PÉCSI TUDOMÁNYEGYETEM

KÖZGAZDASÁGTUDOMÁNYI KAR

GAZDÁLKODÁSTANI DOKTORI ISKOLA

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THE ENERGY SYSTEM OF PÉCS – A SIMULATION MODEL

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Contents

Executive Summary

The global demand for energy has shown a sharp and continuous rise in the last and the current century. The readily available electricity, heating and cooling solutions and transportation have become integral parts of our everyday life. Almost 87% of the world primary energy need supplied by the three main types of fossil fuels, namely oil, natural gas and coal.

There are several positive and negative sides to supplying our energy demand with mainly fossil fuels. They are a very concentrated form of energy and are relatively easy to store. But since they are not evenly distributed on our globe, a high level of dependency can develop for the vast majority of the countries. Also, there is only a limited amount of proven reserves for oil natural gas and coal. Although predictions vary, there is a general consensus that the next century (or the last part of this century) will have to use non-fossil forms of primary energy to supply their needs. The emission of greenhouse gases from the combustion of these three types of fuels already account for over 65% of the CO2 emission in the world, and thus one of the main contributors to climate change. In order to overcome these problems, steps have to be made quickly. There are several levels of decision making involved in the change procedure. Larger scale goals are determined by policies issued by the OECD or the European Union, and local decisions needed which should be in line with the larger scale goals. Local energy management, such as country or city sized decisions have a big impact on how we shape our future.

Local energy management decisions comprise the installation of different types of power plants or issuing policies helping to increase the efficiency of a system. Since energy systems are interconnected networks, some of these decisions have impacts which are unforeseen at the start of the implementation phase. In order for energy management decision makers to be as informed as possible, a system is needed which enables them to assess the potential impact of their decisions.

The goal of the current work is to develop such a system for the city of Pécs, which can model the energy system of the city in order to simulate the impact of potential decisions. This way energy management decisions can be analysed and compared with one another from a number of perspectives before the implementation phase.

The development of such a decision making system requires a detailed literature review, in order to understand the current state of the area, and a step by step plan. Based on

the literature review it is found that a discrete-event simulation model would be the most efficient way of creating such a system. The steps of developing, running and evaluating a discrete-event simulation model are overviewed and shortly analysed. The main part of the dissertation consists of following and implementing these steps in order to reach the goal. The detailed collection, analysis and – where needed – preparation of the data is included for both the demand and the supply side of the system. The demand side consist of the three basic sectors of the city's energy system: electricity, heat and transportation. Both aggregated and the hourly values for each category are determined, occasionally with uniquely developed methods. The supply side of the system consists of the private or community energy conversion units, such as power plants, individual heating and the wide range of input fuel for these solutions. After the collection of the data, a reference model is developed and run, which lets the researcher know whether the developed model works according to intent, and whether it is suitable for simulation of hypothetical models.

Two hypothetical models are developed as an integral part of developing a decision making system. The city of Pécs issued an energy strategy in 2013 which determines several steps that need to be taken in order to make sure that the city has higher energy security, uses more renewable resources and is more energy efficient. In order for the decision makers to be able to compare the benefits and drawbacks of implementing the steps determined in the energy strategy, the hypothetical implementation is simulated and compared to a scenario where the steps are not taken.

The dissertation achieves new results by creating a functioning simulation model of a city sized system with integrating the electric, heating and transportation sector. The methods used to determine the duration curve of the district heating system is also an own contribution of the researcher. The results confirm that the implementation of the energy strategy of Pécs would increase the energy security of the city by using more renewable and local sources to meet its energy demand, and would not use its resources in a less efficient way. With the newly developed simulation model practically any desired scenario can be modelled, and this way the decision makers can analyse the pros and cons of their decision without having to actually implement it.

Importance of energy management

The demand for energy has shown a sharp and continuous rise in the last and the current century. The system that is capable of supplying such a volume of energy through different sub-systems uses a wide source of primary energy, ranging from fossil fuels to renewable sources. Table 1 shows the world consumption of primary energy in 2013 (BP, 2013). Our energy demand is primarily supplied by fossil fuels, such as Oil, Natural Gas and Coal (altogether 86.9%).

Primary energy	Mtoe[1]	%
Oil	4130.5	33.1%
Natural Gas	2987.1	23.9%
Coal	3730.1	29.9%
Nuclear	560.4	4.5%
Hydro-electricity	831.1	6.7%
Renewables	237.4	1.9%
SUM	12476.6	100.0%

Table 1. World consumption of primary energy, 2013 (Source: BP statistical review, 2013)

There are several potential dangers in using such large amount of fossil based fuels in our energy system:

- The burning of fossil fuels directly and indirectly lead to the anthropogenic greenhouse effect.
- They are not evenly distributed throughout the world, which can lead to a high degree of dependency in local energy systems.
- The available amount of such fuels is limited.

It is evident that we have to change how we manage our energy system. There are several levels of decision making involved in the change procedure. Larger scale goals are determined by policies issued by the OECD or the European Union, and local decisions which should be in line with the larger scale goals. Local energy management, such as country or city sized decisions can have a big impact on how we shape our future.

