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Sustainability Analysis of Alternative Fuel Vehicles by using Life Cycle Assessment and Optimisation

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Graduate School of System Design and Management,
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SUMMARY OF DOCTORAL'S DISSERTATION

Name	Kamila Romejko

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Abstract

In recent years, there has been an increasing interest in alternative fuel vehicles (AFVs), such as electric vehicles (EVs), fuel cell vehicles (FCVs) and compressed natural gas (CNG) vehicles, as a promising option for mitigating global warming and reducing energy consumption. Most studies in this area have been conducted on only a few types of powertrains, e.g. EVs and gasoline vehicles; to fill this gap, this study will cover FCVs, CNGs, hybrid electric vehicles, diesel hybrid electric vehicles and liquefied petroleum gas (LPG) vehicles. Moreover, most of the papers focus on the use phase of those vehicles and disregard the manufacturing part, which is energy and emission intensive. The indirect effects of emissions production include severe health problems such as chronic asthma or even mortality. Automakers and policy makers need to investigate the lifecycle emissions of vehicles in different regions. It is crucial to decide if governments should invite EV production into their country, or whether it would be more appropriate to import vehicles. This research is novel because it includes energy security aspects, uses multiple scenario analysis, and investigates FCVs and various stages of AFV's lifecycle in different regions. The objective of the thesis is to systematically assess the sustainability of AFVs. Firstly, the economic pillar of sustainability is being investigated by carrying out optimisation. The optimal AFV portfolio, based on different scenarios to sustain energy security in light of gas and petroleum restrictions until 2030, is being calculated. The Polish market is considered as a case for demonstrating the optimal model. Secondly, environmental and social pillar of sustainability is explored. Life cycle assessment (LCA) has been applied to this research in order to quantify greenhouse gas (GHG) and non-GHG emissions and health impacts of air pollution connected with AFVs. We assessed air pollution from vehicles in Japan, China, and the United Kingdom (UK) and additionally health impact for Poland.

This research help automakers and policymakers recognise investment possibilities and it provides numerical findings for multiple stakeholders such as governments, energy, and automotive companies. The findings from scenario analysis can be used to create government policies and proposals, which was already studied in conventional studies. The results from LCA are crucial for strategic decision making on investment in EVs.

Chapter 1 presents the background and subject of the research, previous studies deliverables, originality, motivation, and objective of the study. In Chapter 2 methods of the thesis are briefly described. Chapter 3 provides qualitative analysis of AFV and insights into automotive industry and energy sectors of the case studied country. The results from interviews suggest that environmental issues are neglected in Poland; the price of the vehicle is the most important reason influencing the purchase. Moreover, the introduction of incentive system for AFVs for both companies and private entities might spur the sales of the cars again.

Chapter 4 elucidates the optimization model, and constraints, variables, and results for vehicle portfolio analysis. The results indicate that it is crucial to introduce all types of powertrains to achieve both economic and energy security objectives. The projected diffusion of FCVs will be more pronounced than that in previous studies, owing to the expected rapid decline in the cost of

both infrastructure and purchase price of cars.

Case study for shale gas revolution and vehicle portfolio analysis is illustrated in Chapter 5. The results of this study suggest that due to shale gas revolution and decrease of gas prices, the portfolio of AFVs improves. Moreover, the results show that increased use of shale gas engenders the high consumption of water. Even though shale gas might improve the AFV portfolio the drawbacks of high water consumption and safety threads might hinder the positive aspects of implementing it in a long run. Water safety measures such as water recycling, reusing and disposal; technology choice; establishing the plants in low-density areas; are crucial while considering investment in shale gas.

Chapter 6 explains the LCA method, scenarios, and data used in the calculations for two case scenarios. Government and automotive companies can use created a model to make crucial decisions while setting up the location of the production plant. The results of the LCA simulations are provided in Chapter 7. Results for the LCA: GHG and non-GHG emissions indicate that EVs do not necessarily decrease pollutant emissions. Only in the UK the environmental cost of GHG and non-GHG emissions for EVs is lower than for GVs. EVs are more environmentally intensive than GVs. The substantial difference between those two is attributed to battery manufacturing EVs produce less CO2 during use phase, but other emissions are still high. However, a high decrease of the cost is projected in the Technological Advancement Scenario, especially for China. The results of the second case study LCA: Health effects imply that the total cost of health issues is lower when import of EVs is from the nearby countries, which generate electricity from clean energy resources or when it is produced in a low emission country locally. Surprisingly, maritime transportation accounts for a substantial portion of the total emissions, because ships use diesel oil. That is why one of the recommendations is to switch from diesel oil ferries to LNG ships. Moreover, in 2025, the monetary cost of health diseases drops dramatically due to significant

technology improvements such as increases in energy efficiency and production, increase in the share of renewable sources in the electricity mix, stricter air emission standards. Finally, conclusions and limitation of the study are presented in Chapter 8.

Key Word (5 words)

alternative fuel vehicles, policy, automotive, sustainability, air pollution

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Abstract

In recent years, there has been an increasing interest in alternative fuel vehicles (AFVs), such as electric vehicles (EVs), fuel cell vehicles (FCVs) and compressed natural gas (CNG) vehicles, as a promising option for mitigating global warming and reducing energy consumption. Most studies in this area have been conducted on only a few types of powertrains, e.g. EVs and gasoline vehicles; to fill this gap, this study will cover FCVs, CNGs, hybrid electric vehicles, diesel hybrid electric vehicles and liquefied petroleum gas (LPG) vehicles. Moreover, most of the papers focus on the use phase of those vehicles and disregard the manufacturing part, which is energy and emission intensive. The indirect effects of emissions production include severe health problems such as chronic asthma or even mortality. Automakers and policy makers need to investigate the lifecycle emissions of vehicles in different regions. It is crucial to decide if governments should invite EV production into their country, or whether it would be more appropriate to import vehicles. This research is novel because it includes energy security aspects, uses multiple scenario analysis, and investigates FCVs and various stages of AFV's lifecycle in different regions. The objective of the thesis is to systematically assess the sustainability of AFVs. Firstly, the economic pillar of sustainability is being investigated by carrying out optimisation. The optimal AFV portfolio, based on different scenarios to sustain energy security in light of gas and petroleum restrictions until 2030, is being calculated. The Polish market is considered as a case for demonstrating the optimal model. Secondly, environmental and social pillar of sustainability is explored. Life cycle assessment (LCA) has been applied to this research in order to quantify greenhouse gas (GHG) and non-GHG emissions and health impacts of air pollution connected with AFVs. We assessed air pollution from vehicles in Japan, China, and the United Kingdom (UK) and additionally health impact for Poland.

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Abbreviations

AFV - Alternative Fuel Vehicle

CNG – Compressed Natural Gas Vehicle,

CO_2 – Carbon dioxide

CVCA - Customer Value Chain Analysis

DHEV – Diesel Hybrid Electric Vehicle,

DV – Diesel Vehicle,

EV –Electric Vehicle,

FCV – Fuel Cell Vehicle,

GHG - Greenhouse Gas Emissions

GV – Gasoline Vehicle,

HEV – Hybrid Electric Vehicle,

IEA - International Energy Agency

LNG - Liquefied Natural Gas Vehicle

LPG – Liquefied Petroleum Vehicle,

MSD - Medium Speed Diesel Vessel

NGV - Natural Gas Vehicle

NO_x - nitrogen oxides

PM - Particulate Matter

RORO - Roll On Roll Off

SO_2 - Sulfur dioxide

UK - United Kingdom

WHO - World Health Organization

1. INTRODUCTION

1.1. Research background

The total global energy demand has almost doubled since 1980 and studies have estimated that approximately 20% of the global energy is consumed by the transportation sector (OECD and International Transport Forum (ITF) 2015).

It has been suggested that the volatility of petroleum prices and rapid technological developments are making Alternative Fuel Vehicles (AFVs) an increasingly promising option for decreasing energy consumption, GHG emissions, diversifying energy portfolio and maintaining energy security (IEA, 2015). The Figure 1 below present the fast spread of AFVs in the future.

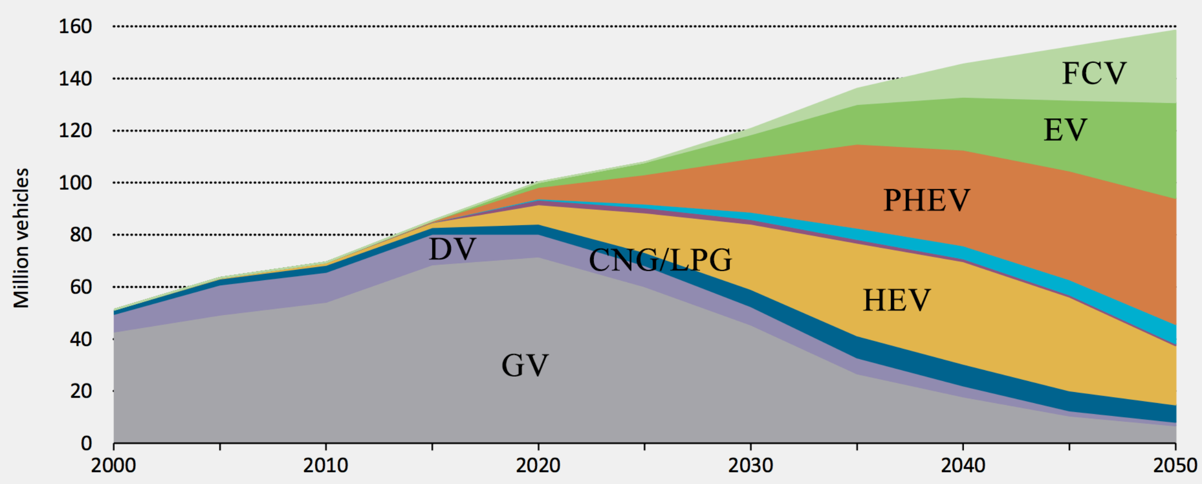


Figure 1 Forecast of the spread of AFVs.

[a] Source : (IEA, Energy Technology Perspectives 2015)

AFVs can be defined as vehicles operating exclusively on an alternative fuels (e.g. electricity or compressed natural gas (CNG)) or on a hybrid of alternative and traditional fuels (U.S. Energy Information Administration 2013). The AFVs investigated in this study are fuel cell vehicles (FCVs), hybrid electric vehicles (HEVs), diesel hybrid electric vehicles (DHEVs), electric vehicles (EVs) and CNG vehicles. Liquefied petroleum gas (LPG) vehicles and diesel vehicles (DV) are not generally considered to be AFVs. It is projected that between 2012 and 2040, the total volume of road vehicles will double; however, research has consistently shown that the adoption of more efficient technologies and switching to alternative fuels will slow the increase in demand for fuel relative to past periods (IEA, 2015). The demand on transportation is projected to be rising and it triggers the increase in CO2 emissions. Road transport emissions will increase by around 70% between 2015 and 2050. Even though the energy efficiency and average CO2 intensity of transport decreases substantially in this time period, the heavy increase in transport demand impede the positive trend (OECD and International Transport Forum (ITF) 2017). Moreover, the world will be faces with fossil fuel depletion. Production of oil from existing conventional fields is forecasted to fall by almost two-thirds by 2040. There is a need to supply the oil from not yet developed or not yet found sources. Furthermore, investment in alternative energy is crucial to lower emissions, global warming and improve energy security (International Energy Agency (IEA) 2015a).

Air pollution is one of the top greatest risk factors for human health. According to pundits, roughly 6.5 million premature deaths are the aftermath of air pollution (International Energy Agency 2016). The cost of the health problems originating from air pollution stood at $330-940B in 2010 for European Union (EC (European Commission) 2013). Industry, power plants, households, transport, agriculture and waste treatment are human-made sources of air pollution (International Energy Agency 2016). Inefficient and poorly regulated fuel combustion, residential heating, vehicles exacerbate the impact of emissions (Romejko and

Nakano 2017). Those activities cause emissions e.g. sulfur oxides (SO_2), particulate matter (PM) and nitrogen oxides (NO_x). More than a quarter of total energy-related emissions of SO_2 are made in China (International Energy Agency 2016). Transportation attributes to over 50% of all energy-related emission of NO_x. For instance, only in China, more than 1 million premature deaths were recorded due to outdoor air pollution caused by particulate matter.

Various AFVs have been developed to reduce greenhouse gas (GHG) emissions, air pollution and move transport economies away from petroleum use. In addition to technological improvements, policy proposals are crucial to the market success of AFVs (Dong et al. 2014). Customers will not find AFVs attractive without an affordable price, easy access to spare parts and repair services and readily available fuel. Equally important, automakers, governments and energy producers will not invest in AFV infrastructure and technology without the anticipation of a sizeable market (Struben and Sterman 2008). According to Christensen (2011), manufacturers have developed many AFV prototypes but have produced only a few on a large scale. Orsato and Wells (2007) stated that large-scale production reaching 250,000 units per vehicle model is necessary to reduce the manufacturing cost and provide affordable products. Companies cannot invest in every technology and must, therefore, develop products most promising for the spread of AFVs.

The environmental benefits of AFVs have attracted the interest of several institutions into further research and development (Mimuro and Takanashi 2014). Governments in the United States (US) and European Union (EU) are implementing incentive systems and long-term introduction plans for alternative fuel vehicles as one of the solutions to environmental problems (Hawkins et al. 2013; International Energy Agency (IEA) 2015b).

Governments are willing to invite manufacturers to establish green production technologies and promote EVs in their countries with the goals of increasing investment, fighting unemployment, promoting clean energy, decreasing energy dependency, creating an environment-friendly image, and meeting the conditions of international agreements on environmental issues. However, sometimes setting the green production technologies does not necessary results in environmental gains. In this study we consider environmental leakage, which happens when rich country imports dirty products from developing countries. This phenomenon leads to displacement of emissions abroad and often an increase in the global pollution (Fæhn and Bruvoll 2009).

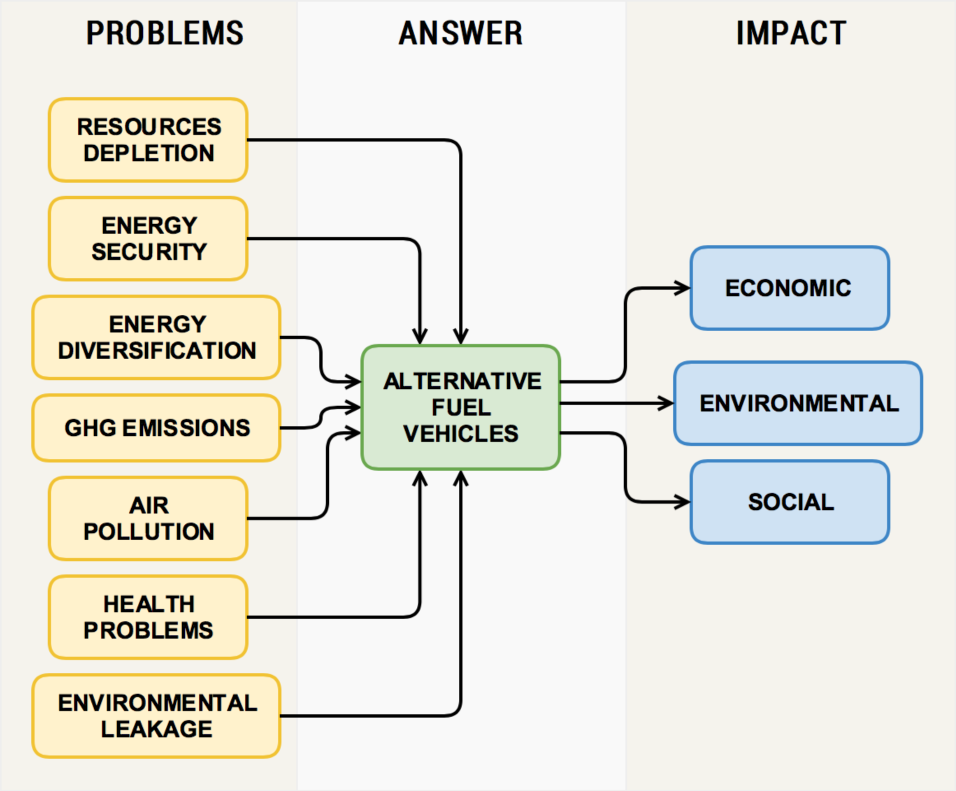


Figure 2 Research problem outline

Fig. 2 presents research problems that have been identified in order to proceed with the study.

1.2. Literature review, motivation and research objectives

There have been plenty of previous studies carried out on Alternative Fuel Vehicles and future energy trends. According to International Energy Agency, the total global energy demand has almost doubled since 1980 and it is forecasted, that if the current trends continue unchanged, it will grow more by 85% by 2050 (International Energy Agency 2015).

Research	LCA	Multiple stages of LCA	GHG	non-GHG	Health effects	Global supply chain	Multiple AFVs	Multiple Size	PLDV	Lorry, Bus	FCV	Taxation	Energy security	Gas	Charging scenarios	Environm. leakage
Nonaka (2010)	X	X	X			Multiple c.	X		X			X				
S. T. Chua (2013)									X			X	X			
Onat et al. (2015)	X		X						X						X	
Y. Arimori (2012)							X		X	X			X			
IEA (2012)						global	X		X	X	X		X			
Zhao (2012)	X		X	X				X	X						X	
H.Choi (2010)									X			X	X			
Faria (2013)	X					X	X		X						X	
Nealer and Hendrickson (2015)	X	X	X			USA		X	X						X	
Samaras and Meisterling (2008)	X		X			USA			X							
Howey et al. (2011)	X		X			UK	X	X	X							
Jochem et al.,(2015)	X	X	X	X	X	Germany		X	X							
Hawkins and Gausen, (2012)	X	X	X	X		global			X		X				X	
Sandy (2009)	X		X	X		USA	X		X		X		X		X	
Guo (2010)	X		X	X	X	China			X							
Marshall et al., (2013)	X	X	X			USA		X	X						X	
Wu and Aliprantis (2013)	X		X			USA		X	X				X			
Elgowainy et al. (2009)	X	X	X			USA			X							
Sheng Yang (2016)	X		X	X	X	China			X							
The Electric Power Research Institute (2007)			X				X		X		X					
Axsen and Kurani (2013)	X					USA		X	X						X	
Kintner-Meyer (2007)	X					USA			X				X		X	
Brady and O'Mahony (2011)	X		X			Ireland			X							
Graham-rowe et al., (2012)									X							
Nanaki and Koroneos, (2013)	X	X	X			Greece	X		X							
Yabe et al., (2015)			X						X						X	
Yagcitekin et al., (2014)									X							
This research	**X**	**X**	**X**	**X**	**X**	**X**	**X**		**X**	**X**	**X**		**X**	**X**		**X**

Table 1 Survey of conventional studies

The conventional studies analysis was carried out and the results are presented in the Table 1.

The analysis of conventional studies shows that either the studies are focused only on one type of the AFVs e.g. EVs (Nakano and Chua 2011; Graham-rowe et al. 2012; Nanaki and Koroneos 2013; Yagcitekin et al. 2014; Yabe et al. 2015) or do not take into account buses or lorries. Moreover, in most of the papers, energy security is not investigated. Numerous researches have studied LCA, however most of them focused only on one stage of vehicle life (Brady and O'Mahony 2011; Howey et al. 2011; Jochem et al. 2015). Many studies investigate GHG emission, but disregard non-GHG emissions and health impact of the vehicles (Elgowainy et al. 2009; Nealer and Hendrickson 2015). Furthermore, there have been no studies, which analyze the impact of the shale gas revolution on AFV's portfolio and its implications. Plenty of studies did not presented a systematic and broader view of the problem. The detailed analysis of the conventional studies can be find in Chapter 3, 4, 5 and 6.

That is why, the originality of this study is that it considers energy security issues, resource restrictions, multiple scenario analysis and takes into account the impact of different stages of AFVs' use on environment, and society in different regions.

This research is motivated by the fact that, AFVs presents a promising option for future transportation systems. The motivation of this research is to improve the global energy, environment and production systems, while using AFVs and sustainable approach.

In this study, two research questions are being investigated:

Question 1: What is the optimal portfolio of Alternative Fuel Vehicles?

Question 2: Where should the production site of Alternative Fuel Vehicles take place?

The objective of this study is to systematically assess the impact of AFVs on economy, environment and society by conducting optimisation and life cycle assessment simulation.

This thesis contributes with insights from interdisciplinary research on Alternative Fuel Vehicles. These results can be used to advantage by automotive companies and national institutions for strategic decision making on transport, energy policy, investment, and for informing policies supporting introduction of AFVs (e.g. government subsidies or tax exemptions). This study would be also beneficial for potential shale gas investors, as it would provide numerical results on water usage. This could influence their decision on investing in shale gas production. Automakers and policy makers need to investigate the lifecycle emissions of vehicles in different regions. It is crucial to decide if governments should invite EV production into their country, or whether it would be more beneficial to import vehicles. The results might encourage switching to EVs, and in order to do that, governments can implement either subsidy or environmental tax deduction. For this purpose, governments need to create target for policy creation, which was already studied by (Nakano and Chua 2011; Nonaka and Nakano 2011).

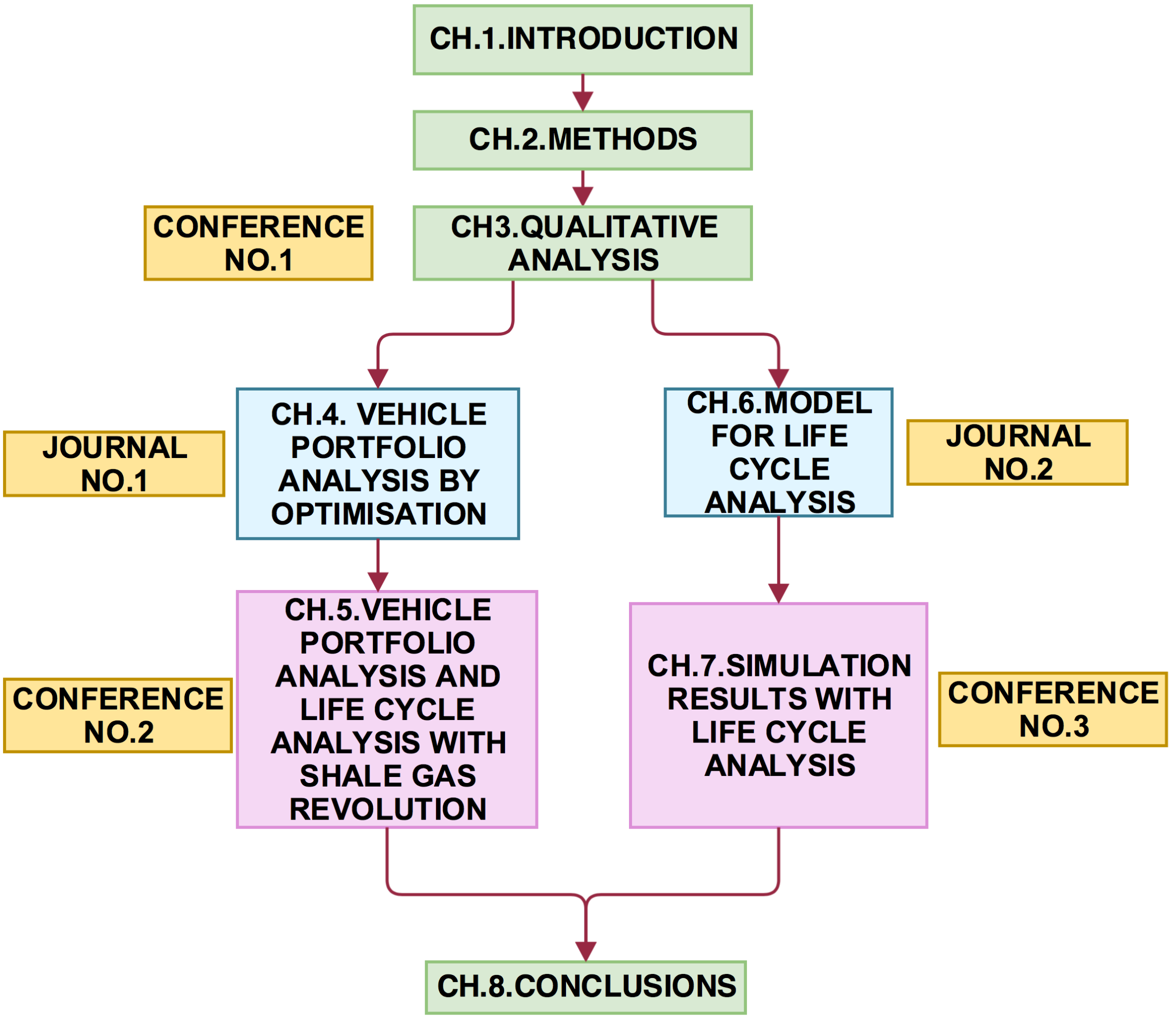
1.3. Structure of research

This paper consists of eight chapters. Chapter 1 presents the background and subject of the research, previous studies deliverables, originality, motivation, and objective of the study. In Chapter 2 methods of the thesis are briefly described. Chapter 3 provides qualitative analysis of AFV and insights into automotive industry and energy sectors of the case studied country.

Chapter 4 elucidates the optimization model, and constraints, variables and results for vehicle portfolio analysis. Case study for shale gas revolution and vehicle portfolio analysis is illustrated in Chapter 5. Chapter 6 explains the LCA method, scenarios and data used in the calculations for two case scenarios. The results of the LCA simulations are provided in Chapter 7. Finally, conclusions and limitation of the study are presented in Chapter 8.

The detailed structure of the research is presented in the Fig 3.

Figure 3 Research structure



1.4. Published papers

Periodically published articles (original articles related to main thesis):

1.K. Romejko, M. Nakano, Portfolio analysis of alternative fuel vehicles considering technological advancement, energy security and policy, Journal of Cleaner Production Vol. 142 (2016) pp. 39–49. doi:10.1016/j.jclepro.2016.09.029.

Impact Factor (JCR): 4.959 (2015)

SCI: 1.721

2.K. Romejko, M. Nakano, Life Cycle Analysis of Emissions from Electric and Gasoline Vehicles in Different Regions, International Journal of Automotive Technology Vol.11 No.4. (2017)

Impact Factor (JCR):: 0.875 (2015)

International conference papers (full-length papers with peer review):

1.K. Romejko, M. Nakano, Introduction of Clean Energy Vehicles in Poland under energy security constraints, In: IFIP Advances in Information and Communication Technology: Advances in production management systems: innovative production management towards sustainable growth. Springer International Publishing, pp. 343-352, (2015). http://dx.doi.org/10.1007/978-3-319-22759-7_40.

2.K. Romejko, M. Nakano, Impact of shale gas revolution on a portfolio of alternative fuel vehicles and water usage: case study on the Polish market, International Proceedings of

Chemical, Biological and Environmental Engineering Vol. 98 (2016) pp.53–60. doi:10.7763/IPCBEE.

3.K. Romejko, M. Nakano, Health impact of Electric Vehicles considering environmental leakage. The case study on Japan, China, UK and Poland., In: IFIP Advances in Information and Communication Technology: Advances in production management systems: innovative production management towards sustainable growth. Springer International Publishing (to be published in September 2017)

2. METHODS

The research concerns market and data study, thus both qualitative methods and quantitative methods are being used. The research is based on three methods. In the beginning of the study, qualitative analysis is conducted. Secondly optimization is carried out. Finally, Life Cycle Analysis is performed.

2.1. Qualitative analysis

The first step is to qualitatively investigate the problem by intelligence gathering, analysis of literature, case studies, stakeholder analysis, statistical analysis and interviews with pundits. The stakeholder's analysis was carried out by the use of Customer Value Chain Analysis (CVCA). Four, core stakeholders were identified i.e. government, manufacturers, energy companies and consumers. Taking into consideration the above, analysis of each of the stakeholders was conducted and interviews with those entities have been carried out. The purpose of Qualitative Analysis is to find causes that prevent popularity of AFVs.

2.2. Optimisation

Following that, qualitative findings were used and combined in quantitative analysis in order to analyze the development of AFVs by 2030. This study thus adopts optimisation model in quantitative analysis to uncover optimal portfolio of AFVs in 2030.

Qualitative analysis is computed from a systematic approach, including two parts: energy security constrains and economical efficiency. The model defines economical efficiency of the vehicle portfolio while considering oil and gas dependency rates. Fig. 4 presents an outline of the optimisation model. Three categories of vehicles are considered: passenger vehicles, buses and lorries. Moreover, 8 types of vehicles are taken into consideration based on engine platform variations (GV, DV, HEV, DHV, CNG, FCV, EV and LPG). The following model takes as input three groups of data: restriction values (gas and oil rates), vehicles characteristics (vehicle price, fuel consumption, average mileage, usage price, etc.) and other preconditions (energy prices, power supply composition, etc.). This data is input into the optimisation model and the output is the optimal volume of new vehicle sales of each AFV. Moreover, three costs are input into the model: infrastructure, vehicle and fuel; their sum creates a total AFV system cost.

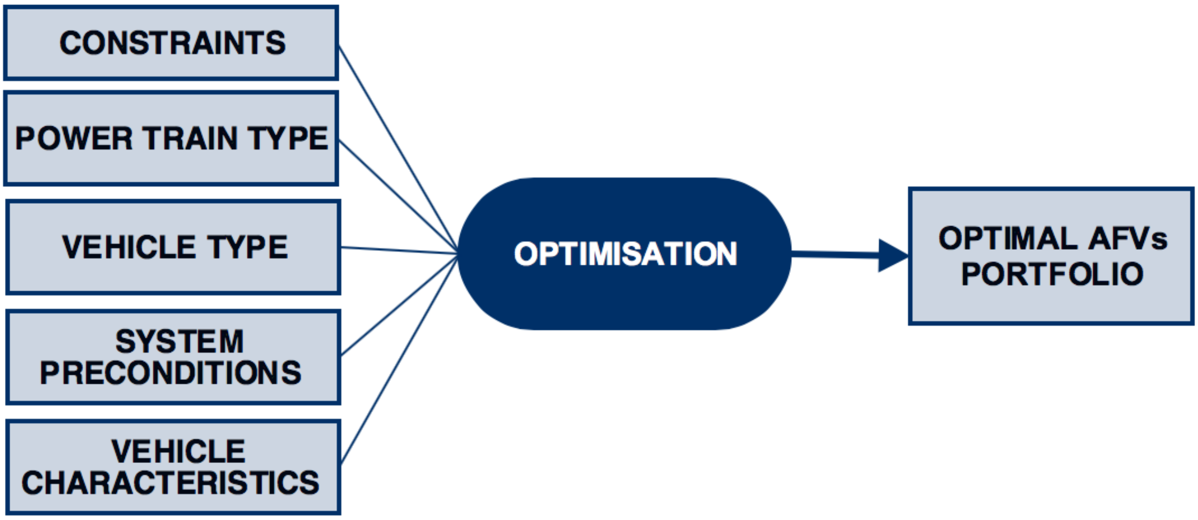


Figure 4 Optimisation model outline

2.3. Life Cycle Assessment

Life cycle assessment is a tool that has been used in most of the recent studies on the assessment and comparison of vehicles(Samaras and Meisterling 2008; Nonaka and Nakano 2010; Ou et al. 2010; Brady and O'Mahony 2011; Faria et al. 2013). Life cycle assessment can identify the environmental impact of a product.

LCA is used three times in this study. Firstly, it is used to assess the impact of shale gas revolution. The outline of the model is presented in Fig 5.

