Czech University of Life Sciences Prague

Faculty of Economics and Management

Department of Trade and Finance

Diploma Thesis

Assessment of the Czech energy mix in the context of renewable and non-renewable energy utilization

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DIPLOMA THESIS ASSIGNMENT

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Thesis title

Assesment of the Czech energy mix in the context of renewable and non-renewable energy utilization

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Objectives of thesis

The thesis identifies all essential components of the Czech energy sector and assesses their optimality for energy production. Each energy source is analyzed based on its characteristics, output, capacity factors, emissions produced and related costs.

In the practical part, five possible scenarios will be introduced and evaluated from the perspective of the economy (costs), environment (compatibility with the climate change agenda) and energy security (self-sufficiency).

The goal is to provide several feasible solutions of resource allocation for the short-to-medium term and evaluate their optimality for the Czech Republic. Critical aspects for creating the feasible energy mix are maintaining energy security, complying with European Union legislation and minimizing the negative impacts on the environment and economy.

Methodology

For the purposes of this thesis, all relevant energy sources utilized in the Czech Republic were analyzed in terms of outputs, capacity factors, costs, the stability of supply and emissions produced. Data for this assessment were gathered from publicly accessible online databases (OECD, Eurostat, Energy Regulation Office and Czech Statistical Office).

The Czech energy sector itself was further assessed in terms of consumption and production and LCOE was calculated for following energy sources: coal, gas, nuclear power, hydropower, onshore wind turbines, and ground-mounted PV systems. The calculation was performed with the aid of LCOE calculator data tool Agora.

Cost components (investment cost, operation and maintenance costs, fuels cost) and expected lifetime were obtained from OECD, and the discount rate was stated as 5%.

Five scenarios were created (lowest emissions release, lowest possible cost, the Czech energy sector focused on nuclear power production, energy mix utilizing only renewable resources and energy mix utilizing only non-renewable resources) via linear programming considering multiple constraints given by natural resources, general demand, and European Union legislation.

Feasibility of each scenario was evaluated based on the self-sufficiency (security perspective), the value of costs (economic perspective) and the amount of produced emissions (environmental perspective).

The proposed extent of the thesis

70 pages

Keywords

energy, Czech Republic, renewable, non-renewable, optimization model, emissions

Recommended information sources

Beran, H., Wagner, V., and Pačes, V. (2018). Česká energetika na křižovatce. 1st ed. Praha: Albatros Media a.s. ISBN 978-80-7261-560-5

Binhack, P., Jaroš, J., Nosko, A., Thim, M. and Tichý, L. (2011). Energetická bezpečnost ČR a budoucnost energetické politiky EU. [online] Google Books. Available at: https://books.google.cz/books?id=EhWFBwAAQBAJ&pg=PA83&lpg=PA83&dq=energetick%C3%BD+mix+%C4% wQAUA4FBDoAQgyMAM#v=onepage&q=energetick%C3%BD%20mix%20%C4%8Dr&f=false [Accessed 13 Mar. 2019].

Drábová, D. and Pačes, V. (2014). Perspektivy české energetiky: Současnost a budoucnost. Praha: Novela bohemica. ISBN 978-80-87683-26-2

Rajan, G. (2006). Practical Energy Efficiency Optimization. [online] Google Books. Available at: https://books.google.cz/books?hl=cs&lr=&id=huWVHNDIsdYC&oi=fnd&pg=PT16&dq=#v=onepage&q&f=false [Accessed 13 Mar. 2019].

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Declaration

I declare that I have worked on my diploma thesis titled "Energy mix development of the Czech Republic in the context of utilizing renewable and non-renewable energy" by myself and I have used only the sources mentioned at the end of the thesis. As the author of the diploma thesis, I declare that the thesis does not break copyrights of any person.

In Prague on 26. 3. 2019 ______________________________

Acknowledgement

I would like to thank prof. Ing. Luboš Smutka, Ph.D. for his advice and support during my work on this thesis.

Energy mix development of the Czech Republic in the context of utilizing renewable and non-renewable energy

Abstract

Thesis „Assesment of the Czech energy mix in the context of renewable and non-renewable energy utilization" inspects all energy sources used in the Czech Republic and their contribution to the total energy production as well as the impact they have on the environment. The primary objective of the thesis is to assess the Czech energy mix and its potential development from the economic, environmental and energy security perspective. The occuring costs, compatibility with the climate change agenda and self-sufficiency in the energy production are calculated separately for 6 different scenarios and then evaluated using objective, quantitative and comparative methods.

Anticipated scenarios of potential outcomes are predicted with respect to both the changes in the European Union legislation, or more precisely their upcoming due date, and expected energy consumption development in the Czech Republic.

Keywords: energy, energy mix, renewable resources, electricity, emissions, Czech Republic, energy consumption, ASEK, EU legislation, transmission network, energy accumulation, linear programming, optimization model

Vývoj energetického mixu České republiky v kontextu využití obnovitelných a neobnovitelných zdrojů

Abstrakt

Diplomová práce „Posouzení energetického mixu České republiky v kontextu využití obnovitelných a neobnovitelných zdrojů“ zkoumá všechny zdroje energie používané v České republice a jejich podíl na celkové produkci stejně jako jejich dopady na životní prostředí. Hlavním cílem této práce je posoudit Český energetický mix a jeho potenciální vývoj z hlediska ekonomiky, dopadu na životní prostředí a zajištění energetické bezpečnosti státu. Výdaje, kompatibilita s bojem proti klimatickým změnám a soběstačnost České republiky v energetické produkci jsou vypočítány pro 6 různých scénářů a vyhodnoceny za použití objektivních, kvantitativních a komparativních metod.

Předpokládané scénáře jsou předpovězeny s ohledem na nastávající změny v legislativě Evropské Unie, respektive blížícího se termínu jejich naplnění a předpokládaného vývoje spotřeby energie v České republice.

Klíčová slova: energie, energetický mix, OZE, elektřina, emise, Česká republika, spotřeba energie, ASEK, legislativa EU, rozvodná síť, ukládání energie, lineární programování, optimizační model

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List of abbreviations

kWh – kilowatt hour

MWh – megawatt hour

GWh – gigawatt hour

TWh – terawatt hour

TJ - terajoule

PV - photovoltaic

EU – European Union

ERO – Energy Regulatory Office

MPO – the Ministry of Industry and Trade

1 Introduction

Modern society consumes large amounts of energy which makes energy industry one of the main pillars of modern society and a crucial part of the infrastructure in the vast majority of countries. If the world was subjected to a blackout lasting more than few days, every essential aspect of our lives would be severely affected. This makes energy an important political topic. Since in the past years the threat of climate change became palpable the focus of the energy industry shifted from the attempt to produce as much energy as possile to the means used in production and their impact on the environment which made the need for change obvious. Impact of the fossil fuels-based power plants has been proven not feasible for the future but currently utilized renewable resources can replace energy coming from these plants just partially and nuclear power plants are a subject of severe controversy. Because of the progressing electrification of both transport and industry the energy consumption is expected to be increasing in the future and with the decreasing production from the coal and oil power plants that poses an issue which needs to be adressed as soon as possible.

The Czech Republic does not have high amounts of sunlight like some of the southern regions, nor it has access to the windy coast like for example Germany. Possibilities of water energy utilization have been virtually depleted and reservoirs of crude oil or gas are insignificant. Furthermore even though energetics is highly dependent on investments, the current economic and political situation in the Czech Republic makes it very unattractive for investors. Investments to the energy sector, whether to the construction of new powerplants or the improvement of the transmission network, are usually of large amounts of money with a long period of the return on investment and since there are many forces putting pressure on the development of the sector and thus its future shape is not yet certain there are not many investors willing to undertake such risks.

The Czech Republic will probably never be completely self-sufficient energy-wise, but it should aim to be as independent as possible. Rapidly increasing demand for energy poses a global issue and our ability to solve it will to an extent shape the future of the Earth.

2 Objectives and Methodology

2.1 Objectives

The thesis aims to identifies all essential components of the Czech energy sector and assesses their optimality for energy production. Each energy source will be analyzed based on its characteristics, output, capacity factors, emissions produced and related costs. In the practical part, four possible scenarios will be introduced and evaluated from the perspective of the economy (costs), environment (compatibility with the climate change agenda) and energy security (self-sufficiency).

The goal is to provide several feasible solutions of resource allocation for the short-to-medium term and evaluate their optimality for the Czech Republic. Critical aspects for creating the feasible energy mix are maintaining energy security, complying with European Union legislation and minimizing the negative impacts on the environment and economy.

2.2 Methodology

The theoretical base of this thesis which introduces the energy sector in the Czech Republic and its main components is created as a result of a synthesis of information from both specialized literature and publicly accessible online sources and databases.

All relevant energy sources utilized in the Czech Republic were analyzed in terms of outputs, capacity factors (calculated from ERO data concerning installed output and energy production data in 2007-2017 for each power source), costs (fixed and variable), stability of supply and emissions produced. Data for this assesment were gathered from publicly accesible online databases (OECD, Eurostat, Energy Regulation Office and Czech Statistical Office).

The Czech energy sector itself was further assesed in terms of consumption and production using data from Eurostat database.

2.2.1 Levied cost of energy (LCOE)

Costs of energy production were calculated via levied cost of energy (LCOE), specifically:

$$\bar{p} = \frac{\sum_{t=0}^{T} \frac{[I_t + M_t + F_t]}{(1+r)^t}}{\sum_{t=0}^{T} \frac{[E_t]}{(1+r)^t}}$$

, where: It= Capital expenditure in the year t

Mt = Operating and maintenance costs in the year t
Ft = Fuel price expenditures in the year t
Et = Net electricity production in the year t
r = Discount rate
p = Electricity production costs

LCOE was calculated for following energy sources: coal and lignite, gas, nuclear power, hydropower (in the Czech Republic dominantly run-of-the-river plant), onshore wind turbines and ground-mounted PV systems. Calculation was performed with aid of LCOE calculator data tool Agora[1].

Cost components (investment cost, operation and maintenance costs, fuels cost) and expected lifetime were obtained from U.S.energy information administration[2], and discount rate was stated as 5%.

The costs of plant operation include all the costs of power generation that are not associated with the initial investment or the use of an energy carrier (fuel costs, including transport costs and taxes). These include the costs of maintenance, and expenses for auxiliary and operating materials, personnel, administration and insurance.

2.2.2 Linear programming

Linear programming is a type of mathematical programming and consists of three main parts – linear objective function, non-negative variables and constraints. Both the linear objective function and constraints are expressed as linear relationships.

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[1] Agora-energiewende.de. (n.d.). *Data & Tools*. [online] Available at: https://www.agora-energiewende.de/en/data-tools/ [Accessed 13 Mar. 2019].

[2] Eia.gov. (2019). [online] Available at: https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf [Accessed 13 Mar. 2019].

Important terms[3]

Vector of solution

$x = (x_1, x_2, \ldots, x_n)$ denotes the optimal solution of the problem. The optimal structure of production is that one through which the decision quantity (e.g., revenues or costs) reaches the extreme value (minimum or maximum). This decision quantity is expressed by a linear function.

Extreme value

Extreme value is the maximum or the minimum of the function which is searched for within the limits of constraints.

Constraints

Constraints are limitations among which the solution is found. There are two types of constraints - non-negativity constraints which needs to be applied for all of the solution vectors and problem specific constraints e.g., scarcity of resources necessary for the production).

Linear objective function

$z = f(x)$ is a function of the vector of the solution. Objective of the linear programming is to find its extreme value – minimum or maximum.

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[3] FRIEBELOVÁ, Jana. *Lineární programování.* [online]. [Accessed on 9.10.2015]. Available from: http://www2.ef.jcu.cz/~jfrieb/rmp/data/teorie_oa/LINEARNI_PROGRAMOVANI.pdf

2.2.3 Mathematical formulation of the model

Finding the extreme of the linear function: $z = c_1x_1 + c_2x_2 + \ldots + c_nx_n$ as a non negative solution of the set of linear equations:

$$\begin{array}{lll} a11x1 + & a12x2 + \cdots + & a1nxn = b1 \\ a12x2 + & a22x2 + \cdots + & a2nxn = b2 \\ \vdots & \vdots & \vdots \\ am1x1 + & am2x2 + \cdots + & amnxn = bm \end{array}$$

where a_{ij} ($i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$) denotes structural coefficients

b_i ($i = 1, 2, \ldots, m$) denotes required numbers

c_j ($j = 1, 2, \ldots, n$) denotes prices

<u>Simplified notation of mathematic model of linear programming</u>

$Ax = b$, $\quad x \geq 0$, $z = c^T x$

A… matrix (n x m) with elements a_{ij} ($i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$)

b … vector of requirements with m rows

c … vector of prices with n rows

x … vector of variables with n rows

o … zero vector with n rows

<u>The process of the model assembly</u>

1. Determining what is the result of the calculation (what components the vector consists of and in what units are they denoted)
2. Deciding how the solution will be optimized (formulate the linear function)
3. Formulation of constraints

Five scenarios were created via linear programming (lowest emissions release, lowest possible cost, outputs recomended by State energy concept, the Czech energy sector with focus on nuclear power, utilization of only renewable resources and utilization of only non-renewable resources) considering multiple constraints given by natural resources availability, legislation considering carbon footprint and demand.

Feasibility of each scenario was evaluated based on the self-sufficiency (security perspective), the value of costs (economic perspective) and the amount of produced emissions (environmental perspective).

For purposes of this thesis several simplifications were estabilished due to the complexity of the investigated topic. Specifically external factors such as the transmission network requirements and the possible developments of energy market were ommitted from the problem formulation. Proposed model concerns solely with costs of electricity generation of different sources and their fundamental characteristics related to the electricity production.

3 Literature Review

3.1 Energy industry

The energy industry is an industrial sector that encompassing production, sale, and distribution of energy. This entails not only the transformation of energy into electric energy or heat in power plants and its following distribution through transmission network but also fuel extraction and manufacturing as well as maintaining the efficiency of the energy production process. To be even more precise, the energy industry consists of the petroleum industry, the gas industry, the electric power industry, the coal industry, the nuclear power industry, and the renewable energy industry.

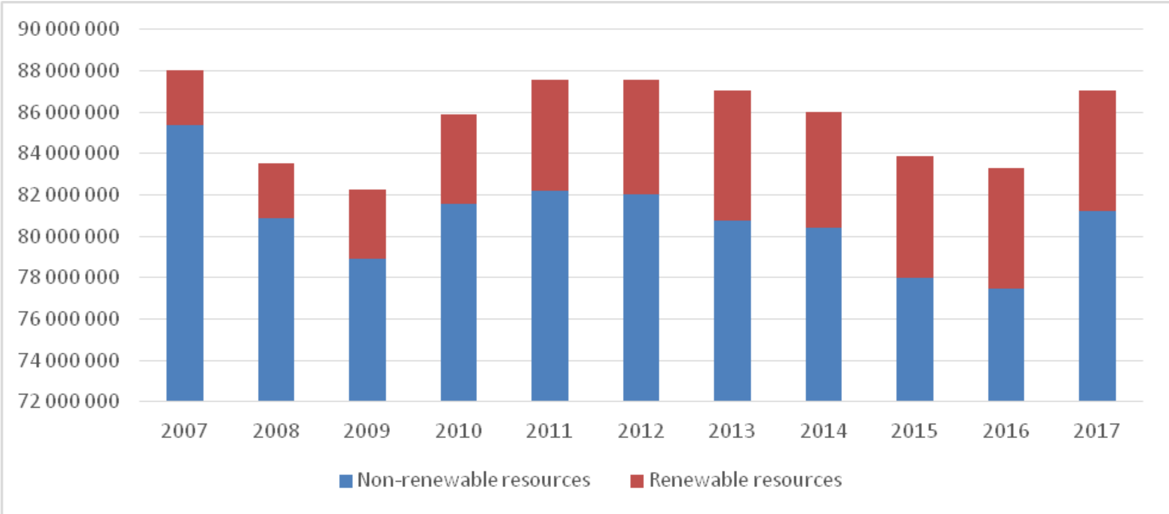
Many sources are possible to utilize in order to produce energy, and they are divisible to categories based on their ability to replenish themselves within frames meaningful to humans, dependability of energy production and amount of chemicals released during the process of production. Energy sources which the reservoirs are finite and therefore depletable such as coal, natural gas, crude oil or uranium, which can be transformed into nuclear fuel, are called non-renewable resources. Utilization of natural occurrences such as wind, water currents, rays of sunlight or geothermal energy is considered as renewable resources. Even though no human activity has a neutral impact on the environment and the manufacturing of the powerplant itself causes the production of a certain amount of emission, renewable resources together with nuclear power are generally considered as zero emission resources.[4]

Both renewable and non-renewable resources have been utilized for thousands of years, long before the invention of electric current but electricity production was until the end of the 20th century dominated by non-renewable resources. However as the negative impacts on the environment became palpable and the rapidly increasing demand brought the imminent point of depletion to the foreseeable future, the focus was drawn to the

[4] Drábová, D. and Pačes, V. (2014). *Perspektivy české energetiky: Současnost a budoucnost*. Praha: Novela bohemica. ISBN 978-80-87683-26-2

renewable resources as well. The boom of the wind, solar and water-based energy production is visible on the graph depicting the production of electricity divided by type of resource.

