The influence of electric vehicles' development on wholesale electricity price - The case of Lithuania

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Abstract

Driven by environmental policymaking, electro-mobility is gaining popularity as an important tool to mitigate the transport induced CO2 emissions and is being subsidized by Governments, creating more incentives for end users to adapt. This dissertation addresses the extensive e-mobility transition's influence on the electricity wholesale market in Lithuania. The global market for Electric Vehicles (EVs) is expanding at an increasing pace, having more Original Equipment Manufacturers (OEMs) announced their intentions to switch their powertrains to electrified ones in the upcoming decade. These global trends are affecting the Lithuanian market as well, which, however, is currently insignificant, accounting for 900 registered vehicles by the end of August 2018. To capture the possible effect on the wholesale market, the analysis is set up to picture the market in 2025, when the number of vehicles is expected to reach around 21000 with an annual growth rate of 57%. The Lithuanian electricity market is participating in the cross-border Nord Pool trading market, where the main bottleneck is the interconnection NordBalt, connecting the Lithuanian price region with Sweden. NordBalt serves as the main access point to the cheaper hydro- and nuclear-based electricity. For the purpose of this analysis, three different days were selected, representing separate characteristic seasons consumption-wise, and a least-squares methodology was applied to estimate price changes. With the predicted market's behavior having an additional load from EVs charging, a neglected wholesale price effect was identified and quantified. These findings anticipate a discussion regarding societal fairness, as the subsidized industry is ultimately affecting the retail price of electricity.

Keywords

Electric Vehicles, Wholesale, OLS, Electricity, Price effect, Lithuania

Resumo

Impulsionada pela formulação de políticas ambientais, a eletro-mobilidade tem vindo a ganhar popularidade, sendo subsidiada como forma de criar incentivos para os consumidores a escolherem. Esta dissertação analisa a influência da transição para a e-mobilidade, no mercado grossista de eletricidade na Lituânia. O mercado global de veículos elétricos (VEs) tem-se expandido a um ritmo crescente, com mais produtores a anunciar a sua intenção de mudar os seus motores para motores elétricos na próxima década. Estas tendências globais afetam o mercado lituano, que, no entanto, é atualmente insignificante, com um registo de 900 veículos até ao final de agosto de 2018. Para captar o possível efeito sobre o mercado grossista de eletricidade, a presente análise pretende retratar o mercado em 2025, quando se espera que o número de veículos atinja cerca de 21000, com uma taxa de crescimento anual de 57%. O mercado lituano de eletricidade participa no mercado transfronteiriço de Nord Pool, onde o principal obstáculo é a interligação NordBalt, ligando a região de preços da Lituânia à Suécia. Funciona como o principal ponto de acesso para obter eletricidade mais barata, baseada em energia nuclear e hidroelétrica. Para efeitos da presente análise, foram selecionados três dias diferentes, representativos das três estações características e diferenciadas no consumo, e aplicou-se uma metodologia de mínimos quadrados ordinários. Os resultados obtidos indicam um claro aumento no preço grossista, devido à carga adicional resultante do carregamento dos VEs, e dão origem a uma discussão relacionada com justiça social, uma vez que esta indústria subsidiada pode assim afetar o preço de retalho da eletricidade.

Palavras Chave

Veículos Elétricos, Mercado Grossista, OLS, Eletricidade, Efeito no preço, Lituânia

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Acronyms

EVs	Electric Vehicles
CHPs	Combined Heat and Power Plants
DHN	District Heating Network
ICEVs	Internal Combustion Engine Vehicles
CO2	Carbon Dioxide
EU	European Union
TSO	Transmission System Operator
DSO	Distribution System operator
NPP	Nuclear Power Plant
TPP	Thermal Power Plant
RES	Renewable Energy Sources
PV	Photovoltaics
MSVI	Monthly Seasonal Variant Indices
DSVI	Daily Seasonal Variation Indices
MC	Marginal Costs
GHG	Green House Gases
PLDVs	Personal Light-duty Vehicles
BEVs	Battery Electric Vehicles
ZEVs	Zero-emission Vehicles

OEMs	Original Equipment Manufacturers
EVSE	Electric Vehicle Supply Equipment
AC	Alternating Current
DC	Direct Current
CCS	Combined Charging System
EC	European Commission
BEMIP	Baltic Energy Market Interconnection Plan
OLS	Ordinary Least-Squares
RSS	Residual Sum of Squares
DSM	Demand-side Management

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Introduction

Contents

The ever-changing world is on the verge of transition towards more efficient and cleaner transport. The majority of economic activities are being supported by the transport means, which unlocks possibilities to expand the markets, breaking the barriers of distance. In the environmental context, the prevailing internal combustion based transportation is accelerating the global warming process, which ultimately will change the climate with severe distortions in weather patterns. The need for more sustainable solutions, especially in a carbon-intensive industry as transport, has given rise for electrified transportation, accelerating the transition with excessive research and policymaking in the field. The Electric Vehicles (EVs) market is growing at an increasing pace, recording a 57% annual growth rate in 2017, accumulating over 3 million vehicles globally [1]. The electrified transport is a direct substitute for internal combustion vehicles. However, it comes with some emerging technical issues down the supply chain.

Within this dissertation, the principal analysis will be done on the EVs influence on the Lithuanian electricity wholesale market. For this purpose, an Ordinary Least-Squares (OLS) methodology will be used to analyze consumption and price dependencies in the Nord Pool open market. The key hypothesis raised within this work is that the increased electricity consumption will have an impact on wholesale price. The outline of this work is divided into four main chapters:

1. ***Introduction*** - in this chapter the motivation, main objectives and the purpose of this dissertation are outlined.

2. ***Literature review*** - within this chapter the main topics regarding electro-mobility are presented. Firstly, the general global development trends, EVs technology and problematics are unveiled, following with Lithuanian transport and energy sector analysis. The literature review is concluded with an explanation of the electricity market's behavior prediction model.

3. ***Research*** - in this part the EVs charging profile analysis is done on the Nord Pool electricity market with regards to Lithuanian price region.

4. ***Conclusions*** - the concluding part of the dissertation, highlighting the primary outcomes and identifying the system's limitations and the intended future work.

1.1 Motivation and purpose

The growing number of EVs is rapidly increasing electricity consumption. Using environmental policies and promoting more efficient transportation means, the transport electrification is being virally promoted publicly. However, in the majority of cases, the less obvious technical and social impacts are left undiscovered. The absence of a critical point of view towards the global transport electrification is creating an overwhelmed positive image in general masses. Thus, the motivation of this dissertation is to investigate the effect of growing e-mobility on electricity wholesale price and highlight the key issues that could make an impact for society.

1.2 Objectives

To obtain the clear picture of what are the dynamics of the wholesale market and what are the key influencers affecting the outcomes, the primaryf objectives have been established:

- Analyze the global tendencies of EVs development with current technologies on the market.
- Identify the arising problematics regarding the broad electrified transport adoption.
- Localize the global trends and translate them to Lithuanian market.
- Summarize the key components affecting the Lithuanian electricity market and highlight the critical infrastructure parts.
- Establish a reliable dataset allowing precise interpretations and analysis.
- Create an electricity market prediction model.
- Identify the system's limitations and propose possible solutions.

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Literature review

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2.1 Electric Vehicles

To completely understand the problematics of EVs development, some of the main closely related topics have to be covered. Talking about transportation, usually, the main issues swirl around the environmental impact of burning fossils, scarce crude oil potentials and an overall supply chain - from oil refineries to petrol stations in the local areas. As EVs are direct substitutes for Internal Combustion Engine Vehicles (ICEVs) regarding the transportation needs, however, the supply chain differs and while it solves the issues of traditional transport means, due to its complexity, causes additional aspects to be taken into account. This literature review aims to provide a brief overview of the main interest points that EVs development are creating.

2.1.1 Global development

The scarcity of crude oil, environmental severe pollution problems, growing carbon dioxide emissions and other factors, initiated a transition towards a more efficient and "greener" economy. Announced in December 2015 and enforced in November 2016, the Paris Agreement set the objective of limiting the increase in the global average temperature to well below 2℃ above preindustrial levels and pursuing efforts to curb the temperature increase to 1.5℃ above pre-industrial levels [2]. The temperature rise is caused by the Green House Gases (GHG), mainly CO2 emissions. Figure 2.1 illustrates the GHG emissions reductions that could be compatible with this target by looking at two carbon budgets that reflect two possible *International Energy Agency* scenarios [3]:

- The reduction of 1170 Gt CO2 of total emissions for the period of 2015-2100, providing a 50% chance of limiting average future temperatures increases to 2℃. It is reflected as Two Degree Scenario (2DS) in IEA methodology.
- The reduction of 750 Gt CO2 accumulatively for the period of 2015-2100, coupled with a 50% chance of limiting average future temperatures increases to 1.75℃. In the IEA methodology its referred as Beyond Two Degree Scenario (B2DS).

In both cases represented in Figure 2.1, energy-related GHG emissions will need to reach net-zero in the second half of this century: close to 2060 for the B2DS and close to 2090 for the 2DS. The transport sector, which currently accounts for 23% of global energy-related GHG emissions, will need to deliver superior emissions cuts for countries to achieve their goals.

Aiming to achieve the decarbonisation of the energy system, a significant role in electrification in all IEA scenarios is played by transport where increasing transport electrification goes together with decarbonising the energy sector. In the 2DS, the plug-in Personal Light-duty Vehicles (PLDVs) stock exceeds 150 million units (10% of the total) by 2030. By 2060, the latter scenario projects that 1.2 billion

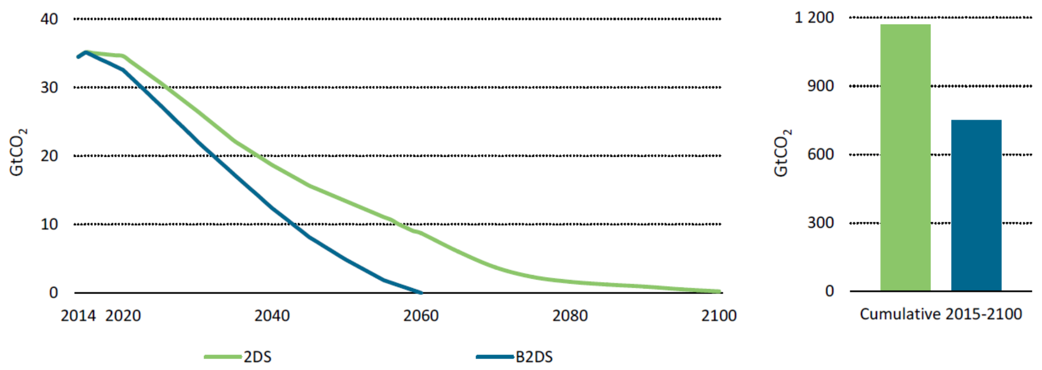

Figure 2.1: GHG emission budgets and emission trajectories to 2100 for the energy sector, 2DS and B2DS.

EVs, representing more than 60% of the total fleet will be on the roads. Under the B2DS, transport electrification happens at an even faster pace - electric cars represent 85% of the entire PLDVs stock by 2060. With zero tailpipe emissions in the case of full-electric driving vehicles, EVs also offer a clean alternative to ICEVs by helping to reduce exposure to air pollution resulting from fuel combustion and limiting noise.

In recent years a dynamic market uptake of electric vehicles has occurred. On-going support and commitments for increased deployment of EVs from policymakers and the automotive industry suggest that this trend is not going to slow down in the coming decade. It is likely, that increased sales volumes, together with growing competition in the development of new technologies, are opted to contribute to continuous reductions in the cost of manufacturing batteries – the most critical cost component for EVs. The density and price dynamics of cells are shown in Figure 2.2 [4].

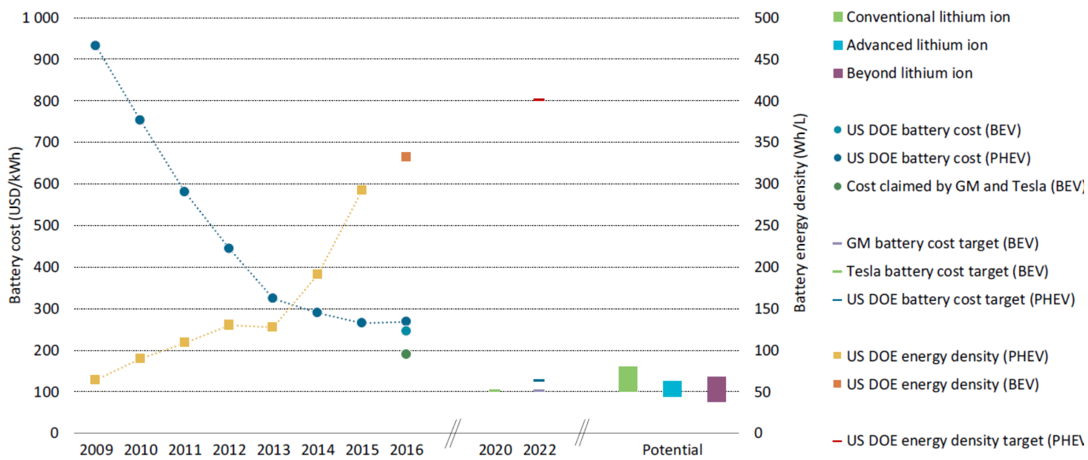

Figure 2.2: Evolution of battery energy density and cost.

In the illustration above, US Department of Energy (DOE) has published their projections on batteries density and costs. As it is seen, the cost of kWh battery produced dropped three-folds, saturating in the last three years. The saturation is followed simultaneously with increasing density of the batteries by five times. The advanced lithium-ion technology is including the silicon alloy-composite anode. Additionally, batteries manufacturers have set their own goals time-wise, including General Motors (GM) and Tesla.

Cost reductions in EV-related technologies further strengthen their competitiveness compared with ICEVs. It is reinforcing the case for road EVs taking an expanding market share, and possibly a leading role in the evolution of transportation. As seen in Figure 2.3 [5] [6], the global stock of electric passenger cars reached 3.1 million in 2017 - an increase of 57% from the previous year. It is similar to the 60% growth rate in 2015 and 2016. Battery Electric Vehicles (BEVs) account for two-thirds of the world's electric car fleet in this case.

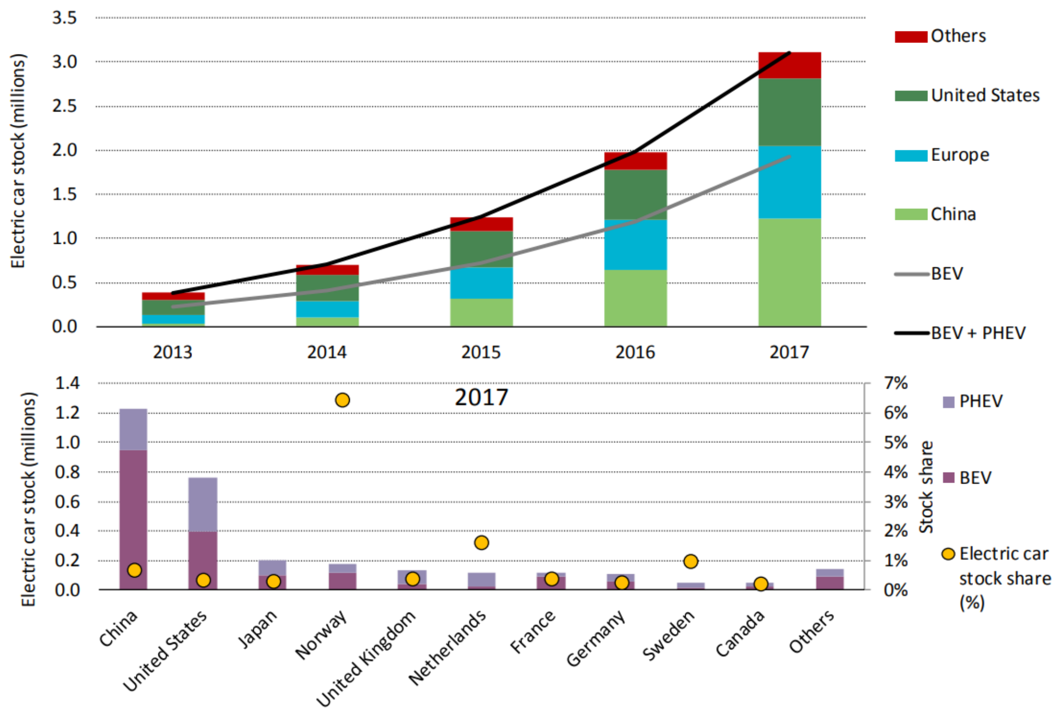

Figure 2.3: Passenger electric car stock in major regions and the top-ten "Electric Vehicles Initiative" countries.