Local energy management decisions can include decisions regarding the installation of different types of power plants or issuing policies helping to increase the efficiency of a system. Since energy systems are interconnected networks, some of these decisions can have an impact which is unforeseen at the start of the implementation phase. In order for energy management decisions to be as informed as possible, a system is needed which enables decision makers to assess the potential impact of their decision.

[1] Mtoe: Million tonnes oil equivalent

Research goal

The personal motivation of the research is related to the recognition of the importance of creating a sustainable and environment friendly energy system for my hometown of Pécs. Decision makers need to be informed about the potential impact of their decisions. Creating a model which enables them to compare energy management scenarios is a vital part of such a decision.

The primary goal of the dissertation is to develop a simulation model (suitable for detailed analysis) of an energy system for a city covering heat, electricity and transportation, together with a wide range of energy conversion possibilities.

The city of Pécs prepared its strategy to comply with sustainable development principles. A sustainable city needs a sustainable energy system and so, in 2013, the city laid its foundation for the building of such a system by developing and publishing its own energy strategy. Included in the strategy are all the requirements for a sustainable energy system – specifically reducing the energy dependence of the city and increasing the proportion of renewable resources within the system.

The developed simulation model is used and analysed as the energy system for Pécs. This analysis evaluates the proposals of the city's energy strategy and compares it to a scenario when the proposals are not implemented. The comparison is for energy security and energy efficiency. Energy security will be evaluated by the proportion of renewable sources in the system and the proportion of locally sourced resources in the final consumption. Energy efficiency will be evaluated by the useful output of the energy system and the amount of input it uses. This model can serve as a tool for decision makers, since there are different pathways a city can take, each having its own advantages and drawbacks. The careful evaluation of how the system will behave before actual implementation enables the decision makers to consider several scenarios of development, and make an informed decision.

The method generally used for evaluating the feasibility and potential effects of such proposals is simulation modelling. Recent literature has numerous studies of energy system modelling ranging from smaller areas - such as regions or islands - to country-size territories. The area of interest is usually one or more of the three sectors of electricity, heat and transportation. In the leading literature of such modelling exercises the researchers primarily analyse country sized energy systems.

Significant studies evaluating similarly sized systems to that of Pécs include Østergaard et al. (2010) who analysed the possibility of reducing fossil fuel usage in the Aalborg Municipality and Frederikshavn through the large-scale integration of low-temperature geothermal heat, wind power and biomass. Antoine et al. (2008) conducted an energy scenario analysis of Malta researching the possibility of integrating more renewable energy sources into the system, whilst Medić et al. (2013) carried out a similar analysis for the island of Hvar. Studies of energy systems which are still regional, but much larger in terms of area and population, include Hong et al.'s (2013) design of an integrated energy pathway for Jiangsu province in China and a new study conducted by Ma et al. (2014) which compares the different paths which Hong Kong could take regarding energy sources and their respective outcomes.

Similarly to the studies mentioned above, a modelling exercise and scenario analysis are needed to determine the potential effects of the reduction of fossil fuel usage and the introduction of major renewable energy sources as proposed in the energy strategy of Pécs.

The dissertation is a unique attempt to build a simulation model for Pécs which covers the areas of heat, electricity and transportation. Similar attempts to model a city sized energy systems are rare, and generally do not analyse the energy system in such detail as the current work. The method developed to determine the duration curve for the district heating system of the city solely based on ambient temperature values is the own contribution of the researcher.

Boundaries of the research

The research focuses on the three basic areas of electricity, heat and transportation. It does not intend to analyse any other area connected to energy use. It is a discrete-event simulation with a deterministic input-output data structure. It optimizes operation through allocation of resources in order to serve a pre-determined energy demand. The simulation uses one hour time steps for the duration of one year at a time. The time step of one hour is widely accepted in the leading literature as a sufficient time step for such modelling purposes. The model works with data on an "as is" basis. Although large efforts are made to make sure that input data is punctual and realistic, the main purpose of the research is to develop a framework where potential decisions can be simulated. Any data set where the quality turns out to be less than satisfactory can be changed later, since the model is developed to be able to handle it.

Build-up of the dissertation

The first chapter discusses the importance of the research topic, followed by a theoretical overlook on simulation modelling, its classifications and its potential drawbacks. The works of Bossel (1994), Maria (1997), Shannon (1998), Law and Kelton (2000) and Banks et al. (2014) are used to introduce the types of simulation methods which could be useful for the research. Difference between discrete and continuous systems, deterministic and stochastic modelling and static versus dynamic modelling is discussed.

Chapter 3 analyses simulation modelling in an extensive literature review of the area and determines the appropriate type of simulation modelling for the current research. A deterministic discrete-event simulation model is determined to be the most efficient for the goals of the research. Chapter 4 determines the steps of such a simulation. Chapter 5 identifies the right framework for the development of the simulation model with the help of Connoly et al's (2010) article: *A Review of Computer Tools for Analysing the Integration of Renewable Energy into Various Energy Systems*, which offers a deep insight into the current status of energy modelling tools.

Chapter 6 starts the simulation procedure by following the steps determined by Banks et al. (2014). Step I formulates the problem and the hypotheses, while Step II. sets the objectives and the overall project plan, which is to develop a simulation model capable of detailed analysis of the energy system of Pécs.