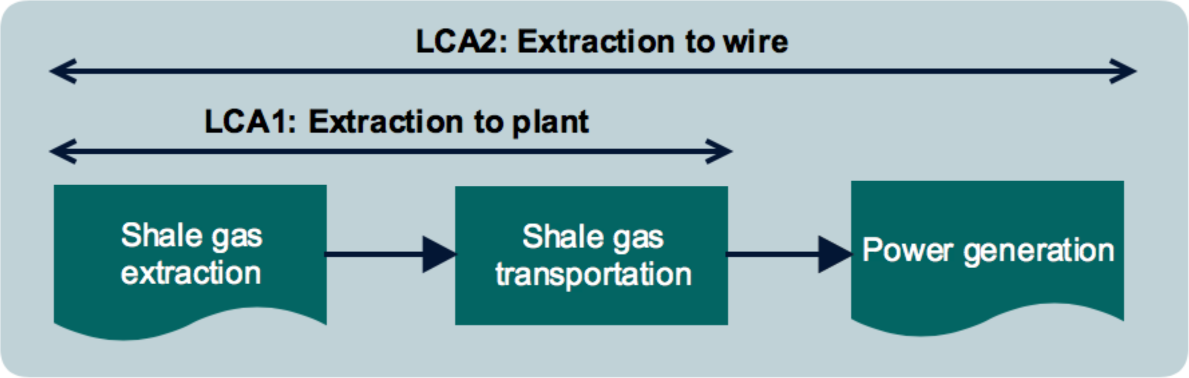


Figure 5 LCA model outline for shale gas revolution

The results from optimization for the second case study are input into the LCA. The model includes water consumption of shale gas on different stages of production for two scenarios. This model is used in Chapter 4.

Secondly, LCA is used to quantify air pollution from EVs and GVs during their lifecycle under two technology scenarios. Three stages are considered i.e. manufacturing, use and end-of-life, the outline of the LCA is presented in Fig 6. This LCA model is used in Section 6.1

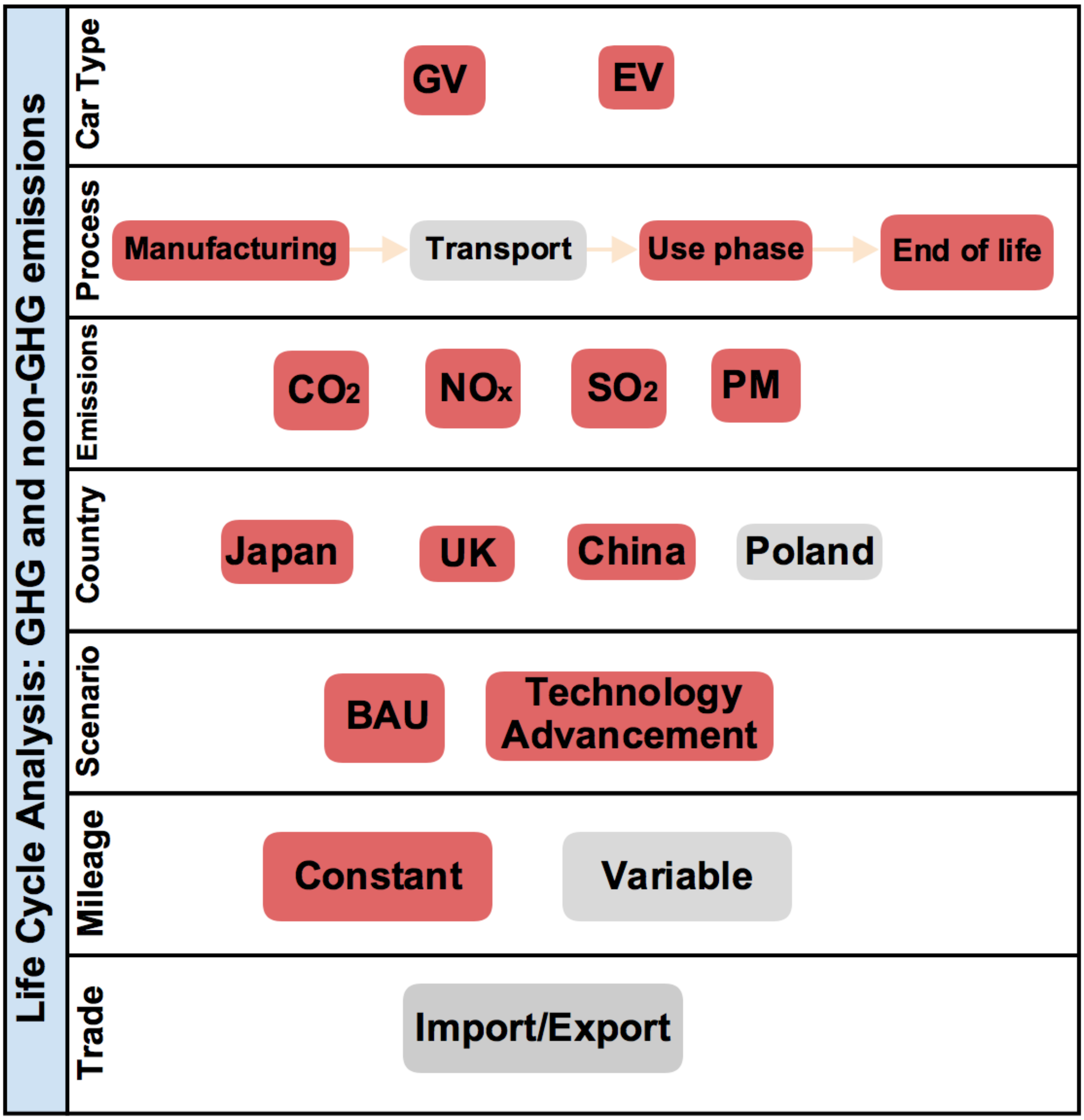


Figure 6 Outline of the LCA for air pollution.

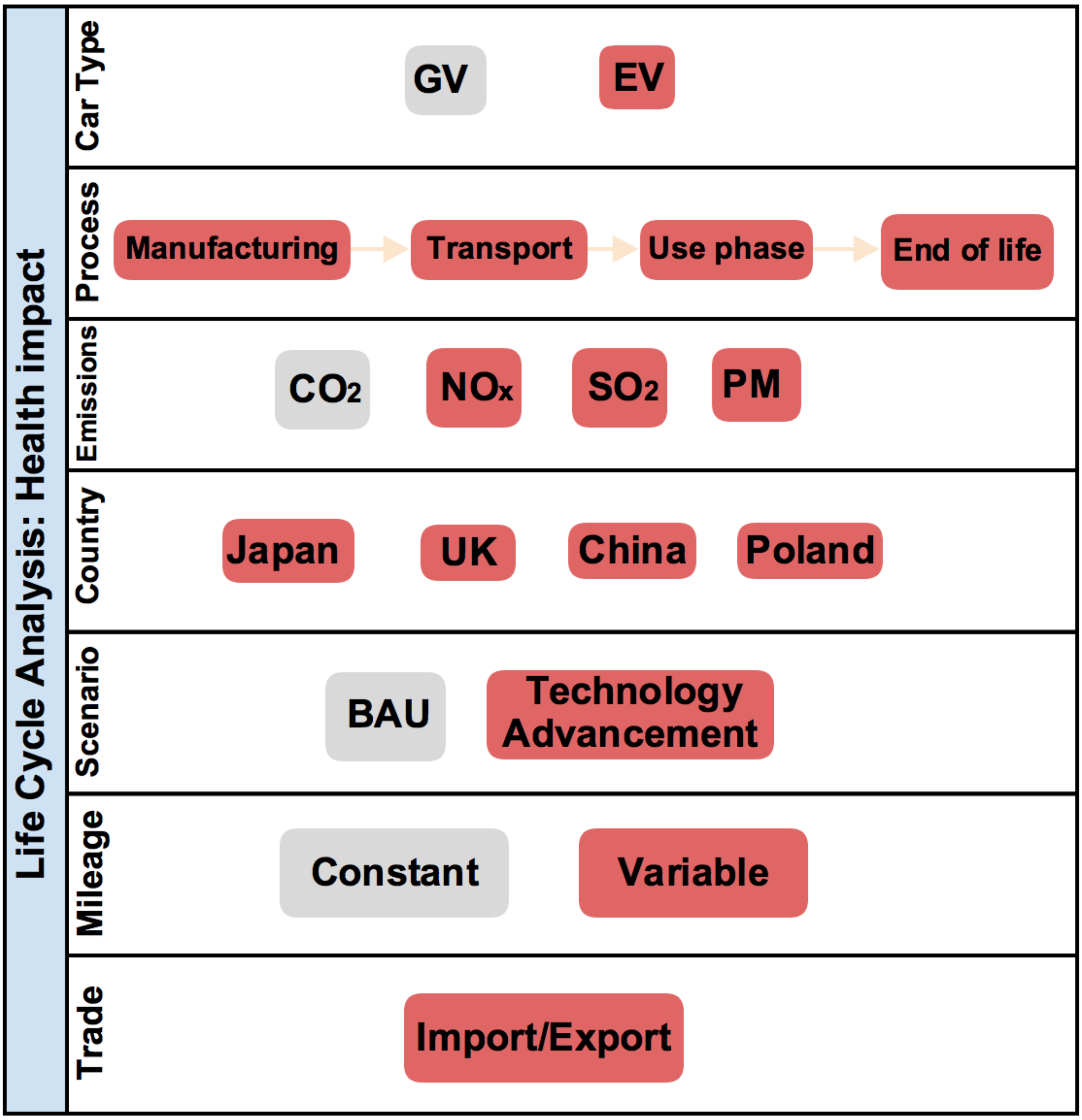


Figure 7 Outline of the LCA for health effects.

Thirdly, LCA is employed to quantify health impact of EVs and is presented in the Fig.7. This LCA considers four stages i.e. manufacturing, transportation, use and end-of-life. The import, export and transportation part of the model are presented in the Fig.8.

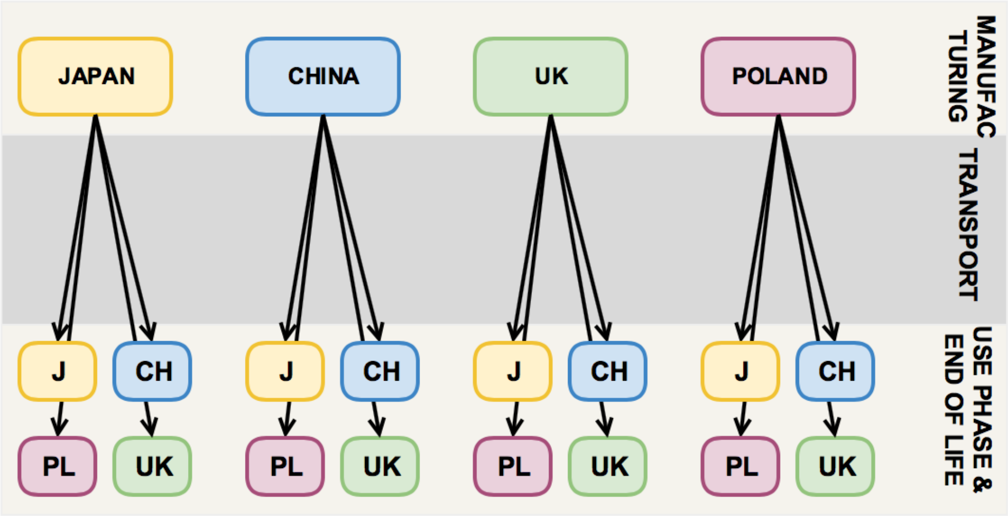


Figure 8 Outline of the LCA for health issues.

3. QUALITATIVE ANALYSIS

3.1. Chapter introduction

Along with increasing crude oil prices, a high pressure is put all over the world for the proliferation of AFV (AFVs), to reduce not only CO2 emissions, but also energy consumption in the automotive sector to provide apt energy security. The transportation sector accounts for approximately 20% of total worldwide energy consumption (International Energy Agency (IEA) 2012). Throughout the years, there have been various types of AFVs developed in order to reduce greenhouse gas emissions and move our economy away from petroleum in transportation.

Despite abundance of the choice, Poland is still lagging behind with sales of AFVs. In 2011, there were only 897 hybrid vehicles registered (Polish Automotive Industry Association 2013). When it comes to ensuring energy security, the situation does not look bright too. 98.2% of Poland's crude oil consumption and 72.4% of Poland's natural gas consumption are being satisfied from import supplies (International Energy Agency (IEA) 2014). Transport sector itself is responsible for over 60% of crude oil consumption in Poland (International Energy Agency (IEA) 2013).

There have been plenty of studies carried out on the AFVs portfolio and future energy trends. The scopes of them were gathered in the Table 1.

Nonaka (Nonaka and Nakano 2011) researched carbon taxation by using LCA and have conducted life cycle cost analysis of AFV cars in order to create a carbon taxation aiming at encouraging customers to choose lower CO2 emission AFVs. However, the analysis was focusing only on assessment of passenger cars, excluding bus and trucks in the research. Most of the conventional studies do not include those types of vehicles.

The objective of S. Chua's research (Nakano and Chua 2011) under the title: "Design of Taxation to Promote Electric Vehicles in Singapore", was to conduct LCA to reach decisions that will have a minimum or no impact to the environment. Nonetheless, this paper examines only EVs and other AFV cars are not taken into consideration.

Only, Arimori's research (Arimori and Nakano 2012) incorporated data concerning bus and trucks. However, far too little attention has been paid to that type of vehicles and results show that those cars have little impact on the final results. In order to construct an optimal portfolio passenger cars, trucks and buses has to be included in the research. What is more, various types of fuel type engines should be also examined in pursuance of a high quality research. There is a necessity for introduction of all range of AFV also in trucks and buses and there influence on fuel consumption cannot be disregarded. In addition to that, most of the researches are mainly focusing on CO2 emissions, forgetting energy security issues. Arimori's research however, does include oil restriction, but is not taking into consideration gas restriction. Moreover, it is written in Japanese.

Table 2 Conventional studies on AFVs

Research	Passenger Vehicle	All types of AFVs	Oil restriction	Gas restriction	Truck& Bus
IEA (2012)	X	X	X		
Y. Arimori (2012)	X	X	X		X
H.Choi (2010)			X		
S. T. Chua (2013)			X		
This research	X		X	X	X

In the case of European countries like Poland, gas is an important source of energy, also in terms of automotive usage. Thus, the model should not be created without incorporating gas restrictions. In line with the above, the originality of this study is, that it includes gas security restrictions due to huge LPG market in Poland and possible proliferation of CNG vehicles in the future.

Section 3.2 explains the methodology and Section 3.3 describes results of qualitative analysis.

3.2. Methodology

In the beginning of the study, intelligence gathering was conducted and research objective and questions were formulated: Why AFVs are not popular in Poland and what policy should be introduced to change the situation? The purpose of Qualitative Analysis is to find causes that prevent popularity of AFVs. Data, potential problems and opportunities were identified in this chapter through collection and analysis of literature, case studies, survey researches, statistical analysis, stakeholder analysis and interviews with pundits. In order to achieve economic goals, a qualitative analysis of both the automotive and energy sector in Poland was carried out. Firstly, stakeholder analysis was carried out by using Customer Value Chain Analysis (CVCA). CVCA is a tool that enables to identify relevant stakeholders, their relationships with each other, and their role in the product's life cycle [10]. Later interviews with stakeholders were conducted. By using this methodology research questions were verified.

Qualitative findings were used and combined in quantitative analysis in order to analyse the development of the AFV market in Poland in the following Chapter 4.

The whole thesis concerns policy, market and data study, which is why both qualitative and quantitative methods are used. The study is conducted in line with the Fig.9.

Figure 9 Research process

3.3. Stakeholder analysis, interviews, statistical and literature analysis

3.3.1. Stakeholder analysis

Fig. 10 presents the analysis of stakeholders and their relationship that was carried out with CVCA. Four main stakeholders were identified: consumer, car manufacturer, government and energy company. The most important stakeholder is government. It receives TAX from other stakeholders and its role is to provide subsidies and policy support.

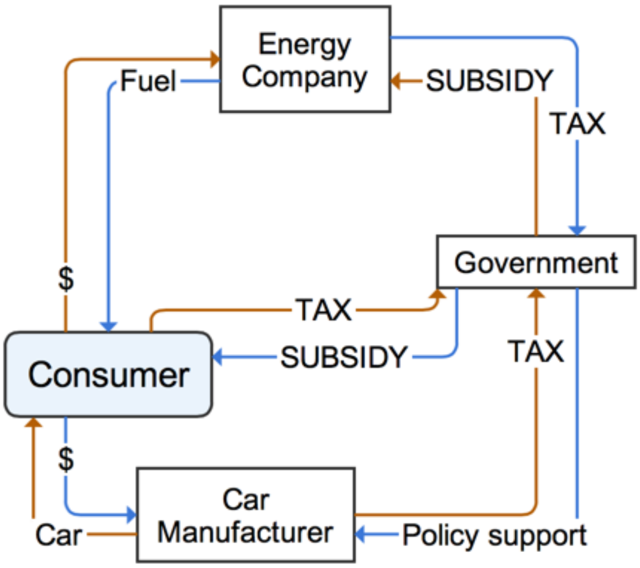


Figure 10 CVCA analysis

3.3.2. Results of interviews

The first interviewee is an expert from Department of Innovation and Industry from Ministry of Economy. He believes that when it comes to terms with governmental stakeholder it is the Ministry of Finance is reluctant on creating an incentive system, rejecting proposals in order to protect the yearly budget. Forgetting that those aids can bring income from other sources. The interviewee believes that change in policy is essential to change the situation. His recommendations include i.e. establishing new scrap incentive system based on the previous experience in Germany. Unless the government introduces aid for customers to buy AFVs, the number of sales will still stand at a minor level. Furthermore, new tax system is crucial to change the situation. The next stakeholders considered in this interview are automakers. Automakers aim at collaborating with local government, which is more willing to achieve aforementioned goals. Low sales means less investment from other countries and less people employed. Moreover, the pundit confirmed the fact that individuals do not wish to buy AFVs because of high prices and prefer to buy used cars, or just cheaper makes. Confusing car tax policy means that buyers postpone their decision on a purchase of a new vehicle.

Another interviewee is Sales Managing Director in Automotive Company in Poland. He stated that government and its policy discourage buyers from purchasing new cars, favoring more affordable non-efficient ones. Furthermore, European policy created an easy access to affordable used cars from Germany. There are numerous problems concerning consumers. Poles are not concerned with environmental issues. There is low affordability of AFVs in Poland. Consumers tend to buy cheaper, not environmental friendly cars. Used cars are changed into LPG-driven vehicles or are using non-efficient diesel engines, which are cheap but not powerful. Polish people have very little knowledge of AFVs. Poles do not know about hybrid and technologies. There is a need to educate consumers, giving them a fresh and realistic view of AFVs. Since people travel for long distances and use cars for many years, AFVs seem like a good investment if people know that they should take into consideration life cycle cost of a vehicle and not only the initial cost. From the pundit point of view automakers expect a higher volume of vehicle sales in Poland. High demand on new vehicles, close proximity of component factories, low turnover of employees and cost of employees are the factors that influence decision on establishing a new vehicle plant. Moreover, the drop in price, could give customers incentive to purchase a AFV. The Tables 3 and 4 sum up the results of interviews with stakeholders.

Table 3 Government view on AFVs problems

Government	**Issues**	**Possible measures**
Government	Protect budget	New scrap incentive system
Automakers	Low sales = low investment; poor collaboration with government	Collaboration with local government
Consumers	High price of AFVs, purchase of used cars; Confusing tax policy	Tax reduction incentives

Table 4 Automakers view on AFVs problems

Automakers	**Issues**	**Possible measures**
Government	Easy access to used cars from Germany Policy and rules discourage purchase of new car	AFVs subsidies
Automakers	A higher volume of sales is expected	Higher demand on vehicles; Proximity of factories;

Consumers	Low affordability of AFVs; Consumers not concerned with environmental issues; Consumers using non-efficient diesel engines Little knowledge on AFVs;	Price drop of AFVs; Education of consumers

Furthermore, Prius price analysis was conducted as shown in Table 5 and was approved by the second interviewee. Price of Prius in Poland is very high, that is why I have examined the reason behind that. The results prove that the premium consists most of the taxes applied by Polish government and not market premium of a Japanese producer. The parameter 1.0 amounts to 2 1700 00YPY.

Table 5 Prius price analysis

Item	Value
Market price of Prius in Japan	1
Cost of Prius in Japan without TAX (8%)	**0.95**
Transport cost	0.01
Customs - 10%	1.06
Excise TAX - 18,6%	1.25
TAX in Poland - 23%	1.54
Cost of Prius in Poland according to calculations	1.54
Market price of Prius in Poland	**1.57**
Market price of Prius in USA	1.13

3.3.2. Statistical, literature analysis and discussions

Current Status of the Automotive Industry in Poland

Automotive is of great importance to the Polish economy. It is estimated that in 2010 the value of exports of Polish automotive industry (vehicles and parts) exceeded 17 billion euro (Polish Automotive Industry Association 2015). Already 16% of Polish exports come from the automotive industry (Polish Automotive Industry Association 2013).

According to GUS data, in automotive areas of Polish automotive sector 381,500 people were employed in 2011, close to two-thirds of which (228,700) in trade and services, and more than one third (152,800) in manufacturing (Central Statistical Office (GUS)). The last figure is accompanied by five positions in industries around automotive. Participation of involvement of Polish automotive industry in GDP creation is steadily growing and in 2013 it amounted to around 6% (PWC 2015). However, in recent years there have been cuts in the sector due to the crisis, which is another problem that Polish people will face in next years to come.

What is more, if we look closely at the data concerning car park in 2012 in Table [1] we can easily notice other concerns. There is an obvious issue with obsolete cars and low purchase of new cars, especially by individuals. As a result, 15 years is a statistical age of a vehicle registered in our country (Polish Automotive Industry Association 2013). That is why more than 98% of cars produced in Poland in 2010 were exported (Polish Automotive Industry Association 2013). The economic climate in recent years did not encourage customers to buy new cars.

The main problems are drops both in car sales and production. In 2012, Polish manufacturers produced 540,000 passenger cars, 27.1% less than in 2011. Poland recorded drops in sales of cars in both individual and companies purchase. In recent years there have been cuts in the sector due to the aftermaths of the economic difficulties of the past 5 years that have strongly affected EU consumers' demand for new vehicles. Data indicate that in 2012 the Polish authorities registered 312,096 new passenger cars and LCVs – less by 8,025 (2.5%) than the year before (Central Statistical Office 2014).

Table 6 Registered car data for 2012

Characteristics	Values
Number of cars	17,2 m
Average age of a car	15,5 y
New cars registered	270 584 unit
Used cars registered	1,5 m
Average age of used imported car	10,2 y
Average life of a car used by the company	4 y
Percentage of petrol fuelled cars	61%
Percentage of diesel fuelled cars	22%
Percentage of LPG fuelled cars	14,37%
Percentage of cars fuelled by other sources	~1%
Percentage of HEV cars	~0.3%

[a] Based on: (Polish Automotive Industry Association 2013; Central Statistical Office 2014)

As a result of those trends, the international role of Poland as an automotive manufacturer has been on decline. The automotive sector is also one of the most important areas of Poland's economy in terms of its role in foreign trade. As global manufacturing capacity increases, automakers have to address excess production seriously. The global automotive market is predicted to be overbuilt by 20-30% by 2016 (KPMG 2015). That are other problems that Polish people will face now and in next years to come, which are drops in production, cuts in working force, preferring locating FDI in other countries than Poland. In order to change the situation, demand on cars has to be at least stable or has to be increased. Manufacturers locate their investment when local demand is high and they have perspectives in the future and at present there is none of the above available. That is why increasing sales or even maintaining them is crucial problem and by conducting my research I can estimate consumer preference and utility functions and later combine them with future scenarios that can support policy makers while making their decision on applying policy to increase car sales in Poland.

On the other hand there is an opportunity for introduction of AFV in Poland since domestic coal reserves are of vital importance for the Polish economy. However, the situation for import of oil and gas is undoubtedly different than it is for coal. That is why Poland should treat introduction of AFV as an opportunity to become more independent from fuel imports and as a way of spurring automotive industry in Poland.

Polish government has recently showed first signs of interest towards AFVs and is considering this area as a future investment. Domestic coal reserves are of vital importance for the Polish economy. However, the situation for the importation of oil and gas is undoubtedly different than it is for coal. That is why Poland should treat the introduction of AFVs as an opportunity to become more independent from fuel imports, and as a way of spurring automotive industry in Poland.

Roots of low car sales

In Poland, the average person earns 17 8204 USD a year, less than the OECD average of 29 016 USD a year, in Japan, the average person earns 27 323 USD a year (OECD 2017). Therefore the first problem recognized while doing the analysis is the affordability of AFV in Poland.

Every year there is around 1.5mln cars registered, but only 270 584 of them are new cars (Polish Automotive Industry Association 2013). The share of new cars registrations stands at only 18%. In 2012, there were 153 905 new cars bought by companies and 116 679 purchased by individuals. Therefore the ratio is 57% in favour for business, the structure and numbers of cars sold for entities are visible in Fig.11.

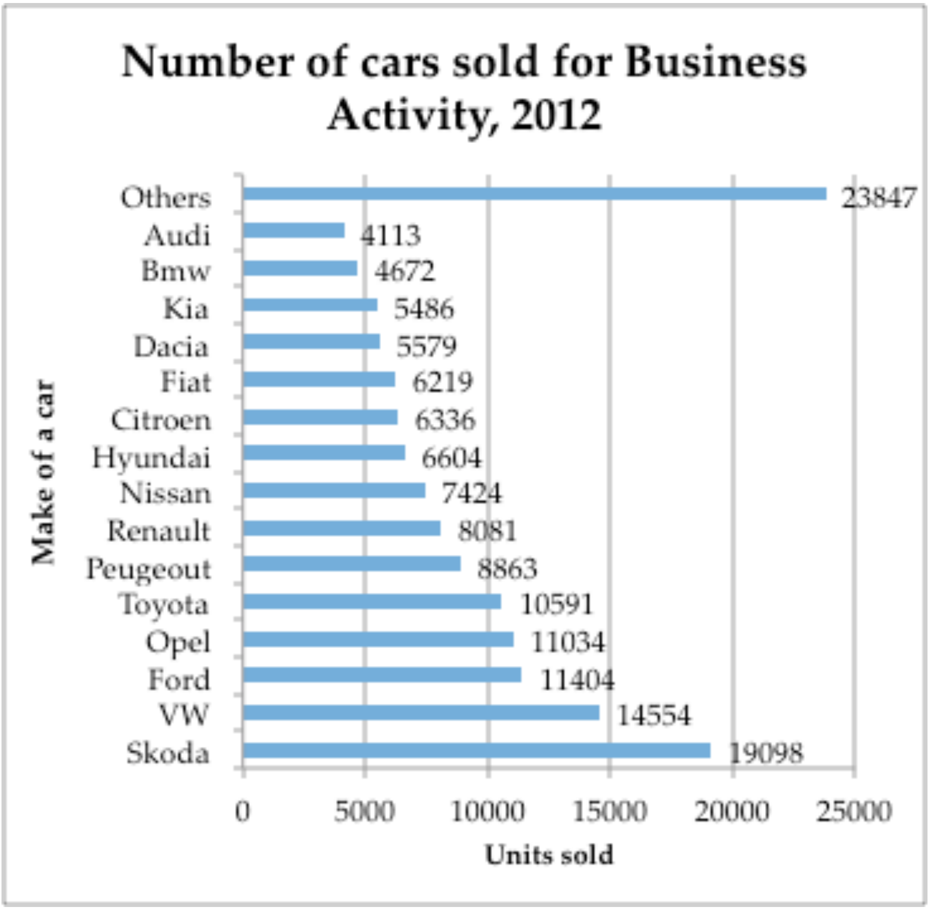


Figure 11 Number of cars sold for business activity in Poland in 2012.

[a] Based on: : (Central Statistical Office (GUS); Polish Automotive Industry Association 2015)

Except for different power purchase price, there are other roots of the problem that cause low volume of new cars sold. Easy access to cheap, used cars from Germany is definitely highly influencing the decision to switch to older cars.

Current Status of the Energy Sector in Poland

Energy security issues are becoming another preeminent topic, especially after considering recent political developments in the Russian-Ukrainian dispute. Energy resources security is a crucial concern for a developing country. Energy security definitions have already been researched by plenty of pundits. The most widely used definition of energy security is provided by International Energy Agency. It defines energy security as 'the uninterrupted physical availability at a price which is affordable, while respecting environment[al] concerns' (International Energy Agency (IEA) 2012).

However, the conception of energy security varies depending on the role of a given actor in the system (e.g. energy distributor).

Poland is mainly an energy importer and a consumer of Russian energy supplies, that's why for the purpose of this research, an application of consumer-oriented definition is needed. A country is vulnerable to interruptions in the physical availability of energy supplies or to unforeseen price hikes when state dependents on imports for a considerable share of its energy supply. Those circumstances are perceived as 'energy dependency'.

According to Balmaceda (Sharples 2012), the definition of energy dependency is as follows:

1.more than one-third of a country's total energy supply comes from foreign sources;

2. more than 50% of a country's annual consumption of a single major energy source comes from foreign sources

3. a country depends on a single external provider for more than 60% of its imports of a major energy source for that country or more than 45% of its consumption of that energy source.

Energy policy in Poland

Polish energy policy's issues are described in a document under the title: "Energy Policy of Poland until 2030", which was prepared by Ministry of Economy and adopted by the Council of Ministers on 10 November 2009 (Ministry of Economy 2009a) .

This resolution presents the strategy of the Polish state, which aims to address the most important challenges that the power industry must face, both in the short and in the long run, until 2030 (Ministry of Economy 2009a).

Within the document, primary directions of Polish energy policy have been set. The ones that are important to this research have been listed below:

- to improve energy efficiency;
- to enhance security of fuel and energy supplies;
- to diversify the electricity generation structure by introducing nuclear energy;
- to develop the use of renewable energy sources, including biofuels.

The main objective of energy policy in the field of improving security of fuels and energy supplies is to ensure energy security by:

1. Enhancing the diversification level of crude oil, gas and liquid fuels supply sources, understood as obtaining crude oil and gas from various regions of the world, from different suppliers, using alternative transport routes;
2. Building crude oil and liquid fuels storage facilities of capacity, which ensures continuity of supplies, particularly in crisis.

The measures set in order to achieve those objectives are plentiful, e.g.: building a terminal for receiving liquefied natual gas (LNG), diversification of supplies by building a transmission system for natural gas supplies from the north, west, and south, as well as building connections to primarily meet the requirement of supply sources diversification; appropriate tariff policy encouraging investment in gas pipeline infrastructure; building infrastructure to allow transport of crude oil from other regions of the world, inter alia from the Caspian Sea region within the Euro-Asian Oil Transportation Corridor project; lifting barriers to development of fuel infrastructure and supporting investment projects in infrastructure with the use of European funds; ensuring fuel transport by sea.

It is not stated however, how much should energy security be improved. The progress in the energy policy implementation will be monitored in particular on the basis of indicators set by various ministries.

Maximum share of total natural gas and crude oil imports from a single direction in the domestic consumption of both those resources has to fall down by 15% till 2030 from the 2007 level. There is no benchmark stating how much should energy security increase, only indicators stated above are directly connected with energy security issues.

Energy mix in Poland

Concurrently, the dominant source of primary energy is coal, followed by oil, natural gas, and minor share of renewables. Nuclear energy is not being produced now in Poland (International Energy Agency (IEA) 2013).

In 2009, 94.0% of Poland's crude oil imports came from Russian suppliers. The remaining portions of crude oil were imported mainly from Algeria (around 2% of the total), the United Kingdom and Norway (around 1% of the total). During the same time period, 82% of gas imports came from Russia, 11% from Germany and small part from Belarus and Ukraine (Ministry of Economy 2009b).

Maintaining an energy structure mix with coal as a main source of supply results in substantial emissions of air pollution, lower efficiency and higher prices of energy. It is important to note that Polish GDP growth was almost always higher than the average EU one in last decade, however we managed to decrease greenhouse gas emission. Moreover, Polish economy is expected to be growing in next years to come as well and in spite of projected 11% increase in demand for final energy between 2006 and 2020, there is a significant, 15% decrease projected in CO2 emissions (Ministry of Economy 2009b).

According to governmental policy stated in "Energy Policy of Poland until 2030: Projection of Demand for Fuels and Energy until 2030" (Ministry of Economy 2009b), the share of hard coal in demand for primary energy is supposed to be decreased in favour of renewable energy. The objectives of the EU targets for renewable energy will require the gross electricity production from renewable energy source at the level of about 18.8% of the total production in 2030. Gas demand is projected to rise by 18% in 2020 and by 43% in 2030 compared with 2010 (International Energy Agency (IEA) 2011). Table 7 shows the changes in the generation of net electricity by fuels till 2030 (Ministry of Economy 2009b). It is forecasted that the net electricity production will moderately rise from the level of ca.140 TWh (2008) to more than 201 TWh (2030) (Sadowski and Romancza 2013).