Figure 1 Ratio of energy produced from renewable and non-renewable resources (2007-2017)



Source: ERÚ - Zprávy o provozu elektrizační soustavy [5]*, own data processing*

In terms of reliability of energy production there are four main types of energy resources:

Type A – best possible sources capable of accumulation, it is possible to store and withdraw energy from them arbitrarily

Type B – high-quality sources, level of output can be quickly lowered or increased based on current demand

Type C – sources of basic performance, it is not possible to adjust the output in response to the changes in demand

Type D – intermittent sources, their output is determined by external parameters, and it is not possible to effectively direct it.[6]

[5] Eru.cz. (2019). *ERÚ - Zprávy o provozu elektrizační soustavy*. [online] Available at: https://www.eru.cz/cs/zpravy-o-provozu-elektrizacni-soustavy [Accessed 20 Feb. 2019].

[6] Beran, H., Wagner, V. and Pačes, V. (2018). *Česká energetika na křižovatce*. 1st ed. Praha: Albatros Media a.s. ISBN 978-80-7261-560-5

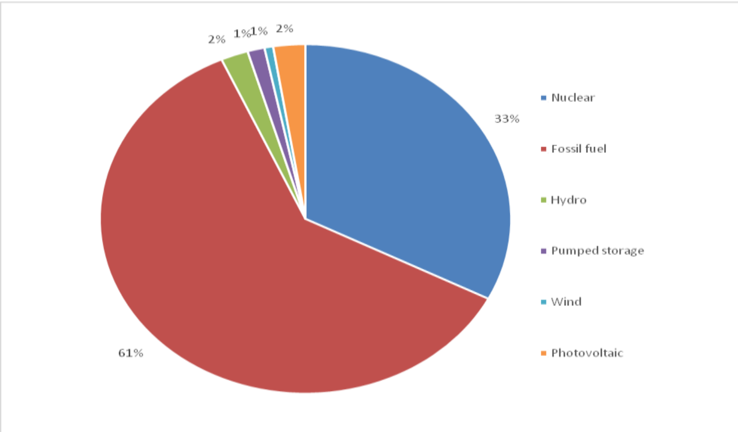
The need for a transition from non-renewable to renewable resources is evident, but since energy is one of the pillars of the Czech Republic's infrastructure, any potential changes have to be executed in a manner that ensures maintaining of energy security.

3.1.1 Non-renewable resources

The fundamental characteristic of non-renewable energy sources is that they are being consumed more quickly than they are recovering, therefore they are not infinite. In other words, they will be exhausted in the foreseeable future and energy sector infrastructure has to take that into account. It is not yet possible to accurately estimate when the non-renewable energy resources will be exhausted, and to an extent, it depends on how efficiently we use the remaining of these resources and how much the product will shift towards alternative energy sources.

Non-renewable energy sources are essential for the industry, but they have a negative impact on the environment - they pollute the air, water and contribute to the greenhouse effect. The principal recognized categories of the non-renewable energy sources are fossil fuels (specifically coal, petroleum, gas) and nuclear energy.

Figure 2 Share of resources in Czech energy production (2017)



Source: ERÚ Zprávy o provozu elektrizační soustavy[7]*,own data processing*

[7] Eru.cz. (2019). *ERÚ - Zprávy o provozu elektrizační soustavy*. [online] Available at: https://www.eru.cz/cs/zpravy-o-provozu-elektrizacni-soustavy [Accessed 20 Feb. 2019].

3.1.1.1 Fossil fuels

Fossil fuels always had a significant place in the structure of the Czech energy sector, and until this day they represent a fundamental source of domestic energy production. This economic utilization of fossil fuels is caused by the existence of vast reservoirs of coal in the territory of the Czech Republic.[8]

The most significant share in the production and exports concerning the energy sector of the Czech Republic is held by coal. Coal is still the fundamental type B powersource which creates the base of the Czech energy mix. Currently, there are 9 operational coal mines: 4 coking coal mines and 5 brown coal mines. In 2000 the share of energy produced from coal was approximately 70%, then the utilization started to decrease gradually. In 2013 after launching of the Temelín and increase of output of Dukovany in combination with the increase of renewable resources utilization the share of energy produced from coal decreased below 50%. Since coal burning produces intolerable levels of emissions, dust and causes an inversion, both individual governments, and the European Union recognize the necessity of transition to more sustainable sources. Nevertheless, the state energy concept should be created in a manner that arranges the transfer to be gradual and ensures that the remaining coal is utilized with the utmost efficiency.

In the past in order to satisfy domestic demand, it was necessary to mine 40 million tonnes of coal annually, but instead 50 million tonnes were mined, and the surplus energy was exported. Sales of energy are rarely performed via contract; usually, it is sold on the stock market, which is set in a way that enables export even if the country has a shortage and therefore restrictions on the production will not ensure ceasing the export. As depicted on the Figure3 and Figure 4, eventhough the Czech Republic mines small amounts of quality coking coal (in comparison with the brown coal mining) it exports majority of it and instead utilizes cheaper less effective brown coal which produces higher amounts of emmissions.

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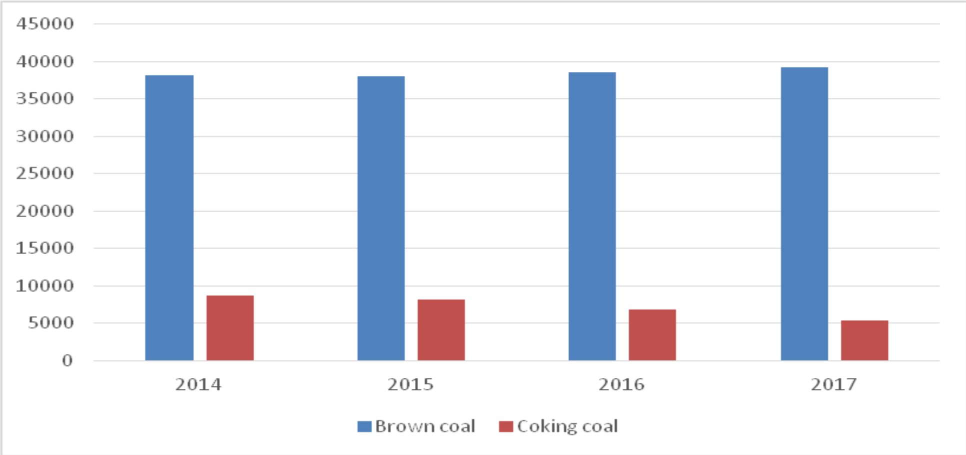
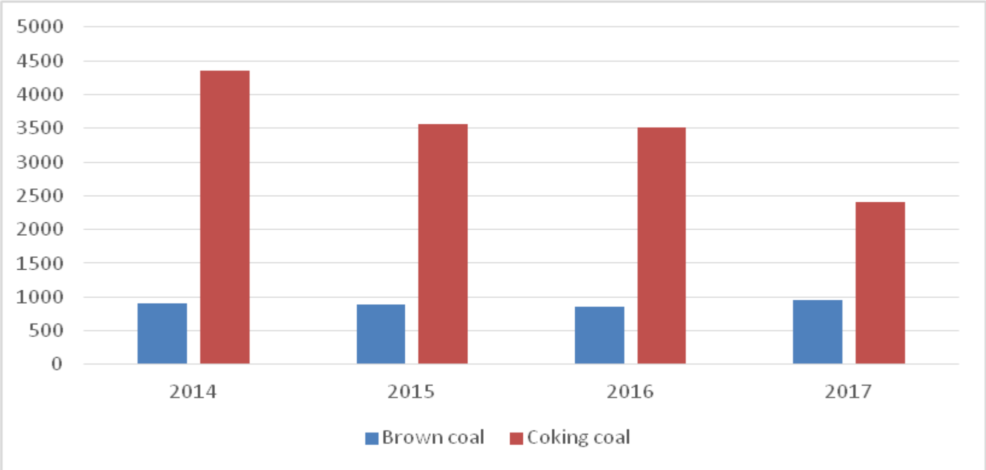
[8] Stats.oecd.org. (2016). *Fossil fuel support country note*. [online] Available at: http://stats.oecd.org/wbos/fileview2.aspx?IDFile=6ff7ed21-0f10-41e2-bf70-c37d793df149 [Accessed 20 Feb. 2019].

Figure 3 Amount of brown and coking coal mined in the Czech Republic (ths tonnes)



Source: ERÚ- Zprávy o provozu elektrizační soustavy[9],own data processing

Figure 4 Czech exports of brown and coking coal (ths tonnes)



Source:ERÚ- Zprávy o provozu elektrizační soustavy[10],own data processing

The generation of coal-based energy itself is not expensive but the externalities are not accounted for in the price. There is also no sufficiently operating system that would

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[9] Eru.cz. (2019). *ERÚ - Zprávy o provozu elektrizační soustavy*. [online] Available at: https://www.eru.cz/cs/zpravy-o-provozu-elektrizacni-soustavy [Accessed 20 Feb. 2019].

[10] Eru.cz. (2019). *ERÚ - Zprávy o provozu elektrizační soustavy*. [online] Available at: https://www.eru.cz/cs/zpravy-o-provozu-elektrizacni-soustavy [Accessed 20 Feb. 2019].

ensure that the fees paid for the negative impact of the powerplants are used to actually to diminish the consequences or compensate people being affected. Another aspect of coal-based energy is that in the future coal could prove itself to be an essential chemical substance of the future, and we might be wasting it for ineffective burning.

Natural gas is a is a type B fossil energy source, excellent for covering for the D types and suitable for both electricity and heat production. Natural gas consists almost entirely of methane and it’s the cleanest of all fossil fuels because eventhough its utilization produces emissions, the amount is between 1/2 and 1/3 of emissions released by coal combustion. Natural gas can be utilised in electricity production as well as heating without further processing. Natural gas can also be refined into liquefied natural gas (LNG) or compressed natural gas (CNG). Natural gas is an excellent energy source in decentralized heating and electricity production, but it’s also popular in industrial processes, since it requires no storage. Natural gas can also be used as as a source of transportation energy.[11]

Another fossil fuel mined in small amounts in the Czech Republic is oil. The number of mined oil deposits has been more or less constant over recent years, but mining itself is gradually declining. Domestic production slightly exceeded two percent of all imports in 2014, and when compared to world mining, Czech domestic production is negligible. Oil is the dominant source of transportation energy even though there are alternatives available in the form of biofuels. Transfer from the utilization of oil to biofuels needs to be monitored and performed in a manner that will not endanger the food security or quality of agricultural soil.

Czech energy is dependent on imports of oil and natural gas, but these strategic raw materials are mined on its territory as well, albeit on a small scale. There are several natural gas deposits located in the Czech Republic, most of which are concentrated in the

[11] Suomen Kaasuenergia. (n.d.). *Natural gas and biogas - Suomen Kaasuenergia*. [online] Available at: https://suomenkaasuenergia.fi/en/natural-gas-biogas/ [Accessed 13 Mar. 2019].

area of the Vienna Basin and the Upper Silesian basin[12] Domestic production accounts for only one to two percent of the imported quantity thus the Czech Republic is dependent on import and strives to remain connected to multiple suppliers in order to maintain security and take advantage of economic aspects such as market price. The most significant part of gas imports comes from Russia (approximately 99%) based on contracts concluded with Gazprom company effective until 2035, the remaining 1% is imported from Norway. Imports of oil from Russia cover roughly 2/3 of the total imported oil the rest is imported from Azerbaijan.

3.1.1.2 Nuclear power

Since the expected lifetime of a nuclear power plant is 60 years, investing in its construction means a long term commitment and with certain controversy which nuclear power production presents it is vital to have stable support of both the government and people. In order to make people feel safe about having a nuclear powerplant in their near vicinity, it is necessary to emphasize the upsides and address all the issues resulting from nuclear power production.

Probably the most defining issue of nuclear energy is the waste and fuel management. Radioactive waste remains dangerous for human health for several thousands of years and since the only possible solution is storage, it is problematic to determine a storage space which will not be rejected by the public. It is expected that power plants of generation IV (which are currently on trial) will be able to utilize burnt out nuclear fuel from older power plants for energy production which would reduce the amount of waste in general. The fuel can also pose a threat if not handled properly but unlike coal, the physical amount of fuel needed for energy production is minimal and easily stored so it can be transported anywhere and stored in the vicinity for the whole lifetime of a power plant.

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[12] FG Forrest, s. (2019). *ČEZ uzavřel dlouhodobou smlouvu na dodávku uhlí pro elektrárnu Počerady se skupinou Czech Coal | Aktuální témata | Skupina ČEZ*. [online] Cez.cz. Available at: https://www.cez.cz/cs/pro-media/aktualni-temata/38.html [Accessed 20 Feb. 2019].

Not every country should produce nuclear energy because the necessity of an educated and technologically developed society is crucial.[13]

Energy produced by nuclear power plants is an essential part of the Czech energy mix. The Czech Republic currently has two power plants – Dukovany and Temelín. Dukovany has four reactors VVER-440, each with installed output 510MWe and Temelín has two reactors VVER 1000 with 1055MWe. Together they produce 4150MWe of energy, which accounts for approximately 35% of the Czech Republic energy demand. Because of the impending shutdown of Dukovany, due to its reaching the end of lifespan in 2035, it is necessary to prepare for the deficit which would occur. In case the government decides to maintain the amount of produced nuclear energy it will be necessary to build two new reactors. There are more potential locations for construction, but the most prepared in terms of project planning is Temelín where new reactors could join those already operating. However, since Dukovany are supposed to be shut down completely, reactors might be built there in order to achieve optimal utilization or infrastructure. Nuclear energy is a type C power source.

