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Electricity production and its environmental effects******

Abstract

Nowadays, increasing energy demand poses increasing challenges to professionals. While aligning with international guidelines and changing societal attitudes urge to prefer renewables and increase efficiency of electric power consumption. Replacing the current aging power plant system holds several issues and tasks that may not have been explored so far. To get an accurate, comprehensive view of these, it is essential to apply full life cycle analysis to ensure sustainable energy production.

Keywords: electric power, power plants, renewable energy, life-cycle assessment

1. Structure of the Hungarian electric power system, electric power distribution

The task of the electric power system is to continuously satisfy consumer side energy demand. Achieving this goal is no easy task. Electricity is a commodity that either cannot be stored in high quantities, or its storage is rather difficult.[1] A sufficient amount of electric energy must also be available at any time. However, momentary interruptions and fluctuations in the system may occur. The reason is that it would be necessary to produce exactly as much energy as needed.

István Bodnár – Dávid Matusz-Kalász – Dávid Faragó – Árpád Bence Palotás – Zoltán Károly Siménfalvi: Electricity production and its environmental effects – Villamosenergiatermelés és környezeti hatásai. *Journal of Agricultural and Environmental Low* ISSN 1788-6171, 2020 Vol. XV No. 28 pp. 86-130, https://doi.org/10.21029/JAEL.2020.28.86

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[******] *This study has been written as part of the Ministry of Justice programme aiming to raise the standard of law education.*

[1] Vajda 1984.

https://doi.org/10.21029/JAEL.2020.28.86

However, consumers cannot be restricted or regulated in terms of their energy consumption. Forecasts obtained by analysing changes in consumer behaviour can be used with good approximation for continuous energy supply.[2]

An interesting fact: the largest electricity consumer is the electric industry itself, that produces it. Power stations operate several high-performance pumps and ventilators. In addition, the operation of multiple lower performance devices (such as lighting, instruments) must also be covered. The self-consumption of power stations can be very different from one another. If we subtract the power station's self-consumption from the electricity generated, we get the net electricity production, which can be distributed between residential and industrial consumers. In the 80's and 90's, self-consumption of the Hungarian Electricity System ranged from 8-9%. Today this rate is lower, around 6-7%. In addition to self-consumption, there is also a network loss due to the extensive electric grid, which increases net electricity demand by almost 10%.[3]

It can be divined from the foregoing that the sum of the net consumption and the network losses results in the gross consumption. Additionally, the total domestic consumption is given by the sum of gross consumption, and self-consumption of the power station system. In recent years, domestic energy production has not been able to cover all domestic demands. The deficit was not perceived because the electric grids of multiple countries are interconnected, so foreign producers are also involved in satisfying domestic demand. Hungary is considered a transit country regarding the electric industry. We primarily purchase electric power from our northern neighbours and transmit it to the Balkan countries in the south. Each year we buy more electricity than we convey, so our so-called electricity import balance is positive. This remaining quantity covers the domestic electricity deficit.[4]

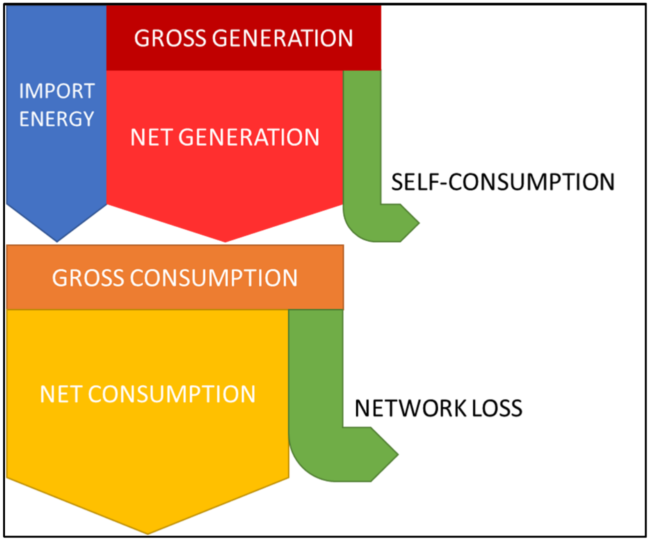

Figure 1: Hungarian electric power balance chart

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[2] Ibid.
[3] Ibid.
[4] Ibid.

2. The role of power stations in the Hungarian electric power system

There are several ways to classify power stations (or power plants) within the electric power system:

First, power stations can be grouped based on their type of operation to either cooperative or non-cooperative power stations. Cooperative power stations operate in accordance with the national power network. Non-cooperative power stations run in island mode operation (in isolation from the national power grid) and supply specifically one consumer or a group of consumers with electricity.

Another grouping possibility is to distinguish between industrial and public power stations. Industrial power stations are designed to meet the needs of an industrial unit or a minor consumer group. They only operate based on the scheduled plant demands. However, they have the opportunity to sell energy to the public power grid if there is surplus that is not used by the plant. Public power stations do not have a specific consumer group, they are dedicated to meet the demands of all the customers; they are designed specifically to provide for the public power grid.

Public power stations can be grouped by the type of energy source. In recent years, the origin of half of the produced energy was from nuclear power stations, more than one third came from fossil fuels and about 5% from biomass fuel. The rest was covered by renewable, and other sources. Delving into the role of public power stations in load balancing, we can talk about base load, load following and peaking power plants.

Without base load power plants, there is no reliable electricity supply. These power stations have a very high annual utilization time (more than 5500 hours/year) and run nearly continually at constant power. The start-up and shut-down times of base load power plants are long, they are non-flexible systems and therefore require continuous operation. As these power stations cover a significant part of the power generated, it is important for them to be modern and up-to-date in order to ensure safe and efficient operation. In addition, base load power plants usually run on cheap fuel for affordable energy prices. In Hungary, such a base load power station is Paks Nuclear Power Plant.

However, unlike the continuous operation of base load power plants, the demand for electricity is constantly changing. The task of load following power plants is to keep up with the load fluctuations. They are more flexible than base load power plants, and can follow the daily or weekly fluctuations in electricity demand. Generally, older base load power plants gradually degrade into load following power plants (for example: Gönyü Power Plant, Tisza II Power Plant, Dunamenti Erőmű Power Plant).

Peaking power plants operate only during periods of peak electricity consumption. Their annual peak utilization time is less than 2000 hours/year. For this purpose, it is only advisable to build low-cost power plants where expensive fuel and low efficiency is allowed. Such power stations are, for example, gas turbine power plants. In addition, so-called stand-by power stations can also be started up, though they should only be launched in case of an excessively high consumer demand. Reserve power plants operate for a maximum of 100-200 hours annually.[5]

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[5] Ibid.