STEPS OF SIMULATION

I.	Problem formulation
II.	Setting of objectives and overall project plan
III.	Model conceptualization
IV.	Data collection
V.	Model translation
VI.	Verified?
VII.	Validated?
VIII.	Experimental design
IX.	Production runs and analysis
X.	More runs?
XI.	Documentation and reporting
XII.	Implementation

Source: Based on (Banks et al, 2014)

The actual model development begins in Step IV and V., which include data collection and model translation. The data collected can be grouped into two distinct categories: Demand side data and Supply side data. The demand side data consists of aggregated and hourly values for the heat, electricity and transportation sectors energy demand. The supply side of the simulation model primarily consists of the energy conversion units the city uses. This includes community solutions - such as power plants – and individual solutions such as different kinds of heating systems and photovoltaic conversion units. This chapter also includes the external data (ambient temperature and solar radiation) needed for an hourly analysis of the simulation model.

The actual simulation phase starts Steps VI. and VII. which include the verification, calibration and validation processes. The verification process checks whether the computer program used for simulation works according to the intent with the model built in. The calibration of the model consists of comparing the modelled data with actual data from the year 2012, and adjusting accordingly. The validation process analyses the input and the output values of the model, and test them against the actual input/output of the system.

After the validation of the model two experimental designs are set up in Chapter 7 (Step VIII). The two alternatives will be the 2020 energy system of Pécs, if they do not implement the specific steps determined in the energy strategy, called (BAU, business as usual), and the 2020 energy system of Pécs, if they do implement all the proposed changes (called ES – Energy Strategy). Step IX. runs the simulations and gathers the needed information from the results.

Chapter 8 includes the implementation of Steps X. through XII. and evaluates the results of the simulation of the two experimental design in terms of the research hypotheses set previously.

The appendices contain data and results on the detailed steps of the model translation phase and the emission of the evaluated energy scenarios. The model translation phase converts the information collected in the previous phase into a form that can be used by the software which helps with the analysis, while the emission analysis phase defines the type of greenhouse gases the model wishes to include and the values of each type for energy sources and energy conversion units.

Hypotheses of the dissertation

The city of Pécs prepared its energy strategy to comply with sustainable development principles. A sustainable city needs a sustainable energy system and so, in 2013, the city laid its foundation for the building of such a system by developing and publishing its own energy strategy. Included in the strategy are all the requirements for a sustainable energy system – specifically reducing the energy dependence of the city and increasing the proportion of renewable resources within the system. The main question of the decision makers: Can the implementation of the energy strategy deliver what it promises in terms of sustainability and energy security?

The developed simulation model is used and analysed as the energy system for Pécs. This analysis evaluates the proposals of the city's energy strategy and compares it to a scenario when the proposals are not implemented. The comparison is for energy security and energy efficiency. Energy security will be evaluated by the proportion of renewable sources in the system and the proportion of locally sourced resources in the final consumption. Energy efficiency will be evaluated by the useful output of the energy system and the amount of input it uses. This model can serve as a tool for decision makers, since there are different pathways a city can take, each having its own advantages and drawbacks. The careful evaluation of how the system will behave before actual implementation enables the decision makers to consider several scenarios of development, and make an informed decision.

In order to analyse any energy system in detail, a validated model needs to be developed which is suitable to conduct further analysis. However, the development of such a model is a complex task and is rarely done for city sized areas for all the three basic areas of energy (electricity, heat and transportation).

H1: It is possible to design a model of Pécs which incorporates the three basic areas of energy (electricity, heat and transportation) and is capable of simulating real life events.

The question whether the actual implementation of the proposed steps of the city's energy strategy would fulfil the expectations regarding the energy security and energy efficiency are essential.

H2: The implementation of the proposed energy strategy of Pécs would increase the energy security of the city.

Whether the energy demand of a city can be fulfilled depends on many factors. The higher degree a city (or any sized energy system for that matter) has control over the energy sources it uses decreases the probability of a situation where there is an energy shortage. Renewable and local energy sources are generally uninfluenced by external factors, as opposed to non-renewable sources, of which there can be a shortage of and their supply does not solely depend on the city's actions.

H3: The implementation of the proposed energy strategy of Pécs would increase the efficiency of the energy supply for the city.

The definition used for determining the energy efficiency of an energy system is the following: "Using less energy to produce greater economic output. It can be expressed as a ratio of useful outputs to energy inputs for a system." (Lovins, 1977; Min and Xing, 2015) An increase in the efficiency would in this case practically mean that the newly developed energy system would be capable of supplying a unit of energy from fewer resources.