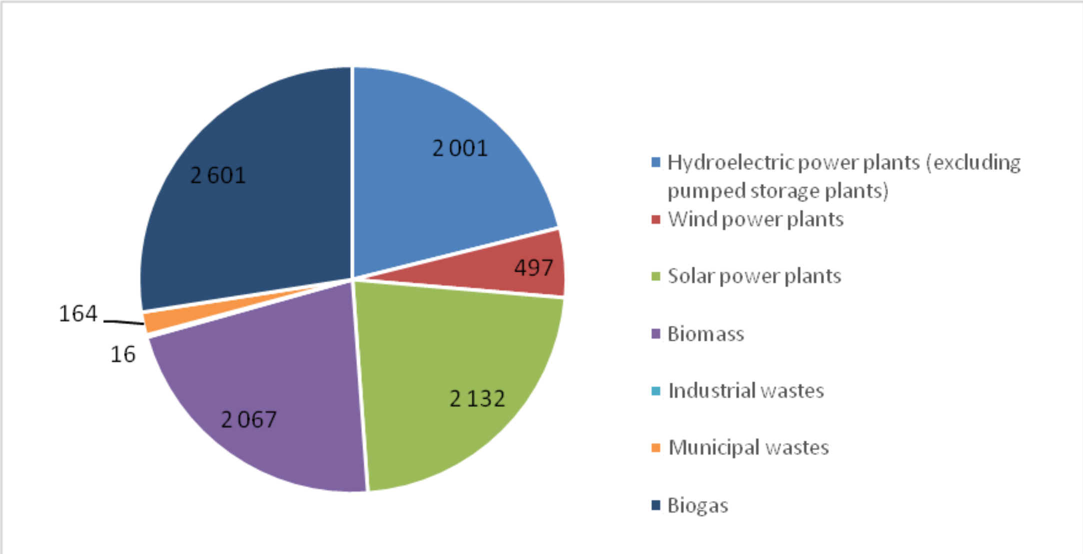
3.1.2 Renewable resources

The Czech Republic currently utilizes renewable resources for producing 10% of the total energy, and it is realistic to expect 30% of energy coming from renewable resources in 2050. However, the transfer from non-renewable to renewable resources needs to be gradual because energy security has to be maintained at all costs. It is also unreasonable to expect a rapid increase in share of renewable energy in 2022 since appropriate technology is not yet available on the market (e.g., turbines which are possible to place on the roof, air conditioning which will not be damaged by inconstant energy supply, the transmission network is not prepared for waves of energy, machinery enabling accumulation and smart energy systems). However, in 2035 the share of energy produced from renewable resources could double. Another aspect which cannot be omitted is that the

[13] Wagner, V. (2018). *Současný stav a budoucnost jaderné energetiky* [online] oEnergetice.cz. Available at: https://oenergetice.cz/elektrina/soucasny-stav-budoucnost-jaderne-energetiky-dil-1/ [Accessed 20 Feb. 2019].

energy sector needs to be considered as a whole and therefore it is not possible to support or subsidize just one branch.

Figure 5 Share of renewable resources on energy production in 2017 (GWh)



Source: ERÚ- Zprávy o provozu elektrizační soustavy[14],own data processing

3.1.2.1 Solar energy

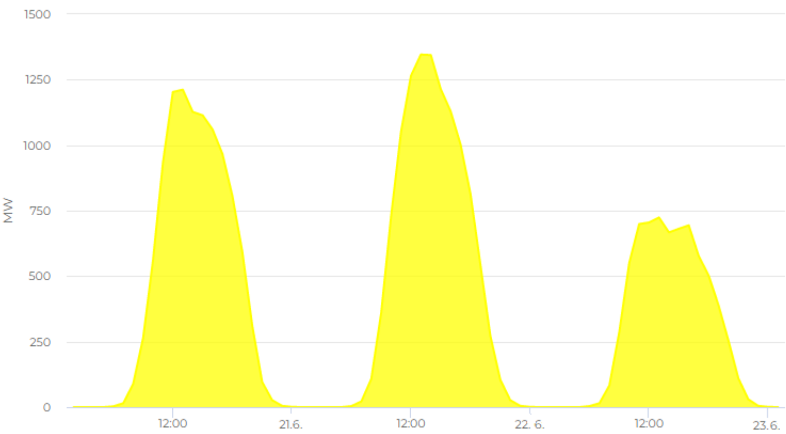
Photovoltaic or solar power plants belong to the category of renewable energy resources. They utilize an undepletable source of energy – sunshine, and during energy production, no emissions are released. Thanks to these attributes solar power plants are favorable to society. The average efficiency of energy production from photovoltaic panels is 10-35%, based on the weather conditions in the location and over time the efficiency decreases by approximately 0,5% per year. Photovoltaic solar panels can have many sizes from small ones attachable the roofs to large planes which can add up to create farms. It is also possible to gradually increase the number of panels which lowers the investment risk. Since it is possible to forecast weather for the 2 following days as well as

[14] Eru.cz. (2019). *ERÚ - Zprávy o provozu elektrizační soustavy*. [online] Available at: https://www.eru.cz/cs/zpravy-o-provozu-elektrizacni-soustavy [Accessed 20 Feb. 2019].

he times of sunrise and dawn, there is a certain level of short-time prediction of the amount of energy produced however solar energy is type source D.

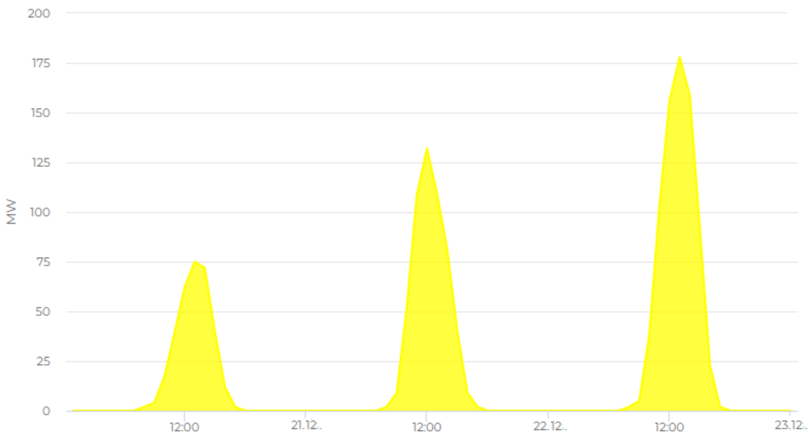
As depicted on the Figure 6 and 7, the production of energy from solar power plants is not nearly balanced and even during the longest days of the year, there are still several hours long periods for which the produced amount is zero. Until the accumulation of energy is possible to the extent where at least during the spring to fall solar energy can be stored and utilized in decentralized structure for the whole 24 hours, solar energy can be used solely for coverng the peak hours or lowering the energy consumption in the context of individuals.

Figure 6 Distribution of PV energy production during summer solstice (2017)



Source: Energostat[15]

Figure 7 Distribution of PV energy production during summer solstice (2017)



Source: Energostat

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15 Oenergetice.cz. (n.d.). [online] Available at: https://oenergetice.cz/energostat [Accessed 22 Mar. 2019].

Solar power plants can be divided into two types – thermal and photovoltaic. Thermal power plants are primarily suitable for heating water thus heating in general. Concentrated thermal solar power plants use mirrors which helps to concentrate the sunshine into the area of efficiency and that enables the plant to reach much higher temperatures than the previous type and potentially enables the transformation of sunshine to electric energy. The second type of powerplant is photovoltaic which uses the direct transformation of solar energy to electric energy. [16]

According to ERO in 2016, there was over 20 000 operating solar power plants with a total installed output over 2 000 MW in the Czech Republic. Approximately half of that was accounted for by powerplants with output between 1 and 5 MW. Czech photovoltaic powerplants produced approximately 2.26 TWh of brutto energy which amount to 2.7% of the brutto production.

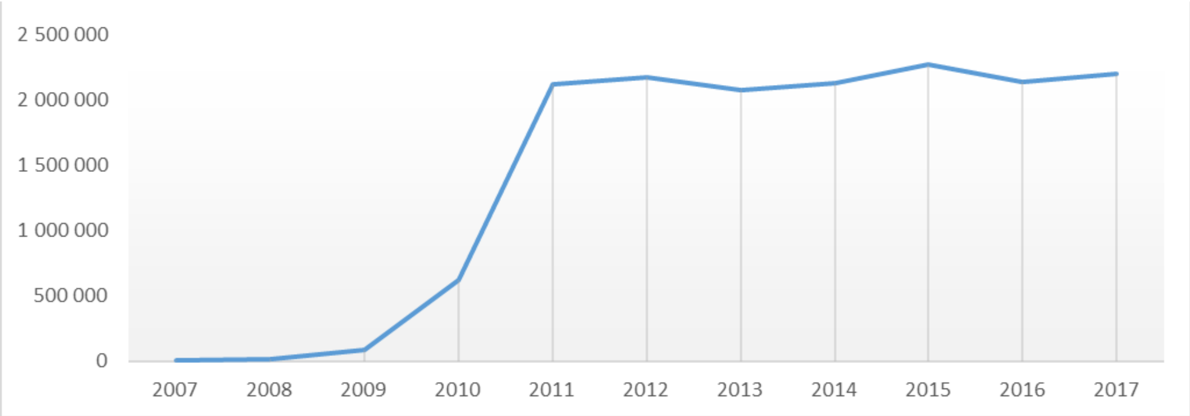
The opportunities for expansion of photovoltaic power plants in the Czech Republic are limited because of the geographical aspects. The Czech Republic is located in the middle latitude, so the efficiency of PV is not ideal, just about 9-13%, and many of the suitable locations are unusable because they are located in protected areas. However if the global approach was taken in the future, photovoltaic panels around the equator could provide a sufficient amount of energy to replace a large amount of fossil energy. For the Czech Republic the utilization of the solar energy is expensive, non-reliable and insufficiently effective until the accumulation issue is solved.

In 2009 and 2010 subsidizing fail occurred in the Czech Republic which resulted in an unprecedented boom of solar energy production. The Czech Republic, which committed to producing 13% of electricity from renewable energy sources by 2020, attempted to motivate people into the utilization of the solar energy with a financial incentive, specifically increased guaranteed prices for electricity from solar energy. The prices went from 6CZK/kW to 15CZK/kW for a minimum of 20 years after the solar panel purchase and the annual purchase price reduction was limited to 95% in order to ensure the return on

[16] Masili, A. (2018). *The true carbon footprint of photovoltaic energy – ONE Only Natural Energy*. [online] Onlynaturalenergy.com. Available at: http://www.onlynaturalenergy.com/2018/07/the-true-carbon-footprint-of-photovoltaic-energy/ [Accessed 20 Feb. 2019].

investment period to be 15 years maximum. The demand for photovoltaic panels multiplied practically overnight, and the guaranteed prices made it impossible for the government to respond to the uncontrollable increase of the number of photovoltaic panels. In 2008 the installed capacity was 40 MW, in 2010 it was already 1959 MW - at that time the 4th most massive installed output in Europe behind Germany, Italy, and Spain.

Figure 8 Production of photovoltaic energy (MWh)



Source: ERÚ- Zprávy o provozu elektrizační soustavy[17]*,own data processing*

The number of subsidies that the government was forced to provide resulted in an increase in the electricity price for the customers through renewable resources support. In 2006 the contribution to the supported energy source was 28 CZK / MWh, in 2013 it reached the highest value of 583 CZK / MWh. In the following years, it was forcibly stopped the value of 495 CZK / MWh, with the remainder being paid from the state treasury for the proceeds of the solar tax. In 2013 the amount of money paid to meet the obligation towards the solar power plant owners was CZK 11.7bn. Energy for the Czech industry in has become the most expensive in Europe thus reducing the competitiveness of Czech companies.

In 2012, 66% of the support of renewable resources was used for solar power plants which produced only a quarter of all renewable energy in the Czech Republic which

[17] Eru.cz. (2019). *ERÚ - Zprávy o provozu elektrizační soustavy*. [online] Available at: https://www.eru.cz/cs/zpravy-o-provozu-elektrizacni-soustavy [Accessed 20 Feb. 2019].

accounted for 3% of total consumption. At the end of 2014 support begun to be used for more efficient energy sources such as hydroelectric power plants and biomass boilers.

Even though the energy production itself does not cause any emissions the process of manufacturing of the power plant, its transportation and disposal are not without environmental impact. Particularly the recycling of the solar panel which reached the end of its life cycle has a hazardous potential because of all the toxic substances used for its manufacturing (e.g., copper, lead, gallium, selenium, indium, cadmium, and tellurium). The expected lifetime of solar panel is approximately 30 years, and since the biggest boom of solar power plants in the Czech Republic was in 2009-2010, the first phase of photovoltaic recycling industry development should be in progress.

The estimated period in which a photovoltaic panel produces enough energy necessary for cleaning the carbon dioxide emitted during its manufacturing is approximately 6 months. In countries, the environmental impacts are more severe, for example in China which uses mostly fossil fuels for energy production the carbon footprint is almost twice as big as in the USA.

Since most of the photovoltaic panels for the Czech Republic were produced in China, not only the number of emissions released as a result was more extensive than necessary, but also the revenues for purchasing them did not go to the Czech energy sector where it should have been used for research and development or curbing the losses caused by the occurred subsidizing fail.

3.1.2.2 Wind energy

Wind power is mostly utilized for electricity production by transforming the kinetic energy of wind into electric energy. Based on the magnitude of the energy production the wind turbines can be divided into 3 groups - small (up to 40 kW), medium (from 40 to 500 kW) and large (from 500 kW above). If there are more wind turbines in one place, we are talking about a wind farm. [18]

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[18] Vitejtenazemi.cz. (2019). *Větrná energie | Vítejte na Zemi*. [online] Available at: http://www.vitejtenazemi.cz/cenia/index.php?p=vetrna_energie&site=energie [Accessed 20 Feb. 2019].

In the Czech Republic, the energy produced by wind power plants is rather marginal. That is mainly caused by geographical aspects of its location since ideal locations for wind power plants are open plains, seashore and mountain ridges and it is highly ineffective to construct wind power plants in other areas. By way of indication, if performance is taken as a basis sea-level wind turbines, that at 500 m, the output will be 5% lower, 7% higher at 800 m and 1200 m at sea level by 11%.[19] Even so, there are several, especially mountain areas, where wind power plants are built in the Czech Republic, such as Krusnohorsko, Jesenicko, and Bohemian-Moravian Highlands. Based on the location the efficiency of wind power plant ranges between 15 and 50%. In the Czech Republic, it is not profitable to build turbines for other than decentralized supply because of the proximity of the German wind farms which have much more favorable conditions for electricity production from wind and therefore in the windy weather the prices of their energy are significantly lower. However, the unstable waves of energy surplus pose a threat to the transmission network of both Germany and their neighboring states.

Wind energy production experienced a sudden increase in production, the amount of energy produced by wind power plants went from 6,2 GW in 1996 to 54,8 GW in 2016. Wind is suitable as both a centralized and decentralized source of energy. It is possible to increase production gradually which leads to a decrease in investment risk.

Wind power is also disadvantaged by its low capacity factor and eventhough it is cheaper than the PV energy, it occupies even more space. Off shore wind turbines do not take up any space but have high costs and need to correlate with the sea governance. The construction is relatively short (lasts up to two months) and after completion of wind turbines will be dismantled within 1-2 days. Wind power plants allow the multifunctional use of agricultural land. Agricultural land can be used almost in its original form as in the case of power lines. However, most of the areas of wind potential identify with the protected landscape areas in the Czech Republic (around 60-70%)[20].

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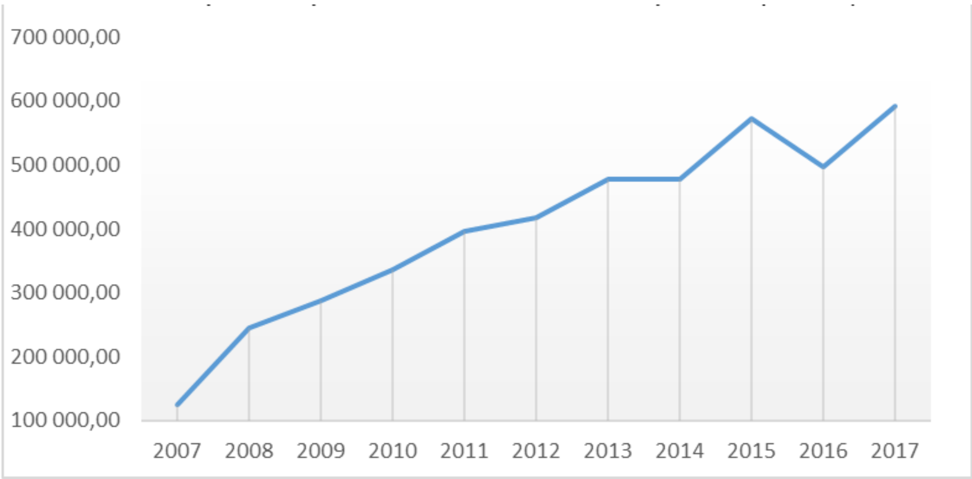
[19] Motlík, J., Šamánek, L., Štekl, J., Pařízek, T., Bébar, L., Lisý, M. and Pavlas, M. (2007). *Obnovitelné zdroje energie a možnosti jejich využití pro ČR*. [online] Cez.cz. Available at: https://www.cez.cz/edee/content/file/vzdelavani/obnovitelne_zdoje_energie_a_moznosti_jejich_vyuziti_pro_cr.pdf [Accessed 13 Mar. 2019].

