THESES OF THE DOCTORAL (PhD) DISSERTATION

ECONOMIC EVALUATION OF WASTEWATER PLANT TECHNOLOGIES AND THEIR ROLE IN ENERGY, NUTRIENT AND CARBON DIOXIDE MANAGEMENT

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1. INTRODUCTION, RESEARCH OBJECTIVES AND HYPOTHESES

I started research on sustainability and renewable energy sources in 2009. My research work on the possibilities and economic aspects of bioenergy, including woody energy plantations, has been gradually expanded to other alternative energy sources and research areas for waste management. As a result, in the recent past, I have been researching the role and potential of wastewater treatment and related options in energy, nutrient and carbon management, in line with the circular economy and sustainability goals.

In parallel with economic development and improved living conditions, the amount of water used and, as a result, the amount of wastewater generated is constantly increasing. Therefore, the use of modern, efficient, yet environmentally beneficial technologies with a proper purification effect is of great importance as steps towards sustainable water management.

Worldwide, an increasing proportion of the population moves to cities and generates an increasing amount of waste, with a significant form of liquid, which is also difficult to handle. In contrast to smaller settlements, the industrial plants operating in cities also emit a large amount of organic matter, the treatment of which, together with the public wastewater, should be solved in an automated and cost-effective way, whereby renewable energy can be produced with anaerobic fermentation and other technological solutions. In addition, there is a great opportunity to utilise the organic matter, macro- and microelement content of wastewater at the site. In my dissertation - approaching the topic through the concept of a circular economy - I mainly focus on the potential and characteristics of these urban wastewater treatment plants in energy production and nutrient management, including their role in reducing carbon emissions. Wastewater treatment is closely linked to each element of the water-energy-nutrient system; therefore, the efficiency, quality, and other characteristics of the purification activity have an impact on the environment, society and the economy.

In my dissertation, my goal is to carry out an analysis focusing on supporting sustainability endeavors, in which the guidelines and connections of “value from waste” and “opportunities from obligations” are realised, in parallel with focusing on a specific area.

The main objectives of my research fit the above described topic:

1. What options are available for the partial/full realisation of energy self-sufficiency or for the production of marketable products for conventional activated sludge technology and for living machine and natural purification technologies, linked to the circular economy concept? What impact does plant size and technology have on the topics studied here?
2. What are the advantages and disadvantages, as well as the economic characteristics of each of the additional technologies and procedures for wastewater management in energy, nutrient management and emissions management in wastewater management?
3. What is the potential at national level for the surveyed complementary procedures for each element of the energy-nutrient-emission system?
4. Under what conditions can the wastewater sludge from the most widespread activated sludge technology be disposed of, contributing as much as possible to sustainability efforts?

In line with the objectives, my **hypotheses** are the following:

H1 – The economic wastewater treatment activities can be implemented primarily for urban integration in order to achieve the highest cost-saving and revenue maximising effect. Furthermore, these wastewater treatment plants provide the most favourable opportunities in respect of energy, nutrient and harmful substances.

H2 – The economic and environmental sustainability of wastewater treatment activities can be significantly improved by integrating different technologies, depending on the size of the plant. These technologies also enable the concept of a circular economy to be realized.

H3 – Additional technologies for wastewater treatment will contribute to national climate protection, as well as economic sustainability in the medium and long term.

H4 – The utilization of sewage sludge and the energy self-sufficiency can be solved most effectively with woody energy plantations.

The following tasks were assigned to the research aims in the order of objectives:

1. Exploring the global and domestic conditions, situation and peculiarities of wastewater treatment activities. Collecting information about the average composition of wastewater and sewage sludge as well as the technological specifics, input and output prices typical of the basic activity/activities.

2. Surveying possible complementary activities, collecting process features, technology specifics, as well as input and output prices.

3. Assessing the influence of plant size and the reality of additional possibilities in Hungary. As a result, designing a novel, circular complex system through the utilisation of the generated sludge and integration of other possibilities into the system.

4. Economic model building, connection options, selection of alternatives and their evaluation and analysis.

5. Based on the above points, potential estimation of unit size and economic analyses (cost-benefit analysis, investment viability analysis, comparative analysis, sensitivity analysis, threshold value analysis) are performed in relation to certain additional technological elements of wastewater management.

6. Analysis of energy self-sufficiency and production, as well as nutrient utilisation and emission reduction possibilities.

7. Determining the possible role of wastewater management in Hungary, performing estimations related to sustainability, energy and emissions reduction targets.

8. Estimating the size of the area on which the total amount of wastewater sludge used as compost can be utilised for energy crop production purposes.

9. Opportunities and limitations of energy crop- and solar energy-based production, and quantification of potential impacts associated with wastewater treatment.

2. MATERIAL AND METHODS

I started my research with secondary data collection, reviewing and processing the relevant national and international literature, including the characteristics and peculiarities of wastewater treatment activities and their development trends. In doing so, I paid special attention to any links of the given activity to circular economy and sustainability.

