Energy 116 (2016) 329–340

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Issues and solutions relating to Hungary's electricity system

Viktor Miklós Kiss [a, *], Zsolt Hetesi [b], Tibor Kiss [a]

[a] Faculty of Business and Economics, University of Pécs (PTE), Rákóczi út 80, HU-7622 Pécs, Hungary
[b] National University of Public Service (NKE), Ludovika tér 2, HU-1083 Budapest, Hungary

ARTICLE INFO

Article history:
Received 12 April 2016
Received in revised form
23 September 2016
Accepted 25 September 2016

Keywords:
Energy system
Electric power system
Sustainability
Simulation
Modelling

ABSTRACT

The great majority of Hungarian electricity generating system's capacity is obsolete and needs to be replaced. Current production is dominated by nuclear power and coal, whilst depending heavily on imported electricity to cover demand. Official plans for the future envisage scenarios also greatly dependent on fossil fuels and/or imported electricity. Currently, there are no specific plans for the large-scale introduction of renewable energy sources or energy independence. This paper shows that it is possible – with no significant change in structure – to develop an electricity power system for the country using a significant amount (25–30%) of renewable sources, which is less dependent on non-domestic sources for generation and which is more environment friendly than the official, forecast scenarios.

1. Introduction

Hungary is facing major challenges over the next decades if it wishes to supply its own electricity needs in a secure, economical and environment friendly way. Due to the fact that practically all of its large[1] (≥50 MW (megawatt)) power plants are to be retired within 15 years, there will inevitably be major changes in the country's system.

The Hungarian TSO (Transmission System Operator) analyses the situation on a yearly basis and publishes the results. The two basic scenarios they have built for the next decades could have significant dangers both environmentally and in terms of energy security. The proposed proportion of renewable sources is extremely low compared to most other European Union countries, and the scenarios are heavily reliant on non-domestic sources.

The current study aims to prove that the country is in a situation where a secure and environment friendly electric power system can be developed in future decades without having to significantly restructure the electric power system, and that the implementation of such a system is economically comparable to other scenarios. It will do so by simulating and comparing the different paths for the Hungarian system over the coming years.

The method generally used for evaluating different paths for energy systems is scenario based modelling. Major publications which incorporate electric power, heating/cooling and transportation into their respective country-size energy system models include Lund and Mathiesen who explored the possibility of a 100% renewable energy system (including electricity, heat and transportation) in Denmark by 2050 with an intermediate step (50% renewable by 2030) in between [1]. Ćosić et al. conducted a similar research for Macedonia with the same time frame (2030 and 2050) and renewable energy penetration (50% and 100%) [2]. Some country-size analyses focus on the effect of one particular energy source within the energy system. Novosel et al. recently published an article researching the possibilities for reverse osmosis desalination for Jordan [3]. The effects of a nuclear reduction strategy were researched by Gota et al. for Romania [4].

Some models lay down the foundation for a detailed analysis of a country's energy system. Connolly et al. [5] develop a simulation model of the current (2007) system of Ireland for the purpose of serving as a base for future analysis. Sáfián [6] conducted a similar research for the 2009 energy system of Hungary, which is a sound initial step and a stimulus for further analysis. The current study takes the idea one step further and creates specific future state scenarios.

Publications – similarly to the current study - focusing solely on the electric power system of a country include the research of Mason et al. on the possibility of reducing the fossil-fuelled

* Corresponding author.
E-mail addresses: kissv@ktk.pte.hu (V.M. Kiss), hetesi.zsolt@uni-nke.hu (Z. Hetesi), kisst@ktk.pte.hu (T. Kiss).

[1] Throughout the paper, the units with a capacity ≥50 MW will be referred to as *large* power plants and units with a capacity <50 MW as *small* power plants.

http://dx.doi.org/10.1016/j.energy.2016.09.121
0360-5442/

electricity generation of New Zealand and replacing it with renewable sources, such as wind and geothermal heat [7]. Krajacic et al. created a model with a similar goal for Portugal, where they researched the possibilities to replace the high proportion of imported oil and gas within the country's energy system with renewable sources [8]. Elliston et al. conducted a research for Australia, where they explored the technological options for the transition to a 100% renewable based electricity supply [9]. A recent study – published by Cho and Kim - discusses the feasibility and potential impact of establishing a renewable source based electricity supply system for Korea [10].

As the short literature review shows, the transition from traditional, dominantly fossil-fuel based electricity generation to a more renewable and flexibly based system is a very timely question. Due to the fact that Hungary is looking at a major transition in its electric power system, developing a model in line with the leading literature and detailed analysis seems essential.

2. The scope of the article

The primary goal of the article is to develop a model for the electricity system of Hungary, which is capable of analysing future scenarios. The developed model is used to simulate the current plans of Hungary regarding the future of their electric power system and an alternative system developed by the authors, which seeks to model a conservative, realistically possible scheme inclusion of renewable energy sources.

The results are evaluated and compared in terms of the security of electricity supply, their effect on the environment, and their economic feasibility. The security of supply will be evaluated by the amount of domestic versus foreign sources for electricity production and the renewable energy share within the system. Their effect on the environment will be compared by their respective emission intensity (gCO2 eq./kWh-e) and a detailed evaluation discussing investment; operation and fuel costs of the scenarios will provide the basis for comparison in terms of economic feasibility. A sensitivity analysis will be conducted in relation to changes in electricity demand and CO2 prices.

The study would like to show that it is possible to include a significant amount of domestic and renewable energy sources in the Hungarian electric power system without performing major changes within the structure of the system - and also that this would improve the energy security of the country, have a lower negative impact on the environment, and would be comparable to other (fossil fuel-based) scenarios financially.

3. Hungary's current electric power system

Most of the large power plants operating in Hungary are basically at least forty years old, the majority having been built in the 1960s and 1970s. There are, nevertheless, a few new, relatively modern blocks installed at various existing plants, and some peaking power plants are relatively new (post-2000). Please refer to Table 1 for the details of the country's production capacities. The data are from the latest year for which data were available (2013).

According to the Hungarian TSO [11] there were only two power plants where the yearly capacity factor exceeded 63.8%[2] and could be considered to be a base load power plant. The two power plants were the nuclear power plant in Paks and a coal fired power plant in the Mátra Hills. Although the share of the total capacity of natural gas fired plants in the country is around 60%, these capacities are rarely used and their use is continuously decreasing. In 2014 only 6.7% [12] of the total electricity consumed in Hungary was produced by domestic plants using natural gas, and most of that was produced by CHP (Combined Heat and Power) plants which primarily serve a district heating demand. The severity of the situation for natural gas-fired plants is shown in Fig. 1, where it is clear that their production is gradually being substituted by imported electricity. Even the newly (2011) built 433 MW power plant in Gönyű - which theoretically could reach a 59% efficiency [13] - was being operated on a low, 7.4%, capacity factor in 2014 [11].

The main reason for this trend lies is the nature of the European Network of Transmission System Operators for electricity (ENTSO): It seems that natural gas fired plants are currently not competitive economically. This is not a Hungarian phenomenon, and the decreasing involvement of natural gas fired plants for electricity production is visible in the whole of the ENTSO system. The total share of natural gas in the system has dropped from 16.0% in 2010 to 11.0% in 2014 [12]. The fact which makes Hungary's case special, is that around 60% of the country's capacities are natural gas-fired plants, and if they cannot be economically powered, the country turns to imports, which, consequently, supplied more than one third (33.9%) of the countries consumption in 2014 [12]. This puts Hungary 4th on the list of net importers compared to total consumption in the ENTSO system. Only Luxembourg (75.7%), Lithuania (71.5%) and the Former Yugoslav Republic of Macedonia (34.7%) have a bigger share of their consumption of electricity originating abroad [12]. Although relying greatly on imported electricity is not necessarily a problem, the fact that Hungary has a total electricity generating capacity which is more than 140% of the maximum load for the country (9127 MW to 6419 MW in 2014 [11]), it raises questions.

The answer lies in the structure of the 9127 MW capacity. Most of the large power plants are obsolete, and gradually being demoted into the tertiary reserve capacities and ultimately being retired. Most of this will happen in the next 15 years, which could result in the need to build a significant new capacities in order to comply with capacity regulations.