[20] Motlík, J., Šamánek, L., Štekl, J., Pařízek, T., Bébar, L., Lisý, M. and Pavlas, M. (2007). *Obnovitelné zdroje energie a možnosti jejich využití pro ČR*. [online] Cez.cz. Available at: https://www.cez.cz/edee/content/file/vzdelavani/obnovitelne_zdoje_energie_a_moznosti_jejich_vyuziti_pro_cr.pdf [Accessed 13 Mar. 2019].

Figure 9 Wind power production in the Czech Republic (MWh)



Source: ERÚ- Zprávy o provozu elektrizační soustavy[21]*,own data processing*

There are two types of noise the wind power plant emmits - mechanical noise, the source of which is the engine and aerodynamic noise that is caused by the interaction of the flowing air with the surface of the rotor blades. Wind farms, especially on high tubes or wind farms, disrupt the landscape but not more than high-voltage lines, factory chimneys or other technical facilities which are also necessary for the population. Even though wind energy is an infinite source that does not cause emission release, there are still many of their opponents who are displeased with the disruption of landscape wind farms pose and the noise they produce.

3.1.2.3 Hydro energy

Water is the most traditionally used renewable resource in both the Czech Republic and the world in general. In the past, the water was apart from transportation mainly used in the production industry such as water hammers and mills, and now it is primarily used for electricity production. Based on its installed output hydropower plants can be divided into two groups- small (up to 10 MW) and large (over 10 MW). Hydroelectric power plants account for approximately 3.5% of electricity production in the Czech Republic.

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[21] Eru.cz. (2019). *ERÚ - Zprávy o provozu elektrizační soustavy*. [online] Available at: https://www.eru.cz/cs/zpravy-o-provozu-elektrizacni-soustavy [Accessed 20 Feb. 2019].

With a few exceptions, all large Czech hydropower plants are located on the Vltava River, where they form the so-called Vltava cascade. [22]

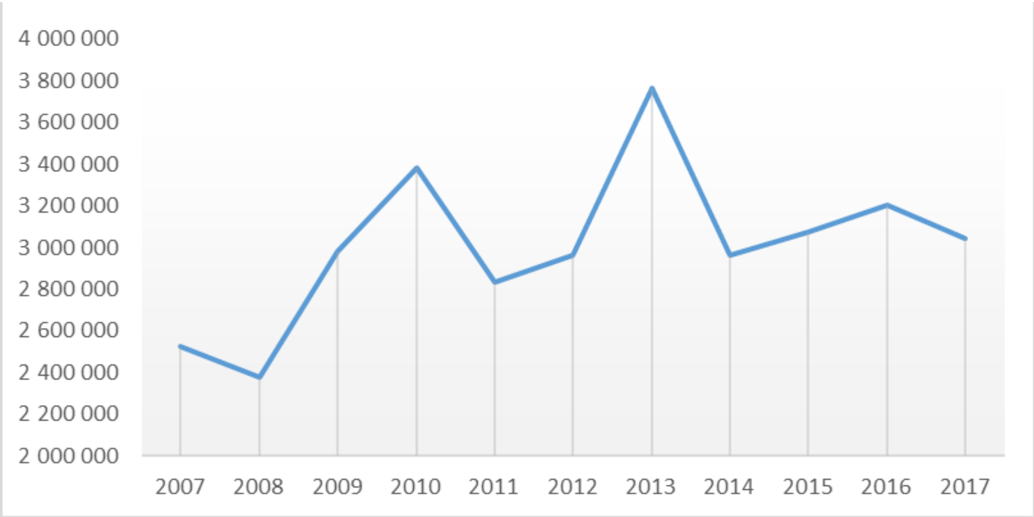
There are three main types of hydropower plants: impoundment (sometimes also called conventional), diversion, and pumped storage. The most common type of hydroelectric power plant is an impoundment facility which transforms of potential energy of dammed water into electric energy via generator turbine. Water is released from the dam arbitrarily either to maintain the level of the reservoir or when there is a change in electricity demand. The second type, diversion, have no or minimal reservoir capacity and the energy is produced solely from upstream which means that surplus cannot be utilized in any way. Pumped storage hydropower plant is the only tool used for accumulation of energy. It consists of two connected reservoirs in different heights. In times of energy surplus, the water is pumped into the upper reservoir from where it can be released to the lower one through a turbine generator when the necessity of energy release emerges.[23]

In the Czech Republic, there are 9 big (over 10MW) hydropower plants with a total installed output 753MW and 1614 small hydropower plants with a total installed output 348 MW. Apart from classic hydropower plants, there are 3 pumped storage plants - Velké Stráně (650 MW), Dalešice (480 MW) and Štěchovice II (45 MW). [24]Pumped storage is the only type A energy source owned by the Czech Republic; other hydropower plants are type B. Hydro powerplants are suitable for covering for type D sources. As depicted on the Figure 8 and Figure 9, the hydropower plants do not provide stable supply of energy and virtually can be used solely for covering the peaks of demand.

[22] Vitejtenazemi.cz. (2019). *Vodní energie | Vítejte na Zemi*. [online] Available at: http://vitejtenazemi.cz/cenia/index.php?p=vodni_energie&site=energie [Accessed 20 Feb. 2019].
[23] Energy.gov. (2019). *Types of Hydropower Plants*. [online] Available at: https://www.energy.gov/eere/water/types-hydropower-plants [Accessed 20 Feb. 2019].

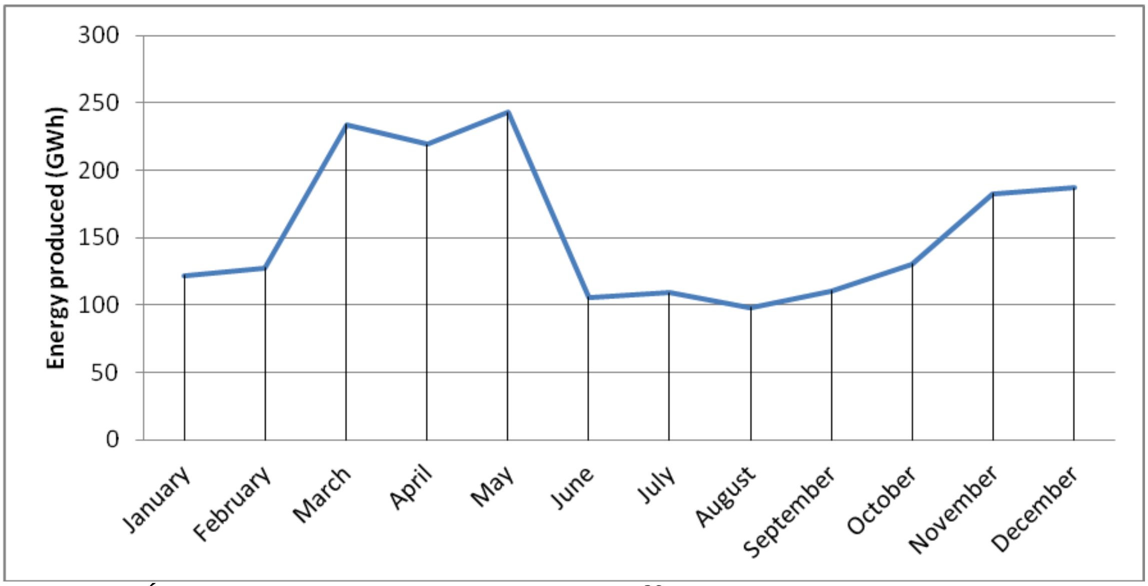
[24] Vobořil, D. (2016). *Vodní elektrárny - princip, rozdělení, elektrárny v ČR*. [online] oEnergetice.cz. Available at: https://oenergetice.cz/elektrina/vodni-elektrarny-princip-a-rozdeleni/?fbclid=IwAR2BoaEUhR0bUPwalisNRL_VuASshZ97vIPdAaRJGBkmS1tVDUMFR8YOJXw [Accessed 20 Feb. 2019]

Figure 10 Hydroenergy production in the Czech Republic (MWh)



Source: ERÚ- Zprávy o provozu elektrizační soustavy[25]*,own data processing*

Figure 11 Hydroenergy production (2017)



Source: ERÚ- Zprávy o provozu elektrizační soustavy[26]*,own data processing*

[25] Eru.cz. (2019). *ERÚ - Zprávy o provozu elektrizační soustavy*. [online] Available at: https://www.eru.cz/cs/zpravy-o-provozu-elektrizacni-soustavy [Accessed 20 Feb. 2019].

[26] Eru.cz. (2019). *ERÚ - Zprávy o provozu elektrizační soustavy*. [online] Available at: https://www.eru.cz/cs/zpravy-o-provozu-elektrizacni-soustavy [Accessed 20 Feb. 2019].

The return on investment is currently estimated in 15 years for the run off river power plants. However since the life expectancy of the power plant is with proper maintenance even hundred years the long return on investment period is not criticalfor investors. There is also a possibility of obtaining the governmental support provided for renewable energy sources.

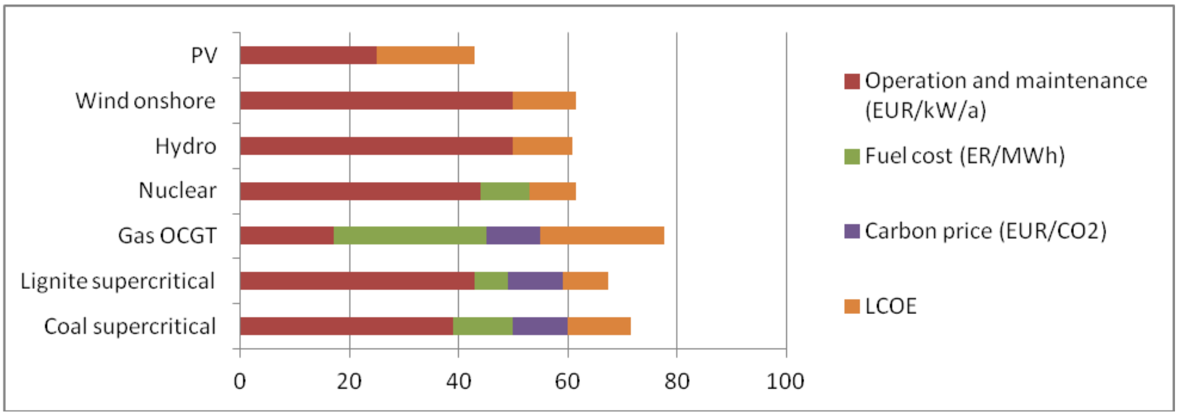
Eventhough hydropower plants do not emmit emissions and they use an infinite source of energy instead of fuel, their impact on the environment has been deemed negative my many specialsts. Especially the construction of water reservoirs with priority hydropower utilization is the subject of extraordinary attention and often hard criticism. This criticism is motivated by concerns about destruction of valuable natural complexes in the affected areas, especially the so-called river phenomena with a number of animal and plant species.

3.2 Energy mix composition

Energy mix has to fullfil several criteria in order to be considered as feasible. Specifically it is energy security, economic efficiency, enviromental compatibility and positive impacts on the macroeconomy. Energy security, prerequisite for the operable energy mix, is more difficult to achieve since the energy demand has been increasing rapidly for several years andd this trend is not estimated to cease. The large demand for energy leads to international competition in terms of resources and causes the negative impacts of non-renewable resources utilization to become potentialy fatal but since the consumption is not expected to decrease, these issues needs to be solved in order to maintain functioning global energy sector.

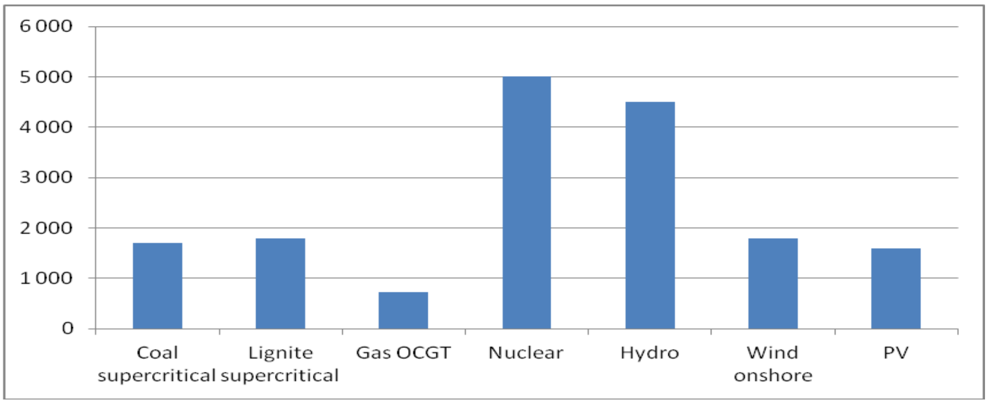
Every resource utilization has advantages and disadvantages as well as different costs compossition. While photovoltaic panels and wind turbines do not require fuel supply since they utilize an infinite power source, for natural gas the cost of fuel composes the biggest part of the price. Fuel for nuclear power plants is relatively cheap (in comparison with the energy production) but the costs of operation and maintanence are extremely high since the potential malfunction could have fundamental consequences.

Figure 12 Variable costs composition



Source: vgb.org[27], own data processing

Figure 13 Investments cost (EUR/kWh)



Source: vgb.org[28], own data processing

Carbon footprint is an indicator of energy, product and service consumption impact on the environment by measuring the amount of greenhouse gases that correspond to the company's activities or production. Carbon footprint calculation is used as a measure of of observing the international comittments such as Kyoto Protocol as well as the national and corporate commitments to reduce greenhouse gas emissions. Reducing the carbon footprint of the businesses contributes to climate protection by decreasing of the greenhouse effect

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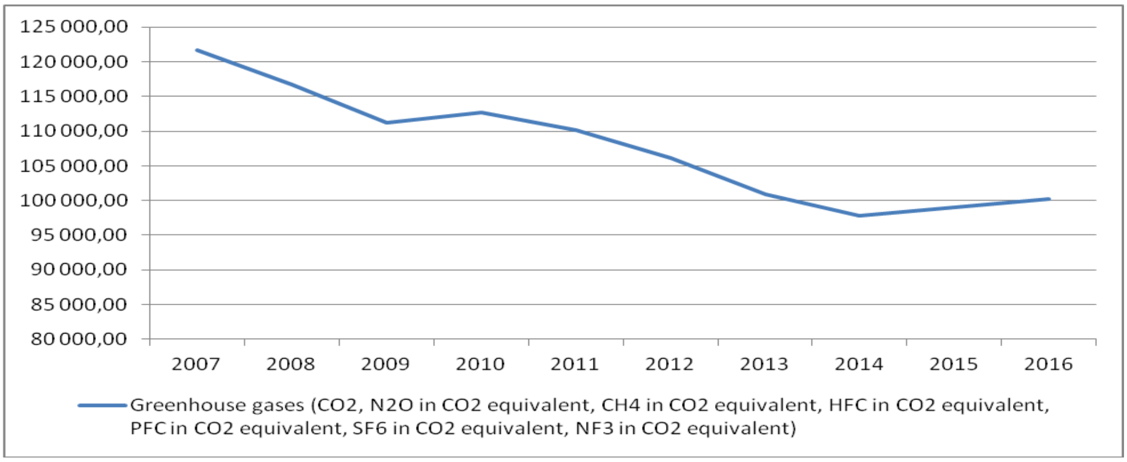
27 Vgb.org. (2018). - *VGB PowerTech*. [online] Available at: https://www.vgb.org/en/annual_report.html [Accessed 13 Mar. 2019].