Table 7 Generation of net electricity divided by fuels [TWh]

	2006	2010	2015	2020	2025	2030
Hard coal	86.1	68.2	62.9	62.7	58.4	71.8
Lignite	49.9	44.7	51.1	40.0	48.4	42.3
Natural gas	4.6	4.4	5.0	8.4	11.4	13.4
Oil products	1.6	1.9	2.5	2.8	2.9	3.0
Nuclear fuel	0.00	0.00	0.00	10.5	21.1	31.6
Renewable energy	3.9	8.0	17.0	30.1	36.5	38.0
Pump water	0.97	1.00	1.00	1.00	1.00	1.00
Waste	0.6	0.6	0.6	0.6	0.7	0.7
TOTAL	**147.7**	**128.7**	**140.1**	**156.1**	**180.3**	**201.8**
Share of RES energy [%]	2.7	6.2	12.2	19.3	20.2	18.8

[a] Based on: (Ministry of Economy 2009b)

The energy from wind power plants will have the largest share 8.2% of the forecast gross total production in 2030 (Ministry of Economy 2009b; Sadowski and Romancza 2013).

Due to the environmental requirements set by EU, nuclear power plants will appear in the mix of electricity sources. It is assumed that the first nuclear power plant will appear in 2020. In total, three nuclear units power should operate with a net total capacity of 4,500 MW by 2030.

In line with the above, comparison of Polish situation with the basic energy dependency definition provided by Balmaceda, uncovers the fact, that Poland meets the three requirements of this definition. That is why the assumption is that Poland’s energy security is not guaranteed. In case of Poland, there is a threat to security of crude oil supplies, as well as a threat of monopolistic price fixing. This is a result of the market being dominated by supplies from one direction only – Russia. In order to avoid such a situation, the level of supply diversification needs to be enhanced. In line with the government statement (Ministry of Economy 2009b), it is crucial not only to boost the number of suppliers, but at stake is to eliminate situation, where oil and gas comes from a single area, and its transmissions are controlled by a single entity.

Energy Use in The Transportation Sector

The transport Sector is responsible for 64% of the crude oil consumption in Poland. When it comes to the gas consumption by the sector, 37% of total demand is consumed by industry, followed by residential use, and transportation (International Energy Agency (IEA) 2011). In the time period between 1998 and 2012, demand for diesel grew by 70%, and demand for LPG almost doubled. Currently, diesel is used in the largest quantities, followed by gasoline and LPG. Trucks are using the largest amount of diesel fuel. However, 56% of total consumption is due to passenger vehicles (Chlopek et al. 2012).

Influence of Russian-Ukrainian dispute on energy security

Dependency on Russian energy supplies is often cited as a threat to Central European energy security. Imports to the EU from Russia are dominated by crude oil and gas. Cuts of gas importation have happened before, e.g in 2009 during Ukrainian-Russian gas dispute. Moreover, Russia introduced a ban on imports of fruits and vegetables from Poland in 2014, depriving it of a major export market. Along with increasing crude oil prices and unstable political situation in Ukraine, the Polish citizens and government have opened their eyes, and urge securing energy safety issues. Currently, Europe is dependant on Russian energy supplies and if there are any further unpleasant developments of the Russian-Ukrainian dispute, Poland might find it severely difficult to secure basic energy demand for both private users and companies.

Shale gas in Poland

The expansion of shale gas has a remarkable impact on the growth of importance of natural gas in the world's structure of primary energy sources and it is projected that there will be a significant drop of price of this fuel (Baranzelli et al. 2015). It has been known for many years, that Poland has rich shale deposits. However, it was the technological innovations that led to the shale gas revolution in North America that opened up the possibilities, for these reserves to be commercially exploited. There are three areas, where the potential for commercial exploitation is located in Poland: Podlasie Basin (east and east-central), the Baltic Basin (northern) and Lublin (southeast) (Johnson and Boersma). The US EIA estimated that technically recoverable shale gas resources are roughly 187 tcf (5300 bcm), or nearly 900 times Poland's 2010 consumption of gas. However, the Polish Geological Institute released in 2012 a draft assessment stating that this amount is much lower, estimating 1920 bcm of shale gas, of which somewhere between 350 bcm and 770 bcm is likely recoverable. The infrastructure for gas in Poland is not well developed. Only 54.6% of households currently have access to the gas network (Johnson and Boersma). Furthermore, most of the pipelines are located in industrial area of southwest Poland and around the main urban areas, but not necessarily in the areas where shale gas would be produced (Johnson and Boersma).

Supreme Audit Office in Poland (Naczelna Izba Kontroli) has recently assessed the functioning of public administration and the business undertaken in connection with the exploration and identification of shale gas in Poland. In the period covered by the audit, search and exploratory activities of shale gas deposits were based on 113 concessions covering nearly 30 percent of Polish territory. However, geological works performed by entrepreneurs proceeded only on a small part of the granted concession area and were often delayed. The reason for the sluggishness was not only economic and financial situation, but mostly from improper government action. What is more the administrative proceedings led by Minister of Environment on granting concessions for prospecting or exploration of shale gas were very unreliable and sluggish. Decisions were issued with an average 132 days, when law stipulated only 30 days for these actions (Forbes Poland 2012).

Four powerful companies have already resigned of further shale search in Poland. Among others American: ExxonMobil and Marathon Oil, Canadian Talisman Energy and French Total. One of the reasons was bureaucracy and extending the work on the new regulations (Supreme Audit Office in Poland (Naczelna Izba Kontroli) 2014).

3.4. Summary

This chapter has examined both the automotive and energy sector in Poland. This study was designed to conduct detailed qualitative analysis of the problems associated with AFVs in Poland.

The stakeholders of the analysis are: government, manufacturers and individuals. The three, core stakeholders are highly influencing each other's. Taking into consideration the above, analysis of each of the stakeholders was conducted and in order to research government and manufacturers interviews with those entities have been carried out.

All of the above interviews provided insight into Polish automotive sector and confirmed the problems that were found during the research. Environmental issues are neglected in Poland, price of the vehicle is the most important reason influencing the purchase. Moreover, introduction of incentive system for AFVs for both companies and private entities might spur the sales of the cars again.

4. MODEL FOR VEHICLE PORTFOLIO ANALYSIS BY OPTIMISATION

4.1. Chapter introduction

The total global energy demand has almost doubled since 1980 and studies have estimated that approximately 20% of the global energy is consumed by the transportation sector (OECD and International Transport Forum (ITF) 2015). It has been suggested that the volatility of petroleum prices and rapid technological developments are making alternative fuel vehicles (AFVs) an increasingly promising option for decreasing energy consumption and maintaining energy security (IEA, 2015). AFVs can be defined as vehicles operating exclusively on an alternative fuels (e.g. electricity or compressed natural gas (CNG)) or on a hybrid of alternative and traditional fuels (U.S. Energy Information Administration 2013). The AFVs investigated in this study are fuel cell vehicles (FCVs), hybrid electric vehicles (HEVs), diesel hybrid electric vehicles (DHEVs), electric vehicles (EVs) and CNG vehicles. Liquefied petroleum gas (LPG) vehicles and diesel vehicles (DV) are not generally considered to be AFVs. It is projected that between 2012 and 2040, the total volume of road vehicles will double; however, research has consistently shown that the adoption of more efficient technologies and switching to alternative fuels will slow the increase in demand for fuel relative to past periods (IEA, 2015). Recent analysis suggests that energy consumption in the transportation sector is expected to decline from 26.7 quadrillion Btu in 2012 to 25.5 quadrillion Btu in 2040, owing to a considerable decline in energy consumption through AFV use (U.S. Energy Information Administration 2014).

Various AFVs have been developed to reduce greenhouse gas (GHG) emissions and move transport economies away from petroleum use. In addition to technological improvements, policy proposals are crucial to the market success of AFVs (Dong et al. 2014). Customers will not find AFVs attractive without an affordable price, easy access to spare parts and repair services and readily available fuel. Equally important, automakers, governments and energy producers will not invest in AFV infrastructure and technology without the anticipation of a sizeable market (Struben and Sterman 2008). According to Christensen (2011), manufacturers have developed many AFV prototypes but have produced only a few on a large scale. Orsato and Wells (2007) stated that large-scale production reaching 250,000 units per vehicle model is necessary to reduce the manufacturing cost and provide affordable products. Companies cannot invest in every technology and must, therefore, develop products most promising for the spread of AFVs.

Numerous studies have investigated AFVs and their future portfolios (Nakano and Chua 2011; Graham-rowe et al. 2012; Nanaki and Koroneos 2013; Yagcitekin et al. 2014; Yabe et al. 2015). However, they only examined EVs or HEVs and did not consider other AFV types. In another work, the Electric Power Research Institute (2007) evaluated the impact of adding petrol (gasoline) hybrids and petrol plug-in hybrids to vehicle fleet until 2030. However, they examined neither FCVs nor electric vehicles (EVs). Most studies disregard FCVs or minimise their impact owing to outdated data. Toyota has launched an FCV into commercial production and Honda has introduced their own hydrogen FCV into the market ('Toyota, Honda get ready to launch their FCVs', 2014), and it is of utmost importance to these and other companies to accurately forecast the implementation of FCV powertrains using new data. Sandy (2009) analysed and compared the societal benefits of deploying AFVs; the most realistic of the study's scenarios (a hydrogen FCV scenario) concluded that a value of approximately $330 billion per year could be saved in terms reductions in GHG emissions, petroleum consumption and urban air pollution. The cumulative social cost of delaying the introduction of hydrogen vehicles from 2015 to 2025 would rise by $16 billion in 2025 (Sandy 2009). However, the benefits of hydrogen can be accomplished only if it is produced using renewable energy. Sharma and Krishna (2015) determined that solar energy is apparently the only source of renewable energy suitable to producing enough hydrogen to accommodate a hydrogen economy. Krishnan et al. (2015) focused on assessing hydrogen as an alternative fuel in a national portfolio. They concluded that sufficient improvements in FCV investment could allow such vehicles to outperform petrol and plug-in hybrid electric vehicles (PHEVs), providing a sustainable economic option under a high renewable-power-generation portfolio, although only light duty vehicles (LDVs) were examined. In line with the above concerns, significant literature has been published on obtaining optimal portfolios using optimisation techniques; however, not all types of AFVs have been investigated and most studies have disregarded FCVs. This study seeks to remedy these gaps in the research by analysing FCVs and other types of powertrains.

Gifford and Brown (2012) assessed four types of economy using well-to-wheel analysis of automotive transportation scenarios (i.e. operation cost, primary energy consumption, GHG emissions and water usage). They found that CNG vehicles scored the highest in all four metrics in two of their scenarios. Nevertheless, their research did not include infrastructure cost. Wu and Aliprantis (2013) examined models for both transportation and national energy planning, although they did not research FCVs and their influence. Onat et al. (2015) recently presented an interesting study that tackles not only environmental but also economic and social issues of sustainability in promoting AFVs. The study used a novel approach integrating compromise programming and a life cycle sustainability assessment (LCSA) framework. The conclusion from the baseline scenario was that internal combustion vehicles (ICVs) are dominant only in terms of social and economic aspects, while HEVs are preferred when environmental aspects are considered (Onat et al. 2015b). One of the major weaknesses of the study was that it disregarded FCVs, and therefore, no attempt to quantify energy security was made. Onat et al. (2015a) conducted one of the most comprehensive literature reviews on the environmental impacts of AFVs. The research evaluated and compared around 40 previous LCA studies in detail. According to the research, HEVs are the dominant vehicle type studied, and the majority of the articles make only a comparison between ICVs and AFVs. Moreover, LCA carried out by Onat et al. (2015a) examined 50 states, considered regional driving patterns and marginal and state average electricity generation mix while incorporating GHG emissions and energy consumption. Axsen and Kurani (2013); Kelly et al. (2012); Kintner-Meyer (2007); Samaras and Meisterling (2008) used LCA as a research method; however, their focus was on PHEVs and neither EVs nor FCVs were considered. In reviewing the above literature, it was found that although several attempts have been made to investigate AFVs and their implementation, most studies did not do so systematically. To address the gaps in the previous literature, this study investigates four case scenarios: Business As Usual (BAU), Energy Security, Low Petroleum Price and Subsidy.

Considerable literature has been published on the environmental or economic impacts of AFVs (Hermann et al. 2007; Hawkins and Gausen 2012; Nanaki and Koroneos 2012; Faria et al. 2013; Marshall et al. 2013; Nanaki and Koroneos 2013). However, the energy security aspects of such vehicles should also be investigated. The uncertainty of future demand and supply of petroleum and gas poses a threat to energy security (IEA, 2012). To address this, the European Union (EU) has created a framework by which nations and automakers may decrease energy consumption and GHG emissions by 2020. These regulations will affect vehicle portfolios in the forthcoming years and innovations will be crucial to meeting the challenges set by the EU (Köhler et al. 2013). The conflict between Ukraine and Russia has also sparked interest in the topic of energy security in the EU as imports of resources to the EU have been interrupted in the past by political circumstances in Eastern Europe (Umbach 2010). Hedenus et al. (2010) determined that the cost of petroleum disruption may be €29.5–31.6bn in the EU-25 countries. Wu and Aliprantis (2013) focused on LDV models used for national energy and transportation planning in the US; their results indicated that if aggressive electrification of LDVs were introduced along with investment in renewable energy, annual petrol consumption could be decreased by 66%. A comprehensive analysis of AFVs should include social, environmental and economic indicators (Litman 2008). The European Commission (EC) listed employment, contribution to GDP, injuries and external costs of the transportation as indicators for evaluating the social and economic sustainability outlook of the transportation system (Dobranskyte-Niskota et al. 2007). A multi-criteria analysis of AFVs should be thoroughly examined to propose a holistic approach (Onat et al. 2014). Moreover, according to Litman and Burwell (2006), the socio-economic aftermaths of transportation should be investigated because quality of life is at stake. There have been only a few attempts to investigate those three dimensions. An extensive study conducted by Onat et al. (2014) considered both socio-economic and environmental impacts of AFVs and proposed 19 macro-level sustainability indicators for a scenario analysis. Another study by Onat et al. (2016) integrated the LCSA model and system dynamics to create a detailed sustainability impact assessment of AFVs. Although extensive research has been conducted on the environmental and economic aspects of AFVs, only few studies have prioritised energy security issues. To overcome this gap, we developed a model that considers resource restrictions.

Governments of EU countries are slowly attempting to shift from fossil fuels to renewable energy, not only for environmental benefits, but also for energy security reasons, but these are still minor sources of global energy production. Recent developments within the field of natural gas extraction from shale rock have changed the US energy mix dramatically (Wang et al. 2014). The shale gas revolution is also a promising option for countries like Poland and China to diversify their coal-based economies and additionally improve the energy security of many countries (Wang et al. 2014).

Motivated by the findings from the above literature and conventional studies and by the lack of studies on the security aspects of introducing AFVs, this study examines opportunities for the integration of AFVs into transportation systems while considering energy security. This study aims to use an optimisation technique to develop future scenarios of AFV penetration that provide energy security. The study considers passenger vehicles, lorries and buses over a target implementation period till 2030. Several scenarios for integrating five types of AFV powertrains are investigated in accordance with improvements in technology, energy security, sensitivity of petroleum prices and national subsidies. These results can be used to advantage by automotive companies and national institutions for strategic decision making on transport and energy policy and for informing policies supporting introduction of AFVs (e.g. government subsidies or tax exemptions).

In Section 4.2 of this study, the constraints and modelling approach is described. In Section 4.3, variables and input data sources are presented.

4.2. Methods

4.2.1. Model

This section presents the development of an optimisation model to calculate an optimal portfolio for three vehicle categories: passenger vehicles, lorries and buses. The model consists of two parts: energy security constraints (petroleum and gas restrictions) and economic efficiency of a transportation system with AFVs. Fig. 12 shows an outline of the optimisation model. In this study, we evaluated seven engine platforms (CNG, HEV, DHEV, EV, FCV, LPG, DV and GV), where DV and gas vehicle (GV) refer to diesel and petrol fuelled vehicles, respectively. Six energy sources used in transportation (hydrogen, electricity, CNG, LPG, petrol and diesel) were considered. Vehicle characteristics (e.g. fuel consumption and price) and other preconditions (e.g. energy prices) were also input into the model, with details explained in Section 3. The model outputs are the optimal volume of vehicle sales in each year and the total cost of introduction and integration of AFVs.

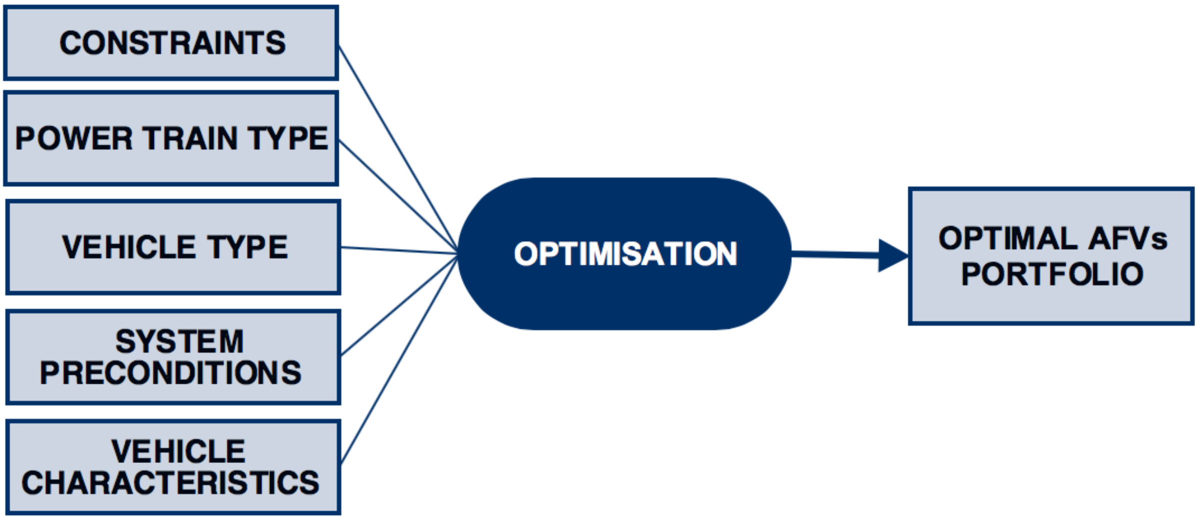


Figure 12 Optimisation model outline

Three costs are input into the model: infrastructure, vehicle and fuel; their sum creates a total AFV system cost. Based on this definition, the AFV system cost is formulated as follows (1):

$$min\ f_k(x_{jk})$$

$$f_k(x_{jkl}) = \sum_i \sum_j \sum_l S_{jkl}(x_{jkl}) A_l F_{jkl} E_{ikb} + \sum_j \sum_l x_{jkl} V_{jkbl} + \sum_j \sum_l \frac{x_{jkl} T_j}{I} \qquad (1)$$

$$S_{jkl}(x_{jkl}) = x_{jkl} + S_{jkl-1} - \frac{S_{jkl-1}}{U_l}$$

i: Type of energy [petrol, diesel, CNG, LPG, hydrogen, electricity]

j: Vehicle type [passenger vehicles, lorries, buses (GV, DV, HEV, DHEV, CNG, LPG, EV and FCV)]

l: Vehicle category [passenger vehicles, lorries, buses]

k: Object year [2014–2030]

f_k: k yearly AFV system cost [PLN]

x_{jk}: Volume of new vehicle registrations in k years of the vehicle type j in the vehicle category l

S_{jk}: Number of vehicle possessions in k years of the vehicle type j in the vehicle category l

U_j: Average tenure of use of the vehicle category l [Year]

F_{jk}: Possession average real run fuel consumption in k years of the vehicle type j [MJ/km] in the vehicle category l

A_j: Annual average mileage of the vehicle type j [km] in the vehicle category l

E_{ikb}: Energy price in k years of the energy i [PLN/MJ] in b Scenario [1-4]

b: Scenario [1–4]

V_{jkb}: Vehicles' price in k years of the vehicle type j [PLN/stand] in b Scenario [1-4] in the l category

T_j: Infrastructure price of the vehicle type j [PLN/Spot]

I: Ratio of the number of AFV possessions to the required number of infrastructures

The model in Eq. (1) defines fuel, vehicle and infrastructure costs. The objective of the function is to calculate the new sales of vehicles while minimising the total cost of implementing AFVs.

The restriction functions are presented in Eqs. (2) and (3). The numerator sets total petroleum (Eq. 2) and gas (Eq. 3) expenditure while the denominator defines total energy consumption.

$$D_k \geq \frac{\sum_j \sum_l S_{jkl}(x_{jkl}) A_l (O_{jkl} + F_{jkl} G_{jkl})}{\sum_j \sum_l S_{jkl}(x_{jkl}) A_l F_{jkl}} \tag{2}$$

$$H_k \geq \frac{\sum_j \sum_l S_{jkl}(x_{jkl}) A_l (P_{jkl} + F_{jkl} M_{jkl})}{\sum_j \sum_l S_{jkl}(x_{jkl}) A_l F_{jkl}} \tag{3}$$

D_k:k year petroleum dependency rate desired value ($D_k \in [0, 1]$)

H_k:k year gas dependency rate desired value ($H_k \in [0, 1]$)

S_{jk}: Number of vehicle possessions in k years of the vehicle type j in the vehicle category l

A_j: Annual average mileage of the vehicle category l [km]

O_{jk}: Petrol and diesel consumption per [in k years of the vehicle type j in the vehicle category l] 1-km run [MJ/km]

F_{jk}: Possession average real run fuel consumption in k years of the vehicle type j in the vehicle category l [MJ/km]

G_k: Rate of use of crude petroleum power ($G_k \in [0, 1]$) in G_{jk}:k year power supply composition

P_{jk}: Amount of petrol consumption per [in k years of the vehicle type j in the vehicle category l] 1-km run. [MJ/km]

M_{jk}: Rate of use of gas power ($M_k \in [0, 1]$) in M_{jk}:k year power-supply composition

Owing to rapid improvements in technology, the prices of AFVs and of their attendant infrastructure have declined dramatically. Furthermore, as the new data used here come from production companies and are therefore more reliable, more accurate estimates can be made. Other original facets of this study are that the model has been improved and that several changes, such as adding LPGs, have been made to adapt to the model. For this study, four case scenarios were investigated and are presented in Table 8 below:

Table 8 Scenario types

	Baseline scenario (technological developments)	Energy security constraints	High petroleum price	Low petroleum price	Subsidy
Scenario 1 - BAU	X				
Scenario 2 - Energy Security	X	X	X		
Scenario 3 - Low petroleum price	X	X		X	
Scenario 4 - Subsidy	X	X	X		X

Scenario 1: BAU: Baseline scenario including technological developments.

Scenario 2: Energy Security: BAU Scenario with energy security constraints and increase in petroleum price over the next 15 years.

Scenario 3: Low petroleum price: BAU scenario with energy security constraints and low petroleum price. As the price of petroleum is uncertain, this study develops a sensitivity analysis to improve the understanding of petroleum's influence on portfolio results. Recent developments in the global market have resulted in a dramatic decrease in petroleum prices (Chen 2015); for this reason, a low-petroleum-price scenario is being investigated. The low-petroleum-price projections were provided in a recent report by the IEA (2015).

Scenario 4: Subsidy: Scenario 2 with subsidy. This assumes PLN16,000 worth of subsidies for HEV, DHEV, EV and FCV development and PLN8,000 for CNG development. Following the example of other EU nations, the Polish government implements a subsidy to encourage the use of AFVs (Filho and Kotter 2015).

Biofuels were not investigated independently in this study because engine fuels in Poland must contain biocomponents (e.g. petrol should contain 7.16% esters and 10.3% ethanol (Polish Automotive Industry Association, 2015).

4.2. Data, variables and preconditions

4.2.1. Vehicle type (j)

The study was based on eight types of vehicles (GV, DV, HEV, DHEV, CNG, FCV, EV and LPG) for each of the three categories (passenger vehicles, buses and lorries). The main assumption is that CNG would be introduced for GVs rather than natural gas vehicle (NGV) or liquefied natural gas vehicles (LNGs). This assumption is based on the fact that CNG vehicles are already used in the Polish market and CNG stations already exist in the country.

The model also includes LPG as 14.52% of the vehicles in the Polish market use LPG fuel and an increase in its sales is projected (Chlopek et al. 2012; Automotive Market Research Institute SAMAR 2015a). Note that PHEVs are included in this study under the term HEV and not in a separate category, as these are treated as a single type of vehicle in the registration process in Poland.

The types of AFVs considered were also selected according to government regulations affecting forecasts of road transport activity (Ministry of Economy 2009a). All eight types of vehicles were chosen to compare their respective data; however, GV, DV and LPG vehicles were not considered to be AFVs.

4.2.2. Volume of new vehicle registrations *(x_{jk})*

According to Poland’s Central Statistical Office (Central Statistical Office, 2008), the country’s population is expected to decrease by approximately 3.5% from 2008 levels to 2030. However, the Polish economy is rapidly expanding at present and GDP forecasts by the Ministry of Finance of Poland and the Council of Ministers (2014) project that the economy will be constantly expanding from 2014 to 2030. Therefore, the volume of new vehicle registrations cannot be calculated according to population dynamics; correspondingly, this study employs revealed preference data (Automotive Market Research Institute SAMAR, 2015a, 2015b, 2015c; 'List of CNG lorries and buses in Poland,' 2014; Polish Automotive Industry Association, 2015) based on the actual sales of each vehicle category in 2014. To calculate future vehicle sales until 2030, the proportion of new vehicle sales in 2014 against the total number of vehicles in the same year was calculated and set as a constant benchmark for the remainder of the period. Based on this, data from various vehicle portfolio projections (Chlopek et al. 2012; Chlopek and Waskiewicz 2013) were multiplied by this proportion to calculate the volume of new vehicle sales until 2030 (Fig. 13).

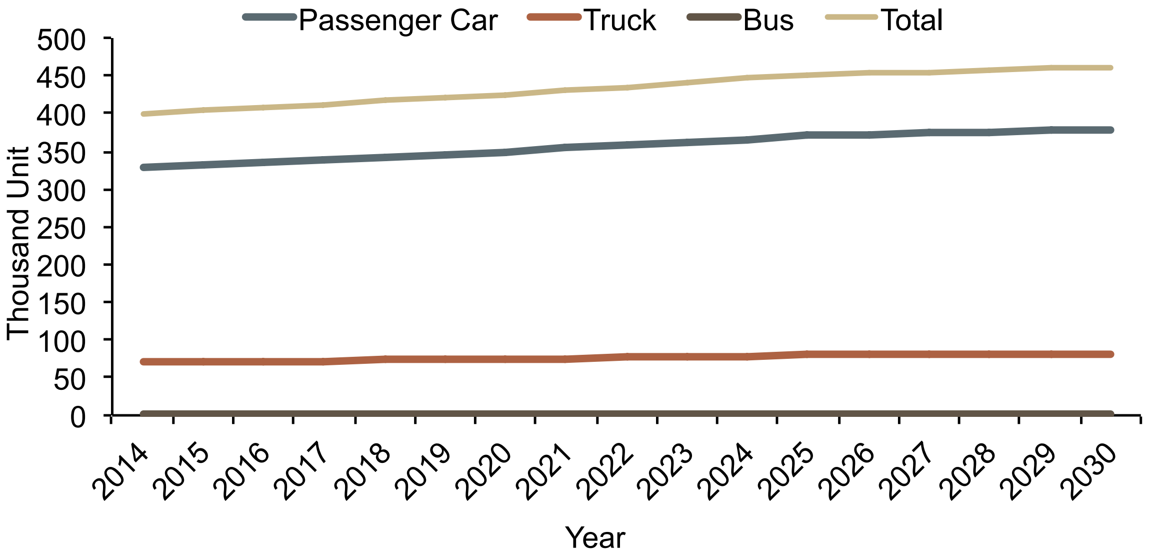


Figure 13 Estimated volume of new vehicle registrations through 2030 [thousands of units]

4.2.3. Number of possessions (S_{jk})

The numbers of each vehicle type in 2014, as shown in Table 9, were estimated based on literature review (Central Statistical Office 2014; Automotive Market Research Institute SAMAR 2015a; Polish Automotive Industry Association 2015; Automotive Market Research Institute SAMAR 2015b; Automotive Market Research Institute SAMAR 2015c). Note that before 2009, there were no vehicles classed as HEV or EV in the Polish vehicle-registration system. Such vehicles were registered as GVs before 2009, making it difficult to estimate their present numbers in the Polish market; however, data from the Polish Automotive Industry Association (2015) were used for production estimates. The numbers of FCVs and DHEVs in 2014 were set to zero owing to a lack of data and their general unavailability in the market. Furthermore, the numbers of buses and lorries were calculated based on their average tenures of use, causing the number of such vehicles to decrease. Because the number of passenger vehicles (Chlopek et al. 2012) is expected to increase till 2030, we decided that this parameter was not affected by average tenure of use but rather by a scrap quota. Further explanation is provided in the next section.

Table 9 Numbers of units owned in 2014

	GV	DV	HEV	DHEV, FCV	CNG	EV	LPG
PV	11,085,536	5,675,734	7,948	-	2,083	189	2,846,868
Truck	670,502	2,409,969	-	-	60	-	184,049
Bus	4,189	97,417	30	0	450	3	799

4.2.4. Average tenure of use (U_j)

According to Samar (2015a), (2015b), (2015c), the average tenures of passenger vehicles, lorries and buses are 17.1, 16.3 and 19.2 years, respectively. In this study, these values were assumed to remain constant till 2030. According to the calculations by the Polish Automotive Industry Association (2015) and Samar (2015a), PVs are being resold and re-registered at a high rate, with only 2% of PVs being scrapped. The average tenure of use of PVs is not considered in our model because it contradicts these real market estimates and the forecasts of Chlopek and Waskiewicz (2013); instead, the above quota of scrapped PVs was used to calculate the numbers of vehicles leaving the market.

4.2.5. Fuel consumption

Fuel consumption differs by vehicle category and type. In addition, automotive fuel consumption has been decreasing each year owing to improved engine performance and reduced air resistance and vehicular weight. Dodds and McDowall (2014a), (2014b) provided efficiency figures for PVs, and the Japanese Ministry of Environment has investigated improvements for lorries and buses (Ministry of Environment of Japan 2009). Based on this, a 'New car real running fuel consumption' [MJ/km] transition for each vehicle type was created (Table 10).

Table 10 New car real running fuel consumption [MJ/km]

	Year	GV	DV	HEV	DHEV	CNG	FCV	EV	LPG
Passenger Vehicle	2015	2.44	2.30	1.39	1.62	2.44	1.35	0.66	2.44
	2020	2.38	2.15	1.34	1.57	2.38	1.27	0.63	2.38
	2030	2.24	1.86	1.22	1.48	2.24	1.1	0.57	2.24
Lorry bus	2015	10.17	7.54	6.41	4.52	10.17	5.65	3.54	10.17
	2020	9.79	7.26	6.17	4.35	9.79	5.44	3.41	9.79
	2030	9.23	6.83	5.81	4.10	9.23	5.13	3.21	9.23

In addition, fuel consumption includes both 'New car real running fuel consumption' and 'Weighted average real running fuel consumption' of vehicles already available on the market. Note that the diesel efficiency figures may be affected by the recently revealed errors in the reported mileage data of many types of such vehicles, and real diesel fuel consumption should be investigated more closely in future studies (Le Page 2015).