Main results

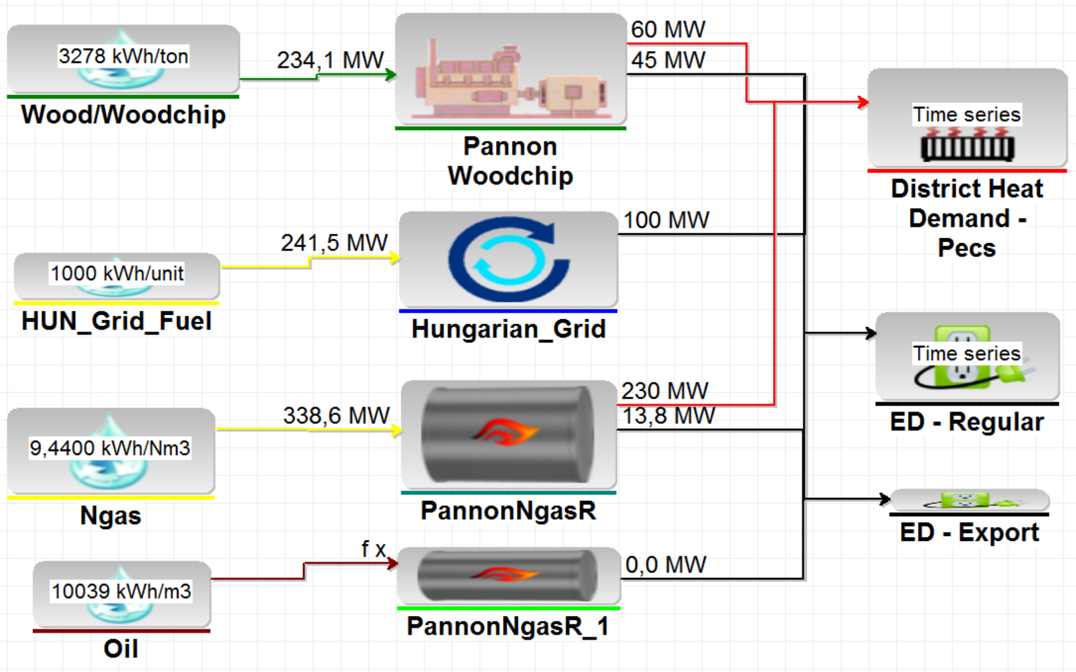
Comparison of the aggregated fuel use and the complex efficiency of the system serve as the main points of comparison for the two scenarios, which help the researcher to evaluate the hypotheses of the dissertation.

H1: It is possible to design model of Pécs which incorporates the three basic areas of energy (electricity, heat and transportation) and is capable of simulating real life events.

The literature review lists the main, state of the art modelling of energy systems published in the leading journals of the area. In order to use these models to forecast the possible outcomes of energy scenarios, a model is developed and validated beforehand in order to assure that it works as intended and is suitable for further analysis. The validation process done by comparing values obtained from the simulation runs of the model with actual, real life values. These values typically include aggregated demands for the analysed sectors (heat, electricity, transportation), aggregated amount of generated energy by conversion units and aggregated fuel use of the system. The deviation of the model values from actual values are determined in absolute and percentage terms. Although there is no widely accepted threshold under which a modelled value can be accepted, the deviation of modelled values generally stay under 2%, with one or two rare exceptions.

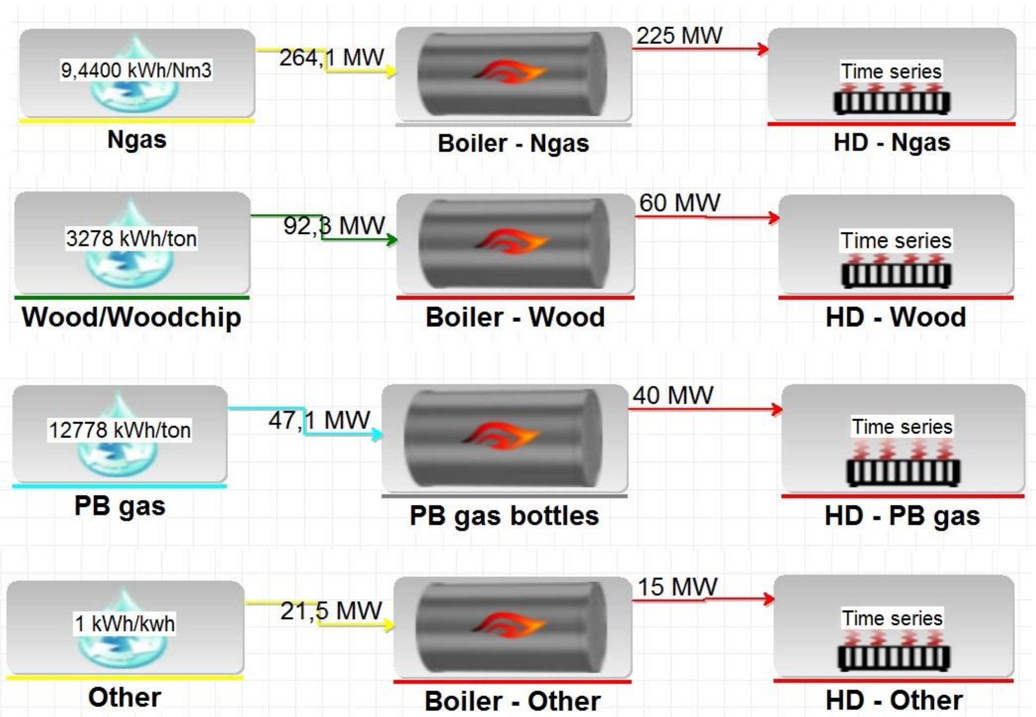
The model for the energy system of Pécs was developed for 3 years, with detailed analysis of both the demand and the supply side. The graphical layout of the model can be found in Figure 1 through 3. The energy conversion units producing the needed energy are in the middle section of Figure 1, whilst the inputs fuelling the conversion units are on the left hand side.