As a next step, following my visits to the different types and sizes of purification plants and after my personal consultation with the experts in the subject within my primary data collection activity, I have identified the on-site (i.e. related to the size of the purification plant and to its primary activity) and off-site options related to energy/nutrients/emission. Of the different technologies, most of the additional alternatives can be linked to the conventional activated sludge system, mainly due to its higher purification capacity.

As shown in Figure 1, many other (auxiliary) activities can be integrated into the operation of wastewater treatment plants in addition to the purification of wastewater.

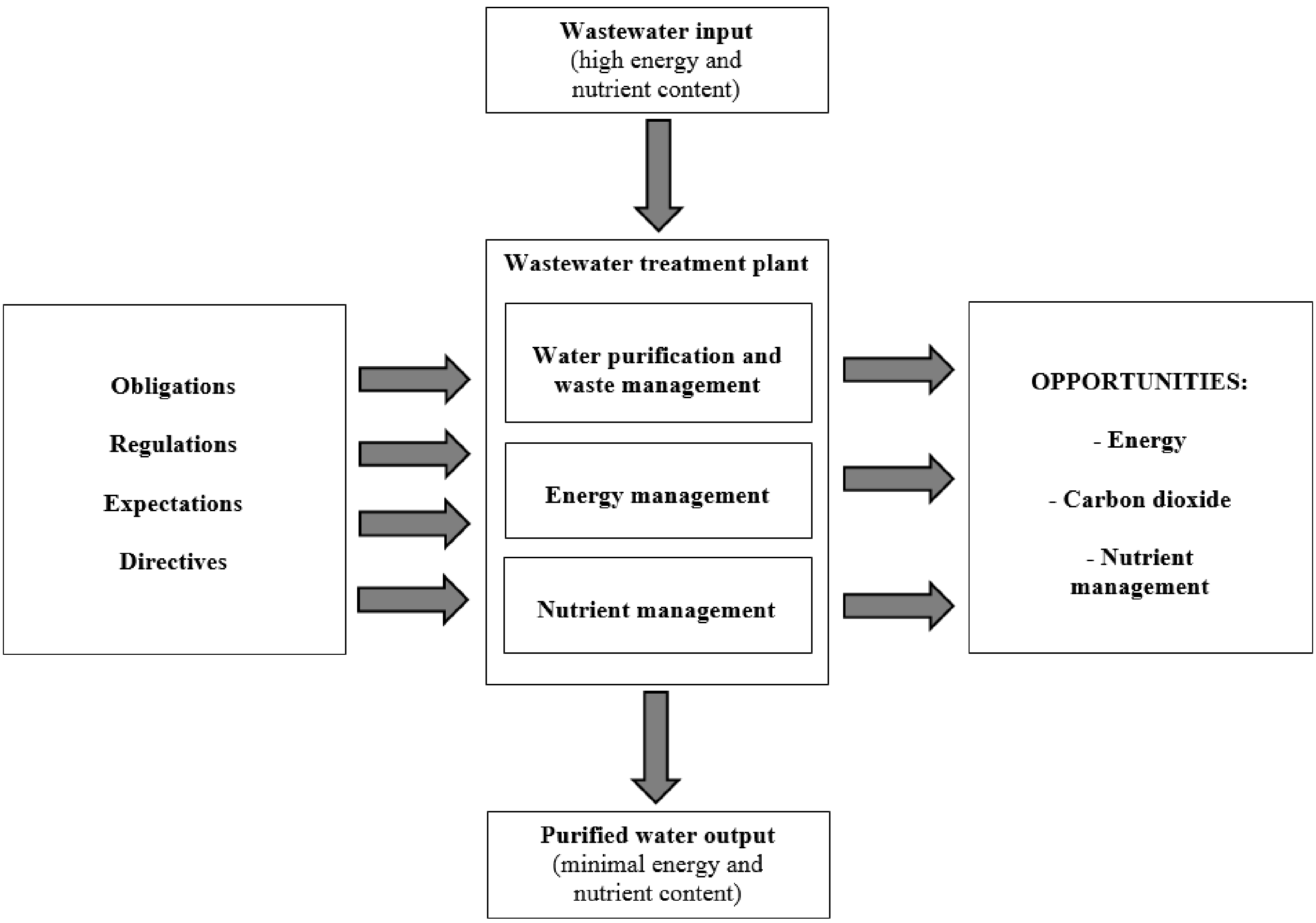

Figure 1. Primary function and additional options of wastewater purification

During my research, I made my calculations on unit size, taking into account average values (average domestic input, output and other technological specifics), but during my work I identified the most important – size-related - modifying and influencing factors for both basic technology and possible complementary technologies.