The increased utilisation of renewable energy sources in recent times has become an increasingly important part of the energy strategy of the world and EU countries. The reason for this is almost the same for all countries: as a result of the steady increase in energy demand and the associated fossil fuel demand, the gradual decrease of available reserves, energy prices have risen dramatically in recent years (excluding the fall in demand and the accompanying decline in prices caused by the global economic crisis). This tendency will likely continue in the future. Extensive energy prices result in continuous capital outflow from countries that cover the majority of their needs of fossil fuels from import. Economic-wise this situation is extremely unfavourable for them.[6, 7]

As a result of the gradual decline in fossil fuel reserves, the remaining stocks are concentrated in a few parts of the world (mostly in the Middle East and post-Soviet states), thus drastically reducing the diversification of supply chain. This reduces the security of energy supply of countries without own stocks, rendering them politically vulnerable. These problems are exacerbated by the fact that through the use of fossil fuels which accumulated over the course of millions of years, bonded pollutants are rapidly released into the Earth's atmosphere. These pollutants are damaging to the atmosphere and can trigger or enhance processes (such as global warming and climate change) that can result in serious casualties and damages in the near future. While making energetics and economy more energy-efficient and more 'green' burdens the current generation with a significant cost, failing that will require multiplied costs in the future. The unfavourable effects of fossil energy use are of particular concern to Hungary, as Hungary has to rely on import for about two-thirds of its primary energy sources, and one-third of its electricity needs. The situation is exacerbated by the fact that 40% of Hungary's primary energy use is from natural gas, most of which can be obtained from a single source, via the gas pipeline to our country through Ukraine. Although the country's energy consumption is growing only slightly, the share of imported energy sources is constantly increasing due to the gradual decrease of domestic primary energy source extraction. Hungary's energy intensity is well below the average of developed countries, which indicates that the country's energy consumption is too high compared to its economic performance.[8]

3. EU objectives

In order to avoid the negative effects listed above, the European Union has set more and more ambitious objectives to increase energy efficiency and renewable energy use within its territory in recent years. In the following, the binding regulations and objectives for Hungary in the field of renewable energy use will be reviewed. Directive 2009/28 / EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources sets the European Member States with a 20% share of renewable energy in gross energy consumption by 2020. Hungary has committed to a 13% share of renewable energy.

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[6] Ibid.

[7] Bodnár 2017.

[8] Bodnár 2014.

The Directive also requires each Member State to ensure that the share of energy from renewable sources within the field of transportation, the final consumption is increased to at least 10%. To this end, the share of biocomponents in fuels was increased from the 1st of January 2020.[9]

(percentage, %)										
Denomination	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Final gross electricity consumption	7,0	7,1	6,4	6,1	6,6	7,3	7,3	7,3	7,5	8,3
Heating and cooling	17,0	18,1	20,0	23,3	23,7	21,3	21,3	21,0	19,9	18,1
Transport	5,8	6,1	6,1	5,9	6,2	6,9	7,1	7,6	7,6	7,7
Final gross energy consumption	11,7	12,7	14,0	15,5	16,2	14,6	14,5	14,3	13,5	12,5

Table 1: Proportion of renewable energy distribution in final gross energy consumption[10]

(terajoule, TJ)					
Generation	**2014**	**2015**	**2016**	**2017**	**2018**
Domestic waste, renewable	1 845	2 756	2 766	1 930	1 626
Biomass	98 928	105 221	100 570	98 952	89 262
Biogas	3 323	3 335	3 708	4 141	3 850
Biofuels	12 823	16 030	17 187	17 629	18 699
Solar	647	956	1 346	1 749	2 759
Geothermal	3 800	4 426	5 026	5 590	5 866
Hydropower	1 084	842	932	792	799
Wind	2 365	2 495	2 462	2 729	2 185

Table 2: Generation of primary renewable energy sources[11]

4. Power plant performance today

If we look at Hungary's power plant performance data, we can see that the installed capacity has declined from 10,000 MW to 8,500 MW over the last decade. This phenomenon can be explained by the decommissioning of obsolete power plants and the lack of construction of new power plant units.

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[9] Bodnár 2017.

[10] Hungarian Energy and Public Utility Regulation Authority (2020).

[11] Ibid.

This performance data includes the production capacity of power plants that do not usually operate, such as the Dunamenti Erőmű Power Plant, the Debrecen and Nyíregyháza Combined Cycle Plants, and the Tisza II Power Plant. According to this, the practically available power in 2015 was only 6,566 MW, which includes base load, load following and peaking power stations.[12]

This means that the 1,200 MW of reserve capacity present in 2012 has almost entirely disappeared. Since – for the safe operation of the electrical grid – 5% of the installed capacity is required to operate as reserve power capacity, currently in Hungary this can only be ensured with the help of imports. Considering today's electricity consumption patterns, peak daily consumption often exceeds 6,500 MW of power demand, so without the utilization of imported energy our country's electricity supply can not be satisfied. There are currently 17 large power plants installed in Hungary with a gross installed capacity of 7,415 MW (net capacity of 6,916 MW), but this power cannot be fully exploited due to the self-consumption of the power plants and due to the so-called permanent shortage. Permanent shortage is inflicted by power plants that are operational, yet are not operating. The permanent shortage is 1,222 MW, so the available power plant capacity is 5,964 MW, plus the net power of small power plants, which is 1,524 MW.[13]

(GWh)					
Energy source	**2014**	**2015**	**2016**	**2017**	**2018**
Nuclear	15 649	15 834	16 054	16 098	15 733
Coal	6 114	5 908	5 758	5 098	4 834
Natural gas	4 240	5 108	6 479	7 838	7 234
Oil	76	77	63	85	90
Biomass	1 702	1 660	1 493	1 646	1 799
Biogas	287	293	333	348	331
Domestic waste, renewable	137	208	245	160	162
Hydropower	301	234	259	220	222
Wind	657	693	684	758	607
Solar	67	141	244	349	620
Geothermal	0	0	0	1	12
Other	173	204	290	284	360
Sum-total	**29 403**	**30 360**	**31 902**	**32 885**	**32 004**

Table 3: Gross electric energy generation

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[12] Bodnár 2017.

[13] Hungarian Energy and Public Utility Regulation Authority (2020).

5. Power plant performance in the future

Due to the increasing trend of consumption, the gross domestic peak load may reach 7,500 MW by 2030. Future power plant configurations must meet these demands. Let's see how power plant capacity will change in the near future. The current units of Paks Nuclear Power Plant are now roughly 35 years old. Starting in 2032 they are scheduled to be decommissioned. Most power plants that were built in the 1950s and '60s have already been closed down and rebuilt in the latter decades. Power stations of similar age, such as the oldest units of the Mátra Power Plant, and the power plants located in Oroszlány and Bakony are also closing in to the end of their design lifetimes. Sooner or later, the Quick-start Reserve Power Plants (Lőrinci, Litér, Sajószöged) are also going to need replacements. As a result, the current power plant capacity will be reduced to around 5,300 MW by 2025, which will also not be fully available. However, as consumption will continue to grow and peak loads are likely to exceed 7,000 MW by then, the import dependency of Hungary will rise severely.[14]

In the medium term, power plant construction projects are already underway will be finished. The decommissioning of aging power plants continues. With the construction of Paks II. Nuclear Power Plant, the capacity of the largest power generating unit is going to increase to 1,200 MW, requiring an additional 800 MW of tertiary system reserve. Due to the significant increase in the share of renewable capacity, a viable form of energy storage (to compensate for the fluctuating system loads) is also required. Renewable technologies will be so cheap that financial support will not be necessary to invest into them.[15]

By investigating the specific investment cost of renewables, it can be stated that the cost of biomass power plants has not changed, but that of solar and wind power plants has been continuously decreasing, and will continue to do so. Out of conventional power plants, open-cycle gas turbine power plants possess the lowest investment costs at present, and will do so in the future. Lignite and bituminous coal power plants will remain high-priced. The problem with gas-fired power plants, is that their operating costs are highly dependent on gas prices, which – as of today – is still a major problem in Hungary. The total capacity of household-scale (distributed) solar power plants (solar power plants with a built-in peak power of less than 50 kW) is growing exponentially in Hungary. Of all the power plant types, the construction of solar power plants has developed at the highest rate.