Figure 1.: Graphical layout, district heating and electricity system



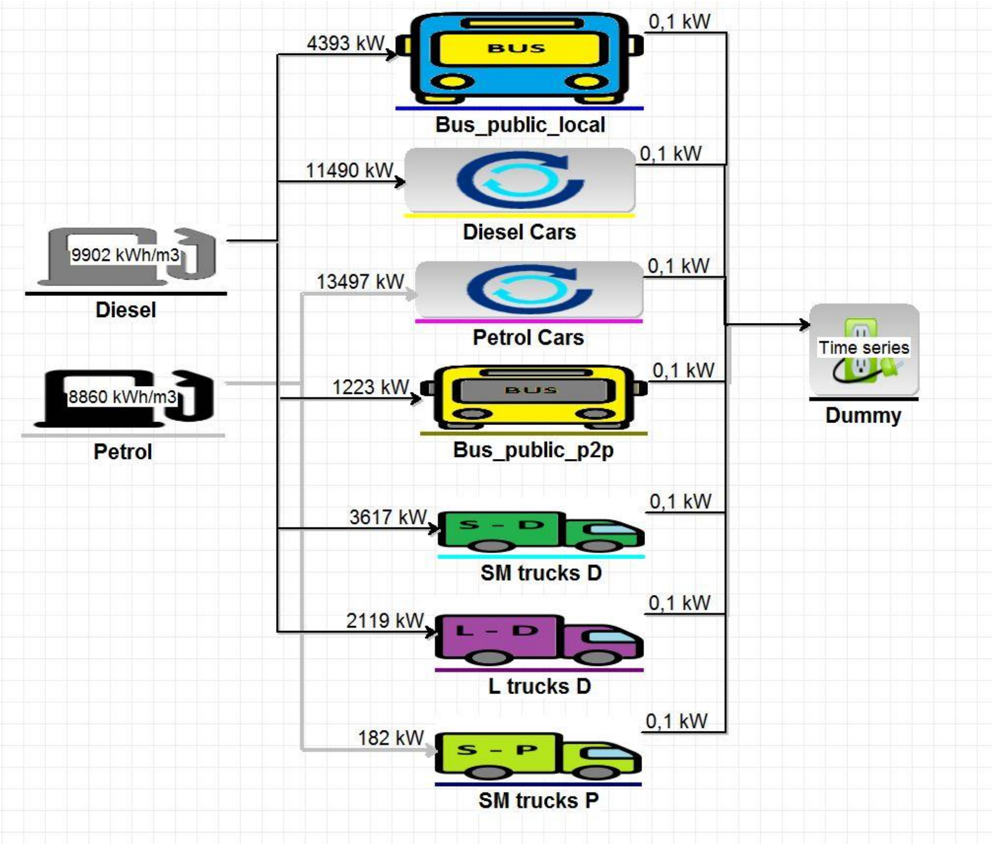
Source: Own edition

Figure 2.: Graphical layout, individual heating systems



Source: Own edition

Figure 3.: Graphical layout, transportation system



Source: Own edition

This model was then used for simulating the year 2012 from which year actual data was available, thus the developed simulation model could be validated. The validation of the reference model was made by comparing the aggregated values within the system for the modelled and the actual data. The results of the comparison can be found in Table 2.

Table 2.: Validation of the 2012 Reference model

	Actual	Modelled	Diff. Unit	Diff. %
District heat demand (TJ)	1 488	1 497	9.0	0.6077
Peak district heat demand (MW)	191	188	2.9	-1.5183
Heat production of CHP unit (biomass) (TJ)	1 068	1 052	-17.2	-1.6133
Heat production of CHP unit (natural gas) (TJ)	420	422	2.4	0.5623
Natural gas demand (Individual heating systems) (TJ)	1 316	1 321	4.8	0.3635
PB demand (Individual heating systems) (TJ)	300	302	2.1	0.6848
Wood demand (Individual heating systems) (TJ)	105	106	0.6	0.5854
Other demand (Individual heating systems) (TJ)	126	127	1.2	0.9689
Electricity demand (TJ)	1 620	1 625	4.9	0.3048
Electricity production of CHP unit (biomass) (TJ)	N/A	789	N/A	N/A
Electricity production of CHP unit (natural gas) (TJ)	25.2	25.3	0.1	0.5629
Fuel use of vehicles (petrol) (TJ)	432	433	0.5	0.1233
Fuel use of vehicles (diesel) (TJ)	724	722	-1.6	-0.2216

Source: Own edition

The results obtained from the simulation of the reference model are very close to the actual values, the differences being invariably below 2% (mostly below 1%). The results clearly confirm that the developed model represents the energy system very closely and that it is, in consequence, satisfactory to conduct simulations for future energy systems. Therefore H1 is accepted.

H2: The implementation of the proposed energy strategy of Pécs would increase the energy security of the city.

Energy security is evaluated by the proportion of renewable sources in the system and the proportion of local versus external resources in the system.

