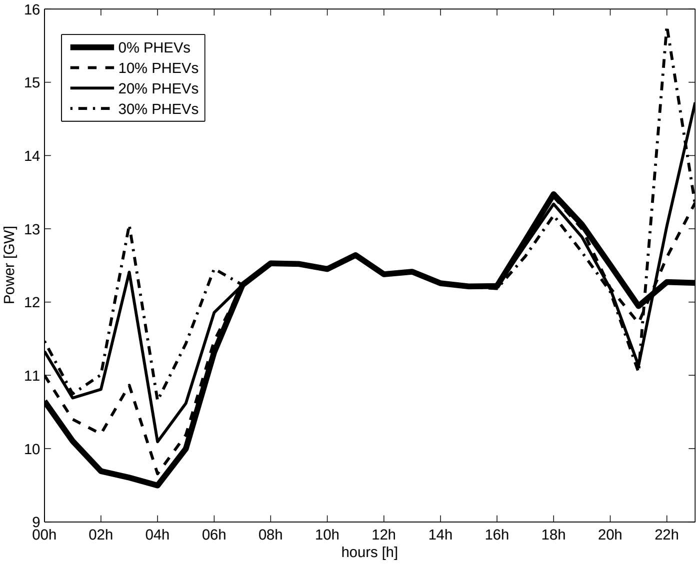

Fig. 6.2: Total load for coordinated charging and discharging and minimization of charging cost.

household loads used to determine the optimal charging profiles and the industrial and residential loads used in the E-simulate model. The peak of the industrial and residential loads occurs earlier compared to the household loads used to determine the optimal charging profiles in previous chapters. Apparently, there is a significant difference between the household loads of the previous chapters and those used in the E-simulate model. In the previous chapters, only household loads are considered and the industrial loads are not taken into account. Therefore, the charging profiles and the total load do not perfectly match. These differences cause a non negligible efficiency loss. An extra peak occurs in the morning as vehicles must be fully charged before their first trip in the morning.

The results of the minimization of the voltage deviations are shown in Fig. 6.4. The vehicles also charge when residential and industrial loads are large, in the evening, and discharge when the peak of the evening is diminished. As explained above, other household profiles are used to determine the optimal charging profiles compared to the residential and industrial loads of the E-simulate model. A small peak occurs in the morning since vehicles must be fully charged before their first trip.

In Fig. 6.5 - 6.7, discharging is no longer possible and the vehicles are only able to charge. In general, the power needed to charge the PHEVs is lower compared to the scenarios in which the vehicles are also able to discharge. In Fig. 6.5, minimization

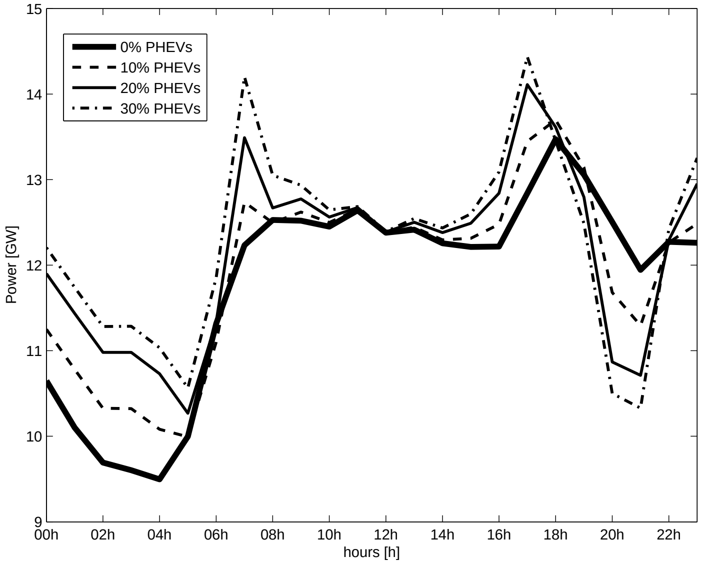

Fig. 6.3: Total load for coordinated charging and discharging and minimization of power losses.

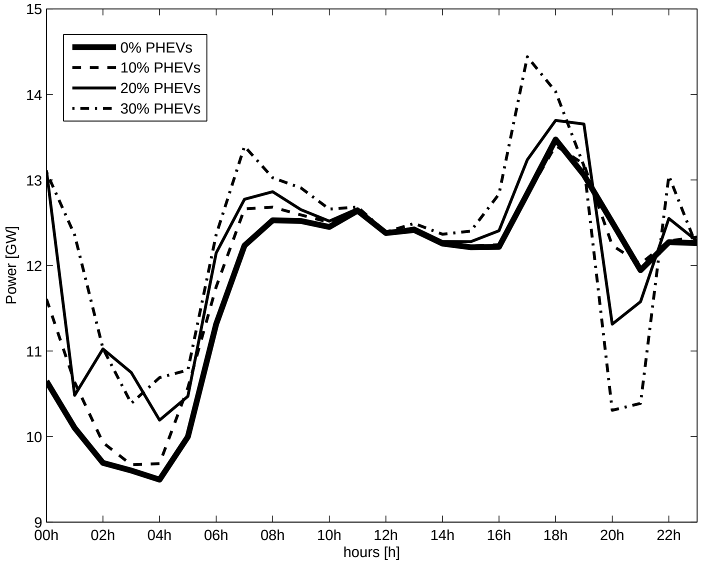

Fig. 6.4: Total load for coordinated charging and discharging and minimization of voltage deviations.

of the cost function is displayed. The vehicles do not discharge before 22h00. A second peak in the total consumption in the evening occurs at 22h00 when the night tariff starts. However, this peak is considerable smaller compared to the scenario in which discharging is also possible. Since the vehicles are now not able to discharge, the energy required to fully charge these vehicles is significantly smaller.

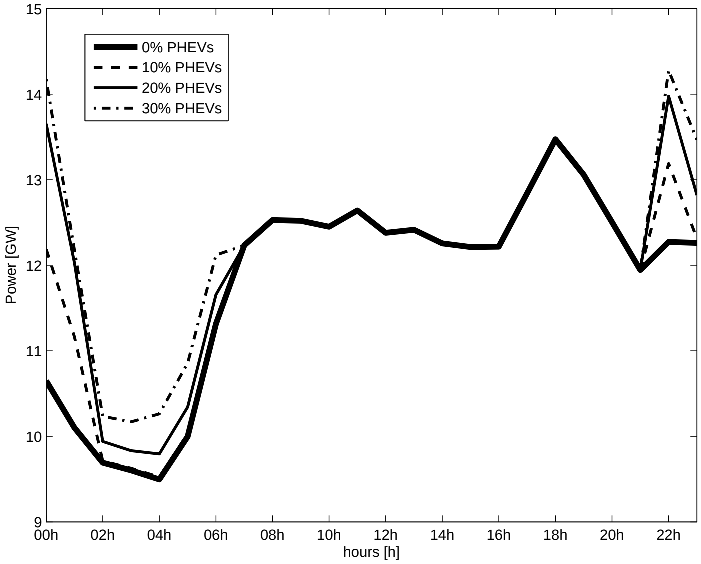

Fig. 6.5: Total load for coordinated charging and minimization of charging cost.

In Fig. 6.6, the power losses in the distribution grid are minimized. The vehicles mainly charge overnight. However, the peak in the evening is slightly enlarged due to vehicles which charge when the evening peak occurs. The charging profile and the residential and industrial loads do not perfectly match for reasons mentioned above. Also, a new peak in the morning occurs. The vehicles mainly charge overnight.

When the voltage deviations are minimized, the vehicles are mainly charging overnight as shown in Fig. 6.7. The peak in the evening is also slightly enlarged. The vehicles charge overnight and still, peaks occur overnight.

6.4.2 Feasibility of the solutions

The feasibility of the solutions for charging and discharging is represented in Table 6.1. For uncoordinated charging, there is not enough capacity for a

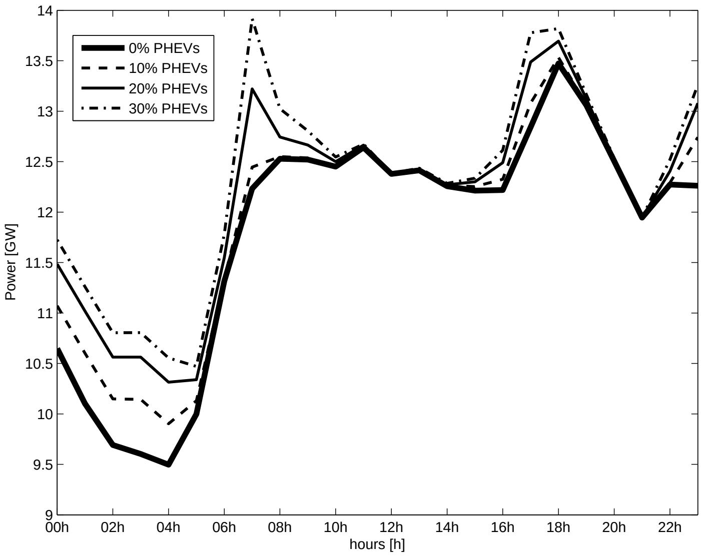

Fig. 6.6: Total load for coordinated charging and minimization of power losses.