The share of renewable energy in domestic electricity production reached 14.19% in 2016, which is above the 13% target set for 2020. The Hungarian electricity generation by source is as follows: biomass fuel 47%; wind energy 22%; biogas 10%; hydropower 7%, solar 6%, and the remaining 8% from other sources. It can be seen that biomass – which is a combustion-based energy source – is a major contributor to renewable based energy generation. Let's investigate the existing capacity and consider the possibilities.[16]

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[14] Bodnár 2017.

[15] Ibid.

[16] Bodnár 2019.

Due to geographical and social constraints, it is not likely for Hungary to have significant hydropower production in the foreseeable future. Our current largest hydroelectric power plant is the Kisköre Hydroelectric Power Plant with an installed capacity of 28 MW, which is half of the total national hydropower capacity. Significant capacity expansion would be possible on the Danube in parallel with the expansion of the Paks Nuclear Power Plant, and in the form of pumped hydroelectric energy storage facilities in the North Hungarian Mountains.

Wind energy utilisation stagnates since 2010. There are currently 37 wind farms with more than 170 wind turbines in the country. The current regulations make it difficult to set up new farms. This is further exacerbated by the fact that some wind turbines have been temporarily shut down due to lack of proper maintenance.

The increase in the peak capacity of photovoltaic power plants carries a major opportunity. Photovoltaic power plants have undergone significant improvements in recent years. Total capacity was only 2 MW in 2010, 77 MW in 2014, 640 MW in 2018, and 960 MW in 2019. The exponential growth is attributable to both distributed solar power plants and high-capacity solar farms. The current largest solar power plant is Paks with 20.6 MW. In recent years, solar power stations with considerably high capacity were built in Bükkábrány, Felsőzsolca, Százhalombatta and Visonta, and several power plants are currently under construction.[17, 18, 19]

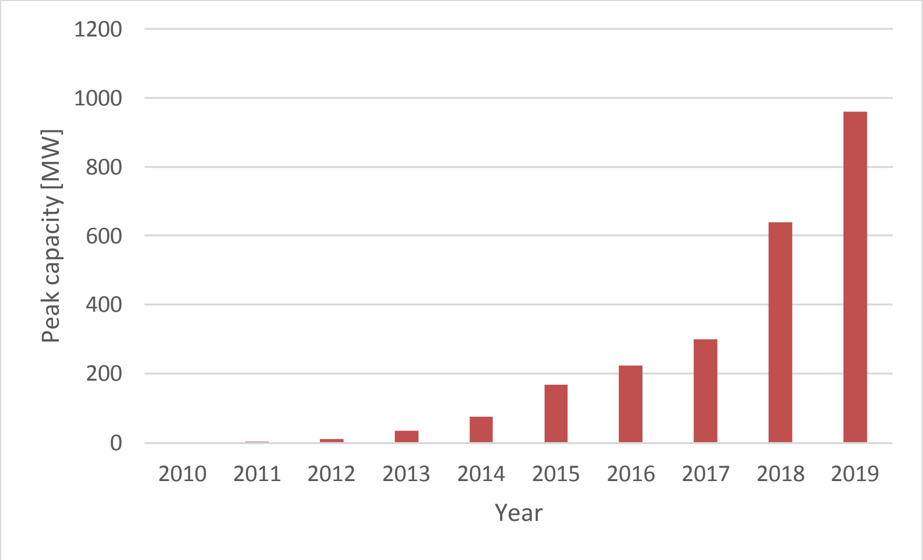

Figure 2: Peak capacity of the Hungarian solar electric power generation in the last century

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[17] Győri 2015.

[18] Ziborács et al. 2017.

[19] Kulcsár 2018.

There is only one geothermal power plant in Hungary with 3 MW installed capacity. It was established in 2017 in Tura. There is considerable potential for further expansion and the construction of new geothermal power plants, but the construction is rather cumbersome and risky – both financially and environmentally. The perception of geothermal energy is further tainted by the fact that low water temperature infers that only low-efficiency (6-10%) ORC (Organic Rankine Cycle) power plants can be built. In case of geothermal power plants, a combined heat and power plant (or cogeneration plant) is much more profitable, a combined heat and power plant provides useful heat for district heating in addition to electricity generation, as does the Tura plant.[20]

Hungary currently utilises about 15% of its total biomass potential. If the full potential was to be harnessed in a biomass-fired power plant, a new power plant could be built with a total capacity of about 2,800 MW. Naturally, we need to think about further expansion of solar and wind power plants, but the utilization of municipal solid waste and refuse-derived fuels (or secondary fuels) in power plants should also be kept in sight.[21]

Figure 3 shows the expected composition of the total power plant output of Hungary by 2030. If the Paks I. Nuclear Power Plant and the Mátra Power Plant are decommissioned, and no more renewable power plants are built, then gas- and oil-fired power plants and the Paks II. Nuclear Power Plant will remain. Of these, the Paks II Nuclear Power Plant dominates as the most powerful base load power plant of Hungary. However, none of these plants are powered by domestic fuel, hence we would become a highly import-dependent nation.[22, 23, 24]

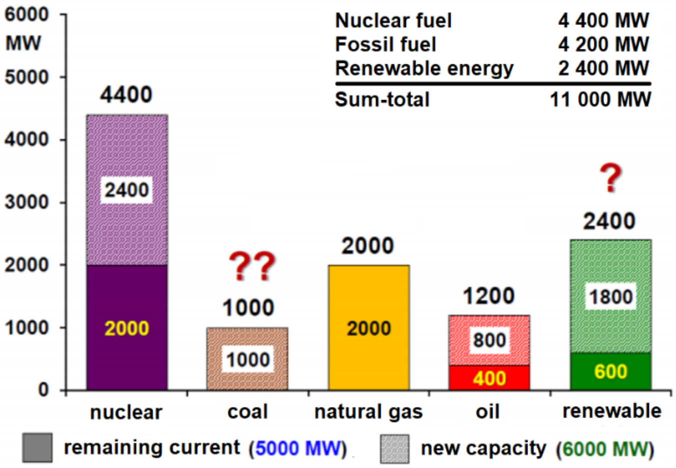

Figure 3: Prognosis of installed power plant capacities by 2030[25]

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[20] Haffner 2017.