This graph, published in "Global EV Outlook 2018" [1], reflects the dynamics of EVs under "Electric Vehicles Initiative" (EVI) scope. The top-ten participants of this initiative are outlined in the graph above and are reflecting the vast majority of global EVs market. Around 40% of the global electric car fleet is in China, where the number of electric cars on the road surpassed 1 million in 2017, while the European Union and the United States each accounted for about a quarter of the global total. By far, Norway has the world's highest share at 6.4% of electric cars in its vehicle stock. While the number of electric vehicles is notably on the rise, only three of the EVI member countries have a stock share of 1% or higher: Norway (6.4%), Netherlands (1.6%) and Sweden (1.0%) [5] [6].

Moreover, to make the transition quicker in pace, the number of countries have announced their intentions to forbid the purchase of ICEVs or entirely ban ones on the road. Such European countries are outlined in Table 2.1 [1].

Table 2.1: Announced sales bans for ICEVs.

Country	2025	2030	2032	2040	2045
France [7]				X	
Ireland [8]		X			
Netherlands [9]		X			
Norway [10]	X				
Slovenia [11]		X			
Sweden [12]					O
Scotland [13]			X		
United Kingdom [14]				X	

In the table above, **"X"** marking stands for the countries, which are intending to ban sales of ICEVs or, on the other hand, promote sales of only Zero-emission Vehicles (ZEVs). Additionally, Sweden has been marked with **"O"**, meaning that Swedes are going to ban ICEVs completely on their roads by 2045. It is an unprecedented case in the automotive industry when national policymakers and governments are intervening with the policy and regulations on such scale. While it is rather difficult to announce such goals nation-wide, there are European cities that are having their individual goals, regardless of the central government through city pollution and environmental policies. The list of such cities is in Table 2.2 [1].

Table 2.2: Announced access restriction mandates in local jurisdictions.

Local jurisdictions	2024	2025	2030
Athens [15]		X	
Barcelona [16]			O
Copenhagen [16]			O
London [16]			O
Madrid [15]		X	
Milan [16]			O
Paris [17]	X		O, &
Rome [18]	X		
Stockholm [1]			&

Here **"X"** marking stands for diesel access restrictions, varying from full restriction in the city territory to forbidding diesel vehicles to enter particular areas; **"O"** marking stands for fossil-fuel-free streets declarations and **"&"** marking indicates complete ICEVs restrictions in the territory. When looking at ICEVs bans, it is relevant to highlight that Germany's Federal Administrative Court granted cities the right to set an access restriction ban on based specific emission levels (NO2) recently [19]. The German government dismissed the idea of a nationwide diesel ban [20], but Germany is reportedly considering the use of a national labeling scheme based on the emission performance of vehicles, similar to the one adopted in France in July 2017 [21] [22]. That allows cities to target vehicles taking into account their environmental performance.

The transition towards transport electrification is being acted upon from OEMs as well. Some of the major OEMs key statements have been outlined in Table 2.3.

Table 2.3: Announcements by OEMs related to curbing or halting production of diesel ICEVs

OEM	Action
Fiat Chrysler [23]	Phase out diesel across its model line-up as of 2022.
Honda [24]	Discontinue production and sales of a flagship diesel-powered vehicle in Europe.
Porsche [25]	No diesel units for major models of the brand; focus on optimized ICEs, PHEVs and BEVs.
Subaru [26]	Withdraw diesel car production and sales by 2020.
Toyota [27]	Stop selling diesel cars in Europe by the end of 2018.
Volvo [28]	Stop developing diesel engines

The statements indicate the undergoing transition from diesel-based to the electrified powertrain.

2.1.2 Prevailing technologies and standards

The industry of EVs is somewhat new and, as the road to maturity is still underway, the system is allowing research breakthroughs and new standardizations. Aiming for better competitiveness, lacking a will of cooperation and political aspects have brought few prevailing standards for charging when it comes to EVs. In general, all of the charging equipment falls under the Electric Vehicle Supply Equipment (EVSE) terminology, and the characterization is done under these conditions:

- Level: the power output range of the EVSE outlet.
- Type: the socket and connector used for charging.
- Mode: the communication protocol between the vehicle and the charger.

Characterizing the power output, there are three main groups - levels, that can be identified: 1) Conventional plugs (level 1) - an extra slow charging, mainly from households traditional sockets using

Alternating Current (AC) (power output up to 3.7 kW); 2) Slow chargers (level 2) - using specific plugs with external power transformers in AC (power output in-between 3.7 kW and 22 kW); 3) Fast chargers (level 3) - utilizing external power transformers and depending on the current type established different standards: AC power output in-between 22kW and 43.5kW and Direct Current (DC) power output currently identified as up to 200kW. Different regions have established different plug types and standards, which are causing a market differentiation in technological aspect. Additionally, there are differences in communication methods of the different charging protocols, which rely on different physical connections. In the case of Level 2 and 3 AC chargers, there is a single protocol per type, and the same protocol is also used for Tesla connectors. In the case of DC fast chargers, Combined Charging System (CCS) connectors are coupled with power line communication (PLC) protocols, which are typically used in smart-grid communications, while CHAdeMO, Tesla and Chinese GB/T use controller area network communication, which was initially developed for components inside cars [29]. An overview of the central regions and their characterizations is outlined in Table 2.4 [4].

Table 2.4: Overview of the EVSE characteristics in the main regions.

<table>
<tr><th colspan="2"></th><th>Conventional plugs</th><th colspan="2">Slow chargers</th><th colspan="3">Fast chargers</th></tr>
<tr><td colspan="2">Levels</td><td>Level 1</td><td colspan="2">level 2</td><td colspan="3">Level 3</td></tr>
<tr><td colspan="2">Current</td><td>AC</td><td colspan="2">AC</td><td>AC, triphase</td><td colspan="2">DC</td></tr>
<tr><td colspan="2">Power</td><td><3.7 kW</td><td>>3.7 kW and <22 kW</td><td><22 kW</td><td>>22 kW and <43.5 kW</td><td colspan="2">Currently <200 kW</td></tr>
<tr><td rowspan="7">Type</td><td>China</td><td>Type I</td><td colspan="2">GB/T 20234 AC</td><td rowspan="2"></td><td>GB/T 20234 DC</td><td></td></tr>
<tr><td>Japan</td><td>Type B</td><td>SAE J1772 Type 1</td><td>Tesla</td><td>Accepts all IEC 62196-3 standards</td><td rowspan="5">Tesla and CHAdeMO (IEC 62196-3 Type 4)</td></tr>
<tr><td>Europe</td><td>Type C/F/G</td><td colspan="2">IEC 62196-2 Type 2</td><td>IEC 62196-2 Type 2</td><td>CCS Combo 2 (IEC 62196-3)</td></tr>
<tr><td>North America</td><td>Type B; SAE J1772 Type 1</td><td>SAE J1772 Type 1</td><td>Tesla</td><td>SAE J3068</td><td>CCS Combo 1 (SAE J1772 & IEC 62196-3)</td></tr>
<tr><td>Australia</td><td>Type 1</td><td colspan="2">IEC 62196-2 Type 2</td><td rowspan="2"></td><td>Accepts all IEC 62196-3 standards</td></tr>
<tr><td>Korea</td><td>Type A/C</td><td colspan="2">IEC 62196-2 Type 2</td><td>CCS Combo 1 (IEC 62196-3)</td></tr>
<tr><td>India</td><td>Type C/D/M</td><td colspan="2">IEC 62196-2 Type 2</td><td>IEC 62196-2 Type 2</td><td>CCS Combo 2 (IEC 62196-3)</td><td>CHAdeMO</td></tr>
</table>

It is worth mentioning, that level 1 and 2 chargers are commonly adopted and utilized in the residential area, meaning that those chargers are not publicly available. For public charging points, in most of the cases, governments are investing to establish a convenient infrastructure for EVs charging. The European Commission (EC) in 2014 announced its intentions to spend into Trans European Transport Network (TEN-T) under the alternative fuel infrastructure promotion directive (Directive 2014/94/EU) an estimated 0.8 billion USD in-between 2017 and 2020 [30]. Simultaneously, in the period from 2017 through 2027, the United States, under their project "Electrify America", set to invest in charging infrastructure up to 2 billion USD [31]. The public spendings on nation-wide infrastructure are increasing incentives for EVs adoption and are taken as a fiscal policy measure. However, the federal funds are not efficiently absorbed in all the cases. As an example, as Brown S. reports, the publicly allocated funds in the United Kingdom are struggling to be deployed due to the inactivity of local authorities resulting in the waste of public funds [32].

The overall growth of EVs industry and policy support from major countries around the world is a positive signal achieving electrification goals. Ambitious goals and environmentally cautious mindsets have started a transition towards a less polluting transportation sector. However, with an increased number of vehicles on the roads, a significant demand for electricity is expected to occur. Additional charging loads are not only affecting ramping national consumptions but might cause grid congestions if the system is not adjusted accordingly. The overall problematics are analyzed in the following section.

2.1.3 Problematics

By the end of 2017, the estimated global electricity demand accumulated from electrical transport was 54 terawatt-hours (TWh) (Figure 2.4) - a comparable amount to an average sized European country. Most of the demand (91%) is located in China where the consumption is mostly due to electric two-wheelers and buses. The high popularity of these transport modes in the Far East resulted in combined 87% of electrical transport electricity demand worldwide. However, electricity demand for EVs has increased the most out of these three modes since 2015 by 143% [4]. In the following graph, LDV stands for light-duty vehicles.

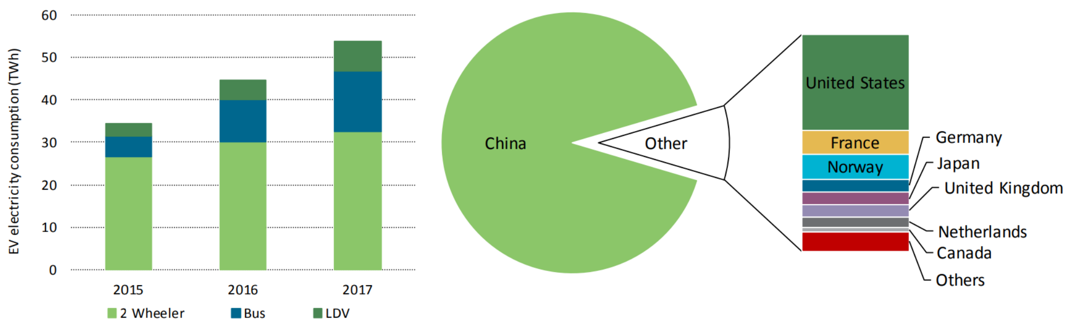

Figure 2.4: Total electricity demand from EVs by country, 2017.

The rising demand for electricity due to the electrification of transport is an issue, but it is manageable if the supply capacity is concerned. The amount of GWh required to supply the charging of EVs is easily coped with an existing generation infrastructure as there is a lot of reserve capacity left for security purpose. However, the main problems occur when the charging behavior is analyzed in depth. Firstly, the majority of EVs charging is done in the residential area, where the low-voltage grid is present. The system's infrastructure is designed to supply the aggregated households' consumption in the area, which usually consists of around 200 separate houses with an average inlet power of 10kW. If the maximum capacity is reached in the particular neighborhood, the additional load would need to be reinforced with an expansion of the infrastructure itself.

Additionally, the occurrence of the charging load is closely matching with the peak consumption of the household itself, creating an exaggerated peak in the evening. With an increasing number of EVs, the demand for electricity for the same particular residential area is expected to rise, causing additional constraints on the local grid. It is a technological constraint which will have to be addressed in the near future.

From the electricity wholesale price point of view, the increasing consumption of electricity will result in the distortion of prices. The fact that the peak charging load profile is matching with the ordinary electricity consumption peak in the evening, imposes that the price sensitivity will be higher. On a daily basis, the differences in the price range depend on the particular situation in the market. This is influenced by many factors: available generation capacity, its Marginal Costs (MC) structure, transmission lines status and any maintenance of the whole supply chain. The price setting of the electricity market is discussed later in Section 2.3.1.A, thus, in practice, the additional amount of electricity that will be required to be delivered will increase the price. The rising wholesale electricity prices due to transport electrification will be translated to the whole society, including ones, who do not employ any of the electrified transport means. This raises a discussion of fairness, which will be addressed throughout the dissertation.

2.2 Transport in Lithuania

The Lithuanian passengers' transport sector accumulatively has almost 1.3 million registered vehicles, accounting for 456 cars per 1000 inhabitants (European Union (EU) average - 505 vehicles per 1000 inhabitants) [33]. The sector has few statistical issues, which are affecting the further transition to the electrified transport. Firstly, Lithuania has an exclusive market for pre-owned vehicles, which serves as a center of attraction for buyers from Belarus, Poland, Latvia, Russia, and other countries. This ever growing secondhand fleet vehicle market has created a highly unbalanced system between new and secondhand vehicles sales. Secondly, according to the Eurostat database, Lithuania has the oldest cars fleet in EU, accounting for almost 81% of all vehicles to be over ten years old. This imposes a peculiar consumption habit, suggesting that the market for new cars is small (2.3% of vehicles are less than two years old) [33].

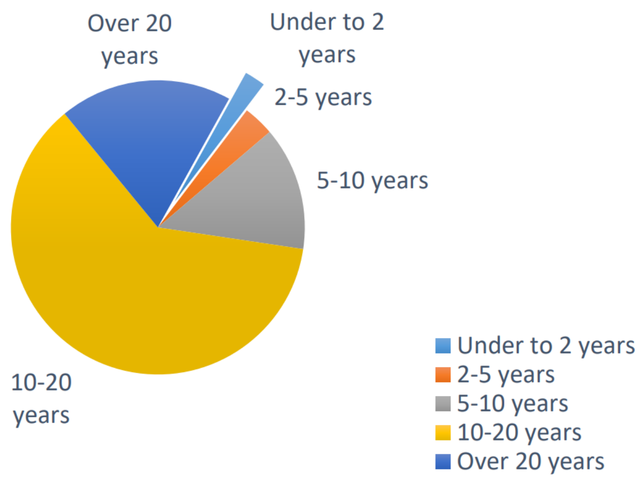

Figure 2.5: Passenger vehicles in Lithuania by age, 2016.