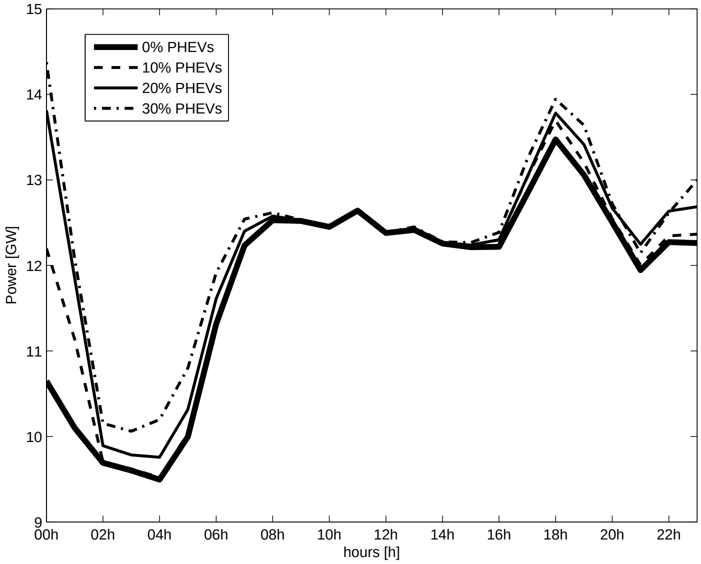

Fig. 6.7: Total load for coordinated charging and minimization of voltage deviations.

penetration level of 20% or more. The vehicles charge when the residential and industrial loads are already large. Therefore, there is not enough peak capacity to provide the extra energy required to charge the PHEVs, even with the four extra power plants which can generate power and transport it into Belgium. In the scenario with the double tariff cost function, the capacity is not enough for a penetration level of 30% due to a large peak in the evening. For the other scenarios, enough generation capacity is available to provide the extra energy.

	Uncoordinated	**Coordinated**		
PHEVs [%]		**charging cost**	**voltage deviations**	**power losses**
10	+	+	+	+
20	-	+	+	+
30	-	-	+	+

Table 6.1: Feasibility of the generation capacity for the scenarios with charging and discharging.

The results are shown in Table 6.2, when discharging is not possible. The energy to be produced to charge the vehicles is lower compared to the scenario in which discharging is made possible. No capacity problems occur when charging is coordinated. The result of uncoordinated charging is represented for the completeness of the table.

6.4.3 Fuel type

The impact on the electricity generation systems is represented in this paragraph. Fig. 6.8 shows the generation per fuel type for an entire day if no PHEVs are present. The solid line represents the load. The load does not always coincide with generation. The difference between the load and the generation is set off by the use of pumped hydro storage and net import. During the night, the generated energy is larger than the load because water is pumped into the storage. During the day, the load is larger compared to the generation because the stored water is used to generate electricity. The generation overnight is clearly lower than during the day. The power plants based on gas mostly take care of the fluctuating demand.

	Uncoordinated	**Coordinated**		
PHEVs [%]		**charging cost**	**voltage deviations**	**power losses**
10	+	+	+	+
20	-	+	+	+
30	-	+	+	+

Table 6.2: Feasibility of the generation capacity for the scenarios with charging.

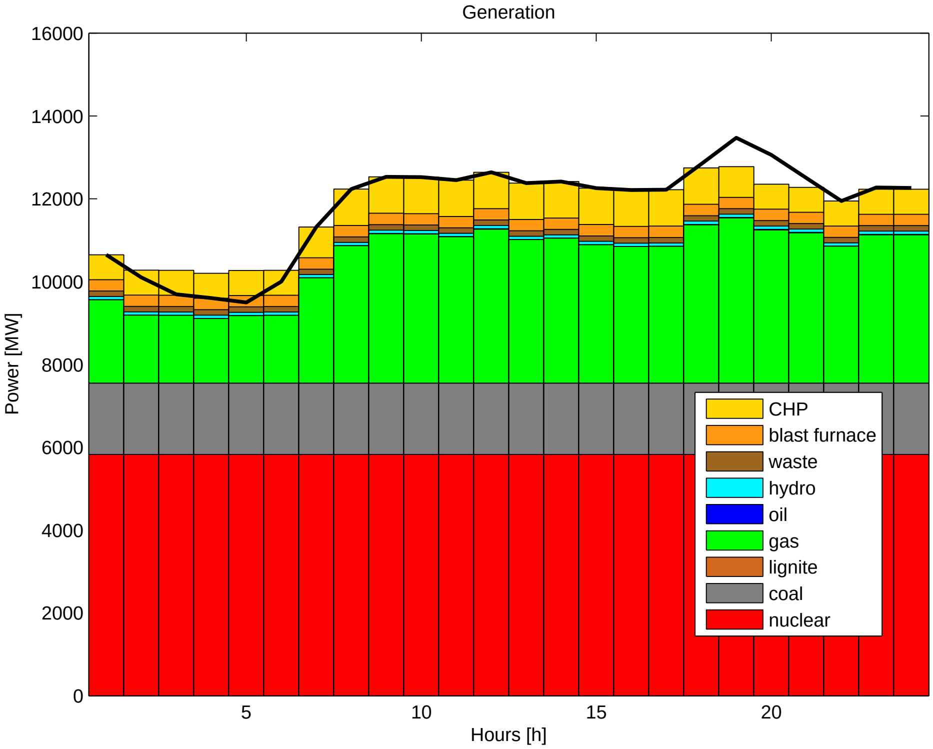

Fig. 6.8: Generation for a penetration level of 0% PHEVs.

A penetration level of 30% is considered for this analysis, because this has a large impact on the total load. The load of the PHEVs takes about 4% of the total load. Uncoordinated charging is not considered as there is no feasible solution for a penetration level of 20% or more. Only charging and not discharging is considered here.

In Fig. 6.9, the results of coordinated charging with the charging cost for double tariff as an objective function are shown. The generation is increased from 22h00, when the night tariff is valid compared to the reference case, in which no vehicles are present. Overnight, from 00h00 up to 07h00, generation is also higher. So the vehicles mainly charge during night. The power plants based on gas will mainly produce the extra energy.

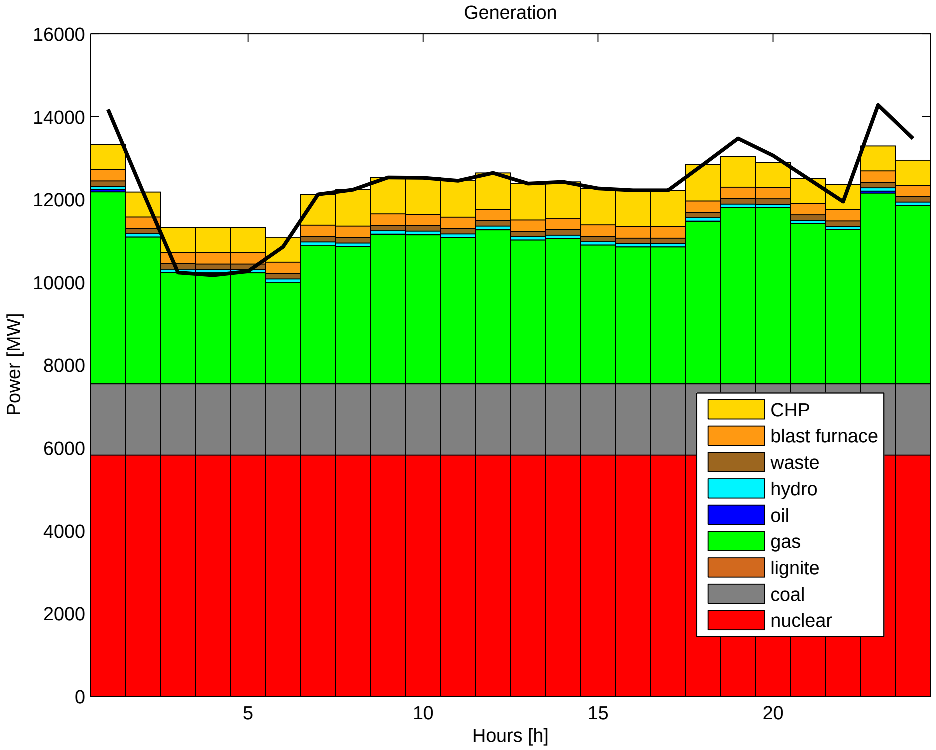

Fig. 6.9: Generation for a penetration level of 30% PHEVs with as objective function a cost function and coordinated charging.

Fig 6.10 shows the generation for coordinated charging and as objective function the power losses in the distribution grid. Generation is increased during the last hour of the day and overnight up to 06h00. The generation profile is more flat overnight because the charging profile is also more flat. Gas power plants take care of the extra electricity generation, but they can produce more or less at a constant power during the night. An extra generation peak now occurs in the morning. Generation is more smooth in the morning for this scenario.

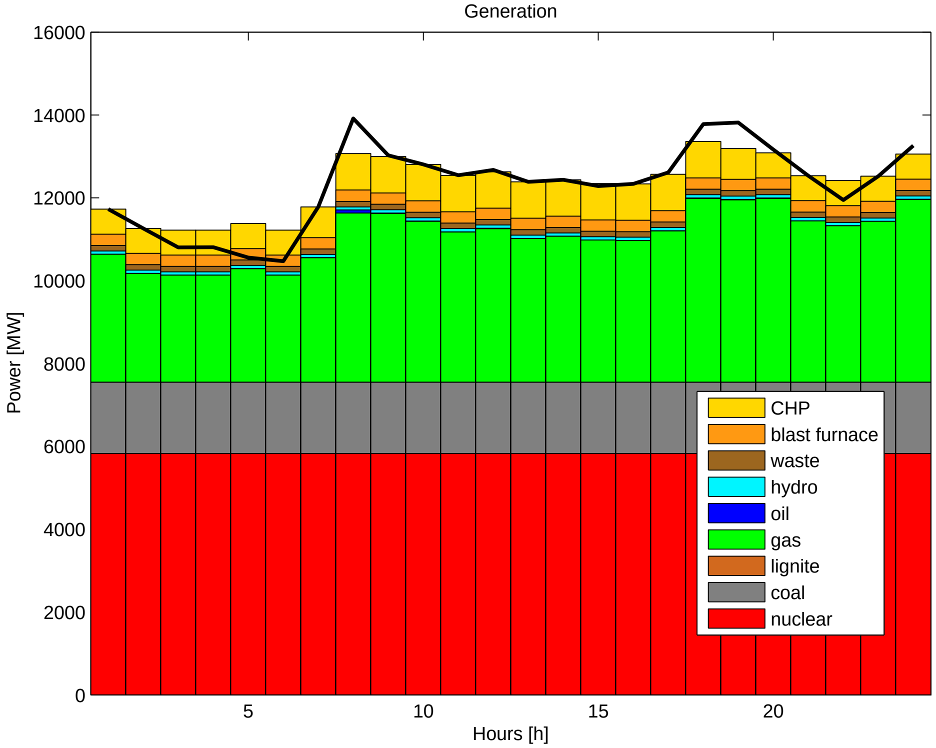

Fig. 6.10: Generation for a penetration level of 30% PHEVs with as objective function a power losses function and coordinated charging.

