Clean Alternative

SILESIAN UNIVERSITY OF TECHNOLOGY

Contemporary Problems of Power Engineering and Environmental Protection

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More renewable and sustainable future

Building the future of energy sector of the 21st century is not just about going from dirty fuels to cleaner renewable ones. It is also a problem of sustainability of the future solutions as well as the feasibility of their implementation. The transition towards more renewable energy is creating new fascinating opportunities, but on the other hand, it crates complex challenges. The renewables are now part of the energy mix and are rapidly gaining market share. They bring benefits such as energy mix diversification together with better environmental performance. They make it possible to create distributed energy systems, and its capacity is expected to be doubled in next decade. New challenges are related to energy storage, changes in economic systems and business models what could reflect on social aspects. This is also the question of new models of energy policy, security and reliability of supply.

This monograph is a result of Conference "Environmental Protection and Energy", held on December 9th 2016 at the Department of Energy and Environmental Engineering of Silesian University of Technology in Gliwice, Poland. It was 4th edition of the Conference which is co-organized by students of Clean Fossil and Alternative Fuels Energy MSc program as a part of project based learning implementation activity. The conference was a real success in numbers: nearly 160 scientists participated and more than 90 presentations were given during the Conference.

The Conference was a special event, because it is practical example of implementation of new didactic methods. The event was organized in “learning by doing” manner and according to “project based learning” requirements. Students created a virtual company which has conducted practical project aimed to organize the Conference. Students were divided into working groups, with leaders and the project manager. Full documentation of project was also created. The value of such approach to teaching is that students experience the heavy burden of responsibility and have possibility to see practical effects of their work. They can notice why precision planning is important. They face the consequences of their mistakes and they have to react is crisis situations. For students, this was not only learning of project management theory with elements of risk management but also soft skills like teamwork and leadership. This was a “playground” for students to learn how to act in real life environment.

The monograph consists of 24 chapters discussing different issues related to energy in environmental context. The chapters are sometimes surprisingly holistic, some of them are extremely specific. This reflects the young spirit of authors who come from different universities and countries and have different perspective in looking at the power sector. What unites them is the passion to science and strong will to make a change. We are glad that we could help them and we hope that the experience of participating in conference and contributing this monograph will serve as an inspiration for future achievements in dealing with environmental and energy challenges.

Krzysztof Pikoń

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Table of Contents

Integration of the variable renewable energy sources in energy systems

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Abstract

No matter if the world global warming problem is truly a problem that exists, the threat of the consequences of not doing anything have started the process of turning from conventional fossil fuel fired power plants into the renewable energy generation systems. These days all over the world we can observe a huge increase in electricity production from renewable energy sources. Moreover the technology is developing every single year – and the production of renewables is becoming more and more cost effective. Renewables offers large amount of benefits like the emergence of new jobs, reduction in fossil fuels import necessity and most obvious, CO_2 emissions mitigation. However, a lot of the renewables are variable renewable energy sources which operating conditions are inseparably related with the weather conditions at the specific period. Those sources such as wind power plants or solar panels unfortunately arise certain challenges of both technical and economical nature. Those challenges have to be properly addressed and require both short and long term solutions.

Keywords: renewables, variable renewable energy sources, integration, growth, expansion, solutions

1. Introduction

It was more than a two decades ago when the electric power generation sector started its transformation from exclusively centralized and industry like integrated model which was mostly controlled by a government towards much more efficient business model that also included private ownership [1].

Considering different world regions transformation followed by different factors. The most influential to the transformations include:

- Already established and ongoing restructuring processes of the energy market (including evolving regulation).
- Shale gas revolution in the US (that significantly reduced coal demand for production of the electricity and simultaneously enlarged the usage of natural gas) that increased the low-cost coal export .
- Fukushima nuclear accident that happened in Japan that resulted in a dramatic turnover of a nuclear power generation systems development in most of countries
- increased oil prices variations – after a long period of high oil prices there was a significant decrease in 2014 that influenced all fossil fuel prices
- Increased tensity between huge oil and gas exporters
- Rising concerns regarding global warming problem

Those factors combined together along with the increased environmental awareness of harmful impact of electricity production based on fossil fuels resulted in many countries in development of more environmental friendly power generation systems. The legislation supporting renewable energy sources had been developed. Those regulations supported especially variable renewable energy sources such as wind power plants or solar photovoltaic for example by means of reduction of capital expenditure (CAPEX) [1]. For example in Japan, feed-in–tariffs (policy that offers long term contracts for renewable energy producers) has been introduced for renewable energy sources. Accelerated by arising nuclear concerns after Fukushima accident, those tariffs have reached 450 USD/MWh to push the development of variable renewable energy sources. [1]

2. Renewables today and in the future

Over the past decade renewables have achieved a rapid rate of growth. Some hard facts regarding the renewable energy sources have to be shown:

- 164 over all countries in the world had set targets regarding electricity production from renewable energy sources and 134 have implemented renewable energy policies (including units commissioned by the end of 2015)
- From 2004 to 2014 globally installed capacity of renewables increased from 814 GW to 1712 GW respectively. Main contribution to the increased renewables increase include wind and solar power units. Change in the installed solar power amounts from 3 GW to 181 GW and in case of wind power plants from 48 to 370 GW (annual growth rate – 23% and 51% respectively).
- Only in 2015, 150 GW of new renewable energy sources was added globally – it is more than for all other sources combined together (coal, nuclear, gas, and hydro projects). This contributes to around 60% of new power installed in 2015. Most of the power units installed was dominated by solar and wind – 103 GW, where shares of those sources were 41 GW and 62 GW respectively.
- Electricity produced from renewable energy sources reached more than 22% of global annual production in 2014. Most of the electricity (73%) is a hydro power plant contribution. Growth of variable renewable energy sources is most significant, however, it should be remembered from what reference level it has started.
- Without taking into account hydro power plants, global electricity supply that is provided by means of renewables is approximately 6.2%, where variable renewable energy sources have their share of 4% (in 2014).
- Quite low shares of variable renewable energy sources contribution in electricity production can be explained not only by the smaller capacity installed than for hydro power plants but also by means of available operating hours per year. We have 3700 h for hydro, 2000 h for wind and 1200 h for solar energy sources [1].

Fig. 1.1 shows the actual and forecast of the structure of electricity production:

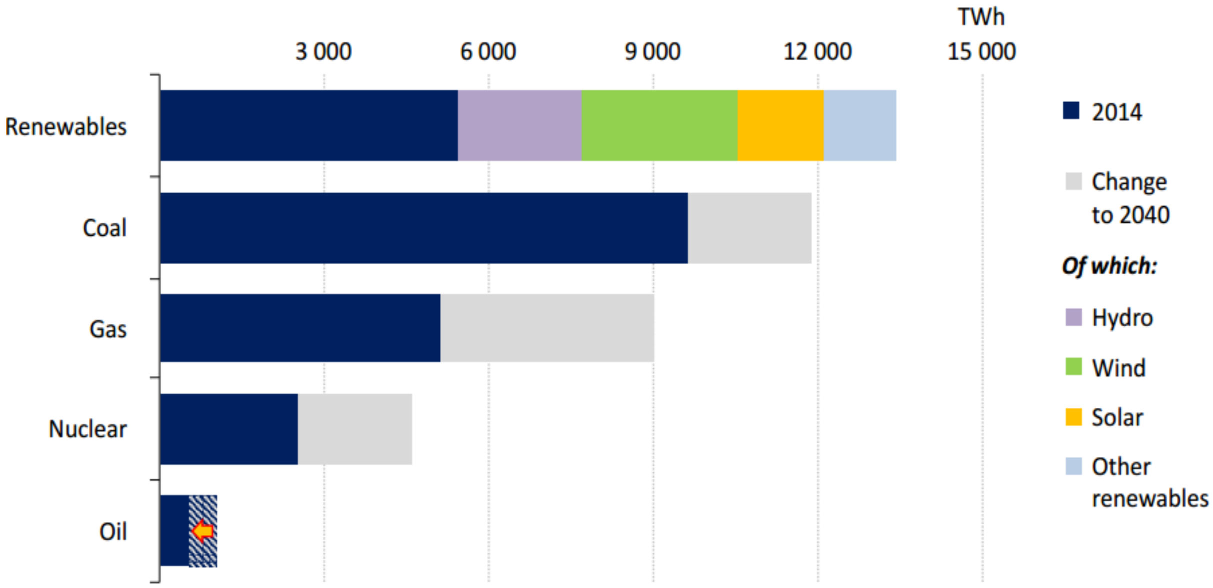

Fig 1.1 Global electricity production by source [2]

What should be underlined are two main things:

- It is predicted than in 2040 the main source of worlds electricity will be renewable
- Variable renewable energy sources will increase their share in global electricity production quite significantly

3. Main reasons for further development of renewables

The reasons of the transformation of energy markets have been already stated. However, not only reasons but also particular goals have to be addressed. Renewables contribution in energy production is significantly increased and the main short and long term goals to achieve are:

- Stabilizing electricity production impact on the climate mainly by means of decarbanization of the energy system
- Ensuring of long term energy security for all of the involved courtiers
- Providing the alternative answer for further growing energy demand of constantly increasing world population
- Delivering electricity to the electricity-lack areas
- Improvement of transportation of electricity in the long distances from the places where the energy is generated to the end users (what is crucial in terms of variable renewable energy sources that are very often located in long distances from cities)[3].
- Implementing electricity generation units in places with lack of the proper electricity systems

Fig. 3.1 shows one of the goals – delivering energy to people with lack of access to electricity grids:

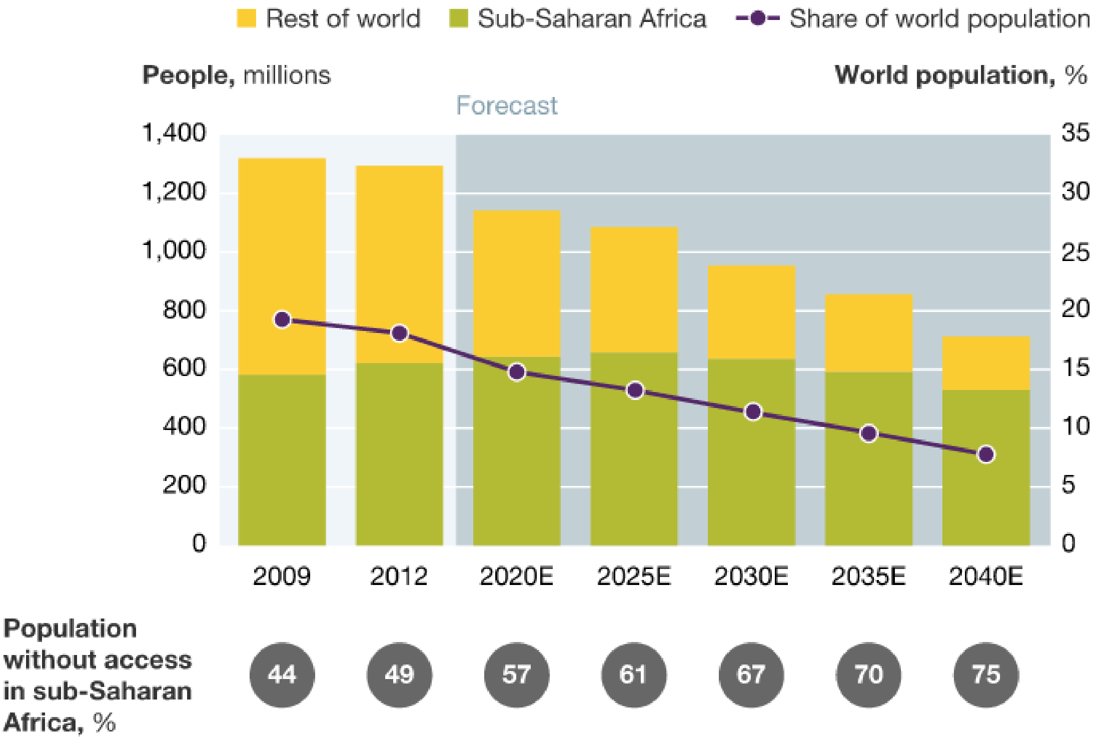

Fig 3.1 Global population without access to the electricity grids - historical, nowadays and future predictions [4]

Developement of renewable is a fact, however, those of renewable that are specified as a variable renewable energy sources (VRES) create certain challenges that have to be solved in order to achieve all of the previously mentioned goals.

4. Main challenges and possible solutions

Variable renewable energy sources, because of its dependence on to the local weather conditions, have a significant impact on the already existing power systems. Those impacts cover different areas of interests and result in a various of challenges.

- Impact on traditional fleets – because of the increase of VRES systems, the operational conditions of traditional power units have been influenced and thus many of them may be operated right now in an inefficient manner. Both, wind and solar radiation depend on the weather conditions at a specific time and location, and therefore conventional electricity generation units have to be ready to adjust their power generation demand – sometimes it may exceed their flexibility limits.
- Impact on distribution and transmission grids – increasing number of VRES causes problems in the electricity distribution. Most of the conducted case studies are showing that along with the expansion of VRES new transmission and distribution systems have to be implemented in order to ensure no bottlenecks existence. Effect is usually enhanced by the location of VRES power units which are mostly located in large distances from the end users. Variable renewable energy sources may also cause the reverse power flows. Therefore, power energy systems that are capable of withstanding those types of unplanned events are needed.
- Impact on customers – even though that VRES development causes the wholesale prices drop of electricity, it also produces additional costs to the power systems. Those costs unfortunately are usually transferred directly to the end users and results in higher energy bills [1].