The unit size was defined as 100 000 PE (population equivalent) due to the following reasons:

- in Hungary, the same plants with a capacity of 100 000 PE or more are responsible for purifying the majority of the generated wastewater,
- sewage sludge digestion can be economically performed due to plant size (KÁRPÁTI, 2016)

I carried out my research on the basis of the average wastewater input, output and other technological specifics in order to provide unit plant and national level estimates of the possible effects and results of each alternative, by incorporating the most important modifying effects resulting from the size of the plant.

2.1. The course of calculations

The course of my calculations in each examined partial area is shown in Figure 2.

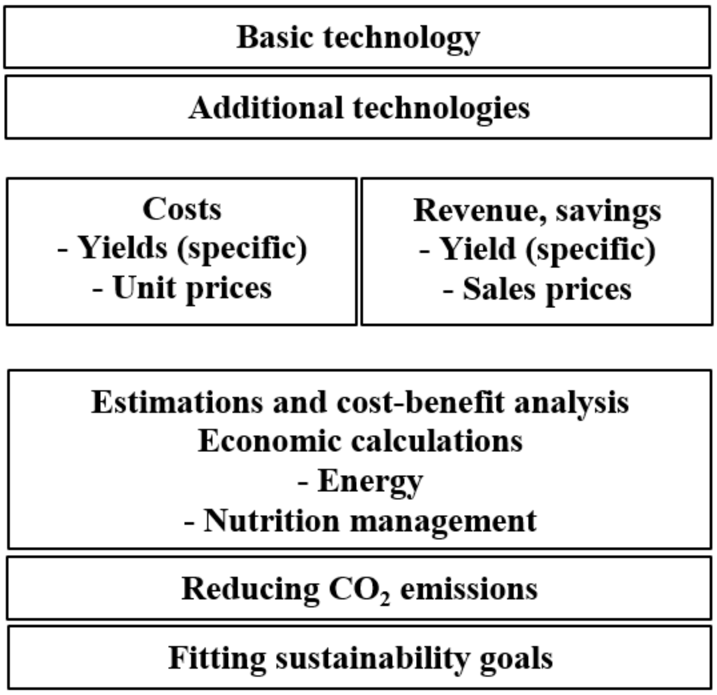

Figure 2. The process of calculations

In the course of my work, I have compiled a complete technological cycle to estimate the potential role of each basic and complementary technology in energy, nutrient and CO_2 management, and have carried out an economic analysis of each complementary technology. In the case of CO_2 emissions, I only quantified direct emissions. The technological elements taken into account in the concept of circular economy compiled by me, and their connection possibilities, are illustrated in Figure 3.