4.2.6. Vehicle price (V_{jkb})

The costs of vehicles for 2015 were based on prices available in the market. The prices of PVs for subsequent years were derived from a study conducted by McKinsey & Company (2010) for mid-size cars in the EU market. As the results of this study are based on McKinsey's (2010) estimates using proprietary industry data, it can be considered a more reliable and accurate estimate of costs (Dodds and McDowall 2014a). The prices in McKinsey's (2010) study did not include taxes, and our study follows suit because from 2015, private owners can deduct the tax while making a purchase in Poland ('Deduction of VAT on personal vehicles for company cars in 2015,' 2015). In September 2015, the FCV

Toyota Mirai was expected to be sold at a price of €66,000 in Europe ('Toyota, Honda get ready to launch their FCVs,' 2014). Based on this, the forecast data were adjusted to real market costs in 2015. McKinsey (2010) did not include research on CNG and LPG vehicles; in our study, the rates for these were based on DV costs as their current market prices are comparable (Sielicki 2015). The DHEV price followed the price of HEVs. The future costs of CNGs, EVs, HEVs and FCVs in the lorry and bus categories were taken from Japanese government estimates as European data on these types of AFVs are scarce (Ministry of Environment of Japan 2009). Moreover, GV, DV and LPG vehicle pricing for lorries and buses should not change each year. Moreover, in Scenario 4 (Subsidy), the cost of HEVs, DHEVs, EVs, FCVs and CNGs would decline by PLN16,000 and by PLN4,000 (for CNGs) owing to governmental policy encouraging the use of these PVs. According to Filho and Kotter (2015) and Mock and Yang (2014), most of the EV, HEV and FCV subsidies in Europe are between €4,000 and €5,000. The CNG subsidy is lower because of energy security issues. It was assumed that the subsidies for HEVs, DHEVs, EVs and CNGs would last until 2020 while those for FCVs would last until 2025.

The price pathways of passenger vehicles, lorries and buses, respectively, for Scenario 1 (BAU), Scenario 2 (Energy Security) and Scenario 3 (Low Petroleum Price) are shown in Figs. 14–16.

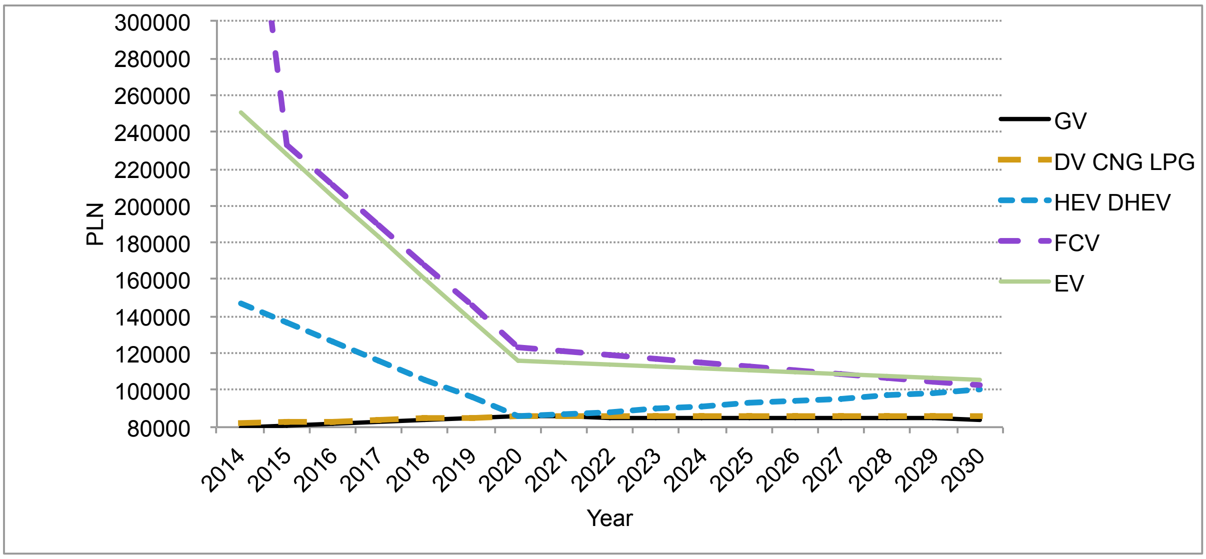


Figure 14 Estimated passenger vehicle prices through 2030 for Scenario 1 – BAU, Scenario 2 – Energy Security and Scenario 3 – Low Petroleum Price [PLN]

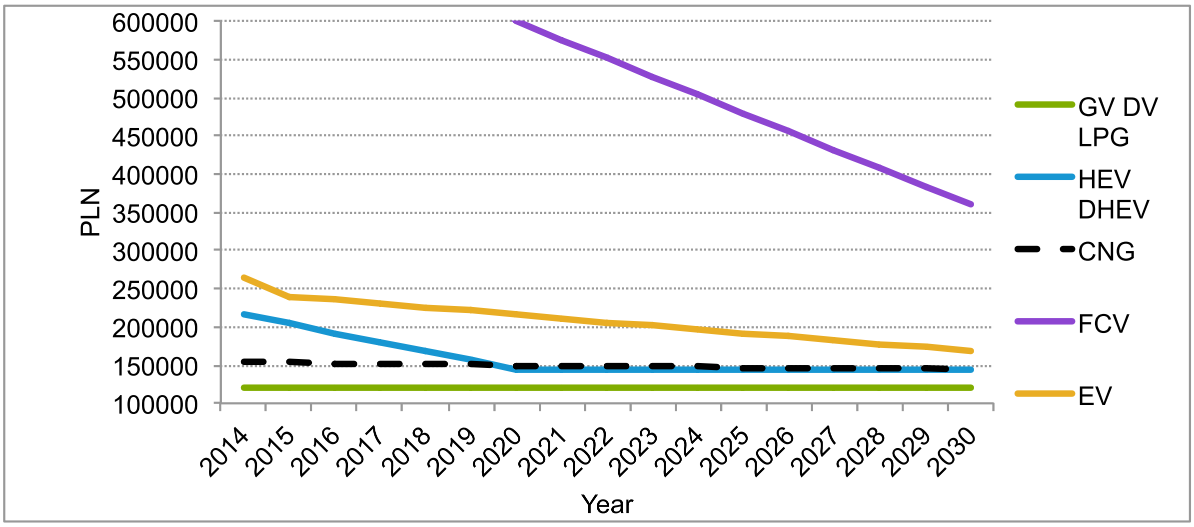


Figure 15 Estimated lorry price through 2030 for Scenarios 1 – 4 [PLN]

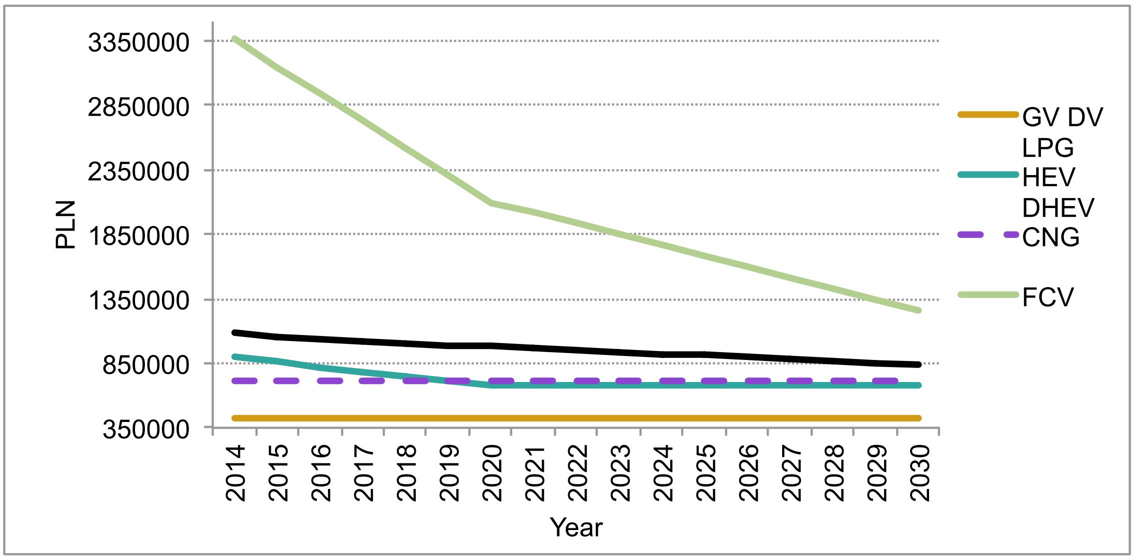


Figure 16 Estimated bus price through 2030 for Scenarios 1 – 4 [PLN]

4.2.7. Energy price *(E_{ikb})*

Five types of energy sources are assessed in this study: petrol, diesel, CNG, LPG, electricity and hydrogen. The pathways of these energy prices were modelled according to the literature, i.e. using a research conducted by the IEA (2015, 2012) and real market data and forecasts provided by Chlopek and Waskiewicz (2013). Chlopek and Waskiewicz (2013) forecasted energy prices in Poland from 2010 to 2030, with their prices from 2014 to 2015 adjusted according to the average prices on the market for each year to provide more robust results (Polish Organization of Petroleum Industry and Trade (POPIH), 2015a).

The price of hydrogen was calculated on the basis of data from the IEA (2005). According to this report, the cost of hydrogen at a decentralised level would be USD35–50/GJ. It is projected that the hydrogen coming from centralised gas and coal stations with CCS would cost around USD10–12/GJ from 2020 to 2030 (IEA, 2005). The data above were used in the BAU, Energy Security and Subsidy Scenarios 1 (BAU), Scenario 2 (Energy Security), Scenario 4 (Subsidy), although Scenario 3 (Low Petroleum Price) used low petroleum-price predictions based on data from the IEA (2015). Petrol, diesel and gas prices were calculated using formulas (4)–(7) based on the literature (Lezon 2015):

$$P_k^G = P_k^C + T^C + T^V + O^V + M^R + M^V \tag{4}$$

$$P_k^D = P_k^C + T^C + T^D + O^D + M^R + M^D \tag{5}$$

$$P_k^L = P_k^M + T^C + T^L + O^L + M^R + M^L \tag{6}$$

$$P_k^N = P_k^D \times n + T^C + T^N + O^N + M^R \tag{7}$$

$P^G k$: year petrol price [PLN/l]

$P^D k$: year diesel price [PLN/l]

$P^L k$: year LPG price [PLN/l]

$P^N k$: year CNG price [PLN/l]

$P^C k$: year petroleum price [PLN/l]

$P^M k$: year gas price [PLN/l]

T^C: VAT tax [PLN/l]

T^V: Petrol excise tax [PLN/l]

T^D: Diesel excise tax [PLN/l]

T^L: LPG excise tax [PLN/l]

T^N: CNG excise tax [PLN/l]

O^V: Petrol fuel surcharge [PLN/l]

O^D: Diesel fuel surcharge [PLN/l]

O^L: LPG fuel surcharge [PLN/l]

O^N: CNG fuel surcharge [PLN/l]

M^R: Refining margin [PLN/l]

M^V: Petrol distribution margin [PLN/l]

M^D: Diesel distribution margin [PLN/l]

M^L: LPG distribution margin [PLN/l]

n: Diesel–CNG parity

Note that there is no set margin price in Poland for the refinement of petroleum, petrol or diesel; instead, these prices change according to current market conditions and sometimes drop when sudden hikes in petroleum price occur. The petroleum, diesel and gas-refining margins were calculated based on data from 2014, and the margin from 2014 was set as constant until 2030. The CNG price in Poland was calculated assuming an eco-diesel parity and an excise tax, fuel surcharge and fuel tax (Sliwka et al. 2014). The prices of these fuels were calculated according to the current tax rates (Lezon 2015), with the results by scenario shown in Figs. 17 and 18.

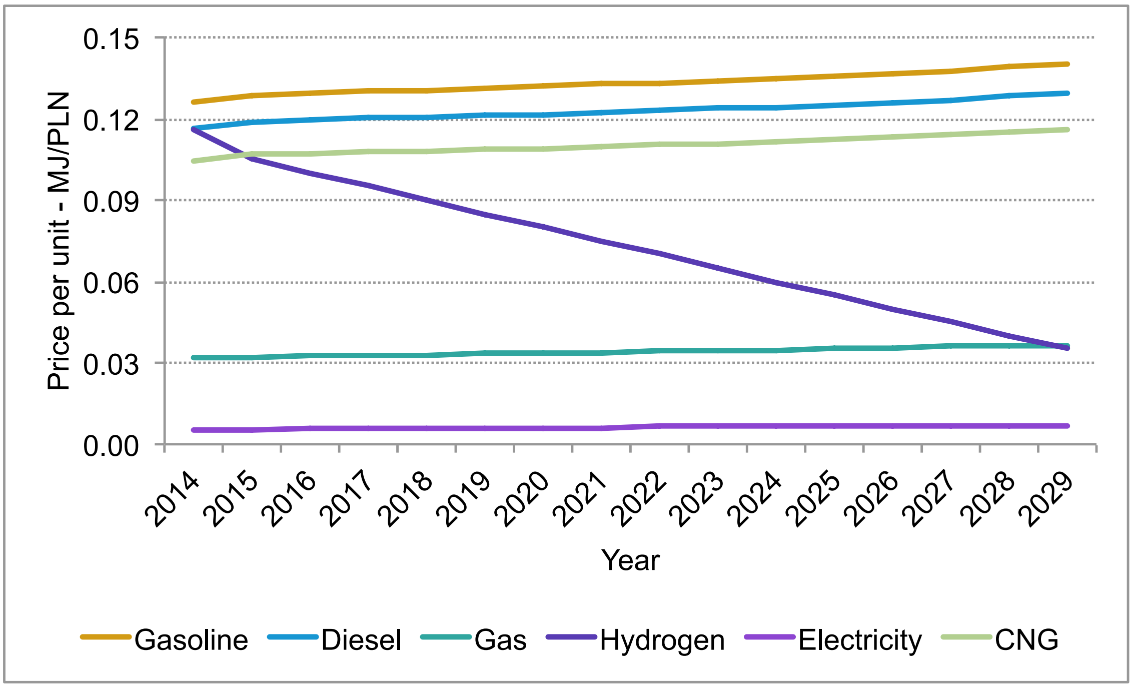


Figure 17 Estimated energy prices until 2030 [PLN] in Scenario 1 – BAU, Scenario 2 – Energy Security and Scenario 4 – Subsidy.

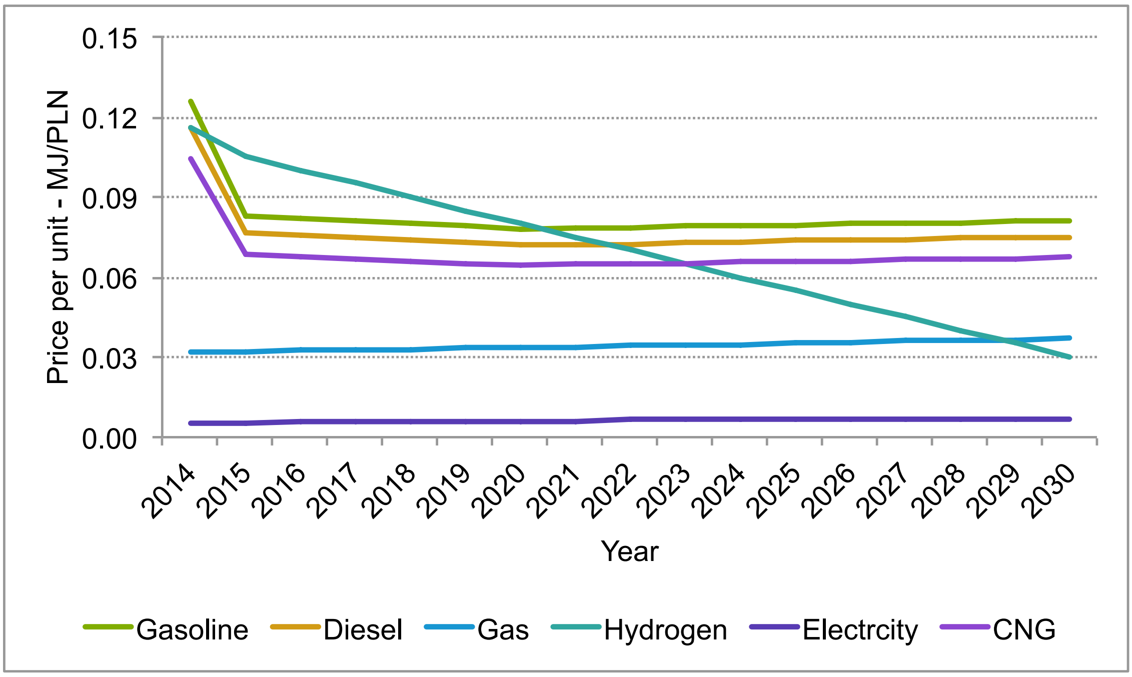


Figure 18 Estimated energy prices until 2030 [PLN] in Scenario 3 – Low Petroleum Price

4.2.8. Infrastructure cost (T_j)

The infrastructure cost in this research is provided by the third term on the right-hand side of formula (1). First, the ratio of service stations (SSs) to the total number of GVs was calculated. There were 6,552 stations and 11,760,227 GVs in 2014 (Polish Organization of Petroleum Industry and Trade (POPIH), 2015b), and this ratio is assumed to be applicable as a benchmark for AFVs as well. The cost of infrastructure per charging spot is based on the literature (McKinsey & Company 2010; McKinsey & Company 2014); the EV infrastructure cost is an average of the cost of establishing a slow-charging station (for which full charging takes 5–7 h, e.g. at a home or business location) and quick-charging stations (80% of full charging is achieved in 30 min, e.g. at a shopping centre location). The cost of a 3.7 kW slow-charging station with two outlets is PLN8,500 and that of a 50 kW quick-charging station is PLN45,000 (McKinsey & Company 2014). As the installation of house charging stations is essential to the success of an EV economy, PLN1,500 was added to the infrastructure per EV unit sold (McKinsey & Company 2014). The CNG infrastructure cost was estimated at PLN3,000,000 per station according to the data found in Smith et al. (2014).

These values should not change by year. It was also assumed that the market for SSs for GVs, DVs, HEVs, DHEVs and LPGs will be saturated until 2030, so there should be no additional costs associated with purchasing this type of vehicle. This assumption is based on the fact that according to Polish market data, the number of gas stations is not increasing. The number of stations was 6,552 in 2015, 6,745 in 2013 and 6,756 in 2012 (POPIH, 2015b). Thus, we assumed that further expansion of infrastructure for GVs, DVs and LPGs was not necessary (Polish Automotive Industry Association 2015). The cost of FCV infrastructure was set to PLN8,500 per unit; this figure, as calculated by McKinsey & Company (2010), includes operational and capital costs for retail stations as well as the costs for distribution from the production site to the retail station.

Table 11 lists the modelled costs of AFV infrastructure.

Table 11 Infrastructure cost per unit sold [PLN]

Type of powertrain	Cost
EV	1,514
CNG	1,671
FCV	8,500
GV · DV · HEV · DHEV · LPG	-

4.2.9. Power demand composition

According to the IEA (2013), the difference between power demand and supply is insignificant; correspondingly, data on power demand composition provided by the Polish Ministry of Economy (2009b) were used as a proxy to calculate power demand composition. Figure 19 represents the change in power demand composition until 2030.

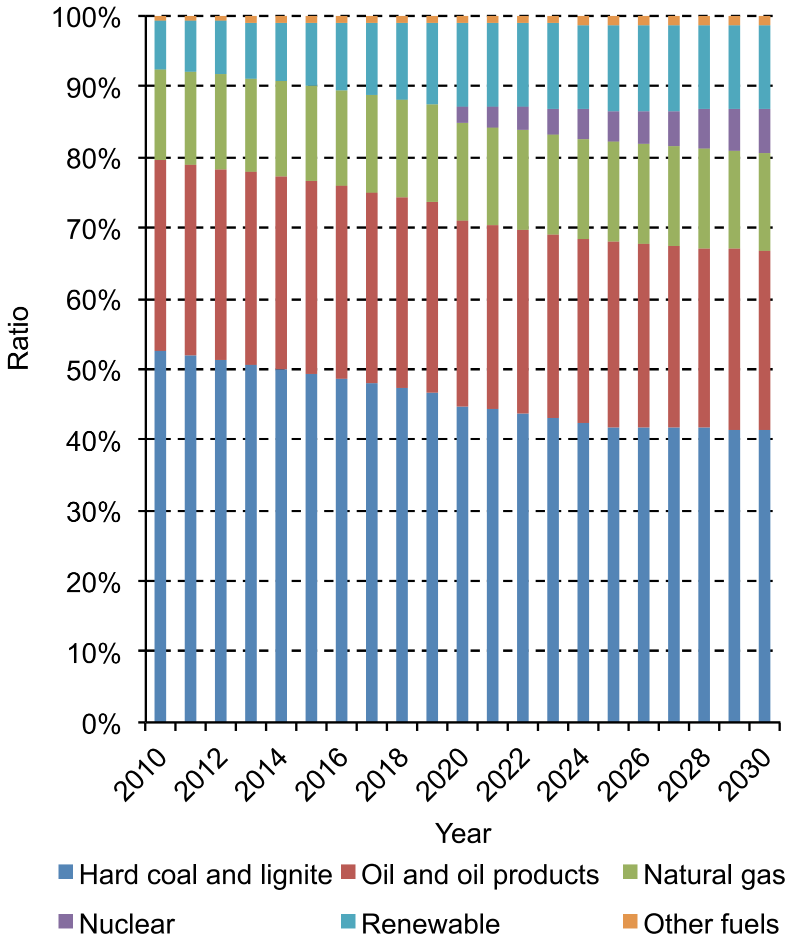


Figure 19 Power demand composition until 2030 [PLN]

4.2.9. Annual average mileage *(A_j)*

The annual average mileage differs for passenger vehicles, lorries and buses. Moreover, these values differ among subcategories of these vehicle types owing to a number of determinants (e.g. purpose and size of the vehicle). In line with this, annual average mileages were calculated based on the data provided by Chlopek and Waskiewicz (2013) and were assumed to be constant until 2030. The final values are presented in Table 12 below.

Table 12 Annual average millage

Type of vehicle	Years
Passenger Car	7,905
Lorry	14,500
Bus	25,000

4.2.10. Setup of restriction values (*D*, *H*)

In this study, four automobile portfolio scenarios were examined. Scenarios 2–4 show a 15% decrease in petroleum and gas consumption. As stated in Section 2.2, this numerical target, which is the only target set in the scenario analysis, reflects the government's energy security-based goal to decrease imports from single sources by 15% by 2030 (see *Energy Policy of Poland until 2030*), corresponding directly to energy security issues. Thus, this rate was set as a scenario-restriction reflecting limit on petroleum and gas imports.

4.4. Simulation results with Optimisation

Numerical results of four scenarios and discussions with respect to the implementation of AFV portfolios are illustrated in below Sections. In the scenarios presented in this section, an optimisation technique was applied to forecast optimal solutions for implementing the integration of AFVs with given energy-security constraints in Poland until 2030.

4.4.1 Total vehicle fleet

In Scenarios 2, 3 and 4, both petroleum and gas energy-security issues were investigated. However, if gas security is disregarded and only petroleum is considered, then the deployment of AFVs is significantly slower. Moreover, in Scenario 1 (BAU), GVs and DVs are sold in large quantities and the spread of AFVs is marginal. The results also show that a drop in prices is necessary for successful diffusion of alternative vehicles; such a drop would have to be achieved by either technological developments, governmental subsidies or both. Furthermore, the total cost of integrating AFVs amounts to PLN146bn, PLN152bn, PLN120bn and PLN156bn for Scenarios 1, 2, 3 and 4, respectively. Scenario 4 (Subsidy) is the most expensive owing to the presence of government subsidies, but the spread of AFVs is the greatest at 4,250,000 units. Scenario 3 (Low Petroleum Price) is the most economic as a result of an assumed decline in global petroleum prices, but the diffusion of AFVs is significantly lower at 3,420,00 units. In the BAU Scenario, only 36,000 AFVs are introduced to the market.

In optimising the portfolio, it was found that gas and petroleum restriction quotas are not independent. Both energy security objectives cannot be accomplished at the same time if the reduction in the entire system cost, which involves decreasing petroleum price and surging gas consumption, is assumed. In the BAU Scenario, petroleum dependency increases and gas use declines by 6.15%. In the Energy Security, Low Petroleum Price and Subsidy Scenarios (2, 3 and 4), the petroleum dependency rate decreases by 15%, but the gas consumption rate increases from 10.5% to 23.36, 23.25 and 23.24%, respectively. Nevertheless, Chlopek and Waskiewicz (2013) predicted that gas spending will increase in the coming years. Furthermore, as the possibility of extraction and distribution of Polish shale gas is currently being investigated (Baranzelli et al. 2015), it was decided that the cost of gas should be minimised.

The transition of the overall vehicle fleet from 2014 to 2030 in Scenario 2 (Energy Security) is shown in Fig.20.

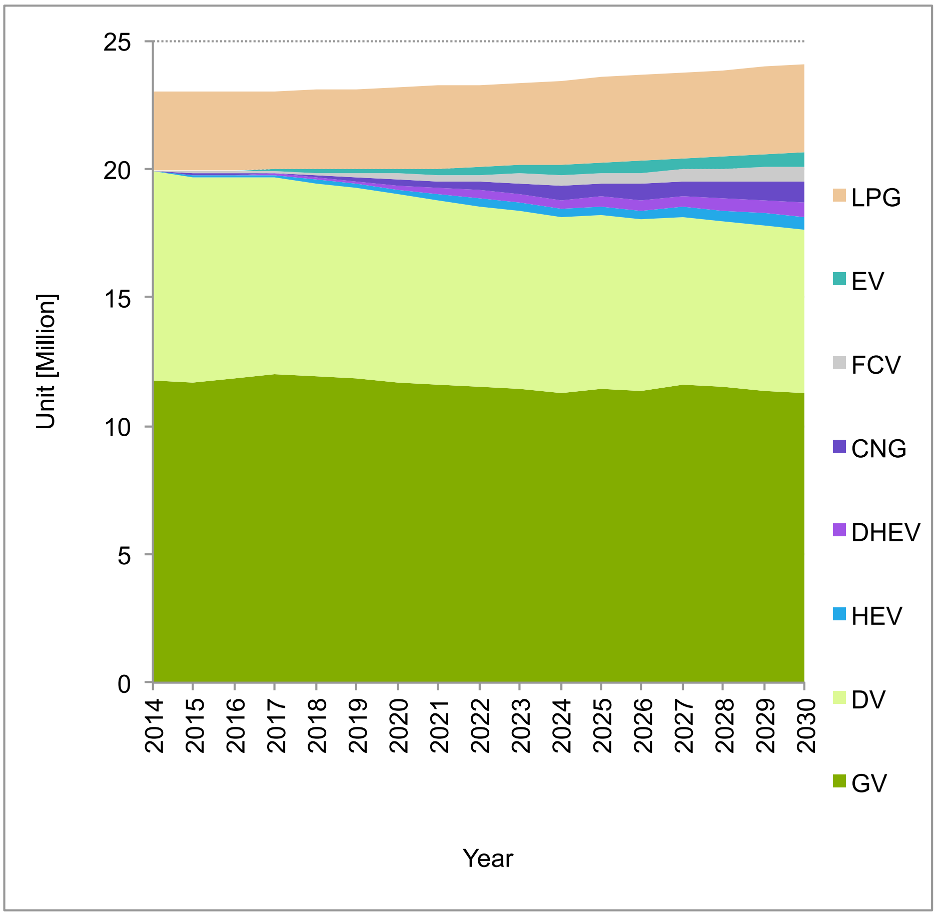


Figure 20 Transition of overall vehicle fleet (old vehicles + new registrations) from 2014 to 2030 for PVs, lorries and buses for Scenario 2 – Energy Security [Million units]

Although the results of AFV implementation seem modest, it is important to note that only approximately 400,000 new vehicles are sold every year in Poland, and the scrap ratio of PVs is low. From 2015 to 2030, the number of HEVs in the market is projected to increase by approximately 500,000 units; corresponding projected increases for DHEVs, CNGs and EVs and FCVs are approximately 550,000, 820,000 and 600,000 units, respectively.

4.4.2 Passenger vehicles

Owing to a lack of restrictions under the basic (BAU) Scenario, GVs and DVs are sold in the largest quantities. In the Energy Security Scenario, GVs, CNGs and LPGs have the highest volumes of sales, with the combination of low price and a substantial increase in the energy efficiency of CNG and LPG vehicles making those powertrain platform combinations favourable. In the Low Petroleum Price Scenario, the lower cost of petroleum increases the sales of GVs; however, the number of LPG sales is still high to outweigh the increase in petroleum use. HEVs, FCVs and EV vehicle sales increase the most under the Subsidy Scenario, under which 2,000,000 vehicles are subsidised at a cost of around PLN2bn. Sales of GVs and LPGs are lowest under this scenario. The anticipated sales between 2014 and 2030 are shown in Fig. 21.

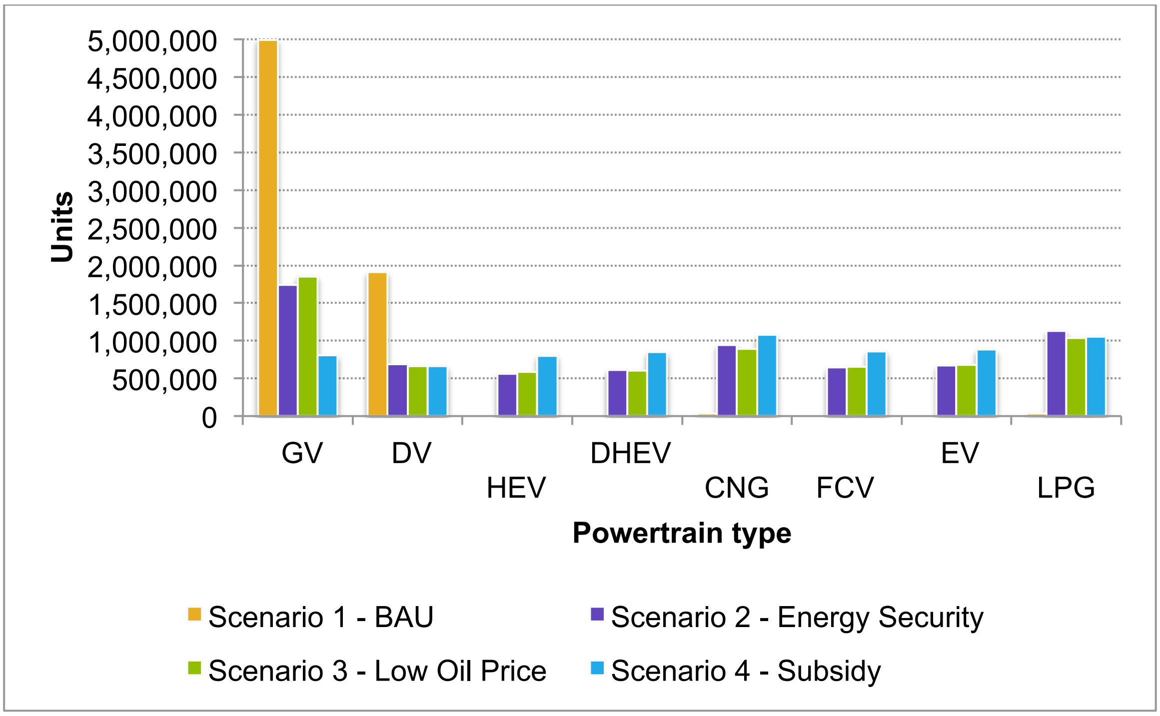


Figure 21 Total sales projected between 2015 and 2030, by type of PV, for Scenarios 1, 2, 3 and 4 [units]

Under the Energy Security, Low Petroleum Price and Subsidy Scenarios, noticeable increases in the sales of AFVs occur between 2015 and 2030. Interestingly, nearly all types of AFVs gain a similar proportion of sales or approximately 600,000 units each for HEVs, DHEVs, FCVs and EVs under Energy Security. Although there were more than 200,000 GVs sold in 2014, this figure is projected to fall to 36,694 units in 2030; over the same period, DV sales are projected to decrease by approximately 70%. In all the above three Scenarios, including Energy Security [2-4], CNG is the engine platform for which projected sales are the highest among AFVs. LPG is a fuel that increases the most overall until 2030, as a number of reasons including low prices, petroleum restrictions and no-additional infrastructure cost make it the most affordable type of fuel.

4.4.3 Lorries

In BAU, Low Petroleum Price and Subsidy Scenarios (1, 3 and 4, respectively), the portfolio of lorries and buses does not change significantly.