In order to deal with those challenges a lot of actions and possible solutions should be implemented. Those solutions refers both to the technologies and to the market design. In this article only the technological solutions will be presented. Basically these are:

- Better weather forecasting – improvement in accuracy of forecasting can ensure lowering of variable renewable energy sources integration costs. What is more, better weather forecasting can provide a proper knowledge to the energy grid operators to achieve reduction in costs spent on reserves and network balancing costs.
- Improved flexibility of generation – this feature is needed to answer the rapidly changing load conditions resulting from rapid changes of weather. Short start-up and shutdown times along with the improved flexibility of power units is crucial. These needs causes increased fuel consumption and faster wear of devices – therefore it may result in higher emissions. Implementing proper improvements and upgrades to already existing power generation units is crucial.
- Dynamic transfers – by means of transferring electricity in real time, electronically controlled and properly balanced generation in certain areas/countries in which the power generator physically is located. Not only it can help with integration of VRES but also provide benefits to the customers that do not use renewables.
- Transmission Expansion – increasing amount of electricity produced, not only VRES causes the need to develop more electricity grids of better parameters in order to improve system flexibility. Transmission capacity with increasing amount of VRES installed will be crucial in order to optimize current flow and ensure access to more geographically spread out resources.
- Distribution networks modifications – it is crucial to eliminate existence of bottlenecks to energy produced from VRES. It is also necessary to counteract reverse current flows.
- Improve the visibility of distributed generation – in upcoming years it is predicted that distributed generation is going to increase in a serious manner.It is crucial to maintain and improve the coordination between distribution network operators and transmission network operators to remove scheduling conflicts.
- Quick responses to actual demands – it is necessary to maintain a properly designed systems in order to provide quick responses to the changes resulting from weather changes and VRES operation conditions.

- Energy storage systems – there are already various of different ways to storage energy that are currently in use e.g batteries, compressed air energy storage, hydrogen energy storage or flywheel devices. Those solutions have to be developed and implemented in order to provide better flexibility to the power systems. Probably it is the most important technological solution comparing to others [1].

5. Conclusions

According to various of sources, development of renewable energy sources and especially variable renewable energy sources, especially taking into account concerns related to the environmental issues is inevitable. The branches of renewables that are going to achieve the strongest growth in future are most probably wind power plants and solar photovoltaics sources. Unfortunately, their strong dependency on weather coditions, especially when they reach certain generation capacity may create series of problems.

Conventional power plants, considered the existence of such renewables in the transmission and sub-transmission grids will no longer be a part of a base load suppliers and therefore their flexibility need to be improved. Moreover, the non-optimal unit operationmay cause the overall annual efficiency decrease, and increased wear rate of devices may occur.

What is more, distributed generation of the energy, also due to “prosumers” is most likely to expand,thus transmission and distribution systems have to be properly developed. Other issue that also have to be taken into account is the capacity of the transmission and distribution grids. Due to the expansion of the VRES most likely the current capacity will have to be increased and proper electrical connections between different countries and crucial regions will have to be maintained.

Despite of the concerns that growth of VRES will result in, still there are some clear advantages. Due to the character of such a sources, they provide an easier possibility to deliver an electricity within the certain regions that are placed very far away from convectional power generation units. Moreover, renewables may decrease the number of people that suffer from lack of electricity. Finally, related to the VRES technologies (such as energy storage technologies) an overall development can also be observed. Those technologies may not only help to solve problems related to unpredictable behaviour of VRES but also provide better elasticity of conventional generation units.

Acknowledgements

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Evaluation of the rehydration process of an ion exchange resin made from sulfonation and crosslinking polymer matrix of recycled expanded polystyrene

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Abstract

Fundamental research consists in the evaluation of the rehydration process of an ion exchange resin made from sulfonation of polystyrene, used in packaging and packing, in order to determine whether a significant decrease in ion exchange capacity exists. A primary evaluation to the resin, was performed, determining the parameters established in ASTM D 2187-94 (2004), to characterize it, providing a basis for comparison between the initial resin and the rehydrated. Also, these properties were compared with the parameters established for, PUROFINE PFC-100 commercial resin, determining that the resin made exhibit similar features as the commercial one. It was performed, three processes of dehydration and rehydration consecutive, evaluating within each process, the total ion exchange capacity of the resin and establishing the percent decrease thereof. Finally, it was determined that for all dehydrations made, the percent decrease in exchange properties was less than one percent. Recommended as the optimum maximum, three dehydrations by resin.

Keywords: recycled polystyrene, hydration, total ion exchange capacity, percent decrease.

1. Introduction

The ion exchange resins are three-dimensional hydrocarbon chains, to which have been added ionizable groups, through processes of sulfonation, amination or analogous; resulting from them cationic and anionic exchange resins. [2, 3]

By subjecting the expanded polystyrene waste in a process of sulfonation and crosslinking the polymer matrix; it permits sulfonic and sulfone groups link the styrene monomer unit groups. This provides a hydrophilic character and the ion exchange capacity to the material. Thus, obtaining an alternative to recycling polystyrene, generating a cation exchanger with low energy consumption and low cost. [2, 4]

In this process, it is obtained as a result, a resin, composed mostly of water. This presents a difficulty in handling the resin. So, it is considered important, the evaluation process of dehydration and rehydration of it. And the regeneration of its main properties, determining whether there is significant loss in its total ion exchange capacity.

ASTM D2187 - 94 (2004) refers to evaluation methods covering the determination of physical and chemical properties of ion exchange resins used in water treatment properties. These methods are intended to the evaluation of new and reclaimed material; making it possible to determine the decrease in exchange capacity of the resin due to hydration and rehydration process. [1]

2. Methodology

The project includes five stages: pre-treatment and recycling of expanded polystyrene, sulfonation of the polymer matrix and preparation of the sodium salt of the ion exchange resin, primary evaluation of the resin, dehydration and rehydration, and secondary evaluation of the ion exchanger. [3, 4]

2.1 Pre-treatment and recycling of expanded polystyrene

It was applied a pre-treatment process to the material used to produce the resin, consisting of expanded polystyrene degassing, to reduce the volume of the spheres and optimize the space available for the sulfonation.

2.2 Sulfonation of the polymer matrix and preparation of the sodium salt of the ion exchange resin

It was used as sulfonating agent a mixture of fuming sulfuric acid, oleum, as a ten percent and concentrated sulfuric acid as the ninety percent and applying a sulfonation time equal to two hours; following the recommendations given in the research *Development of an ion exchange resin from the sulfonation and crosslinking expanded polystyrene recycling for the separation of metal ions in solution.* After sulfonation, the sulfonated polystyrene was neutralized in their acid form, using a sodium hydroxide solution, to bring the hydrogen potential of the mixture to a value greater than ten. Obtaining the sodium salt of the resin. Washings were done with demineralized water to remove excess acid that may be free therein. [1]

2.3 Dehydration and rehydration

For the dehydration process a convection oven was used, at a temperature of 104 °C for 18 hours. It was made a mass reconstitution of the resin, adding demineralized water to the dried sample.

2.4 Evaluation of the resin

It was performed an evaluation of the properties of the resin, using as quantitative technique, the parameters set in ASTM D 2187-94 (2004). It was determined the backwash density, high water retention, capacity of salt splitting and total capacity of the ion exchange resin and the regeneration capacity of these properties after rehydration. [1]

3. Presentation of results

In the process of sulfonation and crosslinking of the polymer matrix of expanded polystyrene, it is obtained as a result, a resin composed mostly by water. This presents a difficulty in handling the resin and an increase in cost thereof. Which decreases its economic feasibility and marketability. For this reason, it is considered important, the evaluation of the process of dehydration and rehydration of the resin.

3.1 Ion exchange capacity of the initial resin

Tab 1. Total ion exchange capacity of the initial resin obtained by sulfonation of polystyrene.

Ion Exchange Capacity	**Value**
Per mass of wet resin, meq/g	9.716
Per mass of dry resin, meq/g	149.253
Per milliliter of settled and backwashed material, meq/mL	10.002

3.2 Initial characterization of the resin according to ASTM D 2187-94 (2004)

The evaluation of the resin was oriented in the determination of the total ion exchange capacity, and the effect produced by the process of dehydration and rehydration. To meet this goal, the total ion exchange capacity of the starting resin in milliequivalents per gram of wet resin, per gram of dry resin and per milliliter of settled and backwashed material were determined; these results are shown in chart I.

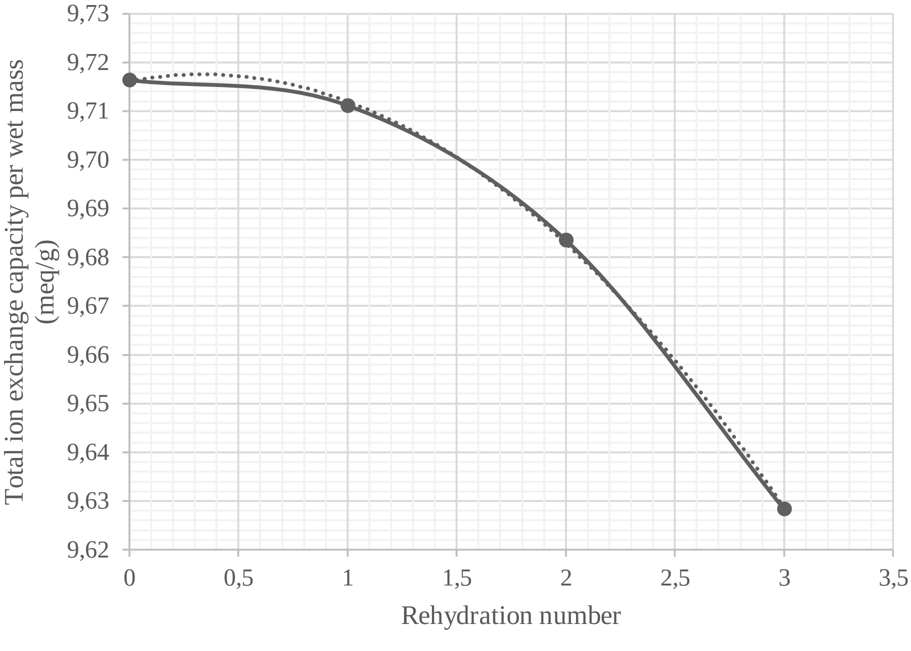
Tab 2. Determination of characteristics of the resin obtained by sulfonation of polystyrene. Source: Compiled based on results.

Characteristic	**Value**
Backwash density g/mL	1.030
Maximum percent retention of water %	93.490
Salt-splitting capacity per mass of wet resin meq/g	0.137
Salt-splitting capacity per mass of dry resin meq/g	2.101
Salt-splitting capacity per milliliter of settled and backwashed material meq/mL	0.141

In order to establish a basis for comparison of the rehydrated resin to the initial characterization, it was conducted the evaluation, done with the parameters established as optimal in the previous investigation. Thus, backwash density, high water retention capacity and the ability of a neutral salt splitting of the resin were determined. The results are shown in chart II. The assessment was made based on the methods described in ASTM D 2187-94 (2004), "Standard Methods of evaluation of the physical and chemical properties of ion exchange resin particle properties." [1, 4]

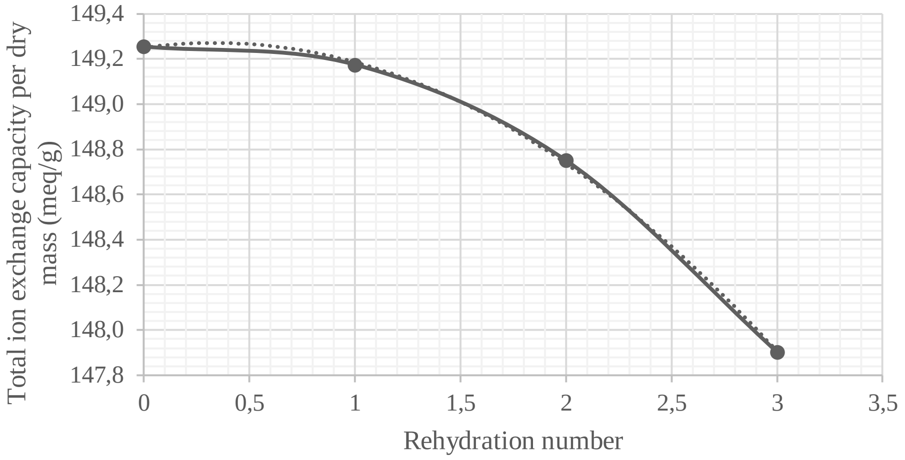
3.3 Performance of the total ion exchange capacity of the rehydrated resin regarding to the initial

In figures 1, 2 and 3, the performance of the total ion exchange capacity per wet gram, dry gram and per milliliter of settled and backwashed of rehydrated resin regard to the initial is patterned. This model fits a second order polynomial behavior, which has a maximum in the initial resin and a decreasing trend to a minimum.



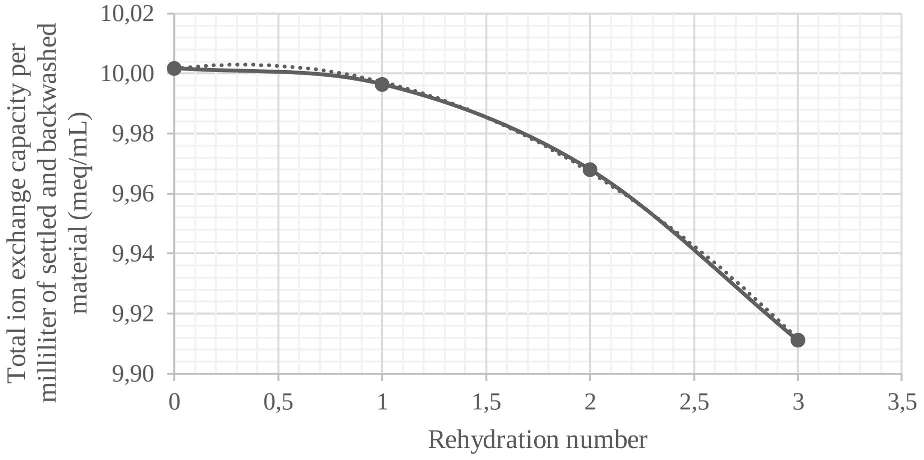
Mathematical model	**Correlation coefficient**	**Validity interval**
$C_w = -0.0125R^2 + 0.0083R + 9.7161$	0.9997	[0.3] R

Fig 1. Performance of the total ion exchange capacity per wet mass of the rehydrated resin regarding to the initial. Source: Compiled based on results, with Microsoft Excel 2013.



Mathematical model	Correlation coefficient	Validity interval
Cd = -0.192R2 + 0.1281R + 149.25	0.9997	[0.3] R

Fig 2. Performance of the total ion exchange capacity per dry mass of the rehydrated resin regarding to the initial. Source: Compiled based on results, with Microsoft Excel 2013.