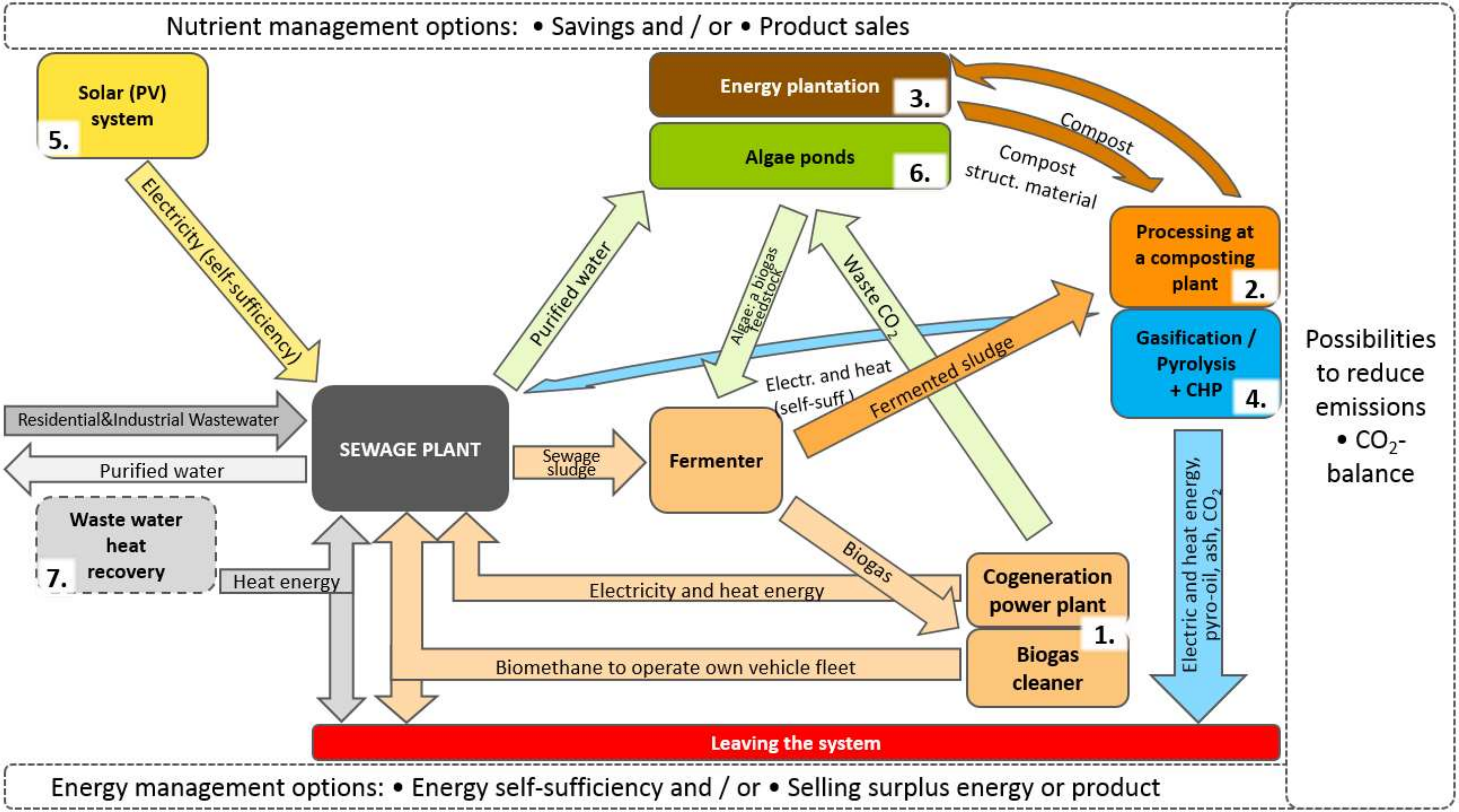

Figure 3. Possibilities of the circular process based on wastewater

The data specific to the technologies was summarised in an Excel-based model. The model is suitable for a complex assessment of the cost-benefit and economic analysis of the primary technology and the additional (technological) options based on it, taking into account the input and output factors.

I used the following methods during my research work (Table 1).

Table 1. Summary of the applied methods

Method	Partial area, aim
Cost-benefit analysis	Biogas use and complementary technologies
Comparative analysis	Comparison of complementary technologies
Investment viability analysis	Complementary technologies
Sensitivity analysis	Main input and output factors
Threshold value analysis	Minimum values of the main input and output factors
Potency estimation	The potential role of primary and complementary technologies per unit size and at national level

3. MAIN FINDINGS

Based on my primary and secondary data collection, I found that the conditions of energy production, nutrient management and CO_2 emission reduction options - mainly due to their size and technological characteristics - are fulfilled by the activated sludge technology and have the highest possibility of realisation. On plants operating a natural purification system (mainly root zone systems), there is minimal possibility to integrate additional technologies into the system, although they are capable of high-quality, cost-effective purification in the case of a sufficiently large area and precise implementation. Due to the low or medium capacity of the living machine technology, energy production based on the digestion of sewage sludge is not realised, even though it is capable of outstanding quality purification in a greenhouse-type building with special pool areas and the involvement of different plant and animal species. In addition, the use of sewage sludge in agriculture is, in most cases, hampered by the relatively small amounts and varying quality of sewage sludge, the difficulties of the authorisation process and the associated strict requirements, according to experts. As a result, according to my information, the majority of the sewage sludge generated on these sites is transported to and processed by the largest regional treatment plants.

Accordingly, in addition to describing the possibilities and economic aspects of solar energy self-sufficiency related to living machine technology, I primarily focus on the additional elements related to activated sludge technology.

I present my conclusions and suggestions in accordance with the set of objectives laid out in the section "Introduction, objectives" chapter and in their order.

1. What options are available for the partial/full realisation of energy self-sufficiency for conventional sludge technology based on conventional sludge technology and natural purification technologies or for marketable product production, linked to the circular economy concept? What is the impact of plant size and technology on the examined options?

During my research, I reviewed the characteristics of the most widely used activated sludge technology, the living machine technology and the natural (primarily root zone) technologies and identified their limitations. As a result, I have concluded that, due to the specificity of the given technologies, the examined additional solutions can be best adapted to the activated sludge technology. However, plant size has a crucial influence in this respect. It can be stated that the size of the treatment plant - in accordance with the principle of economies of scale - fundamentally influences the possibilities of energy and nutrient management, as well as the specific investment and operating costs. In smaller plants (under 50 000 PE capacity), partly due to the small amount of sludge produced, and partly due to the strict regulations of the produced compost, the application of solutions enabling utilisation for energy or nutrient management purposes is not economical and problematic. Regarding the efficiency of purification, it can be mentioned there is no emission limit value for total phosphorus and total nitrogen concerning the smaller (below 10 000 PE) plants, based on the Decree No. 28/2004. (XII. 25.) of the Ministry of Environmental Protection. As a result, these plants can operate, but at the same time, environmental risks are involved.