Correspondingly, only the Energy Security results pertinent to these vehicles are presented below. Fig.22 shows the transition of the total lorry fleet from 2014 to 2030. According to estimates by Chlopek and Waskiewicz (2013), the number of lorries will decrease through 2030. CNG lorries proliferate the most among all AFVs under this scenario and account for 10.7% of the total fleet in 2030. The spread of other types of AFVs varies from 2% to 3%. Even so, in 2030, the use of non-AFVs remains dominant, with 48.5% of vehicles being DVs, 13.16% GVs and 17.58% LPGs.

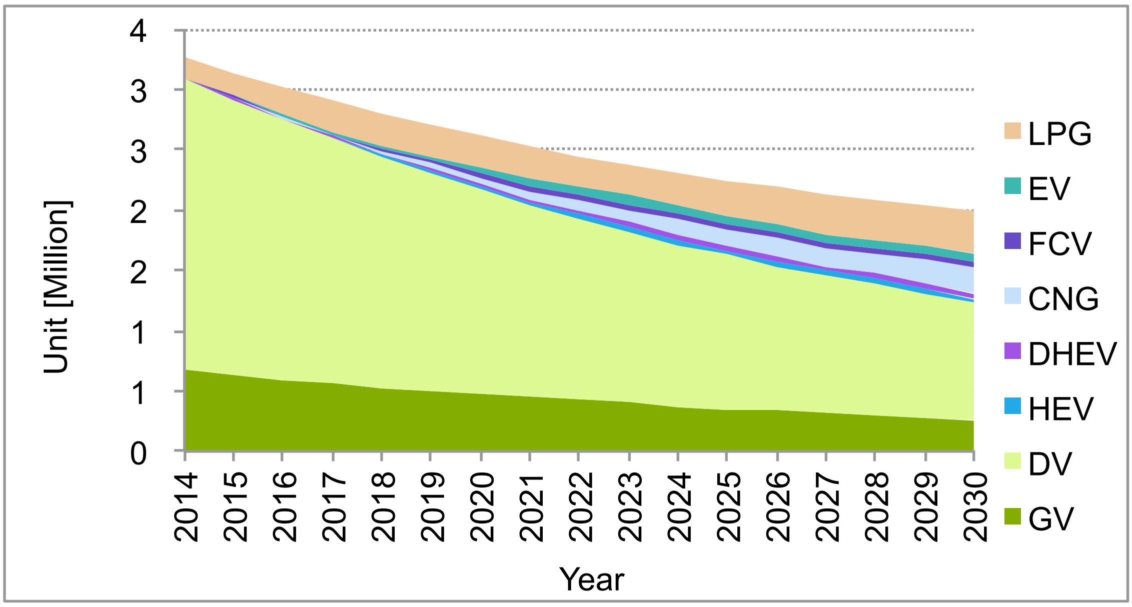


Figure 22 Transition of total lorry fleet from 2014 through 2030 in Scenario 2 – Energy Security [Million units]

The most striking observation emerges in the transition of new sales of lorries. In total, LPG lorries increase the most, with 430,958 units sold in 2030, followed by 290,095 CNG lorries and more than 100,000 DV and EV lorries 100,000 in the same year. However, EV distance restrictions for trucking applications indicate that CNG vehicles should be promoted more to reduce petroleum consumption by lorries. It was also found that even though there were 40% fewer lorries than passenger vehicles in 2012, they were consuming almost the same amount of fuel as passenger vehicles. At stake is support for the sale of AFV lorries because the increase in energy efficiency of such vehicles would be high and their decrease in fuel use would be significant. Furthermore, it is easier to aim for company clients rather than for private users as the former generally have more resources to buy new vehicles.

4.4.4 Buses

As indicated earlier, the portfolio of buses does not markedly vary between the BAU, Low Petroleum Price and Subsidy Scenarios.

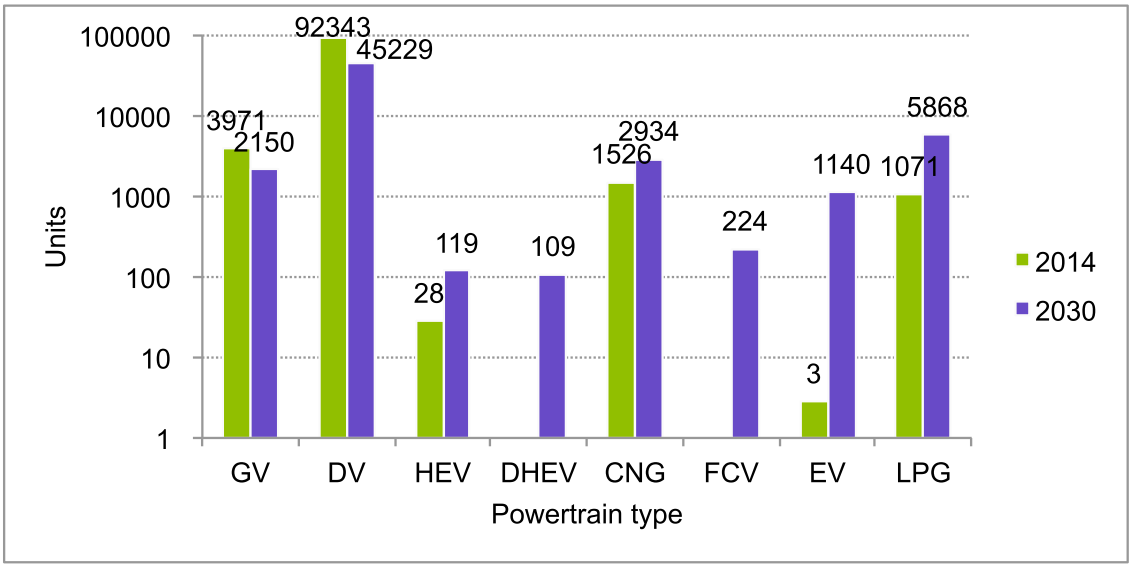


Figure 23 Transition of total bus fleet from 2014 through 2030 in Scenario 2 – Energy Security [units]

Fig. 23 shows the transition of the overall bus fleet under the Energy Security Scenario. The use of GV and DV buses decreases in favour of LPG and AFV buses by 46 and 52%, respectively. Compared with 2014, CNG and EV sales improve the most among AFVs. According to these results, the implementation of AFV buses does not correspond to a significant decrease in the use of petrol as their numbers are projected to decrease. However, such vehicles could play a crucial role in improving the public perception of AFVs. In this manner, AFV buses should be considered for use in public transportation systems.

4.4.5 Discussions and summary

This study was designed to determine future portfolios of AFVs considering the energy-security constraints that will have to be dealt with in 2030. The portfolio model developed in this study uses an optimisation technique, which is integrated with the Polish national energy and transportation strategy. As evaluated in this study, the proposed method is applicable for the estimation of AFV uptake and fleet sizes under a number of scenarios. This method can be used by automakers to investigate which products are the most promising for the AFVs, and the methods used in this research may be applied by other researchers to future studies on policies regarding the use of AFVs in other countries. This research can serve as a basis for the government to recognise which types of AFVs best suit the Polish situation and to determine the most appropriate policy instruments to benefit consumers and meet larger policy objectives. The major contribution of this research is the framework for the establishment of governmental subsidies and a guide for automakers for developing hydrogen- or battery-based technologies.

Compared with results from previous studies (Romejko and Nakano 2015), the sales of FCVs are not projected to be marginal but should instead rise dramatically. A possible explanation for this may be the fact that new data were used here. Under our new estimates, the cost of FCVs, hydrogen and related infrastructure are all projected to drop significantly owing to technological improvements. The diffusion of FCVs is significant as delaying their introduction will result in huge economic losses over the long term (Sharma and Krishna 2015). Hydrogen fuel is facing many challenges with respect to, e.g. establishing infrastructure, cost reduction and production; however, it is a promising fuel for the future, and according to McKinsey & Company (2010), automakers have already improved FCV performance and succeeded in lowering the price of such vehicles. Other authors (Lee et al. 2009; Leaver and Gillingham 2010; Offer et al. 2010; Krishnan et al. 2015) also support moving into fleets with a high percentage of FCVs to achieve economic objectives. The findings of the current study are consistent with those of Onat et al. (2015), who found that ICV becomes the dominant vehicle type in the Baseline Scenario when only economic aspects are considered. Our results concerning governmental support also seem to be consistent with other research (De Haan et al. 2007; Struben and Sterman 2008; De Haan et al. 2009; Browne et al. 2012; Shepherd et al. 2012; Brand et al. 2013), which found that subsidies and tax incentives create a positive impact on the diffusion of AFVs. The findings of this study differ from estimates published by the IEA (2012); under their most probable scenario, they project a long-term 4°C rise in global temperature considering recent (although prior to the 2015 United Nations Climate Change Conference) international commitments to limit emissions and efforts to enhance energy efficiency. The IEA 4°C scenario projects that the overall fleet size of petrol and diesel vehicles will continue rising until 2030 and that there will be an insignificant increase in CNG and DHEV, HEV and EV and FCV markets, as well as a slow penetration rate for these. The discrepancy with our projections in terms of the rate of proliferation of AFVs may be a result of our access to new predictions of the prices of these types of vehicles. It is crucial to underline that this research focuses mainly on economic objectives, and there is a strong need (Onat et al. 2014) to discuss and investigate both environmental and socio-economic indicators in future studies.

Several conclusions emerge from the Case Study 1, which are linked to the proliferation of AFVs. One of the more significant findings is that under the non-BAU Scenarios (2–4), it is crucial to introduce all types of powertrains to achieve both energy security and economic objectives; the desired results cannot be accomplished by introducing only one type of AFV. The second major finding is that the spread of FCVs could be similar to that of other AFVs owing to the expected rapid decline in the cost of both infrastructure and purchase price of such vehicles. One of the issues that emerge from these findings is that it is of utmost importance to begin investing in FCV support and infrastructure. A similar conclusion was presented in the research conducted by Offer et al. (2010). CNGs will gain a large market share by 2030 if relevant infrastructure is made abundant. This finding has important implications for the government, which should seek a reliable CNG supply (Sliwka et al. 2014). Furthermore, we recommend that the government set a subsidy for AFVs; this could improve public perception and possibly support an increase in the market penetration rates of AFVs. Comparable suggestions regarding this issue have been reported (Brand et al., 2013; Browne et al., 2012; De Haan et al., 2009; Shepherd et al., 2012; Struben and Sterman, 2008).

5. VEHICLE PORTFOLIO ANALYSIS AND LIFE CYCLE ASSESSMENT WITH SHALE GAS REVOLUTION

5.1. Chapter introduction

The past decade has seen the rapid development of Alternative Fuel Vehicles (AFVs). AFVs are vehicles operating on an alternative fuel such as hydrogen, electricity, etc. (U.S. Energy Information Administration 2013). The scarcity of resources, the climate change by GHG emissions, energy security and so forth have triggered the interest among lawmakers, automakers and researchers on AFVs and their implementation of sustainable transportation systems. Technologies using hydrogen and batteries will become increasingly popular due to the price drop and broader availability in the market (Dodds and McDowall 2014a).

Governments of EU countries are slowly attempting to shift from fossil fuels to renewable energy, not only for environmental benefits, but also for energy security reasons, but these are still minor sources of global energy production. Recent developments within the field of natural gas extraction from shale rock have changed the US energy mix dramatically (Wang et al. 2014). The shale gas revolution is also a promising option for countries like Poland and China to diversify their coal-based economies and additionally improve the energy security of many countries (Wang et al. 2014).

Due to the decrease of prices of oil on global markets, the pace of popularization of AFVs is impeded and the extraction of shale gas has noted a significant slowdown as well. However, according to the energy outlook for 22nd February 2016 by the IEA, the prices of oil will sharply increase before 2020, due to the insufficient investment in new production (2016a).

Indisputably, with the increase in oil price, the government will push the extraction of shale gas, also in Europe (Radio Poland 2015). There have been no studies, which analyze the impact of the shale gas revolution on AFV's portfolio and its implications. It is of utmost importance to treat this topic in a systematic way and provide a broader view of the consequences of using shale gas in an economy.

The process of production of shale gas is connected with a heavy consumption of water, especially during extraction phase. Moreover, there are other possible risks associated with shale gas production, i.e. water contamination; surface spills of drilling, fracking, and flowback fluids; cumulative adverse impacts on communities and ecosystems; air pollution; induced seismicity (Ground Water Protection Council (GWPC) and ALL Consulting 2009).

The objective of this study is to determine the implication of the shale gas revolution on a portfolio of AFVs and water usage in an example of the Polish economy. The scenario of a low-priced natural gas is being presented. This study would be beneficial for the government, as well as automakers and potential shale gas investors as it would provide numerical results on water usage and vehicle portfolio as a consequence of implementing shale gas into a sustainable transportation system. Even though shale has might improve the AFV portfolio the drawbacks of high water consumption and safety threads might hinder the positive aspects of implementing it in a long run.

Section 5.2. outlines quantitative methods to the study. The originality of this method is the integration of Life cycle assessment and optimization model. Water consumption is generated as an aftermath of shale gas used to supply energy for vehicles investigated in this study hence two methods are integrated in order to provide analysis of this phenomenon. The scenario of low-priced natural gas and petroleum is described in the section mentioned above.

The numerical results and findings are presented in Section 5.3. Section 4 concludes the research.

5.2. Methods

5.2.1. Model

The qualitative part of this study integrates an optimization model described in Chapter 4 and life cycle assessment. The same optimization model from Section 4.2.1 is used, which contains multiple energy preconditions and transportation variables.

In this case study, only personal vehicles are investigated. Scenario for low-price natural gas and petroleum is being investigated. The low price of the natural gas is associated with the development of shale gas on the case study's market. The energy security restriction of petroleum has been set to 10%, while gas spending is minimized. The results of the calculations are in $.

The outline of the optimization and Life Cycle Assessment process are presented in Figure 24.

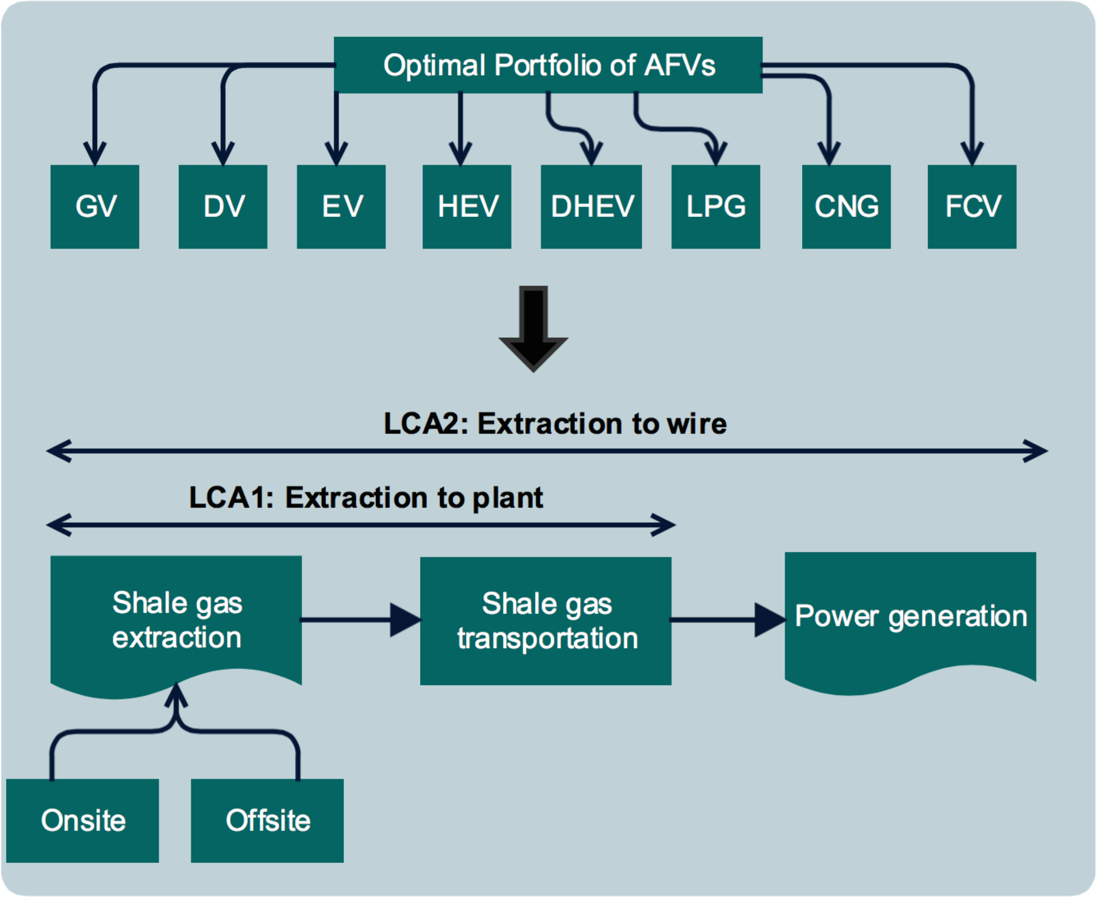


Figure 24 Outline of methods

Life cycle assessment

Life cycle assessment includes water consumption of shale gas on different stages of production (extraction, processing, transportation and power generation). The outline of the Life Cycle Assessment process is presented in Figure 1 above. We are considering 2 scenarios, LCA1: Extraction to plant, which includes extraction and transportation of shale gas, LCA2: Extraction to wire, which includes extraction, transportation and power generation coming from shale gas. The focus of the study is on the production of the shale gas hence water consumption during vehicle usage is not taken into consideration.

The originality of this approach is the integration of LCA and optimization model. Water consumption is generated as an aftermath of shale gas used to supply energy for vehicles investigated in this study hence two methods are integrated in order to provide analysis of this phenomenon.

5.2.2 Data, variables and preconditions

The data for optimisation model are in line with the data supplied in Section 4.2 Howeve, in this case we consider the drop of gas price due to shale gas revolution. The prices of gas have been changed in this study. The average price of natural gas has been set to 0,25 $ per m^3. The detailed estimation of gas price can be found in Section below. The oil prices are assumed to be low, that is why all other energy are in line with Scenario 3 – Low Petroleum Price from the study from Section 4.

Shale gas extraction and transportation

Shale gas extraction is relatively new to Polish economy, in line with this; the data on shale gas extraction, e.g. rate, size and cost are taken from the most reliable source - the US. The average lifespan of the shale gas well is set to 30 years (Corrie E. Clark, Jeongwoo Han, Andrew Burnham, Jennifer B. Dunn; Sullivan and Paltsev 2012). The average gas production of one well over six months for shale gas plays in the U.S. varies depending on the site size and resources, in Barnett play it amounted to 30000m^3 per day, in Haynesville to 15000m^3 per day, in Fayetteville to 50000m^3 per day and Marcellus to 100000m^3 per day (Hughes 2014).

The initial production is considerably higher than the above values, but the decline rate of shale gas is also significant. That is why the average production rate of the well is 60,000 m3 per day per well from the conventional studies (Hughes 2014; U.S. Energy Information Administration (EIA) 2016a).

Water usage for production of shale gas consists of direct (onsite) consumption during extraction of shale gas and indirect (offsite) consumption during supply chain production.

The heavy direct consumption of water, connected to the shale gas production, is associated with fracturing and drilling processes (Corrie E. Clark, Jeongwoo Han, Andrew Burnham, Jennifer B. Dunn). The rate of water consumption is also highly variable and depends on the geology and drilling techniques and rate of the flowback water recycling. The flowback water can be recycled, in Marcellus region, 95% of the flowback water is recycled, in other regions, the amount is significantly lower, e.g. 20% in Barnett and 0% in Haynesville (Corrie E. Clark, Jeongwoo Han, Andrew Burnham, Jennifer B. Dunn). In Marcellus play, 4,5 million gallons of water are used per well yearly for fraccing, drilling and construction activities (around 12,300 gallons per day). In Barnett it amounts to around 3,0 million gallons for fraccing and 270,000 gallons for drilling and construction (Corrie E. Clark, Jeongwoo Han, Andrew Burnham, Jennifer B. Dunn; Ground Water Protection Council (GWPC) and ALL Consulting 2009). The average amount of the US shale gas plays is set to 4Mbarells, which states to 15,141MT yearly, around 0.685 l/ per m3 of shale gas (taking into consideration that daily production is 60 000m3). Those numbers are higher in China, and according to Chang (Chang et al. 2014), water consumption amounts to around 25MT of water per shale gas well. The substantial difference corresponds to more advanced technologies, reuse of flowback water and favorable geological conditions in the U.S. in comparison with China. It is probable, that American companies will deliver the technology to the country used in the case study, which is why we have decided that the average direct use of water for m3 of shale gas is 0.685l/m3.

Indirect consumption of water is linked mainly to forestry and agriculture industry, steel rolling and distribution and production of water (Chang et al. 2015). According to benchmark, around 34% of entire water consumption results from direct water usage, and 65% originates from indirect use (Chang et al. 2015).

All things considered, total water consumption during shale gas production is set is 2,0l per 1m3 of shale gas. Water consumption during shale gas transportation is minimal and amounts to 0.01l per 1m3 of shale gas Table 13 presents data connected to water consumption during shale gas production and transportation.

Table 13 Water consumption during each stage of shale gas production

Stage	Unit	Primary energy (kJ)	Water consumption (l)
Extraction	1 m³	4,800.00	2.00
	1 MJ	134.00	0.06
Transportation	1 m³	200.00	0.10
	1 MJ	5.60	0.00

Power generation from shale gas

Estimates for water consumption in power generations were based on a combined-cycle power plant since the GHG emissions are lower than in the combustion turbine power plant. The estimated value of water consumption is set to 0.8l/kWh [16], [17], while primary energy use amounts to 7.06 MJ/kWh (Chang et al. 2015).

The average price of natural gas extracted from shale gas has been set to 0.12$/m3 (without taxes), which is an average industrial price of gas in the U.S. in 2016 (Meldrum et al.),(U.S. Energy Information Administration (EIA) 2016b) The price of natural gas that is nowadays imported from Russia was around 0.37$ per m3 between 2014-2016 (Grzegorz Łyś 2015). The high-price results from long-term agreements signed between Poland and Russia. The price should decrease significantly within the next years due to the launch of LNG terminal and resources' cooperation with other countries. Therefore, the average price of a m3 of natural gas has been set to 0,25 $ per m3. All other parameters and data concerning LCA and shale gas were gathered in Table 14.

Table 14 Parameters concerning LCA and shale gas production

	Unit	Amount	Data source
Natural gas price	\$/m^3	0.25	[18],[19]
Shale gas price	\$/m^3	0.12	[15]
Shale gas well lifespan	year	30	[10],[11]
Shale gas well average production	m^3/well/day	60000	[12],[13]
Shale gas fracturing water consumption	m^3 (ton)	15141	[10],[14]
Water consumption of power generation	l/kWh	0.8	[16],[17]

5.3. Simulation Results with Optimisation and Life Cycle Assessment

The results of scenario of low-priced natural gas and petroleum are described in the sections below. In this section of the research, Poland is taken as a case study.

5.3.1 Vehicle portfolio

In this model, six energy sources are considered (LPG, CNG, diesel, petrol, electricity and hydrogen). Scenario for low-price natural gas and petroleum is being investigated. The low price of the natural gas is associated with the development of shale gas on the case study’s market.

The energy security restriction of petroleum has been set to 10%, while gas spending is minimized.

The first set of analyses examined the impact of the introduction of cheap natural gas and petroleum, as a response to shale gas revolution, on vehicle portfolio. The numerical results are shown in Figures 25, 26 and 27.

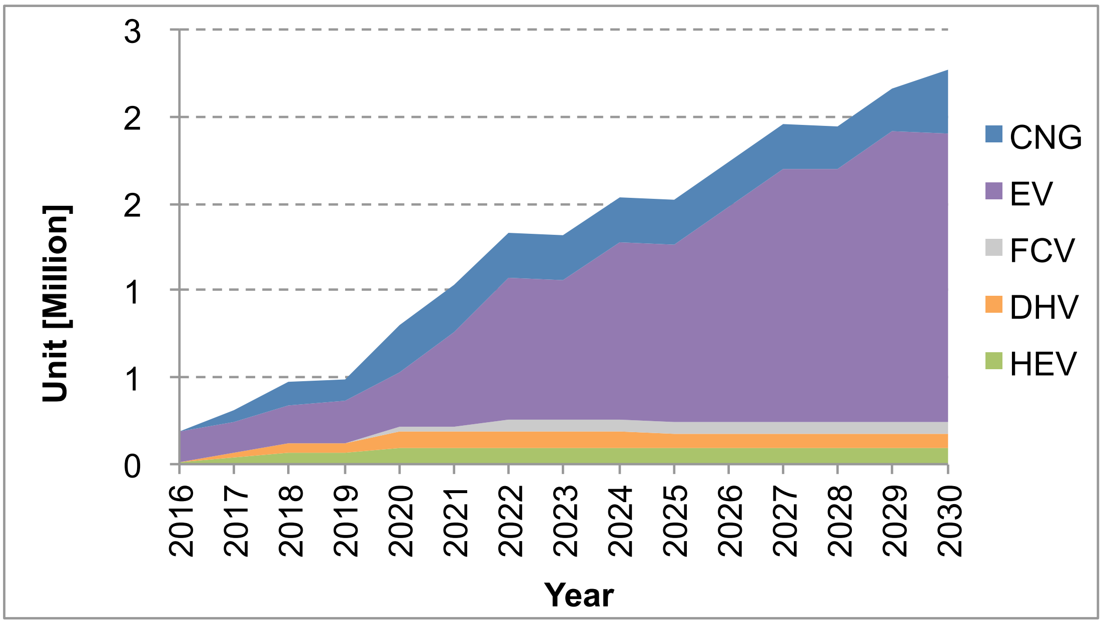


Figure 25 Total vehicle possession of the AFVs.

In Figure 2, EV gains the most within AFVs. EV has surged substantially in the given time period. This result may be explained by the fact that around 13,7% (2016) and 14.5 % (2030) of electricity in Poland come from gas. 50% of hydrogen is produced from gas as well, however, the high prices of FCV and hydrogen price make it less favorable than EV. The combination of electricity and gas use is the most advantageous in AFVs in terms of energy security and price mix. There was no significant increase in HEV, DHEV due to petroleum restrictions. CNGs are using natural gas, however, their spread is not so high as it would be expected, due to the price of CNG fuel. In Poland, the price of CNG fuel is calculated according to petroleum benchmark and not natural gas price.

The transition of total vehicle portfolio between 2016 and 2030 is presented in the Figure 26 below. The Figure shows that there has been a gradual decrease of GV and DV, slight increase of FCV, CNG, DHEV and HEV and a steady rise of EV and LPG.

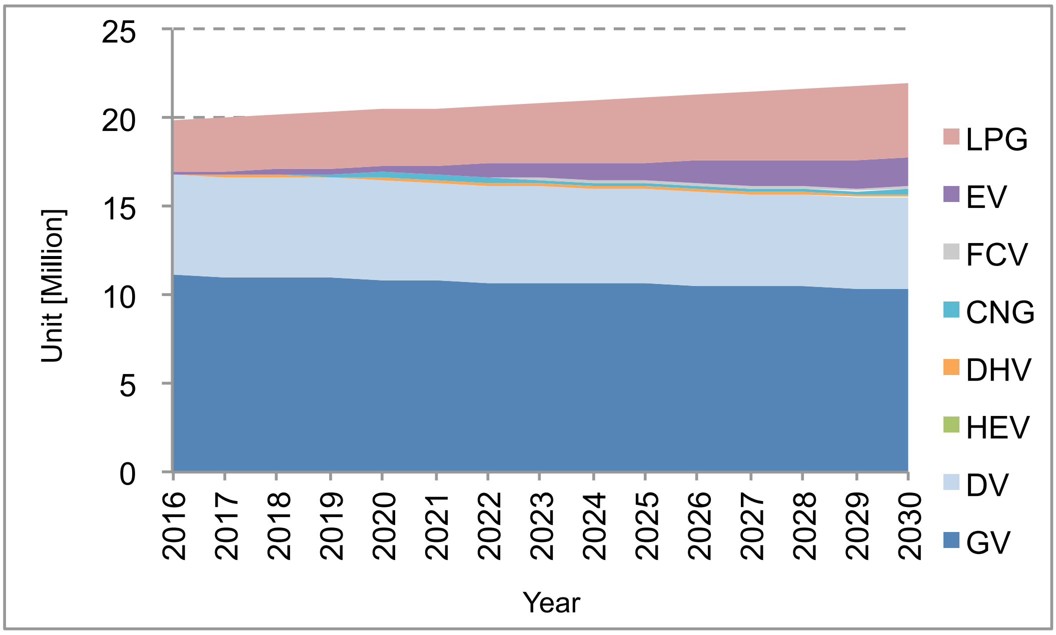


Figure 26 Changes in total vehicle portfolio between 2016 and 2030

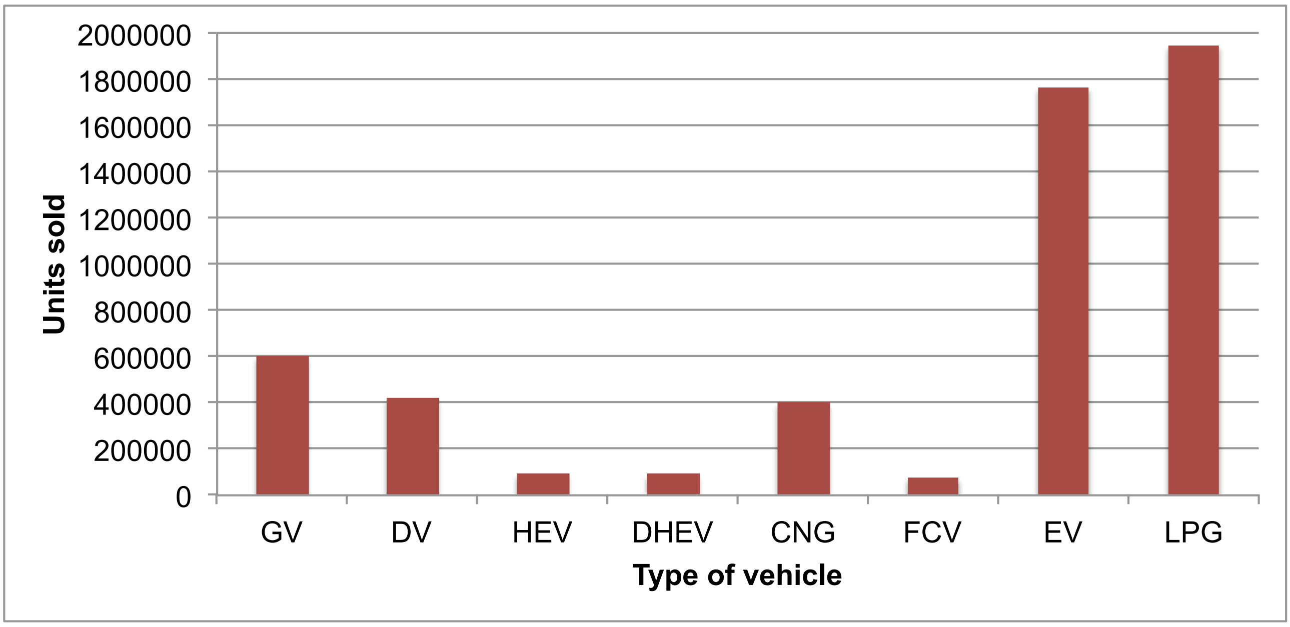


Figure 27 Total sum of units sold between 2016 and 2030 by type of vehicle

Figure 27 presents the data for total units sold between the time period. In total, the vehicle, which recorded the most sales between 2016 and 2030, is LPG, followed closely by EV, while GV and DV sales remain low.

5.3.2 Water usage

The total water consumption is calculated as the sum of natural gas used to supply LPG, CNG, EV and FCV.