Mathematical model	Correlation coefficient	Validity interval
Cb = -0.129R2 + 0.0086R + 10.002	0.9997	[0.3] R

Fig 3. Performance of the total ion exchange capacity per milliliter of settled and backwashed material of the rehydrated resin regarding to the initial. Source: Compiled based on results, Microsoft Excel 2013.

3.4 Decreased in total ion exchange capacity of the resin in order to rehydration process

Tab 3. Percent decreased in total ion exchange capacity of the resin in order to rehydration process. Source: Compiled based on results.

Rehydration number	Percent decreased, %
1	0.05
2	0.34
3	0.91

The percentage decrease of the total ion exchange capacity in the resin due to each rehydration was evaluated. This rate of increase is, in all cases, less than one percent, this shows that the hypothesis proposed in the investigation, exposing that it is possible to conduct the dehydration and rehydration of a resin obtained from the sulfonation of polystyrene foam of recycled origin, without any significant loss in ion exchange capacity, is affirmative. Likewise, the correlational hypothesis, which states that the total ion exchange capacity of the resin decreases by ten percent in each regeneration, has been proven. [1,4]

3.5 Comparison of characteristics of the processed resin to PUROFINE PFC-100 commercial resin

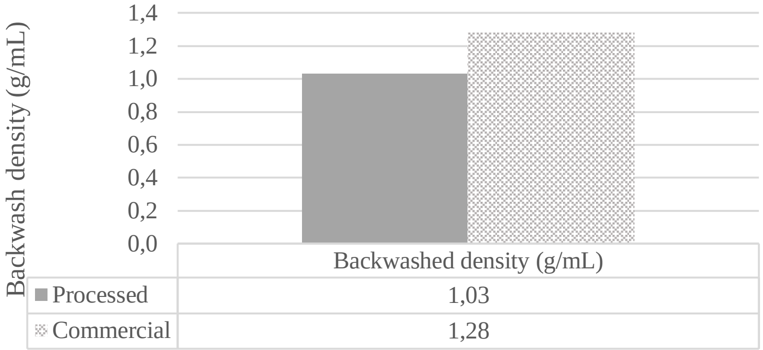


Fig 1. Comparison of Backwash density of the resin made of polystyrene to Purofine PFC-100 commercial resin

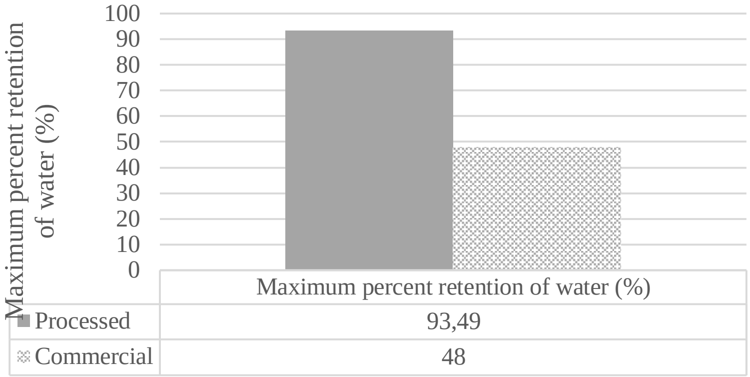


Fig 2. Comparison of maximum percent retention of water of the resin made of polystyrene to Purofine PFC 100 commercial resin. Source: Compiled based on results, with Microsoft Excel 2013.

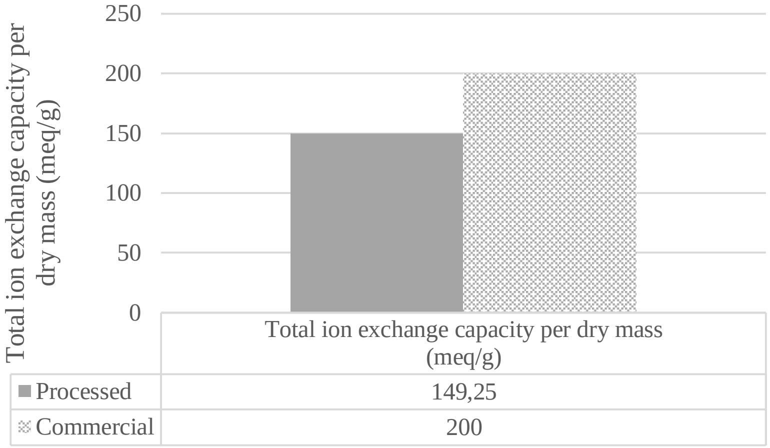


Fig 3. Comparison of total ion exchange capacity per dry mass of the resin made of polystyrene to Purofine PFC-100 commercial resin. Source: Compiled based on results, with Microsoft Excel 2013.

The determined properties were compared with commercial sulfonated polystyrene resin Purofine PFC-100. The density of backwashing, as the total ion exchange capacity, figure 4 and 6, are lower in the processed resin than in the commercial, this is because clots present in the gel, reduce the density backwash as increases the amount of water retained in the polymer net. The ion exchange capacity is lowered due to decreased surface area of contact of the resin with the ion exchange medium.

Backwash density determines the density of the material in its maximum water retention, this value is greater than the average density of water at the conditions under which the experiment was performed; it promotes circulation of the resinous material in the backwash, while improving the regeneration of the resin. It is seen in figure 5 that the maximum water retention, unlike the other properties, to the resin is made higher than for the commercial. If the resin has a greater number of sulfonic groups increases solubility of the material and decreases the percentage of high water retention. Since the resin is prepared on a laboratory scale, the sulfonation is weaker than that used for commercial resin; generating a lower proportion of sulphonic groups present in the polymer network. [1, 4, 5]

4. Conclusions

With the analysis of the presented data, the conclusions obtained based on the results are the following.

1. The total ion exchange capacity per wet mass of the initial resin obtained by the sulfonation of polystyrene is 9.716 meq/g.
2. The total ion exchange capacity per dry mass of the initial resin is 149.253 meq/g.
3. The total ion exchange capacity per milliliter of settled and backwashed material of the initial resin is 10.002 meq/g.
4. The values obtained for the total ion exchange capacity of the resin made from recycled polystyrene sulfonation origin, correspond to the average value established in ASTM D 2187-94 (2004).
5. The total ion exchange capacity of the resin rehydrated regarding the initial, performs a second order polynomial model, having a maximum in the initial resin and a downward trend to a minimum.
6. The percent decrease in total ion exchange capacity of the resin due to the dehydration and rehydration process is less than one percent, for all trials.
7. The backwash density is lower for the ion exchange resin made from sulfonation of polystyrene recycled origin, than commercial sulfonated polystyrene resin Purofine PFC-100.
8. The ion exchanger processed has developed smaller proportion of sulfonic groups than the commercial, hence its ion exchange capacity is less.
9. The resin produced has a higher maximum percent retention of water compared to the commercial resin evaluated.
10. The backwash average density of the prepared resin is 1.03 g/mL.
11. The average resin made allows maximum water holding 93.49 %.
12. The salt splitting capacity of the initial resin obtained by the sulfonation of polystyrene per wet mass is 0.137 meq/g, per dry mass of the initial resin is 2,101 meq/g, and per milliliter of settled and backwashed material is 0.141 meq/g.

In order to improve the future analysis of data, the recommendations for the research are the following.

1. Set limit regeneration of ion exchange resin in three dehydrations.
2. Check the temperature of the dehydration process of the resin does not exceed 104 °C.
3. Avoid splitting spherules when performing the backwash process, using a column that holds the height corresponding to the volume of resin to evaluate.

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Applications of phase change materials in buildings

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Abstract

Phase change materials have multiple applications in thermal energy storage and can reduce the energy needs for heating and cooling of the building. The paper shows the potential ways and profits of using PCMs in construction industry. Different materials with various properties can support e.g. heat pumps, solar collectors, PV panels and HVAC systems (heating, ventilation and air conditioning). PCMs are also desired in developing of passive houses and can significantly increase their heat capacity without increasing building's weight. Also, the reduction of the environmental impact thanks to these components is considered in this work.

Keywords: phase change materials, HVAC, PCM

1. Introduction

Constantly growing energy needs in the recent years force us to seek new solutions for energy industry. Building sector in the European Union both for commercial and residential buildings covers about 37% of the final energy needs. About 2/3 of that energy is connected with providing the indoor thermal comfort conditions, which includes heating and cooling. These facts show the potential possibilities for energy savings in this field. By the rationalization of these needs large quantities of primary energy can be saved which also leads to the reduction of the environmental impact caused by the conventional energy sources [1].

There are different ways of diminishing the impact of the surrounding environment on the building's interior. One of the possibilities which has gained more popularity in the last decades is the use of phase change materials (PCMs) in construction of buildings. PCMs are substances which are able to store latent heat and release it when it is needed. The change of phase occurs in the material when certain temperature is obtained dependent on the type of material. Its huge potential comes from the fact that the sensible heat is much lower than the latent heat absorbed in the material by solidifying and melting. A high storage density is their strong advantage because by a slight difference in the temperature they can store a large heat flux. The application of liquid-solid phase change of the material is more often used because liquid-gas phase change is impractical due to the large pressure and volumes of the gas state. [2]

In table 1 are presented the examples of materials used in the construction of buildings. PCM material in this case is a mixture of fatty acids with melting temperature of 22°C. Provided heat capacity is the effective specific heat in the range of 18-28°C, which also considers the heat of the phase change. [1]

Tab.1. Comparison of construction materials

Material	**Specific heat, kJ/(kg ·K)**	**Specific heat, MJ/(m^3·K)**	**Density, kg/ m^3**
Water	4.20	4.20	1000
Concrete	1.00	2.30	2300
Steel	0.47	3.67	7800
Gypsum board	0.84	1.18	1400
Brick	0.84	1.34	1600
Wood	1.60	0.96	600
PCM	**18.0**	**15.7 - 18**	**870-1000**

PCMs can be grouped into two main categories depending on their chemical background. They are split into organic compounds such as polyethylene glycols and salt-based products like Glauber's salt. Pros and cons of each type are presented in table 2.

Tab.2. Types and properties of different PCMs

	Advantages	**Disadvantages**
Organics	Simple in application Non-corrosive Without supercooling No crystalizing	Combustible Usually higher costs Lower latent heat capacity Often wide range of melting temperatures
Salt based	Usually lower costs Higher latent heat capacity Inflammability Specific melting point	Additives are needed for long term use Corrosive to some metals Vulnerable to supercooling Can crystalize and lose the heat capacity

Because the heat from PCM is released or absorbed when the transition temperature occurs, this is the most important factor for the overall efficiency. Due to the diverse temperature in different parts of the world and different applications in building sector the significant modifications of materials can be done. For example Glauber's salt freezes in 32.5°C which makes it relevant for implementation in solar heating systems. By adding other salts to this material we can decrease that temperature to 8.3°C which perfectly fits the requirements of air conditioning equipment. However, the strong disadvantage of some salt based PCMs is that after melting, the crystals isolate from the saturated solution and sink to the bottom. In the freezing process these crystals can't combine again with the saturated solution and that results in the loss of thermal energy storage capacity with every cycle. Another problem that can occur in these PCMs is supercooling, which is the process of lowering the fluid temperature below the freezing point without solidifying [3].

2. The implementation of PCMs in buildings

In highly efficient buildings, like passive houses or zero emission and zero energetic buildings it is crucial to use materials with good thermal performance of the insulation as well as high quality heating, ventilation and air conditioning systems (HVAC) and decent envelope airtightness. Many contemporary office buildings are fully glazed which reduces their mass and decreases their ability to store heat. That results in high heating and cooling loads thereby increasing operational costs. The application of PCMs in similar cases can be an efficient way of reducing peak loads [2].

There are several ways of implementing PCM into the building. These are as follows:

- used as the component of construction materials and elements (PCM is implemented into the material structure)
- by placing PCMs into special containers of particular shape and volume, which are placed in the free spaces of the building
- by building the small quantities of PCMs into interior equipment especially into blinds which in this situation act as the solar collector
- by placing PCMs between PV systems and building envelope

2.1. PCM used into the structure of the construction material

PCMs can be applied by mixing them with the construction elements made of e.g. concrete or gypsum. Appropriately prepared material in the form of microcapsules in the size range from few to few hundreds micrometers is placed in the structure of the construction material which can be seen in Fig.2.1. Thanks to the small size of the capsules and their polymer surroundings the mechanical properties of the created composite aren't diminished. They contain about 80% of the PCM. Due to the safety issues (often used hydrocarbons are flammable) the amount of PCM in the structure usually doesn't exceed 20% of the composition. Beside the microcapsules also granules in the size range of millimeters are incorporated into construction materials structure. They are immersed in concrete or used in the capacity layers of heated floors. Another possibility of using the granules is filling the empty spaces of the airbricks with them like in Fig.2.1 [1].

An important fact is that during the freezing process the volume of the PCM decreases about 10-20%. In the case of efficiency thermal conductivity of the new composite plays a dominant role. With higher amounts of PCM in the structure the thermal conductivity decreases. Through the recent years new ways of improving thermal conductivity has been used. These are, e.g. addition of graphite nanosheets and incorporating aluminum honeycomb into the structure. Thanks to these solutions the increased thermal storage capabilities and energy distribution are obtained [4].

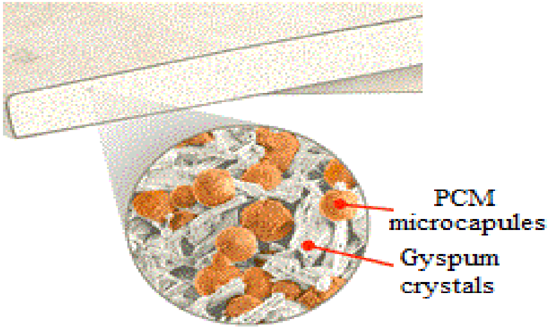

Fig.2.1 Gypsum with incorporated PCM [5] Fig.2.2. Bricks with incorporated PCM macrocapsules [6]

Another approach which has a strong potential in improving energy efficiency is mixing PCM with insulation. The insulation performance of polyurethane foam together with increased thermal capacity of PCM can be a very effective way of reducing the environmental impact due to the heat losses. Recent studies have been mainly concentrated on the thermal energy storage capacity; although they have omitted the parameters important for the insulation materials like heat transfer resistance. So that further researches on this composite have to be made in order to maximize its performance. Reduction of the energy for heating and cooling using PCMs in interior and exterior walls reaches levels of 11% and 48% respectively and strongly depends on conditions[6][7].