Fig. 6.11 shows the scenario with as objective function the voltage deviations. Generation during the night has more peaks compared to the previous scenario. Generation mainly increases during the first two hours of the day, i.e. between 00h00 and 02h00. There is a small increase of the generation overnight. It must be emphasized that charging profiles are not determined exactly for the residential load used in E-simulate.

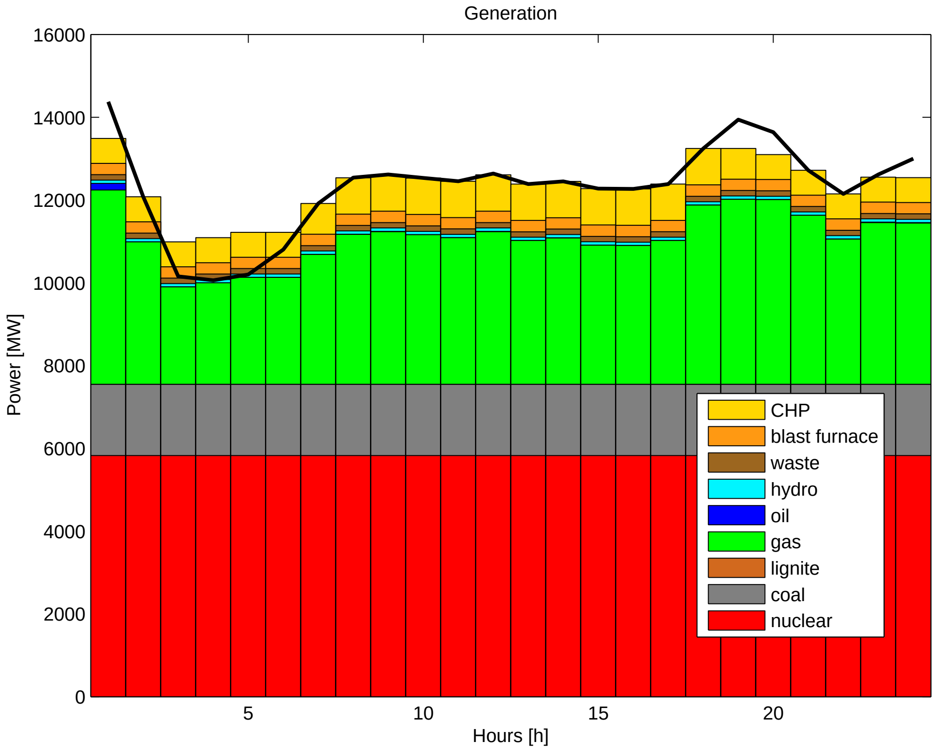

Fig. 6.11: Generation for a penetration level of 30% PHEVs with an objective function a voltage deviation function and coordinated charging.

6.4.4 Generation cost

The additional total generation cost for charging PHEVs is represented in Table 6.3 for all scenarios. This generation cost contains the fuel and start-up costs. The charging cost is compared with the reference scenario, i.e. without vehicles. The extra generation cost is given as a percentage of the generation cost of the reference scenario. The vehicles are only able to charge. As already mentioned in section 6.4, not all scenarios have feasible solutions. Coordination of the charging reduces the generation cost. The difference between the scenarios when coordinated charging is applied is not significant. The scenario in which the cost of charging is minimized for the vehicles owners, does not minimize the generation cost of the power plants. The scenario in which the power losses are minimized gives the lowest cost and the scenario in which the voltage deviations are minimized gives the highest cost. Both the generation cost at the level of the power plants and the charging cost at the level of the distribution grid could be minimized to achieve charging at the lowest cost.

	Uncoordinated	**Coordinated**		
PHEVs [%]		**charging cost**	**voltage deviations**	**power losses**
10	3	2.6	2.7	2.0
20	/	6.6	6.9	5.7
30	/	9.6	10.3	9.5

Table 6.3: Additional generation charging cost for charging PHEVs [%].

Next to the generation cost, the specific energy cost, i.e. the total generation cost divided by the total consumption, is also essential. This energy cost is shown in Table 6.4. If the charging is not managed, the energy cost is the largest. The scenario with the minimization of the power losses in the distribution grid gives the lowest energy cost. If the voltage deviations are minimized, the energy cost is rather large. The scenario with minimization of charging cost reduces the energy cost compared to the scenario with minimization of voltage deviations. However, it is very difficult to give a statement about the impact on the total generation cost. Therefore, more samples and more days of the winter season must be evaluated. It can be concluded that coordination of PHEVs improves the generation and specific energy cost. But it cannot be concluded which of the objective functions gives the best result. The generation and specific energy cost increase when the number of vehicles grows.

6.4.5 Emissions

The additional CO_2 emissions due to the electricity generation of the entire day are calculated in this paragraph for all scenarios. Table 6.5 gives the result for the scenarios for charging. The results are given as a percentage of the reference case, the scenario without PHEVs. The coordination of the charging reduces total emissions. The difference between the scenarios of coordinated charging is not significant. No conclusions can be drawn of which objective function gives the best results. This can be explained because the objective functions are chosen to optimize the impact on the distribution grid and not the impact on the electricity generation systems. Obviously, the total emissions due to electricity generation

	Uncoordinated	**Coordinated**		
PHEVs [%]		**charging cost**	**voltage deviations**	**power losses**
0	0.0198	0.0198	0.0198	0.0198
10	0.0201	0.0200	0.0200	0.0199
20	/	0.0204	0.0205	0.0203
30	/	0.0207	0.0209	0.0207

Table 6.4: Energy cost for charging PHEVs [€/kWh].

increase if the number of vehicles grows. The amount of CO_2/km depends on the consumption of the vehicle and therefore, the net effect cannot be unambiguously calculated.

	Uncoordinated	**Coordinated**		
PHEVs [%]		**charging cost**	**voltage deviations**	**power losses**
10	2.1	1.8	1.9	1.4
20	/	4.1	4.4	4.0
30	/	6.5	6.1	6.1

Table 6.5: Additional CO_2 emissions for charging PHEVs [%].

6.5 Conclusions

The existing E-simulate model is used to determine the impact of a fleet of PHEVs on the electricity generation system. The charging profile for the Belgian zone is summed with the residential and industrial load of the E-simulate model. The household loads, used to define the optimal charging profiles, differ significantly of the residential and industrial loads. This leads to an efficiency loss.

The moment in time of charging is also essential for the power plants. If no coordination system is applied, there is insufficient peak capacity to charge the vehicles. The current capacity is sufficient to charge a maximum penetration level of 30% if the charging is coordinated. The coordination shifts charging to the off-peak hours. If coordinated charging is applied, the charging profiles are determined in such a way that they optimize the utilization of a residential distribution grid and not the electricity generation systems. However, coordination of the charging improves the utilization of the generation capacity compared to uncoordinated charging. In that case, CO_2 emissions and generation cost are reduced. There is no considerable difference between the three scenarios of coordinated charging (and discharging) with different objective functions. In contrast to the previous chapter, it cannot be distinguished which objective function is the most suitable to optimize the generation capacity since these functions are chosen to optimize a distribution grid. Clearly, a better optimization of the generation system can be achieved by optimizing at the level of the generation system by implementing the generation cost and the available capacity of the power plants.

7

Conclusions

7.1 Summary

Plug-in hybrid electric vehicles are gaining popularity in the search for alternative vehicles. At that moment, these vehicles are the most promising alternative, because they still have an internal combustion engine and a fuel tank for emergencies or extending the range. A second alternative are battery electric vehicles, also suffering from a limited range but as battery technology evolves, this handicap is likely to disappear. PHEVs can also drive in full electric mode for a limited distance and the batteries can charge on-board or from the electricity grid and thus reduce the oil dependency. In contrast to alternative vehicles based on hydrogen, the charging infrastructure for PHEVs at home already exists. Nevertheless, reinforcements of the distribution grid may be necessary. PHEVs have some major drawbacks as well. The electric range of these vehicles is rather limited. Their batteries are expensive and remain a critical issue because it is not assured that the lifetime of the batteries equals the lifetime of the vehicles. The size of the battery pack, necessary to drive a certain distance, is also rather large and takes a significant volume in the vehicle. TREMOVE expects that the penetration level of plug-in hybrid electric vehicles is to be 30% of the light duty vehicle fleet by 2030.

In this work, the emphasis lies on the impact of charging PHEVs on the distribution grid. Nowadays, PHEVs become more often the subject of a study in the research domain of the integration of PHEVs, but rarely the impact on the distribution grid in terms of power losses and voltage deviations is investigated. Because of the growing interest in smart grids nowadays, coordination of charging becomes an option to reduce concerns for electric vehicles. In the literature, the valley-fill method is frequently used to improve the impact on the global electricity system. This method does not impose constraints to grid. The method presented in this work gives a more accurate and global overview of the impact of these PHEVs on the low-voltage grid. To the authors opinion, it is too often assumed that PHEVs only cause problems on the level of the electricity generation system. This work indicates that PHEVs may cause serious grid problems on the low-voltage level if the charging of PHEVs is not managed.