Figure 28 illustrates water consumption of shale gas for LCA1: Extraction to plant (red and green) and LCA2: Extraction to wire (red, green and violet)

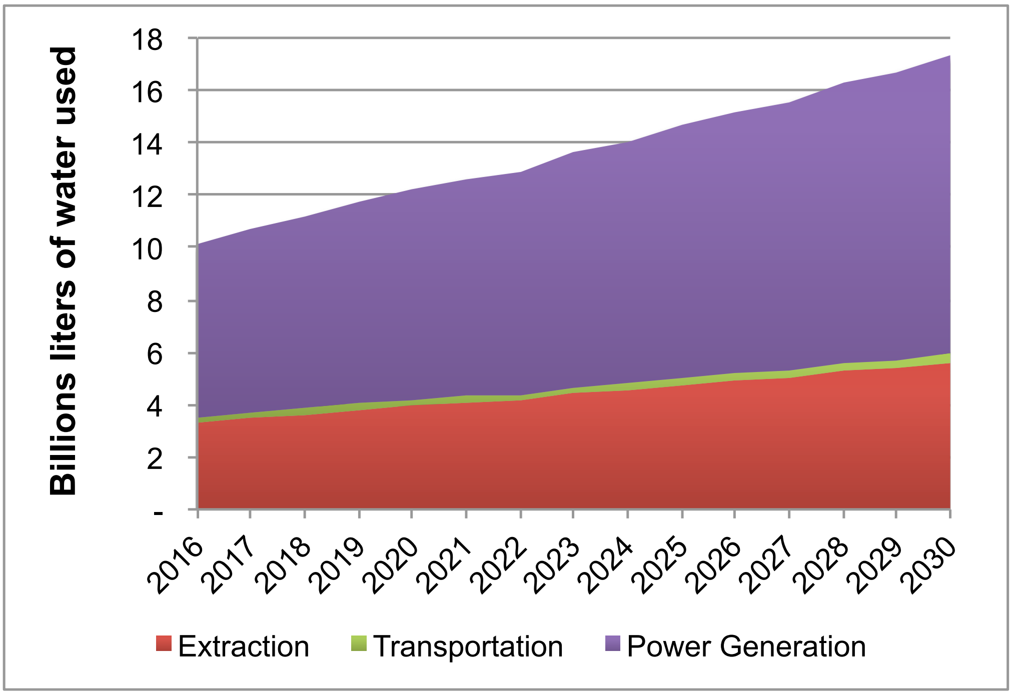


Figure 28 LCA1 and LCA2 - water consumption of shale gas in billions of liters between 2016 and 2030

In LCA1 around 71 billions of liters of water are used in this stage of shale gas production in order to provide natural gas supplies for passenger vehicles. It is projected, that totally 67 billions of water are consumed during extraction, which amounts to 95% of the whole extraction to plant consumption. Only 5% comes from the transportation process, which is 4 billions of water.

In LCA2, the rate of total extraction to wire amounted to around 205 billions of liters of water between 2016 and 2030. 65.79% comes from power generation, 32.4% from extraction and 1.7% from transportation.

It is important to note that if the government switch from natural gas to shale gas, the extra usage of water amounts to the extra water used during the extraction of shale. The usage from gas production and transportation are similar in both natural gas and shale gas (Feng et al. 2014). That is why, the government has to be prepared in this situation for an increased usage of water in the amount of 4 billion liters a year.

In comparison, the yearly water supply to the city of Warsaw in 2014 reached around 120 million liters (The capital city of Warsaw: Energy Infrastructure 2015). By contrast, annual consumption of water in extraction to the wire has amounted to around 10 billion in 2016 and 17 billion in 2030. Moreover, there has been a myriad of questions raised regarding the water quality, wastewater and its disposal, spills and groundwater disturbance in the area of shale gas extraction (Rodriguez and Soeder 2015). Significant increase in the use of water for shale gas production could affect the availability of water for residents within the area (Rodriguez and Soeder 2015). Those threads have to be minimized, for instance, technologies such as wastewater recycling, storage and disposal; non-toxic hydraulic fracturing fluids or additives like guar gum are being adopted during shale gas production (Rodriguez and Soeder 2015).

5.3. Summary and discussion

The Case study 2 examined the impact of a feasible shale gas revolution on a portfolio of AFVs and water usage and provides findings for multiple stakeholders. Conventional studies revealed that there are opportunities to explore shale gas in Poland (Uliasz-misiak et al. 2014; Lis and Stankiewicz 2016). Results of this qualitative analysis suggest that the shale gas revolution substantially impacts the portfolio of AFVs due to the significant decrease of gas prices. The results of this study indicate that due to shale gas revolution, the portfolio of vehicles positively on behalf of AFVs. The most important finding to emerge from this study is that the drop of GV and DHV is recorded in favour of EV and LPG. Moreover, the results for LCA1 and LCA2 cases show that increased use of shale gas engenders the high consumption of water. Those findings suggest that, if the shale gas is introduced in Poland, minimization of water-oriented issues is crucial.

6. MODEL FOR AIR EMISSIONS BY LIFE CYCLE ASSESSMENT

6.1. Chapter introduction

About half of global air pollution is attributed to emissions from coal- and oil-fired power plants, vehicles, and industrial facilities and associated with mortality and health problems such as asthma, respiratory problems, and cardiopulmonary diseases (Korzhenevych et al. 2014; International Energy Agency 2016). According to the International Energy Agency (IEA), air pollution is the cause of ~6.5 million premature deaths each year with significant costs to the global economy

In the European Union, more than 175,000 were recorded due to outdoor air pollution caused by PM. At the same time, it was more than 1 million in China (International Energy Agency 2016). In 2014 in Cracow (Poland), there were 188 days, in which PM was higher than advised 50 µg/m3. In January 2017, in Warsaw (Poland), the PM level was seven times above the secure PM level described by World Health Organization (WHO) (2017). According to WHO, 33 out of Europe’s 50 most polluted cities are located in Poland, due to high dependence on the coal industry, residential heating, intensive usage of vehicles and low investment in green technologies (Huber 2017).

The most common cause and effect relations of emissions were gathered in Table 15 below.

Table 15 Health impact of pollutants

Pollutant	Impact	Specification of impact
PM	Chronic Mortality	All-causes
	Acute and Chronic Morbidity	Respiratory Cardio-pulmonary Carcinogenic (cancer) Cerebrovascular Otitis media Asthma
NO_x	Acute Morbidity	Pulmonary effects in asthmatics Reduced lung-growth Leukaemia Asthma
SO_2	Acute and Chronic Mortality	All-causes
	Acute and Chronic Morbidity	Cardio-pulmonary

Source: Table based on (Korzhenevych et al. 2014)

Plenty of studies have been conducted on Electric Vehicles, however, most of them focus on the use phase of those vehicles and disregard manufacturing part, which is energy and emission intensive. Indirect effects of energy production can cause severe health problems, e.g. asthma or even chronic mortality. It is crucial to decide if the governments should invite production in their country, or if it would be more apt to import vehicles.

Governments are willing to invite manufacturers to establish green production technologies and promote EVs in their countries. However, both the benefits and drawbacks of locating production facilities in different regions should be carefully assessed prior to making decisions. Factors that influence environment-friendly production include the components of the electricity mix, dependency on coal energy, technological advancement, and the efficiency of energy and production. Very little attention has been paid to analyzing the indirect effects of locating production facilities in various countries. The governments should thoroughly evaluate the advantages and disadvantages of inviting manufacturers to their country or directly importing the finished products.

According to Held et al. (Held and Baumann 2011), EVs produce less environmental burden than internal combustion vehicles during the use phase. Furthermore, according to Buekers (Buekers et al. 2014), replacing internal combustion vehicles with EVs in France would result in substantial environmental and health profits amounting to 2.5 Eurocents per kWh. Those advantages can be reached due to a significant use of low-polluting energy sources (Buekers et al. 2014). In Sweden, only 6 g/km of CO_2 is produced during the use phase because most of the electricity is generated in hydroelectric power plants (Jochem et al. 2015). However, various studies simultaneously dispute the environmental benefits of EVs. Hawkins et al. (Hawkins et al. 2013) suggest that it is counterproductive to promote EVs in regions where electricity is produced from oil, coal, and lignite combustion. In China, electricity mostly comes from coal-fired power plants and Ji states that replacing gasoline vehicles (GVs) with EVs would have adverse effects on public health and the environment (Ji et al. 2012). Similar results were found in (Buekers et al. 2014), where the external costs for replacing GVs with EVs were close to zero in both Poland and Estonia. In line with these previous studies, despite decreased emissions from EVs during the use phase, the production processes might greatly influence the total impact of these vehicles on the environment and make them less environmentally friendly than GVs.

Numerous studies have investigated EVs and their environmental impact. However, most researchers have assessed only one stage of the vehicle life, e.g., the use phase (Howey et al. 2011; Ji et al. 2012; Jochem et al. 2015). This approach favors EVs because they produce lower CO_2 emissions during use. Most studies disregard the end-of-life phase of the vehicles (Nonaka and Nakano 2011; Zhao et al. 2012; Buekers et al. 2014). At the same time, recycling and disposal of EVs can substantially influence the final results of the life cycle assessment (LCA). Furthermore, the bulk of the papers focus mostly on the US market (Kintner-Meyer 2007; Samaras and Meisterling 2008; Elgowainy et al. 2009; Sandy 2009;

Axsen and Kurani 2013; Marshall et al. 2013; Wu and Aliprantis 2013; Nealer et al. 2015a), that is why there is no need to further explore this region. Moreover, many studies consider only the greenhouse gas (GHG) emissions, e.g., carbon dioxide (CO_2) and disregard the non-GHG emissions, e.g., *nitrogen oxides* (NO_x), *sulfur dioxide* (SO_2), and *particulate matter* (PM) (Elgowainy et al. 2009; Jochem et al. 2015; Nealer and Hendrickson 2015). The survey of conventional studies is gathered in Table 16. Only a few of papers have focused on the impact of AFVs on air pollution. Furthermore, health effects are neglected in most of the studies. Only (Guo et al. 2010; Yang and He 2016) conducted the study while incorporating the effects of vehicles on health issues. However, the before-mentioned studies concentrate on only one country, China. Moreover, most of the papers investigate only one stage of vehicle's lifecycle, mostly usage. Therefore, there is a necessity to examine the gaps.

Table 16 Survey of conventional studies

Research	AFVs	LCA	Air pollution	Health effects	Multiple countries
Nonaka [9]	X	X			
Brady [10]	X		X		
Zhao [11]		X	X		
Romejko [12]	X				
Faria [13]	X	X			X
Guo [7]			X	X	
Sheng Yang [8]			X	X	
This research	X	X	X	X	X

This study uses a more systematic approach to obtain a complete picture of the environmental impact of EV's. The objective of the case study 1 is to compare the entire life cycle of EVs and GVs in multiple regions with a focus on GHG and non-GHG emissions and the cost of air pollution to the economy. LCA was applied to assess air pollution through the life cycle of the vehicles under two technology scenarios. We performed the assessment for three countries that show great interest in introducing and promoting EVs in their markets: China, Japan, and the United Kingdom (UK). Those countries have the highest sales and market share of EVs till 2015 (International Energy Agency (IEA) 2015c). China has the largest market for electric cars with over 200 000 new registrations yearly. However, In China, most of electricity is produced from coal and EVs could hinder health and the environment quality (Ji et al. 2012). Japan is most famous for its high-technology and the production Nissan Leaf, which is the world's best-selling EV (Nissan Official Website 2017). The United Kingdom is not a main automotive producer, but invites investment from manufacturers (fourth largest vehicle producer in Europe), moreover its electricity mix consist of high percentage of renewables (International Energy Agency (IEA) 2016a).

The results of this study can be used by governments and automotive companies to move toward sustainable manufacturing.

In this case study 2, we consider environmental leakage, which happens when rich country imports dirty products from developing countries. This phenomenon leads to displacement of emissions abroad and often an increase in the global pollution (Fæhn and Bruvoll 2009). According to (Ghertner and Fripp 2007), the consumption-based approach is necessary to calculate the impact of production activities. Hence, in this study, we quantify environmental leakage according to consumption-based approach and base the calculations on ‘who consumes the product’. Therefore, the objective of the case study 2 is that it estimates the health effects cost of EVs throughout the total lifecycle and compares it among several countries while taking into consideration environmental leakage. Additionally, Poland case is being investigated. Poland’s electricity is based on coal and the air pollution is high. Poland has just established an “Electromobility Development Plan for Poland”, which implies that till 2025 there will be a million EVs on the polish roads. The government of Poland is also interested in investment in automotive industry (Ministry of Energy of Poland 2017).

Section 2 describes the LCA model used for two case studies. Vehicle assumptions, scenarios, and the data used in the calculations are explained in Section 3.

6.2. LCA model

Life cycle assessment is a tool that has been used in most of the recent studies on the assessment and comparison of vehicles (Nonaka and Nakano 2010; Notter et al. 2010; Lucas et al. 2012; Hawkins et al. 2013; Egede et al. 2015). Life cycle assessment can identify the environmental impact of a product. The evaluation formula of baseline LCA is shown in Eq. (1-6).

$$LCA_{i,s,e,k}^{total}(y) = \left(LCA_{i,s,e,k}^{prod}(y) + LCA_{s,e,k}^{trans}(y) + LCA_{i,s,e,k}^{use}(y) + LCA_{i,s,e,k}^{EoL}(y)\right) \times R \tag{1}$$

$$LCA_{i,s,e,k}^{prod}(y) = \sum_{m} n_{m,k}(y) \times C_{i,s,k}(y) \times E_{e,m,k}(y) \times PH_e \tag{2}$$

$$LCA_{s,e,k}^{trans}(y) = F(y) \times E_{diesel}(y) \times PT_e \times D_k \tag{3}$$

$$LCA_{EV,s,e,k}^{use}(y) = \sum_{m} n_{m,k}(y) \times C_{EV,s,k}(y) \times E_{e,m,k}(y) \times PH_e \times M_k \tag{4}$$

$$LCA_{GV,s,e,k}^{use}(y) = J_{GV,s,e,k}(y) \times PL_e \times M_k \tag{5}$$

$$LCA_{i,s,e,k}^{EoL}(y) = \sum_{m} n_{m,k}(y) \times C_{i,s,k}(y) \times E_{e,m,k}(y) \times PH_e \tag{6}$$

i: vehicle type [GV/EV]

s: scenario [BAU/Tech. Adv.]

e: emission type [CO_2, NO_x, SO_2, PM]

k: country investigated (Japan/ China/ UK)

n: energy ratio (Japan/ China/ UK)

y: year [2016-2025]

m: type of energy used (coal, nuclear, gas, etc.)

J: permitted emissions for GV [kg per km]

C: energy consumption [kWh]

E: air emissions of CO_2, NO_x, SO_2, PM from energy production[kg per kWh]

J: permitted emissions for GV [kg per km]

M: mileage [km]

R: production rate [units]

F: energy used to transport one vehicle on a diesel MSD ship per km [kWh per km]

E_{diesel}: air emissions of NO_x, SO_2, PM from energy production in MSD ferry ship [kg per kWh]

D: distance in ferry transportation [km]

PH_e: Monetary damage conversion cost of high-height emissions for CO_2, NO_x, SO_2, (energy production) PM [€ per kg]

PL_e: Monetary damage conversion cost of low-height emissions cost (transportation) for CO_2, NO_x, SO_2, PM [€ per kg]

PT_e: Monetary damage conversion cost of ship transportation emissions cost for CO_2, NO_x, SO_2, PM [€ per kg]

$LCA_{i,s,e,k}^{total}$- total cost [€]

$LCA_{i,s,e,k}^{prod}$- cost in manufacturing phase [€]

$LCA_{i,s,e,k}^{trans}$ - cost in transportation [€]

$LCA_{i,s,e,k}^{use}$- cost in use phase [€]

$LCA_{i,s,e,k}^{EoL}$ – cost in End of Life phase [€]

The equation (1) presents the total cost of a lifecycle of vehicles. It is a sum of three stages, i.e. manufacturing, use phase and end of life of vehicles. Second equation outlines the cost of emissions from manufacturing stage. The equation (3) presents the transportation phase of vehicles on ships. The equation (4) and (5) describes the use phase of GVs and EVs. Final equation (6) defines the cost of End of Life stage of the vehicles.

The differences in the model are described in the below Sections.

The case study was conducted on Japan, China, Poland and the United Kingdom (UK). According to (International Energy Agency (IEA) 2015c), China, UK and Japan are the countries with the largest EV sales and market share till 2015. Moreover, China was the largest market for electric cars with over 200 000 new registrations (International Energy Agency (IEA) 2015c). However, in China, most of electricity is produced from coal and according to (Ji et al. 2012) EVs could hinder health and the environment quality (Ji et al. 2012). Japan is a country, which produces Nissan Leaf, the Nissan LEAF, which is the world's best-selling EV(Nissan Official Website 2017). The United Kingdom is not a main automotive producer, but invites investment from manufacturers, moreover its electricity mix consist of high percentage of renewables (International Energy Agency (IEA) 2016a). On the other hand, Poland's electricity is based on coal and the air pollution is high. Poland has just established an "Electromobility Development Plan for Poland", which implies that till 2025 there will be a million EVs on the polish roads. The government of Poland is also interested in investment in automotive industry (Ministry of Energy of Poland 2017).

In this chapter SO_2, PM and NO_x are investigated, because they are the main pollutants, which damage cost is the highest among all primary pollutants (Korzhenevych et al. 2014). GHG emissions are in 82.5% caused by CO_2 (U.S. Environmental Protection Agency 2017)). Moreover, there are international standards in road transportation for the emission of those pollutants (Korzhenevych et al. 2014).

6.2.1 Case study 1: GHG and non-GHG emissions

In this study, we used LCA to determine the GHG and non-GHG emissions at each stage in the life of a vehicle. Figure 29 presents an outline of the LCA. Red fields indicate the fields investigated in this part of the study.

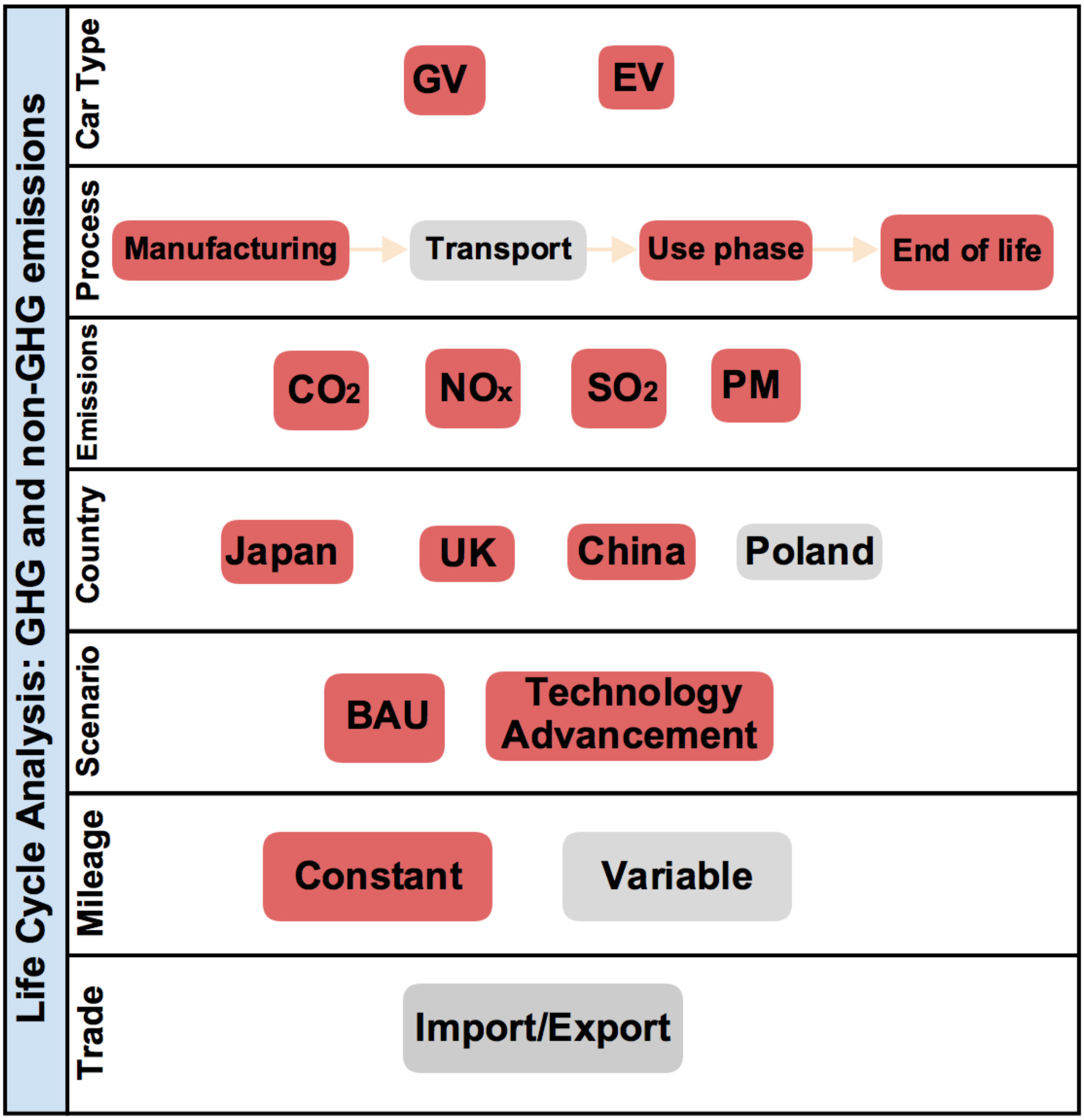


Figure 29 Outline of LCA1

The pollutants under consideration are those that cause the most damage to human health, such as those that contain fine particulate matter (PM), nitrogen oxides, and sulfur oxides (Korzhenevych et al. 2014). The manufacturing, use, and end-of-life phases are examined for CO_2, NO_x, SO_2, and PM. Under PM, we investigate the combination of PM_{10} and $PM_{2.5}$. The case study is conducted for Japan, China, and the UK that will produce and use EVs and GVs over a 10-year period (2016–2025).

In the analysis, two scenarios are explored. The first scenario, Business As Usual (BAU), does not assume a change in the energy mix or a technology improvement. Therefore, the data are constant for the years 2016–2025. The second scenario, Technology Advancement (Tech. Adv.), is intended to present the benefits of global technology advancement and the pathway of countries towards a more renewable-friendly energy mix in accordance with the suggestions from the IEA, presented in *World Energy Outlook 2015* (International Energy Agency (IEA) 2015a). Tech. Adv. considers technology improvements in electricity generation and thus a decrease in pollutant production; implementation of stricter emission standards for vehicles; an increase in the energy efficiency of manufacturing, use phase, and recycling of EVs; and an increase in renewables in the energy mix. In this case study, mileage is constant and amounts to 10,000km and transportation is not taken into consideration, that is why M= 10,000km and $LCA_{i,s,e,k}^{trans} = 0$.

6.2.2 Case study 2: Health impact of air pollution

The LCA method was used in Case study 2 to quantify the health impact of EVs during their manufacturing stage, transport, use phase and end of life stage. The case study was conducted in Japan, China, Poland and the United Kingdom. The picture below presents the outline of the LCA. In line with it, we calculate 16 cases of vehicle life cycle. In the picture J, CH, PL and UK stand for Japan, China, Poland and United Kingdom respectively. EVs are used during a 10-year period. Moreover, the scenarios for 2016 and 2025 are being investigated as well in order to compare the improvements in the technologies.

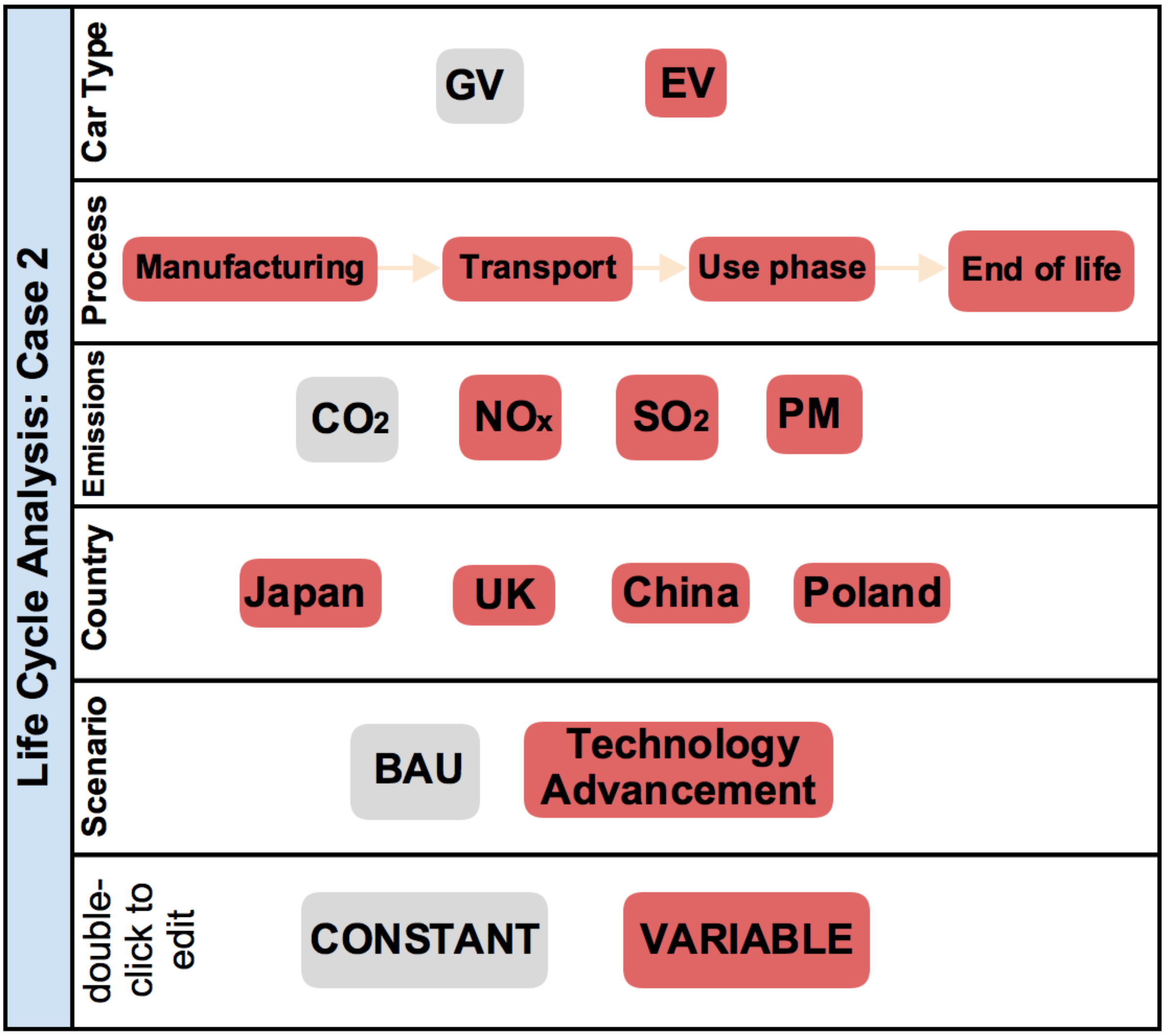


Figure 30 Outline of LCA2

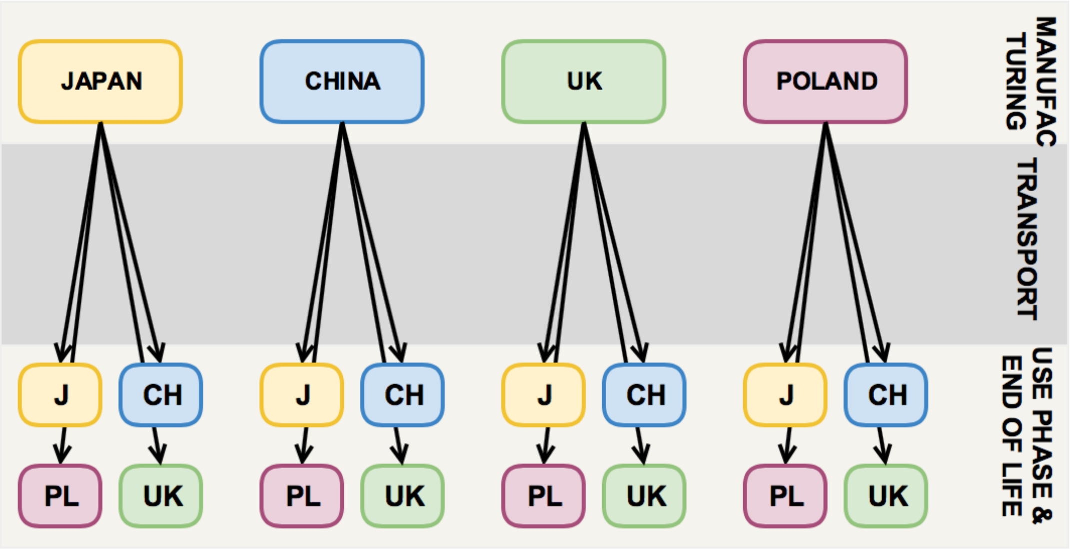


Figure 31 Import, export and transportation in LCA2

There are a couple off differences between LCA model in Case study 1 and 2. In this case study, transportation is taken into consideration, the model is calculated for Technology Advancement scenario only and moreover Poland is included in the calculations. In addition, the average mileage distance is not constant in this case. Furthermore, we are considering environmental leakage and therefore we use consumer-base approach (Ghertner and Fripp 2007), which assumes that consumers are bearing the full responsibility for the impacts of producing the goods they consume. Due to the above, we are taking into consideration the total emissions that were produced i.e. manufacturing and transportation and add them to the cost of the importing country. The changes and additional data gathered for this case study are defined in the below sections.

6.3. Vehicle assumptions and data analysis

6.3.1 Basic vehicle assumptions

There is a wide variety of EVs produced globally. However, in this study, we base our specifications on Nissan Leaf equipped with a 24-kWh battery. The model is available in all three markets and has high sales volume in UK and Japan. In China, the price of Nissan Leaf is high and sales are low, which is why the locally produced Chinese model, is more popular. The Chinese model is not available in other countries (Ayre 2016). In in this study we investigate a typical gasoline vehicle that is comparable in size to Nissan Leaf. We used the data collected by the Argonne National Laboratory from 35 plants located in the United States (Sullivan et al. 2010). Table 17 shows the main characteristics of EVs and GVs used in our analysis.

Table 17 Characteristics of vehicles

	EV	GV
Vehicle model	Nissan Leaf	Comparable average GV
Vehicle weight (kg)	1,493	1,532
Annual mileage (km)	10,000	10,000
Battery capacity (kWh)	24	-
Battery life (km)	150,000	-

Battery life varies across different regions and weather conditions (Nealer et al. 2015b). However, for this analysis, we assume that the battery lifespan is 150,000 km and that only one battery is needed during the 10-year period (Hawkins et al. 2013). We assume no battery replacement in the 10-year usage period, since the Nissan Leaf guarantees the battery for around 160,000 km (2016b). The location of EV introduction is set to urban areas because most EVs are used in urban areas for short-distance travel. These data are set for household cars and do not differentiate between EVs and GVs. However, in order to make the results comparable between the countries and the vehicle types, we assume an annual distance of 10,000 km for case study 1. Moreover, even if the driving distance varies, it will not significantly influence the final results because no battery replacement will be needed at distances below 150,000 km. For the case study 2, annual average vehicle mileage differs among the case study countries. For China it is 14,496 km (Chen 2005), for Japan 9,300 km (FIA Foundation 2003), UK 12,713km (Department for Transport 2015) and 8,257 km in Poland (Chlopek and Waskiewicz 2013). Since the data do not distinguish types of vehicles, we assume that the distance is same for all types of passenger vehicles. The energy efficiency of EVs was set to 0.20 kWh/km (Nealer et al. 2015b; Jochem et al. 2016) for the BAU scenario and 0.15 kWh/km for the Tech. Adv. scenario. The total weight of the GV assumed in this study is 1,532 kg and that of the EV is 1,569 kg, which basically consists of 1,275 kg plus an additional 294 kg of the lithium-ion battery (Aguirre et al. 2012).

6.3.2. Electric mix and emission cost

The energy mix data for the BAU scenario is based on data from the latest IEA report for September 2016 (International Energy Agency (IEA) 2016a); data for Japan, Poland and the UK are from 2015 and the newest data for China are from 2014. Table 18 presents the findings for the BAU scenario. We assume that the energy mix does not change and that the numbers are constant for the years 2015-2025.