3.1. The case of Paks and Paks II nuclear plants

Paks in a small city located in the central area of the country, on the banks of the Danube. It is best known for having the sole nuclear power plant in the country, operating four reactors with a total capacity of 2000 MW. The power plant - in operation from 1982 - was always a major contributor to the domestic power system and is now responsible for approximately 50–55% of the total domestic electricity production. It recently had its operating license extended until 2035. Hungary, however, will not lack a nuclear power plant after that date, since the country has signed an inter-governmental agreement to build new blocks for the nuclear power plant, named Paks II., which will consists of two 1200 MW reactors for a combined capacity of 2400 MW. Their commercial operation is planned to be started around 2025 [14]. Although this date might easily be delayed, it is possible that Hungary will operate a total of 4400 MW of nuclear capacity for a couple of years. It is very difficult to predict the potential length of the overlap period, and so our research focuses on the time period (starting from approximately 2030) when there is to be only one nuclear power plant in operation.

4. Future plans

This chapter analyses the current plans of Hungary regarding their electric power system for the next decades, and the analysis considers both the demand and the supply sides using the plans developed by the national TSO, the National Energy Strategy [15],

[2] Hungarian threshold for base load power plants.

Table 1
List of Power Plants and their electricity production characteristics. 2013 [11].

Name of PP	Capacity MW	Capacity factor	Input	% of electircity produced	Commissioned and on-stream
Paks	2000	87.7%	Nuclear	50.7%	1986
Dunamenti (CHP)	1069	10.1%	N.gas	3.1%	1976
Mátra (CHP)	950	74.0%	Coal	20.3%	1973
Tisza II.	900	0.0%	N. gas	0.0%	1979
Vértes Erőmű (CHP)	240	38.5%	Coal	2.7%	1960
Pécs (CHP)	120	46.6%	Biomass	1.6%	1966
Bakonyi Erőmű (CHP)	102	2.2%	Coal, Biomass	0.1%	1962
Csepel II. (CHP)	410	26.5%	N.gas	3.1%	2000
Gönyű	433	7.4%	N.gas	0.9%	2011
Budapesti (CHP)	406	27.8%	N.gas	3.3%	1972
Debrecen (CHP)	95	10.8%	N.gas	0.3%	2000
BVMT	116	1.0%	N.gas	0.0%	2011
Open Cycle Gas Turbines	410	0.3%	N.gas	0.0%	1998–2000
ISD Power (CHP)	65	15.8%	N.gas	0.3%	1953
Borsodi	137	0.0%	Biomass	0.0%	1957
Tiszapalkonyai	200	0.0%	Coal	0.0%	1959
Total large PP's	7653	–	–	86.3%	
Small CHP's (aggr)	986	31.4%	N.gas	8.9%	–
Small Bioth. PP's (aggr)	149	33.7%	Biomass	1.5%	–
Primer Renew.	409	26.5%	RES	3.1%	–
Total small PP's	1544	–	–	13.7%	
Total Hungarian system	9197			100.00%	

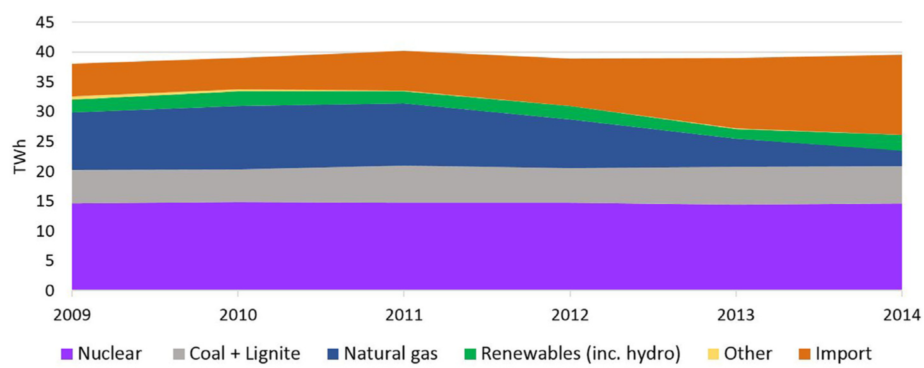


Fig. 1. Energy sources of electricity consumption of Hungary, 2009–2014, own edition, based on [12].

Table 2
Net electricity demand growth rate scenarios [17].

	Scenario		
	A	B	C
Growth rate up to 2020	1.3%	0.9%	1.4%
Growth rate after 2020	1.0%	0.7%	1.2%

and the country's National Renewable Energy Action Plan (NREAP [16]).

4.1. Demand side

The total demand and the maximum load that needs to be supplied are difficult to forecast decades in advance. The Hungarian TSO has devoted an individual publication to the issue of future demand characteristics [17], where it develops three different scenarios (Scenarios A-C) of the growth rate of the total net electricity demand[3] within the Hungarian electric power system (Table 2). The calculations behind the projected values are based on historical data which suggest that there is a high, positive correlation between the GDP of Hungary and its net electricity use [17]. Scenario A predicts a steady growth due to the projected economic growth and the moderately effective implementation of efficiency measures in the system. Scenario B predicts a slower growth due to wide implementation of efficiency measures in the electric power system, while Scenario C forecasts a higher growth in the net electricity use.

Based on the calculations using the forecast growth rate laid down in the scenarios, the projected total net electricity demand is expected to be between 44.7 TWh and 48.4 TWh in 2030 compared to the current (2014) 39.5 TWh. Simultaneously, the maximum peak demand is forecast to grow by around 70 MW/year, resulting in an approximate value of 7500 MW by 2030 [17]. Please refer to Fig. 2. The study of the TSO also acknowledges the importance of active demand side management in the power system, but, due to the high level of uncertainty surrounding forecasting by these methods, it chooses to exclude them from its calculations.

4.2. Supply side

According to the analysis of the Hungarian TSO, only 4665 MW of the currently operating capacity is going to be available by 2030, which would mean that in order to be able to supply the maximum

[3] Power plants' own use and distribution losses are not included.

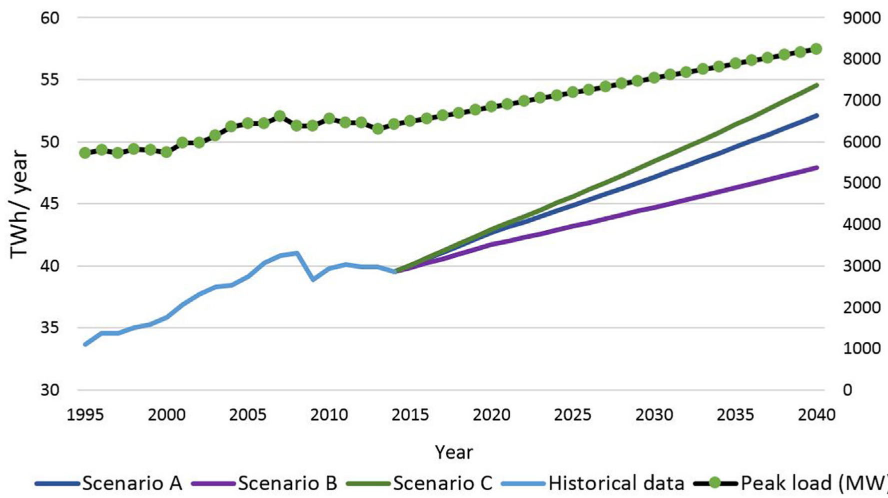


Fig. 2. Projected electricity use and peak load, Hungary. Own edition, data based on [17].

load and to comply with supply safety regulations, approximately 7300 MW of new capacity needs to be built [11]. Their study analyses two scenarios for the potential construction of this large amount of capacity. One is where each currently proposed new power plant is included (Version A), and one where only those power plants are included which the experts at the TSO feel are realistic, taking into account the current trend of the vast under-utilization of natural gas fired plants (Version B). The proposed plans for the two scenarios are listed in detail in Table 3.