Table 3 shows the fuel demand for both the BAU and the ES models. In the ES model natural gas was primarily replaced by renewable energy sources. This was due to the larger district heating system, the introduction of the biogas plant and to the fact that the alternative heating solutions targeted individual buildings formerly heated by natural gas. The Energy Strategy model has a 14.14% lower import of electricity, indirectly reducing the use of coal and nuclear energy. The total efficiency of the system is lower in the ES model, due to the introduction of the biogas plant, which uses a vast amount of biomass for its production and has a low efficiency rate of conversion. Since, according to the Energy Strategy, the input for the biogas plant should comprise materials otherwise considered as waste (municipal and agricultural) this is not a major concern.

Table 3.: Fuel input for BAU and ES models (TJ)

TJ	Business as usual	Energy strategy	Difference TJ	Difference %	Source	RES
Biomass (straw)	3 201.1	3 279.0	77.9	2.43	Local	Yes
Natural Gas	2 084.4	1 390.9	-693.5	-33.27	External	No
Biomass (wood)	1 432.6	1 902.9	470.3	32.83	Local	Yes
Diesel + Petrol	1 108.9	1 058.8	-50.2	-4.52	External	No
Nuclear	877.1	753.1	-124.0	-14.14	External	No
PB gas	271.8	0.0	-271.8	N/A	External	No
Coal	311.5	267.4	-44.0	-14.14	External	No
Other	114.5	0.0	-114.5	N/A	Local	Yes
Other (external)	131.1	112.6	-18.5	-14.14	External	Yes
Oil	20.5	31.3	10.9	53.00	External	No
Solar + Geothermal + Air	0.0	439.0	439.0	N/A	Local	Yes
Municipal & Agricultural waste	0.0	2 520.3	2 520.3	N/A	Local	Yes
Total	95 53.6	11 755.4	2 201.8	23.05		

Source: Own edition

For further comparison, the total demand for fuel is adjusted for consumption in Table 4. The proportion of renewable energy in final consumption is notably larger in the ES model (65.9%

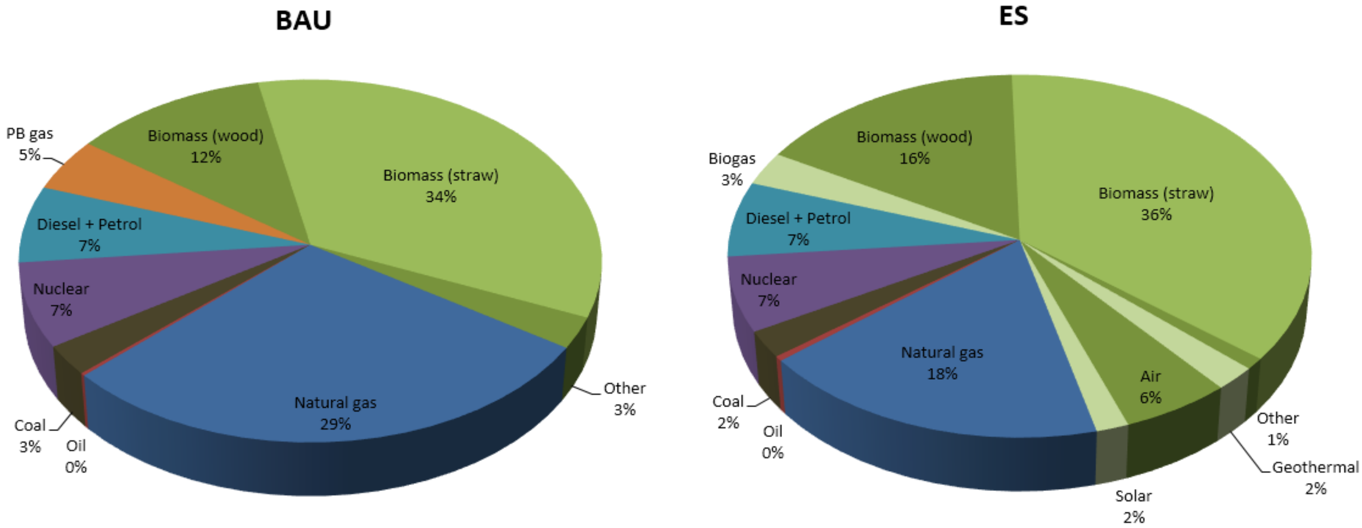
as opposed to 49.1%, Figure 4) - an important indicator in terms of sustainability and energy security.

Table 4.: Fuel use, adjusted for consumption

TJ	BAU	ES
Natural gas	1 399.9	852.4
Oil	11.1	19.7
Coal	128.8	112.2
Nuclear	363.1	315.5
Diesel + Petrol	333.0	317.7
PB gas	230.9	0.0
Biogas	0.0	142.5
Biomass (wood)	570.8	771.1
Biomass (straw)	1 673.9	1 714.7
Other	134.4	47.6
Geothermal	0.0	101.0
Air	0.0	265.0
Solar	0.0	79.0
Total	4 845.9	4 738.3

Source: Own edition

Figure 4.: Comparison of renewable energy as a proportion of final consumption



Source: Own edition

Table 3 shows all externally sourced fuel usage as smaller in the ES model, except for a minor increase in the demand for oil. Table 5 shows the aggregated change in the 'local vs. external' sources needed for the two different strategies.