Table 18 Electricity mix in BAU scenario

Electricity production by source in 2015 (%)				
	Japan	China	UK	Poland

Nuclear	0.93%	2.33%	20.85%	0.00%
Oil	8.95%	0.17%	0.54%	1.29%
Coal	33.77%	71.14%	22.76%	80.71%
Natural gas	38.94%	2.17%	29.53%	3.83%
Hydro	8.98%	18.70%	2.59%	1.48%
Wind	0.52%	2.46%	11.97%	6.57%
Biofuel and waste	4.12%	1.01%	9.52%	6.08%
Solar	3.79%	2.02%	2.24%	0.04%

At the 21st Conference of the Parties (COP21) (International Energy Agency (IEA) 2015b) meeting in 2015, all countries agreed under a legal framework to establish actions to decarbonize many sectors and combat air pollution. They committed to keep the global temperature increase well below 2°C and even try to limit it to 1.5°C. According to the IEA, actions to decarbonize the energy sector would cost about USD 9 trillion between 2016 and 2050 (International Energy Agency (IEA) 2015b). Investment in technology, cost reductions, and strong low-carbon policies in the energy sector will be needed to comply with those agreements.

In 2015, two reactors restarted in Japan after the Fukushima nuclear accident and according to Ministry of Trade, Economy and Industry (METI), the share of nuclear power will rise to about 22% by 2030 (Kakudo 2015). During the same time period, coal will reach 26%, LNG will reach 27%, and renewables will reach 24%. As a result of the accident, the energy supply mix changed dramatically in Japan. Imports of fossil fuels increased, which triggered higher prices for electricity and increased CO_2 emissions (International Energy Agency (IEA) 2016b). Before the Fukushima Daiichi nuclear accident, the Japanese energy roadmap was aiming at expanding nuclear energy's share to about 50% by 2030. Japan plans to reduce CO_2 emissions by 22% from the 2013 level (International Energy Agency (IEA) 2016b). Nuclear power in Japan is important to ensure energy security and decrease CO_2 emissions.

China has been investing heavily in the construction of nuclear and hydroelectric power plants in recent years. China has pledged to grow the share of non-fossil fuels in the energy mix to about 20% by 2030 and lower the carbon intensity of its GDP by about 60% from the 2005 level by 2030 (International Energy Agency (IEA) 2015a). According to the IEA scenario, China's coal share is forecasted to decline significantly to 50% by 2040. China's policy support will spur a rise in renewable energy to about 30% by 2040.

The EU 2030 framework targets the share of renewables to reach 27%, reduce GHG emissions by at least 40% below 1990 levels, and improve energy efficiency by 27% (International Energy Agency (IEA) 2015a). According to IEA estimates, coal's share in EU in 2040 would amount to 6% of its power generation.

In the Tech. Adv. scenario, we assume a gradual change in the energy mix starting in the year 2016. Table 19 presents the final electricity generation share in 2025, according to the estimates by the IEA (International Energy Agency (IEA) 2015a), provided in the "New Policies Scenario," which includes the countries' pledges towards environmental issues. IEA predicts scenario for Europe as a whole, which is an inaccurate scenario for Poland, since the electricity mix is based on coal. In view of this fact, we use the forecast conducted by the Polish government (Polish Ministry of Economy 2016).

Table 19 Electricity mix in Tech. Adv. scenario in 2025

Electricity production by source in 2025 (%)				
	Japan	China	UK	Poland
Nuclear	20.55%	7.87%	23.34%	6.47%
Oil	2.73%	0.07%	0.64%	1.27%
Coal	27.33%	57.39%	17.27%	67.34%
Natural gas	27.33%	6.03%	19.78%	7.92%
Hydro	8.58%	16.21%	11.85%	1.39%

Wind	1.41%	7.09%	15.63%	9.25%
Biofuel and waste	4.81%	2.92%	6.71%	5.79%
Solar	7.26%	2.41%	4.78%	0.57%

The external cost of air pollution and transportation has a considerable influence on the environment and society. In this section, we present the assumed damage values of those harmful factors for both electricity production and transportation.

According to the literature review performed by Becker et al., the cost of CO_2 emissions varies in several studies between €70 and €486 (Becker et al. 2012). In this study, the cost of CO_2 is set to a constant value of €120 per ton (Jochem et al. 2016) for all countries. The prices of other emissions from electricity production, based on the European average price (Korzhenevych et al. 2014), are also set as constants for a clear comparison between the three countries. Transportation costs were higher because emissions are located near the ground in dense, urban areas. The data used in this study correspond to the values evaluated in the Ricardo-AEA study (Korzhenevych et al. 2014) conducted for the European Commission. Emission prices for maritime transportation were calculated as an average price of the available damage cost of pollutants in sea regions (Korzhenevych et al. 2014). Those cost factors quantify the effects of emissions on health, materials, and crop losses (Table 20).

Table 20 Emissions cost in €

	Emissions cost		
	Electricity production (€ per ton)	Transportation (city) (€ per ton)	Transportation (maritime) (€ per ton)
CO_2	120	120	-
NO_x	8,050	10,640	3,688
SO_2	9,350	10,241	5,613

PM	18,850	270,178	15,913

6.3.3. Manufacturing

This study adapts a gate-to-gate analysis of manufacturing processes, similar to the studies by Sullivan and Hawkins (Sullivan et al. 2010; Hawkins et al. 2013). LCA starts at the manufacturing gate when materials in the form of pellets, billets, and ingots arrive at the factory. Later, the parts are fabricated and eventually assembled into vehicles. During this time, transformation processes such as metal and polymer forming, assembling and fastening, and painting take place (Sullivan et al. 2010). In these calculations, we do not include raw material extraction or production of the basic materials. However, the energy necessary for operating the plant, lighting, heating, and air conditioning is included in the analysis.

In order to produce GVs, 33,924 MJ of energy is needed, whereas the base of an EV (without the battery) needs 38,094 MJ plus additional energy for the production of the battery (Sullivan et al. 2010). Those numbers are constant for each country and scenario. In this study, we assume a yearly production of 50,000 units of EVs and GVs over a 10-year period.

Battery production

The greatest difference between the manufacturing of GVs and EVs is the production of lithium-ion batteries (Nealer et al. 2015b). Battery production is an energy intensive process and the estimates vary depending on the battery type and the region in which it is produced (Samaras and Meisterling 2008; Elgowainy et al. 2009; Lewis et al. 2012; Buekers et al. 2014). According to the estimates gathered in “Cradle to Grave” (Nealer et al. 2015b), the production of a 294-kg battery (including material, production, and manufacturing) requires between 7,569 and 12,353 kWh of energy. Therefore, we set our assumption at the mid-level of 10,000 kWh. According to Buekers (Buekers et al. 2014) and Lewis (Lewis et al. 2012), it is possible that more energy is used in a battery's production process than during its usage depending on the energy mix. In total, the production of the whole EV with a 294-kg battery requires 74,094 MJ (Sullivan et al. 2010) in the BAU scenario.

Previous studies suggest that the outlook for the battery industry looks promising with the lower battery costs, higher performance, and stronger alliances (Poullikkas 2015; Zhao et al. 2015; International Energy Agency (IEA) 2015c). First, in the Tech. Adv. scenario, we include the improvements in the battery recycling technology, which lead to a 15% decrease in energy consumption during battery manufacturing (Hendrickson et al. 2015; Nealer et al. 2015b). Then, we assume a further 20% decrease in energy used for production of a 294-kg battery, which is "very" feasible to achieve, because lower estimates for battery production found in other sources are at a similar level (Division 2010; Lewis et al. 2012).

6.3.4. Use phase

BAU scenario

EVs and GVs create emissions at different times: the pollution attributed to EVs is produced indirectly in factories, whereas GVs pollute directly during the use phase. Emission standards have been set for GVs by governments and institutions for the production of new vehicles.

The *Euro VI* standard, introduced in 2014, is being implemented by the UK and Japan (Minjares and Williams 2016) and will soon be implemented in China (Yang et al. 2015). It presents maximum emission rates for pollutants such as NOx and PM. SO_2 is not included in the *Euro VI* standard because SO_2 is usually not emitted from well-refined gasoline. The emissions for GVs during the use phase in the BAU scenario, based on *Euro VI*, are presented in **Table 5**. According to the European law, new vehicles registered in the EU cannot emit more than an average of 130 g of CO_2 per km. Similar laws are also in effect in Japan and

China. Therefore, CO_2 emissions for GVs in the BAU scenario are set as follows: 166 g/km for China (Transport Policy Portal 2013), 130 g/km for the UK, and 125 g/km for Japan (Mock and Yang 2014). Permitted emission levels are presented in Table 21.

Table 21 Emissions from GVs in BAU scenario

	Emission (g/km)		
	China	Japan	UK
CO_2	166	125	130
NO_x	0.06	0.06	0.06
SO_2	-	-	-
PM	0.0045	0.0045	0.0045

The volume of emissions coming from EVs during the use phase depends on the energy efficiency of the battery, energy mix of the country, and air pollution emissions per kWh. In the BAU scenario, we assume that an EV requires 0.2 kWh per km. Air pollutant emissions per kWh of electricity production are set as constant for the three countries and for both scenarios. The data for pollutants are adapted from the study by Buekers (Buekers et al. 2014). However, the emissions generated from coal are different between the countries and scenarios because different energy efficiencies and technologies are used in each country. We used the higher estimates calculated by the IEA for NO_x, SO_2, PM (International Energy Agency 2012), and CO_2 (Hussy et al. 2014). Emissions from electricity generated from coal for Poland were taken from IEA (IEA Clean Coal Centre 2015). The government implemented new emission standards for coal from 2016. The data concerning emissions coming from electricity production are presented in Tables 22 and 23.

Table 22 Emissions from coal power plants

Emission (kg/kWh)

	China	Japan	UK	Poland
CO_2	9.55.E-01	8.36.E-01	8.73.E-01	9.55.E-01
NO_x	1.90.E-03	4.80.E-04	9.00.E-04	2.40.E-03
SO_2	6.00.E-03	3.30.E-04	1.00.E-03	6.60.E-03
PM	4.50.E-04	4.20.E-05	3.50.E-05	2.10.E-04

Table 23 Emissions from electricity production

	Emission (kg/kWh)			
	NO_x	SO_2	PM	CO_2
Nuclear power plant	4.27.E-05	6.86.E-05	2.34.E-06	1.21.E-02
Light oil gas turbine	6.51.E-04	9.90.E-04	1.28.E-05	8.53.E-01
Hard coal*	5.98.E-04	3.34.E-04	1.76.E-05	6.19.E-01
Natural gas	1.95.E-04	1.38.E-04	3.56.E-06	3.73.E-01
Waterpower	7.57.E-05	2.30.E-05	5.28.E-05	1.22.E-02
Wind	2.60.E-05	2.76.E-05	6.29.E-06	9.08.E-03
Biomass	1.76.E-03	1.43.E-04	4.86.E-05	1.80.E-02
Solar	1.12.E-04	1.68.E-04	2.90.E-05	5.35.E-02

Technology Advancement scenario

We assume that the *Euro VII* standard will come to life in 2020 and that the emissions for GVs will be downgraded considerably. Experts predict that *Euro VII* will impose half of the *Euro VI* emissions for NO_x (Tinham 2016). Similar standards will be implemented in the US. In the US, especially in California, the standards are more stringent than in the EU and we assume the US Federal Tier 3 and California LEV III standards for the years 2020-2025 for PM and NO_x (Delphi 2013). Further CO_2 reductions are supposed to be implemented in 2020 (in the EU in 2021), and the amount of the emission limits would be 125 g/km for China, 95 g/km for the UK and Poland, and 105 g/km for Japan (Mock and Yang 2014). The data is presented in Table 24.

Table 24 Emissions from GVs in Tech. Adv. scenario

Emission (g/km)			
	China	Japan	UK
CO_2	125	95	105
NO_x	0.03	0.03	0.03
SO_2	-	-	-
PM	0.0019	0.0019	0.0019

In the Tech. Adv. scenario, we assume that EV energy efficiency slowly increases from a value of 0.20 kWh in 2015 to 0.15 kWh in 2025. In compliance with the implementation of new policies and emission standards, technologies such as advanced ultra-supercritical (A-USC), integrated gasification combined cycle (IGCC), and integrated gasification fuel cell (IGFC) are planned to be introduced in those three countries. The average CO_2 emissions produced by the above-mentioned technologies are 670, 670–740, and 500–550 g/kWh, respectively (International Energy Agency 2012). Japan plans to introduce new plants with the IGCC technology, which emit about 670–740 g/kWh and to start implementing IGFC before 2030. That is why we set 700 g/kWh as a benchmark. For the UK and China, emissions are set to 750 and 800 g/kWh as feasible options in compliance with the international pledges for minimizing emissions. The data for NO_x, SO_2, and PM were taken from the policy options from (International Energy Agency 2012) for non-GHG emissions and from (International Energy Agency 2016) for China. China set new standards to limit the emissions from coal plants: for NO_x, the limit is 100 mg/m^3, for SO_2 it is 100 mg/m^3, and for PM it is 30 mg/m^3 for new plants (International Energy Agency 2016). The future emissions from electricity generated from coal for Poland were adjusted to the UK levels. Table 25 presents the data for emissions from coal generation in 2025.

Table 25 Emissions from coal power plants in 2025

Emission (kg/kWh)

	China	Japan	UK	Poland
CO_2	8.00.E-01	7.00.E-01	7.50.E-01	8.00.E-01
NO_x	4.20.E-04	2.10.E-04	2.10.E-04	2.10.E-04
SO_2	4.20.E-04	6.00.E-05	6.00.E-05	6.00.E-05
PM	1.00.E-04	2.00.E-05	2.00.E-05	2.00.E-05

6.3.5. End of life

According to the literature, emissions produced during vehicle disposal are not significant for GVs or the main bodies of EVs (Hawkins et al. 2013; Nealer and Hendrickson 2015; Nealer et al. 2015b). We assume that the disposal of EVs and GVs differs only in the disposal of the EV battery. The energy requirement for the disposal of an GV and the main body of an EV is set to 1,297.33 MJ of energy (Aguirre et al. 2012). Battery recycling is a relatively new technology for EVs and it is difficult to estimate the cost because battery vehicles are still a novelty on the global market. According to Aguirre (Aguirre et al. 2012), it is cheaper to use virgin battery material than recycled material because the recycling of batteries is more energy intensive. Based on their findings, we use a benchmark of 31 MJ/kg for battery recycling in the BAU scenario. The gathered data are presented in Table 26.

Table 26 Energy production from end-of-life phase

End of life energy production (kWh)		
	GV	EV
Main body	360.37	360.37
Battery	-	2531.67
Total	360.37	2892.04

Nealer et al. suggest that there is a potential for reducing the emissions from battery production in the future (Nealer et al. 2015b). In the Tech. Adv. scenario, we assume that battery recycling technology will improve and the battery will be recycled, which will cause a 15% (Hendrickson et al. 2015; Nealer et al. 2015b) reduction in energy consumption during battery manufacturing. Moreover, we assume a 20% reduction in battery production and disposal as an aftermath of technology advancement.

6.3.6. Transport

Global transport of large quantities of new vehicles is primarily carried by ships. We calculate the emissions produced during transportation from the main port of dispatch to the main port of arrival. For Japan, the port of entry is Yokohama, for the UK is Bristol, for China is Shanghai and Gdańsk for Poland. The distance is calculated according to data from (Shipping Quotation Platform 2017). The assumption is, that the shipping takes place on Roll On Roll Off (RORO) base (Belson 2012), which capacity is 7,200 EV vehicles (Toyofuji Shipping Co Ltd. 2017). This type of vessel is used to due to the fact that most of the vehicle producers use this type of shipment in order to maximize capacity and minimize time. The g/kWh emissions of medium speed diesel vessel (MSD) were taken from (Moreno-Gutiérrez et al. 2015) and the energy cost in kWh/t-km of freight-transport was based on (McKay 2008).

6.3. Summary

In this chapter methods for environmental and social evaluation of AFVs were presented. Life Cycle Assessment has been chosen as a method to calculate both environmental and social impact of AFVs. The proposed LCA model takes into different stages of AFV's i.e. manufacturing, use, end of life and transportation. Mathematical mode, two case studies, two scenarios and parameter values are described in details.

7. SIMULATION RESULTS WITH LCA MODEL

7.1. Case 1 with environmental issues

Emission levels were computed for four pollutants under two technology scenarios for both EVs and GVs.

7.1.1. Life cycle assessment for vehicles produced in 2016

Results for vehicles produced in 2016 and estimated to be used over a 10-year period until 2025 are presented in Tables 27-32.

Table 27 Total LCA for 10 years of use for vehicles produced in 2016 in BAU - Japan

Japan	Emissions (kg)			
	NO_x	SO_2	PM	CO_2
GV				
Manufacturing	3.58	2.53	0.23	4,786.22
Use phase	6.00	0.00	0.45	12,500.00
End of life	0.14	0.10	0.01	183.04
Total	9.72	2.63	0.69	17,469.26
EV				
Manufacturing	7.83	5.53	0.51	10,454.20
Use phase	7.61	5.38	0.49	10,158.58
End of life	1.10	0.78	0.07	1,468.95
Total	16.54	11.69	1.07	22,081.73

Table 28 Total LCA for 10 years of use for vehicles produced in 2016 in BAU – China

China	Emissions (kg)			
	NOx	SO2	PM	CO2
GV				

Manufacturing	13.12	40.37	3.12	6,529.95
Use phase	6.00	0.00	0.45	16,600.00
End of life	0.50	1.54	0.12	249.73
Total	19.63	41.92	3.69	23,379.68
EV				
Manufacturing	28.67	88.18	6.82	14,262.91
Use phase	27.86	85.69	6.63	13,859.60
End of life	4.03	12.39	0.96	2,004.12
Total	60.55	186.26	14.41	30,126.64

Table 29 Total LCA for 10 years of use for vehicles produced in 2016 in BAU – UK

UK	Emissions (kg)			
	NO_x	SO_2	PM	CO_2
GV				
Manufacturing	4.24	2.91	0.16	3,018.04
Use phase	6.00	0.00	0.45	13,000.00
End of life	0.16	0.11	0.01	115.42
Total	10.40	3.03	0.62	16,133.46
EV				
Manufacturing	9.26	6.37	0.35	6,592.10
Use phase	9.00	6.19	0.34	6,405.69
End of life	1.30	0.89	0.05	926.27
Total	19.56	13.45	0.74	13,924.06

Table 30 Total LCA for 10 years of use for vehicles produced in 2016 in Tech. Adv. Scenario - Japan

Japan	Emissions (kg)			
	NO_x	SO_2	PM	CO_2
GV				
Manufacturing	2.23	1.10	0.15	3,062.51
Use phase	3.00	0.00	0.19	10,500.00
End of life	0.09	0.04	0.01	117.12
Total	5.32	1.14	0.35	13,679.63
EV				
Manufacturing	4.12	2.03	0.28	5,649.21
Use phase	3.55	1.75	0.24	4,875.05
End of life	0.56	0.28	0.04	767.13
Total	8.23	4.05	0.57	11,291.39

Table 31 Total LCA for 10 years of use for vehicles produced in 2016 in Tech. Adv. scenario – China

China	Emissions (kg)			
	NOx	SO2	PM	CO2
GV				
Manufacturing	3.06	2.54	0.65	4,595.23
Use phase	3.00	0.00	0.19	12,500.00
End of life	0.12	0.10	0.02	175.74
Total	6.18	2.64	0.86	17,270.97
EV				
Manufacturing	5.65	4.68	1.20	8,476.52
Use phase	4.87	4.04	1.03	7,314.91
End of life	0.77	0.64	0.16	1,151.06
Total	11.29	9.36	2.39	16,942.49

Table 32 Total LCA for 10 years of use for vehicles produced in 2016 in Tech. Adv. scenario - UK

UK	Emissions (kg)			
	NO_x	SO_2	PM	CO_2
GV				
Manufacturing	2.12	0.80	0.16	2,055.48
Use phase	3.00	0.00	0.19	9,500.00
End of life	0.08	0.03	0.01	78.61
Total	5.21	0.83	0.35	11,634.09
EV				
Manufacturing	3.92	1.47	0.29	3,791.62
Use phase	3.38	1.27	0.25	3,272.02
End of life	0.53	0.20	0.04	514.88
Total	7.83	2.94	0.58	7,578.52

The results reveal that CO_2 emissions during the manufacturing and use phases of EVs in all countries in the BAU scenario are at similar levels. For example, for Japan, it is 10,454 kg of CO_2 during manufacturing and 10,158 kg in the use phase. During the manufacturing phase, EVs are more environmentally intensive than GVs. Those findings support the results of a previous study conducted by Hawkins et al. (Hawkins et al. 2013) . The substantial difference between the CO_2 emissions from GVs and EVs is attributed to battery manufacturing. They amount to 6.93 kg in China, 5.05 kg in Japan, and 3.2 kg in the UK. In the Tech. Adv. scenario, they are 5.58 kg, 4.07 kg, and 2.57 kg for each of the three countries, respectively. At the same time, according to Argonne's report (Sullivan et al. 2010), CO_2 emissions are around 2.72 kg and those in Hawkins et al. (Hawkins et al. 2013) are 4kg and 4.62 kg. Moreover, the results suggest that only in the UK are the total CO_2 emissions of EVs lower than those of GVs. This could be linked to the large share of renewables in the UK and low emissions during electricity production from coal. In China, producing and using EVs does not improve CO_2 emissions. Instead, it exacerbates the pollution in the BAU scenario because of the widespread use of coal-fired power plants. The research conducted by Jochem et al. also states that EVs do not automatically decrease CO_2 emissions (Jochem et al. 2015). Even though Japan has the lowest emissions from coal burning, the total LCA is still more favorable for GVs. In a prior study by Nonaka et al., EVs in Japan emit less CO_2 than GVs (Nonaka and Nakano 2010). Japan changed its electricity mix after the Fukushima Daiichi accident and more electricity has been produced from coal, oil, and natural gas since then.

The results show that CO_2 emissions during the use phase of EVs for both scenarios are lower than for GVs and they significantly decrease in the Tech. Adv. scenario. Those findings support the results of Brady and Mahony (Brady and O'Mahony 2011) on the emissions during the use phase of EVs.

The current study found that the end-of-use phase of EVs accounts for about 5% to 6% of the total CO_2 emissions in both scenarios. These results differ from the study by Aguirre et al. (Aguirre et al. 2012), in which the disposal of EVs accounts for only 1% of the total CO_2 emissions. However, the figure is low in (Aguirre et al. 2012), because the study included battery recycling as a subset of the battery lifecycle.

Our results indicate that the total emissions of NO_x, SO_2, and PM are higher for EVs than for GVs in both scenarios. There are two reasons for this: First, in 2016, the production of EVs required twice as much energy as the production of GVs because battery production is energy intensive. Second, indirect EV emissions are higher during the use phase, related to the electricity production in power plants. GVs emit less as a result of high emission standards for new vehicles set by the countries in this study. Other results consider the emissions of SO_2. In the BAU scenario, a single EV produces over 183 kg of SO_2 during its 10-year life cycle in China, whereas in Japan it is only 11.5 kg and in the UK it is 13.24 kg. High emissions in China are the consequence of substantial pollution during electricity production in coal-fired power plants. In the Tech. Adv. scenario, all countries improve their electricity mix and advanced technologies are introduced in coal-fired power plants. Therefore, SO_2 emissions for EVs in China drop by about 37% from the BAU scenario. In Japan, total pollution decreased between 19% and 26%, 18% and 37% in China, and 11% and 32% in the UK.

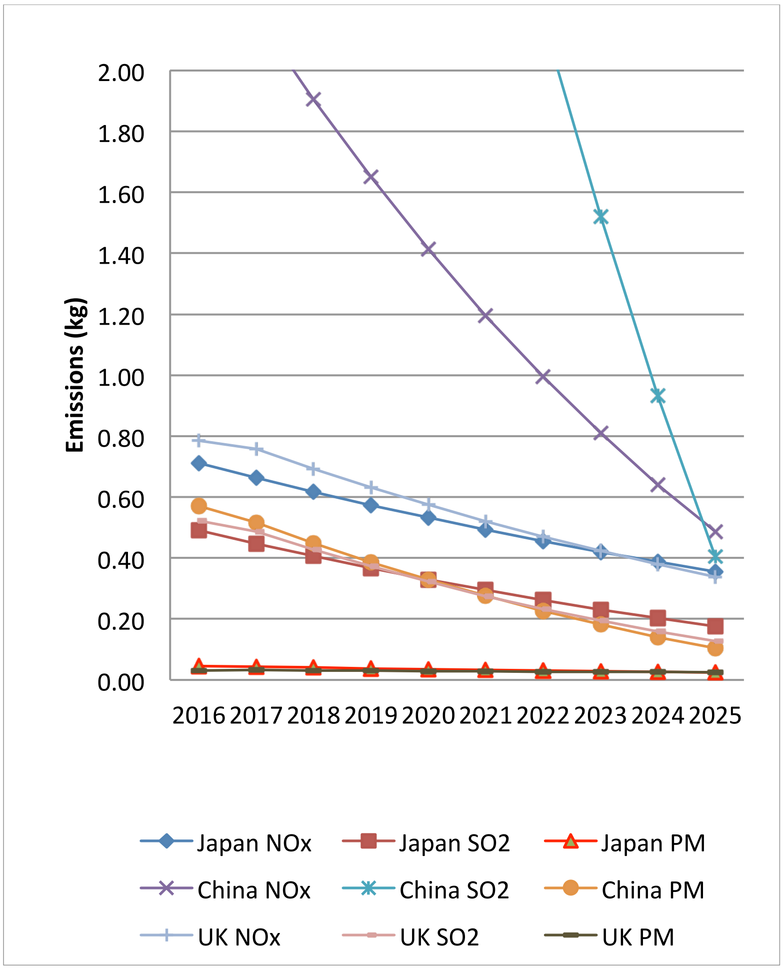


Figure 32 EV emissions for 10,000 km for Tech. Adv. scenario between 2016 and 2025.

Figure 32 shows plummeting yearly emissions in the use phase of EVs over the years in the Tech. Adv. scenario. The comparison of the results from both scenarios show that the most significant decrease in emissions took place in the use phase of EVs in all three countries over a 10-year period.

Although the emissions of NO_x, SO_2, and PM from both GVs and EVs decrease over the duration of the Tech. Adv. scenario, the volume of those pollutants is still higher for EVs. This LCA shows, that it is counterproductive to introduce EVs in countries where electricity is produced from coal or oil and those findings are consistent with the results of Hawkins et al. (Hawkins et al. 2013).

7.1.2. Life cycle assessment for vehicles produced in 2025

This case presents vehicles produced in 2025 and used for 10 years to better illustrate the technology advancement over time. Figure 33 presents the total CO_2 emissions for the Tech. Adv. scenario.

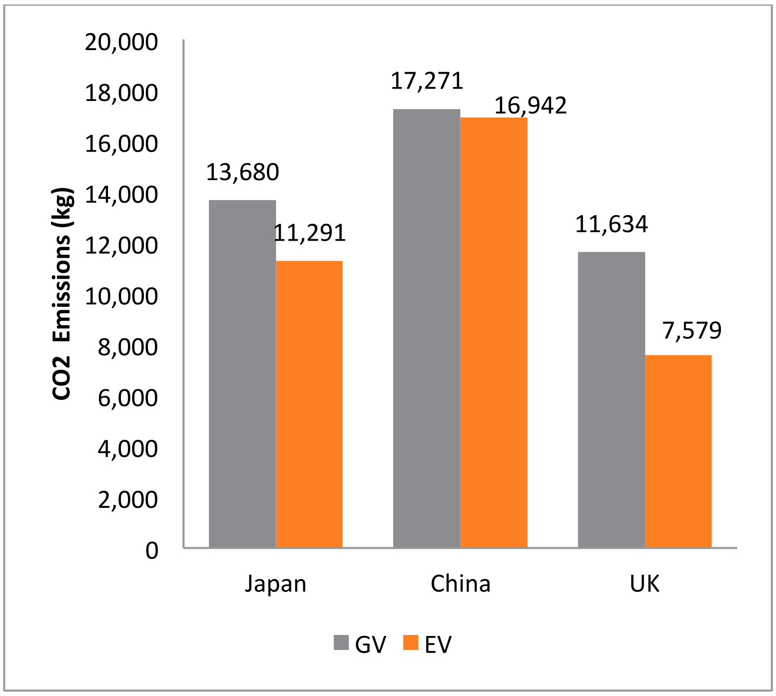


Figure 33 CO_2 emissions for Tech. Adv. scenario.

Under the Tech. Adv. scenario, pollutant levels decrease significantly for EVs and total CO_2 emissions for those vehicles are lower than for GVs in all countries. A substantial discrepancy is recorded for the UK, where the CO_2 emissions for GVs are 11,634 kg and only 7,469 kg for EVs.

Figures 34-36 illustrate the emissions for the BAU and Tech. Adv. scenarios for EVs produced in 2025.

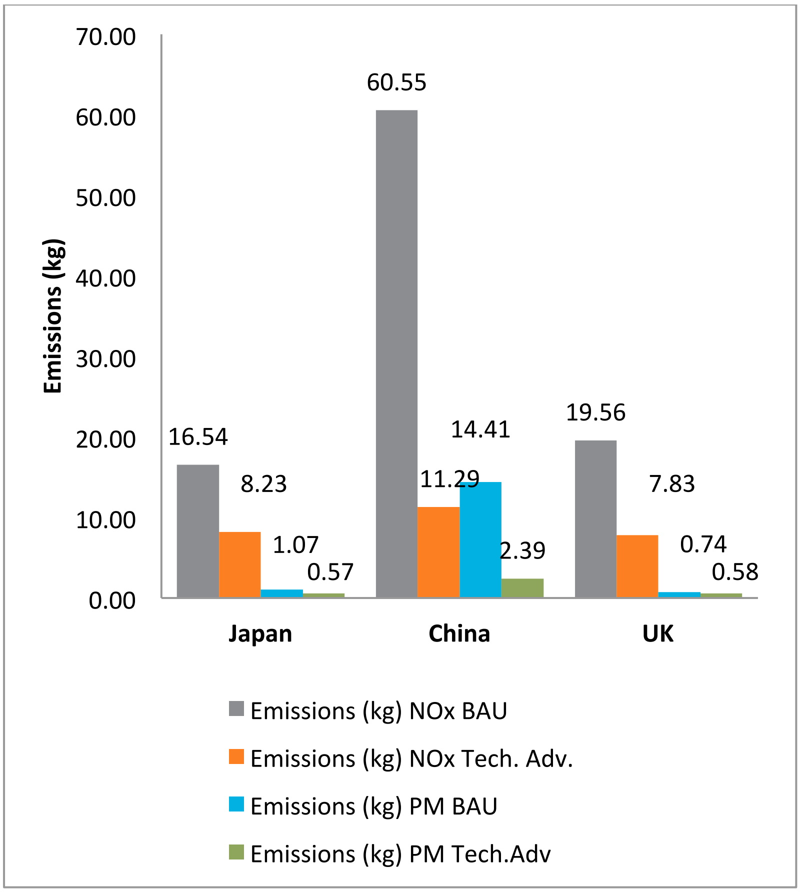


Figure 34 NO_2, PM emissions for Tech. Adv. scenario.

In this case, the greatest decreases are recorded for emissions in China because of the improvements in technology. China is introducing carbon capture and storage (CCS) technology in its plants and invests heavily in renewables. The UK is experiencing further decreases as a result of energy efficiency improvements and limited coal use in electricity production. In Japan, the reduction is connected with the reintroduction of nuclear power and an increase of renewables in the energy mix.