Moreover, with the rising controversy of Germany's environmental policies regarding diesel emissions, a movement of banning diesel vehicles with lower than the Euro-6 standard in major cities is picking up. The Euro standard is directly imposing emission limits for particles and Carbon Dioxide ($CO2$), which are the cause of environmental exhaustion and lead to health issues. It has been reported that cities are failing to meet the EU imposed environmental standards and it is up to the local municipalities to enforce such restrictions [34]. It has been already stated that, starting from January 1st 2019, vehicles with higher emission levels than Euro-4 standard will be restricted to enter cities of Stuttgart and Frankfurt [35] [36]. These environmental policies will directly influence the secondhand vehicle's market in Lithuania, as Germany serves as the leading import country for used vehicles [37]. A regulation aimed to tighten the environmental exhaustion from transport sector is seen to have a double effect probably. The local emission levels in the majority of German cities will be sustained or lowered; however, the number of unexploitable vehicles will increase. Therefore, the price of secondhand vehicles will be reduced. It is estimated that only in Germany 9 million cars will be affected by the new regulation, resulting in dropping prices by 15%-20% in the used vehicles market. Since used EVs market is insignificant and purchases of new vehicles are unlikely, the adoption of transport electrification will not happen on quick pace without the external incentives in the near future.

Currently, there are around 900 registered EVs on Lithuanian roads, accounting for less than a 1% of total newly registered vehicles annually. As the statistics indicate, the ratio between brand new and used EVs on average is 1:2 respectively, suggesting that the consumers are following the analog pattern, having a preference for a pre-owned vehicle. The general annual growth of electrified private passengers' transport since 2012 was on average of 55%, showing no significant fluctuations in the growth rate [38].

Analyzing the incentives system for EVs adoption, Norway is usually taken as an example. This Scandinavian country has promoted electrification of transport starting back in 1996, giving tax exemptions and subsidies for EVs purchases. It has been proved that the direct incentive system has a positive influence on the growth rate of EVs, as in Norway 57% of total new vehicles purchases are EVs. Due to economic differences, Lithuania cannot sustain the financial weight of subsidizing electrification of transport in the same way as Norway does, however, there are initiatives and an indirect incentives system, which helps to motivate the purchase choices. The main incentive that the Government is offering is the free charging infrastructure until 2023. Currently, a nation-wide infrastructure project is under development, which by the end of 2019 will be providing a public fast-charging station on every major state highway not more than 50 km apart. This will allow a long distance coverage with EVs without fuel costs. Besides the charging infrastructure, there are few minor tax exemptions, such as registration and emission fee, which are applied for EVs owners, as well as free parking in city centers in major municipalities. Comparatively, the system is not incentivising the mobility significantly to create an exponential growth in the near future. Thus, the prognosis of future development is not foreseeing a change in growing pace. At the moment, the electrification of transport in Lithuania is a politically unpopular topic, creating no expectations for the system to evolve further.

2.3 Energy sector in Lithuania

Sudden political switch, after the collapse of the Former Soviet Union in 1991, was followed by complex changes in all sectors of the Lithuanian economy, including the Energy sector. During the period 1990-2009, the role of nuclear fuel was very important. Lithuania was a nuclear country, having a single Ignalina Nuclear Power Plant (NPP) located in the north-east, close to the border of Belarus near the town called Visaginas. A double reactor power plant (Unit 1 and Unit 2) played a key role in the Lithuanian energy sector producing up to 70-80% of the electricity. During the process of accession into the EU, one of the country's obligations was a decision on the early closure of Ignalina NPP. It was agreed that Unit 1 of this power plant would be closed before 2005 and Unit 2 in 2009. Even after the closure of Unit 1 at the end of 2004, this power plant was dominating in the electricity market – its share in the balance of gross electricity generation in 2009 has been almost 70.7%. After the closure of Ignalina NPP, Lithuanian Thermal Power Plant (TPP) ("Lithuanian TPP") became the largest electricity generation source considering the installed capacity. "Lithuanian TPP" can cover up to 50-60% of the gross internal consumption. But the cost of electricity production at this power plant is high due to the high price of natural gas. Thus, currently, more than half of required electricity is imported from neighboring countries. The electricity generation structure is shown in Figure 2.6 [39] [40].

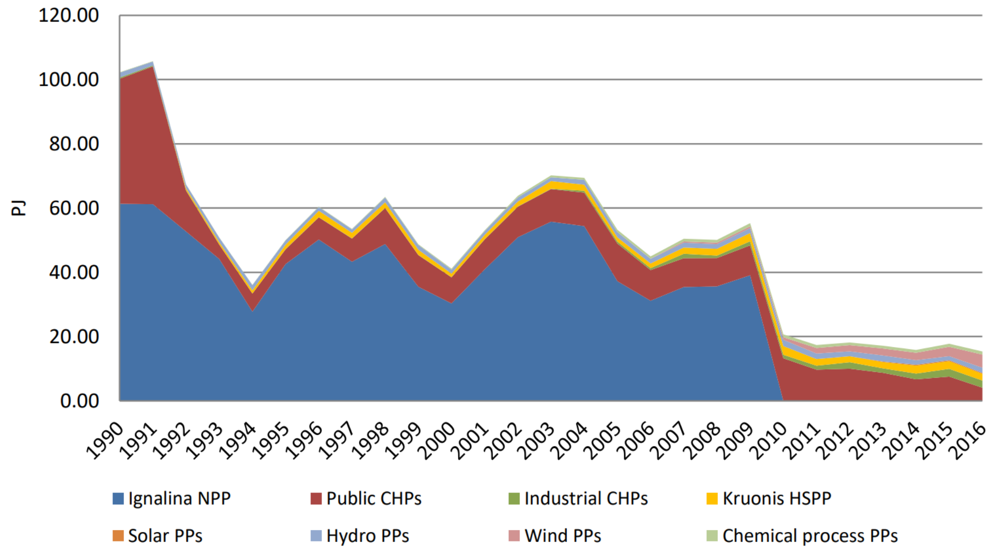

Figure 2.6: Structure of electricity generation in Lithuania

The Baltic Energy Market Interconnection Plan (BEMIP) was signed in 2009, seeking to diversify and ensure the energy supply to the Baltic States. Connecting Lithuania, Latvia and Estonia to neighboring EU countries and the internal market is the main priority of the BEMIP Action Plan. This priority requires the full implementation of the internal market rules to enable three Baltic States to participate in the EU electricity market. The interconnection between Lithuania and Poland (project *LitPol Link*) is entirely in line with the EU energy policies and National energy strategies in the region. The 500 MW power link connecting Lithuania and Poland was put into operation in December 2015. By 2020, the *LitPol Link* will start operating at a 1,000 MW capacity. The EC, through the European Energy Programme for Recovery, provided funding for the construction of electrical interconnection between Lithuania and Sweden - *NordBalt*. *NordBalt* is a submarine power cable between Klaipeda in Lithuania and Nybro in Sweden. The implemented project promoted trading between Baltic and Nordic electricity markets, as also to increase the security of power supply in both markets. This interconnection is a high voltage direct current cable with the length of 450 kilometers. The cable was commissioned in 2016 unlocking a total of 700 MW interconnection capacity. It is considered to be the primary connection with the Northern European electricity market - NordPool, allowing direct access to Renewable Energy Sources (RES) and nuclear-based electricity [40].

Taking into consideration general EU energy policy, the country's energy policy is focused on the gradual increase of consumption of renewable energy resources and the growth of energy efficiency. Green electricity generation was almost stable and wholly dominated by hydropower in Lithuania during the period 1990-2000 (see Figure 2.7) [39]. Since 2000 green electricity generation portfolio became more diversified and renewable electricity generation volume was increasing on average by 12.0% per

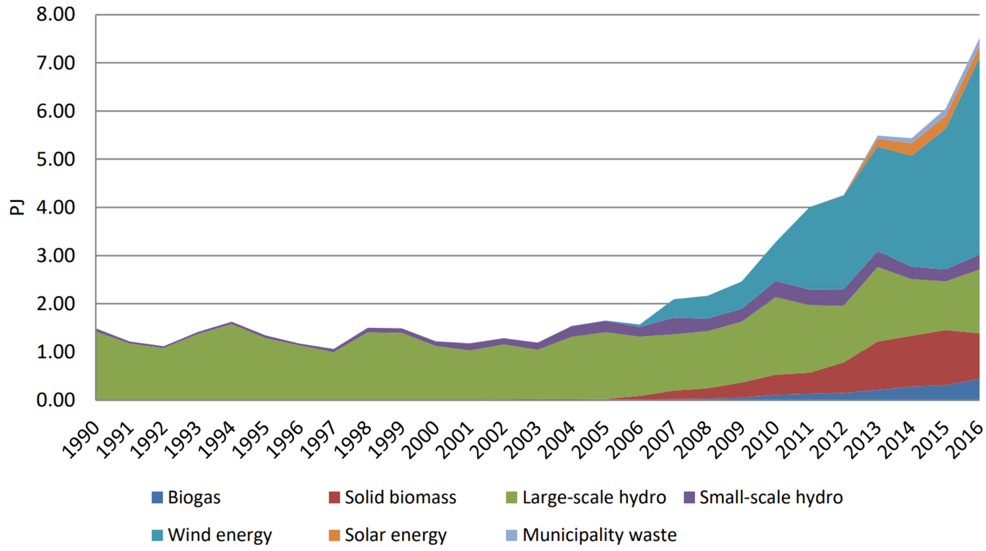

Figure 2.7: Green electricity production in Lithuania

year. In 2016, electricity generation from renewable energy sources was dominated by wind power, generating about 54.4%, followed by hydro power, producing 21.7%, and biomass, biogas and municipality waste, about 20.7% of green electricity. Solar electricity contribution to the structure of green electricity production was 3.2% in 2016. Totally 7.52 PJ (2088.6 GWh) of green electricity was produced in 2016.

2.3.1 Electricity market

The electricity market is the complex system of relationships formed between entities in the process of trading the electricity. What makes the electricity market exceptionally different is that the electricity cannot be stored on the high scale, meaning that the system must be balanced at any given moment. The production side has to meet the demand side, and all of the processes have to be strictly monitored and controlled by its parameters. The overall system is illustrated in fig. 2.8 [41].

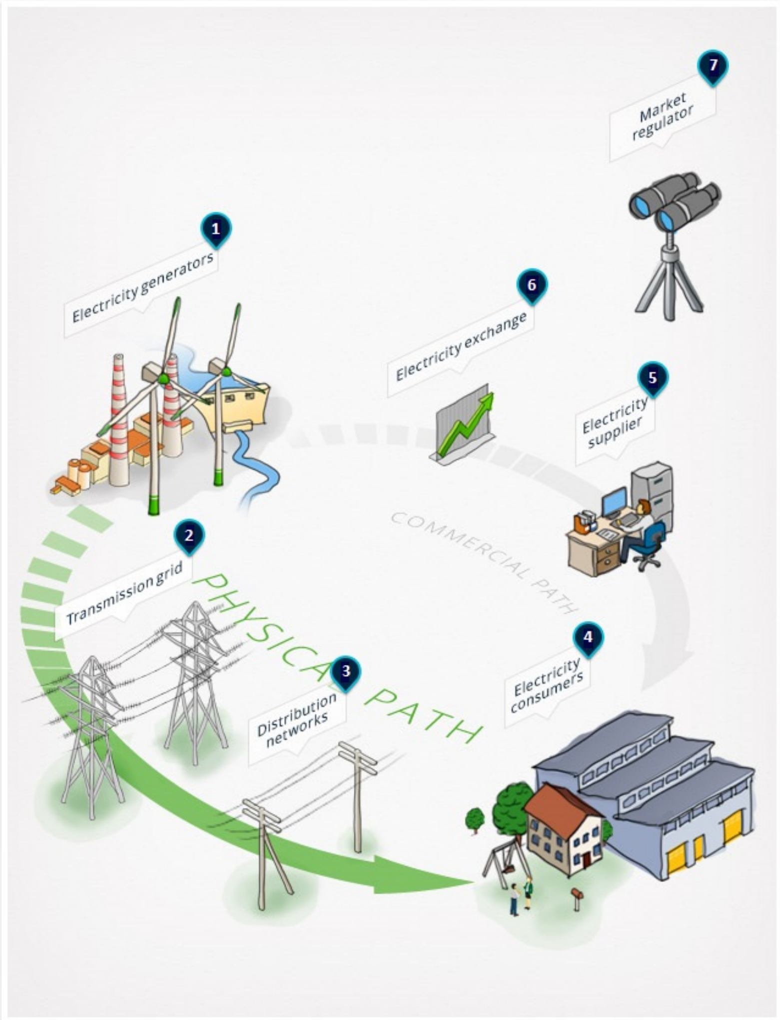

Figure 2.8: Overall electricity market system's visualization with main actors: 1 - Electricity producers, 2 - Transmission grid, 3 - Distribution grid, 4 - Electricity customers, 5 - Electricity suppliers, 6 - Electricity exchange, 7 - Regulator.

The system can be divided into two separate paths - a physical one and commercial. Along both paths the key actors align: **1) Electricity producers** - are power-generating companies which compete in the wholesale market and sell electricity to suppliers in the electricity exchange or under bilateral agreements concluded in advance; **2) Transmission grid** - Electricity is transmitted via the transmission grid and distribution grids from the generation source to the customers. The "postal stamp principle" applies in Lithuania, meaning that the price for the transmission service is the same irrespective of the customer's location. This creates equal conditions for all customers to use the electricity infrastructure; **3) Distribution grid** - the Lithuanian distribution network operator *Lesto* distributes electricity to the end-users, ensures connection of new consumers to the distribution network, operates, maintains, manages and develops the low-voltage distribution network; **4) Electricity customers** - the users of electricity for domestic or commercial purposes. Customers settle up with suppliers for the electricity consumed and pay for the distribution service to the transmission/distribution system operator, depending on the grid to which the customer is connected; **5) Electricity supplier** - legal persons holding licenses to supply electricity; they compete among themselves and buy electricity in the wholesale market in order to sell it to customers; **6) Electricity exchange** - trading in electricity takes place on the electricity exchange, where electricity producers and suppliers conclude purchase and sale transactions. The price in the electricity exchange is formed by the demand and supply balance. Thus a transparent wholesale electricity price is ensured; **7) Regulator** - an independent institution which supervises market participants, provides a competitive environment and sets regulated tariffs for customers.

Like any other commodity market, the electricity market consists of wholesale and retail trade in electricity. Power generating companies that sell electricity to suppliers take part in the wholesale trade. The transaction is including both the Transmission System Operator (TSO) and the Distribution System operator (DSO) which come into the relevance of purchasing electricity as they are witnessing some losses in the transmission/distribution systems and have to compensate the difference. Participants of the wholesale trade may enter into bilateral agreements directly or conclude purchase/sale transactions on an electricity exchange. The retail market trade is made between the customers and electricity suppliers through bilateral agreements. The overall balance of the system - generation and consumption predictions and regulation, is done at the TSO level.

The Lithuanian electricity market was vertically integrated, meaning that the generation, transmission and distribution entities were under one monopoly group, which was highly regulated and monitored. After EU has published the 3rd energy package in 2009 [42], the focus was set on liberalization of gas and electricity markets. That meant that the generation, transmission and distribution operators had to be separated, creating a less monopolist environment, allowing more competition and clearance in the fields [43]. Up until now, the Lithuanian electricity market is partially liberalized, having separate entities for each of the value chains. However, only business and commercial users can choose their operator, leaving the residential sector still bound to a single provider. The liberalization for commercial users began in 2010, allowing 400kW assigned power inlets to select the independent operator. By the beginning of 2012, all commercial entities with 30kW inlets could choose among the list of independent operators, marking the end of partial liberalization period. According to the Lithuanian Ministry of Energy, the market is opting to be opened for residential end users in 2020 [44].

In 2014, as one of the energy security procedures, Lithuania entered a largest electricity trading market in Europe - Nord Pool. A market coupling procedure unlocked a new chapter of wholesale electricity exchange in the country.