The following criteria can be used for the additional options examined:

- Sewage sludge digestion and cogeneration or biomethane production and use: the lower size limit is plants with forty to fifty thousand PE. With cogeneration energy generation, self-sufficiency of around 60% of electricity and about 100% of thermal energy can be achieved at a 100 000 PE plant. For larger plants, the indicators are even more favourable (82% and 138% at 300 000 PE, 92% and 156% at 500 000 PE, respectively). In the current economic environment, the purification of biogas and the production and use of biomethane can be justified if the energy self-sufficiency is already realized and/or the utilization and sale of the generated waste heat is not ensured.
- Sewage sludge compost recovery and nutrient management: The use of average quality sewage sludge compost can replace significant amounts of nitrogen and phosphorus fertiliser (as well as the amount of CO_2 needed to produce them). I recommend its application primarily in crop production for non-food purposes and energy plantations. The presence of anaerobic technology has a positive effect on the quality of sewage sludge due to heat treatment, which can facilitate or speed up safe use.

- Energy plantation biomass production and utilisation: the yield of woody energy plantations is positively affected by the application of sewage sludge compost, and energy plantations contribute to the purification of heavy metal contaminated soils. The energy generated by the use of biomass can also contribute to the energy self-sufficiency of the treatment plant and the sale of excess energy. For the purpose of energy self-sufficiency, the most preferred solution of the examined methods is the installation of a wood gasification unit equipped with a CHP unit.

  As it has been pointed out above, growing herbaceous and woody energy crops for the production of heat and electricity is primarily justified in areas with unfavourable production conditions for food crops. The soil protection effect of plantations is also worth mentioning, as about 60% of Hungary's arable land is prone to erosion or deflation.

- Energy production with solar power: Solar energy-based electricity self-sufficiency may be a good solution in the case of plants that do not reach the size limit of the economical implementation of sludge digestion or the use of sewage sludge as compost is not a possibility.

- Using the CO_2 content of purified wastewater and flue gas in algae ponds: the use of algae (especially semi-intensive or intensive technologies) can be an effective solution for the recovery of flue gas, which also has a significant capital requirement. Algae cultivation can only be justified on plants with higher purification capacity, and is currently not competitive with other cultivation methods.

- Sewage heat recovery: Primarily for larger plants with four to five hundred thousand PEs or more, without compromising effective and economical purification (i.e. maintaining the required wastewater temperature). In Hungary, there is only one such plant in Budapest.

The utilisation of waste heat generated by cogeneration energy production, or the utilisation of the produced biomethane, as well as the economical operation of similar systems in the case of heat pump heat recovery can be ensured primarily in the vicinity of a city or industrial area.

H1 – The economic wastewater treatment activities can be implemented primarily for urban integration in order to achieve the highest cost-saving and revenue maximising effect. Furthermore, these wastewater treatment plants provide the most favourable opportunities in respect of energy, nutrient and harmful substances. **Confirmed.**

2. What are the advantages and disadvantages, as well as the economic characteristics of each complementary technology and process from the energy and nutrient management and emission aspect?

Through the determination of economic characteristics, I was able to quantify the contribution of complementary technologies to economic sustainability. At the same time, it is important to mention that, although wastewater treatment plants and sewage systems belong to the group of public goods, I excluded the quantification of external effects in my analysis. The peculiarities and economic details of each additional process are described below in above mentioned order.

- Sewage sludge digestion and cogeneration or biomethane production and use: Cogeneration energy production and biomethane purification and utilisation in Hungary are mutually exclusive technological possibilities. The former has a lower investment cost (a cogeneration unit costs 81.3 million HUF per unit plant size), which can generate yearly savings of 27.7 million HUF, while the biogas purification plant with a filling station has an investment cost of 235 million HUF and 204 million HUF without a filling station, providing yearly revenue of 61.8 million HUF if sold as fuel and 7.6 million HUF if fed into the natural gas networks. In terms of CO_2 emission savings, cogeneration energy production is the most favourable solution, with a volume of 1790 t CO_2/year (12.4 million HUF).
- Sewage sludge compost recovery and nutrient management: By composting fermented sludge, significant amounts of nutrients are recovered. In the case of a plant with 100 000 PE, the quantity of this substance is 24 t N and 12 t P active substance per year (with 5.3 M HUF/year and 3.9 M HUF/year). The value of CO_2 emitted by this fertiliser thus replaced is 1.9 M HUF/year.
- Energy plantation biomass production and recovery: Energy plantations, with the proper choice of wood species, are able to produce favourable yields even in less-