Table 5.: Local vs. external sources of energy, adjusted for consumption

TJ	Local	External
Business as usual	2 379	2 467
Energy strategy	3 121	1 617
Difference (TJ)	742	-850
Difference (%)	31.2%	-34.4%

We can see that implementing the Energy Strategy model produces a 34.4% lower demand for externally sourced energy. Since the local fuels are all renewable, whilst externally sourced energy mainly comprises fossil fuels (natural gas, nuclear energy, petroleum and coal) originating outside the country, the ES not only decreases its own energy dependence, but contributes to the energy independence of Hungary. The results show that implementing the Energy Strategy would be advantageous in terms of energy security due to the higher proportion of renewable sources used and the higher proportion of local energy sources. Therefore H2 is accepted.

H3: The implementation of the proposed energy strategy of Pécs would increase the efficiency of the energy supply for the city.

An energy system is considered more efficient if it can deliver the same amount of energy from a smaller amount of resources. The analysis of the simulation showed us that the Business as Usual model delivers 4.840 TJ, while the Energy Strategy model delivers 4.742 TJ of useful energy to the city, while exporting 85 and 111 TJ of electricity respectively.

When analysing the efficiency rate of the two supply networks (Table 40), it is clear that the two strategies do not differ greatly in the total energy content of their respective fuel demand (9,553.6 to 9,651.7 or a 1.03% difference). The same can be concluded for the final consumption of energy regarding the three analysed sectors of electricity, heat and transportation. As a result, the respective efficiency rates of the two analysed systems are very close to each other. The Business As Usual scenario has an overall system efficiency of 50.3%, while the Energy Strategy scenario has a marginally higher, 51.6% efficiency.

The hypothesis cannot be rejected. It is important to note that there is only a marginal difference, which can be well within the margin of error for such a large energy system. The final conclusion for the hypothesis is that implementation of the proposed energy strategy of Pécs would not decrease the efficiency of the energy supply of the city considerably.

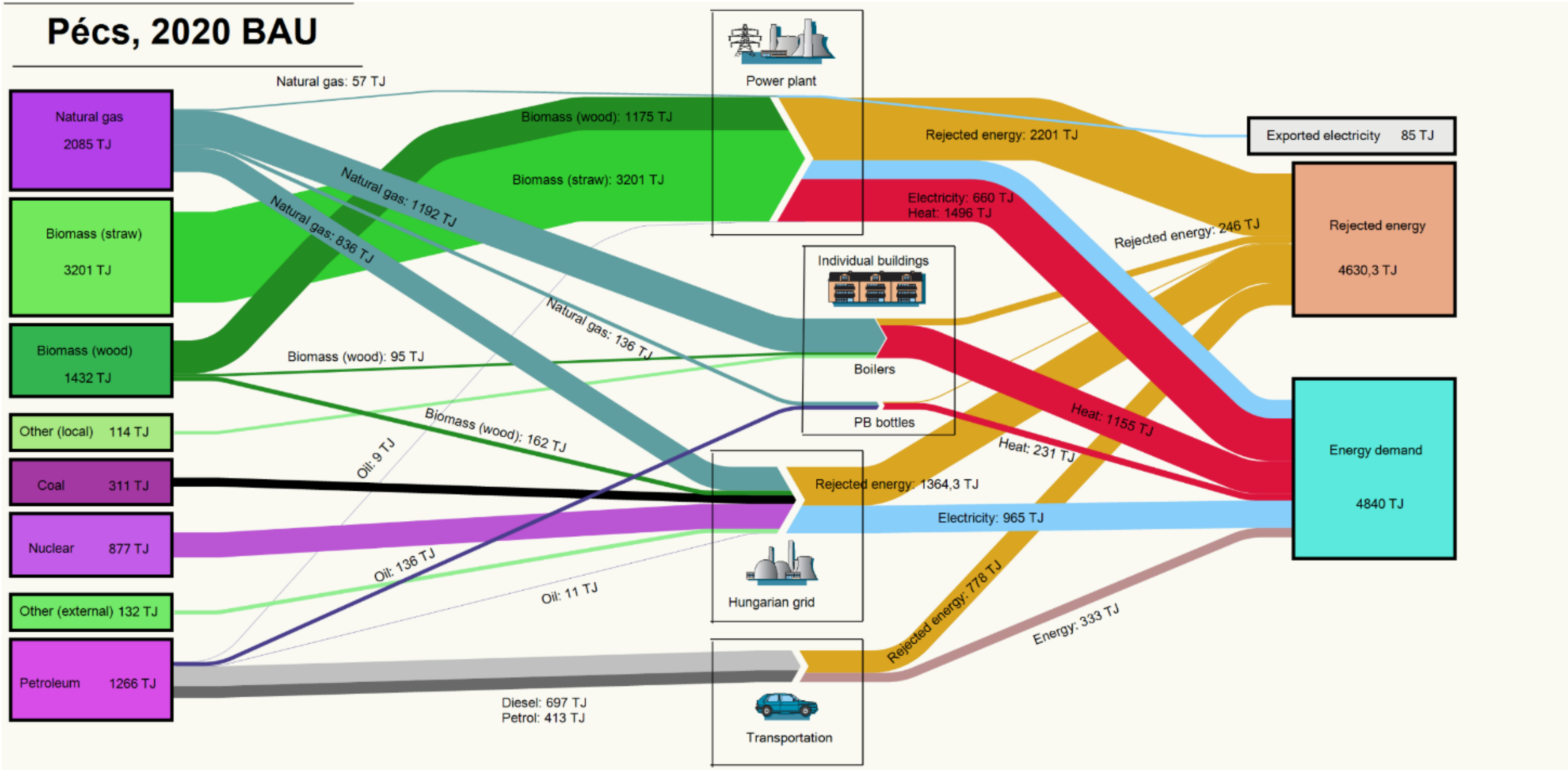
Table 6.: Efficiency of BAU and ES models