[21] Bodnár 2017.

[22] Ibid.

[23] Haffner 2018.

[24] Aalto et al. 2017.

[25] Stóbl 2015.

The efficiency of the Mátra Power Plant is currently 29%, while the efficiency of newly installed lignite power plants could reach 43%. For this reason, it is necessary and justified to build a new power plant in the Mátra as well. The big question is, who will undertake the construction of two 500 MW units? The biggest problem is that we will have 5,400 MW of base load power plants (atomic and coal) with non-flexible regulation.[26]

Figure 3 shows the composition of total domestic power generation by fuel as expected by 2030. It is noticeable that compared to 2020, nuclear energy will dominate with its 40% share. As the total capacity of gas-fired power plants will decrease by 900 MW, Hungary's dependence on natural gas will drop significantly.[27, 28, 29]

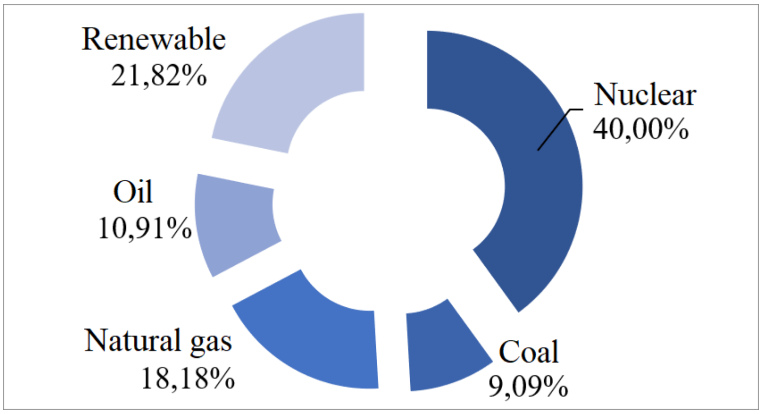

Figure 4: Prognosis of total domestic power generation by fuel by 2030[30]

The power plant structure of Hungary could be developed in such a way that import becomes entirely dispensable by 2030. Load fluctuations will decrease compared to 2020, as we assume that there will be some energy storage facilities built into the electric grid by then. If we calculate a fictive average daily gross production in 2030, we get approximately 5,600 MW. In addition to the current units of the Paks Nuclear Power Plant, the two units of Paks II. Nuclear Power Plant will also operate with 1,200 MW capacity per unit by 2030. With renewables and a much-needed lignite-fired power plant, gas-fired ones will need to run even less than today. At dawn, when system load is at nadir, even the capacity of the units of Paks II. may need to be reduced, which is far from economical for a base load power plant. The problem can be solved, for example, by exporting excess energy, that is if any one of the neighbouring countries are willing to buy it.[31, 32, 33]

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[26] Bodnár 2017.
[27] Ibid.
[28] Haffner 2018.
[29] Aalto et al. 2017.
[30] Bodnár 2017.
[31] Ibid.
[32] Haffner 2015.

In summary, it will be necessary to build new power plants in the future to replace old base load and load following power plants that are still operating but will be decommissioned with time. Highly flexible peaking power plants are also in need of replacements. In addition to nuclear energy, by establishing lignite- and biomass-fired power plants as well as solar and wind power plants (of which the prices are rapidly diminishing), the security of the electric grid of Hungary can be greatly increased.

6. Solar and biomass power plants in Hungary

Biomass is the dominant renewable energy source of Hungary. In recent years, however, solar power plants have been rapidly multiplying, and their installation will likely remain decisive in the near future. The peak capacity of solar power plants installed in Hungary has reached 960 MW in 2019. This capacity is exactly the same as the installed capacity of the Mátra Power Plant. Despite this, the annual energy production of solar plants is roughly one-tenth of the annual energy production of the Mátra Power Plant. Since the Mátra Power Plant is a base load power plant that can continuously run at rated capacity (with the exception maintenance stops), the annual peak power utilization rate is above 90%. On the contrary, solar power plants can operate at their rated capacity for 1 to 2 hours per day, because they are only exposed to ideal circumstances during the day. Without sunlight, they cannot produce. This means a daily 12 hour guaranteed deficit. In the intermediate period, solar energy flux can be described by Gaussian distribution. As a result, their annual peak power utilization rate averages around 10%. In Southern Hungary this rate can reach 12-14%, while in Northern Hungary it is usually 8-9%. Solar power plants currently operating in Hungary have an active surface area of 6 km^2, and a required area of more than 15 km^2 due to the type of the installation. The number of solar panels is around 4 million. If we were to place these solar panels in a row, we would have to walk more than 6,200 km from first to last.

7. Life Cycle Assessment

Today, Life Cycle Assessment (LCA, also known as Life Cycle Analysis) is one of the most widely used environmental management techniques. Using it is most expedient for the investigation of services, products and technologies that are capable of replacing one another. Through the analysis, we quantify and estimate the environmental impacts (including energy costs, resource requirements) that a product generates over its entire life cycle (production, distribution, utilization and disposal).[34]

According to ISO 14040 standard, Life Cycle Assessment can be defined as follows: ”LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, by (a) compiling an inventory of relevant inputs and outputs of a product system; (b) evaluating the potential environmental impacts associated with those inputs and outputs; (c) interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.”

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[33] Aalto et al. 2017.

[34] Bodnár 2017.

The life-cycle approach is the result of responsible corporate behavior. In constantly changing market, no company can achieve long-term success without environmental management. There are many environmental management tools and methods to enhance the efficiency of handling environmental issues. Choosing the appropriate method is a difficult task, and is influenced by several factors, such as environmental policies and regulations. Environmental policy is a commitment to minimize the adverse environmental effects of service, production, and technology activities and emissions. To achieve this, opportunities to use environmentally friendly products and cleaner production technologies throughout the entire life cycle of production and waste management should be brought to the fore. In the classical sense, we can only call a product or technology environmentally friendly if the product itself as well as the waste generated during its production and consumption pose neither direct nor indirect adverse environmental impacts. In this sense, the ecological balance of a given product from "cradle to grave" is positive, but at least neutral to the environment. In practice, a waste-free process of production and consumption is inconceivable, therefore the use of a positive indicator in this case implies that there are less adverse environmental impacts in relation with the given products and technologies. Recognizing the environmentally friendly nature of a product or technology is no easy task, and in practice there are many contradictions. While the necessity and usefulness of LCA is beyond dispute, there are often criticisms that the method is time-consuming, costly, and often incomplete, as data of each life cycle steps is either deficit or not available. Obtained LCA results are often hard or impossible to incorporate into product design, or into the dynamic system of corporate environmental management. Life Cycle Assessment was originally developed as a decision support tool that distinguishes products or services from an environmental point of view. To simplify the overall analysis, it is possible to examine only certain effects or certain steps of the product life cycle.[35]

Life cycle assessment (LCA) is a process of evaluating the environmental burdens associated with a product, process, service or activity by:[2] (1) identifying and quantifying the energy and materials used and the wastes released to the environment; (2) assessing the impacts of those energy and material uses and releases to the environment; (3) and identifying and evaluating opportunities for environmental improvements. Today these applications include government policy, strategic planning, marketing, consumer education, process improvement and product design. They are also used as the basis of eco-labelling and consumer education programs throughout the world. According to ISO 14040:2006: "A systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle." The Life Cycle

Assessment study has four main phases (Figure 5): (1) The goal and scope definition phase: the scope, including system boundary and level of detail, of an LCA depends on the subject and the intended use of the study. The depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA. (2) The inventory analysis phase (LCI phase): is the second phase of LCA. It is an inventory of

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[35] Ibid.

input/output data with regard to the system being studied. It involves the collection of the data necessary to meet the goals of the defined study. (3) The impact assessment phase (LCIA phase): is the third phase of the LCA. The purpose of LCIA is to provide additional information to help assess a product system's LCI results so as to better understand their environmental significance. (4) The interpretation phase: Life cycle interpretation is the final phase of the LCA procedure, in which the results of the LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition.