It is important to note that the list of plants in Table 3 is merely a projection, and there is no publicly available data of any specific steps that have been taken apart from the proposed construction of the Paks II. nuclear power plant. Scenario A lists a total of 3385 MW of new, large natural gas fired plants, 180 MW of new, small natural gas fired plants and a relatively modest amount of renewable energy based energy conversion units, out of which the use of different kinds of biofuels and new wind turbines are dominant. Scenario B takes into account the unlikely appearance of new large natural gas fired plant construction and only calculates a modest amount (1100 MW) of new OCGT's (Open Cycle Gas Turbines) which are likely to be used as peaking power plants. Also Scenario B predicts that by 2030 only one of the blocks of the new nuclear power plant will be in operation, but the other block is to be built soon afterwards. In terms of small plants Scenario B is identical to Scenario A.

Table 3
List of planned new capacities by 2030, Hungary [11].

	Capacity, MW		Input
	Version A	Version B	
Paks II.	2400	1200	Nuclear
Csepel III.	450	–	N. gas
Tisza II.	1215	–	N. gas
Szeged	920	–	N. gas
Almásfűzitő	800	–	N. gas
OCGT	700	1100	N. gas
Small N.gas fired units	180	180	N. gas
Biomass and waste	671	671	RES
Wind turbines	600	600	RES
Hydro	20	20	RES
PV panels	70	70	RES
Geothermal plants	65	65	RES
Total:	8091	3906	

The Hungarian Ministry of National Development has accepted and published a National Energy Strategy [15] which proposes several different scenarios for the supply side of the national electric power system. Determined to be the most realistic is a so called “nuclear-coal-green” scenario, which proposes the installation of a new nuclear power plant, the installation of a new coal fired power plant (preferably with clean coal technology) and a very modest increase in renewable energy utilization. Since the publication date, the new nuclear power plant has been agreed on, but there are no publically available data on specific steps taken for the construction of the new coal-fired plant. The possible increase of renewable energy utilization is analysed in the country's National Renewable Energy Action Plan [16]. However, the plan only contains plans until 2020, and only includes extremely modest amounts of renewable sources.

4.3. *Energy utilization potential*

The following section will analyse the renewable energy utilization potential for the country and introduce the plans for a Pumped Hydroelectric Storage facility.

4.3.1. *Solar energy potential*

Currently Hungary has 22.6 MW of photovoltaic capacity installed [18]. This is a 3.9 Watt per inhabitant installed capacity, which is the 6th smallest value in the European Union [18]. According to [19] the amount of annual global horizontal irradiation for Hungary is between 1100 and 1350 kWh/m^2 (depending on the geographical location), which makes the country a relatively good site for installing photovoltaic panels.

4.3.2. *Wind energy potential*

Hungary currently has 330 MW of installed wind capacity which is responsible for around 2% of the total electricity production of the country [11]. The volume of installed capacity makes up only 0.3% of the total EU wind capacity [20], has not changed since 2011 and there are currently no specific plans to increase it. According to the analysis conducted by Ernst and Young audit firm [21], this is because of insufficient grid capacity, high connection costs and a very difficult permission-granting process. The European Wind Energy Association (EWEA) came to a similar conclusion in analysing the case, but still stated that the country has a medium term wind energy potential of 1.8 GW [22].

The current research uses this 1.8 GW potential as a base number for conducting the analysis. The wind speeds in Hungary generally do not exceed 5 m/s. The mountain ranges and the north western regions are considered the best possible locations (winds exceeding 7 m/s) for the installation of wind capacities. Most current wind farms are located in the latter region.

4.3.3. Geothermal energy potential

According to Geothermal Finance and Awareness in European Regions (GEOFAR), Hungary has a unique geological position astride the Pannonian Basin, where a few high-enthalpy resources have been discovered [23]. The Geothermal gradient in Hungary is 50°C/100 m as an average (reciprocal geothermal step 20 m/°C), which is about one and a half times the world average [24].

4.3.4. Biomass potential

The utilization of biomass in our case is twofold. We calculate on the basis of the sustainable yield of forests and the secondary agricultural by-products of the country. In both cases only the by-products of sustainable cultivation are taken into consideration. Currently, 22% of the country's area is covered by forests [25]. The yearly yield is 13 million m^3, of which 7 million is already utilized. The remaining 6 million m^3 has the energy content of roughly 18.2 MWh (calculating with 0.76 g/cm^3 and 4 MWh/tonne). This enables the operation of 759 MW of capacity with a 31% electric efficiency and an 85% load factor. These capacities would be capable of cogeneration in order to maximise the utilization of the input.

According to the Hungarian Central Statistical Office, there is agricultural cultivation on more than 5.3 million hectares (53 000 km^2). The secondary agricultural by-products generally yield 0.05–2 W/m^2[26], so utilizing 10% of the potential amount would enable the operation of 250 MW of additional capacity.

4.3.5. Pumped hydroelectric storage facility

In 2007, an impact study was constructed for the development of a Pumped Hydroelectric Storage facility in the North-Eastern part of Hungary [27]. The proposed facility had an electricity generating capacity of 600 MW and a head of 220 m. Although the plan was not implemented, the plans still remain valid. This energy storage facility is used as an essential factor of the proposed energy system.

5. Modelling the scenarios

The following section introduces the used method and the software, followed by the specific details connected to the model building process and the rules of simulation.

5.1. EnergyPRO

The tool used for the detailed analysis of the scenarios is energyPRO. EnergyPRO is a deterministic input/output tool able to analyse energy systems in detail. The software was initially developed by Henrik Lund in the 1980s and later made commercial in collaboration with EMD (Energy and Environmental Data) [28]. It is capable of modelling electricity and heating/cooling related projects with a wide range of built-in technologies. It is highly customizable, with access to databases for ambient conditions (NCAR, CFSR(2)[4]), which enables the realistic modelling of intermittent renewable sources such as solar- and wind power. The software is used for a wide variety energy system modelling projects. The research of Sorknaes et al. analyse how combined heat and power (CHP) units can be economically feasible by providing balancing services to the electricity system [29]. Wang et al. use it to model the solar heat production in their CHP district heating system [30] and to calculate the solar thermal output and the heat storage level in their optimization model of smart hybrid energy systems [31]. Fragaki et al. explore the economic sizing of gas engines and thermal storage for CHP and power plants [32], while Fragaki and Andersen use the software to investigate whether CHP plants with thermal stores could be suitable for sustainable energy production [33]. Lund et al. used energyPro to investigate the possible strategies for small CHP-plants in Lithuania [28], while Østergaard analysed the impacts of electricity, heat and biogas storage on renewable energy integration [34].

Table 4
List of total available capacities by fuel, 2030.

Capacity, MW	BAU1	BAU2	ALT
Nuclear	2400	2400	2400
Natural Gas (CHP)	1746	1350	1350
Natural Gas (electricity)	5452	2057	2857
Newly built base load PP	*3385*	*0*	*500*
Pre-2015 PP	*2067*	*2057*	*1257*
Newly built peaking PP	*0*	*0*	*1100*
Biomass (CHP)	858	845	1074
Wind turbines	600	600	1800
PV panels	70	70	1400
Hydro	20	20	20
Geothermal plants	65	65	200
Clean Coal	0	0	600
Total	11 211	7407	11 701
Hydro pumping station	0	0	500

5.2. Building the scenarios

In order to evaluate the electric power system of Hungary for 2030 and onwards, a similar simulation model needs to be built as in the leading literature. The research develops and simulates three different scenarios, Business As Usual 1 (BAU1) and Business As Usual 2 (BAU2) and an Alternative scenario (ALT). The BAU1 and BAU2 models are based on the Version A and Version B[5] predictions (please refer to the Future plans section), while the ALT model is the representation of the results of the authors' research done on the possibilities of the country regarding the improvement of its electric power system with regard to energy security, economic feasibility and environmental consciousness. Please refer to Table 4 for the summary of the installed capacities.

5.2.1. Modelling renewable sources

Modelling intermittent renewable sources is a more complicated procedure than the modelling of conventional energy conversion units. In the BAU1 and BAU2 scenarios the relatively small number of PV panels and wind turbines are centralized on their respective best location(s). In the ALT scenario, the photovoltaic panels are installed mostly in households throughout the country. The number of individual households in the country is 4.1 million [35]. If 20% of these install a relatively small photovoltaic system of 1.7 kW, the country would have a 1.4 GW of aggregated capacity. The installation of photovoltaic power stations would also help reach this level, which would result in a 142 Watt per inhabitant installed capacity, which would still be under the *current* average (171.5 [18]) in the European Union. The model uses this

[4] NCAR: National Centre for Atmospheric Research, CFSR(2): Climate Forecast System Reanalysis.