2.3.1.A Price setting

The electricity market is shaped with numerous producers capable of selling their electricity at any time. However, as in any other commodity market, the producers which have the lowest marginal costs will be selling first compared to the ones with higher marginal costs. So, once the supply and demand bids have been elaborated and submitted by the corresponding generation and demand agents, the Market Operator evaluates, for every hour of the day-ahead, a merit order scale down by ordering the supply bids in ascending price order and demand bids in descending order. After that, the Market Operator carries out the matching market price point by the intersection of the merit order supply curve with the demand curve. An example is given in Figure 2.9 [45].

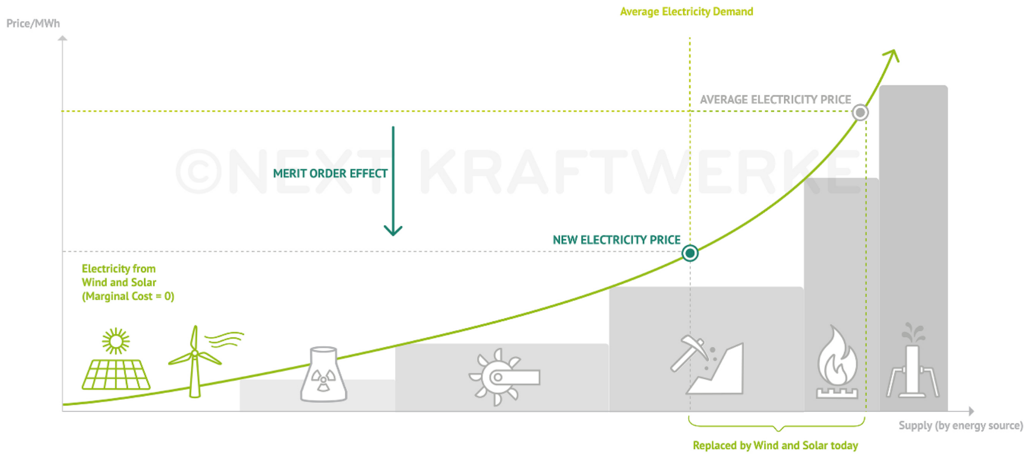

Figure 2.9: Merit order effect on electricity price with renewable energy sources.

Since renewable generators extract the energy from a natural source (wind or sun, e.g.), they can produce electric power with very low, close to null, operating costs. It allows renewable generators to submit their bids offering energy at exceptionally low marginal cost. The methodology of evaluation of the merit order generation scale down made that when a renewable generator provides a bid with a certain amount of energy, the Market Operator inserts the renewable bid on the left-hand side by right-shifting the merit order generation/sale curve. This right-shifting produces a noticeable effect on the reduction of the market price. The integration of renewable induces a displacement of the operating point of the wholesale market towards a lower clearing price, a small increment of the traded energy and, as a consequence, a reduction of the total cost of the traded energy in the wholesale market. That is the principal mechanism, and its main effects, on the market of the very well-known merit-order effect of renewables. As a result, this allows lowering the market price by boosting the incentive for higher renewable energy penetration in the market, lowering overall CO_2 emissions [46]. However, the same effect punishes the reserve producers, which are needed to cover up the intermittent electricity production from renewables, as the weather conditions are inconsistent.

2.3.2 Lithuania in Nord Pool

Nord Pool is the physical wholesale marketplace for the Nordic countries and the Baltic states. It is the largest power market in Europe, and 84% of the consumption for the region was traded in the electricity market in 2017. Within the Nord Pool region, there are no individual national electricity markets [47].

For achieving an interconnected cross-boarders power market, a market coupling methodology is used. It combines all producers and customers across, setting a unified price range for any given hour. However, due to limitations of interconnections between separate countries, the bottleneck effect occurs, and for this reason, other market management methods are enforced. The Nordic and Baltic market uses market splitting. Implicit auctions are used for the formulation of area prices, the allocation of cross-border capacity, and congestion management in the day-ahead market. The price differentials emerge as a function of insufficient transfer capacity between the bidding areas. For each country, the local TSO decides which bidding areas the country is divided. In 2018, the number of Norwegian bidding areas was five. Denmark had two bidding regions (Eastern Denmark and Western Denmark). Finland, Estonia, Lithuania, and Latvia constituted one bidding area each. The Swedish TSO divided Sweden into four bidding areas. As for the current situation, Lithuania is connected with the fourth price region of Sweden located in the South of Sweden, using the NordBalt underwater sea cable. For this dissertation, the market split in between these regions was taken as one of the most important boundary rules to establish a more consistent and region-dependent study.

Further analysis will take into account the days when the congestion of the cross-border interconnection would cause a market split. In general, bidding areas can have a balance, deficit or surplus of electricity, and electricity will flow from regions where the price offered is lower towards areas where demand is high and the price offered is higher. As for Lithuania, because more than half of electricity demand is covered with the import, a deficit will occur having a saturated interconnection of NordBalt. The result is that all producers are paid according to the calculated area price, and similarly, all consumers pay the same price as set for that particular region [48].

However, market splitting is not the same thing as the separation of markets. Market splitting is a form of congestion management. It is used to level out price differences. It increases the price in the low-price area and decreases the price in the high-price area. This technique is used in the Iberian market as well, tackling interconnections between Spain and Portugal.

Speaking of the wholesale market in general, it has many functions. First and for most, the wholesale marketplace provides information about the price of electricity. The spot market determines the reference price for day-ahead or intraday deliveries of electricity in the wholesale market. The financial market provides reference prices for the physical delivery of electricity in the future. Changes in the rates of spot contracts, options, and futures in the wholesale market indicate that the prices charged from end consumers will change as well. For this reason, electricity exchanges are essential for all electricity consumers whether they participate in the wholesale market or not. Secondly, the wholesale marketplace provides a distribution channel for electricity producers and a source of supply for electricity suppliers and large electricity consumers such as industrial firms. Lastly, wholesale market products help system operators to ensure the security of supply and maintain system frequency in real time [49].

2.4 Electricity market's behavior prediction model

In the recent decade, the electricity market has switched in its nature quite severely - from separate local markets to liberalized interconnected ones. Centralized markets with monopolized generation, transmission and distribution operators were more comfortable to predict and manage. Aiming for higher efficiencies and transparency, a liberalized market scheme became more favorable, especially in Europe. It allowed various independent producers to enter the market, leading on to start a competition environment. At the same time, an open market methodology enables trading electricity without having a generation source, which was impossible with the centralized structure. It caused a rising interest in understanding the price variations and its predictability for short-, mid- and long-term approach.

Within this dissertation, the ultimate goal is to test the predictability of electricity wholesale price with relation to increased national consumption due to the presence of the EVs charging load. The hypothesis raised is that the price will rise with increased consumption. The data inputs of these two variables are continuous and ordered, giving values on an hourly resolution continuously annually. The nature of this data alignment suggests that the OLS method can be applied to determine the relation factor of inputs. In practice, this methodology is frequently employed determining various markets behavior.

An OLS methodology refers to the case where there is a continuous response variable and a single explanatory variable. This means that this methodology is tackling the determination of *y* variable (response variable) variations in regards to *x* variable (explanatory variable). In general terms, the scattered data points can be approximated with a corresponding a fitting straight line, which is indicating the approximated relationship between the data sets. The expression of such fitting sequence is shown in Equation (2.1).

$$y = \alpha + \beta x \tag{2.1}$$

In the equation above, α is an intercept point, and β is a regression coefficient. The regression line indicates the relation of *y* to *x*, underlining how will one change with regards to another. This linear model is derived using an algorithm that minimizes the sum of the squares of the distance from each data point to the line, producing a line of best-fit. A well-defined example is provided by Hutcheson G. et al. in a book "Statistical Modeling for Management", where the consumption of ice-cream is being predicted by the outside temperature. The hypothesis is that the consumption will increase with increased outside temperature. A regressed straight line of this relationship is shown in Figure 2.10.

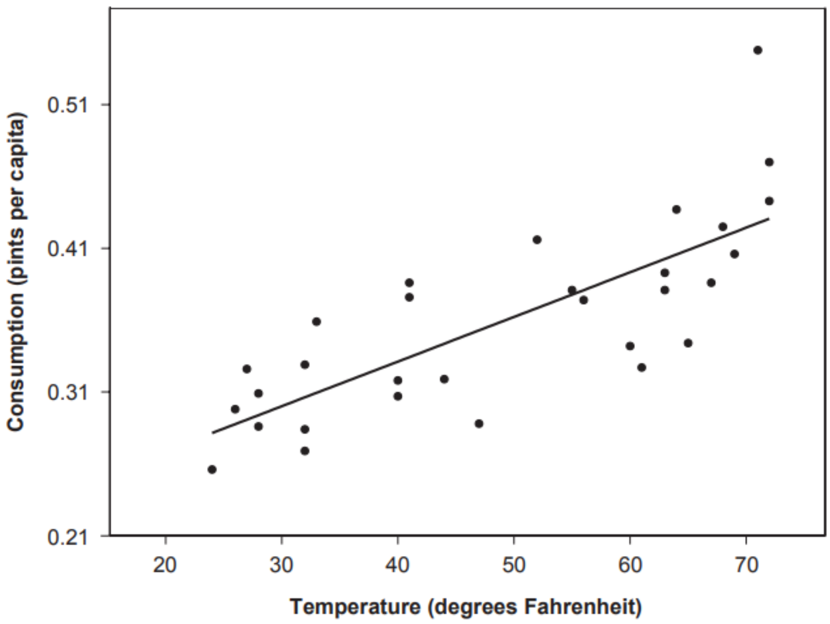

Figure 2.10: An example of the regressed line using the OLS technique. Adopted according to Hutcheson G. et al.

To indicate of how well the model fits the data, model-fit statistics needs to be computed. How well the model fits the data can be determined by comparing the original data set with those predicted from the model. The difference between these two values are called residuals and provides an indication of how well the model predicts each data point. Summing up the deviances of residuals for all the data points after they have been squared (in order to remove any negative values) provides a measure of the data deviation from the overall model. The sum of all the squared residuals is known as the Residual Sum of Squares (RSS) and primarily provides a measure of model-fit. A poorly fitting model will deviate markedly from the data and will consequently have a relatively large RSS, whereas a good-fitting model will not vary significantly from the data and will, therefore, have a relatively small RSS (a perfectly fitting model will have an RSS equal to zero, as there will be no deviation). The RSS statistic, therefore, provides a measure of model-fit and can be used to determine the significance of individual and groups of parameters for a regression model.

To highlight the effect the *x* variable has on *y*, a separate model needs to be established, where *y* values are compared to the $\bar{y}$ mean value. The mean value provides the best prediction for the value itself if no additional information about the continuous variable is available. In this case, the residuals for such a model are merely the difference between each data point and the mean of the distribution. The deviance of these two models can be computed using generic Equation (2.2) [50].

$$deviance = (x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + ... + (x_k - \bar{x})^2 \tag{2.2}$$

The graphical illustration of residuals for both models is shown in Figure 2.11 and Figure 2.12 respectively.

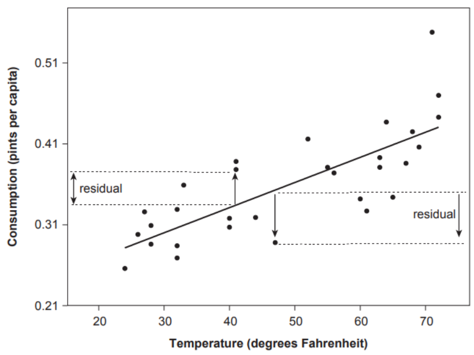

Figure 2.11: Example of residuals for regression model. Adapted according to Hutcheson G. et al.

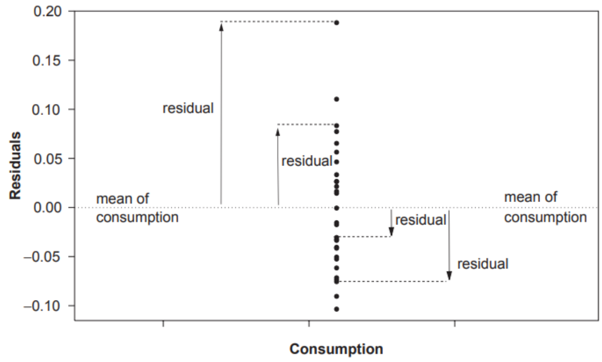

Figure 2.12: Example of residuals for a mean value model. Adapted according to Hutcheson G. et al.

For an OLS regression model, the effect of the explanatory variable can be assessed by comparing the RSS statistic for the full regression model with that for the mean value model (see Equation (2.3)) [50].

$$RSS_{diff} = (RSS_{\bar{y}}) - (RSS_{regression}) \tag{2.3}$$

To determine the significance of how *x* variable influence *y*, few methods can be used - F-statistic and t-value. Both of these approaches are usually used in any statistical calculation tool and acquired automatically. The general rule, in order to state that the response variable is influenced significantly by explanatory variable, P-value has to be low (10^{-04} of the power at least). This value is automatically computed with the statistical analysis tool and can be used to determine if the model explaining the two of the variables is correct. If the model is correct, a widely used methodology of R^2 is applied to indicate the percentage of variation in the response variable that is "explained' by the regression model established before. Usually, R^2 is referred to a determination coefficient. The equation for R^2 is outlined in Equation (2.4) [50].

$$R^2 = \frac{RSS_{diff}}{RSS_{\bar{y}}} \tag{2.4}$$

Values of determination coefficient R^2 are in-between 0 (explains 0% of variables) and 1 (explains 100% of variables), and it allows to compare different regression analysis. To increase the accuracy of the proposed model, sometimes multiple OLS techniques are applied, where for the particular period numerous determination coefficients R^2 are established. It is incredibly relevant analyzing the behavior of variables in the period, where different characteristic curves are witnessed, for example, electricity consumption profile on a daily cycle. To have a reference R^2 value of overall period an adjusted weighted R^2_{adj} can be computed using Equation (2.5), where RSS_{diff} and $RSS_{\bar{y}}$ are the corresponding residual sum of squares and *n* number of observations for regression function *i*.

$$R^2_{adj} = \frac{\sum_{i=1}^{n} \frac{RSS_{diff,i}}{n_i}}{\sum_{i=1}^{n} \frac{RSS_{\bar{y},i}}{n_i}}; \tag{2.5}$$

This equation will allow comparing the regression model fit later on when multiple OLS regression functions will be compared to a single polynomial quadratic regression. The latter is fitting the line in a quadratic function, with an expression of as follows:

$$Y_{quadratic} = \alpha x^2 + \beta x + \zeta \tag{2.6}$$

where α and β are regression coefficients for variable *x*, and ζ is the interception point.

Despite being a statistically unsophisticated methodology, the OLS technique is still one of the most frequent methods used for electricity price predictions [51]. This approach will be used for the research part in the following chapter.

3

Research

Contents

3.1 Methodology

To analyze the impact of EVs charging on the national electricity grid the system's boundaries have to be defined. Undergoing a simulation on Lithuanian electricity market, it is essential to understand that the electricity is being purchased on an open market - Nord Pool, with numerous actors, involved down the supply chain: generators, transmission operators, different locations of each one. Moreover, the wholesale price of electricity is being affected by some factors:

Interconnections: This causes technical constraints on the electricity price as the capacity transmitted from one price region to another is limited with the power capacity of the transmission cable. The saturation on the specific cable limits the accessibility creating a market split scenario.

Maintenance: High influence on the overall price of electricity is being caused by the seasonal maintenance which undergoes periodically. The maintenance of interconnection lines for cross-border accessibility to different price region of Nord Pool plays a significant role for an importing country of electricity like Lithuania.