favoured areas, thanks to their rapid growth, and can significantly reduce the heavy metal content of the soil. The resulting biomass – depending on the age of plantation, this value is between 16 – 24 a.t. per hectare in the case of cutting every two years – may contribute to improving the economic characteristics of wastewater management by means of energy self-sufficiency and by selling the extra electric and heat energy if a cogeneration plant is connected to a wood gasification or pyrolysis unit. The NPV of the plantation, covering the entire life cycle (15 years) in a two-hectare area, is 754,000 HUF with an internal rate of return of 24%. The energy balance of the plantation is between 1:36 - 1:21, depending on the delivery distance (10 - 40 km). With a transport distance of 30 km, the NPV is already in the negative range. According to my calculations, on a 100,000 PE plant, 92 hectares would be needed for total energy self-sufficiency (in addition to cogeneration). Return on the necessary wood gasification + CHP system can be realised in 7 years. If all sewage sludge were to be composted, 290 hectares would be required if calculated with the maximum applicable amount of active substance (170 kg N/year in nitrate sensitive areas). The payback period for the 360 kW_{el} CHP unit designed for this purpose and the wood gasification unit serving the CHP unit is 7.4 years, with a 19% internal rate of return. In the case of biogas- and wood gasification-based cogeneration energy production, the cornerstone of economical operation is the utilisation of waste heat accounting for about 55-60% of the produced energy. The efficient and full use of waste heat is hampered by the fact that not only the thermal energy self-consumption of the plant decreases during the summer period, but the amount of produced biogas is also higher than in the winter period, i.e., it is quite problematic to plan continuous and full heat utilisation. Naturally, the heat demand of the population also decreases during the summer. During this period, it is possible to meet the technological heat demand of sludge drying or that of production plants, as well as the utilisation in district cooling. The use of pyrolysis technology can be a solution to the difficulties of utilising the waste heat produced, especially during the summer. However, there are many other alternatives in addition to heating fuel. As a matter of course, these procedures involve additional processing and refining costs.

Due to the significant capital demand, serious logistical challenges, and operational safety, I would like to first consider building a smaller, self-sufficient energy system. The capacity of the system can then be expanded and, in parallel, the amount of biomass produced on energy plantations increases due to the age of the plantations. Establishing plantations for several consecutive years is easier to implement (distributed capital demand), which also contributes to reducing the quantity fluctuations of the wood chips produced.

- Solar power energy production: Complementing cogeneration energy production on a unit-sized plant, the total self-sufficiency of electricity can be realised with an approx. 870 kW_{el} system. According to my calculations, the discounted payment period is of the investment is 13.5 years (17.7 million HUF NPV). If we carry out the investment analysis for the useful life of solar cells, the result is a positive NPV of 183 million HUF. In a 50,000 PE plant, where cogeneration energy production based on anaerobic digestion is assumed to have not been established, a return on investment of 13.3 years, plus a NPV of 229 million HUF will result from a 30-year investment analysis. In the case of solar power energy production, synchronous mode is recommended by all means for several reasons: (1) the wastewater treatment plants were originally connected to the public grid; (2) the energy produced by the solar system is not only available at the time of use; and (3) the investment in high cost-demand batteries can also be avoided.
- Utilising the CO_2 content of purified wastewater and flue gas in algae ponds: if the algae utilisation is sized for the CO_2 content of the flue gas, 6 hectares would be needed for a semi-intensive greenhouse and 4 hectares for an extensive artificial pond. The value of the investment is rather significant: 950 million HUF and 328 million HUF, respectively. The value of CO_2 replacement and biodiesel produced by the utilisation of the algae is 179 million HUF and 9 million HUF, respectively. For this reason, I suggest algae production only if significant state support is available.
- Sewage heat recovery: In the case of a suitable (metropolitan) environment and wastewater production level, the payback period is very favourable (up to 3-4 years for a new construction) thanks to its favourable COP value. With a capacity of hundreds of thousands or even millions, it is possible to achieve a high level of

profitability and CO_2 savings. However, there is only one such system in Hungary, located in the capital. It can also be said that heat pump systems are not intended to provide power for self-sufficiency purposes of the plant, but to provide heating and hot water supply for office buildings or plants along the line of the pipeline system.

Applying the examined additional options, the system generates minimal waste, with emphasis on the 3Rs of the circular economy, i.e. reduction, reuse and recycling. According to this, in addition to purified water, wood ash, the unused portion of the CO2, and the produced electric and heat energy that exceeds the demand of energy self-sufficiency or other energy-related products are discharged from the system. Thus, the system contributes to minimizing losses and environmental pollution.

H2 – The economic and environmental sustainability of wastewater treatment activities can be significantly improved by integrating different technologies, depending on the size of the plant. These technologies also enable the concept of a circular economy to be realized. **Confirmed.**

3. What is the potential at national level for the surveyed complementary procedures for each element of the energy-nutrient-emission system?

There are a number of complementary procedures that can be used on the basis of wastewater treatment - as a mandatory task - and the generated by-products. There procedures can clearly contribute to the current national targets for renewable energy, CO_2 reduction and sustainable nutrient management.