[5] With the exception of the new Nuclear power plant. It is assumed to be working on full capacity by 2030.

conservative amount of 1.4 GW of installed photovoltaic panels.

Since the amount of solar energy coming in at different locations in the country can differ significantly at discrete points in time, the study built a separate, small scale model simulating smaller amounts of photovoltaic capacity installed at 32 separate locations in Hungary and ran with data for three different years (2012–14). The solar radiation and ambient temperatures for each hour and each location are determined with the help of the CFSR(2) database available through the energyPRO software. The approach to the virtual installation of the 1.8 GW of wind capacity was similar to the installation for the PV panels. A separate model was built with data from 7 of the windiest locations in the country, and simulated with data from three separate years (2012–14). The principle behind the decentralized locations for both the solar panels and the wind turbines is that the relative intermittency is lower than if the capacities were installed at centralized locations, thus decreasing the volume of sudden changes in production. Please refer to Fig. 3 for the graphical layout of solar panels and wind turbines.

In order to accommodate the amount of intermittent renewable energy coming into the system, the previously discussed 500 MW (60 GWh storage capacity) pumped hydroelectric storage was built into the model. The storage is primarily used by the intermittent resources, but can be accessed by other operating capacities if needed. Please refer to Fig. 4 for the graphical representation of this sub-system and Fig. 5 for graphical layout of the ALT model.

Regarding the biomass use, using only the sustainable yield of forests and the secondary agricultural by-products would make it possible to install roughly 1000 MW of CHP capacity. In order to ensure that the scenario remains feasible, only 800 MWs of capacity is built into the system.

For the utilization of the geothermal potential, a conservative value of 200 MWe of installed capacity was used. One of the best locations for the installation of a geothermal plant is the south-western part of the country, where a specific impact study was made for the utilization of the 130 °C water [36]. A geothermal well with a moderate yield (100–120 l/s) allows for the operation of a 250–500 kW(e) ORC (Organic Rankine Cycle) plant. The cost of the installation of such plants is relatively high (Table 8). For this reason, the current research only calculates on a moderate amount of 200 MW(e) capacity.

For the simulation of the demand side of the electric power system the modest growth scenario is used (Table 2, Scenario A). It is important to note that the developed model is capable of simulation with any demand pattern if needed.

5.3. Rules of modelling

The scenarios simulate a point in time where the currently operating blocks of the nuclear power plant are retired, and the newly built ones are in operation.

The used methodology by energyPRO is an hourly analysis for the year 2030, balancing the available supply and demand with respect to priority and availability. The results are detailed energy balances, economic results and emissions data for all three scenarios.

The order of priority for production is the following: Nuclear plant, CHP plants (both natural gas and biomass fired), renewable sources, natural gas fired plants, imports. The Pumped Hydroelectric storage is primarily used by intermittent sources. The pre-2015 built natural gas fired (non CHP) plants are not used in the simulation and represent a tertiary reserve. The only exception for this is the relatively new 433 MW Gönyű Power Plant (built in 2011).

All models calculate with the respective self-consumption of power plants stated in Ref. [11], and a transmission loss of 7% within the electric power system. The natural gas fired CHP plants only operate when there is a heat demand, while the biomass fired CHPs operate with an 85% capacity factor, simulating the current practice of using these power plants year-round, regardless of heat demand. The CHPs respective heat to electricity ratio (system average: 1.2:1) and efficiency (system average: 61%) are defined with the help of the official supply side analysis of the Hungarian TSO [11].

The model is capable of dynamically changing the transmission loss of the system. The self-consumption of power plants can also be changed. The simulation was run with data for the intermittent renewable sources from 2012, 2013 and 2014. Since the results showed practically no difference on aggregate level, the data from the latest year (2014) were used for the results.

The scenarios were run and checked for every time step (hour) in order to verify that they work according to specification.

6. Results

The results section includes the short summary and demonstration of the simulation, followed by the comparison based on

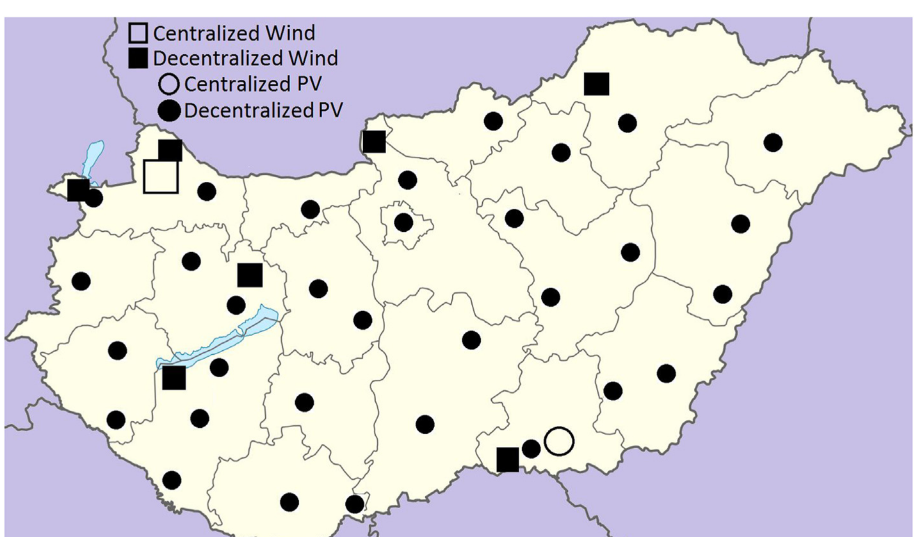


Fig. 3. Location of centralized and decentralized PV panels and wind turbines for the scenarios.

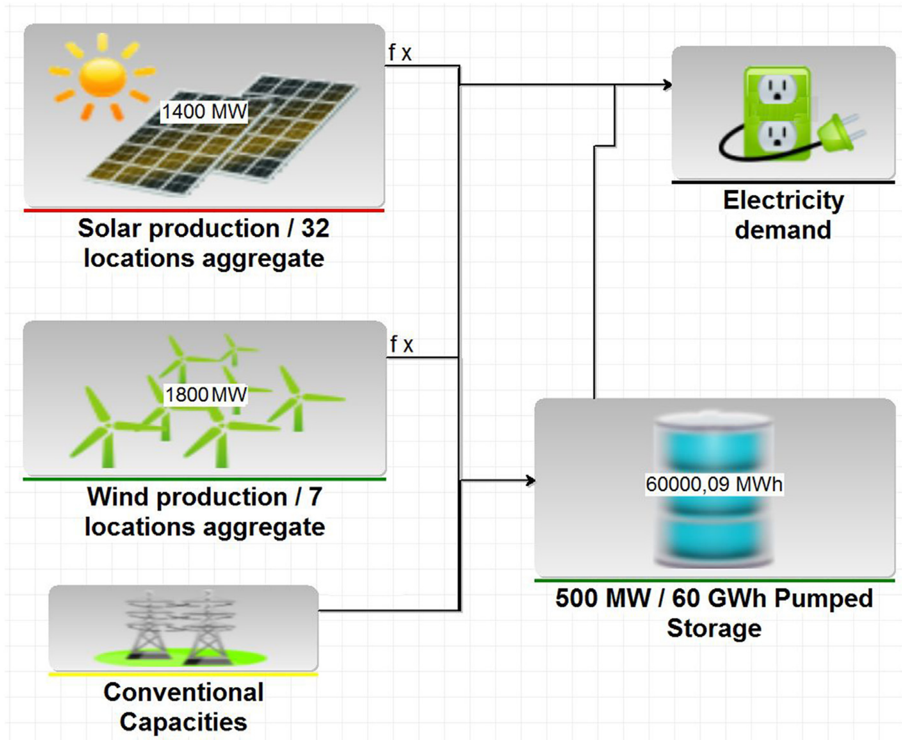


Fig. 4. Pumped hydroelectric storage system, alternative scenario.

energy security, environment consciousness and economic feasibility and a sensitivity analysis regarding electricity demand and CO2 prices.