28 Vgb.org. (2018). - *VGB PowerTech*. [online] Available at: https://www.vgb.org/en/annual_report.html [Accessed 13 Mar. 2019].

and companies therefore use the carbon footprint as one of the key indicators of social responsibility and environmental sustainability. For entities involved in the European Emissions Trading Scheme, reporting GHG emissions is compulsory. GHG Protocol procedure divides emissions into 3 categories by origin: direct emissions (where emissions are released directly to the air), indirect emissions (related to consumption of purchased energy) and emissions resulting from activities that arise from sources outside the control or ownership of the enterprise (such as emissions released from plane used for travelling during business trips or depositing waste in a landfill). [29]

Figure 14 Greenhouse gases trajectory in the Czech energy sector (thousand tonnes)



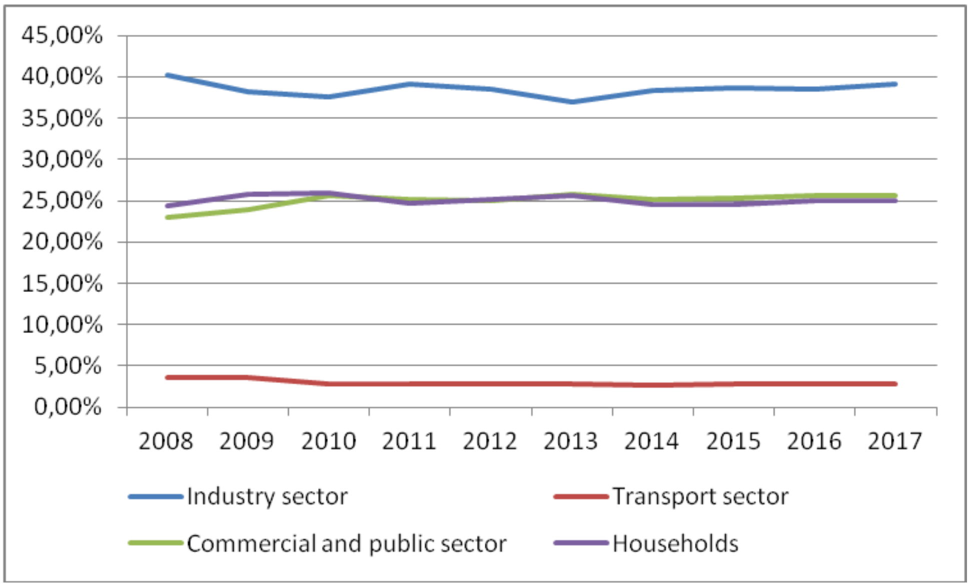
Source: Eurostat[30], own data representation

Energy sector operations severely affect the macroeconomy of every state. However, the Czech Republic which is an industrial economy with majority of energy consumed in the industry sector is even more dependent on energy supply than many other states. Potential shortage or in an extreme case blackout would lead to major decrease of GDP. Simmilarly if prices of energy increased the competetiveness of the Czech producers would be threatened and the GDP would be negativelly affected as well.

[29] Snizujemeco2.cz. (n.d.). *Uhlíková stopa | Snižujeme CO2*. [online] Available at: https://snizujemeco2.cz/cs/uhlikova-stopa [Accessed 13 Mar. 2019].

[30] Ec.europa.eu. (2018). *Database - Eurostat*. [online] Available at: https://ec.europa.eu/eurostat/data/database?node_code=nrg_cb_e [Accessed 13 Mar. 2019].

Figure 15 Electricity consumption by sector as a % of GDP



Source: Eurostat[31], own data representation

Since the cheapest and also the cleanest is the energy that does not have to be produced at all, therefore energy conservation is the only energy solution with no environmental impact. However, energy conservation should not be pursued in form of decreasing production or comfort of people but rather with the help of modern technologies and good practices. Although excessive demands for manufacturers to conserve energy might lead to losing competetiveness and relocation of manufacturers abroad, reasonable requirements in terms of technology or resources management could apart from decrease in energy consumption event induce increase of profit. Commitments to energy saving are the goals of national policies of developed countries, but it should be taken for granted that all individuals will contribute through their behavior. It is expected that in the near future the state-wide resolutions will be passed in forms of load management, smart cities concepts or as an aspect of industry 4.0.

[31] Ec.europa.eu. (2018). *Database - Eurostat*. [online] Available at: https://ec.europa.eu/eurostat/data/database?node_code=nrg_cb_e [Accessed 13 Mar. 2019].

3.2.1 Triangulation of costs, emissions and consumption

Every feasible energy mix needs to find and maintain balance between cost of generated electricity and amount of produced emissions while attempting to produce as much energy as possible. Every energy mix option has disadvantages and advantages in terms of stability of supply, economic efficiency and global warming mittigation.

Eventhough renewable energy is enviromentally more favourable it poses threats in terms of costs fluctuations, unstability of supply and siting restrictions. Hydro, photovoltaic and wind energy are disadvantaged by their low capacity factor and the dependence on external factors. Furthermore eventhough the renewable energy has less devastating impact on the environment it is still not environment neutral. Wind turbines and both water dams and run-off-the river plants disrupt the ecosystem and PV panels include a high amount of toxic substances which also pose a threat to nature.

However, non-renewable sources are not optimal either. Oil has a great utility but fluctuating prices and supply, natural gas energy provides stable supply, relatively low emission release but the fuel is expensive and coal energy granted provides stable energy supply, possibility to regulate the output and its generation is not expensive, but the amount of emmissions released into the atmosphere is gigantic. Nuclear energy is great in ensuring energy security, provides a stable supply, is cost effective and compatible with the environmental protection but poses a risk in terms of the radioactive waste and in case of a disaster it poses a threat to global society.

Impact on environment and cost of electricity generation are closely related. The costly externalities aside, price of electricity is also driven by emission allowances. Emission allowances determine what is the exceptible amount of greenhouse gases produced in Europe per certain time period and allocate according number of allowances to each EU member state. Member states then divide their share among the greenhouse gas producers in their territory. One allowance allows one tonne of carbon dioxide to be released into the air and if enterprise wants to release more, it has to buy more allowances at European energy exchanges market. Higher the market price is, the more the more expensive is the price of electricity. For the years 2013 to 2019, the Czech Republic has almost 108 million emission allowances available and of this amount, the state has already distributed 96 million. Most of them were granted to ČEZ Group. [32]

3.2.2 Current energy mix of the Czech Republic

The Czech energy sector has gone through many significant changes since the beginning of the century. Apart from the liberalization of the electric energy and biogas markets the share ratio of the Czech energy mix changed accordingly. Domestic consumption of electric energy last year was the highest since 1990. According to ERO, brutto net consumption increased to 72,4 TWh, and the netto consumption reached the 60,9 TWh. The most significant increase in consumption occurred in households, which increased from 2015 by 437 GWh which amounts to a 3% increase. Further energy consumption development will depend on many factors, but a certain increase in energy consumption is very probable with the predicted automatization and electrification of industry and electromobility. [33]

Figure 16 Energy sources production crieteria (2017)

Resource	Installed output (MWh)	Production (MWh)	Capacity factor	Full load hours
Wind energy	308,00	591 000,00	19.09%	1 673
Nuclear energy	4 290	28 339 600	78.45%	6877
Hydroenergy	2 264	3 040 000	15.44%	1354
PV energy	2 070	2 193 400	9.27%	739
Coal energy	13 335	52 873 700	48.18%	4224

Source: csve.cz[34], own data processing

[32] solidpixels., h. (2018). *Emisní povolenky ženou ceny elektřiny nahoru*. [online] Carbounion. Available at: https://www.carbounion.cz/radce/emisni-povolenky-zenou-ceny-elektriny-nahoru-jak-to-bude-dal [Accessed 22 Mar. 2019].

[33] Majling, E. (2017). *Spotřeba elektřiny v ČR loni dosáhla desetiletého maxima*. [online] oEnergetice.cz. Available at: https://oenergetice.cz/elektrina/spotreba-elektriny-cr-loni-dosahla-desetileteho-maxima/ [Accessed 20 Feb. 2019].

[34] Csve.cz. (2017). *Aktuální instalace - ČSVE - Větrné elektrárny | Větrná energie*. [online] Available at: http://www.csve.cz/clanky/aktualni-instalace-vte-cr/120 [Accessed 13 Mar. 2019].

The Czech Republic currently gains 50% of energy from combustion of brown coal (with the gas blocks it puts fossil fuels slightly over 50% of the share), 35% energy comes from nuclear sources and the rest is gathered from renewable resources (including the waste processing). Coal-based power plants contribute to the energy mix by 10 GW, gas by 2 GW, nuclear power accounts for 4 GW and hydropower plants (including pumped storage) for 2 GW which altogether surpasses the amount demanded. In the last years, the gross energy production was approximately 80 TWh out of which 60 TWh was necessary for satisfying the demand, and the rest was exported. The Czech Republic is an energy exporter and provides its transmission network for the transportation of energy between the north and south of Europe. Germany which thanks to its coastal wind power plants deals with intermittent energy production and sends produced energy to be accumulated in pumped storage dams in Austria through the Czech Republic. This causes that Germany stores energy cheaply but buys it out expensively while the Czech Republic is not adequately compensated for providing the transit route and security. Although there is a possibility of a model where a share of produced energy is used to compensates participants. [35]

According to the Energy Regulatory Office (ERO) report[36] on the operation of the power plants system, domestic electricity consumption in 2017 rose to its highest over the past 10 years. Gross electricity consumption in the Czech Republic grew last year from 72.4 TWh to 73.8 TWh, and similarly, net consumption has also risen to its ten years maximum. Consumption rose most in households - consumed 437 GWh (+ 3%) more electricity in 2017 than in 2015.

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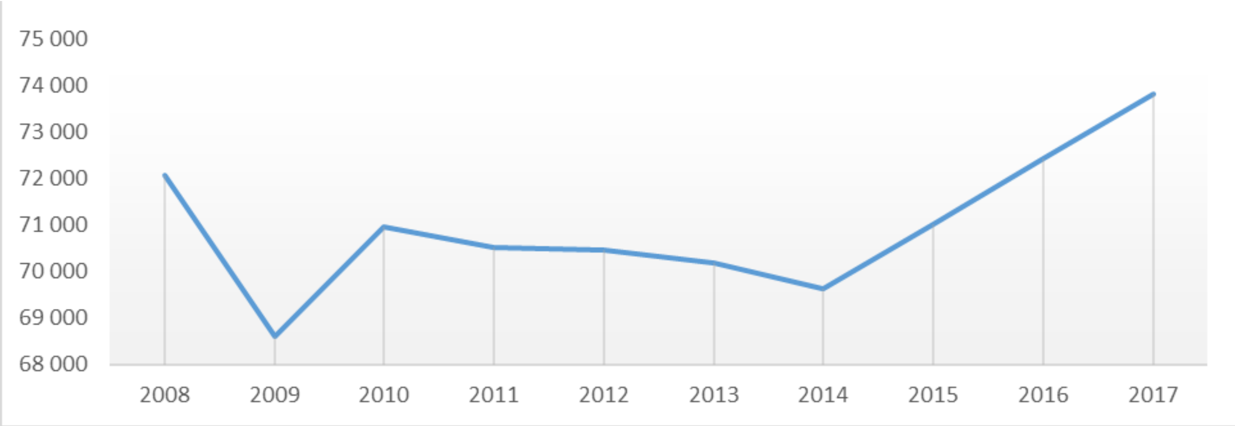
[35] oEnergetice.cz. (2017). *Infografika: Česká energetika v 21. století*. [online] Available at: https://oenergetice.cz/energetika-v-cr/infografika-ceska-energetika-21-stoleti/ [Accessed 20 Feb. 2019].

[36] Eru.cz. (2019). *ERÚ - Zprávy o provozu elektrizační soustavy*. [online] Available at: https://www.eru.cz/cs/zpravy-o-provozu-elektrizacni-soustavy [Accessed 20 Feb. 2019].

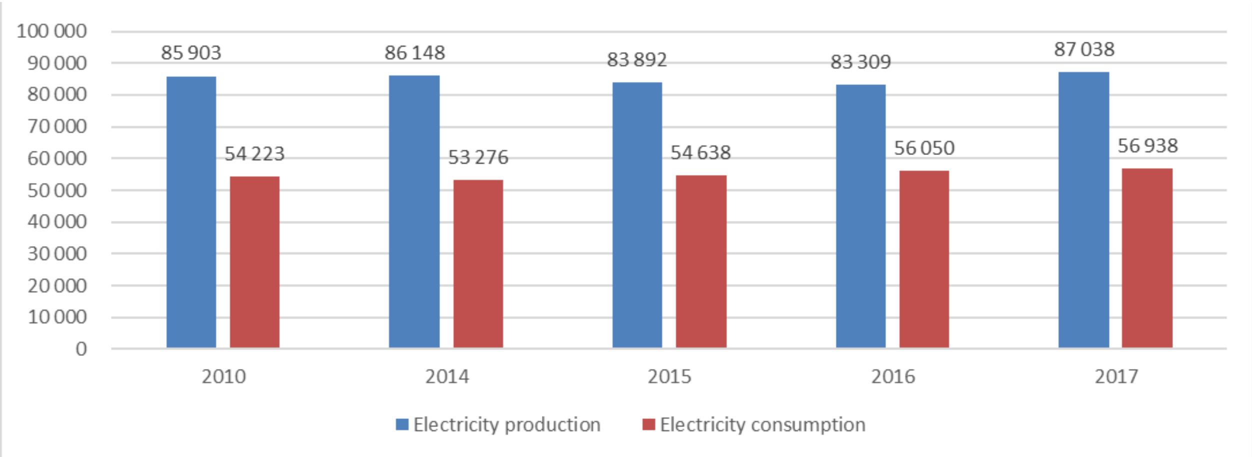
Figure 17 Electricity consumption Brutto (GWh)



Source: ERÚ- Zprávy o provozu elektrizační soustavy[37],own data processing

The electricity production and exports decreased slightly in comparison with the previous years. As in previous years, 2017 negative balance was almost 11 TWh. Despite the higher cross-border flows from the Czech Republic, the balance decreased by 590 GWh (- 12.3%) compared to 2015. Considering the increase in consumption and production decline, the net export value decreased slightly in 2016 but in 2017 increased almost back to the 2015 level.

Figure 18 Balance of production and consumption (milion kWh)

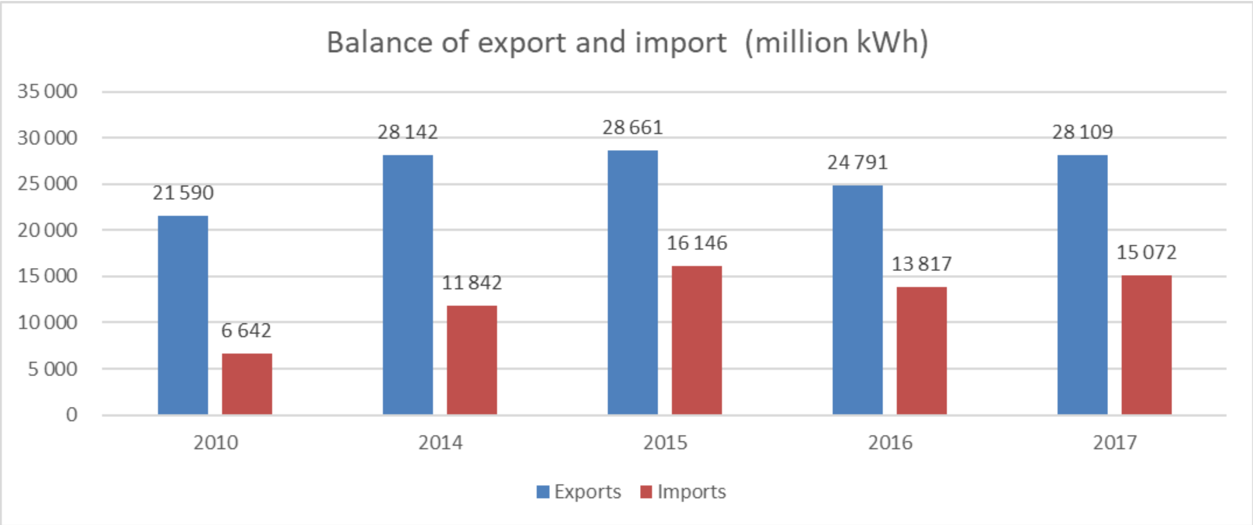


Source: ERÚ- Zprávy o provozu elektrizační soustavy[38],own data processing

[37] Eru.cz. (2019). *ERÚ - Zprávy o provozu elektrizační soustavy*. [online] Available at: https://www.eru.cz/cs/zpravy-o-provozu-elektrizacni-soustavy [Accessed 20 Feb. 2019].