An important factor for application of bigger volumes of PCMs is their placement. It has a meaningful impact on the overall thermal performance. In the ordinary lightweight buildings PCMs are placed in the macrocapsules and incorporated into the wall in ways presented in Fig.2.3.

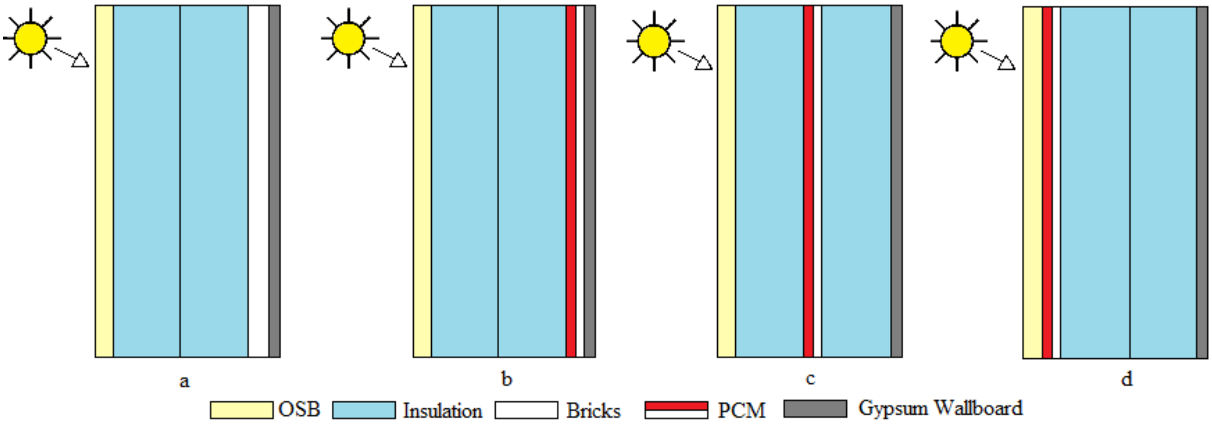

Fig.2.3 Different PCM placement in wall: a – without PCM, b – next to the internal layer, c – between two layers of insulation, d – next to the outer layer (oriented strand board) [6]

2.2. PCM used in the free spaces of the building and with additional equipment

In buildings there are free spaces filled with air which has a weak thermal capacity. PCMs can be placed in these spaces by using special containers fitted to the certain size. The most common placement for the containers is under the floor or over the suspended ceiling. They are often accompanied by the system of inlet air ducts with ventilators. Air in this case acts as the heat carrier. In this application PCM is placed in simple plastic bags or cylindrical containers. Heat accumulation is also desired when we consider renewable energy supply like in the passive houses. Heating with solar collectors and heat pumps due to its low operating temperatures is usually performed with the use of pipes placed in the floor. Underfloor heating creates the opportunity of increasing thermal energy storage using PCMs near the heat source which isn't so easy when we consider regular radiators.

Another factor which can increase the profitability of the heat pump heating is the fact that the driving energy at night can be cheaper due to the used night rates. Abovementioned solutions are presented in Fig.2.4.

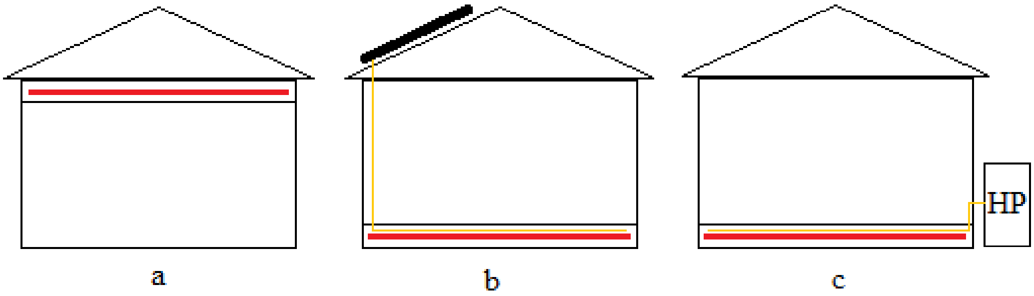

Fig.2.4 Location of PCMs in building's free spaces: a – PCM over suspended ceiling b – PCM next to the floor heating powered by solar collectors, c – PCM next to the floor heating powered by heat pump

The heat originated from e.g. people or office equipment radiates to the building's envelope and can be then accumulated. In the offices this heat is usually removed to the environment by the intensive ventilation during night. Also the sun rays which are coming to the interior are reflected from the walls containing PCMs and can be the additional heating benefit. Opportunity of bigger sun energy accumulation comes from the possibility of adding the transparent insulation at the outer building surfaces. It is usually made by placing the glass panes over the space filled with air. Sun rays heat the hollow space and then the energy is transported to the wall with PCM through the transparent insulation like in Fig.2.5.

Other possibilities of incorporating PCMs for heat retaining purposes is placing the separate container (usually cylindrically shaped) filled with them and situated inside or out of the building. This method is especially used for higher heat demands in bigger buildings or in the industry. Other interesting way is placing the PCMs in PV panel vicinity. A finned container is placed between the back side of the panel and the roof or wall like in Fig.2.5 The space between them is filled with air for transporting the heat from the panel to the building at night. Second important function of this system is cooling down the panel. Its efficiency strongly depends on the working conditions and decreases with the temperature growth. Thanks to this idea we can produce more electrical energy and reduce the expenses on heating [1] [6].

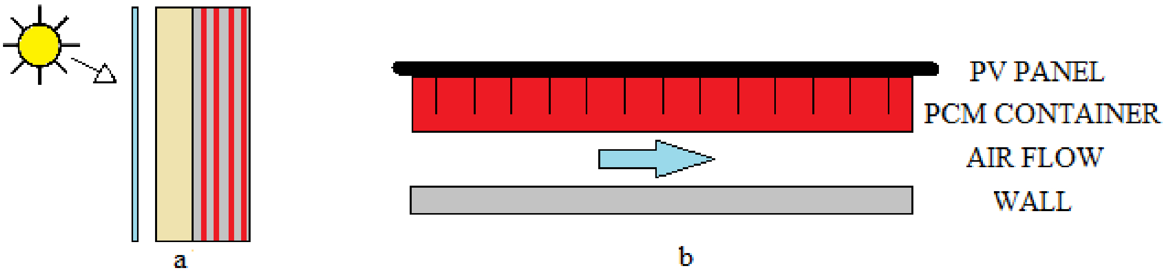

Fig.2.5 PCMs applications: a – Sun energy accumulation by the system consisting of (from left to right) glass pane, air, transparent insulation, wall with PCM, b – Cooling of PV panel associated with building heating

The application of free cooling presented in Fig.2.6 is based on the accumulation of the cold available at night at the outside of the building. The accumulated power is then released during daytime for cooling of the interiors. The problem connected with this method is the fact that in some regions the temperature especially in summer doesn't drop to the appropriate level and for the needed time. It results in the lack of solidification of the PCM and that issue can be avoided by increasing its thermal conductivity. Free cooling system with the same power as the ordinary air conditioning unit consumes 9% less energy. Although the investment costs are 10% bigger the payback time of such an innovation is about 3-4 years [8].

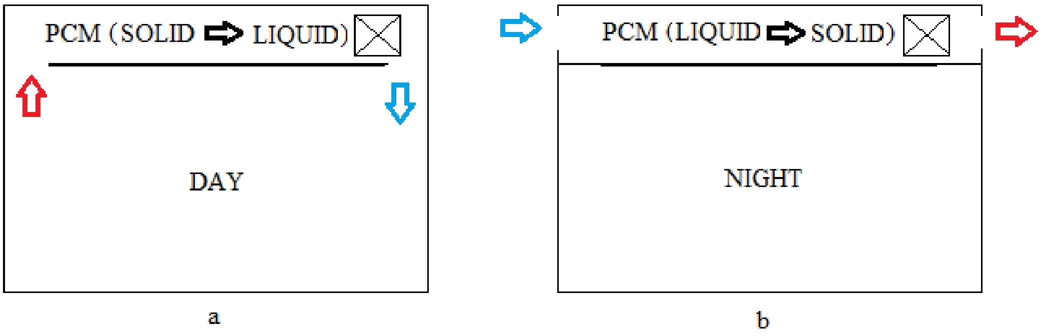

Fig 2.6. Working principle of free cooling: a – Presents heating of PCM due to the convection and radiation from the room (room air ducts open). Cooled air is transported back to the room by the fan.
b – During night outer ducts are opened which allows remove the heat from the building to the outside.

3. Conclusions

Application of PCMs in buildings can give both economic and environmental benefits. Usage of these materials can be reasonable especially in certain regions due to the thermal dependency. To find the best performance a numerous simulations must be made to find the optimal material and its placement. PCMs are very promising in the developing sector of passive and plus-energy-houses and by combining them with other technologies we can significantly reduce the energy demands for cooling and heating. Worth notice is the fact that the addition of PCM to concrete decreases its density which can have a significant impact on the building's weight. Also the mechanical properties of the composites aren't significantly changed which makes them very competitive in the building construction industry.

Acknowledgements

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Analysis of influence of landfill gas cofiring on selected maintenance parameters of hypothetical GTCC system

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Abstract

Landfill gas utilization may be obligatory, if stated by law, and may be profitable, if used to electric energy production. This paper includes description and results of analysis related to landfill gas cofiring in gas turbine. A simplified mathematical model, representing hypothetical GTCC power plant is presented. Basic analysis of selected model's parameters is described, and number of assumptions made are discussed. Results of analysis are indicated and explained in details.

Keywords: landfill gas, cofiring, gas turbine combined cycle

1. Introduction

Landfill gas (LFG) states a mixture of volatile compounds, formed as by-products of both organic and inorganic decomposition processes, appearing at the landfill. Chemical composition of landfill gas may vary widely [1,2], depending mainly on type of waste being disposed, fraction of inorganic matter in total volume of wastes, as well as time of decomposition - thus, several stages ("phases") of decomposition are distinguished [1]. Moreover, composition of gas vary also on depth of specimen's intake - layers located near rid of landfill will be characterized with larger fractions of nitrogen and oxygen, since diffusion of ambient air may occur there [1]. However, basing on various resources, one may state, that LFG consists mainly of methane, carbon dioxide, nitrogen, oxygen, hydrogen sulfide, ammonia and volatile organic compounds (including organic chlorine compounds). Due to high content of methane, as well as other potentially dangerous gases, law may introduce its obligatory utilization - in example by flaring [1,3].

Relatively high content of methane makes the landfill gas interesting fuel for distributed energy production facilities. Unfortunately, remarkable content of toxic volatile compounds (i.e. hydrogen sulfide, ammonia, siloxanes, chlorine compounds and other) leads to necessity of primary and/or secondary LFG purification before any utilization in such facilities. Despite this fact, utilization of landfill gas in local power or power-and-heat plants may lead to significant profits for local communities, landfill operators as well as national power system [2]. The main technology, utilized in order to derive power from LFG, state the internal combustion engines, however, in some cases, gas turbines are preferred (mainly due to their high power outputs and relatively convenient use in cogeneration systems) [2].

In this paper, the influence of landfill gas in mixture with natural gas supply on selected maintenance parameters of hypothetical gas turbine combined cycle (GTCC) power plant are investigated. Moreover, several cases of different fractions of landfill gas in fuel mixture are analyzed.

2. Model of gas turbine combined cycle (GTCC) power plant

Mathematical model, representing hypothetical GTCC power plant, which was used for further analysis, was designed in EBSILON Professional 12.0 environment. The model consists of number of elements, representing simplified system of gas turbine combined cycle power plant, including: natural gas pipeline, landfill gas pipeline, fuel mixer, ambient air pipeline, elements of gas turbine system: air compressor, combustion chamber, flue gas expander; electric generator (interconnected with gas turbine system by shaft), flue gas pipeline, simple heat recovery steam generator: superheater, evaporator and economizer, steam pipeline, steam turbine and feedwater supply. The model scheme is shown in Fig. 2.1 In order to perform valid analyses, several assumptions were made.

Chemical composition of both natural and landfill gases was assumed as shown in Table 1. Composition of landfill gas, which was assumed, is affordable in fourth stage of waste decomposition (between 10 and 20 years after waste disposal start-up) [1]. Assumed composition of natural gas is typical for highly calorific natural gas, distributed by operator [4]. Both fuels were assumed as dry gases. Air excess ratio in combustion chamber was assumed to be equal to 1.5, provided the presence of additional cooling air stream, injected to the chamber, of constant mass flow. Furthermore, efficiency of gas turbine system elements were stated. Both compressed air and flue gas pressures were set constant. Performance of heat recovery steam generator was set either by definition of terminal temperature differences (of selected heat exchangers) or by feedwater pressure values. Steam turbine operation was set by defining constant value of steam outlet pressure. Summary of assumptions made during model design is indicated in Table 2.