Fig. 6 demonstrates a five-day period in the ALT scenario. The production of the same type of power plants are aggregated for better visualization, but the modelling procedure simulates each power plant individually. The base power plants operate at full capacity (no scheduled maintenance in the visualized 5-day period), while the natural gas fired CHP's operate to fulfil their respective heat demands. The intermittent energy sources either produce to the power grid, or – in case of overproduction – to the pumped storage. The energy in the pumped storage in the simulation is used as soon as possible, but during actual use it will be possible to use it in the light of electricity prices. Also, in the simulation, the production of natural gas fired plants are cut back if there is no demand, but during actual operation, it will be possible for them to use the pumped storage facility if it is inefficient to operate them under a certain load.

Fig. 7 graphs the source of domestically consumed electricity adjusted for consumption. The volume of the nuclear production is the same for all three scenarios. The excessive use of the newly built natural gas fired power plants BAU1 can be clearly seen. The electricity production from the biomass fired CHP plants make up the vast majority of the renewable share in the BAU scenarios. BAU2 has a very significant amount of imports (41.3%), due to introducing only a very small amount of new capacity. The ALT scenario looks well balanced and diversified with major contribution from renewable sources other than biomass. Appendix A shows the detailed flow (Sankey) diagram developed from the results obtained from the simulation of the ALT scenario.

6.1. Energy security

Energy security is evaluated by comparing the amount of domestic versus foreign sources for electricity and renewable energy share. Both the source of the fuel used to generate electricity and the amount of imported electricity in the system are included. Table 5 summarizes the results.

As Fig. 8 demonstrates, from an energy security point of view BAU1 and BAU2 hold a risk. Since for both scenarios, only 16% of the used electricity is produced form domestic sources, the rest is either produced domestically, but from a foreign fuel source, or is imported electricity. The same can be said regarding the share of renewable sourced electricity adjusted for consumption. The alternative model has almost 40% of electricity use generated from domestic sources, and almost 30% of electricity use from renewable sources.

6.2. Environment

The impact of the different scenarios on the environment are evaluated by their respective global warming potential, measured by gram of CO2 equivalent emission/kWh-e produced. The data is from the latest available publication by the Intergovernmental Panel on Climate Change [37]. In all cases, the median lifecycle emissions are used for evaluation. This way not only the direct emissions are taken into consideration, but all the emission connected to their respective infrastructure and supply chains. Please refer to Table 6 for specific values.

Table 7 summarizes the specific, calculated results for all three scenarios. It is important to point out that the emissions connected to the imported electricity (making up 41.3% in the BAU2 scenario) is not included due to the fact that it is practically impossible to predict the future state of the whole ENTSO system 15 years in advance. The lowest value for BAU2 in this case only means that there is a large uncertainty, rather than that this is an optimal scenario in this respect. The BAU1 and the ALT scenarios both supply more than 97% of the demand from domestically produced

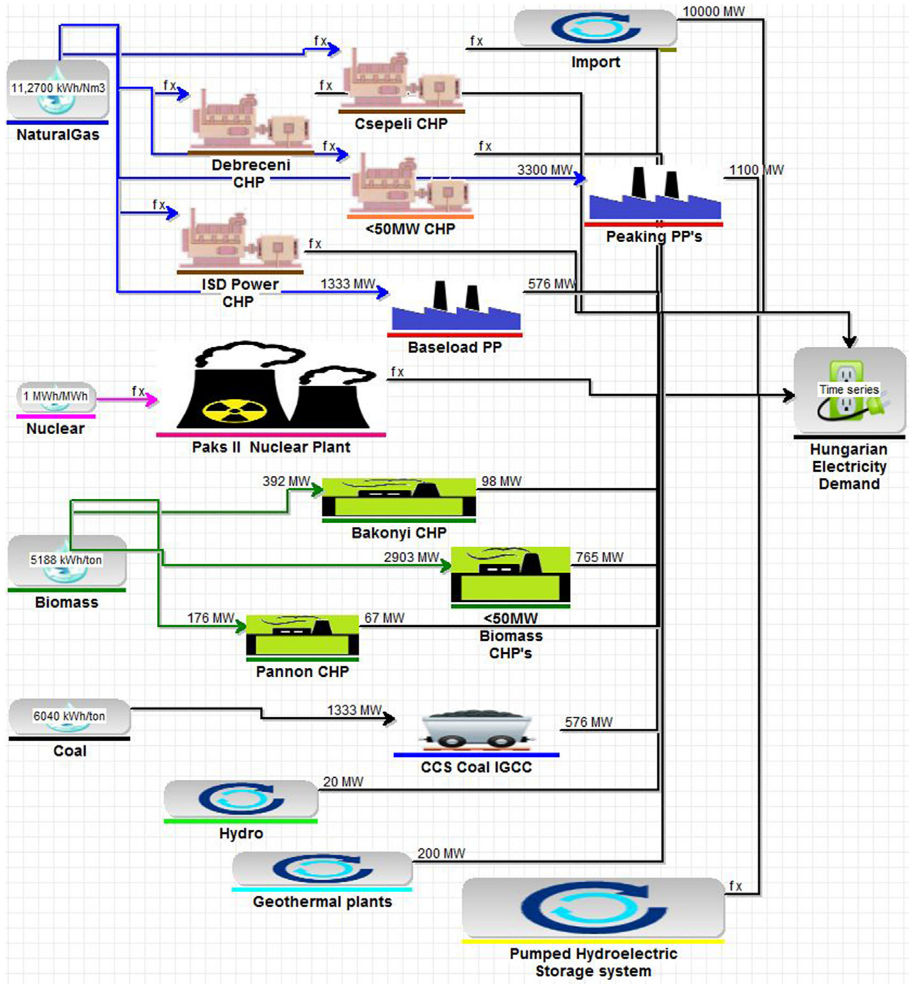


Fig. 5. Graphical layout – ALT model.

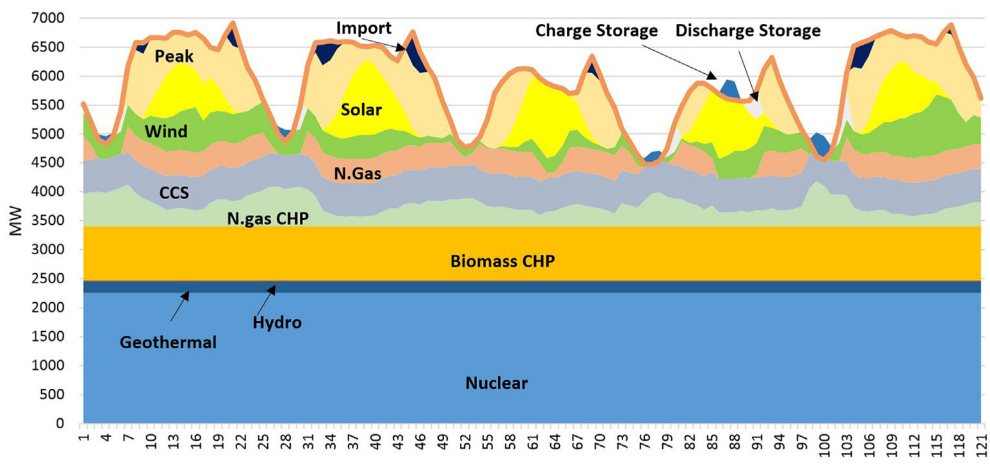


Fig. 6. Visualization of simulation (ALT scenario).

electricity, and so their emission values can be compared. Due to the larger volume of renewable sources – which tend to have lower emissions than fossil fuel based energy conversion procedures –, the total yearly emission of the ALT scenario is 35.1% lower than the BAU1 model.