Total gross electricity production has been gradually decreasing for four consecutive years and in 2016 has reached 83.3 TWh, which is 586.4 GWh less (- 0.7%) than in 2015. However, in 2017, the production increased to 87 TWh. Production last year was traditionally dominated by coal, coal-based power plants accounted for 36.2 TWh of electricity.

Figure 19 Balance of export and import (million kWh)



Source: ERÚ- Zprávy o provozu elektrizační soustavy[39]*,own data processing*

Nuclear power plants, the second most significant contributors of the energy production sector accounted for 24.1 TWh with the year-on-year decrease of production by 2.7 TWh which occurred among other difficulties because of the completion of welding controls and preparation of the Dukovany for further operation. The most substantial year-on-year increase in gross electricity production, by almost 50%, was reported in 2016 with 1300 GWh for gas-fired power plants, although their installed capacity remained the same as the

[38] Eru.cz. (2019). *ERÚ - Zprávy o provozu elektrizační soustavy*. [online] Available at: https://www.eru.cz/cs/zpravy-o-provozu-elektrizacni-soustavy [Accessed 20 Feb. 2019].

[39] Eru.cz. (2019). *ERÚ - Zprávy o provozu elektrizační soustavy*. [online] Available at: https://www.eru.cz/cs/zpravy-o-provozu-elektrizacni-soustavy [Accessed 20 Feb. 2019].

year before (1 363 MW). Due to the unsuitable weather conditions, energy production from Czech wind turbines decreased by 76 GWh(- 13%). A decrease in production has also occurred in the case of photovoltaic power plants with a capacity of 2068 MW at the end of last year. Compared to 2015, their production was lower by 132 GWh (by 6%).

Approximately 5-10% of the energy consumed was dispensable, in other words, shortage in that extent would not significantly affect the comfort of the people such as a temporary shutdown of electronic billboards and advertisements, illumination of shop windows, limiting the lighting on corridors to half of the fluorescent lamps, lowering the heating by 5 degrees.

3.2.3 Energy market and transmission network

The main features of trading with electricity is no possibility of storage and the unique process of transport. Since electricity is transferred through the grid from the producer to a consumer through the path of least resistance, it is impossible to identify the energy produced in a particular source, let alone send it to a designated consumer.

In order to balance the power grid the amount of the energy delivered must be equal to the amount of the energy withdrawn (plus transmission losses). If this criterion is not fulfilled, the transmission network will experience surplus performance which will increase the network vulnerability to power failure and network frequency degradation. In order to avoid this situation, each national electricity system is subordinated to a dispatching center which, by means of control ensures the balance of power. In the Czech Republic ČEPS, a.s. has been entrusted with this task. Electricity traders are responsible for the deviation they cause. Under certain consequences this responsibility can be transferred - a typical example is a household type consumer who uses energy as needes and the trader with whom he has a contract is responsible for him.

It is, therefore, possible to divide the electricity market consumers into retail and wholesale - wholesale consumers having the responsibility for the imbalance (typically the manufacturer) and the retail which responsibility is transferred to another party (typically a small customer).

There are many actors in the energy market. The essential ones are manufacturers, purchasers, dealers, stock exchange (in the Czech Republic PXE a.s.), distribution system operator (who deals with the distribution of electricity to end consumers and controls its quality to match the law), transmission system operator (who manages the transmission systém, in the Czech Republic the position is held by ČEPS a.s.), operator of electricity market (who registers participants and processes all transactions) and Energy Regulatory Office (ERO).

The energy market can be further divided into an unorganized market where bilateral agreements are concluded (two parties agree on a trade independently and are not restricted by rules) and organized market where participants have one central counterparty (such as the stock market).

The electricity market is currently deformed by regulatory interventions. Producers receiving subsidies for production no longer need to sell the energy for a price that would cover their costs on the market, and they can sell electricity for a meager price. However, the customer pays these costs instead of the price for the electricity in the price for the regulated items.[40]

Another division that is necessary to make is between the energy distributor and energy provider. An energy distributor is a company that possesses a license for the distribution of electric energy. This company operates the distribution network and provides the transportation of energy from the powerplant to a household. In the Czech Republic, there are three operating electricity distributors – ČEZ, E.ON and PRE and three distributors of gas – RWE, GasNet, E.ON and Pražská Plynárenská. That means that the Czech Republic is divided into 3 sectors of which each is administrated by one of the companies. A distributor cannot be switched by the consumer; it is given by the location of the household or company.

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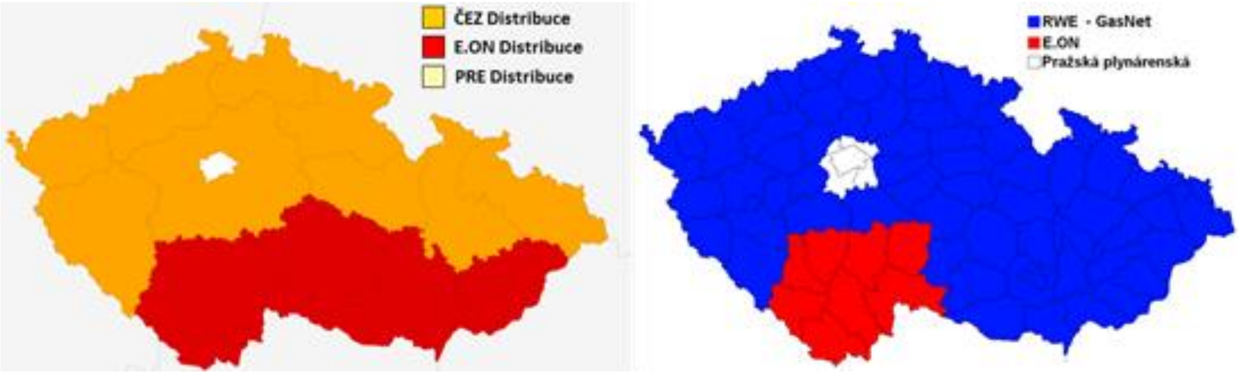
[40] Salavec, J. (2017). *Trh s elektřinou - specifika, účastnící trhu a rozdělení*. [online] oEnergetice.cz. Available at: https://oenergetice.cz/elektrina/trh-s-elektrinou/trh-s-elektrinou/?fbclid=IwAR2GD2ztMLREZa4_dtZhpVI1AvCBec5sztRmV6GsllT5YDnj3orxpQdFIpw [Accessed 20 Feb. 2019].

Figure 20 Map of energy and gas distributors



Source: Dodavatelé elektřiny.cz[41]

An energy provider is a company that sells energy to companies or households as a commodity. Every consumer has the right to chose a provider based on the prices and conditions, and the respective distributor is obliged to transport the energy through its network. There is a large number of energy providers in the Czech Republic with different specializations – some of them are focused on households while others only handle bulk consumers. There is specific division among the providers between the traditional ones who dominated the Czech market before the energy market liberalization (ČEZ, RWE, PRE, E.ON) and the so-called alternative ones who entered the market after 2006.

Currently, the transmission network of the Czech Republic consists of 3 510 km of 400 kV and 1 909 km of 220 kV. Another 6 of 110 kV with a total length of 84 km.[42] The necessity of investments into stabilization and development of the transmission network is palpable because of the increasing instability of transmission of our neighboring states caused by their transition to renewable resources. Fees for neighboring states which endanger the stability of the Czech transmission network are non-existent, and domestic customers are reimbursing the resulting costs.

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[41] Dodavatelektriny.cz. (n.d.). *Rozdíl mezi dodavatelem a distributorem elektřiny | Přehled dodavatelů elektrické energie a zemního plynu*. [online] Available at: https://dodavatelektriny.cz/index.php/uzitecne-informace/dodavatel-distributor-rozdil [Accessed 22 Mar. 2019].

[42] Galetka, M. (2016). *Vznik a vývoj přenosové soustavy elektrické energie*. [online] TZB-info. Available at: https://energetika.tzb-info.cz/elektroenergetika/13645-vznik-a-vyvoj-prenosove-soustavy-elektricke-energie [Accessed 20 Feb. 2019].

3.3 Future development of the Czech energy sector

3.3.1 EU legislation

The European Union evolved from the European Coal and Steel Community through the European Economic Community and the European Atomic Energy Community, but none of these institutions attempted to achieve a common energy policy. The EU imports energy at 2.5 percent of its annual GDP. In figures, it is 270 billion euros for oil imports and 40 billion euros for imports of natural gas.

According to the Lisbon treaty, the energy sector is in the design of each member state, but the EU sets limits and requirements which need to be observed. Even though the European Union poses regulations and requirements it does not guarantee the availability or price of energy; every state is responsible for its energy mix. Emergency measures might be applied in case of war or natural disasters but not because of the changes in the structure of the neighboring state energy sector even though the result might be just as crippling. [43]

After 2004, there has been a rather dynamic development of both legislation and strategic documents in the context of efforts to develop a new EU energy policy. In 2006 the so-called Green Paper aiming at sustainability, competitiveness, and security of supply was introduced and later examined in two "packages." The European Council then adopted an Energy Policy Action Plan in March 2007, and the European Commission started presenting the legislative proposals in September 2007. The key legislative packages are the so-called third liberalization package and climate-energy package that contains a set of regulations and tools on how to achieve set goals.

In November 2010, the European Commission published a Strategy for a competitive, sustainable and secure energy COM (2010) 639 defining EU energy policy priorities for 2011-2020 and providing an overview of the current state of EU energy policy. The main focus of the strategy was achieving energy efficiency in Europe, building a functioning integrated energy market, strengthening the position of consumers, achieving

[43] Euroskop.cz. (2019). *ČR a EU - energetika*. [online] Available at: https://www.euroskop.cz/9101/sekce/cr-a-eu---energetika/?fbclid=IwAR3cX3-UnUk6Oxgry7JnBhLysiDuBSXaXJOXqJWya9FR3symhXrZY-E6BTQIpw [Accessed 20 Feb. 2019].

the highest level of security and security of energy supply and advancement in technologies development.

Energy also plays a vital role in the economic strategy called the Europe 2020, in which member states are committing to achieve the share of renewable energy in their energy mix. Energy targets are closely intertwined with climate policy and the EU commitment to reduce emissions. The binding target for the Czech Republic in terms of energy efficiency is to produce 13% of energy from renewable resources by 2020, according to Directive 2009/28 / EC. Each member state is also required to submit a National Energy Efficiency Action Plan every three years. The National Renewable Energy Action Plan of the Czech Republic proposes a target for the share of energy from renewable sources of 13.5% and the 10.8% share of energy from renewable sources in final gross consumption in transport. These targets will be evaluated with the possibility of being modified. The minimum targets are those set out in Directive 2009/28 / EC.

The Energy Strategy 2030, adopted in October 2014, set specific targets for both energy production and climate protection. The strategy sets a reduction of at least 40% of greenhouse gas emissions by 2030 compared to 1990 levels, renewable energy is required to account for at least 27% of energy consumption, and energy efficiency has to correspond to EU level. The Energy Strategy 2030 also defined qualitative targets, including the reform of the EU Soil Emission Trading Scheme or a new reporting framework by the member states.

In February 2015, the European Commission adopted a package of energy policy measures to ensure affordable, secure and sustainable energy for European citizens. On February 25, 2015, the Framework Strategy for the Establishment of an Energy Union was published, aiming at securing the energy supply, sustainability, and competitiveness of the internal energy market.

The Energy Union was created to enable the EU able to cut energy import expenditures. This expenditure annually reaches approximately € 350 billion. The Energy Union also set itself the objective of modernizing aging energy infrastructure, fully integrating its energy markets and coordinating national energy prices. As part of the building of the energy union, the Commission published the gas security packages, and in particular the "Winter Energy Package" in November 2016, which includes legislative proposals on energy efficiency and the proposal of reforming the electricity market, renewable technologies. In particular, the proposed reform of the electricity markets, where the capacity cuts are required as well as 30% energy savings target in 2030, has prompted considerable controversy between member states, which is likely to prolong negotiations for the adoption of legislation.

Several proposed legislative acts have already been negotiated in the framework of building the energy union. In October 2017, the Council adopted a regulation of the security of gas supply. The general objective of the regulation is to strengthen the European Union's energy security, reduce its dependence on third-country energy supplies and enable it to tackle potential gas supply crises quickly and effectively. In December 2017, the Council agreed on negotiating positions on the four legislative proposals contained in the Clean Energy Package: Governance, Renewable Energy and the Internal Electricity Market (consisting of two initiatives). This package is part of the energy union strategy. Clean energy is also essential for achieving the European Union's energy and climate goals for 2030.

In June the Council and the European Parliament agreed on the compromise of the Energy Efficiency Directive. By 2030, energy efficiency in the EU should increase by 32.5% compared to the projected scenarios but unlike in the case of renewables, the target is not binding, and a revision will be made in 2023 to increase the target.

In 2011, on the basis of a study by the European Climate Foundation, the Commission proposed four ways to reduce greenhouse gas emissions by at least 80% compared to 1990 levels by 2050, while creating more sustainable, competitive and safer energy system. The cornerstones of the so-called roadmap, which is the main long-term strategic document, are energy efficiency, renewable energy, nuclear energy, and carbon capture and storage.

The primary EU law (Articles 170-172 TFEU) concludes the necessity of linking European regions in order to build the internal market, increase employment and sustainable development. In the energy sector, these trans-European networks are divided into nine main directions, focusing on linking isolated regions with European gas, oil, and electricity markets.

The implementation of TEN-E projects is funded partly by the European Union and partly by the relevant member states. For this purpose, the Connecting Europe Facility

(CEF) was established in 2013, with a budget of € 30.4 billion, of which € 5.35 billion is devised for energy.

Nuclear energy was one of the first areas of cooperation in Europe - the European Atomic Energy Community (Euratom) was founded in 1958 to promote peaceful research and utilization of nuclear energy. Over time, Euratom has become an essential element in the application and control of safety standards in nuclear power, which, in addition to the safety of the power plants themselves, also affect the handling of nuclear fuel, the disposal, and disposal of nuclear waste, or the protection against radioactive radiation. Euratom also holds the key role in the field of research, for example under the direction of nuclear fusion research and the construction of the ITER Demonstration Fusion Reactor.[44]

3.3.2 Possible outcomes

The main trends that will have a decisive impact on the future development of the Czech energy sector are decentralization, decarbonization and the increasing utilization of information technology. The gradual increase of energy consumption is expected because of the imminent electrification and automization of both industry and transportation. The net increase is projected to reach 64 TWh in 2020 and 67 TWh in 2025. In 2050, the projected net electricity consumption will exceed 80 TWh, with a 6% increase in electricity consumption in 2050 (4.6 TWh) to drive cars with electric drive.[45] In order for the Czech energy sector development to be successful it needs to be ensured that the country has sufficient energy supply, operates with reliable energy sources, maintains sufficient control of the power supply, the network infrastructure has to be renewed and developed according to the best technology available and all blocks in Temelín, as well as all of the pumped storage hydropower plants, have to remain operational for the 2050 horizon.

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[44] Euroskop.cz. (2018). *Energetická politika*. [online] Available at: https://www.euroskop.cz/8950/sekce/energetika/ [Accessed 20 Feb. 2019].

[45] Wagner, V. (2018). *Možné scénáře a rizika vývoje elektroenergetiky v Česku*. [online] oEnergetice.cz. Available at: https://oenergetice.cz/energetika-v-cr/mozne-scenare-rizika-vyvoje-elektroenergetiky-cesku/ [Accessed 20 Feb. 2019].