Seasonal temperature variations: Due to the high heating demand during the cold season in Nordics, Combined Heat and Power Plants (CHPs) are turned on, regardless of MC of electricity generation. Moreover, increasing heating demand is being translated to the electricity grid, as there is a significant number of households not connected to the District Heating Network (DHN). During the warm period - cooling demand increases translating to higher capacities needed from the electricity grid. A similar effect is witnessed in the summertime when increased outside temperature is causing additional cooling demand.

Understanding the key factors which influence the electricity price on the market, it is necessary to draw the system's boundaries. It allows keeping parameters constant while others could be adjustable. For this particular case, to bring the simulations closer to the real conditions, three main scenarios are analyzed depending on the time frame: ***Winter period, Summer period and Spring/Autumn period***. These periods are representing three various demand curves, resulting in the different price dependency on the grid load. To make these scenarios comparable on the technical point of view, the exact dates were chosen, during which the connections are maintenance-free, NordBalt connection working on highest capacity and main electricity generators are not in the maintenance. Having the NordBalt connection working on the full capacity, an additional increase of a local consumption would have to be supplied within the local regions, resulting in a market split price-wise. This allows picturing a characteristic Lithuanian electricity market with its relative behavior.

Having in mind these constraints, the reference days for each of the periods are:

- *28th of February, 2018,* representing **Winter** period;
- *10th of April, 2018,* representing **Spring**/**Autumn** period;

- *12th of June, 2018,* representing **Summer** period.

Since EVs charging dynamics are relevant on an hour to hour price dynamics, hourly electricity consumption and price curves were established for each of the chosen days. An example of such days is shown in Figure 3.1.

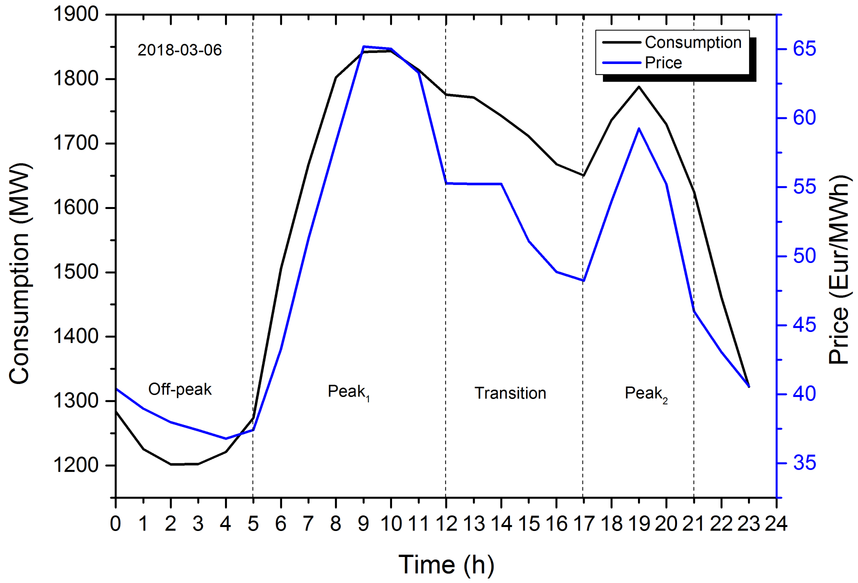

Figure 3.1: An Hour to hour consumption and electricity price dynamics for 6th of March, 2018. *Note: Consumption and price axis are off-set*

A single day can be separated into several specific periods consumption-wise: Off-peak, Peak No. 1, Transition and Peak No. 2 periods. As for example, 6th of March was taken, which has two exaggerated consumption peaks occurring in the morning and the afternoon, the intermediate consumption during the work hours and low consumption period during the night time. The consumption pattern in most of the cases is similar and repetitive, however, as will be seen later, the exact hours during which the consumption changes will deviate, and the peaks might modify depending on the season.

To analyze and quantify an impact of increased consumption a regression model has to be established (see Section 2.4). In this dissertation, different regression models were used to obtain higher determination coefficients for each of the days. If the analyzed day is being regressed depending on the day's period, different equations are acquired. The best-fit regression function will be chosen independently for each of the periods according to the computed values of determination coefficient R^2.

For EVs development in Lithuania, an average growth model has been applied (Table 3.1). Due to the fact that in August 2018 the number of EVs was insignificant, reaching 900 registered vehicles according to the national database [52], the analysis of the impact is translated and recalculated for the year 2025.

For this particular case, the growth was kept constant at 55% annually - an accumulated average value of previous years. It is a conservative approach concluding from the overview done in **??**.

Table 3.1: EVs development in Lithuania until the end of 2018

	2014	2015	2016	2017	2018
Number of EVs	63	159	337	620	970
Actual growth	63	96	178	283	350
Growth rate	0%	52%	85%	59%	24%

Having a predicted number of private EVs in 2025, a charging behavior must be established. For the purpose of this dissertation, the approach of Hao Q. *et al.* work was used, which focused on EVs charging behavior and its impact on China's electricity grid [53]. The charging patterns were divided into three different charging scenarios: vehicles being charged twice, once and every other day. Acquiring the outcomes of the simulation, Hao Q. *et al.* used variables, such as the average driving distance, the EVs' battery state of charge and number of private EVs, which are technically affecting the charging load. This allowed achieving a close to reality average charging load for a single vehicle. Also, a wireless charging method was analyzed, as it is the recent trending research field for EVs interaction with the grid. The Chinese market is the leading one regarding the electrification of transport (see Section 2.1.1), producing the highest number of studies in the field with the conclusions being the most complete. An example of private EVs charging load of a single day and different scenarios are illustrated in Figure 3.2 and Figure 3.3 respectively [53]. To picture more realistic scenario a similar load profile was followed using a single charging per day approach.

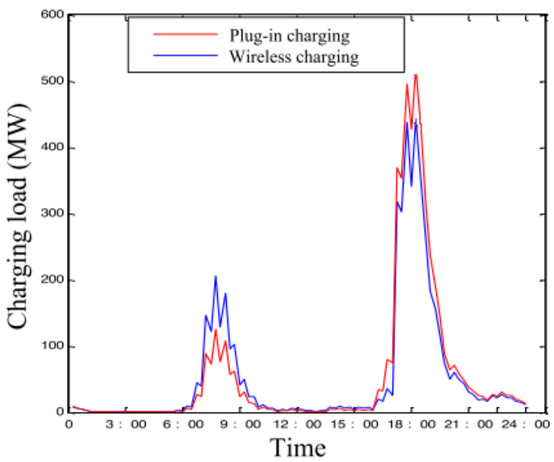

Figure 3.2: Charging load profiles of private EVs example, adopted according to Hao Q. *et al.*

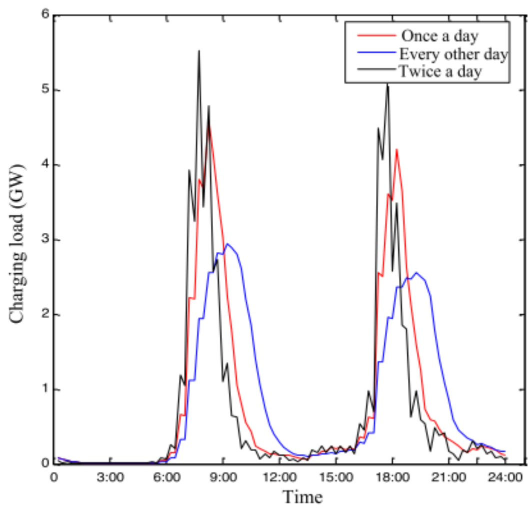

Figure 3.3: A different charging scenario's impact on China's electricity grid in 2015 by Hao Q. *et al.*

Having a behavioral prediction model of EVs' charging and the number of private vehicles expected in 2025 an adjusted model will be established. This will allow comparing the price differences having an additional load from the increased number of EVs and the price for the usual demand.

3.1.1 Data collection

To establish a robust simulation of EVs influence on wholesale electricity price a reliable dataset needs to be assembled. The critical data components and their sources are as follows:

- ***Wholesale electricity prices*** - acquired directly from the wholesale market database - NordPool [54], with an hourly accuracy.

- ***Local electricity consumption*** - obtained from national TSO "Litgrid" database with an hourly accuracy (in Lithuanian) [41].

- ***EVs' statistics*** - adopted according to national transport registration institution database "Regitra" (in Lithuanian) [52].

- ***Mean outside temperature*** - gathered from weather forecasting database with hourly accuracy [55].

- ***Interconnections statuses*** - obtain from national TSO "Litgrid" database with an hourly accuracy (in Lithuanian) [41].

3.2 Data analysis

3.2.1 Consumption variations

First of all, to draw a better picture of the wholesale electricity price dynamics in Lithuania, a seasonal variation has been analyzed. It has a high influence on the consumption curve, as well as the electricity price itself. Having exaggerated seasons, few characteristic loads occur throughout the year. As it is identified in Figure 3.4, the electricity consumption rises and drops depending on the mean outside temperature. Even though electricity consumption is not only depending on the outside temperature, the dependency is quite significant. A specific peak profile occurs during the cold period and keeps dropping as the weather becomes milder.

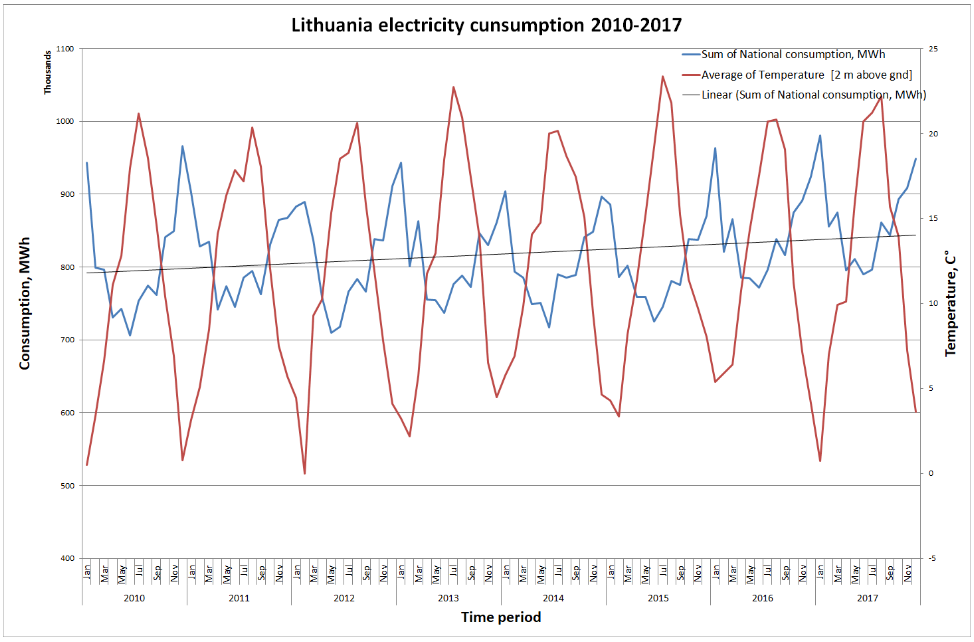

Figure 3.4: Electricity consumption in Lithuania from 2010 until 2017 with average daily temperature variations.

As Figure 3.4 indicates, the milder winter time, the lower consumption peak occurs. At the same time, during hot summertime, an additional consumption increase is witnessed as the temperature rises above the comfort level, causing an additional cooling demand from the grid. The black dashed line indicates a linear trend-line for the consumption curve, which means that the overall tendency of an annual consumption increases slightly. It is affected by a few main factors - the rising mean temperatures translating into higher cooling demands and overall economic development in the country.

For a more accurate monthly variation of the electricity consumption, a Monthly Seasonal Variant Indices (MSVI) methodology was used. The primary purpose of this analysis is to show an average normalized variation throughout the year to the respect of an average value. These indices allow seeing during which periods the consumption increases/decreases. The graph calculated using this expression [56]:

$$MSVI_{ij} = E_{ij}/\bar{E}_j \tag{3.1}$$

Where $MSVI_{ij}$ is the index value for a month *i* in year *j*, E_{ij} is the monthly electricity consumption for a month *i* in year *j*, and $\bar{E}_j$ is the monthly average electricity load for year *j*. The MSVI distribution is indicated in Figure 3.5.

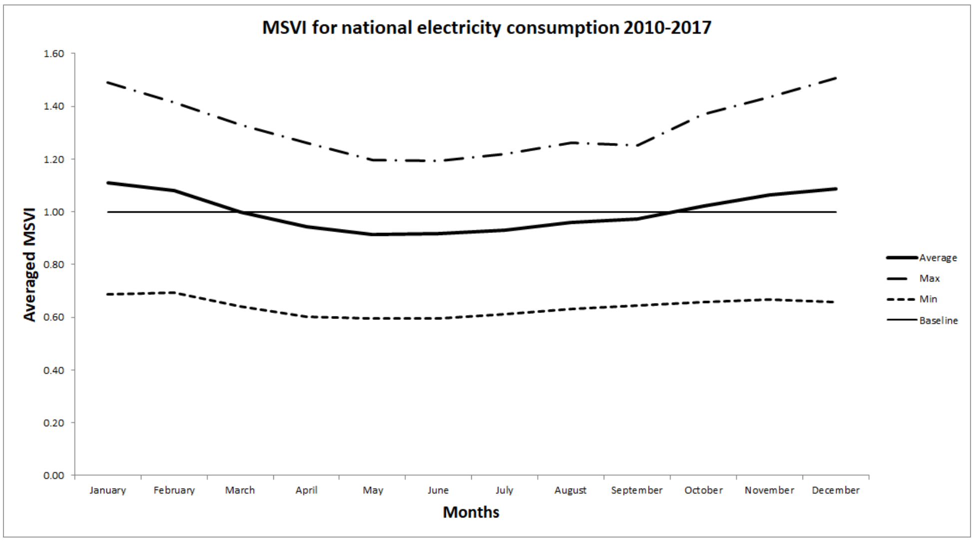

Figure 3.5: MSVI for Lithuanian electricity consumption during 2010-2017.

The thick black straight line indicates normalized MSVI curve, while dashed and dot-dashed curves represent MSVI values to the respect of averaged minimum and maximum values respectively. To highlight, all of the values are averaged for each of the month using the data from 2010 until 2017. It is seen that the consumption is above baseline during winter time in Lithuania, meaning that the consumption is above average during these periods. Consumption decreases gradually until May, after which, the temperature is high enough to induce additional load due to cooling demand.

The MSVI curve can be separated into three periods during which different consumption patterns occur. The first period would be during the cold period when heating demand is present. The second period is the transition one, situated between summer and winter times when the load is not affected by cooling or heating demand. And the third one is the summer period when the temperature is high, and the cooling load is necessary. These three periods are interesting while analyzing the influence of EVs additional load to the grid as they will act on different consumption levels, as well as, different price ranges and their dependency expressions.

As there are consumption patterns' differences on the monthly scale, the consumption levels highly depend on the specific weekday as well. As an economically healthy country operates the majority of its activity during the weekdays (from Monday until Friday) there are deviations of consumption occurring based on that. The similar methodology to the MSVI allows analyzing the variations occurring during the weekdays of any given week. A Daily Seasonal Variation Indices (DSVI) method aggregates every consumption data from 2010 until 2017 and normalizes it to separate weekdays. The general expression is as follows [56]:

$$DSVI_{ijk} = E_{ijk}/\bar{E_{jk}} \tag{3.2}$$

where $DSVI_{ijk}$ is the index value for the day *i* in the week *j* and the year *k*, E_{ijk} is the monthly electricity consumption for same day *i* in the week *j* and the year *k*, and $\bar{E_{jk}}$ is the average electricity load for the week *j* in the year *k*. The DSVI of national consumption is illustrated in fig. 3.6.