6.3. Economic evaluation

Table 8 summarizes the cost value for three different groups, namely Capital cost, O&M (Operations & Maintenance) and Fuel cost, all projected to USD/MWh of produced electricity. Since the

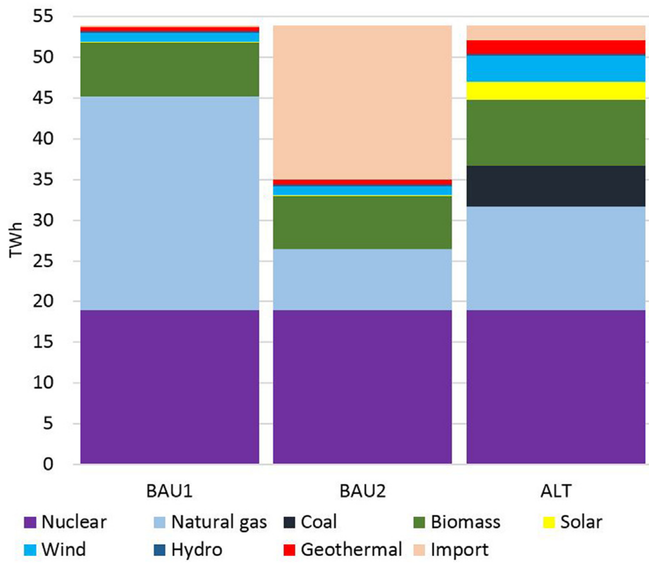


Fig. 7. Source of electricity (adjusted for consumption), 2030.

Table 5
Amount of fuel use (TWh).

	Source	Renewable	Fuel input/Total			Fuel input/Adj. For consumption		
			BAU1	BAU2	ALT	BAU1	BAU2	ALT
Nuclear	Foreign	No	58.1	58.1	58.1	18.9	18.9	18.9
Natural gas	Foreign	No	56.3	20.6	38.3	26.3	7.5	12.7
Coal	Domestic	No	0.0	0.0	11.2	0.0	0.0	5.0
Biomass	Domestic	Yes	19.8	19.8	30.2	6.6	6.6	8.1
Solar	Domestic	Yes	n/a	n/a	n/a	0.1	0.1	2.3
Wind	Domestic	Yes	n/a	n/a	n/a	1.1	1.1	3.2
Hydro	Domestic	Yes	n/a	n/a	n/a	0.2	0.2	0.2
Geothermal	Domestic	Yes	n/a	n/a	n/a	0.6	0.6	1.7
Imported	Foreign	n/a	n/a	n/a	n/a	0.2	19.0	1.8
Total						53.9	53.9	53.9

scenarios simulate *future* states of the Hungarian electric power system, it is also important to calculate with the potential change in these costs. Table 8 demonstrates data from the publication of the National Renewable Energy Laboratory of the U.S. Department of Energy, which predicts the aforementioned costs for 2030 [38]. The document contains predictions from a wide variety of respectable institutions, including:

1. Energy Information Administration (EIA), model name: *AEO*

Table 6
Emission intensity (gCO2 eq./kWh-e) [37].

Nuclear	12
Gas - Combined Cycle	490
CCS Coal IGCC	200
Biomass	230
PV	41
Wind	12
Hydro	24
Geothermal	38

Table 7
Emission intensity (1000 ton/year).

	BAU1	BAU2	ALT
Nuclear	227.1	227.1	227.1
Gas -Combined Cycle	12 891.2	3679.4	6232.4
CCS Coal IGCC	0.0	0.0	1009.3
Biomass	1507.9	1507.9	1860.6
PV	4.8	4.8	92.6
Wind	13.4	13.4	38.3
Hydro	4.2	4.2	4.2
Geothermal	21.6	21.6	64.0
Total	14 670.2	5458.4	9528.6

2. National Renewable Energy Laboratory (NREL), model name: *NREL-SEAC*
3. Pacific Northwest National Laboratory (PNNL), model name: *MiniCAM*
4. ICF International, model name: *EPA*
5. Electric Power Research Institute (EPRI), model name: *MERGE*

Since the predictions of these institutions do vary, we represent our results based on each of the institutions' predictions.

Using the data from Table 8, the total cost of the three scenarios are calculated with cost values from all five predictions. Since it is extremely difficult to predict import prices, the scenarios calculate with the current year ahead baseload comparison price for Hungary which stands at 40.45 Eur/MWh (44.03 USD/MWh) [40], which was determined by PLATTS, the leading independent provider of information and benchmark prices for the commodities and energy markets. Also the annual cost (capital + operation) of $2.6 million was added to the ALT scenario, as determined in the impact study on the hydroelectric pumping station for Hungary [27].

Table 9 shows that for all five predictions, the cost of the ALT model is the highest. It is important to note that BAU2 is the least expensive because it contains a large proportion of imports (35.2%). If the relatively cheap fossil based electricity production is coming to an end, than the BAU 2 scenario could be a highly risky one, and in the long term, could easily prove to be the most expensive of all

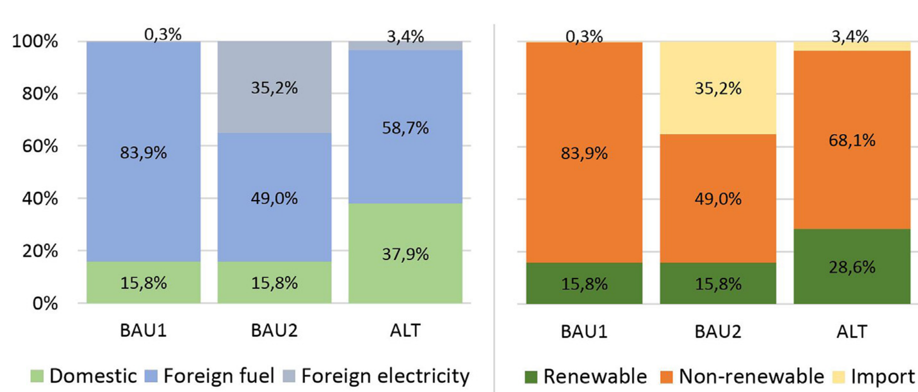


Fig. 8. Share of Domestic and Renewable sources.

Table 8
Cost values [38].

$/MWh	Capital cost					O&M					Fuel cost				
Model no.	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Nuclear	29	38	30	38	50	12	12	11	12	28	13	13	12	13	13
Combined Cycle (N. gas)	8	9	9	9	11	3	5	4	3	8	39	42	36	41	39
Advanced Coal with CCS	20	35	22	23	35	8	9	9	8	24	17	20	18	20	20
Biomass	27	31	23	36	38	15	20	10	15	22	17	31	19	21	26
Solar – PV	182	84	155	255	319	6	3	14	6	179	0	0	0	0	0
Wind	45	38	39	66	74	8	7	8	9	36	0	0	0	0	0
Hydroelectric[a],[39]	71	71	71	71	71	4	4	4	4	4	7	7	7	7	7
Geothermal[b]	43	43	33	130	130	20	23	10	23	23	0	0	0	0	0

1 - AEO, 2 – NREL, 3 - MiniCam, 4 - EPA, 5 - Merge.
[a] The costs of the Hydroelectric plant were not covered in the base document used [38], the similar publication of the U.S. Energy Information Administration is used [39].
[b] The Electric Power Research Institute does not list values for geothermal energy conversion (No. 5 – MERGE model). The largest values of the other 4 predictions are used.

Table 9
Total cost (million$/year) and average cost ($/MWh), 2030.

	AEO		NREL		MiniCam		EPA		Merge	
	Total	Average	Total	Average	Total	Average	Total	Average	Total	Average
BAU 1	2768	51.4	3215	59.6	2655	49.3	3167	58.8	3970	73.7
BAU 2	2585	48.0	2919	54.2	2491	46.2	2928	54.3	3636	67.5
ALT	3057	56.7	3325	61.7	2892	53.7	3769	69.9	5247	97.4

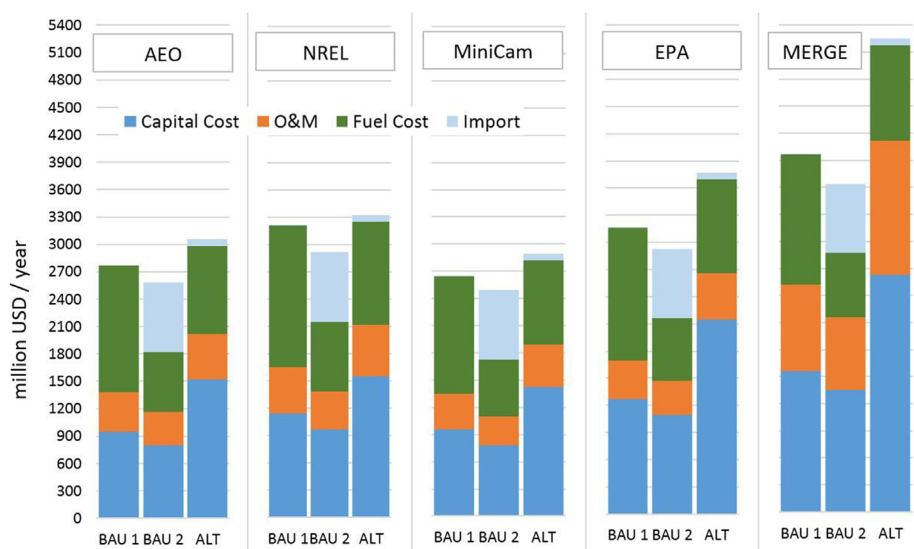


Fig. 9. Cost components for the three scenarios.