Tab 1. Composition of fuels assumed for analysis [1,4]

Compound name	**Content in fuel , %vol.**
Natural Gas	
Methane	97.800
Ethane	0.340
Propane	0.330
n-Buthane	0.330
Nitrogen	1.000
Carbon dioxide	0.200
Landfill Gas	
Methane	60.000
Nitrogen	7.000
Carbon dioxide	30.000
Oxygen	2.958
Hydrogen sulfide	0.010
Ammonia	0.010
Ethyl mercaptane	0.012
Chlorine	0.010

Tab 2. Summary of assumptions and design constants

Parameter	**Symbol**	**Value**	**Unit**
Pressure in combustion chamber	p_c	350	kPa
Cooling air stream	m_{ca}	70	Kg/s
Compressor internal efficiency	η_{ic}	0.88	
Gas turbine internal efficiency	η_{itg}	0.88	
Superheater upper temperature difference	DTN_{sph}	520	K
Economizer upper temperature difference	DTN_{eco}	15	K
Fuel mass flow	m_f	5	Kg/s
Pressure at the steam turbine outlet	p_{sto}	20	kPa
Load of combustion chamber	Q_{cc}	0.97	

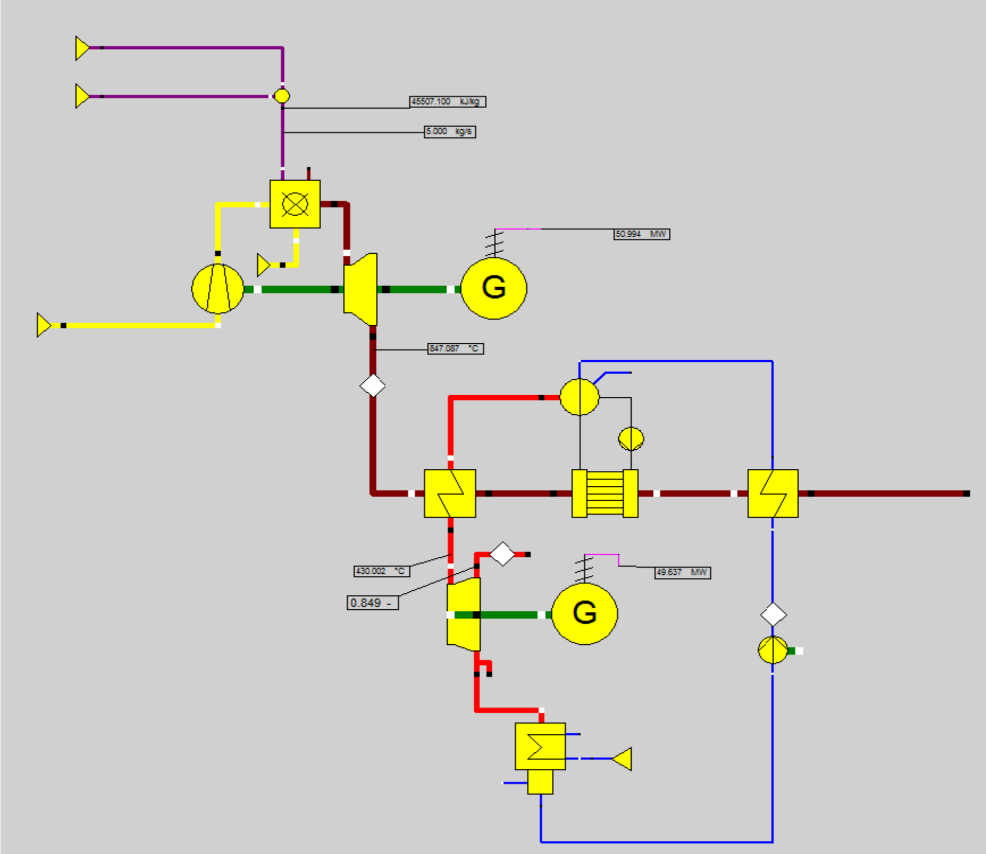

Fig. 2.1 Scheme of analyzed GTCC power plant layout

3. Analysis and its results

Gas turbine, the crucial element in system being analyzed, was supplied with fuel, being a mixture of natural and landfill gas in varying fractions. The objective of analysis performed was to examine, how an increase in landfill gas mass fraction in the fuel would affect values of selected maintenance parameters of designed system. Thus, analysis of the off-design system maintenance was performed, while the only variables in next cases of investigation were mass flows of both natural and landfill gas. There were five cases of system's fuel supply being investigated: first, the reference state was obtained, while system was supplied only with natural gas. Maintenance parameters obtained in this case were assumed as nominal ones. Next cases involved increase in mass fraction of landfill gas in fuel mixture by 2.5%, 5%, 10% and 20%, respectively.

Maintenance parameters, which were investigated, were stated as:

- exhaust gas temperature at the gas turbine outlet T_{GTO};
- electric power derived by gas turbine generator N_{elGT};
- exhaust fumes temperature at the heat recovery steam generator outlet (HRSG) T_{KO};
- electric power derived by steam turbine generator N_{elST};
- steam temperature at the outlet of superheater in HRSG T_{st};
- quality of steam at the steam turbine outlet X;
- efficiency of electricity generation in the system η_{elB}.

In order to calculate the last mentioned parameter, lower calorific values of natural and landfill gases were computed. Net calorific values were approximated using calorific values of gaseous components of fuels, obtaining 48675 kJ/kg for natural and 18687 kJ/kg for landfill gases (at ambient conditions, meaning p=101.325 kPa and T=15°C), respectively. Basing on fuels mass fractions, chemical power derived to the combustion chamber by both fuels ($\mathrm{Ech}_{\mathrm{NG}}$ for natural and $\mathrm{Ech}_{\mathrm{LFG}}$ for landfill gas, respectively) were calculated.

Results of analysis performed are shown in Table 3. Graphical interpretation of data obtained is indicated in Fig. 3.1 and Fig. 3.2.

Tab 3. Results of analysis according to selected parameters.

Parameter	**Nominal case**	**Case I [2.5% LFG]**	**Case II [5% LFG]**	**Case III [10% LFG]**	**Case IV [20%LFG]**
T_{GTO}, °C	851	851	850	849	847
N_{elGT}, MW	58.3	57.5	56.4	54.6	51.0
T_{KO}, °C	80.0	79.8	79.7	79.3	78.7
N_{elST}, MW	51.7	51.4	51.0	50.2	48.6
T_{st}, °C	431	431	432	433	434
X, -	0.850	0.850	0.850	0.851	0.852
Ech_{NG}, kW	243375	237534	231206	219038	194700
Ech_{LFG}, kW	0	2429	4672	9344	18687
η_{elB}, -	0.452	0.454	0.455	0.459	0.467

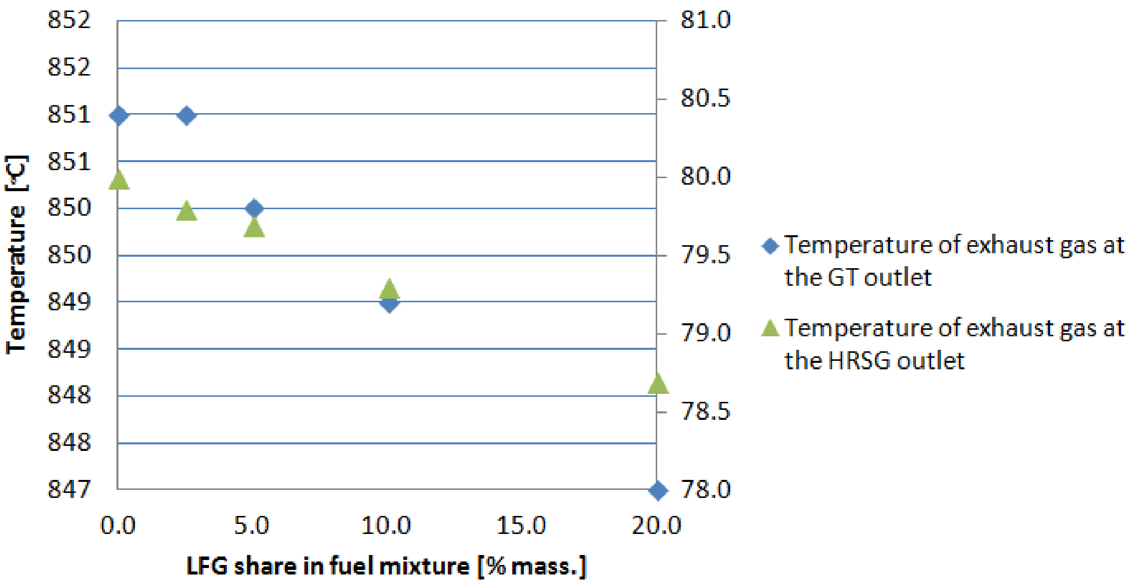

Fig. 3.1 Dependence of exhaust gas temperature on LFG share

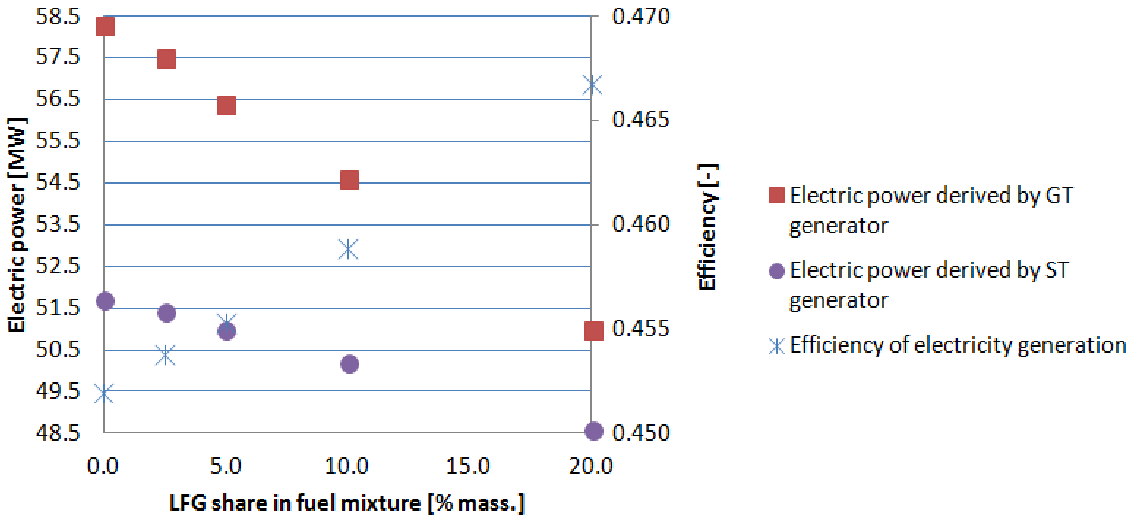

Fig. 3.2 Dependence of power produced and efficiency of electricity generation on LFG share

4. Conclusions

Results of analysis performed prove, that increase in landfill gas share in fuel derived to gas turbine, lead to almost linear decrease in electric power produced by gas turbine generator. Moreover, one may state simultaneous drop in power produced by steam turbine generator. That fact is caused by derivation of fuel with incomparably lower LCV; that results in lower total chemical power derived to the system. This coincides with decrease in exhaust fumes temperature at the expander outlet being observed.

However, it should be stated, that both parameters, devoted to steam part of the system - steam temperature at the heat recovery steam generator outlet and steam quality at the turbine outlet are characterized by visible increase. That fact proves the better maintenance conditions for unsophisticated HRSG system, as one assumed in this paper. This is connected with lower exhaust gas temperature at the HRSG inlet, and increase in superheater share of total heat flux transferred in HRSG. This allows to decrease the risk of moist steam appearance at the steam turbine outlet, keeping other parameters constant.

Moreover, visible rise in electric power generation need to be discussed. That fact is caused by lower air compressor load and better maintenance conditions of HRSG subsystem - as it might be seen in Fig. 3, drop in power produced by gas turbine is almost linear, while fall in power produced by steam turbine is perhaps of polynomial shape, and, what is crucial, definitely lower than in gas turbine case. Recalling the fact of supplying the system with rapidly decreasing calorific fuel, obtained efficiency trend seems to be explainable.

Concluding, cofiring of purified landfill gas in gas turbine combined cycle power plants may lead to vital advantages, which include lower compressor load (due to decrease in equivalence ratio needed to obtain acceptably low exhaust fumes temperature at the gas turbine inlet) and better maintenance conditions for simple heat recovery steam generator systems. This may be particularly important for old-type, low-efficient CCGT systems, as well as cheaper, low-power layouts, designed for distributed use. However, it should be clearly stated, that landfill gas cofiring has significant disadvantages: crucial drop in total electric power produced by given unit and decrease in exhaust fumes temperature at the HRSG outlet - what leads to rise in risk of corrosion and quick steam generator's depreciation, especially considering corrosive properties of landfill gas. Thus, high purification of collected landfill gas is necessary.

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The PV cell temperature effect on the energy production and module efficiency

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Abstract

The photovoltaic cooling conditions directly influence cell temperature which plays a significant role in PV efficiency as well as on electrical energy production. This value is affected by a large number of environmental variables such as ambient temperature, solar direct and diffusive radiation, wind speed, etc. In all PV cell types cell temperature increase results in efficiency decrease and in consequence in lower electrical power that PV supply under standard test condition. This phenomenon plays an important role during the hot period. The paper presents mathematical models for PV power and cell temperature determination. The results of the analysis show how the thermal conditions influence energy production as well as the PV module efficiency. The presented analysis shows that under realistic weather condition for Poland instantaneous power during the summer time - when the energy production is the highest - can be as much as 21% lower in reference to the nominal PV conditions which may cause monthly energy production up to 10% lower.

Keywords: Photovoltaic temperature, efficiency, electrical power production

1. Introduction

Nowadays the electrical energy production has to take into account environmental aspect and this aspect may play a significant role in the economic success of the project. The rapid growth in renewable energy systems has reached in 2015 the faster growing with global investments than traditional energy systems [1]. The care for the environment is obvious not only because of the global warming effect – which reasons are still unknown – but because the Earth and air pollutions significantly influence the quality and the length of life for all living organisms.

One of the widely used renewable energy systems are the systems which use semiconducting module directly converting solar radiation into electrical energy - photovoltaic modules (PV). Despite the significant progress that has been made in the last decade, the increase in electrical efficiency of PV systems and reducing their production cost are still major research goals, both in basic and applied ones, especially when considering the relatively high overall investment in PV systems [2]. It is well known that inverter and photovoltaic cell performance strongly depends on the working temperature and in the critical situation of devices overheat the system will radically decrease power (inverter security) or even shut down. The typical efficiency of the photovoltaic cell defined under Standard Test Conditions (STC) varied depend on the cell type (Polycrystalline silicon, Monocrystalline silicon, and Thin film amorphous silicon) and depends on the cell operating temperature. The temperature has an influence on the generating power – with increasing the temperature the voltage decreases – as final effect electrical efficiency [3]. In the literature, many correlations on the module power determination can be found [6,8,10]; and all presented correlations require module temperature coefficients, the incident solar radiation and module operating temperature. The module efficiency at Standard Test Conditions (STC) is defined at 25 ^{0}C for solar radiation 1000W/m^2 and wind speed 1 m/s. Among the models for PV module temperature estimation the air temperature and the solar radiation only are taken into account. For a large number of models, the wind speed variation influence is not taken into consideration. But it is obvious that the wind has a large effect on PV temperature. There are two effects related to the wind depending on its speed; the positive effect is to reduce the temperature module which finally increases efficiency and the negative influence is in high wind speed situations lead to the destruction of the structural composition, especially in the solar farms.