PHEVs can charge at varying power and at different locations. Fast charging may be applied in parking lots or at charging stations. Fast charging is not considered in this work because these stations are not connected to the low-voltage grid, but rather to the medium-voltage. Slow charging probably occurs at home and the focus in this work lies on the latter. Although, the energy required to charge these vehicles is only a few percent of the total consumed energy in Belgium, this has a non-negligible impact on the distribution grid because the PHEV loads increase the total load of a residential distribution grid. The impact on the electricity generation system is also investigated. For both, the moment in time when the vehicles charge is crucial. The distribution grid is investigated in terms of grid parameters such as power losses, voltage deviations, feeder and transformer overloads. For the moment, the distribution grid is a passive grid, transformed into an active grid to cope with new technologies such as distributed generation units and plug-in hybrid electric vehicles. Plug-in hybrid electric vehicles can be considered as controllable loads.

Initially, the impact on the distribution grid is analyzed. Some assumptions are made for the model. An adapted IEEE test grid is used as a radial residential distribution grid. Three charging periods are considered, i.e charging during day, overnight and in the evening. If the charging of the batteries of PHEVs is not coordinated, the vehicles likely start to charge when they have the opportunity to plug in or after a fixed start delay. The power rating of the charger is assumed constant at 4 kW. Batteries of the PHEV are depleted at the start of the charging period and must be fully charged at the end. The backward-forward sweep method is performed to obtain the load flow analysis to determine grid parameters. It is observed that the power losses increase when the number of PHEVs increases. The voltage deviations become too large according to the EN50160 standard for uncoordinated charging during the evening when the penetration level of PHEVs is 30% or higher. In the evening, the vehicles are plugged in when arriving from work and charge when the evening peak occurs in the household loads. The extra energy required for charging the plug-in hybrid electric vehicles, must be transported on the already heavily loaded distribution grid at that moment. For charging during the day, problems may occur from a penetration level of 50% or higher. If night charging is applied, no problems occur. Therefore, uncoordinated charging of PHEVs potentially lead to reliability and instability problems and must be coordinated to avoid grid problems.

This coordination optimizes the use of the grid by minimizing the power losses. The objective function, i.e. the sum of the power losses, is a quadratic function of the transported power. Since the constraints are linear, the quadratic programming technique can be applied. In this case, the power rating of the charger is no longer constant, but can vary between 0 and 4 kW. The optimization program determines for each connected PHEV the optimal charging profile minimizing grid impact. Coordinated charging reduces the power losses and also voltage deviations. The vehicles now charge at the moment the household load is lower. The voltage problems in the evening, in the assumption that the charging period of the PHEVs is limited to the evening between 18h00 and 21h00, cannot be solved for a penetration level of 40% or higher. During the evening, the charging period is rather short and there are not much opportunities to optimize charging. However, penetration levels above 40% can be supported during night and day if coordinated charging is applied. Coordinated charging can be implemented by a smart meter and real-time pricing to avoid charging at moments the distribution grid is already heavily loaded. This is defined as load shifting or demand-side-management.

Up till now, only deterministic data is used; perfect forecasting of the household loads and the availability of the PHEVs are assumed. A variation of the household loads is applied to introduce an error in forecasting, but these variations do not have a major impact on the results. Although, it is important to know when the peak load occurs, the level of the peak is not important because charging during these peaks is already avoided. Another programming technique, i.e. dynamic programming, is also considered. This technique leads to a higher computation time and required storage and the results are not improved. Therefore, this technique is not further analyzed.

The impact on a small distribution grid is investigated for a PHEV penetration level of 30% and overnight charging. The reference case is the scenario without PHEVs. No grid problems occur in this case. If PHEVs charge without coordination, the transformer and the feeder must be upgraded and the grid reinforced. However, if the charging of the PHEVs is coordinated, such reinforcements can be postponed. However, the remaining capacity of the feeders and transformers is reduced. For the coordination of the charging, smart meters must be implemented. Both reinforcement of the grid and the implementation of smart meters lead to extra costs for the DSO.

When PHEVs are connected to the electricity grid, they can charge, but they also have the opportunity to reinject energy into the grid and thus support the grid to ensure stability and reliability. This is defined as vehicle-to-grid operation. Grid services, such as primary and secondary frequency control are possible for PHEVs, but may not be profitable for the PHEV owner. The energy and capacity payment may not compensate for the wear of the batteries. The power, delivered for tertiary control, is too large and the duration too long to be feasible. Voltage regulation and load management are the only grid services that are considered in this work and easy to implement. Coordinated charging can already be considered as load management and thus as a kind of grid service since the load is shifted from the peak to the off-peak hours. The voltage control is implemented for one specific heavily loaded day during winter. Without any PHEVs, no voltage problems occur during charging between 19h00 and 06h00. For a PHEV penetration level of 10% and without any coordination system, voltage problems occur during the evening peak and for higher penetration levels, also overnight. For coordinated charging, the objective function can be a cost function with a double tariff, i.e. night and day tariff. An extra voltage constraint is added to the list of constraints to limit voltage deviations. As a result, voltage problems are solved in all cases when coordinated charging is implemented. If there is any energy left in the batteries when the vehicles arrive at home from work, vehicles discharge until 22h00, when the night tariff starts. This example shows that it is possible to solve the voltage problems for a heavily loaded day. It is uncertain that voltage problems can be solved if there are already problems without PHEVs connected. To solve the voltage problems in that case, PHEVs must be connected when the voltage is too low and must have enough energy left in their batteries to inject into the grid.

For coordinated charging, several objective functions can be investigated to compare the grid impact. Three objective functions are discussed, i.e minimization of power losses, voltage deviations and charging cost. If the charging cost is minimized, no incentive is given to improve the grid quality because the loads of the grid are not incorporated in the objective function. If there is any energy left in the battery, they discharge until 22h00. When the night tariff starts at 22h00, the vehicles are starting to charge, but the household load is still large. Therefore, this has a significant impact on the grid. The vehicles charge rather randomly overnight. For the second objective function, i.e. the minimization of the voltage deviations, the loads are indirectly incorporated in the objective function via the nodal voltages and currents. This objective function ensures that the charging does not occur during the peak hours as the voltage deviations become too large. If the household loads are high, the vehicles discharge to raise the voltage level. The third objective function is the minimization of the power losses. The household loads are directly incorporated in the power losses function. This objective function gives a flat profile for the total load overnight, preferable for the power plants as in that way they can generate energy at constant power and operate in their optimal working point. Such a flat profile cannot be achieved during the day, because not enough vehicles are connected to discharge and to reduce the large peaks in the load. If vehicles are able to discharge, they discharge during the peak hours and most of the batteries of these vehicles are depleted. More energy must be stored in the batteries during the night increasing power consumption overnight. If the vehicles are not able to discharge, their batteries are not fully depleted when they arrive at home from work. Therefore, consumption during the night is lower.

To give a more general overview, a simulation of an entire day, is performed. Driving profiles for full-time employees are modelled with the availability analysis. If charging is not coordinated, voltage problems occur for a penetration level of 50% or more. The voltage problems occur at the end of the distribution grid. The coordination of charging reduces the percentage of excessive voltage deviations significantly. PHEVs can also be combined with distributed generation units such as photovoltaic panels, wind turbines and CHP. All three are connected to the low-voltage grid. The excess of energy generated by DG units can be used to charge PHEVs. If the sum of the household load, the DG load and the load of PHEVs is smaller than zero, there is injection of energy in the grid. Consequently, the power plants or the DG units must be curtailed if this causes too large voltage levels on the distribution grid. Without coordination, the DG units and PHEVs are not matched well. This must be avoided. Therefore, matching DG units and PHEVs must be coordinated. Generally, if the penetration level of DG units is increased, the number of excessive voltage deviations decrease. When the charging cost is used as objective function, the vehicles discharge when the electricity price is high and at the same moment the DG units generate energy. A more complex coordination system is required, including loads. On the other hand, if the power losses are considered as objective function, PHEVs and DG units can perfectly match for this specific day. This analysis states that it is possible to combine PHEVs with DG units for this specific day. However, it may be assumed that for other heavily loaded days, the combination of DG units and PHEVs is also possible. Nevertheless, the values of the result may differ.

If charging at work is possible, vehicles can be fully charged when they drive home from work. Therefore, they can start twice a day with a fully charged battery. This increases the proportion of electric driving. This scenario is also more demanding for the distribution grid because the vehicles have an extra opportunity to charge the batteries.

Charging of PHEVs does not only have an impact on the distribution grid because the extra energy required must not only be transported but also generated. With the program E-simulate, the impact on the electricity generation system is investigated and the estimated energy is studied for a penetration level up to 30%. The charging profiles, determined for the three objective functions, are also considered. Without any charging coordination system, the vehicles mostly charge during the evening peak, when the vehicle owner arrives at home. There is not enough peak capacity to ensure the provision of the extra energy required to charge vehicles during peak hours. Coordination of the charging and discharging can almost solve this problem. If discharging is possible, the scenarios with the minimization of the power losses and the voltage deviations do not show capacity problems. For the minimization of the charging cost, generation problems occur for a penetration level of 30%. If discharging is made unavailable, no generation problems at all occur. The reason is that not all batteries are depleted at the end of the day and less energy is required to fully charge them compared to the scenario where discharging is available and the vehicles discharge during peak hours. The energy, injected into the grid, must also be stored in the batteries at a later moment. If coordinated charging is applied, mostly the gas power plants generate the extra energy for the PHEVs. The impact of the objective functions on the generation and the emissions is not significant. However, it is clear that the coordination of charging, in general, reduces the emissions and the generation cost in all cases. It must be stressed that the objective functions, used to determine the optimal charging profiles, are those optimizing the use of the distribution grid. Further optimizations of the electricity generation system are of course possible if the parameters of this system are taken into account.