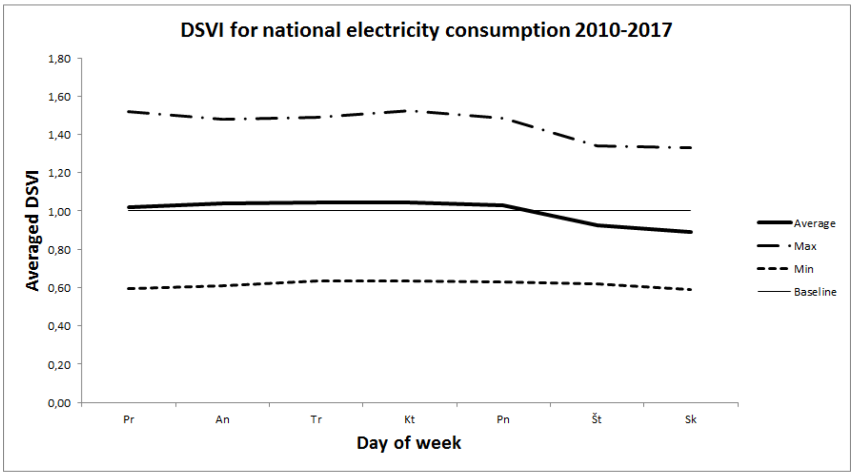

Figure 3.6: DSVI for Lithuanian electricity consumption during 2010-2017

From the DSVI curve, it is seen that the consumption pattern is divided into two separate periods - workdays and weekends. During the workdays, consumption is a bit above the total normalized average, however, it drops significantly during the weekends (see Figure 3.7). That is explained with falling economic and industrial activities during these days. Having this in mind, the period of workdays is more relevant for further analysis as it will picture a more realistic simulation of EVs charging performance on the grid.

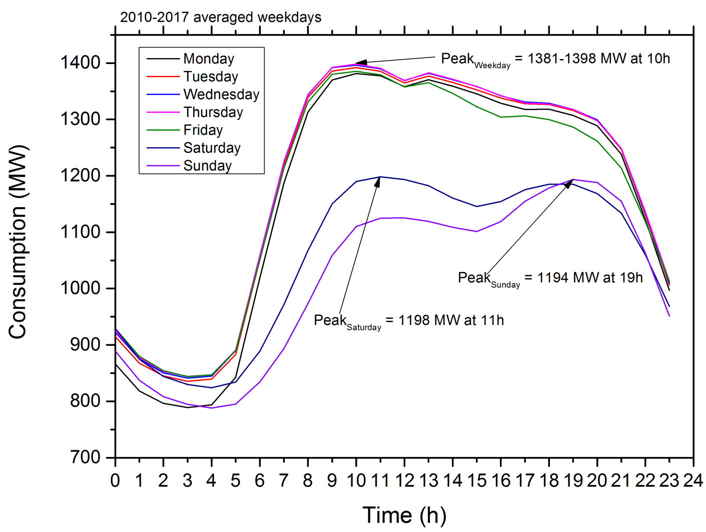

Figure 3.7: Consumption curves of different weekdays. Averaged values from 2010 until 2017.

3.2.2 Charging behavior and load

The Lithuanian EVs market is insignificant in numbers at the current stage, reaching around 900 private vehicles on the road by the end of August 2018. The charging load is not affecting the national consumption in a way that the wholesale price would change significantly. For this reason, the analysis of the situation is being recalculated for the year 2025, expecting that by that time, the fleet size will have risen to the levels that could be considered consumption-wise. As it was mentioned in Section 3.1, the average annual growth of EVs in Lithuania since 2014 was 55%. If the growth rate is kept constant for the rest of the years until 2025, the EVs fleet will reach around 21000 as shown in Table 3.2. It is a somewhat conservative approach, having in mind that the global EVs' market is picking up. However, due to the fact that there are no current significant national incentives in Lithuania, avoiding unnecessary future speculations, the growth rate remained the same. The number of vehicles is essential calculating the aggregated charging load which will be included in the national consumption.

Table 3.2: EVs development in Lithuania until 2025

	2019	2020	2021	2022	2023	2024	**2025**
Number of EVs	1513	2355	3661	5688	8830	13706	**21268**
Actual growth	543	842	1306	2026	3143	4875	**7562**

For charging behavior analysis the Hao Q. *et al.*(2015) approach was taken into account. The main idea is led by the scenario, where the vehicle is being charged a single time throughout the day. Normalizing dataset from Chinese market study, a single vehicle's average charging load is obtained. Such0 charging load is illustrated in Figure 3.8.

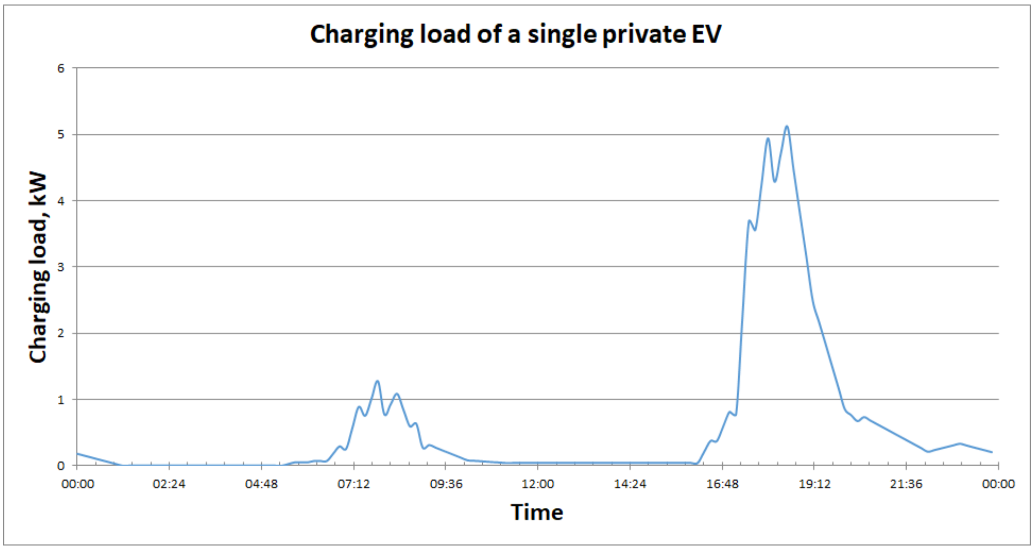

Figure 3.8: An aggregated single vehicle's charging load

Two particular load peaks are occurring throughout the day - first in the morning and second in the afternoon. Such behavior is based on the idea that vehicles' owners are plugging some of the cars around their offices in the morning. However, the majority of the load is kept during the after-work hours, upon the arrival back home. It is worth mentioning that all of the latter peak load will be consumed on the residential area, where low voltage electricity grid is present. This additional load may induce congestion and overload on these grids, however, for the scope of this dissertation, the consumption is taken as a fact, which will influence the national consumption on the wholesale market. The issues regarding the low-voltage grid are ignored and not analyzed.

Having an aggregated average load behavior, it is possible to extrapolate the overall load with regards to the actual Lithuanian situation in 2025. If the number of vehicles in Lithuania in that period is included and followed the same charging pattern, the characteristic charging load for all vehicles is acquired. For such scenario some restrictions have been applied - the overall load is calculated having in mind that realistically 100% EVs participation on daily charging load is not possible. A fraction of vehicles are not charged daily or utilized on a daily basis, thus the number of cars have been reduced to 70% to picture a more realistic situation. The load with restrictions is illustrated in Figure 3.9.

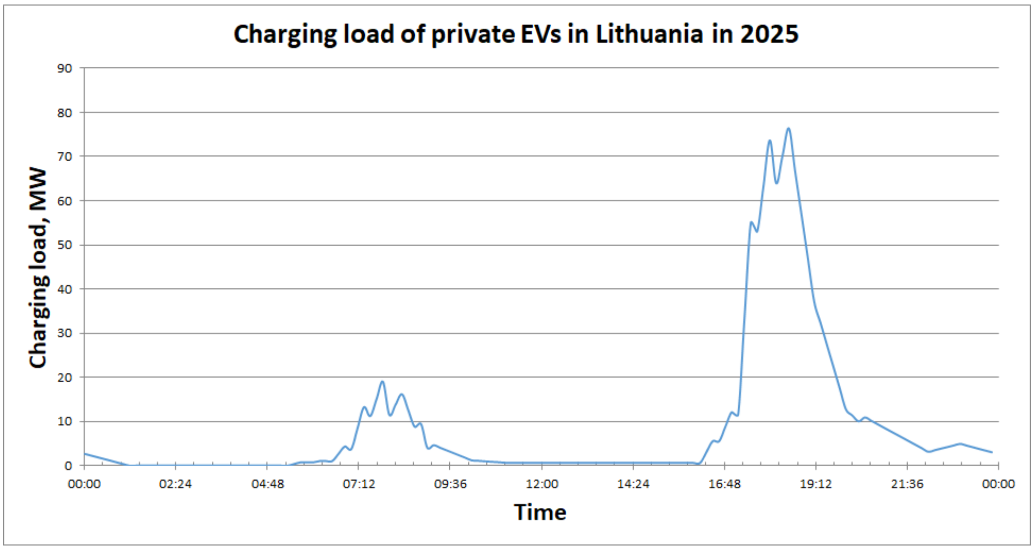

Figure 3.9: An aggregated EVs charging load in Lithuania in 2025

The peak load is witnessed in between 18:00 and 19:00, reaching the maximum peak of $76MW$ at 18:30. The analysis had 10 minutes resolution, resulting in sudden rises and drops around the peak. In the further study, to match existing data of electricity consumption and market prices, an hourly approximation was introduced. For this reason, averaged values of each hour were recalculated. That affected the peak consumption values, making them lower since the averaging was done.

3.2.3 Electricity market behavior

As seen in Section 2.4, forecasting an electricity market behavior, a regression method is one of the more frequently used approaches. Having a significant data set it is possible to predict the price behavior depending on the consumption's historical data. Further, in this dissertation, the regression was made introducing a few approaches - multiple regression curves and polynomial quadratic regression methods. To highlight, the multiple regression methodology refers to multiple linear regressions done on different periods, but not a multi-variable regression. In both of the cases, the aim is to establish a prediction model of the price, with a change of consumption, making a price to be a response variable and consumption the predictor variable. The multiple regression method includes an analysis of separate periods, regressing a particular part of the day, whereas polynomial quadratic regression takes into account the whole day.

3.2.3.A Winter season analysis

As it is mentioned in Section 3.1, the highest consumption of the whole year lays on the winter time due to the high heating demand. To analyze a scenario, how will the EVs charging load perform in a high demand period, one of the coldest days of 2018 was chosen - 28th of February. Most importantly, this day obeys all of the preset system analysis boundaries: the NordBalt interconnection is fully saturated, resulting in considerable Lithuanian and Swedish regions' market split. The consumption and price variations are presented in Figure 3.10.

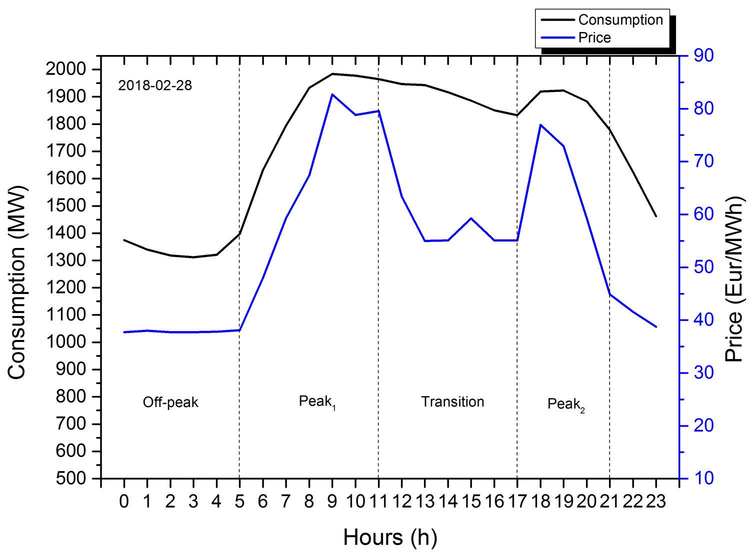

Figure 3.10: Consumption and price variations on February 28th of 2018. *Note: Consumption and price axis are off-set*

As it is illustrated in fig. 3.10, the day's variations are divided into characteristic periods, during which the different patterns of consumption occurs. There are two peak periods - in the morning and the evening explained due to the rational behavior of society. Then there is a transition period, where the consumption is higher than usual and finally the off-peak period when the consumption is at the lowest points. Having a day divided into separate periods, it is possible to conduct different regression functions on each of the curves using OLS methodology. This is illustrated in the fig. 3.11.

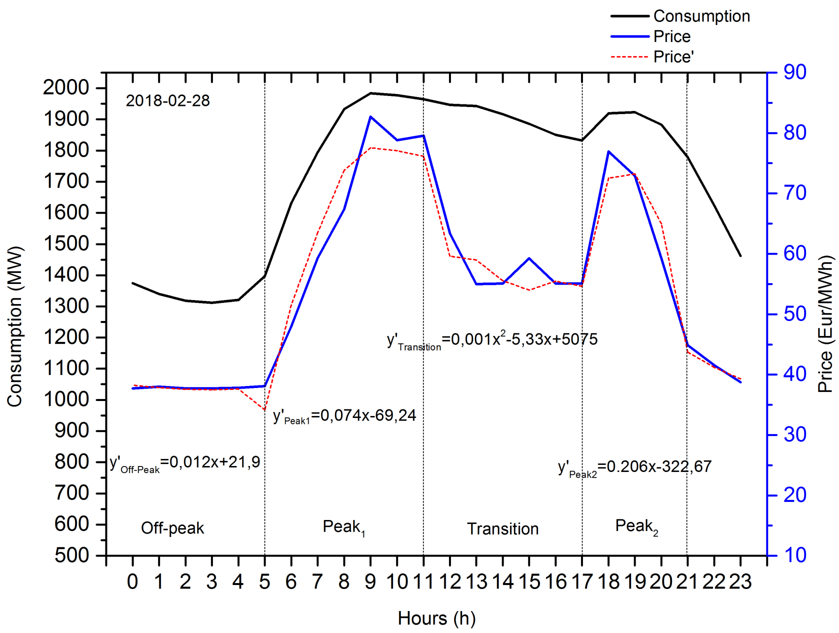

Figure 3.11: Consumption and price variations with regression curves on February 28th of 2018. *Note: Consumption and price axis are off-set.*

Initially, different regression functions were calculated for each of the periods aiming for a better determination coefficient. The P-values and the determination coefficients are as follows:

Table 3.3: Significance and determination coefficients for multiple regression curves applied for 28th of February, 2018.

	Off-Peak	Peak No. 1	Transition	Peak No. 2
Significance coefficient (P-value)	4.845 x 10^{-4}	4.87 x 10^{-4}	5.7 x 10^{-2}	9.67 x 10^{-4}
Determination coefficient (R^2)	0.93	0.928	0.43	0.92

High determination coefficient during the peaks and off-peak periods indicates that the variations of price are closely explained by the dynamics of consumption. Moreover, the α regression coefficients are positive, noting that with an increase of consumption the price will increase by the factor of α. The model is not perfect as the transition period is regressed with low accuracy, having only 0.43 of determination coefficient and relatively high P-value. For this particular period, the price is dropping even though the consumption remains more or less the same. That is explained with the fact that the number of observations is small and the price curve behavior is inconsistent with consumption curve dynamics during these particular hours. Additionally, the mismatch of the price dynamics and consumption curve occurs due to the fact that the supply has been penetrated with the lower marginal cost generation, reducing the sensitivity of the price in this period. The rest of the significance coefficients are low enough to state that the regression model is a good fit.