By 2020, the EU requirement is to reduce greenhouse gas emissions by 20% compared to 1990 levels which will most likely be accomplished by the Czech Republic. However, the EU targets for the 2050 horizon are far more ambitious. The proposed reduction of greenhouse gas emissions in the energy sector would mean almost complete decarbonization in the Czech Republic by the exclusion of fossil fuels and the eventual application of Carbon capture and storage (CCS) technology. This development is considered in the low emission scenario which thoroughly explores the potential of renewable resources with the supplementation of nuclear power and gas.[46]

The Czech Republic is currently an electricity exporter with sufficient reserves in production and output. At the same time, its network assists with the transportation of large amounts of energy from southern Europe to south Europe while maintaining the stability in our region. There is a minimal storage option for electricity, so the energy demand needs to be covered at all times even though there are a quite significant daily and seasonal variations in the range of 5.5 to 10.5 GW. Less power is needed on weekends, holidays and at night and also in the summer the demand for energy is lower than in winter.

The future development of the energy resources structure of the Czech grid will be influenced mainly by the European Union's legislation and policies and their impact on the energy sectors of European countries. Several possible scenarios can be predicted, but so far it has been impossible to determine which one will eventually occur.

The Czech Republic has not used the surplus in energy production as an opportunity to focus on building low-emission sources. By postponing the necessary steps for a long time, the Czech energy sector has gotten into a situation where the current lack of options poses a problem. The ecologization of coal-based power plants have taken place for only a fraction of power plants, and since power plants which will not meet the operating criteria by 2022 have to be shut down, the Czech Republic faces a threat of decommissioning of 40% of its coal power plants.

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[46] Vobořil, D. (2016). *Infografika: Výhled elektroenergetiky ČR do roku 2050*. [online] oEnergetice.cz. Available at: https://oenergetice.cz/elektrina/infografika-vyhled-elektroenergetiky-cr-roku-2050-2/ [Accessed 20 Feb. 2019].

The situation is even more complicated because of the similarly drastic changes occurring in most of Europe. In 2022 Germany will shut down all of its nuclear power plants as well as several coal-based plants and rely mostly on renewable resources. On the one hand this will prevent a massive amount of emissions from being released into the air, but on the other hand, the stability of the network and balance of energy will be threatened. It can be expected that the massive surplus will occur during a favorable summer day but during winter inversion when the electricity consumption will be high, but the wind and sunshine will be negligible the deficit is imminent.

4 Practical Part

Analytical part of the thesis is devoted to assessment of scenarios connecting the costs of electricity generation, production and carbon footprint. Five scenarios were proposed based on the potential of the Czech Republic and evaluated according to the methodology. First scenario attempts to achieve the lowest possible carbon footprint while observing the constraints given by demand, second scenario is aiming to the lowest possible costs while not exceeding the carbon footprint limitations, third scenario focuses on utilizing the full potential of the Czech nuclear power plants and fourth and fifth scenarios asses the Czech energy mix utilizing only the renewable or non-renewable resources.

4.1 Model of the Czech energy mix

4.1.1 Structural coefficients

For the Czech energy mix optimization model structural coefficients were stated as:

Coal-based power	… c
Nuclear power	… n
Wind power	… w
Hydropower	… h
Solar power	…s
Gas-based power	…g

4.1.2 Linear objective function

The objective linear function for the minimization of costs in the Czech energy mix is stated as:

$$\mathbf{z = c_c c + c_n n + c_w w + c_h h + c_s s + c_g . g \text{ -> min}}$$

where c, n, w, h, s, g depict the non-negative amount of energy produced from specific resources and c_c, c_n, c_w, c_h, c_s are levied cost of specific resource-based electricity.

For the Czech energy system LCOE was calculated as follows:

Power source	LCOE (CZK/kWh)	LCOE (CZK/MWh)	LCOE (CZK/GWh)
Coal	1.9	1 900	1 900 000
Nuclear	2.16	2 160	2 160 000
Gas	2.75	2 750	2 750 000
Hydro	1.21	1 210	1 210 000
Wind	1.46	1 460	1 460 000
Photovoltaic	1.13	1 130	1 130 000

The final linear objective function is then stated as:

$$\mathbf{z=1\,900\,000c + 2\,160\,000n + 1\,460\,000w + 1\,210\,000h + 1\,720\,000s + 2\,750\,000g \text{ ->min}}$$

4.1.3 Constraints

Non-negativity of parameters: $c, n, w, h, s, g \geq 0$

Electricity demand: $c + n + h + s + g \geq 66\ 765{,}05$ GWh

Emissions released (CO_2)[47] [48]:

$$0.82c + 0.49g + 0.048s + 0.024h + 0.012n + 0.011w \leq 92\ 832.812\ ktCO_2$$

Maximum potential output[49] [50]:

$c \leq 56\ 326.195$

$n \leq 29\ 502.330$

$w \leq 515.330$

$h \leq 3\ 064.779$

$s \leq 1\ 529.361$

$g \leq 5\ 249.693$

[47]Brückner, T., Fulton, L. and Hertwich, E. (2014). *Technology-specific Cost and Performance Parameters*. [online] Ipcc.ch. Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf [Accessed 13 Mar. 2019].

[48]Mzp.cz. (2017). [online] Available at: https://www.mzp.cz/C1257458002F0DC7/cz/prechodny_narodni_plan_cr/$FILE/OOO-PNP_CR_2014-11_17_REV_vestnik-20170719.pdf [Accessed 13 Mar. 2019].

[49] Eru.cz. (2019). *ERÚ - Zprávy o provozu elektrizační soustavy*. [online] Available at: https://www.eru.cz/cs/zpravy-o-provozu-elektrizacni-soustavy [Accessed 20 Feb. 2019].

[50] Schierhorn, P. (2018). *Czech power grid without electricity from coal by 2030: Possibilities for integration of renewable resources and transition into a system based on decentralized sources*. [online] Glopolis.org. Available at: http://glopolis.org/wp-content/uploads/Czech-Grid-Without-Coal-By-2030_fin.pdf [Accessed 13 Mar. 2019].

4.2 Scenario 1 – minimization of emissions release

The first scenario aims to achieve the lowest possible emissions release while observing set constraints.

Minimize:

$z = 0.74c + 0.49g + 0.048s + 0.024h + 0.012n + 0.011w$

Subject to:

c + n + h + s + g + w >= 66 765.05 (electricity demand)

c<=56326.195 (maximum output of coal-based power plants)

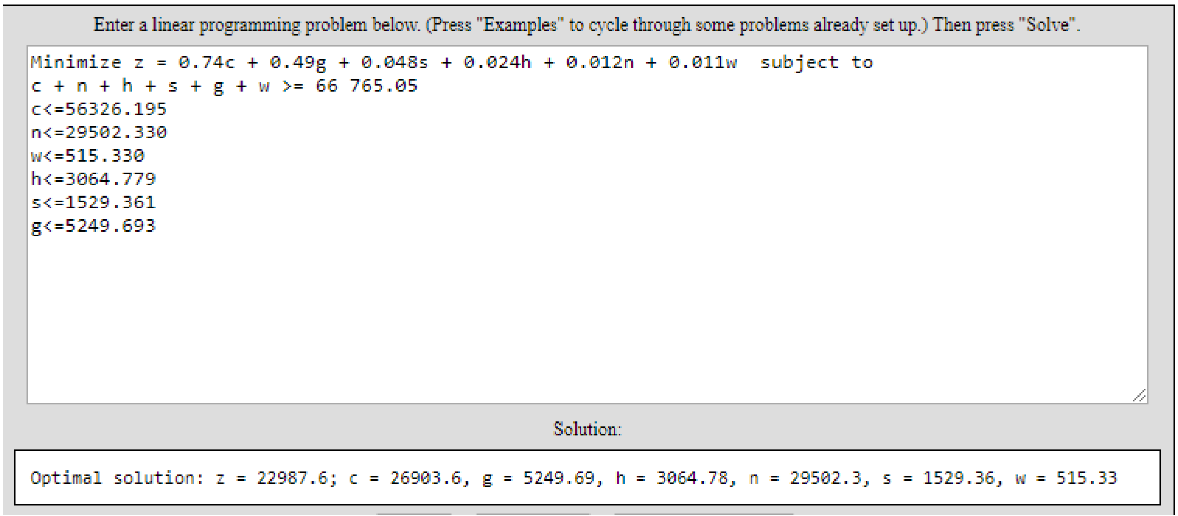
n<=29502.330 (maximum output of nuclear power plants)

w<=515.330 (maximum output of wind power plants)

h<=3064.779 (maximum output of hydroenergy power plants)

s<=1529.361 (maximum output of solar power plants)

g<=5249.693 (maximum output of gas-based power plants)



Optimal allocation of resources (GW):

c = 26903.6, g = 5249.69, h = 3064.78, n = 29502.3, s = 1529.36, w = 515.33

Costs: **136 369 720 300 CZK**

Emissions released: **22 987.6 $ktCO_2$**

Minimum released emission solution for Scenario 1 proposes utilizing coal-based power plants for production of 26 903.6 GW, hydro energy power plants for 3 064.78 GW, nuclear power plants for 29502.3 GW, solar systems for 1 529.36 GW, wind turbines for 515.33 GW and gas-based power plants for 5 249.69 GW.

Total costs of this energy mix are 136 369 720 300 CZK and the amount of CO_2 emissions released during the process is 22 987.6 kt.

Concerning the stability of electricity production, this model appears to be feasible as well because the majority of the electricity is produced by type B power source and another significant amount by type C.

4.3 Scenario 2 – minimization of costs

The second scenario aims to achieve the lowest possible costs of energy generation while considering the constraints.

Minimize:

z =1900000c + 2160000n + 1460000w + 1210000h + 1720000s + 2750000g

Subject to:

c + n + h + s + g + w >= 66 765.05 (energy demand)

0.74c + 0.49g + 0.048s + 0.024h + 0.012n + 0.011w <=92832.812 (emissions release)

c<=56326.195 (maximum output of coal-based power plants)

n<=29502.330 (maximum output of nuclear power plants)

w<=515.330 (maximum output of wind power plants)

h<=3064.779 (maximum output of hydroenergy power plants)

s<=1529.361 (maximum output of solar power plants)

g<=5249.693 (maximum output of gas-based power plants)

Enter a linear programming problem below. (Press "Examples" to cycle through some problems already set up.) Then press "Solve".

```
Minimize z = 1900000c + 2160000n + 1460000w + 1210000h + 1720000s  + 2750000g subject to
c + n + h + w + g + s >= 66 765.05
0.82c + 0.49g + 0.048s + 0.024h + 0.012n + 0.011w <=92832.812
c<=56326.195
n<=29502.330
w<=515.330
h<=3064.779
s<=1529.361
g<=5249.693
```

Solution:

```
Optimal solution: z = 125623000000; c = 56326.2, g = 0, h = 3064.78, n = 5329.38, s = 1529.36, w = 515.33
```

Optimal allocation of resources (GW):

c = 56 326.2, g = 0, h = 3 064.78, n = 5 329.38, s = 1 529.36, w = 515.33

Costs: **125 623 000 000 CZK**

Emissions released: (56 326.2x0.82)+(3064x0.024)+(5329.38x0.012)+(1 529.36x0.048)+ +(515.33x0.011) = **46 404.05 ktCO_2**

Cost optimal solution for Scenario 2 proposes utilizing coal-based power plants for production of 56 326.2 GW, hydroenergy power plants for 3 064.78 GW, nuclear power plants for 5 329.38 GW, solar systems for 1 529.36 GW and wind turbines for 515.33 GW. Calculated solution also suggests ommiting the gas-based power generation.

Total costs of this energy mix are 125 623 000 000 CZK, and the amount of CO_2 emissions released during the process is 46 404.05 kt.

Concerning the stability of electricity production, this model appears to be feasible as well because the majority of the electricity is produced by type B power source.

4.5 Scenario 3 – maximum nuclear power output

The third scenario aims to achieve the lowest possible costs of energy generation while focusing on nuclear power production.

Minimize:

z = 1900000c + 2160000n + 1460000w + 1210000h + 1720000s + 2750000g

Subject to:

c + n + h + s + g + w >= 66 765.05 (electricity demand)

0.82c + 0.49g + 0.048s + 0.024h + 0.012n + 0.011w <=92832.812 (emissions release)

c<=56326.195 (maximum output of coal-based power plants)

n<=29502.330 (maximum output of nuclear power plants)

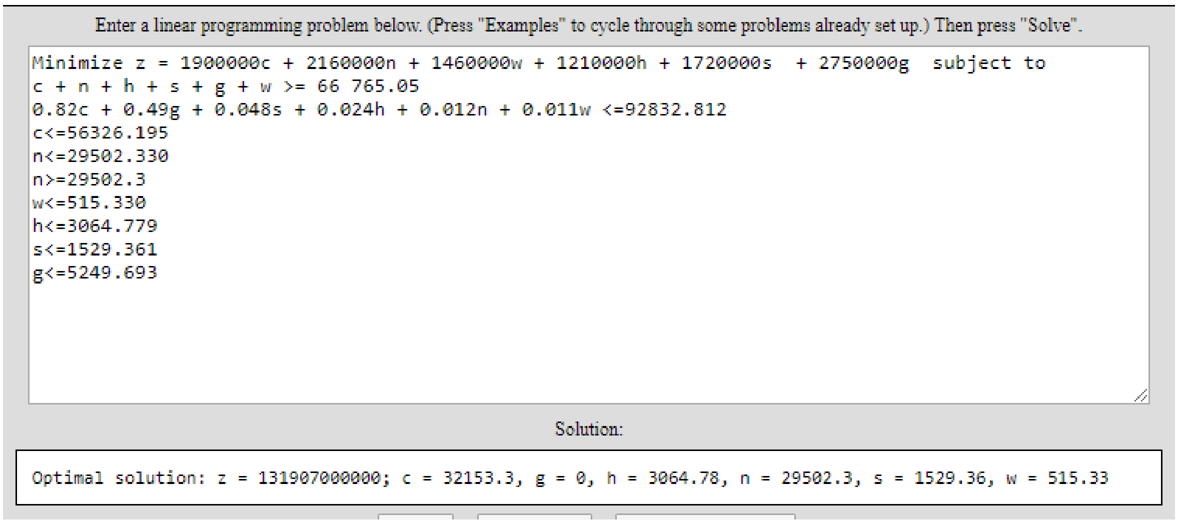
n>=29500 (minimum output of nuclear power plants)

w<=515.330 (maximum output of wind power plants)

h<=3064.779(maximum output of hydropower plants)

s<=1529.361(maximum output of solar power plants)

g<=5249.693(maximum output of gas-based power plants)


Enter a linear programming problem below. (Press "Examples" to cycle through some problems already set up.) Then press "Solve".

```
Minimize z = 1900000c + 2160000n + 1460000w + 1210000h + 1720000s  + 2750000g  subject to
c + n + h + s + g + w >= 66 765.05
0.82c + 0.49g + 0.048s + 0.024h + 0.012n + 0.011w <=92832.812
c<=56326.195
n<=29502.330
n>=29502.3
w<=515.330
h<=3064.779
s<=1529.361
g<=5249.693
```

Solution:

```
Optimal solution: z = 131907000000; c = 32153.3, g = 0, h = 3064.78, n = 29502.3, s = 1529.36, w = 515.33
```

Optimal resources allocation:

c = 32153.3, g = 0, h = 3064.78, n = 29502.3, s = 1529.36, w = 515.33

Costs: **131 907 000 000 CZK**

Emissions released:

(32153.3x0.82)+(3.064x0.024)+(29502.3x0.012)+(1529.36x0.048)+(515.33x0.011)

= 26 874,22 ktCO_2

Cost optimal solution for Scenario 4 proposes utilizing coal-based power plants for production of 32 155.6 GW, hydro energy power plants for 3 064.78 GW, nuclear power plants for 29 502.3 GW, solar systems for 1 529.36 GW and wind turbines for 515.33 GW. Calculated solution recommends omitting gas-based power generation.

Total costs of this energy mix are 131 907 000 000 CZK, and the amount of CO_2 emissions released during the process is 26 874,22 kt.

Concerning the stability of electricity production, this model appears to be feasible as well because the majority of the electricity is produced by type B power source and another significant amount by type C.