There are several studies reported the testing of temperature and thermal effect on PV energy and efficiency. An interesting study was performed by Siddiqui *et al.* (2012) [4] where they developed a three-dimensional numerical model able to predict the thermal and electrical performance of the PV panel for varying environmental and operating conditions. The results show variation in efficiency from 8.47% to 10.5% with linearly increasing electrical energy. The analysis of wind incident angle on PV module was studied by Kaplani *et al.* (2014) [5] where was demonstrated an accurate determination of the wind velocity and wind stream incidence angle on front and back of the PV panel. The results show that the PV temperature slightly decrees by increasing wind incidence angle, particularly at high wind velocities. Ceylan *et al.* (2014) [6], analysed an influence of the different ambient temperature on PV temperature predicted according to the solar radiation and ambient air temperature. Pantic *et al.* (2016) [7], developed linear and nonlinear models to predict the effect of solar temperature on output power and efficiency. The results have been compared with five different models and show that the nonlinear model much better complies with variations in solar radiation intensity and temperature of the solar module. Garcı´a *et al.* (2004) [8], estimated the yearly performance and temperature of PV based in Nominal Operation Cell Temperature for different orientations and tilted angles for different PV modules while Mattei *et al.* (2005) [9], tested temperature and electrical efficiency for polycrystalline PV module using NOCT method and energy balance method with different heat transfer correlations. The results showed that the most accurate model is based on the energy balance and uses the solar transmittance & solar absorption coefficient with a value of 0.81. Xing Ju *et al.* (2013) [10], presented improved method for estimating the temperature of solar cells operating under high concentration conditions when the solar cell temperature is in the range 10–120ºC. The results indicated that the model was accurate and that it can be used over a wide range of operating conditions.

The thermal behaviour of a photovoltaic module for three different wind speeds (0.77 m/s, 2.14 m/s, and 5.76 m/s) was tested by Armstrong *et al.* (2010) [11]. In that research, it has been shown that there is a parasite difference in convective and radiative heat loss from the panel for the different wind speeds. The wind speed dependence was also studied by Schwingshackl *et al.* (2013) [12]. They tested several existing models to evaluate the PV module temperature as a function of solar irradiance, ambient temperature and wind speed and has been found that the inclusion of wind cooling effects plays a fundamental role for in PV module temperature estimation. Radziemska (2002) [13] investigated the influence of the temperature and the wavelength on electrical parameters of crystalline silicon solar PV used the stand and a thick copper plate protected the solar cell from overheating. The plate was working as a radiation, heat sink or as the cell temperature stabiliser. During the heating process up to 80°C a decrease in the output power (-0.65%/K), fill-factor (-0.2%/K) and of the conversion efficiency (- 0.08%/K) in the tested PV module has been observed.

The CFD simulation with finite element method was performed by Jicheng Zhou *et al.* (2015) [14], in order to compute temperature distribution in the photovoltaic module. The simulations show that the cell temperature decreases with the adjacent cell interval increase and the optimal value of adjacent cell interval has been evaluated. Similar work was done by Kaldellis *et al.* (2014) [15]. They analysed temperature and wind speed impact on the efficiency of PV installations and the results of analysis confirmed that the operating temperature of a module and wind speed plays an important role in the conversion process and the electrical efficiency and power output are significantly influenced.

In this research mathematical models for photovoltaic module electrical power and for cell temperature determination is presented in order to analyse the PV cell temperature effect on the electrical energy production and on the system efficiency. All analysis were performed under real weather conditions and verify using in-situ measurement on experimental PV system.

2. Photovoltaic power and temperature modelling

The heat transport phenomena inside and around the PV module is very complicated and without detailed analysis, the module temperature can’t be easy evaluated. In the literature, a large number of correlations have been proposed for the PV temperature determination literature. Typically, two type of equations is presented first base on the energy balance equation and second type base on the PV panel efficiency equation. The most accurate expressions are based on the thermal energy balance equation. In the case of the photovoltaic module, the absorbed solar energy is directly converted into electrical energy and into internal heat which is the main reason for module temperature increase. At the same time, the thermal energy is dissipated to the environment. In order to PV operate at the lowest possible temperature heat exchange with the surrounding air must be maximised and good cooling conditions have to be applied.

The energy balance equation [16] on a unit area of the photovoltaic module which is cooled by losses to the surroundings air can be written as the flows:

$$\tau\alpha G_T = \eta_c G_T + U_L \left(T_c - T_a\right) \tag{2.1}$$

where τ is the solar transmittance of any cover over the PV array [%], α is the solar absorptance of the PV array [%], G_T is the solar radiation incident the PV array [kW/m^2], η_c is the electrical efficiency of the PV array [%], and the U_L is the coefficient of heat transfer to the surroundings [kW/m^2·°C]. The PV cell temperature and the ambient temperature in Celsius are T_c and T_a respectively. The equation (1) states that a balance exists between the solar energy absorbed by the PV array and the electrical output and the heat transfer to the surroundings. Rewriting the eq. (1) the following formula for the cell temperature determination can be used:

$$T_c = T_a + G_T \left(\frac{\tau\alpha}{U_L}\right)\left(1 - \frac{\eta_c}{\tau\alpha}\right) \tag{2.2}$$

The main difficulty in eq. (2) is to evaluate the component ($\alpha\tau / U_L$). Instead of that component direct evaluation the following formula has been proposed in the literature [12] which uses the nominal operating cell temperature $T_{c,NOCT}$:

$$\frac{\tau\alpha}{U_L} = \frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}} \tag{2.3}$$

The nominal operating cell temperature (NOCT) is the surface temperature that the PV array would reach if it were exposed to $G_{T,NOCT}$ =0.8 kW/m^2 of solar radiation, under the ambient temperature of $T_{a,NOCT}$ =20°C, and a wind speed of 1 m/s. Assuming that the component $\tau\alpha / U_L$ is constant, the above equation can be substituted into eq. (2) to yield:

$$T_c = T_a + G_T \left(\frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}}\right)\left(1 - \frac{\eta_c}{\tau\alpha}\right) \tag{2.4}$$

For a large number of panels the component $\tau\alpha$ is almost constant and has the values of 0.9. Assuming that the PV array operates at its maximum power point (MPP) – which is typically the case – the cell efficiency is with some approximation equal to the maximum power point efficiency $\eta_c = \eta_{mp}$ - where η_{mp} is the efficiency of the PV array at its maximum power point [%]. It has to be notice that the cell (maximum power point) efficiency η_{mp} strongly depends on the cell temperature T_c. For the most cases, first order approximation can be used assuming that the efficiency varies linearly with temperature according to the following equation:

$$\eta_{mp} = \eta_{mp,STC}\left[1 + \alpha_p \left(T_c - T_{c,STC}\right)\right] \tag{2.5}$$

where α_p is the temperature coefficient of power [%/°C], $T_{c,STC}$ cell temperature under standard test conditions (STC 25°C).

Using the model equations eq. (4) and eq. (5) it is possible to determine the cell temperature under specific solar radiation G_T incident on the solar plane. In addition to eq. (5) and (6), there is a number of other equations for T_c evaluation found in the literature [16,17,18,19,20].

In order to calculate the PV electrical power P_{PV} (kW) depends on the solar radiation and module temperature the following formula [21] was used:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) \left[1 + \alpha_P \left(T_c - T_{c,STC} \right) \right] \tag{2.6}$$

where Y_{PV} is the rated capacity of the PV array [kW] , f_{PV} is the PV derating factor introduced in order to take into account external factors effecting on PV array (impurities, efficiency losses, shading) and $T_{c,STC}$ is the PV cell temperature under standard test conditions.

3. Experimental and numerical results

The weather data (solar radiation, air temperature) and PV system instantaneous power were acquired from the weather sensors (Pyranometers, Thermometer) located at AGH University of Science and Technology campus, building D4 where the photovoltaic solar system has been installed. The global solar radiation and the air temperature data were taken for the year 2015, from 1st January to 31st December with the sampling 5 minutes, at location 50.066354N, 19.918191E, Krakow, Poland. In Fig.1 (a) the local monthly average ambient temperature T_{air} base on the measurement and (b) the monthly average daily total solar radiation G presented.

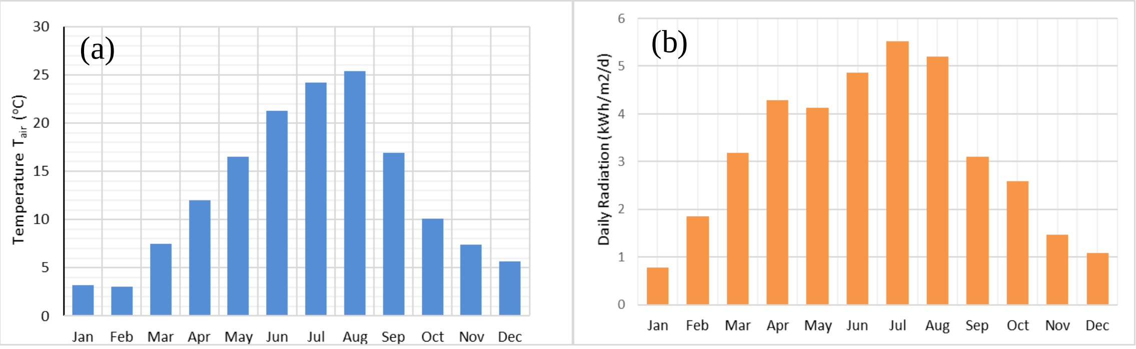

Fig.1.1 The ambient temperature T_{air} (a) and the monthly average daily total solar radiation (b).

For the analysis, the polycrystalline silicon PV system with electrical power P=1000W was used. The panel specifications with all required temperature coefficient are presented in table 1. The considered in this work the PV derating factor was 0.85 and the ground reflectance 0%.

Tab. 1 PV types specifications [16]

PV type	Average value of efficiency at STC , %	Temperature coefficient of power , %/°C
Polycrystalline silicon	13.0	-0.48
Monocrystalline silicon	13.5	-0.46
Thin film amorphous silicon	5.5	-0.20
Monocrystalline/amorphous silicon hybrid	16.4	-0.30
Thin film CIS	8.2	-0.60

For the analysis, two different models for the inclinations angle β and azimuth angle γ were used. The first model assumes the fixed PV panels orientation with angles $\gamma = 0^o, \beta = 25^o$, while in the second model PV panels follow the Sun beam direction i.e. system is equipped with the tracking system.

Fig. 2 shows the results of simulations base on the realistic weather data. The PV module temperature and electrical power for one arbitrary selected day (24th August 2015) are presented together with measured ambient temperature and solar radiation considered here as model inputs.

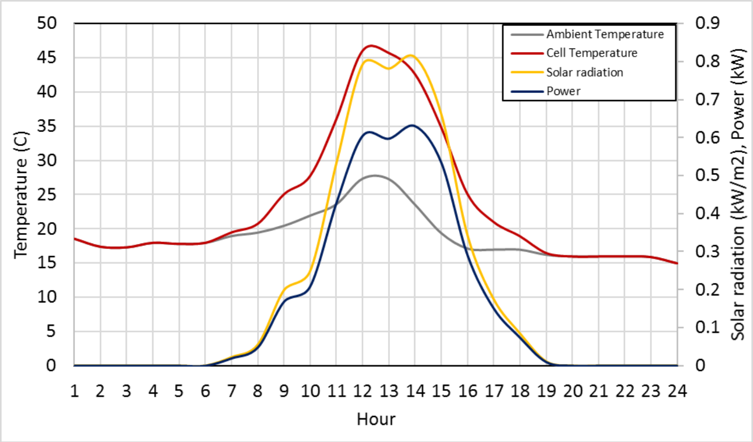

Fig. 2.1 The PV module temperature and electrical power distribution together with model inputs ambient temperature and solar radiation (24th August 2015) – for the non-tracking system.

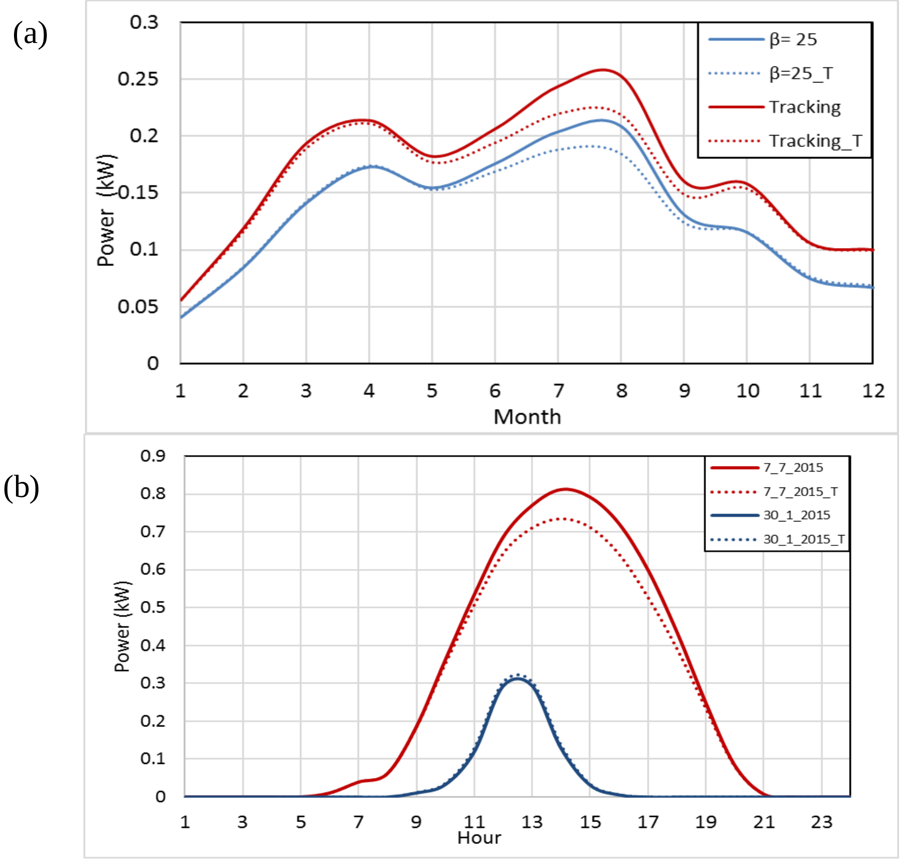

Fig. 3.1 The monthly average PV power generation for polycrystalline silicon with and without temperature effect(a); power generation with and without temperature effect for two selected days (b).