In general, uncoordinated charging of a significant amount of PHEVs lead to problems for both grid and generation system. Fortunately, the coordination of the charging can reduce this problem for both systems. It is important to incorporate loads into the optimization problem to minimize the grid impact. The double tariff function is not suited to avoid grid and generation problems. Therefore, a more flexible pricing system must be introduced. The minimization of the voltage deviation reduces the power losses and voltage deviations, but the charging profile still shows large peaks. The scenario in which the power losses are reduced gives the best results. The power losses and voltage deviations are significantly reduced compared to uncoordinated charging. The charging profile is determined in such a way that the total load of the grid, especially during night, is a flat profile. This flat profile is preferable for the power plants. This means that the plants can deliver a constant power. Moreover, power plants could operate in their optimal working point and achieve a better performance. The conclusions of this work are only valid for the described model, containing a well described PHEV model, household loads, driving profiles etc. Obviously, other parameters give other results. However, it still can be postulated that the charging of PHEVs has considerable impact on the electricity system in general and neglecting a coordination management lead for certain to problems for these systems. However, the amount of the PHEVs, required to make the grid instable, depends on the layout of the grid, which can differ locally. Also, in a local distribution grid which is already heavily loaded problems occur much faster compared to for instance a new local distribution grid with large reserve capacity for reasons of growth.

7.2 Future work

This research fits in a larger domain in which the transition from a passive grid to an active or smart grid is investigated. The research area is still very new and under development. In a smart grid, not only PHEVs are considered, but also distributed generation units etc. All technologies must be considered as an interactive system and matched. The communication between PHEV owners or fleet managers, distributed generation units and the DSOs are becoming important in future. The requirements for the communication, such as the real-time demands and the limitations of the band that is needed to have a good working smart grid, need further research.

Most of the distribution grids are radial grids. The IEEE test grid is only one example of a radial residential distribution grid. Not only houses with garages could be considered, but also apartment blocks, town houses without garages, SMEs and schools. The impact on these different types of buildings or a combination can be investigated. The test grid contains only 33 nodes of households. A larger grid must be considered to give a more global overview.

Synthetic household loads and measurements are used. To get more general applicable results, better and more varied household loads must be measured and utilized in this optimization problem. The shape of the household loads can have a large impact on the optimal charging profiles and thus the achieved results. The exact forecasting of the type of household load, for instance when the evening peak occurs, is essential. Maybe it is necessary to have a household profile combined with a type of house as mentioned in the paragraph above.

Also the driving profiles are important. Since only full-time employees are considered in this work, other type of vehicle owners must also be investigated. Business models are important to give an idea which type of vehicles different kind of households will have in future.

Obviously, the psychological behaviour of the PHEV owners is essential. Not enough information is achieved at this moment to give a global overview. An important question that arises is whether PHEV owners will play on the safe side and add more energy to their batteries than necessary to fulfil the daily distances.

In this work, the combination of distributed generation units and PHEVs is initiated. However, this area is not fully explored and more investigation is necessary to optimize this combination. The growing interest in PV panels has an impact on the distribution grid. If these panels generate energy during the day, when the load is already low, the voltage level may be too high. PHEVs could be linked with these panels. PHEVs could also be used as storage when the electricity price is low and reinject energy into the grid when the price is high.

Three objective functions are investigated, i.e. the minimization of the power losses, voltage deviations and charging cost. The impact of these functions on the grid parameters is examined. Other objective functions such as a charging cost function with real-time pricing can also be considered. Even, a multi-objective optimization program, using two or more objective functions, could also be of interest. Other optimization programming techniques or other solvers may be used for this optimization problem.

The objective functions of the optimization problem are selected to minimize the local grid impact, on the level of the distribution grid or low-voltage grid. This work demonstrates that charging PHEVs also has an impact on the electricity generation system. The optimal charging profiles, determined by the optimization program, locally minimize the grid impact, but do not minimize the impact on the electricity generation system as a whole. If the impact on the electricity generation system is investigated, the objective functions must contain parameters of this system. Eventually, both systems could also be investigated together.

The optimization model requires a lot of forecasting. For instance the driving profiles, the load of the households and the behaviour of the PHEV owners must be forecasted. Since errors will be introduced in this forecasting problem, the forecasting could be changed by real-time adjustments.

A

Sensitivity analysis: summer

The results of the sensitivity analysis for the summer are represented. The same conclusions as for the winter can be drawn. In general, the power losses and the voltage deviations are lower for the summer compared to the winter due to the reduced household demands.

Scenario	**Charging period**	**30% uncoordinated**	**30% coordinated**
Beginning of the grid	**21h00-06h00**	1.4	1.3
	18h00-21h00	2.6	2.5
	10h00-16h00	1.9	1.7
End of the grid	**21h00-06h00**	3.0	2.6
	18h00-21h00	7.8	7.2
	10h00-16h00	4.6	3.9

Table A.1: Placement of PHEVs: average of the ratio of power losses to total power [%].

Scenario	**Charging period**	**30% uncoordinated**	**30% coordinated**
Beginning of the grid	**21h00-06h00**	3.8	3.3
	18h00-21h00	5.4	5.0
	10h00-16h00	4.8	3.8
End of the grid	**21h00-06h00**	6.1	4.2
	18h00-21h00	10.6	9.1
	10h00-16h00	8.7	5.6

Table A.2: Placement of PHEVs: average of the maximum voltage deviations [%].

Scenario	**Charging period**	**0%**	**30% uncoordinated**	**30% coordinated**
Short	**21h00-06h00**	0.5	1.1	0.9
	18h00-21h00	0.7	2.3	2.2
	10h00-16h00	0.6	1.5	1.3
Long	**21h00-06h00**	1.7	3.5	3.0
	18h00-21h00	2.2	8.3	7.7
	10h00-16h00	2.0	5.2	4.4

Table A.3: Length of the lines of the grid: average of the ratio of power losses to total power [%].

Scenario	**Charging period**	**0%**	**30% uncoordinated**	**30% coordinated**
Short	**21h00-06h00**	1.5	2.4	1.8
	18h00-21h00	1.4	3.8	3.4
	10h00-16h00	1.4	3.3	2.3
Long	**21h00-06h00**	4.7	7.9	5.7
	18h00-21h00	4.5	13.2	11.4
	10h00-16h00	4.5	11.0	7.3

Table A.4: Length of the lines of the grid: average of the maximum voltage deviations [%].

Scenario	**Charging period**	**30% uncoordinated**	**30% coordinated**
6 kWh	**21h00-06h00**	1.8	1.5
	18h00-21h00	3.7	3.3
	10h00-16h00	2.4	2.2
16 kWh	**21h00-06h00**	3.0	2.4
	18h00-21h00	NA	NA
	10h00-16h00	4.4	3.8

Table A.5: Battery capacity: average of the ratio of power losses to total power [%].

Scenario	**Charging period**	**30% uncoordinated**	**30% coordinated**
6 kWh	**21h00-06h00**	4.4	3.2
	18h00-21h00	7.6	5.3
	10h00-16h00	5.4	3.9
16 kWh	**21h00-06h00**	6.2	4.2
	18h00-21h00	NA	NA
	10h00-16h00	8.2	6.0

Table A.6: Battery capacity: average of the maximum voltage deviations [%].

Scenario	**Charging period**	**30% uncoordinated**	**30% coordinated**
2000 W	**21h00-06h00**	2.1	1.9
	18h00-21h00	NA	NA
	10h00-16h00	2.9	2.8
3333 W	**21h00-06h00**	2.2	1.9
	18h00-21h00	4.7	4.7
	10h00-16h00	3.2	2.8

Table A.7: Power rating of the charger: average of the ratio of power losses to total power [%].

Scenario	**Charging period**	**30% uncoordinated**	**30% coordinated**
2000 W	**21h00-06h00**	4.4	3.7
	18h00-21h00	NA	NA
	10h00-16h00	5.4	4.7
3333 W	**21h00-06h00**	4.8	3.7
	18h00-21h00	7.3	7.3
	10h00-16h00	6.8	4.7

Table A.8: Power rating of the charger: average of the maximum voltage deviations [%].

B

Grids

The IEEE 34 node test feeder [72] is displayed in Fig. B.1. This grid is based on an actual distribution grid of Arizona in the USA with a rated voltage of 24.9 kV. Originally, two voltage regulators and a transformer are present. These three components are neglected in this work. The original grid has two feeder types, however in this work, only one feeder type is considered. The voltage of the grid is down-scaled to 230 V. The length of the lines is shown in Table B.1.

node i	**node j**	**length [feet]**
1	2	2580
2	3	1730
3	4	32230
3	5	5804
5	6	37500
6	7	29730
7	8	10
8	9	310
8	10	1710
9	11	10210
11	12	48150
10	13	13740
10	14	3030
14	15	840
15	16	20440
16	17	520
16	18	23330
15	16	36830
18	19	10
19	20	4900
19	21	10
21	22	10560
20	23	1620
20	24	5830
24	25	280
25	26	1350
26	27	3640
27	28	530
24	29	2020
29	30	2680
30	31	860
30	32	280
32	33	4860

Table B.1: IEEE 34 node test feeder.

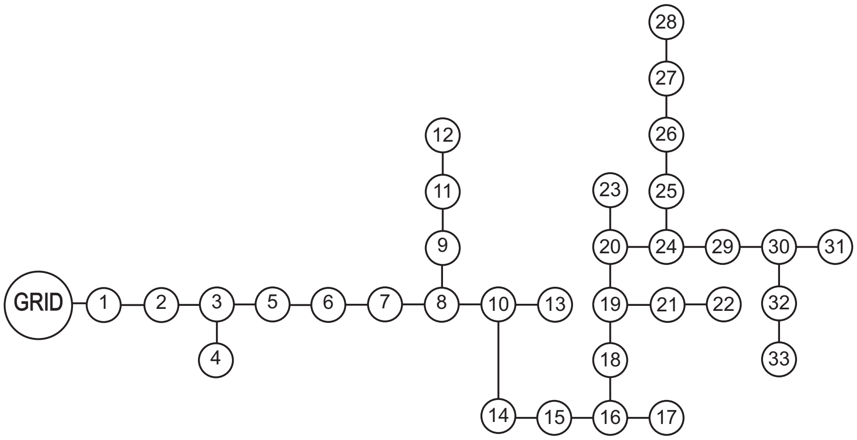

Fig. B.1: IEEE 34 node test feeder [72].