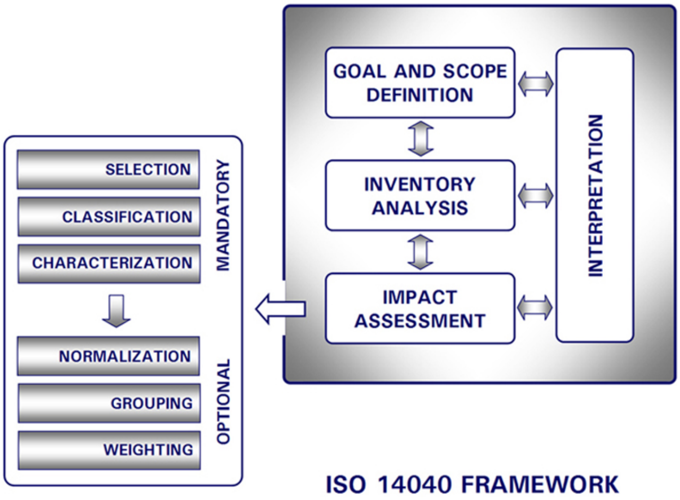

Figure 5: The Life Cycle Assessment framework[36]

8. Environmental emissions from electricity generation

Life Cycle Assessments were performed to determine the environmental emissions of power plants. The most commonly used CML assessment method was chosen for the analyzes. The functional unit is the production of 1 kWh of electricity in a life cycle approach. We examined the values of the seven most representative environmental impact categories. Table 4 shows the specifics of these impact categories.

Global Warming Potential	**GWP**	**kg** CO_2 equivalent
Acidification Potential	**AP**	**kg** SO_2 equivalent
Eutrophication Potential	**EP**	**kg** Phosphate equivalent
Ozone Layer Depletion Potential	**ODP**	**kg** R11 equivalent
Abiotic Depletion Potential elements	**ADP elements**	**kg** Sb equivalent
Abiotic Depletion Potential fossils	**ADP fossil**	**MJ**
Human Toxicity Potential	**HTP**	**kg** DCB equivalent

Table 4: The most common environmental impact categories

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[36] Product Design for the Environment (2020).

In the following section, the environmental impact categories of Hungary, Switzerland, Romania, Slovakia, and the EU-28 are compared. First, let us investigate the global warming potential separately. The figure shows that Romania has the highest CO_2 emission per generation of 1 kWh of electricity. According to 2019 data, all three EU Member States have higher GWPs than the average of the 28 Member States of the European Union. The carbon footprint from electricity generation of Switzerland is almost one-third of the EU-28 average.

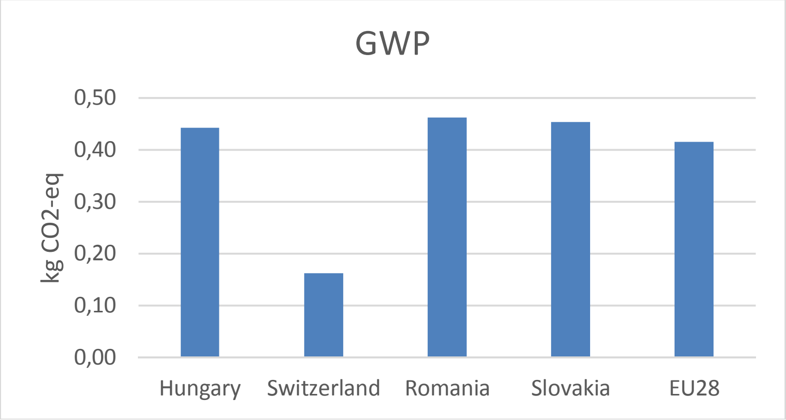

Figure 6: Normalized carbon-dioxide emissions of Hungary, Switzerland, Romania, Slovakia and EU-28

The following Figure 7 shows the normalized environmental impact categories of different countries. It can be seen that Switzerland has the lowest environmental impact for producing 1 kWh of electricity. Slovakia performs at exactly the EU-28 average. Hungary is only 1% above this value. Romania is in less favourable position for most environmental impact categories than the rest of the investigated countries.

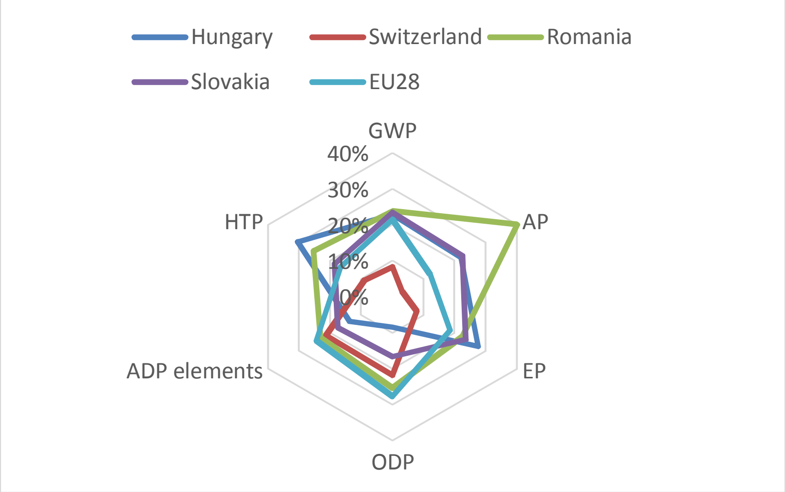

Figure 7: Normalized environmental impact factors of Hungary, Switzerland, Romania, Slovakia and EU-28

The following figure 8. illustrates the depleting abiotic fossil sources. This category shows how much fossil fuels are depleted for each unit of electricity produced; hence it shows a normalized depletion of abiotic fossil fuels. It can be observed that in all countries but Switzerland, and in the EU28, the yield of electricity production is negative. This means that we use more fossil energy than we can produce from it. In Switzerland, because of the high share of renewable energy sources, the depletion of fossil fuels is slower.