To establish a more robust prediction model for the price simulation, another approach was investigated - a polynomial regression model of all day. In this case, no specific characteristic day periods were separated, and the regression model was applied for all hours of the day using a general polynomial quadratic equation as shown in Section 2.4. An illustration of polynomial regression applied for 28th of February is shown in Figure 3.12.

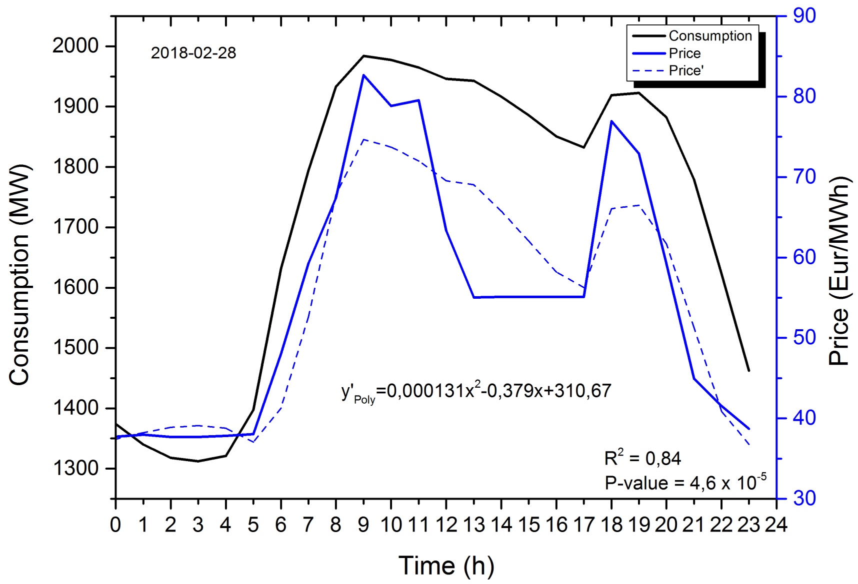

Figure 3.12: Polynomial regression model applied for 28th of February, 2018. *Note: Consumption and price axis are off-set.*

This regression function allowed to achieve $R^2 = 0.84$ overall determination coefficient and rather high significance P-value of 4.6 x 10^{-5}. To compare the determination coefficients for both of the methods the adjusted total value of R^2_{adj} has to be computed. A detailed explanation of multiple regression functions' determination coefficient analysis is given in Section 2.4, from which Equation (2.5) is used acquiring R^2_{adj} for multiple OLS regression functions. The final normalized total determination coefficient for 28th of February is $R^2_{adj} = 0.912$. This suggests that multiple regression lines fit the curves with higher accuracy, and for most, is a better behavioral predictor in the peak No. 2 period, where the additional load for EVs charging will be present. For the rest of the periods' analysis, only multiple regression method will be applied.

After settling with the principal regression methodology, the additional EVs charging load is added with the national consumption. As it is illustrated in Figure 3.13, the additional charging load peak is matching with national consumption peak.

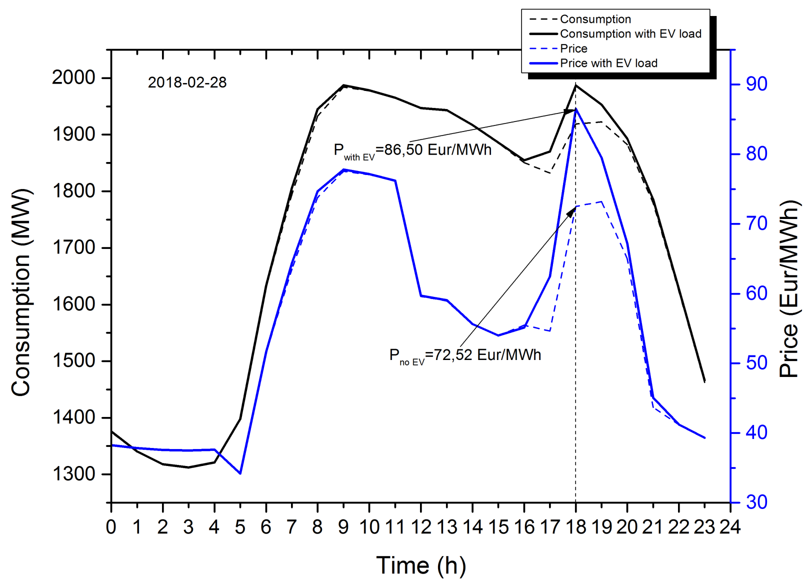

Figure 3.13: Multiple regression model applied for 28th of February with EVs charging load. *Note: Consumption and price axis are off-set*

The graph compares two sets of data: 1) the regular national consumption with regressed price curve (in dash); 2) The added EVs charging load with new price curve for increased demand (in solid). Matching peaks are inducing a more severe effect on the price. It is caused by the fact that for this particular period of the day, α regression coefficient, which is seen in Figure 3.11, is equal to 0.206. High coefficient value is explained by the price region's elasticity in these particular consumption levels, as the merit order dispatch is including high MC electricity generators. This results into significant price difference during the peak hour (18:00). The regressed price curve suggests that the price without EVs' charging profile should be $72.52Eur/MWh$ and with increased load price should peak around $86.5Eur/MWh$. For this particular day, a 3.5% of consumption increase caused by EVs charging load, resulted in 19.3% of increase of wholesale electricity price.

3.2.3.B Spring/Autumn season analysis

Seasons of Spring/Autumn in Lithuanian electricity market are characteristic in their essence - there is no heating or cooling demand present, thus the consumption levels are lower than in winter time. To illustrate the market's behavior in this particular period, April 10th was taken as a reference day. The preset system's boundaries are applying for this date as well - the NordBalt interconnection is entirely saturated, inducing a market split in-between Swedish and Lithuanian price regions. The data analysis for this set of data is repetitive as for the period before, thus the similar approach will be applied. The consumption and price variations are illustrated in Figure 3.14.

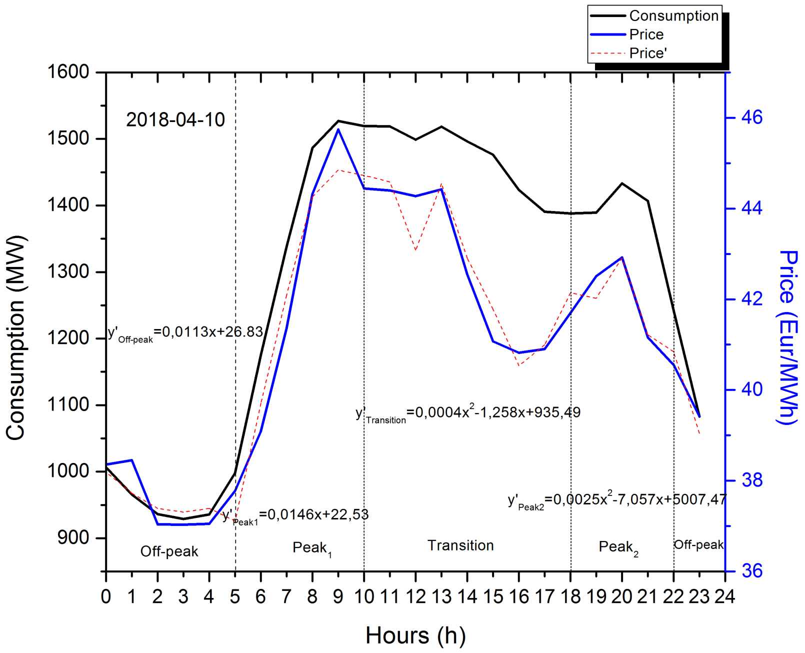

Figure 3.14: Consumption and price variations with regression curves on April 10th of 2018. *Note: Consumption and price axis are off-set*

As it was seen before, the day is divided into characteristic periods, where different regression functions were applied. A noticeable difference compared to the winter season's profile is that the consumption is lower, resulting in lower price range deviation during off-peak and peak hours. Another essential characteristic of such period is that the national consumption in the evening is peaking a few hours later. That is explained with a longer time of sunlight, postponing the domestic lighting load in the evening. The rest of the consumption's profile is repetitive - the off-peak is followed with exaggerated peak No. 1 in the morning, leading to a transition period until the peak No. 2. For this particular day, the OLS linear regression and polynomial quadratic regression functions were applied to achieve higher significance and determination coefficients. In Table 3.4 the corresponding coefficients are outlined.

Table 3.4: Significance and determination coefficients for multiple regression curves applied for 10th of April, 2018

	Off-Peak	Peak No. 1	Transition	Peak No. 2
Significance coefficient (P-value)	1.08 x 10^{-4}	7.0 x 10^{-4}	1.502 x 10^{-4}	4.83 x 10^{-4}
Determination coefficient (R^2)	0.901	0.957	0.877	0.867

For comparison, a single whole day's polynomial quadratic regression was calculated (*attached in Appendix A*), however, as mentioned before, the multiple regression model will be used for further analysis to keep consistent with the results.

Evaluating the overall adjusted determination coefficient R^2_{adj}, a similar Equation (2.5) was applied. Computing the formula, the adjusted $R^2_{adj} = 0.928$ value achieved. The result suggests that the prediction model is fitting well and the regression function explains the dependency with high accuracy. Following the same procedure as in Section 3.2.3.A, an additional load from EVs charging is added. Important to mention, that the charging behavior is kept constant throughout the year, as the behavior will not switch depending on the season. Concluding, the overall consumption and regressed price dynamics with and without the charging load are shown in Figure 3.15.

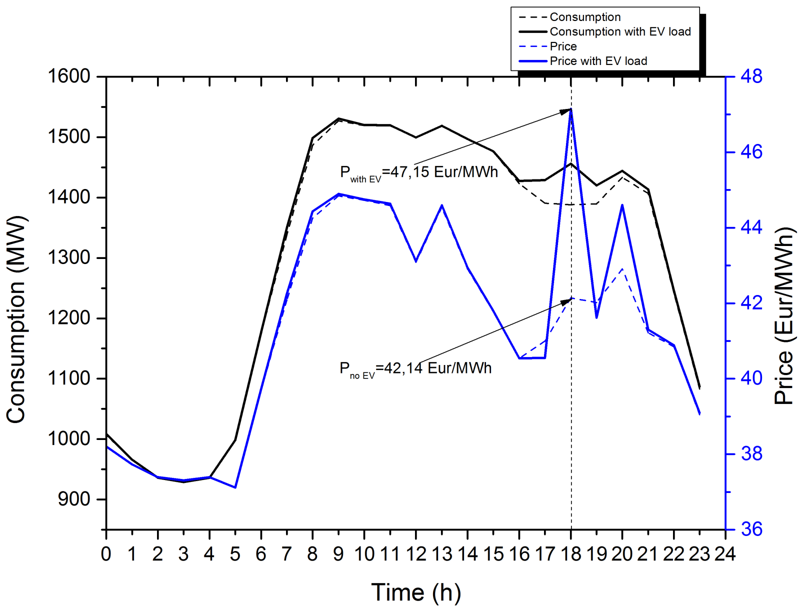

Figure 3.15: Multiple regression model applied for 10th of April with EVs charging load. *Note: Consumption and price axis are off-set*

Due to the fact that the national consumption peak No. 2 is a bit postponed compared to the winter season, EVs charging load falls into the transition period. That will affect the price dependency, as the market's price elasticity in lower consumption levels is higher - there are more available production options than in peak hours. As it is indicated, on peak charging time - 18:00, the regressed price for April

10th without the EVs load is recorded to be $42.14 Eur/MWh$, whereas price with increased consumption is $47.15 Eur/MWh$. So, an increase in consumption by 4.9% will ultimately increase wholesale electricity price for Lithuanian region by 11.9% during the Spring/Autumn period.

3.2.3.C Summer season analysis

Summer season in Lithuania is particular compared to previously analyzed due to two reasons - the consumption is affected by increased cooling demand and the absence of the peak No. 2, which usually occurs in the evening. The cooling demand is increasingly influenced by the mean outside temperature, raising above the comfort levels. However, the effect is not as significant as the heating demand in the winter time. The absence of peak No. 2 can be explained with lack of lighting demand as the sun is setting around 23:00 and the occurring postponed load is slipped under the transition period. For a representing day of the summer period, June 12th was taken as a reference. Again, during this day analysis boundaries are obeyed - full saturation of NordBalt interconnection, which results in a market split price-wise. Consumption and price variations are shown in Figure 3.16.

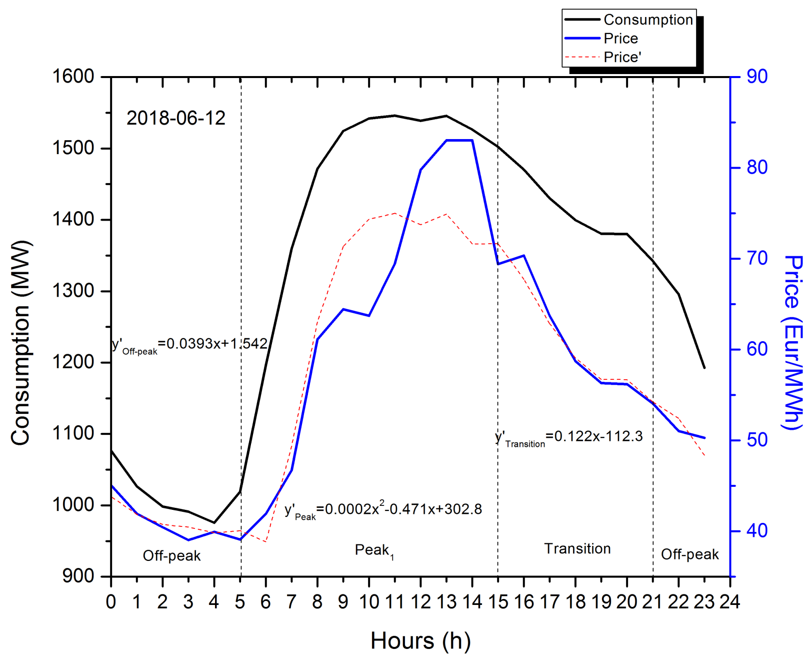

Figure 3.16: Consumption and price variations with regression curves on June 12th of 2018. *Note: Consumption and price axis are off-set*

Again, the day is separated into characteristic periods and regressed accordingly. As mentioned before, there is no dominant peak No. 2, thus,for this reason, the separation was done as follows: an off-peak period leads to an exaggerated Peak No. 1 in the morning, which is longer and broader in its shape, following into transition period. The multiple regression method was applied to each of the phases, using linear regression functions and single polynomial regression. The acquired significance and determination coefficients are outlined in Table 3.5.

Table 3.5: Significance and determination coefficients for multiple regression curves applied for 12th of June, 2018

	Off-Peak	Peak No. 1	Transition
Significance coefficient (P-value)	1,9 x 10^{-5}	2,7 x 10^{-4}	1,6 x 10^{-4}
Determination coefficient (R^2)	0.961	0.816	0.935

For comparison, a single whole day's polynomial quadratic regression was calculated (*attached in Appendix A*), however, as mentioned before, the multiple regression model will be used for further analysis.