Bibliography

[1] International Energy Agency, *Energy Technology Perspectives 2006, Scenarios & Strategies to 2050*, I.E.A. Paris, Ed., 2006.

[2] F. Robelius, "Giant Oil Fields, The Highway to Oil," Ph.D. dissertation, University of Uppsala, 2007.

[3] S. Hadley, "World Energy Outlook 2009," OECD Internation Energy Agency, Tech. Rep., 2009.

[4] International Energy Agency, "Transport, Energy and CO_2: Moving towards Sustainability, Executive Summary," Tech. Rep., 2009.

[5] United Nations, "Kyoto Protocol to the United Nations Framework Convention on Climate Change," Tech. Rep., 1998.

[6] Commission of the European Communities, "20 20 by 2020: Europe's climate change opportunity," Tech. Rep., 2008.

[7] The European Parliament and the Council of the European Union, "Setting emission performance standards for new passenger cars as part of the Communitys integrated approach to reduce CO_2 emissions from light-duty vehicles," *Official Journal of the European Union*, 2009.

[8] ——, "Regulation (EC) No 715/2007, on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (EURO 5 and EURO 6) and on access to vehicle repair and maintenance information," *Official Journal of the European Union*, 2007.

[9] G. Offer, D. Howey, M. Contestabile, R. Clague, and N. Brandon, "Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system," *Energy Policy*, vol. 38, no. 1, pp. 24–29, 2010.

[10] D. Nagelhout and J. Rosenkranz, "Electric driving: Evaluating transition based on system options," Netherlands Environmental Assessment Agency, Tech. Rep., 2009.

[11] D. Haeseldonckx and W. D'haeseleer, "The use of the natural-gas pipeline infrastructure for hydrogen transport in a changing market." *Internation Journal of Hydrogen Energy*, vol. 32, pp. 1381–1386, 2007.

[12] K. Jorgensen, "Technologies for electric, hybrid and hydrogen vehicles: Electricity from renewable energy sources in transport," *Utilities Policy*, vol. 16, no. 2, pp. 72–79, 2008.

[13] H. Maclean and L. Lave, "Evaluating automobile fuel/propulsion system technologies," *Progress in Energy and Combustion Science*, vol. 29, no. 1, pp. 1–69, 2003.

[14] C. Chan and K. Chau, *Modern electric vehicle technology*, P. Hammond, T. Miller, and T. Kenjo, Eds. Oxford Science Publication, 2001.

[15] I. Husain, *Electric and hybrid vehicles: Design fundamentels.* CRC Press, 2003.

[16] J. Miller, *Propulsion Systems for Hybrid Vehicles.* London : IEE, 2004.

[17] M. Ehsani, Y. Gao, and J. M. Miller, "Hybrid Electric Vehicles: Architecture and Motor Drives," *Proceedings of the IEEE*, vol. 95, no. 4, pp. 719–728, 2007.

[18] G. Passier, F. V. Conte, S. Smets, F. Badin, A. Brouwer, M. Alaküla, and D. Santini, "Status Overview of Hybrid and Electric Vehicle Technology," International Energy Agency, Tech. Rep., 2007.

[19] J. Kluge, P. Radtke, H. Wallentowitz, and G. Erdmann, "DRIVE - The Future of Automotive Power," McKinsey&Company, Tech. Rep., 2006.

[20] M. Anderman, "The challenge to fulfill electrical power requirements of advanced vehicles," *Journal of Power Sources*, vol. 127, no. 1-2, pp. 2–7, March 2004.

[21] S. Wirasingha, N. Schofield, and A. Emadi, "Plug-in hybrid electric vehicle developments in the US: Trends, barriers, and economic feasibility," in *2008 IEEE Vehicle Power and Propulsion Conference*, pp. 1–8.

[22] A. Raskin and S. Shah, "The emerge of hybrid electric vehicles," Alliance Bernstein, Tech. Rep., 2006.

[23] P. Denholm and W. Short, "An Evaluation of Utility System Impacts and Benefits of Optimally Dispatched Plug-In Hybrid Electric Vehicles," National Renewable Energy Laboratory, Tech. Rep., October 2006.

[24] P. Taylor and T. Kerr, "Technology Roadmap: Electric and plug-In hybrid electric vehicles," 2009.

[25] C. Samaras and K. Meisterling, "Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy." *Environmental Science Technology*, vol. 42, pp. 3170–3176, 2008.

[26] S. Hadley, "Potential impacts of plug-in hybrid electric vehicles on regional power generation," Oak Ridge National Laboratory, U.S. Department of Energy, Tech. Rep., 2008.

[27] I. Buchmann. What's the best battery? (Last accessed August 2010). [Online]. Available: www.Batteryuniversity.com

[28] P. Häring and H. Giess, "High rate recharge of stationary VRLA batteries," *Journal of Power Sources*, vol. 95, no. 1-2, pp. 153–161, 2001.

[29] J. Taylor, A. Maitra, M. Alexander, D. Brooks, and M. Duvall, "Evaluation of the impact of plug-in electric vehicle loading on distribution system operations," in *2009 IEEE Power & Energy Society General Meeting*, pp. 1–6.

[30] E. Valsera-Naranjo, A. Sumper, P. Lloret-Gallego, R. Villafafila-Robles, and A. Sudria-Andreu, "Electrical vehicles: State of art and issues for their connection to the network," in *2009 10th International Conference on Electrical Power Quality and Utilisation.* IEEE, 2009, pp. 1–3.

[31] C. Rosenkranz, U. Köhler, and J. L. Liska, "Modern Battery System for Plug-In HEV," Johnson Controls-SAFT, Tech. Rep., 2007.

[32] P. Van den Bossche, F. Vergels, J. Van Mierlo, J. Matheys, and W. Van Autenboer, "SUBAT: An assessment of sustainable battery technology," *Journal of Power Sources*, vol. 162, no. 2, pp. 913–919, 2006.

[33] M. Werber, M. Fischer, and P. V. Schwartz, "Batteries: Lower cost than gasoline?" *Energy Policy*, vol. 37, no. 7, pp. 2465–2468, 2009.

[34] S. De Breucker, P. Jacqmaer, and J. Driesen, "Grid Power Quality Improvements Using Grid-Coupled Hybrid Electric Vehicles with a Dual Energy Storage System." in *European Ele-Drive Transportation Conference*, Geneva, Switzerland, 2008.

[35] D. Sauer and R. De Doncker, "Evolution of Batteries and Charging Concepts," in *Seminar Clean Mobility, Limburg Catholic University College, Diepenbeek, Belgium*, 2008.

[36] Altairnano. (2000) NanoSafe Battery Technology. (Last accessed August 2010). [Online]. Available: http://konoctieaa.org/news/articles/NanoSafeBackgrounder060920.pdf

[37] W. Tahil, "The Trouble with Lithium, Implications of Future PHEV production for Lithium Demand," Meridian International Research, Tech. Rep., 2006.

[38] Department for Business Enterprise and Regulatory Reform: Department for Transport, United Kingdom, "Investigation into the Scope for the Transport Sector to Switch to Electric Vehicles and Plugin Hybrid Vehicles," Tech. Rep., 2008.

[39] F. Kalhammer, B. Kopf, D. Swan, V. Roan, and M. Walsh, "Status and prospects for Zero Emissions Vehicle Technology," ARB Independent Expert Panel, Tech. Rep., 2007.

[40] C. Hatton, S. Beella, J. Brezet, and Y. Wijnia, "Charging stations for Urban Settings: the design of a product platform for electric vehicle infrastructure in Dutch cities," in *Electric Vehicle Symposium 24*, Stavanger, Norway, 2009.

[41] R. Tichy and J. Van Zwol, "Fast Charge Becomes a Reality For Li-ion Batteries," Power Electronics Technology, Tech. Rep., 2007.

[42] B. Sovacool and R. Hirsh, "Beyond batteries: An examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition," *Energy Policy*, vol. 37, pp. 1095–1103, 2008.

[43] C. Cai, D. Du, and Z. Liu, "Advanced Traction Rechargeable Battery System For Cableless Mobile Robot," in *International Conference on Advanced lntelllgent Mechatronics AIM*, 2003.

[44] C. Botsford and A. Szcezepanek, "Fast Charging vs. Slow Charging: Pros and Cons for the New Age of Electric Vehicles," in *Electric Vehicle Symposium 24*, Stavanger, Norway, 2009.

[45] P. Clasquin and R. Lowenthal, "The need for a smart charging infrastructure," in *Electric Vehicle Symposium 24*, Stavanger, Norway, May 2009.

[46] FOD Economie, K.M.O., Middenstand en Energie. Afgelegde afstanden in het verkeer, (Covered distances in traffic). (Last accessed August 2010). [Online]. Available: http://statbel.fgov.be/nl/statistieken/cijfers/verkeer_vervoer/verkeer/afstand/index.jsp

[47] T. Becker and I. Sidhu, "Electric Vehicles in the United States: A New Model with Forecasts to 2030," Center for Entrepreneurship & Technology University of California, Berkeley, Tech. Rep., 2009.

[48] S. Logghe, B. Van Herbruggen, and B. Van Zeebroeck, "Emissions of road traffic in Belgium," Transport and Mobility Leuven, Tech. Rep., 2006.