three scenarios. From this perspective BAU1 and the ALT scenario are worth comparing, since their proportion of imported electricity is very low (0.3% and 3.4% respectively). The total cost for the ALT scenario is on average 14.8% higher than that of the also self-supplying BAU1 scenario, with values ranging from 3.4% (NREL) to 32.3% (MERGE). Fig. 9 demonstrates the distribution of the total cost between the cost elements. The higher cost in all cases is primarily due to the relatively high capital cost of the needed new renewable energy based capacities for the ALT scenario.

There is a trade-off between energy security and low environmental impact and low cost, which has to be evaluated by the decision makers.

6.4. Sensitivity analysis regarding electricity demand and CO2 prices

A sensitivity analysis regarding demand has been conducted with Scenario B and Scenario C (slow and high growth rate respectively, discussed in Section 4.1). The results indicate that changes in demand do not cause any structural changes within the operation of the system. The model responds to changes primarily by adjusting the amount of electricity produced by the natural gas-fired peaking power plants, and so the only major difference which the volume of demand causes is in the use of natural gas. The amount of renewable sources used within the system does not change, since their use enjoys priority. The cost and emission intensity varies directly with the amount of natural gas used, but the order of the three scenarios by total cost and emission intensity stays the same.

The EU Emissions Trading System (EU ETS) limits the amount of CO2 which the Power and Heat generation industry is allowed to emit [41], and allowances must be bought for every tonne of CO2 emitted. The price has fluctuated between US$2.64 and US$9.69[6] [42] in the last three years. The model was re-run with prices of US$10, US$20 and US$50 for each tonne of CO2 emitted and added to the total cost of the scenarios presented in Section 6.3. The results indicate that the rankings of the three scenarios by total cost do not change, even with the significant price increase to US$50 per tonne of CO2.

The results of the sensitivity analysis indicate that the model is robust, the ranking of the scenarios (BAU1, BAU2, ALT) for the main result indicators - energy security, emission intensity and economic factors – do not change with the change in electricity demand or a realistic increase in CO2 prices.

7. Conclusion

The paper developed a model capable of simulating the electricity system of Hungary. It was used to simulate three possible scenarios for the electric power system for 2030. Two scenarios simulated the two possible paths determined by the Hungarian TSO, and the third simulated a possible state developed by the authors of the paper. The study used the developed model to compare the three scenarios based on energy security, environmental effect, and economic considerations.

The results show that developing the changes proposed in the scenario of the authors, the country of Hungary would operate an electric power system which is diversified with respect to fuel input, has double the renewable energy share than the business as usual scenarios, and uses 38% domestic sources to cover its electricity demand, compared to 15.8% for the business as usual scenarios. Also, its emission intensity would be 35% less than the business as usual scenario where the current centralized, fossil fuel based production strategy would continue.

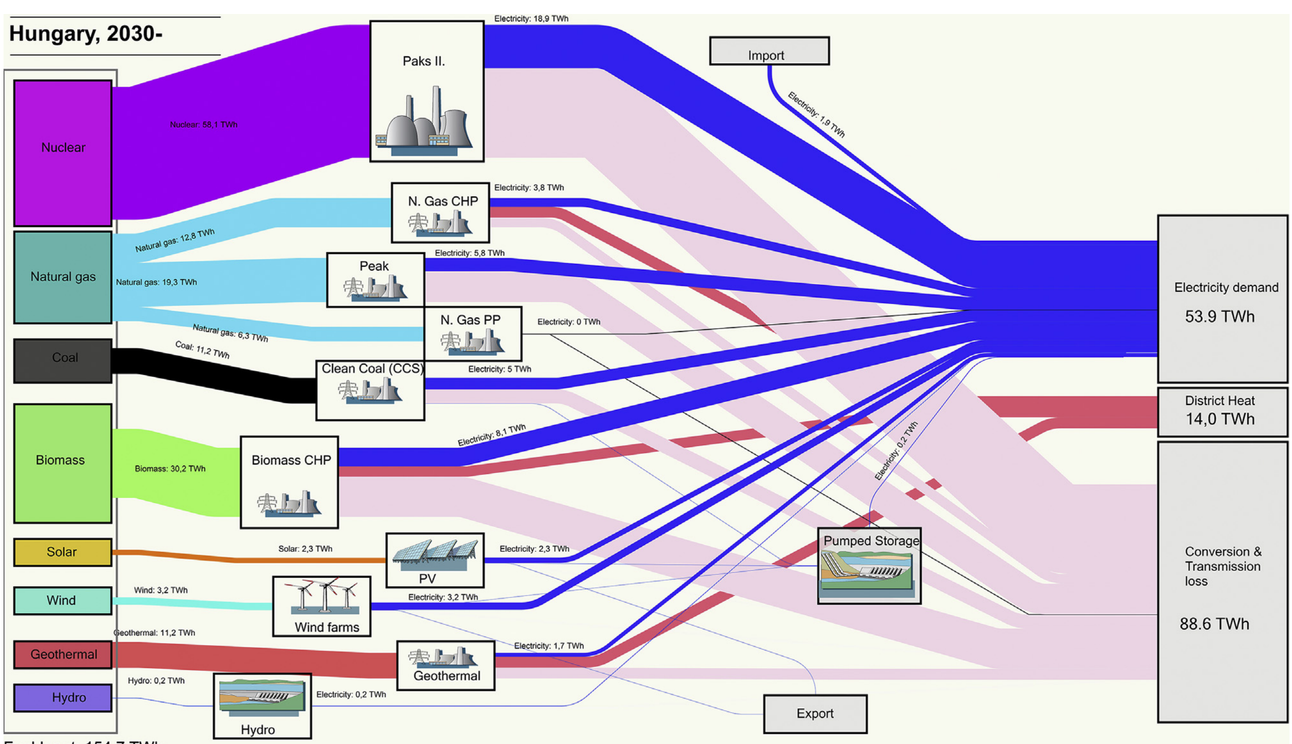
This much more secure and environment friendly electric power system would not be unaffordable, as it was shown that the development and the operation of such a system could be 3.4%–32.3% more expensive to build and operate. However, this costs could be outweighed by the tremendous advantages in energy security and environmental impact.

Acknowledgements

The research was supported by the Pallas Athéné Geopolitical Foundation. The foundation was established to support the Hungarian Government's economic policy through funding scientific think tanks. The authors would like to thank Clifford Chadwick for his help in language editing.

Appendix A

Sankey diagram for the Alternative (ALT) model. (created with Esankey, www.esankey.com).



[6] The allowances are traded in Euros. The values are converted to USD for consistency within the paper.