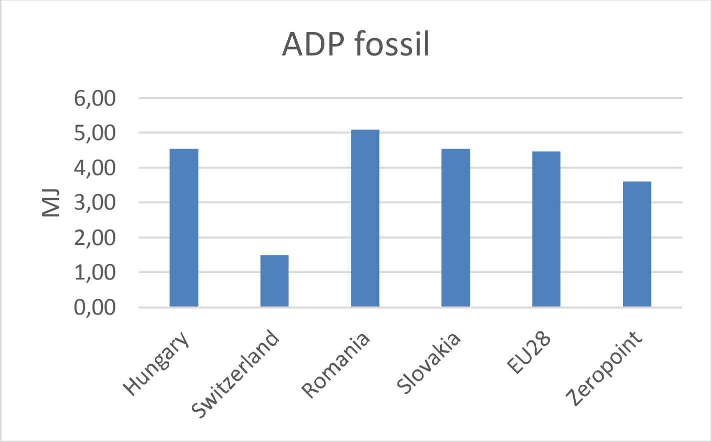

Figure 8: Normalized depletion of abiotic fossil fuels

Finally, let us investigate how Hungary's environmental emissions would progress by 2030 if the planned power plant constructions were finished, and the existing power plants were recommissioned. From renewable energy sources, we can mainly count on the significant construction of solar power plants. The figure 9. shows that the carbon footprint of electricity production will be reduced by more than 23%. Although depletion of fossil fuels will remain negative, it is still expected to improve by around 10%.

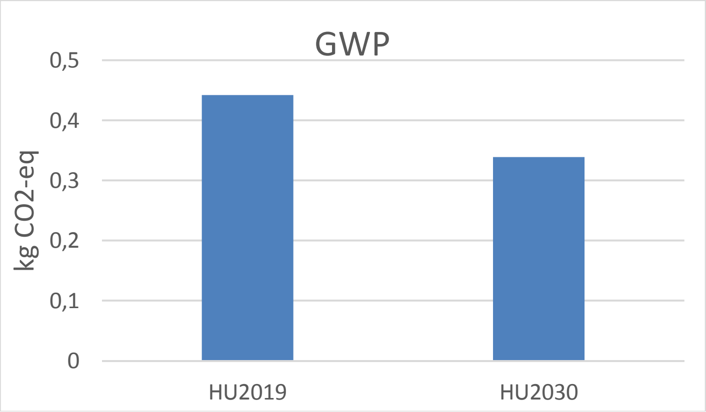

Figure 9: Normalized carbon footprint of electricity production in Hungary in 2019 and its anticipated value in 2030

9. Classification of environmental emissions of power plants

Power plants can be classified into two groups based on their environmental impact and emissions. One class is represented by power plants that facilitate fuel-to-energy conversion. These power plants involve direct emissions. The other class consists of power plants that facilitate energy-to-energy conversion to generate electric power, hence they connote indirect environmental emissions. Power plants with direct environmental emissions usually extract energy from a fuel through burning it. Such power plants run on fossil fuels (coal, petroleum or natural gas), municipal solid waste, refuse-derived fuels, biomass, biofuels etc. Power plants with indirect environmental emissions consist of power plants that run on traditional renewable energy sources (id est hydro-, solar-, wind energy) or nuclear energy. Biomass power plants are different from the rest of the power plants with direct environmental emissions. Since biomass is considered a renewable energy source, and it produce the same amount of carbon-dioxide when burnt as it absorbs during its lifetime, biomass power plants can be considered carbon neutral. However, a net zero carbon footprint can only be achieved by growing at least as much biomass as we have used. Although that's not entirely true either. The production of biofuels has developed significantly in recent years. In some countries, biofuels must be blended in a certain proportion with conventional fuels before sale. There are also examples where the alternative renewable fuels themselves can be purchased at the filling stations. On the other hand, in some countries, selling and using biofuels is explicitly prohibited and sanctioned.[37]

The most well-known biofuel is bioethanol, commonly known as E85, which is a drop-in biofuel that can replace fossil petrol. Another common gasoline substitute is biodiesel, which is mainly produced from vegetable oil or animal fat. The potential of wood gas as an alternative fuel was discovered back in 1901. During the oil shortage of World War II, it was used as a fuel for vehicles and machinery by the military as well as by civilian and agricultural sectors. In the early 1940s, more than one million vehicles operating on wood gas were in service worldwide. By now, this fuel has gotten almost completely forgotten. Finally, biogas should be mentioned as a biofuel capable of replacing natural gas based autogas. The most important prerequisite for energy recovery is that the waste discharged must contain a higher proportion of combustible components than non-combustible components.[38]

The non-combustible components remain in the solid phase as slag and ash, which need further treatments. Post-treatment can include landfill or vitrification (slag smelting) where metals can be recovered, and the remaining inorganic components can be transitioned into glass. A further condition is that the energy recovery should be realized in practice, meaning that the system's energy balance should be positive. Another important aspect is that the energetic utilization of the waste must provide more energy than it needs for processing it.

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[37] Bodnár 2017.

[38] Ibid.

Since construction, operation and end-of-life decommissioning of power plants also require a significant amount of energy and raw materials, carbon neutrality can only really be achieved if these processes are also considered when calculating the carbon footprint. This can mean that to achieve net zero carbon footprint, we need to grow up to 1.5 times more biomass than the power plant uses. Therefore, if we would like to maintain a constant capacity, we would have to grow more and more plants to cover the consumption of the power plant, or by perpetuating the amount of biomass we grow, the amount of burnt fuel (and hence the total net capacity of the power plants) would need to be gradually decreased. Taking these principles into account, the carbon dioxide emissions of electricity produced by biomass power plants may even be negative.

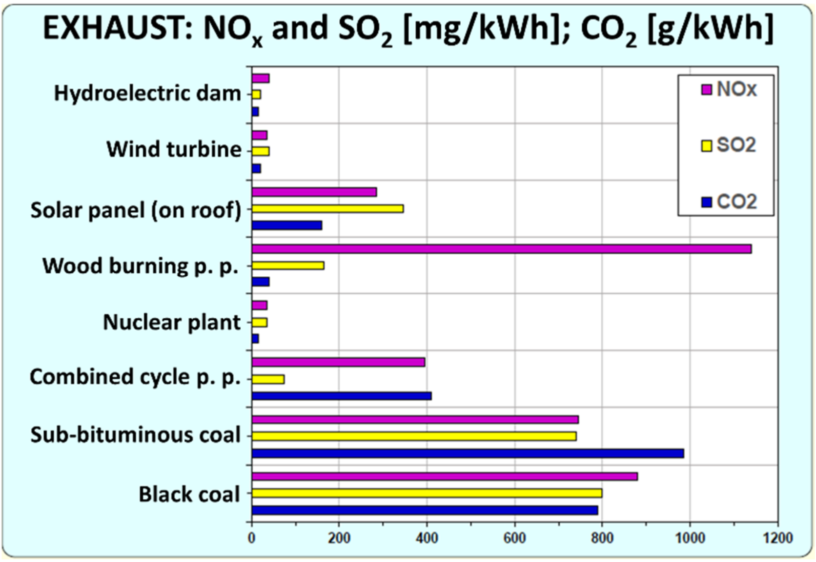

Figure 10: The exhaust comparison of the main energy sources[39]