[49] TREMOVE. A policy assessment model to study the effects of different transport and environment policies on the transport sector for all European countries. (Last accessed August 2010). [Online]. Available: www.tremove.org

[50] FPS Economy, SMEs, Self-employed And Energy. Grootte van het voertuigenpark 2009, (Size of the vehicle fleet 2009). (Last accessed August 2010). [Online]. Available: economie.fgov.be

[51] M. Duvall and E. Knipping, "Environmental Assessment of Plug-In Hybrid Electric Vehicles Volume 1: National wide Greenhouse Gas Emissions," Electric Power Research Institute, Tech. Rep., 2007.

[52] C. Camus, C. Silva, T. Farias, and J. Esteves, "Impact of Plug-in Hybrid Electric Vehicles in the Portuguese electric utility system," in *2009 International Conference on Power Engineering, Energy and Electrical Drives.* IEEE, 2009, pp. 285–290.

[53] C. Silva, M. Ross, and T. Farias, "Evaluation of energy consumption, emissions and cost of plug-in hybrid vehicles," *Energy Conversion and Management*, vol. 50, no. 7, pp. 1635–1643, 2009.

[54] Chevrolet Volt. Chevy volt concept car. (Last accessed August 2010). [Online]. Available: www.chevy-volt.net

[55] U.S. Environmental Protection Agency. What Are the Six Common Air Pollutants? (Last accessed August 2010). [Online]. Available: http://www.epa.gov/air/urbanair/

[56] Flemish Regulation Entity for the Electricity and Gas market. Meteropneming - Gemiddeld verbruik, (Measurement - Average consumption). (Last accessed August 2010). [Online]. Available: http://www.vreg.be/nl/04_prive/05_meteropneming/04_verbruik.asp

[57] A. Wei, "Hymotion Unveils Plug-in Hybrid Kits for Toyota and Ford Hybrids," Green Car Congress, Tech. Rep., February 2006.

[58] Daimler Chrysler, "Overview of DC ZEV Activities," Sacramento, CA, Tech. Rep., 2006.

[59] W. D'haeseleer, "Belgium's energy challenges towards 2030," Commission Energy 2030, Tech. Rep., 2006.

[60] K. Dyke, N. Schofield, and M. Barnes, "Analysis of Electric Vehicles on Utility Networks," in *Electric Vehicle Symposium 24*, Stavanger, Norway, May 2009.

[61] W. Kempton and J. Tomic, “Vehicle-to-grid power fundamentals: Calculating capacity and net revenue,” *Journal of Power Sources*, vol. 144, no. 1, pp. 268–279, 2005.

[62] M. Kintner-Meyer, K. Scheider, and R. Pratt, “Impacts Assessment of Plug-In Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids Part 1: Technical Analysis,” Pacific Northwest National Laboratory, Tech. Rep., 2007.

[63] C. Yang and R. McCarthy, “Electricity Grid: Impacts of Plug-In Electric Vehicle Charging,” Air & Waste Management Association, Tech. Rep., 2009.

[64] S. Blumsack, C. Samaras, and P. Hines, “Long-term electric system investments to support Plug-in Hybrid Electric Vehicles,” in *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*. IEEE, 2008, pp. 1–6.

[65] A. Maitra, J. Taylor, D. Brooks, M. Alexander, and M. Duvall, “Integrating plug-in-electric vehicles with the distribution system,” in *20th International Conference on Electricity Distribution*. Prague: CIRED, June 2009.

[66] A. Jongepier. (2007) Ageing networks: Consume, prolong and replace. Leonardo Energy. (Last accessed August 2010). [Online]. Available: http://www.leonardo-energy.org/ageing-networks-consume-prolong-or-replace

[67] E. Peeters, C. Develder, J. Das, J. Driesen, and R. Belmans, “Linear: towards a breakthrough of smart grids in flanders,” in *I-SUP*, 2010.

[68] E. Veldman, M. Gibescu, J. Slootweg, and W. L. Kling, “Technical benefits of distributed storage and load management in distribution grids,” in *2009 IEEE Bucharest PowerTech*, Bucharest, Romania, June, pp. 1–8.

[69] E. Veldman, M. Gibescu, A. Postma, H. Slootweg, and W. Kling, “Unlocking the hidden potential of electricity distribution grids,” in *20th International Conference on Electricity Distribution*, Prague, 2009, pp. 1–4.

[70] K. Schneider, C. Gerkensmeyer, M. Kintner-Meyer, and R. Fletcher, “Impact assessment of plug-in hybrid vehicles on pacific northwest distribution systems,” in *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, pp. 1–6.

[71] H. L. Willis, *Power Distribution Planning Reference Book*. New York (N.Y.): Dekker, 1997.

[72] W. Kersting, “Radial distribution test feeders,” in *IEEE Power Engineering Society Winter Meeting.*, vol. 2, IEEE Power Engineering Society Winter Meeting. Columbus, Ohio, USA: IEEE, 2001, pp. 908–912.

[73] Flemish Regulation Entity for the Electricity and Gas market. De verbruiksprofielen van huishoudelijke en niet-huishoudelijke elektriciteitsverbruikers voor het jaar 2007, (Consumption profiles of residential and non-residential electricity consumers in 2007). (Last accessed August 2010). [Online]. Available: http://www.vreg.be

[74] Institute for Road Safety Research. (2007) Research commuting behaviour (OVG). (Last accessed August 2010). [Online]. Available: http://www.swov.nl

[75] E. De Caluwé, "Potentieel van demand side management, piekvermogen en netondersteunende diensten geleverd door Plug-in Hybride Elektrische Voertuigen op basis van een beschikbaarheidsanalyse." Master's thesis, K.U.Leuven, 2008.

[76] MON, Projectteam, "Mobility research in the Netherlands," 2007.

[77] E. Haesen, "Multi-objective optimization of the integration of stochastic distributed energy resources in electricity grids," Ph.D. dissertation, Katholieke Universiteit Leuven, 2009.

[78] L. Araujo, D. Penido, S. Carneiro, J. Pereira, and P. Garcia, "A Comparative Study on the Performance of TCIM Full Newton versus Backward-Forward Power Flow Methods for Large Distribution Systems," in *2006 IEEE PES Power Systems Conference and Exposition*, pp. 522–526.

[79] W. Kersting, *Distribution System Modeling and Analysis.* Boca Raton (Fla.): CRC, 2002.

[80] R. M. Ciric, A. P. Feltrin, and L. F. Ochoa, "Power flow in four-wire distribution networks-general approach," *IEEE Transactions on Power Systems*, vol. 18, no. 4, pp. 1283–1290, November 2003.

[81] IEEE Task Force On Load Representation For Dynamic Performance, "Load representation for dynamic performance analysis (of power systems)," *IEEE Transactions on Power Systems*, vol. 8, no. 2, pp. 472–482, 1993.

[82] FOD Economie, K.M.O., Middenstand en Energie. Structuur van de bevolking. (Last accessed August 2010). [Online]. Available: http://statbel.fgov.be/nl/statistieken/cijfers/bevolking/structuur/_huishoudens/index.jsp

[83] *EN 50160, Voltage characteristics of electricity supplied by public distribution systems*, Std., 1999.

[84] S. Boyd and L. Vandenberghe, *Convex Optimization.* Cambridge University Press, 2004.

[85] M. Edvall and A. Göran, "Tomlab quick start guide," Tomlab, Tech. Rep., 2009.

[86] Tomlab®. The tomlab optimization environment for matlab®. (Last accessed August 2010). [Online]. Available: http://tomopt.com

[87] The Mathworks^{TM}, MATLAB®. (Last accessed August 2010). [Online]. Available: http://www.mathworks.com

[88] ILOG, CPLEX solver. (Last accessed August 2010). [Online]. Available: http://www.ilog.com/products/cplex/

[89] E. Haesen, J. Driesen, and R. Belmans, "Robust planning methodology for integration of stochastic generators in distribution grids," *IET Renewable Power Generation*, vol. 1, no. 1, p. 25, March 2007.

[90] J. Rodgers and N. Alan, "Thirteen ways to look at the correlation coefficient," *The American Statistician*, vol. 42, No. 1, pp. 59–66, 1988.

[91] J. Linderoth, A. Shapiro, and S. Wright, "The empirical behavior of sampling methods for stochastic programming," *Annals of Operations Research*, vol. 142, no. 1, pp. 215–241, February 2006.

[92] J. Labadie, "Optimal operation of multireservoir systems: State-of-the-art review," *Journal of water resource planning and management-ASCE*, vol. 130, no. 2, pp. 93–111, 2004.

[93] R. Bellman, *Adaptive control processes : a guided tour*, 2nd ed. Princeton (N.J.): Princeton university press,, 1962.

[94] N. Kumar and F. Baliarsingh, "Folded dynamic programming for optimal operation of multireservoir system," *Water resources management*, vol. 17, no. 5, pp. 337–353, October 2003.

[95] P. Nopmongcol and J. Askew, "Multilevel Incremental Dynamic Programming," *Water resources research*, vol. 12, no. 6, pp. 1291–1297, December 1976.

[96] J. Yi, J. Labadie, and S. Stitt, "Dynamic Optimal Unit Commitment and Loading in Hydropower Systems," *Journal of Water Resources Planning and Management*, vol. 129, no. 5, p. 388, September 2003.

[97] I. Lampropoulos, E. Veldman, W. Kling, M. Gibescu, and J. Slootweg, "Electric vehicles integration within low voltage electricity networks & possibilities for distribution energy loss reduction," in *Innovation for Sustainable Production 2010*, 2010.

[98] J. Green, S. Smith, and G. Strbac, "Evaluation of electricity distribution system design strategies," *IEE Proceedings - Generation, Transmission and Distribution*, vol. 146, no. 1, p. 53, 1999.

[99] U.S. Departement of Energy, "Summary Report: Discussion Meeting on Plug-In Hybrid Electric Vehicles," Tech. Rep., 2006.