Computing a normalized overall R^2 value for all of the periods, repetitively Equation (2.5) was used. finally, the value of $R^2_{adj} = 0.843$ was achieved. It is profoundly influenced by the fact, that number of observations during the least certain transition period is highest, weighing the overall value towards the lower value. Even though the prediction is less accurate compared to other periods, the model is still applicable, as the determination coefficient during the EVs charging load peak (18:00) is above 0.93 and the significance coefficients are in acceptable range. Following the same steps, an additional charging load was added, and a comparison graph was generated, illustrated in Figure 3.17.

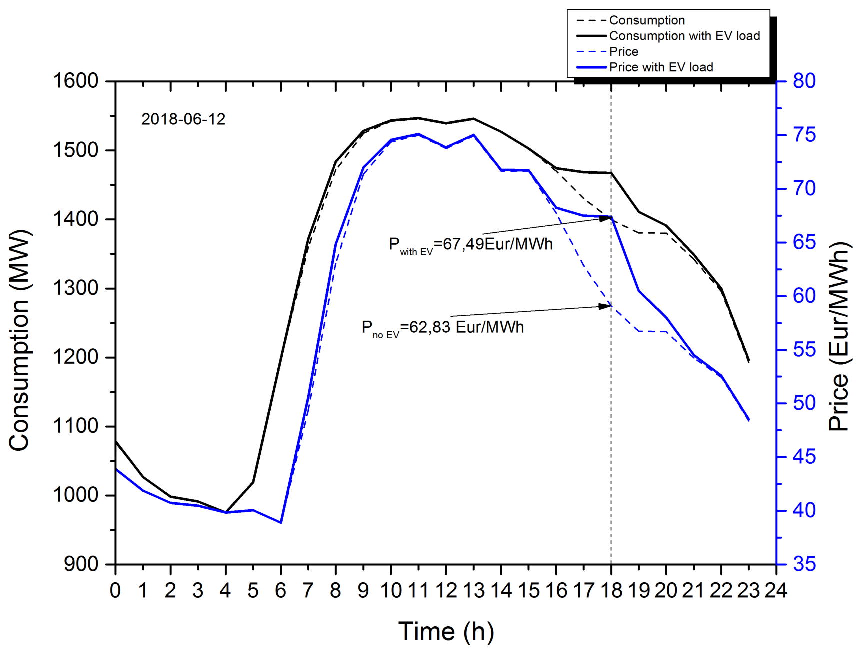

Figure 3.17: Multiple regression model applied for 12th of June with EVs charging load. *Note: Consumption and price axis are off-set*

Analyzing summer's period, it is seen that the consumption levels are similar to Spring/Autumn period - the heating demand is being compensated with decreasing national consumption due to typical vacation period in Lithuania. There are higher deviations of wholesale electricity price compared to off-peak and peak hours. Additionally, as it was seen in Figure 3.15, the EVs charging load peak is not falling under the peak period, suggesting that the price effect will be milder price-wise compared if it would match with the peak as it was in Figure 3.13. The analysis of this reference day gives a result that the regressed electricity price for regular national consumption should be 62.83 Eur/MWh and with added charging load it should be 67.49 Eur/MWh. It is possible to predict, that during this characteristic period an increase of 4.85% of consumption would result in an increase in wholesale electricity price by 7.42%.

3.3 Results and discussion

To summarize, there is a clear indication that the increased consumption due to electrification of transport will affect the wholesale price. The price deviations with peaking charging load are very dependent on the characteristic electricity consumption pattern, creating a more noticeable effect if the charging is matching with natural national consumption peak (as it was seen during Winter's season analysis). The increase of the wholesale price by 19,3% on a particular hour of the day seems to be significant, however, the versatile wholesale market is having even more exaggerated price differences on hourly bases. In a few cases, the price may increase by 200% for a single hour, but this price effect is usually explained with extraordinary system's failures or unexpected breakdowns of crucial supply chain component. For example, an emergency stop of NordBalt interconnection which occurred on March 21st, 2016, has immediately caused a price increase by 40.6% in Lithuanian price region [57]. It is not precisely stating that the system is vulnerable to minor fluctuations, though the NordBalt interconnection is playing an essential role in order to minimize the wholesale price.

This dissertation is not intended to illustrate a perfect electricity market prediction model, which could outline a precise price deviation with adjusted consumption. For the purpose of this work, the primary goal was to indicate an effect which is possible due to increasing transport electrification. The significant confrontations that can be identified are: the wholesale electricity price is affecting the whole society, increasing the retail price; and transportation transition will eventually substitute ICEVs, resulting in distortion in the national budget collection by an excise tax on fossil fuels.

The fact that supposedly having a relatively low number of EVs in Lithuania by 2025 (around 21000) will be translating an additional retail price increase for a country of 2.8 million people is causing doubtful fairness of society benefit. The idea of transport electrification is driven by the environmental policies, tackling the reduction of CO_2 emissions in this sector. For this purpose, governments are choosing to invest public capital in raising an incentive for society to switch into zero emission vehicles. At this moment, without any subsidies for the investment cost, the cost of ownership of new EVs are barely equalizing with conventional ICEVs. The difference is caused by the few factors: inbuilt battery system is still expensive, even though, as seen in Section 2.1.1, the production costs are being reduced annually; the economies of scale achieved by ICEVs are not yet matchable by EVs. For the Lithuanian market case, there are no massive direct investment incentives, which would cover part of the fixed costs related to the ownership of EVs. However, as seen in Section 2.2, the incentives are allocated in utilization part, subsidizing charging costs, parking tickets and allowing to use particular traffic lines in major cities. In other words, the incentive system is focusing on subsidizing the variable costs that end users are witnessing. Additionally, these incentives are arguably applying to the whole society, as the average price of EVs is affordable for just a top fraction of society with higher income levels. Incentives, which refer to the rich part of the community, leading to a higher retail price of electricity will eventually cause negative externalities - the societal marginal cost of transport electrification will be higher than the private marginal cost.

Another effect that could be identified within this dissertation is the possible distortion of the taxation system in Lithuania. Currently, 14.6% of the national budget is gathered from the excise duty tax, including the excise of petrol and diesel products, which are heavily used in transportation [58]. Practically, 21000 EVs will not cause a significant difference of diesel/petrol consumption compared to 1.6 million conventional vehicles on the road. However, in theory, aiming for a complete electrification of the transport sector will minimize the collected excise duty tax, creating a budget gap, which will definitely be filled with additional taxes in other industries. This suggests that significant tax reforms will be needed in the future to rearrange the budget constraints caused by transport electrification.

The raised issues stated above are not meant to criticize or object the electrification of transport. Induced global warming due to excess usage of fossil fuel indicates that the electrification is a favorable solution. However, the major transition in the transport sector will disrupt the existing situation. These effects are practically occurring on a small scale already, thus with the increasing pace of electrification adoption governments will be forced to adapt and enforce some radical changes in the future.

3.3.1 Proposed solutions

The main issue that could be drawn from the empirical results obtained in the dissertation is that the price is more sensitive where the charging peaks are matching with national consumption peaks. There could be two mechanisms identified tackling peaking EVs charging load profile - smoothing out the load by scattering the charging load into separate hours or postpone the peak charging into a less price sensitive time of the day. A technical or behavioral solution can be applied.

Behavioral adjustment. In general, electricity price for end users in Lithuania is not high, reaching

12-20 Euro cents per kWh on average, depending on the tariff. Currently, it is divided into night and day tariffs, differentiating the price fluctuations on the wholesale market in these periods. However, the retail price is not deviating on an hourly basis in either of the price zones. The fact that there is no difference in price wherever it is consumed during the peak or off-peak hours throughout the day is not raising any awareness of personal consumption. Recently, to increase the predictability and adjustments from a demand point of view, the Demand-side Management (DSM) methodology has been introduced. The DSM is an important instrument that can significantly reduce the need for grid upgrades and additional generation capacity due to electrification of road transport [1]. Regulators, utilities, transmission system operators, distribution system operators and retailers are already taking methodology measures and designing policy mechanisms to ensure that the EVs uptake will not overload the power grid. For EVs, DSM mainly consists of the optimization of the charging time of the vehicles, shifting loads to ensure a good match between the power supply and demand with the aim to move the aggregated load of charging related power demand from the peak hours to the off-peak period. It is suggested that a dynamic tariff system needs to be proposed, which would indicate the market's price fluctuations in real or close to real time. A Time-of-use (TOU) or real-time pricing (RTP) mechanisms can be proposed [1]. The latter RTP solution would naturally indicate EVs owners what the current price of electricity is and would be obliged to pay extra for peak hours - when the electricity is more expensive. The TOU solution incentivises the end users to utilize the charging during the hours when the system is less saturated, and discourage using the grid when it is overloaded. The differentiation of price would directly impose a behavioral change from the demand-side point of view, reducing a need of investment into infrastructure to support an increasing number of EVs on the road.

Technical adjustment. While behavioral adjustment is impactful, the precise estimation of how will the demand side behave is rather difficult. It is easier to predict a full load at the peak hours, however the investment into infrastructure would impose unbearable costs, which would ultimately settle among the society. From a technical point of view, there is a solution, which controllably tracks the charging of the vehicle and automatically postpones, or even reverses, it to achieve load shifting. The advantage of this smart charging protocol is that it does not require personal effort from the end user. Smart charging is automatically tracking the on-going price fluctuations in the market, which are indicating the consumption loads, and directly through charging cable communicates with the vehicle itself. This methodology minimizes plug and charge effect when uncontrollably EVs have began to charge at the moment of insertion. The plug and charge effect is inducing the characteristic peak of EVs charging on the grid. Analyzing further, this methodology unlocks Vehicle-to-Grid (V2G) possibility, when EVs are utilized as an external electricity source to power up residential households, as well as provide ancillary services for the grid itself. Employing both, smart charging and V2G, a national consumption peak shaving effect can be achieved [1].

Concluding, both of these adjustments would positively contribute to the future of transport electrification and beyond, as they provide three key benefits:

- Reduction of the need for additional generation capacity by shifting charging loads to periods with lower demand. Moreover, charging in off-peak hours would induce a lower electricity price.
- Optimization and further utilization of existing grid equipment during the day, increasing their efficiency factor and increasing their profitability, therefore reducing their cost per kWh.
- Reducing curtailment of renewable generation by aligning EVs charging with periods of high output from renewables, such as nighttime charging when production from wind generators is often highest or mid-day when Photovoltaics (PV) generation peaks [1].

4

Conclusion

Contents

4.1 Conclusion

To summarize, the analysis done on the Lithuanian electricity market has identified a neglected effect on prices, caused by the upcoming EVs charging load in the national consumption curve. The work was not intended to obtain the most precise electricity market analysis tool with high prediction accuracy, but rather to highlight the possible impact on society. As it has been shown, in a versatile market as Nord Pool, where the region's price fluctuations are dependent on various variables, a relatively low EVs penetration in the area could significantly influence the wholesale price. This effect will cause the retail price to rise accordingly.

These results raised a discussion regarding the societal fairness issue. The transport sector's transition towards electrification will cause just a part of society to use the benefits of subsidized industry, while the rest of society will be witnessing increased retail electricity prices. Such a system will ultimately be exploited by the rich part of the society, as the EVs are considered to be a luxury good. However, the overall influence is severe due to the characteristic charging load, which has an exaggerated peak in the evening. The charging profile is closely related to natural consumers' habits. Therefore, behavioral and technological solutions were presented.Both types of proposed solutions are aiming to create an incentive to postpone the charging, either it is automated or manual. Creating an economic incentive to switch charging habits will help to smooth the profile peak and scatter the load throughout the day, especially in less loaded hours (night time).

In conclusion, the transition towards electrified transportation means is inevitable, and it is very much favorable being environmentally cautious. The aim of this dissertation was to show that this particular adoption of EVs have to be analyzed from different perspectives, especially when the public spendings are concerned.

4.2 System Limitations and Future Work

The analysis of price dependency on consumption was done introducing some key restrictions - particular days had to obey the system's parameters. For this specific work, the limitations were put intentionally to lower the chance of unrelated events, which could make an impact on the final result. Additionally, the knowledge of the overall market is limited, forcing a few educated assumptions without having a definite proof.

Future work is intended to broaden the system's boundaries, introducing more flexible and precise prediction models. Moreover, the analysis was done on a rather complex market, with several countries involved. Thus, to test the model's accuracy, it should be applied to less versatile markets.

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A

Appendix - Different polynomial regression functions

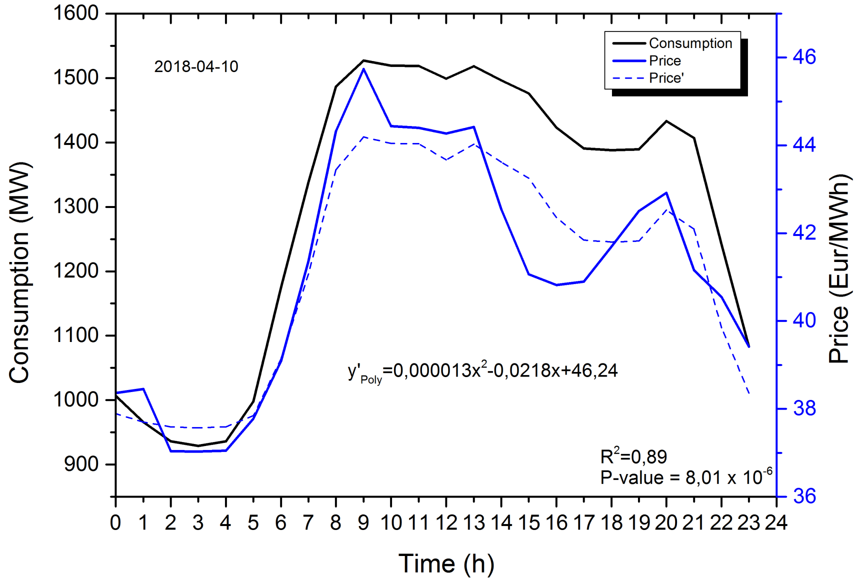

Figure A.1: Polynomial regression model applied for 10th of April, 2018. *Note: Consumption and price axis are off-set.*

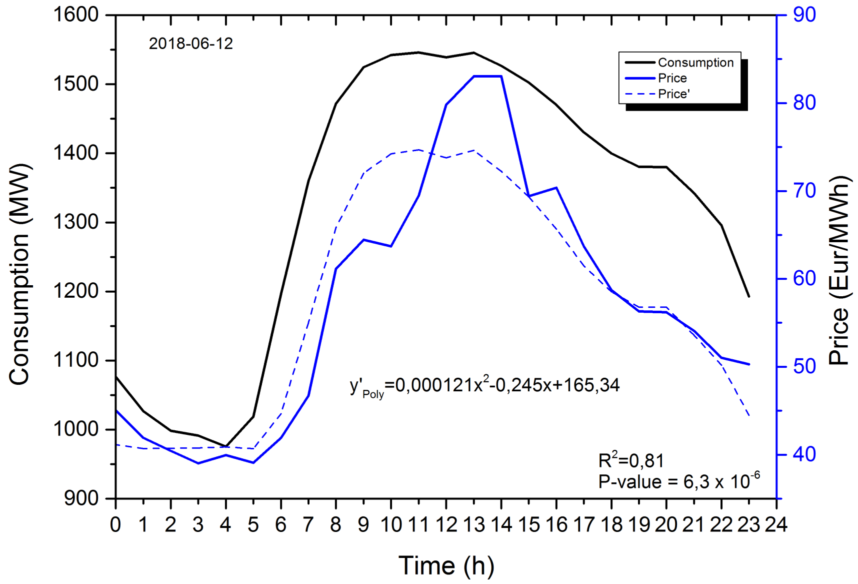

Figure A.2: Polynomial regression model applied for 12th of June, 2018. *Note: Consumption and price axis are off-set.*