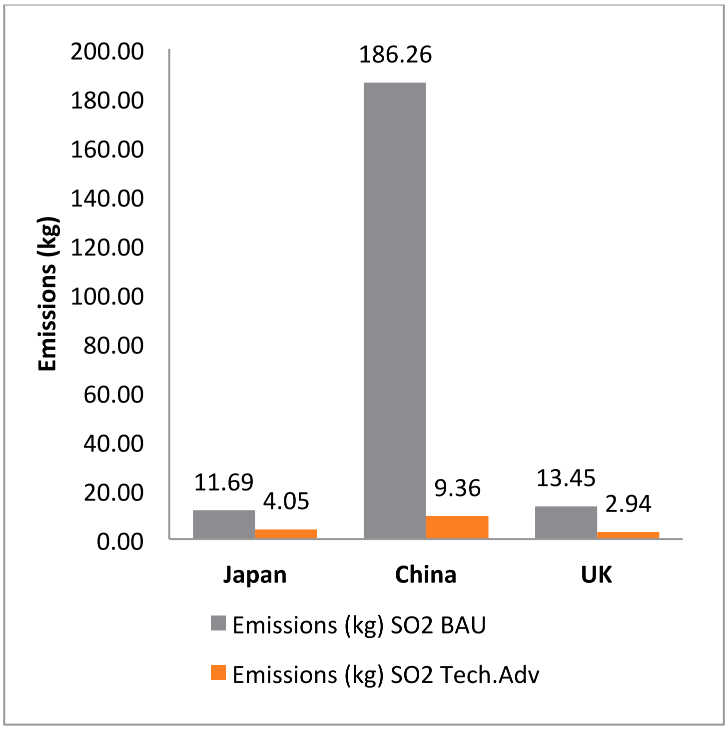


Figure 35 SO_2 emissions for Tech. Adv. scenario.

The findings of the current study are consistent with those of Nichols et al., who found that the PM, NO_x, and SO_2 emissions from EVs are greater than those from GVs in a coal-based electricity mix (Nichols et al. 2015). Moreover, both studies suggest that SO_2 emissions are considerably higher for EVs.

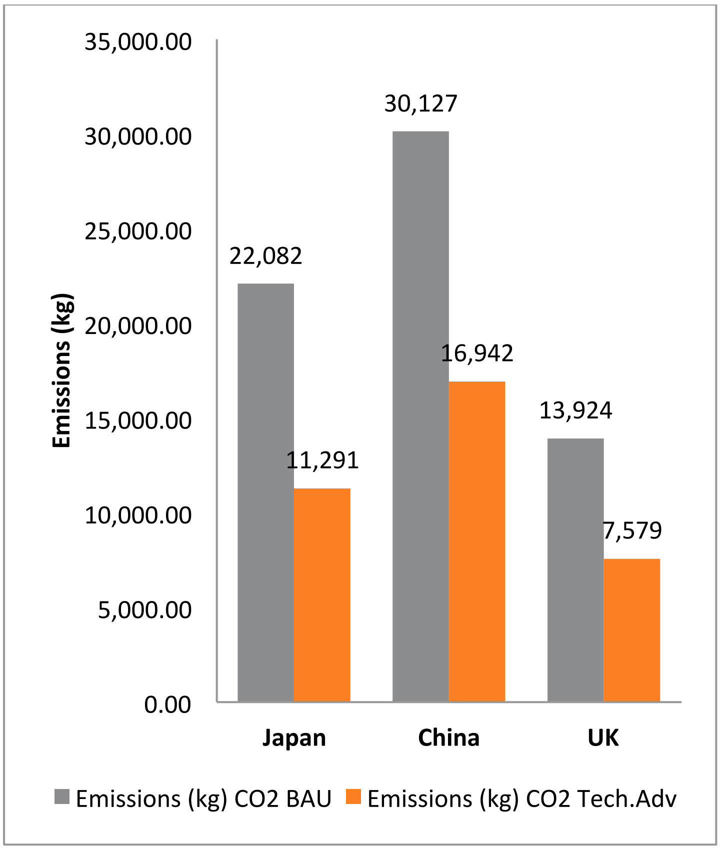


Figure 36 CO_2 emissions for Tech. Adv. scenario and BAU scenario.

The total emissions of EVs in Tech. Adv. scenario are lower than GVs emissions in the BAU scenario. However, it is important to note, that those results are feasible if the commitments of the regions to improve the electricity mix and to lower the emissions will be met. We believe, that those pledges should be fulfilled without difficulties since the countries follow the path of the already-established guidelines. In the study, we also expect the further improvements in the battery technology, however previous studies forecast the technology advancement as well (Lewis et al. 2012; Hendrickson et al. 2015; Poullikkas 2015; Zhao et al. 2015; International Energy Agency (IEA) 2015c).

7.1.3. Total cost of emissions

Table 17 shows the total cost of emissions for both scenarios. We assume that 50,000 vehicles are produced each year and used until the year 2025.

The findings in Table 33 suggest that only in the UK is the cost of total emissions for EV lower than for GVs in both scenarios. In the BAU scenario, EV pollution costs almost twice as much as that from GVs. However, the cost of EV emissions in the Tech. Adv. scenario drops from €3 billion to €1.3 billion. A similar tendency is observed in Japan. Note that EV vehicles produced in 2024 will only be used until 2025. Since production of those EVs is energy-consuming and their use phase is short, the full benefits of EVs cannot be enjoyed in this case (Buekers et al. 2014; Nealer et al. 2015b).

Table 33 Total air pollution cost

Total LCA cost	Cost (€)		
	Japan	China	UK
GV in BAU	1,170,411,356	1,776,855,269	1,094,146,944
EV in BAU	1,456,195,487	3,057,888,214	983,991,824
GV in Tech.Adv.	646,461,535	939,395,540	538,613,896
EV in Tech.Adv.	780,620,458	1,408,200,951	530,051,030

7.2. Case 2 with social issues

The comparisons of results for the 16 cases of vehicle life cycle are presented in Fig. 37 and Fig. 38 below.

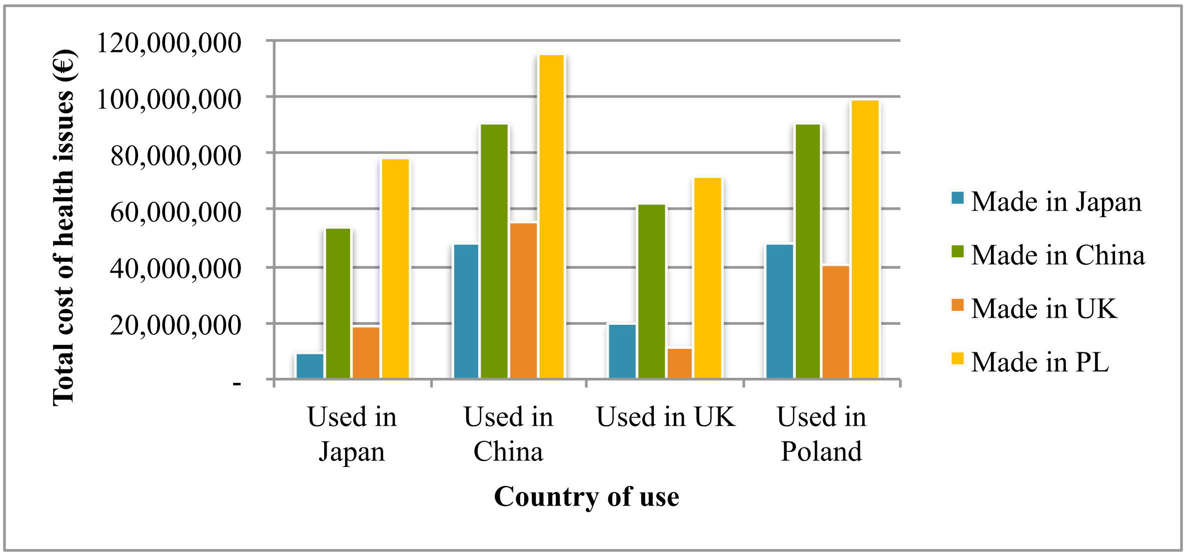


Figure 37 Total health cost associated with EV production, transportation and use (production in 2016)

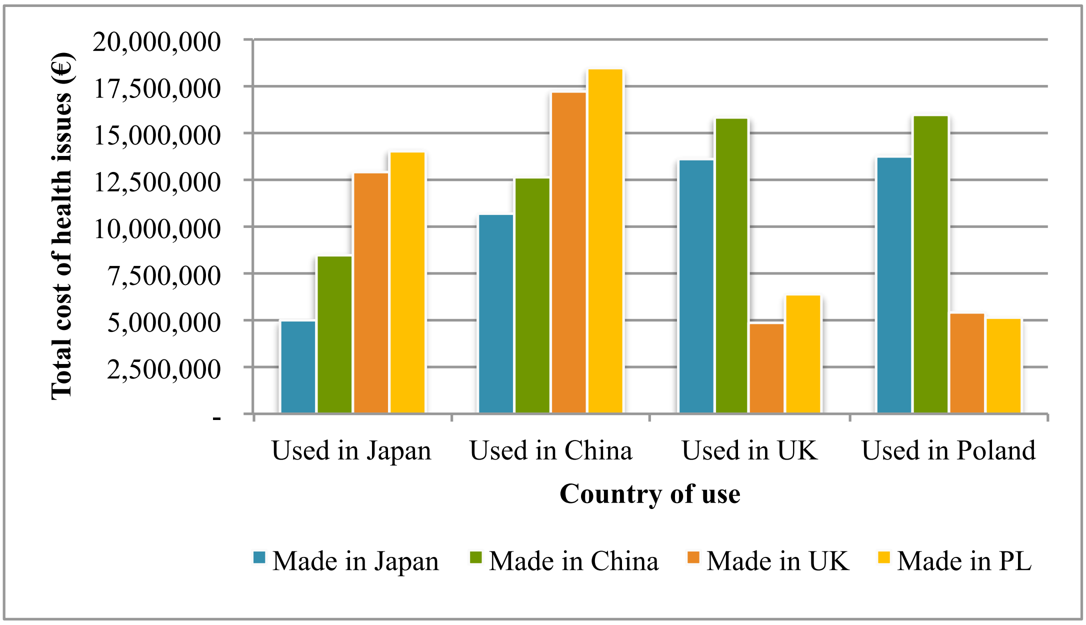


Figure 38 Total health cost associated with EV production, transportation and use (production in 2025)

The findings from Fig. 37 and Fig. 38 clearly present the fact that if we consider environmental leakage, import and export of EVs is not justified in some situations e.g.

where emissions during manufacturing are high or the distance between the countries is substantial.

According to the outcome of the research, the production and use of vehicles in the Japan contribute to the lowest health cost among all 16 cases analyzed in 2016 and it is UK in 2025. Provided that, it would be advised to set additional production of EVs in the UK due to the advantageous electricity mix and the proximity to other European markets. It is seen, from the **Fig. 2**, that for Poland, the apt solution would be to import the EVs from the UK in 2016. In this situation, the total health cost that Poland would have to bear stands at around €40M. In contrast, there was a 95% decrease in the case of the production and use of the EVs in Poland from 2016 to 2025. The slump of the total monetary cost can be explained by the fact that improvement in electricity production technologies and the change of the electricity mix in Poland takes place. In addition, European Union imposes new standards emission for electricity generation. Moreover, the driving distance in Poland is shorter than in the UK. However, for the 2025 scenario, the total cost for EVs made and used in Poland and the EVs produced in the UK and transported to Poland stands at the similar level. In China, for both 2016 and 2025 scenario, the most appropriate solution would be to import the EVs from Japan due to the short distance and the lower emissions of pollutants in Japan.

Moreover, in Japan the cost of LCA would have been expected to be lower. This has a reflection in the change of electricity mix in Japan after Tohoku Earthquake in 2011. Instead of nuclear energy, Japan is using a higher percentage of gas and coal for electricity generation. In 2025 in all cases, the total monetary cost of health diseases drops dramatically due to significant improvement in electricity production, technology efficiency of vehicle and battery production, and new standards for air pollution. The most substantial decrease in terms of value can be noted in the case of producing the EVs in Poland and exporting them to China. This case scenario is worth around €115M in 2016 and no more than €18.5M in 2025.

Another interesting aspect that emerges from analyzing the data is that during the maritime transportation the emission of air pollutants is significant. The analysis showed that only the transportation of an EV from Japan to Poland in 2016 accounted for almost 35% of total lifecycle emissions of NO_x 18% of SO_2 and 59% of PM. In terms of the import of an EV from Japan to the UK in 2016, those results were even higher and amounted to 30% of NO_x, 43% of SO_2 and 76% of PM. The result from this study can be substantiated by the data from (Vidal 2009), which shows that a ship can emit around 5,000 tons of SO_2 annually. The author of the previous-mentioned study asserts that one container ship can produce “almost the same amount of cancer and asthma-causing chemicals as 50M cars”.

Figure 39 Emission usage for EVs made in Japan, transported on diesel oil ships and used in Poland (Made in 2016, 10 years usage)

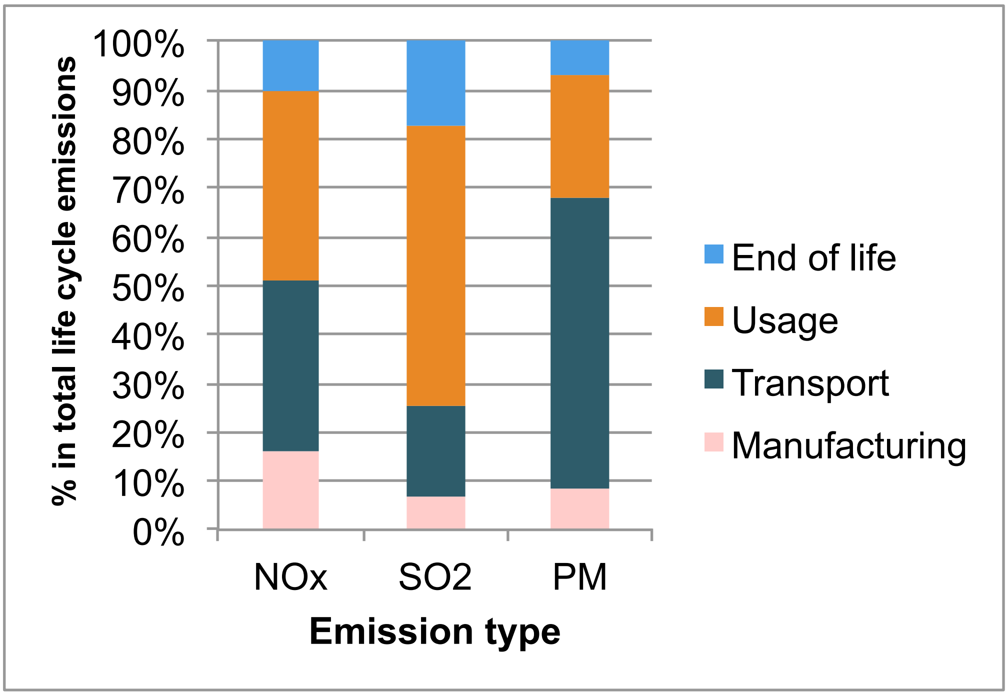
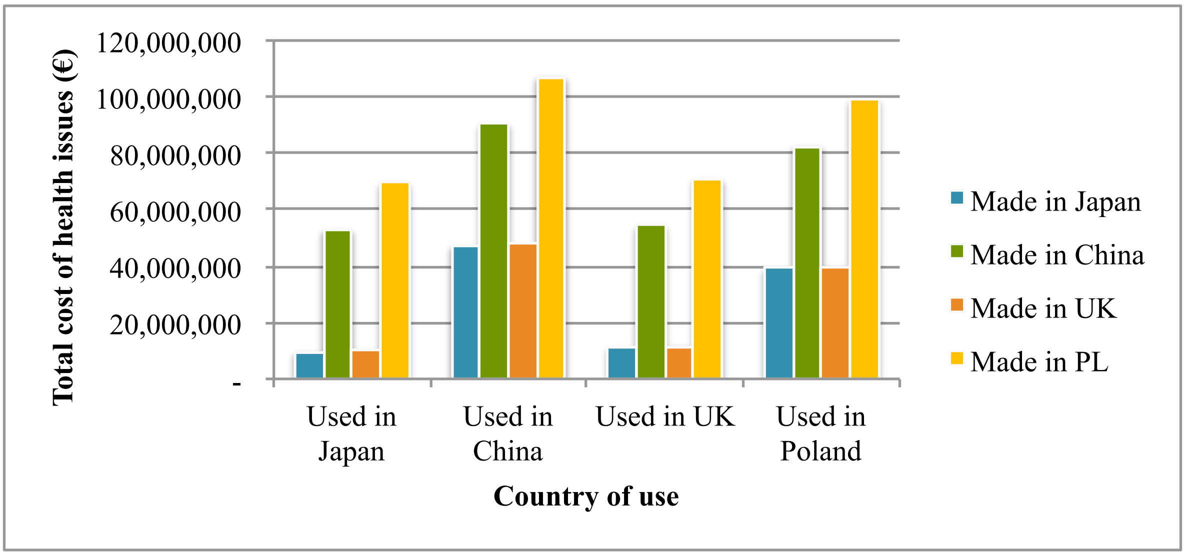


Figure 39 presents emissions for the EV produced in Japan, transported and utilized in Poland. The results shows that only the transportation of an EV from Japan to Poland accounts for almost 35% of total lifecycle emissions of NOx 18% of SO2 and 59% of PM.

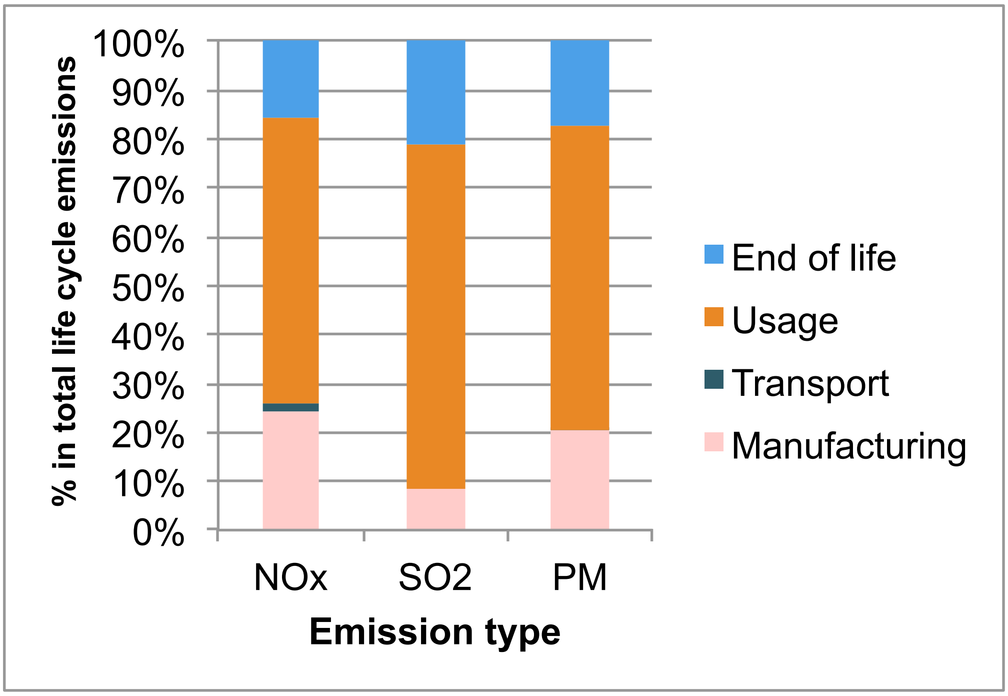
That is why, my recommendation is to switch from diesel marine oil to LNG-fuelled ships. Due to the clean-burning characteristics of natural gas, the use of LNG leads to significant reduction of NOx, SOx and PM. Use of LNG reduces emissions of nitrogen oxides (NOx) to 80%, PM to near 99%, and sulfur oxides (SOx) emissions to near 100%. (Kumar et al. 2011; Burel et al. 2013). Due to those significant reductions, the case for switching from diesel to LNG was calculated. The results for total cost are presented below in Figure 40.

Figure 40 Total health cost associated with EV production, transportation with LNG ships and use (production in 2016)



The most significant decrease in total cost occurs for the EVs made in Japan and transported to Poland (18% decrease) and England (43% decrease). Moreover the cost for EVs made in UK and transported to Japan plummets by 44%. Due to usage of LNG ships long-distance transportation on ships is becoming cleaner and takes only a small percentage of total air emissions.

Figure 41 Emission usage for EVs made in Japan, transported on LNG ships and used in Poland (Made in 2016, 10 years usage)



The significant decrease of emissions from switching from diesel oil to LNG ships is presented in Figure 41. In this case, transportation is producing a not significant percentage of total air emissions.

7.3 Discussions and summary

In the first case study, the GHG and non-GHG emissions of GVs and EVs were calculated and monetized through their lifecycles for two technology scenarios. The major findings and implications are summarized below.

The results imply that EV production is more energy intensive and emits more pollutants than GV production. However, this effect can be compensated for by lower CO_2 emissions during the EV use phase. Using EVs over their entire lifetime can offset the high emissions during the manufacturing process. Nevertheless, the total lifecycle CO_2 emissions of EVs produced in 2016 in comparison with GVs are lower only in the UK. Surprisingly, the CO_2 emissions from EVs in Japan are higher than those of GVs, which could be linked to the significant decrease in electricity production from nuclear power plants following the Fukushima Daiichi accident. In China, total emissions from EV production are substantially higher than those from GVs. The impact of SO_2 emissions from EVs should not be ignored for China; because of high SO_2 emissions, it is currently counterproductive for China to introduce EVs.

High emissions from the manufacturing phase of EVs decrease significantly in the Tech. Adv. scenario. EVs become increasingly more favorable in that scenario due to technological developments, increases in energy efficiency, increase in the share of renewable sources in the electricity mix, and pledges by the three countries for a more environmentally friendly economy. Additionally, if EVs are produced, total CO_2 emissions in 2025 will be lower than those from GVs for all three countries. The reduction in PM, NO_x, and SO_2 emissions during the EV use phase in the Tech. Adv. scenario compared with the BAU scenario is estimated to stand at 20%-26% in Japan, 19%-36% in China, and 11%-36% in the UK.

This analysis confirms the previous findings that clean electricity generation is crucial for the implementation and popularization of EVs globally. Energy produced in coal-fired power plants creates more pollution than any other type of power plant and degrades air quality. Therefore, we recommend further cooperation on reducing global emissions by implementing international policies to increase the share of renewable sources and improve energy efficiency and global standards for air pollution. These findings suggest that governments should thoroughly assess the introduction of EVs. If they decide to go through with it, then they should implement energy-related policies. We recommend locating vehicle production facilities in regions where renewables play a central role in the electricity mix. Such moves were made by Nissan that located their assembly plant in Tennessee where emissions are lower than in other regions (Nealer et al. 2015b).

The monetary value of air pollution on human health is substantial and varies between €520 million in the UK and €3 billion in China. In general, the impact of EV emissions on public health is lower than that of GV emissions because the EV-related pollution is originated far from the cities and not near the ground. Therefore, the cost of EV emissions is lower than that of GV emissions.

The second case study was designed to determine the cost of health problems associated with air pollution, while incorporating environmental leakage. In this research, the rich countries carry the cost of locating production in developing countries and pay the abatement cost back to producing countries. We believe that developed countries, producers and consumers and are to be blamed for the aftermaths of the environmental leakages. The numerical results of this study prove our concern about environmental leakage and the danger of importing the products from developing countries. This study has found that it is advisable to keep local production if the country's electricity is generated from the clean energy source. Additionally, if the electricity mix is unfavorable, it is recommended to import from a nearby-located country of clean electricity mix.

There is a strong need for further regulations and implementation of standards for not only vehicle transportation emission but also maritime transportation. It is also recommended to switch from using marine diesel to ships fueled by liquefied natural gas (LNG), this can considerably reduce not only Sox but also PM emissions. Moreover, that there are still other regulatory challenges to overcome, e.g. according to WHO, the maximum level of emissions is 25 μg/m3 for PM 2.5 and 50 μg/m3 for PM10. Nonetheless, in Poland, the alarming level of PM is set at 300 μg/m3, while in France it is 80 μg/m3(2017). Therefore, at stake is implementing regulations, global policy towards decreasing the air emission level, and unification of the alarming standards. Furthermore, it is also crucial to note that this paper has only analyzed the cost of the health from production, transport and use of EVs. If the cost of GHG emissions would be analyzed the final result would differ. Further improvements in the study could investigate a broader view and include total sustainability analysis of EVs' impact.

8. CONCLUSIONS

Concerns surrounding energy security and climate change, along with improvements in technology have spurred an interest in alternative fuel vehicles. The road transportation sector is responsible for the majority of overall emissions. Advancements in AFVs could stimulate positive changes in the transportation system. In view of the need for more efficient transportation new regulations are being introduced all over the world. Improvements in technology and governmental support policies have already increased the demand for AFVs (Brand et al. 2013).

The majority of human-made air pollution originates from energy use and production, combustion of biomass and fossil fuels (International Energy Agency 2016). Health problems associated with the aftermaths of air pollution are causing a considerable monetary cost for the global economy. In this study, we believe that developed countries, producers and consumers and are to be blamed for the aftermaths of the environmental leakages. Developing countries imports dirty products and this lead to displacement of emissions abroad and often an overall increase in the global pollution (Fæhn and Bruvoll 2009). Therefore, it is essential to include environmental leakage in the studies to provide a realistic and global image of production and its consequences.

8.1. Key findings and recommendations

This research was designed to conduct a systematic analysis of sustainability of AFVs. The purpose of this study was to create an optimal portfolio of AFVs and to decide if the production of the AFVs is justified in some regions due to environmental and social impacts of the vehicles. Firstly, the economic aspects of AFVs were being investigated. Secondly, environmental and social study was carried out. This section presents key findings resulting from this work, as well as limitations and future studies.

As a result of the present research work, the following key findings can be pointed out concerning the sustainability of AFVs.

Economic analysis:

- This paper has examined both automotive and energy sector in Poland. The results from qualitative analysis prove, that considering former evolution of Polish automotive sector, rapid improvements appear difficult to be achieved in a short time. With the present and forecasted future energy mix in Poland, AFVs are clearly much more favorable when compared with GV and DV.
- Firstly, it is crucial to introduce all types of powertrains to achieve both energy security and economic objectives; the desired results cannot be accomplished by introducing only one type of AFV.
- The highest spread of AFVs for Case Scenario 1 would be in CNGs and EVs.
- Secondly, the spread of FCVs could be similar to that of other AFVs owing to the expected rapid decline in the cost of both infrastructure and purchase price of such vehicles.
- One of the issues that emerge from these findings is that it is of utmost importance to begin investing in FCV support and infrastructure
- The government should seek a reliable CNG supply (Sliwka et al. 2014).
- Technological developments are essential in making the change. Nevertheless, non-technological aspects as governmental policy instruments, incentives and consumer-consciousness might play a decisive role in triggering the growth of AFVs.

- We recommend that the government set a subsidy for AFVs; this could improve public perception and possibly support an increase in the market penetration rates of AFVs.
- The shale gas revolution substantially impacts the portfolio of AFVs due to the significant decrease of gas prices.
- EVs are the most optimal vehicles for the Shale Gas Scenario. The combination of electricity and gas use is the most advantageous in AFVs in terms of energy security and price mix.
- Increased use of shale gas engenders the high consumption of water.
- Those findings suggest that, if the shale gas is introduced in Poland, minimization of water-oriented and safety issues issues is crucial. Water quality, wastewater and its disposal, spills and groundwater disturbance in the area of shale gas extraction are the topic that have to be tackled if the shale gas revolution takes place.

Environmental and social analysis:

- The results imply that EV production is more energy intensive and emits more pollutants than GV production. However, this effect can be compensated for by lower CO_2 emissions during the EV use phase. Using EVs over their entire lifetime can offset the high emissions during the manufacturing process.
- Total lifecycle GHG and non-GHG emissions of EVs produced in 2016 in comparison with GVs are lower only in the UK. Surprisingly, the air pollution from EVs in Japan are higher than those of GVs, which could be linked to the significant decrease in electricity production from nuclear power plants following the Fukushima Daiichi accident. In China, total emissions from EV production are substantially higher than those from GVs.

- High emissions from the manufacturing phase of EVs decrease significantly in the Tech. Adv. scenario. EVs become increasingly more favorable in that scenario due to technological developments, increases in energy efficiency, increase in the share of renewable sources in the electricity mix, and pledges by the three countries for a more environmentally friendly economy.
- Clean electricity generation is crucial for the implementation and popularization of EVs globally
- This social case study has found that it is advisable to keep local production if the country's electricity is generated from the clean energy source. Additionally, if the electricity mix is unfavorable, it is recommended to import from a nearby-located country of a clean electricity mix.
- The numerical results of this study prove our concern about environmental leakage and the danger of importing the products from developing countries.
- We recommend locating vehicle production facilities in regions where renewables play a central role in the electricity mix.
- We recommend further cooperation on reducing global emissions by implementing international policies to increase the share of renewable sources and improve energy efficiency, global standards for air pollution and unification of the alarming standards.
- There is a strong need for further regulations and implementation of standards for not only vehicle transportation emission but also maritime transportation
- It is also recommended to switch from using marine diesel to ships fueled by liquefied natural gas (LNG), this can considerably reduce not only SO_x but also PM emissions.

8.2. Contributions

The major contributions of this research work include the development of a methodology for estimation of optimal portfolio of AFVs and environmental and social LCA of them.

As evaluated in this study, the proposed method is applicable for the estimation of AFV uptake and fleet sizes under a number of scenarios. This method can be used by automakers to investigate which products are the most promising for the AFVs, and the methods used in this research may be applied by other researchers to future studies on policies regarding the use of AFVs in other countries. This research can serve as a basis for the government to recognise which types of AFVs best suit the Polish situation and to determine the most appropriate policy instruments to benefit consumers and meet larger policy objectives. The major contribution of this research is the framework for the establishment of governmental subsidies and a guide for automakers for developing hydrogen- or battery-based technologies. After proper technology is developed, the findings can be used to create governmental policies and targets, which was already studied by (Nakano and Chua 2011; Nonaka and Nakano 2011).

Additionally, this study is beneficial for the government, as well as automakers and potential shale gas investors as it provides numerical results on water usage and vehicle portfolio as a consequence of implementing shale gas into a sustainable transportation system.

The LCA methods used in this research can be applied and used in other regions in order to thoroughly assess the introduction of AFVs. Automakers and policy makers need to investigate the lifecycle emissions of vehicles in different regions. It is crucial to decide if governments should invite EV production into their country, or whether it would be more beneficial to import vehicles. If the governments decide to go through with it, then they should implement energy-related policies.

Furthermore, the results of the study highlight the importance of the environmental leakage phenomenon. The present study confirms previous findings and contributes additional evidence that suggests that it is essential to include environmental leakage in the studies to provide a realistic and global image of production and its consequences. Moreover, governments can benefit from this LCA and choose the most sustainable location for the production of EVs.

8.3. Limitations and further work

Finally, a number of important limitations need to be considered. First, the use of biofuels research as a single source of fuel was not considered. This aspect should be studied further in line with the national goal for biofuels to achieve a 10% share of fuels by 2020. Another limitation is that the scrap percentage rates were set as constants. A potential methodical weakness that could have affected our results concerning DVs is that there is a possibility that future demand for this type of non-AFV will significantly plummet; this is contrary to our projection of the increase in the number of AFV engine platforms. Moreover, the data concerning DV energy consumption may be misleading and could differ significantly from real fuel consumption, which should be investigated more thoroughly. In response to recent developments concerning DV emission inconsistencies (Le Page 2015), the next series of studies could elaborate on the impacts of this situation. Although the current methods used in this research present valuable insights, there are still uncertainties in the estimated model parameters such as fuel, infrastructure and vehicle cost. It is important to note that fuel price is highly volatile and the forecasts used in this study may differ in the years to come. Changes in this parameter may profoundly influence the results of the optimisation model. Finally, this study examined only one scenario of technology improvement; in the future, however, even faster vehicle price drops may be expected. This could significantly impact the results of the analysis. Moreover, a limitation of this study is that it assumes constant fuel efficiencies, and that the emissions from sources other than coal-fired power plants are constant among the three countries. In this regard, further research may have to consider those uncertainties.

Further research should be extended and could investigate the sensitivity analysis of factors such as: vehicle efficiencies, the production rate, the recycling rate of the flowback water, the decline rate of shale gas price, technological improvements over time, etc. Moreover, future studies should investigate other types and sizes of vehicles. As mentioned earlier, battery recycling technologies are still developing and should be further investigated.

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