References

[1] Lund H, Mathiesen B. Energy system analysis of 100% renewable energy systems—the case of Denmark in years 2030 and 2050. Energy 2009;34(5):524–31.
[2] Ćosić B, Krajačić G, Duić N. A 100% renewable energy system in the year 2050", the case of Macedonia. Energy 2012;48(1):80–7.
[3] Novosel T, Ćosić B, Pukšec T, Krajačić G, Duić N, Mathiesen BV, et al. Integration of renewables and reverse osmosis desalination – case study for the

jordanian energy system with a high share of wind and photovoltaics. Energy 2015;92(3):270–8.
[4] Gota DI, Lund H, Miclea LA. Romanian energy system model and a nuclear reduction strategy. Energy 2011;36(11):6413–9.
[5] Connolly D, Lund H, Mathiesen BV, Leahy M. The first step towards a 100% renewable energy-system for Ireland. Appl Energy 2011;88(2):502–7.
[6] Sáfián F. Modelling the Hungarian energy system - the first step towards sustainable energy planning. Energy 2014;69(5):58–66.
[7] Mason I, Page S, Williamson A. A 100% renewable electricity generation system for New Zealand utilising hydro, wind, geothermal and biomass resources. Energy Policy 2010;38(8):3973–84.
[8] Krajačić G, Neven D, Carvalho M. How to achieve a 100% RES electricity supply for Portugal? Appl Energy 2011;88(2):508–17.
[9] Elliston B, Diesendorf M, Macgill I. Simulations of scenarios with 100% renewable electricity in the Australian national electricity market. Energy Policy 2012;45:606–13.
[10] Cho S, Kim J. Feasibility and impact analysis of a renewable energy source (RES)-based energy system in Korea. Energy 2015;85:317–28.
[11] MAVIR. Supply side analysis. The mid- and long term supply side capacity development of the Hungarian electrical system [[A Magyar Villamosenergia-rendszer Közép- és Hosszú Távú Forrásoldali Kapacitásfejlesztése]] [In Hungarian] Budapest, Hungary. 2013. Available at:, https://www.mavir.hu/documents/10258/15461/Forr%C3%A1selemz%C3%A9s_2014.pdf/7a379c76-a8d0-42f6-b8e6-bf8c05894a49 [accessed: 03.01.15.].
[12] ENTSO-E - European network of transmission system operators for electricity. Production Data. [internet] Available at: https://www.entsoe.eu/data/data-portal/production/Pages/default.aspx [accessed: 07.08.15.].
[13] E.ON Hungária Zrt. Hungary's most efficient power plant is inaugurated in Gönyű. [internet]. Available at: https://www.eon-hungaria.com/en/press/releases/2011/hungary-s-most-efficient-power-plant-is-inaugurated-in-gonyu [accessed: 02.03.15.].
[14] World Nuclear Association. Nuclear Power in Hungary. [internet] Available at: http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Hungary/[accessed: 23.04.15.].
[15] Ministry of National Development. National energy strategy to 2030. Budapest, Hungary. 2012 [internet] Available at:, http://www.terport.hu/webfm_send/2658 [accessed: 20.09.14.].
[16] Deputy secretariat of state for green economy development and climate policy for the Ministry of National development. National renewable energy action plan. 2010. Budapest, Hungary.
[17] MAVIR. Demand side analysis. Forecast of consumer demand in the Hungarian electrical system [[A Magyar Villamosenergia-rendszer fogyasztói igényeinek előrejelzése]] [In Hungarian] Budapest, Hungary. 2014. Available at:, http://mavir.hu/documents/10258/15461/Fogyaszt%C3%A1selemz%C3%A9s_2013.pdf/2a4a88ae-406d-4fff-882c-3e9575cd8ef4 [accessed: 11.12.14.].
[18] EurObserv'ER. Photovoltaic barometer. 2015 [internet]. Available from: http://www.eurobserv-er.org/photovoltaic-barometer-2015 [accessed: 02.02.16.].
[19] Solargis. Global Horizontal Irradiation (GHI) data. [internet]. Available from: http://solargis.info/doc/free-solar-radiation-maps-GHI [accessed: 07.04.15.].
[20] The European Wind Energy Association. Wind in power - 2013 European statistics. 2013. Available at: http://www.ewea.org/fileadmin/files/library/publications/statistics/EWEA_Annual_Statistics_2013.pdf [accessed: 05.01.16.].
[21] Geist F, Havas I. Renewable Energy Recap: Hungary. Analysis by Ernst and Young audit firm. [internet] Available at: http://www.renewableenergyworld.com/articles/2011/12/renewable-energy-recap-hungary.html [accessed: 2015.02.20.].
[22] The European Wind Energy Association. Eastern winds - emerging European wind power markets. 2013 [internet] Available at: http://www.ewea.org/fileadmin/files/library/publications/reports/Eastern_Winds_emerging_markets.pdf [accessed: 04.01.16.].
[23] Geothermal Finance and Awareness in European Regions. Country profile: Hungary [internet] Available at: http://www.energia.gr/geofar/page.asp?p_id=49 [accessed: 10.02.15.].
[24] Pregun Cs, Juhász Cs. Water resources management and water quality protection. University of Debrecen; 2011 [internet]. Available from: http://www.tankonyvtar.hu/hu/tartalom/tamop425/0032_vizkeszletgazdalkodas_es_vizminoseg/ch02s03.html [accessed 02.12.15].
[25] Hungarian Central Statistical Office. Forestry management data. 2014. Hungary, Budapest.
[26] MacKay David JC. Sustainable energy-without the hot air. Cambridge, England: UIT; 2009.
[27] Szeredi I. Discussion on the installation of a hydro pumping station for Hungary [[Szivattyús energiatározó (SZET) létesítésének kérdései]] [In Hungarian], Budapest, Hungary. 2007 [internet]. Available from:, http://www.sze.hu/~tothp/Renexpo_eloadasok/Szeredi_Istvan.pdf [accessed 09.12.15].
[28] Lund H, Siupsinskas G, Martinaitis V. Implementation strategy for small CHP plants in a competitive market: the case of Lithuania. Appl Energy 2005;82(3):214–27.
[29] Sorknæs P, Lund H, Andersen NA. Future power market and sustainable energy solutions – the treatment of uncertainties in the daily operation of combined heat and power plants. Appl Energy 2015;144:129–38.
[30] Wang H, Yin W, Abdollahi E, Lahdelma R, Jiao W. Modelling and optimization of CHP based district heating system with renewable energy production and energy storage. Appl Energy 2015;159:401–21.
[31] Wang H, Abdollahi E, Lahdelma R, Jiao W, Zhou Z. Modelling and optimization of the smart hybrid renewable energy for communities (SHREC). Renew Energy 2015;84:114–23.
[32] Fragaki A, Anders NA, Toke D. Exploration of economical sizing of gas engine and thermal store for combined heat and power plants in the UK. Energy 2008;33(11):1659–70.
[33] Fragaki A, Anders NA. Conditions for aggregation of CHP plants in the UK electricity market and exploration of plant size. Appl Energy 2011;88(11):3930–40.
[34] Østergaard PA. Comparing electricity, heat and biogas storages' impacts on renewable energy integration. Energy 2012;37(1):255–62.
[35] Hungarian Central Statistical Office. Agricultural data. 2014. Budapest, Hungary.
[36] Hetesi Zs. Impact Study on the geothermal potential of Ráckeve [[Ráckeve város geotermikus energia felhasználási hatástanulmány.]]. Aquaprofit Zrt. 3E- Kft. 2011 [In Hungarian] Ráckeve, Hungary.
[37] Schlömer S, Bruckner T, Fulton L, Hertwich E, McKinnon A, Perczyk D, Roy J, Schaeffer R., Sims R, Smith P, Wiser R Annex III: Technology-specific cost and performance parameters. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann P, Savolainen J, Schlömer S, von Stechow C, Zwickel T, Minx J.C. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. [internet]. Available from: https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_annex-iii.pdf [accessed 13.11.15].
[38] National Renewable Energy Laboratory. U.S. Department of Energy. Cost and Performance Assumptions for Modeling Electricity Generation Technologies. [internet]. Available from: www.nrel.gov/docs/fy11osti/48595.pdf [accessed 15.11.15].
[39] U.S. Energy Information Administration. Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2015. Appendix: Tables for 2040. [internet] Available at: https://www.eia.gov/forecasts/aeo/pdf/appendix_tbls.pdf [accessed 12.03.15].
[40] PLATTS. McGraw Hill Financial. European Power Daily. [internet] Available at: https://www.platts.com/IM.Platts.Content/ProductsServices/Products/europeanpowerdaily.pdf [accessed 11.11.15].
[41] European Commission. Publications Office. The EU emissions trading system (EU ETS). Factsheet. 2013 [internet] Available at: http://ec.europa.eu/clima/publications/docs/factsheet_ets_en.pdf [accessed 01.08.16].
[42] European Energy Exchange. EU Emission Allowances | Secondary Market. [internet] Available at: https://www.eex.com/en/market-data/emission-allowances/spot-market/european-emission-allowances#!/2016/07/29 [accessed 01.08.16].