Hungary has set a target of 14.65% of gross energy consumption in 2020 in the Renewable Energy Efficiency Action Plan of Hungary, which exceeds the EU' expectation of 13%. Although the target value was almost reached in 2017 following the recalculation of domestic energy consumption by households due to an EU regulation (European Commission 431/2014), as the value in question jumped from 10.3% to 14.5%, experience has shown that it resulted in a reduced number of calls for tender for renewable investments to some extent. As 32% of total energy consumption will have to be covered from renewable sources at EU level by 2030 on the basis of the EU's Clean Energy Package, it will also be necessary for individual Member States to further increase their renewable energy production beyond 2020. In my opinion, the additional procedures related to wastewater treatment plants described in my thesis can also contribute to this goal. According to my calculations, cogeneration energy production and use connected to wastewater treatment could contribute 85 million kWh of electricity and 344 TJ of energy per year at a national level to renewable energy production, while using wood chips produced in energy plantations fertilised with sewage sludge compost potentially contributes 132 million kWh and 792 kWh TJ, respectively. For this reason, renewable electricity production would be increased by 0.27% in the case of cogeneration energy production by 0.41% in the case of energy plantations. Including thermal energy, a total of 0.18% (approx. 1,920 TJ) of national primary energy consumption (1,081 million TJ) can contribute to national renewable energy targets.

The extension of the quota system is planned for the future in order to reduce CO_2 emissions. In order to quantify the emission reductions available in wastewater management, I determined the quantity and value of this factor. Based on the 18 Hungarian plants, cogeneration energy production could result in emission savings of 69.2 thousand tons (480 million HUF/year), while the integration of energy-efficient wood chips production and use into the system can potentially result in 124 thousand tons of CO_2 (860 million HUF/year) emission reduction. This value is equivalent to 0.41% of the country's gross CO_2 emissions.

In nutrient management, sewage sludge compost application can potentially save 1,175 t N and 560 t P_2O_5 active substance, amounting to 254 million HUF and 190 million HUF, respectively, while the amount in purified water is 3 430 t N (740 million HUF/year) and 228 t P_2O_5 (77.5 million HUF/year). Algae production could provide an opportunity to produce the latter, with favourable (70-90%) macro-element utilisation efficiency.

Although solar power energy production is one of the "cleanest" energy sources, since emissions are only generated during the production and installation of the system, it would be recommended to use only if (1) anaerobic technology is not economical due to the size of the plant; (2) the resulting sewage sludge cannot be utilised, or (3) it is not possible to produce and use energy wood chips for other reasons (e.g. lack of available area).

The utilisation of wastewater heat can be primarily implemented on the highest output sections of the wastewater system, on the section before plants with more than 500 000 PE, as well as near high-temperature office buildings and plants.

In view of the above described aspects, it can be stated that energy and nutrient management solutions linked to wastewater treatment can, by exploiting the potential of circulating processes, contribute both to increasing the share of energy from renewable sources and to reducing energy import dependency (~ 56%), as well as to achieving emission targets.

H3 – Additional technologies for wastewater treatment will contribute to national climate protection, as well as economic sustainability in the medium and long term. **Confirmed.**

4. Under what conditions can the wastewater sludge from the most widespread activated sludge technology be disposed of, contributing as much as possible to sustainability efforts?

In order to utilise wastewater sludge generated in an increasing amount in wastewater treatment plants, I made calculations for the composting of dewatered sludge and the planning of its placement in woody energy plantations. On the basis of international and Hungarian technical literature, sewage sludge compost has a positive effect on soil life, and its application in appropriate doses, in addition to preserving the macro-element content of the soil, also results in a significant increase in biomass yield. Woody energy plantations have a soil protection effect for almost a whole year, and they can also be cultivated efficiently in less-favoured areas. This fact also contributes to resolving the contradiction of food energy. According to my calculations, a 100,000 PE plant would need to establish a total of approx. 290 hectares of energy plantation to accommodate all generated wastewater sludge. If composting and the integration of energy plantations into the system were a possibility on all purification plants which also apply digestion and have a capacity of over 100,000 PE (18 such plants with a total capacity of 4 815 000 PE), it would be possible to utilise the sewage sludge compost by planting a total of 14,000 ha of energy crops (preferably for two or more consecutive years). Areas prone to erosion and deflation (about 60% of Hungary's arable land) and less favoured areas (a total of 883,558 ha, i.e. 9.5% of Hungary's total area, 14% of the total cultivated area) could be suitable for this purpose. According to my calculations based on my primary and secondary data collection - in connection with the Wastewater Sludge Recovery Strategy -, in my opinion, the composting of the generated sewage sludge is the most favourable solution, which can be utilised on many energy plantations with many advantages. At the same time, it may pose a risk that during composting, energy crop production and biomass utilisation, heavy metals may increase in the soil and the use of ash may also be constrained by its heavy metal content and alkalising effect. However, from the point of feasibility, the potential heavy metal accumulation in the trees' root system, or the availability of agricultural lands within an optimal transport distance may be a limiting factor.