[100] X. Yu, "Impacts assessment of PHEV charge profiles on generation expansion using national energy modeling system," in *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century.* IEEE, 2008, pp. 1–5.

[101] S. Jenkins, J. Rossmaier, and M. Ferdowsi, "Utilization and effect of plug-in hybrid electric vehicles in the United States power grid," in *2008 IEEE Vehicle Power and Propulsion Conference.* IEEE, 2008, pp. 1–5.

[102] J. Tomic and W. Kempton, "Using fleets of electric-drive vehicles for grid support," *Journal of Power Sources*, vol. 168, no. 2, pp. 459–468, 2007.

[103] P. Denholm and S. Letendre, "Grid Services From Plug-In Hybrid Electric Vehicles: A Key To Economic Viability?" National Renewable Energy Laboratory, Tech. Rep.

[104] European Network of Transmission System Operators for Electricity. (2004) UCTE Operation Handbook. (Last accessed August 2010). [Online]. Available: http://www.entsoe.eu/index.php?id=57

[105] Elia. Product sheets. (Last accessed August 2010). [Online]. Available: www.Elia.be

[106] A. Oudalov, D. Chartouni, C. Ohler, and G. Linhofer, "Value Analysis of Battery Energy Storage Applications in Power Systems," in *2006 IEEE PES Power Systems Conference and Exposition*, Proc. 2^{nd} IEEE Power Eng. Soc. Power Systems. IEEE, 2006, pp. 2206–2211.

[107] K. De Brabandere, "Voltage and frequency droop control in low voltage grids by distributed generators with inverter frond-end," Ph.D. dissertation, Katholieke Universiteit Leuven, 2006.

[108] W. Kempton and T. Kubo", "Electric-drive vehicles for peak power in Japan," *Energy Policy*, vol. 28, pp. 9–18, 2000.

[109] Nuon. Electricity tariffs for consumers. (Last accessed August 2010). [Online]. Available: www.nuon.be

[110] J. Pecas Lopes, P. Rocha Almeida, and F. Soares, "Using vehicle-to-grid to maximize the integration of intermittent renewable energy resources in islanded electric grids," in *International Conference on Clean Electrical Power*, 2009.

[111] B. Kramer, S. Chakraborty, and B. Kroposki, “A Review of Plug-in Vehicles and Vehicle-to-Grid Capability,” in *Industrial Electronics, 2008. IECON 2008. 34*th *Annual Conference of IEEE*, 2008.

[112] Energy Saving trust, “Potential for Microgeneration Study and Analysis,” Tech. Rep., November 2005.

[113] N. Stannard and J. Bumby, “Energy Yield and Cost Analysis of Small Scale Wind Turbines,” in *Proceedings of the 41*st *International Universities Power Engineering Conference*, vol. 1. IEEE, 2006, pp. 108–112.

[114] Royal Netherlands Meteorological Institute. Hourly wind data. (Last accessed August 2010). [Online]. Available: http://www.knmi.nl/samenw/hydra/register

[115] N. Shah and H. Cho, “Phev - statistical analysis using real world driving cycles,” Transmission & Hybrid Vehicle Technologies, AVL Powertrain UK, Tech. Rep., 2008.

[116] S. Shao, M. Pipattanasomporn, and S. Rahman, “Challenges of PHEV penetration to the residential distribution network,” in *2009 IEEE Power & Energy Society General Meeting*. IEEE, 2009, pp. 1–8.

[117] C. Roe, A. Meliopoulos, J. Meisel, and T. Overbye, “Power System Level Impacts of Plug-In Hybrid Electric Vehicles Using Simulation Data,” in *2008 IEEE Energy 2030 Conference*, pp. 1–6.

[118] S. Hadley and A. Tsvetkova, “Potential Impacts of Plug-in Hybrid Electric Vehicles on Regional Power Generation,” *The Electricity Journal*, vol. 22, no. 10, pp. 56–68, 2009.

[119] K. Voorspools, “The modelling of large electricity generation systems with applications in emission-reduction scenarios and electricity trade,” Ph.D. dissertation, Katholieke Universiteit Leuven, 2004.

[120] E. Delarue, “Modeling electricity generation systems: Development and applications of electricity generation optimization and simulation models, with particular focus on CO_2 emissions.” Ph.D. dissertation, Katholieke Universiteit Leuven, 2009.

Publication list

All publications can be accessed on the following website:
`http://www.esat.kuleuven.be/electa`

Reviewed journals

[1] K. Clement, E. Haesen, and J. Driesen, "The impact of vehicle-to-grid on the distribution grid," *Elsevier Electric Power Systems Research*, (Accepted for publication).

[2] K. Clement, E. Haesen, and J. Driesen, "The Impact of Charging Plug-In Hybrid Electric Vehicles on a Residential Distribution Grid," *IEEE Transactions on Power Systems*, vol.5, no.1, pp. 371–380, February 2010.

[3] K. Clement, E. Haesen, and J. Driesen, "Analysis of the Impact of Plug-In Hybrid Electric Vehicles on Residential Distribution Grids by using Quadratic and Dynamic Programming," *World Electric Vehicle Journal*, vol.3, pp. 11, May 2009.

[4] P. Tant, K. Engelen, P. Jacqmaer, K. Clement, J. Verveckken, S. De Breucker, J. Driesen and G .Deconinck, "Case-study of an Educational Engineering Project: a Series Hybrid Electric Kart," *Journal sur l'enseignement des sciences et technologies de l'information et des systèmes*, vol.8, pp. 6, 2009.

Conference papers

[5] K. Clement, S. De Breucker and J. Driesen, "The analysis of objective functions applied to the coordination problem of PHEVs to minimize the grid impact," in *Electric Vehicle Symposium (EVS25)*, accepted for publication, Shenzhen, China, 9-5 November 2010, 8 pages.

[6] F. Geth, S. De Breucker, K. Clement and J. Driesen, ”Charging Power Analysis for a Belgian Plug-in Hybrid Electric Vehicle Fleet,” in 5th *IEEE Young Researchers Symposium*, Leuven, Belgium, 29-30 March 2010, 6 pages.

[7] K. Clement, E. Haesen and J. Driesen, ”Analysis of the Impact of Plug-In Hybrid Electric Vehicles on the Residential Distribution Grids by using Quadratic and Dynamic Programming,” in *Electric Vehicle Symposium (EVS24)*, Stavanger, Norway, 13-15 May 2009, 10 pages.

[8] K. Clement, E. Haesen, and J. Driesen, ”Stochastic Analysis of the Impact of Plug-In Hybrid Electric Vehicles on the Distribution Grid,” in 20th *International Conference and Exhibition on Electricity Distribution (CIRED2009)*, Prague, Czech Republic, 8-11 June 2009, 4 pages.

[9] K. Clement, E. Haesen, J. Driesen, ”Coordinated Charging of Multiple Plug-In Hybrid Electric Vehicles in Residential Distribution Grids,” in *IEEE PES Power Systems Conference & Exposition (PSCE09)*, Seatle, Washington, USA, 15-18 March 2009, 7 pages.

[10] P. Tant, K. Engelen, P. Jacqmaer, K. Clement, J. Verveckken, S. De Breucker, J. Driesen and G .Deconinck, ”Case-study of an Educational Engineering Project: a Series Hybrid Electric Kart,” in *Colloque sur l'Enseignement des Technologies et des Sciences de l'Information et des Systmes (CETSIS)edition:7*, Brussels, Belgium, 27-29 October 2008, 6 pages.

[11] S. De Breucker, K. Clement, K. Engelen, P. Tant, J. Verveckken, P. Jacqmaer, J. Driesen and G .Deconinck, ”A Hybrid Electric Kart with Energy Flow Management as a Student Project,” in 19th *International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM 2008)*, Ischia, Italy, 11-13 June 2008, 6 pages.

[12] K. Clement, E. Haesen, and J. Driesen, “The impact of uncontrolled and controlled charging of plug-in hybrid electric vehicles on the distribution grid,” in 3rd *European Ele-Drive Transportation Conference (EET-2008)*, Geneva, Switzerland, 11-13 March 2008, 7 pages.

[13] K. Clement, E. Haesen, and J. Driesen, “The impact of charging plug-in hybrid electric vehicles on the distribution grid,” in *4th IEEE Young Researchers Symposium in Electrical Power Engineering*, Eindhoven, the Netherlands, 7-8 February 2008, 6 pages.

[14] K. Clement, I. Pardon, and J. Driesen, “Standby power consumption in Belgium,” in 9th *International Conference Electrical Power Quality and Utilisation*, Barcelona, Spain, 9-11 October 2007, 4 pages.

[15] K. Clement, K. Van Reusel, and J. Driesen, “The consumption of electrical energy of plug-in hybrid electric vehicles in Belgium,” in *EET-European Ele-Drive Transportation conference*, Brussels, Belgium, 30 May - 2 June 2007, 10 pages.

[16] J. Driesen, K. Clement, S. De Breucker and P. Jacqmaer, “Alternatieve energiebronnen voor motoren: Rijden met een stekker,” *Het Ingenieursblad*, no.5, pp. 16-19, May 2007.

Curriculum vitae

- Kristien Clement-Nyns

- Born March 28, 1980 in Diest, Belgium

- Secondary School:
  Wetenschappen-Wiskunde
  1992 - 1998
  Zusters Van de Voorzienigheid, Diest, Belgium

- University:
  Kandidaat in de Natuurkunde
  1998 - 2000
  Universiteit Hasselt, Belgium

  Burgelijk Werktuigkundig-Elektrotechnisch Ingenieur, Richting Mechanica, Optie Energie
  2000 - 2004
  Katholieke Universiteit Leuven

- Work:
  Research assistant aan de Katholieke Universiteit Leuven, Department Werktuigkunde
  2004 - 2006

  Doctoraatsstudent aan de Katholieke Universiteit Leuven, Departement Elektrotechniek
  2006 - 2010