Environmental impacts of construction, operation and decommissioning should be considered in case of other power plant types as well. Consequently, every power plant burdens the environment with indirect emissions. Direct and indirect emissions together result in the combined environmental impact of a power plant. In case of fossil fuel power plants, most of the emissions are typically direct (up to 90-95% of total emissions). The inverse is true for biomass power plants, where indirect emissions are dominant. Solar-, wind-, and hydropower power plants only have indirect emissions. The calculation of indirect emissions is based on the design lifetime of a power plant. By dividing the environmental emissions from power plant construction, operation and decommissioning by the amount of electricity generated throughout the design lifetime, we get the value of the specific indirect emissions per unit of electricity production. Individual power plants can be assigned different and wide-ranging primary resource requirements. Primary resource requirement is essentially divisible into raw

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[39] Körényi 2019.

material and energy requirements. The latter can also be expressed in terms of material demand, since the energies used are typically fossil based and thus represent fossil material requirements, although they are still measured in units of energy. As the energy density of renewable energy sources (water, wind and solar) is negligible compared to conventional and biomass power plants, their construction requires a high amount raw material and energy. Their space requirement is also significantly higher. Based on these, their indirect environmental emissions are also higher than those of conventional and biomass power plants.

Efficiency deterioration of a power plant from aging should also not be neglected. This mainly affects solar power plants; since solar cells are semiconductor devices, their aging – compared to other power plant types – results in more intensive degradation. Solar power plants are also exposed to environmental effects, such as dust, bird excrements, and other kinds of surface contaminations, which further decrease their efficiency. Therefore, in case of solar power plants, an additional efficiency reduction factor must also be considered.

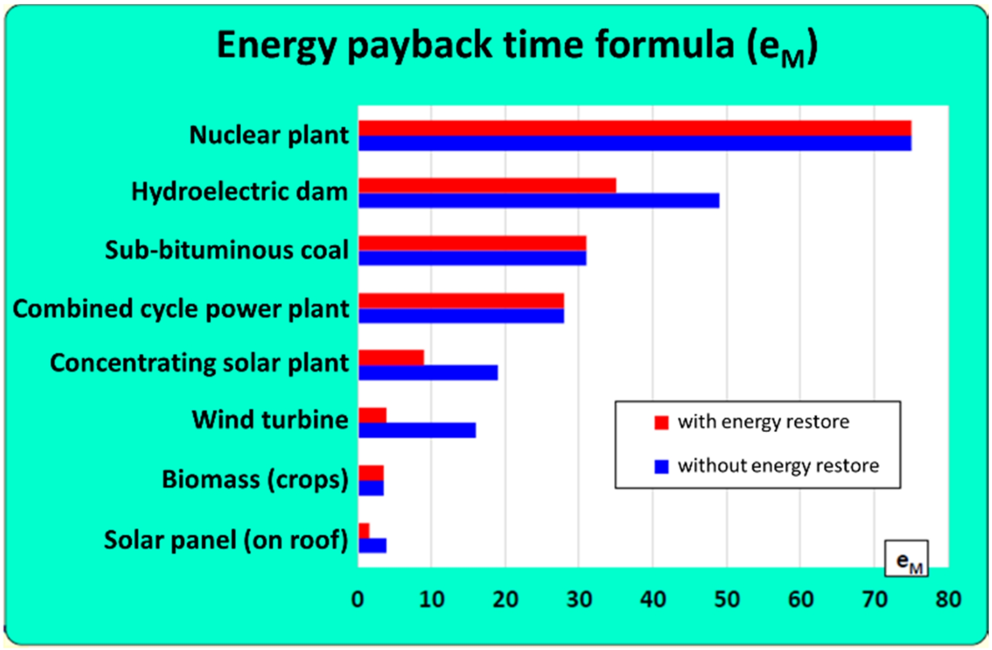

Figure 11: Energy payback time diagram[40]

10. Energy recovery from municipal solid waste

The way in which waste is treated is a subject of controversy all around the world. The waste hierarchy is designed to dampen these contradictions, stating that prevention and minimization are the most appropriate attitude. Beyond technical conditions, reusing and recycling also require a good social attitude.

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[40] Ibid.

Furthermore, beyond the problem of separating the waste, there are also certain factors that exacerbate the situation, such as the treatment of food-contaminated waste. At the higher level of the hierarchy, hence as a less favourable option, there is energy recovery, which is essentially a fuel replacement. Energy recovery puts a greater burden on the environment, but it is much easier to prepare the waste and design the workflows. There are many ways to recover energy from waste; conventional incineration, pyrolysis, gasification, plasma technology.

Depending on the technology, the waste can replace solid fuels or natural gas, and can be facilitated in power plants to produce electricity, cogeneration power plants to produce electricity and useful heat, or in heating plants to produce useful heat for district heating. Burning the waste releases heat energy and produces solid residues and flue gas. The main problem and disadvantage of this method is the flue gas emitted, since it contains hazardous components and greenhouse gases. Ash generated during the process also poses as a setback. Such by-products can only be released into the environment after cleaning. For biodegradable waste, fermentation is the preferred solution where biogas is released. Other methods that involve thermal treatment are also known. Energy recovery in a finer sense means the production of electricity and heat in power plants. However, the production of mechanical energy as a work-related energy type can also be included here, as biofuels are becoming more and more important. The possible energetic utilization can be carried out by conventional incineration, cracking pyrolysis or gasification and plasma technology, or flow incineration (in pieces of equipment). The following sections discuss the most frequently used thermochemical technologies for Waste to Energy.[41]

The most famous thermic treatment processes are:[14] (1) conventional incineration: full oxidative combustion, (2) pyrolysis: thermic degradation of organic material in the absence of oxygen, (3) gasification: partial oxidation, (4) plasma technology: partial oxidation, combination of (plasma-assisted) pyrolysis/ gasification of the organic fraction and plasma vitrification of the inorganic fraction of waste feed.

These technologies can be combined. The more thermochemical approaches such as pyrolysis; gasification and plasma technologies have been applied on selected smaller scale waste streams, and have attempted to control temperatures and pressures of the process. While the application of pyrolysis at low, mid- and high temperature is possible mainly for waste, gasification is suitable for all burnable materials. In connection with plasma technology, the elimination of hazardous waste is done by oxidation, and in this reduction method the goal is to extract raw material. Plasma technology is the least-known process. This process is very suitable for the treatment of organic waste, because at over 5.000 °C even PCBs decompose.[42] The emission levels will be sensitive to the accidental inclusion of waste. The main issue is synthesis gas cleaning. The main constituents of synthesis gas are hydrogen, carbon monoxide, methane and carbon dioxide. Gasification plants produce large quantities of carbon dioxide and, if the synthesis gas is only used for electricity generation, and many times greater, on a power for power comparison basis, than a conventional power plant. Gas engine and turbines typically have low tolerance to impurities in the synthesis gas.

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[41] Bodnár 2014.

[42] Ibid.