H4 – The utilization of sewage sludge and the energy self-sufficiency can be solved most effectively with woody energy plantations. **Partly confirmed.**

4. MAIN CONCLUSIONS AND NOVEL FINDINGS

1. I determined the features and possibilities of the system in connection with the basic elements of the circular economy (3R: reduce, reuse and recycle). According to this, in addition to purified water, wood ash, the unused portion of the CO_2, and the produced electric and heat energy that exceeds the demand of energy self-sufficiency or other energy-related products are discharged from the system. Thus, the system contributes to minimizing losses and environmental pollution.

2. I confirmed that, in terms of feasibility and economy of the examined energy production and nutrient utilisation possibilities, plant size is critical. Due to the high capital requirement and the sensitivity of the production technology, I do not consider the utilisation of algae to be appropriate. For energy self-sufficiency, solar power energy production can be an alternative to biomass-based energy production on compost-fertilised energy crops, if it is not possible to utilise sewage sludge in agriculture. The return of these systems is much more favourable than the purchased electricity, so it is advisable to supplement the basic technology under appropriate conditions.

3. I defined a formula for estimating the specific energy consumption depending on the farm size, based on the characteristics of Hungarian plants, which serves the purpose of calculation of electricity and heat energy depending on the size of the plant:

   $$y = 1{,}909x^{-0{,}24}$$

   where: y = specific electric energy consumption of the given plant (kWh/m^3), x = size of the wastewater plant (Measure: 100 m^3 wastewater/day)

   As a result, I was able to estimate the rate of cogeneration and energy self-sufficiency for plants with different capacities. Consequently, I calculated 63% electrical and 106% thermal energy self-sufficiency for an activated sludge plant of a unit size of 100,000 PE.

4. I confirmed that cogeneration energy production is the most advantageous solution (in the case of utilising the total amount of waste heat produced) from the economic

and environmental aspect (GHG emissions), as compared to the feeding of biomethane into the natural gas network or using it as fuel.

5. I determined the investment cost function of solar cell systems to quantify the potential of solar power energy production (and energy self-sufficiency) - based on the current system costs on the market - for the entire system:

$$y = - 23{,}51\ x^2 + 330\ 368\ x + 1\ 000\ 000$$

   where: y = investment cost of the system (Ft), x = electric capacity (kW_{el})

   In the described formula, the range of interpretation of x (electric capacity of the system in kW unit): $10 \leq x \leq 5\ 000$ (the formula gives a correct result for 10 kW_{el} and 5 MW_{el} solar panel systems). Photovoltaic electricity production can be recommended if the utilisation of the digested sludge on the energy plantation is hindered by inadequate quality or other factors.

6. Based on yield curves from literature and own research, I determined the economic and energetic characteristics of energy plantations required for the disposal of sewage sludge compost. I calculated the specific production cost of the wood chips produced using wastewater sludge compost (16,380 HUF/t, which is 18% less than the market price), as well as its energy balance (1:36).

7. The savings related to the examined alternatives is equivalent to 0.41% of the total gross national CO_2 emissions of Hungary and can generate a 0.18% rise in the level of the national renewable energy targets.

5. PRACTICAL USE OF THE RESULTS

I hope that my research contributes to a more sustainable and economical water management and facilitates the efficient and successful fulfilment of Hungary's current wastewater purification and treatment obligations, primarily in terms of the complementary activities that are connected to the most widely used primary technology (activated sludge). With the help of the model I created, I would like to give the opportunity to any organisation, local government or plant to obtain information on which alternative should be used in environmental and economic terms under the prevailing circumstances. In the course of my work, in addition to the calculations and analyses I used, my aim is to contribute to the shaping of the students' views by presenting the obtained results in an illustrative form, demonstrating the possibilities of energy, nutrient management and emission reduction of waste management and wastewater treatment. To this end, the development of a special interface is underway, which, while taking into account various factors, is suitable for demonstrating the potential and benefits of sustainability and circular economy. The quantification of the benefits of the national economy in the examined areas can contribute to the most effective implementation of state support of investments and developments in the field of wastewater treatment.

6. LIST OF PUBLICATIONS RELATED TO THE DISSERTATION

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Candidate: Zoltán Gabnai
Neptun ID: G5WSSP
Doctoral School: Károly Ihrig Doctoral School of Management and Business
MTMT ID: 10051638

List of publications related to the dissertation

Articles, studies (9)

1. Bai, A., **Gabnai, Z.**: The possible role of large-scale sewage plants in local transport.
   In: Transportation, IntechOpen, London, United Kingdom, "Közlésre elfogadva", 1-24, 2019.
   ISBN: 9789535168775
2. Nagy, D., Balogh, P., **Gabnai, Z.**, Popp, J., Oláh, J., Bai, A.: Economic Analysis of Pellet Production in Co-Digestion Biogas Plants.
   Energies. 11 (5), 1-21, 2018. EISSN: 1996-1073.
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