In Fig. 3 the temperature effect on yearly and daily electrical power using tracking and non-tracking system and two considered here thermal models (with temperature and without temperature consideration) are presented. It can be seen from Fig.3 (a) that the maximum power generation is for the tracking system while for the fixed angle module up to 23% lower value is observed. If the module temperature is taken into account for the electrical power calculations the significant effect on the power generation can be is observed mainly for hot months and in the middle of the day. Thermal effect cause significant power decrease during the hot period and power increasing for the cold period when the air temperature is much bellow 20°C. In Fig.3 (b) the temperature effect on the power generation is presented for two different days (7th of July 2015 and 30th of January 2015) and for the tracking

system. The results confirmed that during the summer the module temperature has a negative effect while during winter has a positive effect on the generated electrical power by using model.

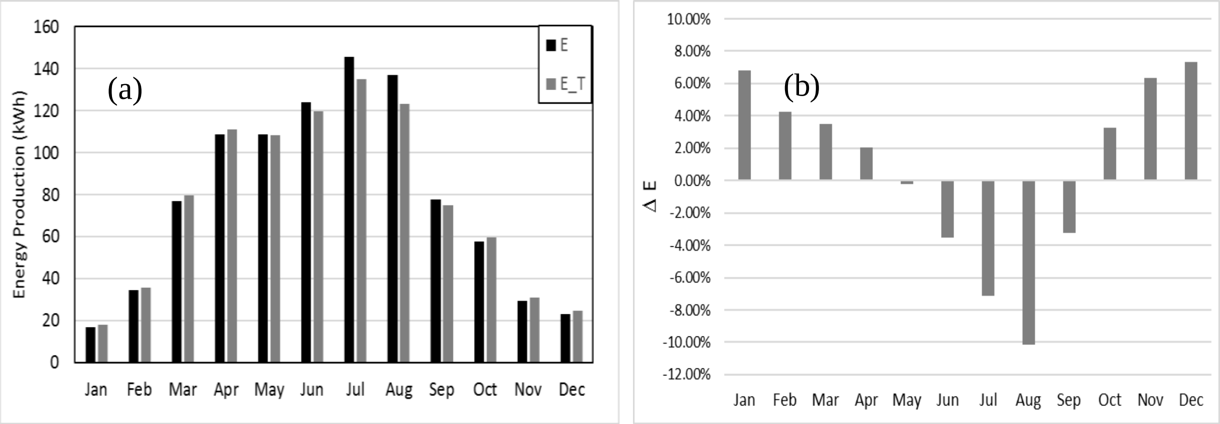

Fig. 4.1 The electrical energy monthly production temperature effect (a) and monthly electrical energy production losses and profits due to module temperature effect (b).

The temperature effect on electrical energy monthly production is shown in fig.4 (a). The symbol E in the legend denote monthly energy production without temperature consideration while symbol E_T is used when the temperature effect is taken into account. Base on the numerical simulation the monthly energy losses/profits due temperature effect are calculated and presented in Fig.4. As can be seen, the temperature effect plays a significant role for hot months as well us for cold months. It should be noticed that for considered location electrical energy production during cold months is very small and the positive effect in the total energy production is not able to compensate energy losses during the hot period.

4. Model Testing

In this section, the comparison between model temperature and in-situ temperature measurement is done. The in-situ temperature was recorded for solar panels located on building D4, AGH University of Science and Technology as shown in fig. 5. The panels located with the slope angle is 7.5^o from the horizontal and azimuth degree is 20° west of south. The cells material is polycrystalline silicon with the specification described in the previous section.

Fig. 5.1 PV array located on the roof of building D4, AGH University of Science and Technolog polycrystalline silicon type.

Fig. 6 shows the calculated temperature vs. experimental measurement for the two days during the winter and the summer period (2nd of January 2015 and 6th of September 2015). According to the mathematical model presented in section 2 the panel temperature is computing via considering the ambient temperature and the solar radiations. It can be seen that for presented days model prediction correlated quite well with experimental measurement.

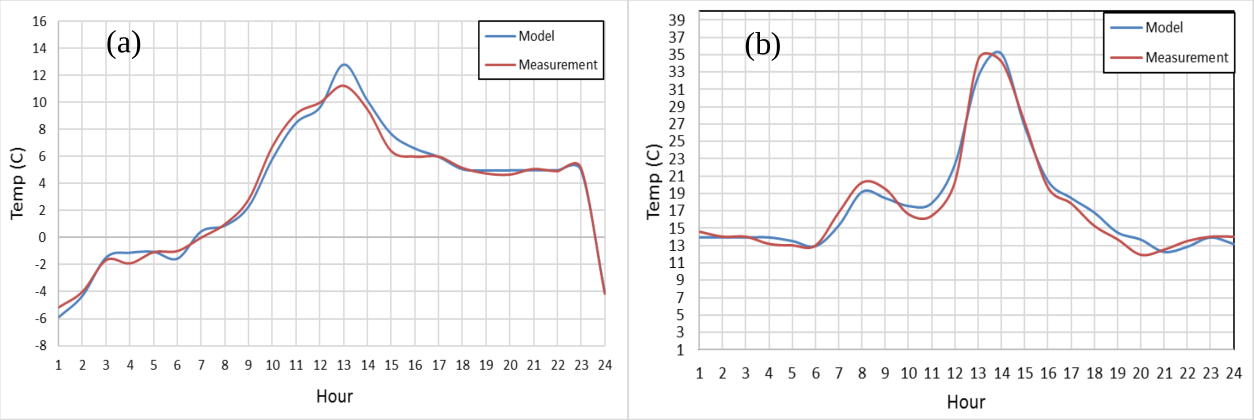

Fig.6.1 Comparison between PV panel temperature using model and experimental measurement for two different days: 2nd of January 2015 (a) and for 6th of September 2015 (b).

5. Conclusions

This work has demonstrated an approach for integration of the effects of the temperature in the PV power production and efficiency. Using the proposed model for PV panel power and temperature calculations it has been showing the effectiveness of the proposed model, which provides tools to better understand the performance and reliability of the system. Model validation shows that there are no big different in the PV panel between real module temperature measurement and model value. It has been observed that the maximum power production is achieved using tracking system which maximizes incident solar radiation. The temperature increase has in general negative effect on the energy production. During the hot period, significant decrease in energy production was observed in reference nominal operation while during other periods energy gain was also observed. For the PV system with polycrystalline silicon modules of the size P=1000W the total electrical production for the analysed year 2015 without temperature effect consideration, was 940 kWh while the electrical energy production with temperature effect consideration was 921 kWh. The module temperature effect (power decrease) was compensated with the power increase at the days when the temperature was much bellow 20°C. However due to very non-uniform energy production during the year (in a hot period almost 75% of energy is produced) the thermal negative effect can't be fully compensated with power gain.

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Visual Basic for Application - atypical tool for typical challenges

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Abstract

Available programs always had and will have some strengths and weaknesses. If they were coupled, client could omit weak points and fully utilize strong points of used programs. Microsoft Excel with Visual Basic for Application is the solution which let everyone to use more efficiently any more advanced software not even being familiar with it. Programs themselves are created to support human work saving both time and money. To maximize the benefits of programs usage one should not only buy proper software. More important is to tailor them to particular task. This paper describes how using VBA program within the Excel, work can be coupled with Engineering Equation Solver. Then which steps may automatize spreadsheet work getting rid of iterative errors. Some basic hints for future programmers and UserForm examples are given as guideline as well.

Keywords: VBA, EES, UserForm, program, condition

1. Introduction

Nowadays world is impossible to be imagined without any computer technology. Either daily calculations or sophisticated researches may be and indeed are based on efficient programs. They let human being speeds up the process of technological evolution. Available hardware, automatics, simulation models depends on at least one program if not whole packs of them. Only in power engineering the market offers plenty of tools devoted to solving the same tasks with different operation approach, syntax language or interface. Thanks to variety users may choose the most tailored one though usually decision is a choice between convenience and speed of work.

The problem becomes even more difficult including user skills which are often related to additional time and money spend on trainings. Sometimes problem may be much more complicated if various fields of science mix in one analyzed case. Companies can also face opposite situation of periodical, monotonous work of people like reporting or analyzing lots of data contained in many spreadsheets. What matters in iterative activities is time saving and elimination of repeating mistakes.

This paper is aimed to show how powerful can be and how many practical applications might be found in one of Microsoft Office Pack’s programs – Excel with built-in Visual Basic for Application tool. Further chapters will describe only a few examples of possible applications which have been personally checked while reader should be aware of possible potential of shown software.

2. Usability of Visual Basic for Application

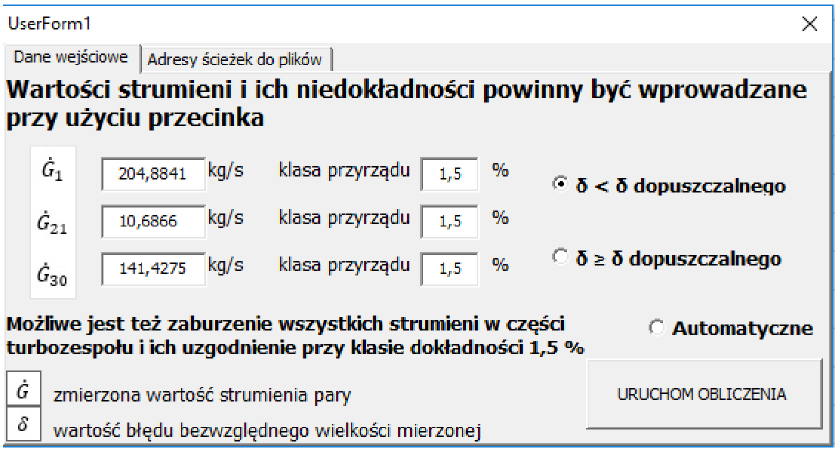
Microsoft Excel is widely available program which almost anybody is familiar with. Visual Basic for Application uses clipboard, CopyFromRecordset method or OLE queries and allows for coupling user-friendly Excel with wide range of external complex programs. Thanks to internal communication user does not have to be experienced in e.g. EES maintenance. Sophisticated program like EES will work as black box for which no theoretical background is needed. Thus instead of training the whole staff the company can hire one specialist who creates the program coupling particular software. Saved time and, in consequence, money will generate reasonable savings.

Apart from this, routine maintenance tasks in program may also be sped up with VBA. Once precisely planned then recorded or programmed procedure can substitute the process of repeating activities. In consequence this approach will minimize or totally eliminate random errors. Given effort and time consumed at the very beginning will repay itself in future and generate more reliable outcome.

2.1. VBA vs. EES

Engineering Equation Solver is a sophisticated engineering tool for complex calculations including those with enormous amount of equations. The program solves problems without rearranging the equations thanks to its iterative way of work. Whenever either loop or if condition appears program will lose its biggest strength. Besides, the power of EES is based on thermodynamic tables and extended built-in help. Unfortunately user needs to be fluent in specific syntax of EES which is not always the case. More information about EES may be found in supplier website[2]. In described example the goal was to create mass and energy balance model for water steam cycle which can be maintained by a person without technical background. User has possibility to insert a few measured values with known accuracy class of flow meters and see their validation. Because lack of engineering knowledge may be problematic the calculations have to be hidden. It is possible with coupling EES with VBA tool. From article point of view crucial is the information how to couple both programs. To do so parametric table needs to be created in EES. It is used then for importing not only input values but also text variable T$ with access path to Excel.

VBA in Excel allows for creating user-friendly graphical interface (GUI) in the form of UserForm elements. These boxes make data loading fast and independent on programming knowledge. VBA procedures can generate messages which together with descriptions guide anyone through the process of implementation. Exemplary UserForm gathers information about chosen mass fluxes $\dot{G}_i$, accuracy classes of flow meters and optional conditions of accepted way of calculation. User before running the program inserts those values in proper cells like is shown below.