With pyrolysis the emission of heavy metals is lower (due to the lack of oxygen), but one of the disadvantages is that the use of pyro oil is accompanied by significant emissions. Besides this, pyrolysis produces a large quantity of pyro coke with a high concentration of heavy metals in the cinders. The new technologies differ from the traditional incineration processes in a way that chemical energy is recovered from the waste. The derived chemical products may be used as feedstock for other processes or as secondary fuel in some cases. The waste is converted into a secondary energy source (a combustible liquid, gas or solid fuel), while it is utilised in a steam turbine, gas turbine or in a gas engine in order to produce heat and/or electricity. The calorific value of the synthesis gas is below that of the natural gas.[43] The tested technologies and the data of tests are shown in Table 5.

Tested Technology	T [°C]	Oxidation factor	Atmosphere	Product	Engine
Pyrolysis	500 1200	$\lambda = 0$ endothermic	-	pyrolysis-gas, coke and oil	gas engine, steam turbine
Conventional incineration	1150	$\lambda = 1{,}5$ exothermic	natural gas additional firing, air	flue gas (<5% burnable), slag and ash	steam turbine
Gasification	1200 1600	$\lambda = 0{,}55$ partial oxidation	air	synthesis gas, slag and ash	gas engine
Plasma-gasification	1200 2000	$\lambda = 0{,}5$ partial oxidation	air, steam	synthesis gas, vitreous slag	gas engine
Plasma technology	3000 5000	$\lambda = 0{,}5$ partial oxidation	steam, O_2 and CO_2 blend	synthesis gas, vitreous slag	gas engine
Natural- and Biogas in cogeneration	650	$\lambda = 0{,}99$ exothermic	air	flue gas (<3% CH_4 content)	gas engine
Coal-fired power plant	500	$\lambda = 0{,}99$ exothermic	air	flue gas (<5% burnable), slag and ash	steam turbine

Table 5: The technologies and the data of the tested

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[43] Ibid.

Regarding thermic treatment of organic industrial waste, we have analysed eleven technologies. The reference quantity was natural gas cogeneration by gas engine. I pointed out Global Warming Potential (GWP) from the environmental categories, because my main goal is to find carbon-dioxide saving technologies. Among these technologies carbon-dioxide is the most significant from all the gases causing greenhouse effect. The functional unit chosen, that is, the base for the treatment comparison, is one kWh of electricity generated. All emissions, materials and energy consumption are referred to in this functional unit (Table 6).[44]

System boundary	Applied methods and functional unit
From the waste charging until the burning of the generated synthetic gas in a gas engine. Normal, steady operating condition.	**Applied methods:** **CML 2001 (November, 2010.)** **Functional unit:** **1 kWh electricity (CHP)**
Operating Condition and exploitage of the power plant	
Operating Condition: **Normal, steady-state condition**	**Exploitage:** **75,34 % power exploitage per year**
Environmental category	Measure
Global Warming Potential (GWP)	**kg CO$_2$- equivalent**
Environmental category definition	
GWP is a relative measure of how much heat a greenhouse gas (for example: CO$_2$, CH$_4$, N$_2$O and FCKW) traps in the atmosphere. It compares the amount of heat trapped by a certain mass of the gas in question to the amount of heat trapped by a similar mass of carbon- dioxide. A GWP is calculated over a specific time interval, commonly 20, 100 or 500 years.	

Table 6: System boundary, and the main parameters of the analysis

According to the results we can say that the most significant figures were achieved by the plasma technologies (Figure 6). These figures are lower than those of the natural gas in cogeneration and the Hungarian average. The most unfavourable rate is observed by the pyrolysis (500 °C). This figure is higher than the one of Hungary's coal-fired power plant in some temperature. This power plant emitted 1.22 kg CO$_2$ per kWhe, which they want to reduce to 0.9 kg by 2016. The higher temperature pyrolysis (1200 °C) is better than the gasification, and the plasma-gasification at some temperatures. The increase of the temperature has reduced the carbon dioxide emission per kWh electricity, because of the higher calorific rate of the synthesis gas. The rates of the conventional incineration are situated between the lower temperature gasification (1200 °C) and the plasma-gasification (1200 °C).

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[44] Ibid.

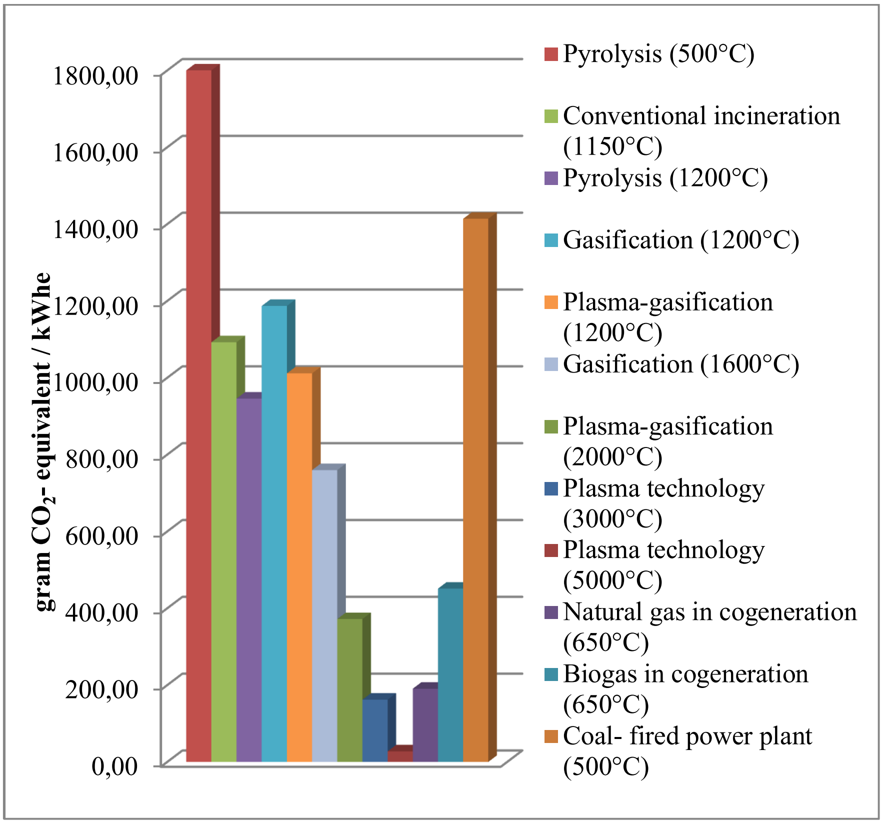

Figure 12: Carbon-dioxide equivalent per kWh electricity emission of the tested technologies

11. Conclusions

Overall, it can be said that the domestic electricity industry is facing a significant transformation. We are at the beginning of a very long process. Predictably, much remains to be done to make domestic electricity generation environmentally friendly and sustainable. We believe that in addition to the domestic conditions, the further expansion of the use of solar energy and biomass can be considered an achievable goal. With regard to solar energy, it is gratifying that a number of investments have been announced, which will allow us to expect a further steep increase in current capacity.

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