4.6 Scenario 4 Only renewable resources utilization

The fourth scenario aims to achieve the lowest possible costs of energy generation without the utilization of non-renewable resources.

Minimize:

$z = 1900000c + 2160000n + 1460000w + 1210000h + 1720000s + 2750000g + 7800000d$

subject to :

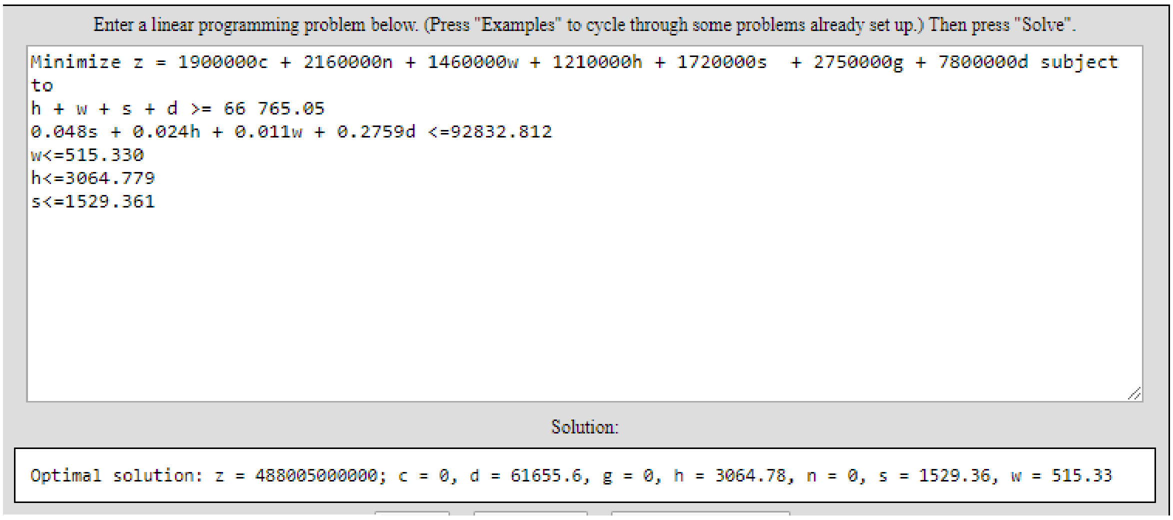
h + s + w + d >= 66 765.05 (electricity demand)

0.82c + 0.49g + 0.048s + 0.024h + 0.012n + 0.011w <=92832.812 (emissions released)

w<=515.330 (maximum output of wind power plants)

h<=3064.779 (maximum output of hydropower plants)

s<=1529.361 (maximum output of solar power plants)



Enter a linear programming problem below. (Press "Examples" to cycle through some problems already set up.) Then press "Solve".

```
Minimize z = 1900000c + 2160000n + 1460000w + 1210000h + 1720000s  + 2750000g + 7800000d subject
to
h + w + s + d >= 66 765.05
0.048s + 0.024h + 0.011w + 0.2759d <=92832.812
w<=515.330
h<=3064.779
s<=1529.361
```

Solution:

```
Optimal solution: z = 488005000000; c = 0, d = 61655.6, g = 0, h = 3064.78, n = 0, s = 1529.36, w = 515.33
```

Optimal resources allocation:

d = 61655.6, h = 3064.78, s = 1529.36, w = 515.33

Costs: **488 005 000 000 CZK**

Emissions released: (3064.78x0.024)+(1529.36x0.048)+(515.33x0.011)+(61655.6x0.2759[51])

= 17 163,4127 ktCO_2

[51] European Environment Agency. (2019). *CO2 emission intensity*. [online] Available at: https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-3#tab-googlechartid_chart_11_filters=%7B%22rowFilters%22%3A%7B%7D%3B%22columnFilters%22%3A%7

Cost optimal solution for Scenario 4 proposes utilizing hydro energy power plants for 3 064.78 GW, solar systems for 1 529.36 GW, wind turbines for 515.33 GW. The engergy deficit which occurs is 61 655 GW. The calculated solution does not consider increasing the energy production possibility because the options for renewable resources were virtually depleted and increase by such a significant amount is in current conditions impossible. The solution assumes that the deficit would be covered by imported energy. Given that average CO_2 release per kWh is very low (because of the rapid increase in renewable energy production in Germany, efficient utilization of hydro energy resources in northern Europe and the high level of nuclear power production in France), total emissions released in this solution are low, but probability that the actual imported energy would come from coal power plants of the neighboring states of the Czech Republic is high.

Total costs of this energy mix are 488 005 000 000 CZK, and the amount of CO_2 emissions released during the process is 17 163,4127 kt. Self-sufficiency in this scenario is extremely low.

B%22pre_config_ugeo%22%3A%5B%22European%20Union%20(28%20countries)%22%5D%7D%7D [Accessed 24 Mar. 2019].

4.7 Scenario 5 Only non-renewable resources utilization

The fifth scenario aims to find the minimum costs variant of energy mix without the utilization of any renewable resources.

Minimize:

z = 1900000c + 2160000n + 1460000w + 1210000h + 1720000s + 2750000g + 7800000d

Subject to:

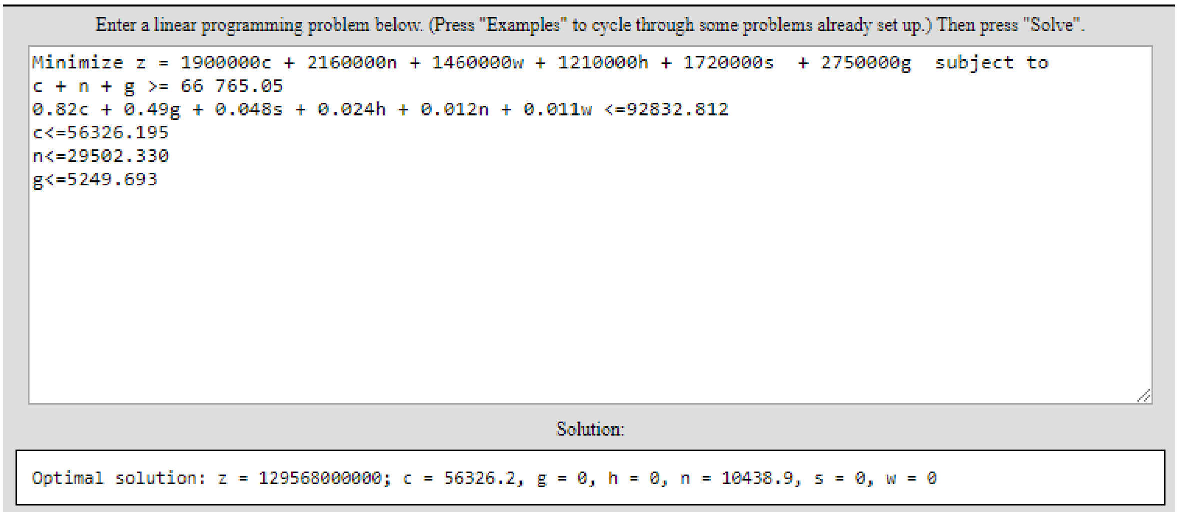
c + n + g >= 66 765.05 (electricity demand)

0.82c + 0.49g + 0.048s + 0.024h + 0.012n + 0.011w <=92832.812 (emissions released)

c<=56326.195 (maximum output of coal-based power plants)

n<=29502.330 (maximum output of nuclear power plants)

g<=5249.693 (maximum output of gas-based power plants)



Optimal resources allocation:

c = 56326.2, n =,

Costs: **129 568 000 000 CZK**

Emissions released: (32155.6x0.82)+(29500x0.012)= **46 312.75 ktCO_2**

Cost optimal solution for Scenario 5 proposes utilizing coal-based power plants for production of 56 326.2 GW and nuclear power plants for 10438.9 GW.

Total costs of this energy mix are 129 568 000 000 CZK, and the amount of CO_2 emissions released during the process is 46 312.75 kt.

Concerning the stability of electricity production, this model appears to be feasible as well because the majority of the electricity is produced by type B power source and another significant amount by type C.

4.8 Results and Discussion

While considering the feasibility of an energy mix for this thesis, there are three requirements which need to be fulfilled. First is the non-increasing costs of the energy mix, second is the observing the commitment made to the EU concerning the climate change, and third is keeping a sufficient level of energy security.

The cost of the energy mix in 2017 was 169 987.474 CZK/kWh.

In 1990 the amount of released CO_2 was 167 765 000 and the Czech Republic committed to decreasing the amount by 40% by 2030, which after the calculation of share of the energy production in the total Czech CO_2 release means that only scenarios with amount of CO_2 lower than 92 832.812 ktCO_2 will be considered as feasible.

	Cost (CZK/kWh)	**Emissions (ktCO_2)**	**Self-sufficiency**	**Feasibility (Y/N)**
Scenario 1	**136 369 720 300**	**22 987.6**	100%	Yes
Scenario 2	125 623 000 000	46 404.05	100%	Yes
Scenario 3	**131 907 000 000**	**26 874,22**	100%	Yes
Scenario 4	**488 005 000 000**	**17 163,4127**	7,7 %	No
Scenario 5	**129 568 000 000**	**46 312.75**	100%	Yes

Out of the five evaluated scenarios four fulfilled all the established requirements. Scenarios 1,2, 3 and 5 are self-sufficient, all offer lower costs of energy mix than the current energy mix and fulfill requirements concerning environmental impact.

There is an obvious pressure for the European states to switch to the renewable resources utilization and the Czech Republic is among those with the lowest share which is unlikely to change in the near future. The states with the largest share of renewable energy are Sweden, Finland, Latvia and Denmark which all possess significant amount of water bodies possible to utilize for energy production. Other countries with a high share of renewable energy production such as Germany or Spain have the windy coast or a large amount of sunshine. The Czech Republic does not have access to enough resources to satisfy the energy demand by renewable resources. The only way to decrease the coal-based energy production, which seems unfavorable in the eyes of the European Union is the increase of nuclear power production. The Czech Republic currently successfully operates two nuclear power plants gathering over 30% of its energy production, but if additional nuclear blocks were built, the share could increase significantly.

Conclusions of the State Energy Concept (SEK) designed in 2012 by the Independent energy committee (NEK II) anticipate the lack of energy caused by the shutdown of the Dukovany power plant in 2035 to be replaced by two new nuclear power blocks as well as launching a new brown coal-fired power plant with a capacity of 660 MW in Počerady. In order to regulate the transmission network, it is assumed that the current role of regulators, currently represented by coal-fired power plants will be held by steam-power blocks, which are expected to be constructed in 2031 and 2045.[52]

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[52] Ministerstvo Průmyslu a Obchodu (2010). *Státní energetická koncepce ČR.*. [online]. Available from: http://www.mpo.cz/dokument5903.html [Accessed on 20.2.2019].

5 Conclusion

Evaluation of scenarios clearly showed that the Czech Republic could not maintain energy security without utilizing a combination of fossil fuels and nuclear power. Out of five scenarios, the two most effective in terms of both costs and carbon footprint were those who emphasize coal-based and nuclear power generation. Similarly, the only unacceptable scenario was the one suggesting the omission of those sources. However, renewable resources proved to be essential in decreasing the amount of released emissions. Due to its location, the Czech Republic does not experience enough sunshine or wind to cover more than only a fraction of the required electricity production and the potential of hydro energy has been virtually depleted- possible expansion would have only marginal values. Utilization of renewable energy to an extent which would cover even half of the energy demand would be nearly impossible and large investments as well as the area of land, none of which the Czech Republic has the surplus of would be necessary.

For the Czech Republic to achieve the optimal energy mix which would combine reliable energy production with the possibility of regulation, feasible costs of energy generation and environmentally sustainable carbon footprint, a combination of coal-based and nuclear powerplants with renewable energy sources need to be utilized. According to European Union legislation, specifically, the requirements concerning the decrease of the carbon footprint, many coal-based power plants face the choice between high investment or shut down. Similarly, the end of expected life cycle of Dukovany nuclear power plant is estimated in 2035, and if the current nuclear blocks are not replaced by then, the Czech Republic will lose one of the fundamental sources of energy. It is, therefore, necessary for the government to make important decisions regarding the future of the Czech energy sector as soon as possible. Otherwise, it might lose the momentum it gained by its high coal-based energy production and succumb into energy deficit.

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7 Appendix

Wind energy												
Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	
Installed output (MW	113,75	148,00	192,00	215,00	217,00	260,00	269,00	283,00	283,00	283,00	308,00	
Production (MWh)	125 100,00	244 700,00	288 100,00	335 500,00	396 800,00	417 300,00	478 300,00	476 500,00	572 600,00	497 000,00	591 000,00	
Hours	8 760,00	8 784,00	8 760,00	8 760,00	8 760,00	8 784,00	8 760,00	8 760,00	8 760,00	8 784,00	8 760,00	
Capacity factor	12,55%	18,82%	17,13%	17,81%	20,87%	18,27%	20,30%	19,22%	23,10%	19,99%	21,90%	19,09%
Full load hours	1099,7802	1653,3784	1500,52083	1560,465116	1828,57143	1605	1778,06691	1683,7456	2023,3216	1756,183746	1918,8312	1 673

Nuclear energy												
Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	
Installed output (MW	3 760	3 760	3 830	3 900	3 970	4 040	4 290	4 290	4 290	4 290	4 290	
Production (MWh)	26 172 100	26 551 000	27 207 800	27 988 200	28 282 600	30 324 200	30 745 300	30 324 900	26 840 800	24 104 200	28 339 600	
Hours	8 760	8 784	8 760	8 760	8 760	8 784	8 760	8 760	8 760	8 784	8 760	
Capacity factor	79,46%	80,39%	81,09%	81,92%	81,33%	85,45%	81,81%	80,69%	71,42%	63,97%	75,41%	78,45%
Full load hours	6961	7061	7104	7176	7124	7506	7167	7069	6257	5619	6606	6 877

Hydroenergy												
Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	
Installed output (MW	2 175	2191,8	2 183	2 203	2 201	2 216	2 229	2 252	2 259	2 262	2 264	
Production (MWh)	2 523 700	2 376 300	2 982 700	3 380 600	2 835 000	2 962 900	3 761 700	2 960 700	3 070 800	3 202 000	3 040 000	
Hours	8 760	8 784	8 760	8 760	8 760	8 784	8 760	8 760	8 760	8 784	8 760	
Capacity factor	13,24%	12,34%	15,60%	17,52%	14,70%	15,22%	19,26%	15,01%	15,52%	16,12%	15,33%	15,44%
Full load hours	1160	1084	1366	1535	1288	1337	1687	1315	1359	1416	1343	1 354

Photovoltaic												
Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	
Installed output (MW	0	40	465	1 959	1 971	2 086	2 132	2 067	2 075	2 068	2 070	
Production (MWh)	1 800	12 900	88 800	615 700	2 118 000	2 173 100	2 070 200	2 122 900	2 263 800	2 131 500	2 193 400	
Hours	8 760	8 784	8 760	8 760	8 760	8 784	8 760	8 760	8 760	8 784	8 760	
Capacity factor		3,72%	2,18%	3,59%	12,27%	11,86%	11,08%	11,72%	12,45%	11,73%	12,10%	9,27%
Full load hours	0	327	191	314	1075	1042	971	1027	1091	1031	1060	739

Coal												
Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	
Installed output (MW	14 978	11 583	11 655	11 793	11 889	11 915	12 158	12 961	12 961	13 088	13 335	
Production (MWh)	59 201 100	54 330 800	51 682 600	53 580 100	53 928 100	51 696 100	50 009 400	50 118 400	51 140 300	53 367 200	52 873 700	
Hours	8 760	8 784	8 760	8 760	8 760	8 784	8 760	8 760	8 760	8 784	8 760	
Capacity factor	45,12%	53,40%	50,62%	51,86%	51,78%	49,39%	46,96%	44,14%	45,04%	46,42%	45,26%	48,18%
Full load hours	3952,6109	4690,6447	4434,37151	4543,227568	4535,96602	4338,7775	4113,42699	3866,8323	3945,6759	4077,723018	3965,0913	4 224