TJ	Aggregated Input	Export	Output	
			Energy Demand	Rejected Energy
Business as Usual	9 553.6	85.0	4 840.0	4 713.6
Energy Strategy	9 651.7	111.0	4 742.0	4 909.7

	Efficiency
Business as Usual	51.6%
Energy Strategy	50.3%

Source: Own edition

Figure 5.: Flow diagram of the BAU model2



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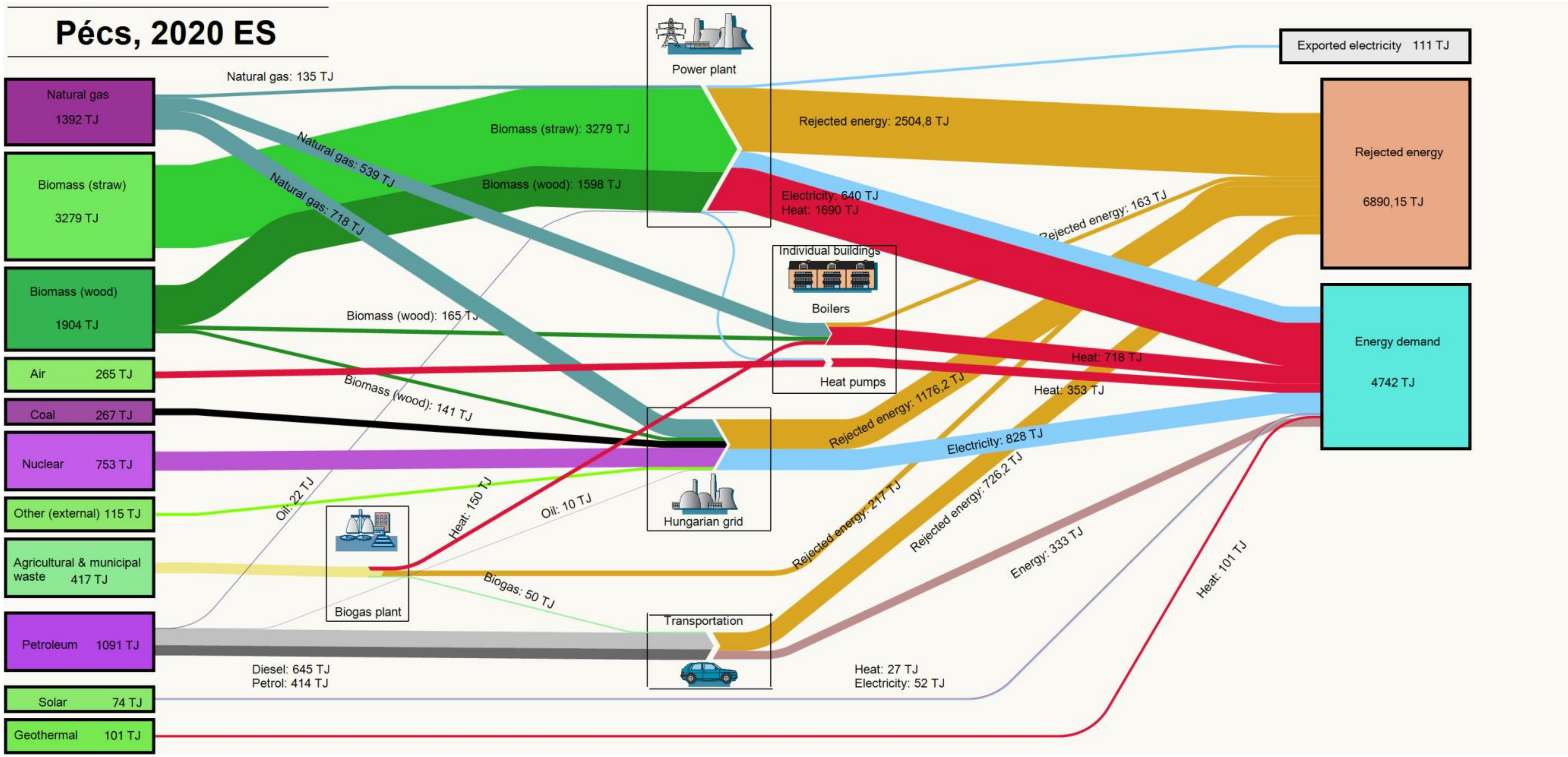
[2] The shades of purple indicaty a non-renewable and of green a renewable energy source
Sankey diagrams created with e!sankey. www.e-sankey.com The values might differ (+- 0.5%) from Table 2 and Table 3 due to rounding

Figure 6.: Flow diagram of the ES model3



[3]The shades of purple indicaty a non-renewable and of green a renewable energy source
Sankey diagrams created with e!sankey. www.e-sankey.com The values might differ (+- 0.5%) from Table 2 and Table 3 due to rounding

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