Wartości strumieni i ich niedokładności powinny być wprowadzane przy użyciu przecinka

$\dot{G}_1$ 204,8841 kg/s klasa przyrządu 1,5 %
$\dot{G}_{21}$ 10,6866 kg/s klasa przyrządu 1,5 %
$\dot{G}_{30}$ 141,4275 kg/s klasa przyrządu 1,5 %

● **δ < δ dopuszczalnego**
○ **δ ≥ δ dopuszczalnego**

Możliwe jest też zaburzenie wszystkich strumieni w części turbozespołu i ich uzgodnienie przy klasie dokładności 1,5 %

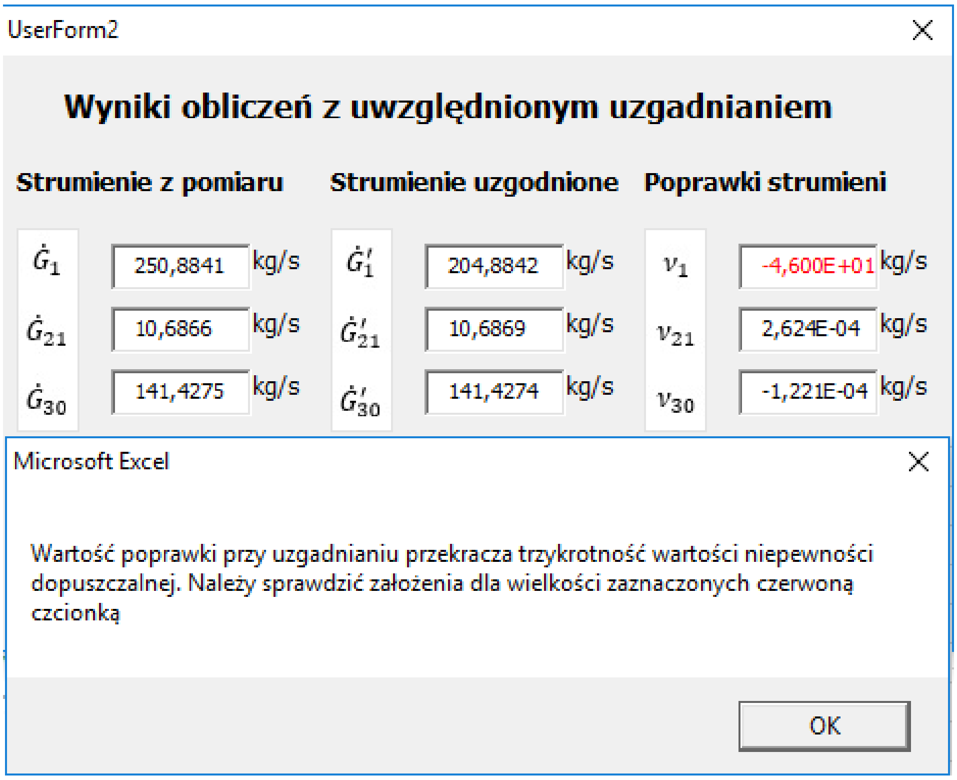
○ **Automatyczne**

$\dot{G}$ zmierzona wartość strumienia pary
δ wartość błędu bezwzględnego wielkości mierzonej

Fig. 2.1. Exemplary view of UserForm for input data[1]

Furthermore, start-up data will be sent to EES program which calculate and send back results with no need of interference. In this paper description of EES or VBA code is not included but can be found in Bachelor Thesis devoted to problem of EES coupled with VBA[1]. Important to know is the fact that once codes and access paths are written no longer specialists are needed to operate. EES is working as invisible background (black box) which imports data from spreadsheet and exports it later to file with extension '.txt'. It is available one more time to implement to Excel file.

Analysis of results may also be hidden in the internal code of VBA and generate responses to user like shown in the figure. Whenever correction exceeds allowed value of absolute error it is given in red colour. Moreover, explanation of the problem is given in message box to inform the user about problem. Because Excel gives a lot of charts, graphs and other forms of data presentation, the same results may be automatically shown in a given way, set in the same internal code. This eliminates risk of improper code changes and necessity of training for the whole staff.



Wyniki obliczeń z uwzględnionym uzgadnianiem

Strumienie z pomiaru		Strumienie uzgodnione		Poprawki strumieni	
$\dot{G}_1$	250,8841 kg/s	$\dot{G}'_1$	204,8842 kg/s	ν_1	-4,600E+01 kg/s
$\dot{G}_{21}$	10,6866 kg/s	$\dot{G}'_{21}$	10,6869 kg/s	ν_{21}	2,624E-04 kg/s
$\dot{G}_{30}$	141,4275 kg/s	$\dot{G}'_{30}$	141,4274 kg/s	ν_{30}	-1,221E-04 kg/s

Wartość poprawki przy uzgadnianiu przekracza trzykrotność wartości niepewności dopuszczalnej. Należy sprawdzić założenia dla wielkości zaznaczonych czerwoną czcionką

Fig. 2.2. Exemplary view of UserForm with communicate box[1]

2.2. VBA in reporting

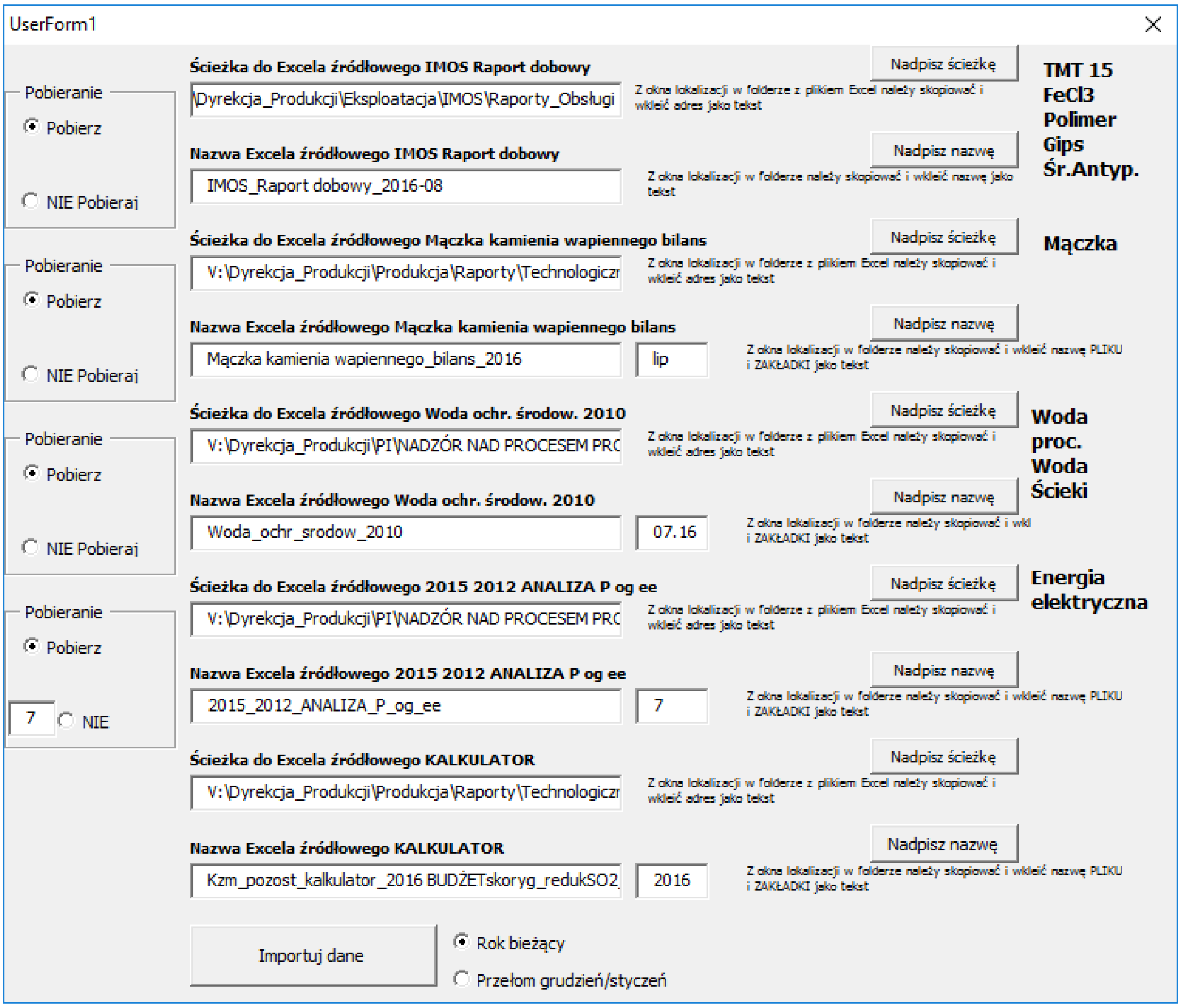
Whenever user is responsible for preparing reports or analysis which consists of data gathered in various independently prepared files repeating the same activities each time consumes a lot of time but also creates threat of random mistakes. In such a situation VBA also may face the problem with internal procedure for downloading and uploading data from given locations. User according to communicates needs to only specify own demands.

n researched example one of the worker was made to collect data for wet flue gas desulphurisation installation. Thanks to VBA it was possible to create automated Excel spreadsheet for analysis in which user has to specify only access paths and actual dates of source files. Because of the time differences in file updates one can mark which files should be used in particular case. Since it is possible to change each access path and overwrite it, spreadsheet can be used in any computer with various folder organization without interfering in the code.

Data may be collected and imported not only from other Excel spreadsheets but also common in companies programs like SAP used to manage business operations and relations[3].

Once more, the integral codes do not be described in details in this particular paper as each time this communications can relate to clipboard, CopyFromRecordset method or OLE queries. Approach to each of possible ways of writing the code can be found in many either dedicated to particular problem or supporting each program websites.

Each code can consist of as many constraints and limitation checks as it is needed. For example, in both above programs whenever cell in UserForm is left blank default content may appear. Fortunately for user in case of having not enough information program may suggest what kind of data is supposed to be given in specific cell. Values if out of range change their colours as well which at the end protects user against any mistake described in-advance. Moreover, with this approach program will show where is the error if it appears.



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Energia
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● Rok bieżący
○ Przełom grudzień/styczeń

Fig. 2.3. Exemplary view of UserForm for access path input

2.3. VBA programing's hints

Books and websites may be a fruitful sources of information for creating new codes whenever producer of codes has at least basic knowledge. Nevertheless, there are some tips which should be known at the very beginning. Some may be derived from above examples. First of them is related with decimal separator. In Excel spreadsheet and EES one can find coma as decimal separator while in VBA the same role plays the dot.

Moreover, in VBA dot separator is fixed and change of it is not possible. As coupled programs communicate to each other not unique separators generate risk of misunderstandings. The simplest way to assure proper work is to choose dot as one valid sign for all tools. In described example there were used extensions .Text and .Value in VBA code.

Whenever file is saved everyone has to be aware that using spaces or polish letters may results in one more misunderstanding in some programs with respect to English syntax. Because of this it is fully recommended to use only English signs and underscores instead of mentioned spaces.

In case of EES program which major advantage is iterative way of computing calculations all the conditions and loops should be given and checked in VBA before exporting data from spreadsheet. What is more, in both direction of transferring data order of values matters. Before using coupled programs the coupling procedure should be tested in terms of proper data transfer which is a major source of mistakes.

Even though, VBA is user-friendly tool which depends on specific cells and any manual change of data location or value influences the final result with not known size of this impact. One of solutions is storing important data in frozen spreadsheet or at least other than the main one. For sure hiding spreadsheet does not work in such situations as it makes values unreadable.

3. Summary

Variety of programs available in the market can be treated either as advantage or disadvantage for single users and companies. Each of the programs the more complex options offer the more expensive it is. Therefore not everybody can afford using such sophisticated tools or even if experienced worker is rather seldom. Excel with VBA offers solution which can minimize cost of skilled workers and amount of licenses. Once prepared, the code may be hidden from used so he can work with the data through UserForm any task without any programing or scientific knowledge.

Very often problem is not a complexity of the task but its repeatability which is simply waste of time. In this case one more time VBA occur helpful software since periodical activities with lots of constraints can be programed or recorded. This approach assure user that once properly done procedure will not generates human errors. Time consumed for writing a code will save much more future time with respect of e.g. lack of mistakes and no necessity to check all the conditions one by one each time.

The more constraints and checking conditions appear in internal program the better effect of final work user can get. In comparison to manual calculations or usage of programs like EES, Excel as common software is free of difficulties related to user’s maintenance. Thanks to that even person not being a specialist in technical branch can properly execute tasks being guided through ordered communicates. Nevertheless, one should be careful of manual influencing the code as both Excel and VBA are sensitive to switching cells’ directions on which they are based.

Acknowledgements

This paper has been developed as a part of InnoEnergy activity in Clean Fossil and Alternative Fuels Energy MSc program.

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Climate changes – the rise of tides

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Abstract

Since the beginning of the millennium, CO_2 emissions have increased more than ever. Despite all efforts to reduce this problem, the Greenhouse Effect has only been aggravated. Due to this situation, the world is being presented with consequences such as the rise of the average global temperature and the thaw of the poles and land ice. The main results are the rise of the sea level, which may swallow land areas, induce drastic and harmful climate changes and even health problems. This article has the objective of listing the main causes for emissions of pollutant gases, analysing the ice poles reduction as well as detailing the main measuring mechanisms, reviewing the regions of the whole globe which have been suffering the most impacts of the rise of tides and finally listing and analysing some purposed solutions.

Keywords: greenhouse gases, ice poles reduction, rise of the sea level, climate changes, environment

1. Introduction

> "Climate change does not respect border; it does not respect who you are - rich and poor, small and big. Therefore, this is what we call 'global challenges,' which require global solidarity."
> - Ban Ki-moon, 8th Secretary-General of the United Nations

Nowadays, public concern over Global Warming is acknowledged. Children are being taught how to recycle and how to reduce their CO_2 footprint, by saving power and reducing waste. Environmental discussions and political and economic decisions related to climate changes have been increasing in number and relevance through the years. Although this is an important indicator that the concern about environmental issues is rising, it is not, unfortunately, increasing at the same rate as the climate change causes and impacts.

It is important to analyse this problem, area by area and section by section, to understand which counter measures are ideal to guarantee a sustainable world.

The problem starts with the uncontrolled emissions of pollutant gases to the atmosphere. For that reason, all the sources must be identified and analysed, to understand which one of them may be reduced or even closed. It is also important to understand why, despite all the concern, emissions are increasing.

One of the first impacts of Global Warming to consider is the thaw of the ice poles. Their area has been decreasing rapidly and dramatically. We are reaching a catastrophic level! It is important to find different and innovative mechanisms to measure the real size of this problem.

This results in the rise of the sea level which, for instance, swallows coast lands and islands and changes sea currents, changing also region's climates around the world.

Global Warming already has human and economic victims around the globe, such as climate refugees and agriculture challenges

2. Greenhouse Gases

Greenhouse gases (GHG) are all the gases that absorb and emit radiation within the thermal infrared wavelengths (from 8 to 15 μm). They consist on elements that keep and even increase the average temperature of the atmosphere. It is important to mention that the GHG are not exclusively harmful. In fact, without them, the average temperature of the surface of the earth would be a lot lower (-18ºC). On the other hand, when in excessive concentration, GHG may increase the temperature more than the desired and, in extreme cases, more than what the survival of ecosystems allows.

Greenhouse Effect functions as following: the sun emits radiation to the earth; part of it is absorbed by the earth's surface, but some of it is reflected again to the atmosphere. If the earth didn't have an atmosphere, the reflected radiation would go to outer space, but because of it, part of the radiation is reflected to the earth again and the rest of it goes away. Greenhouse gases intensify this process, retaining a bigger portion of the radiation, just like a normal greenhouse.

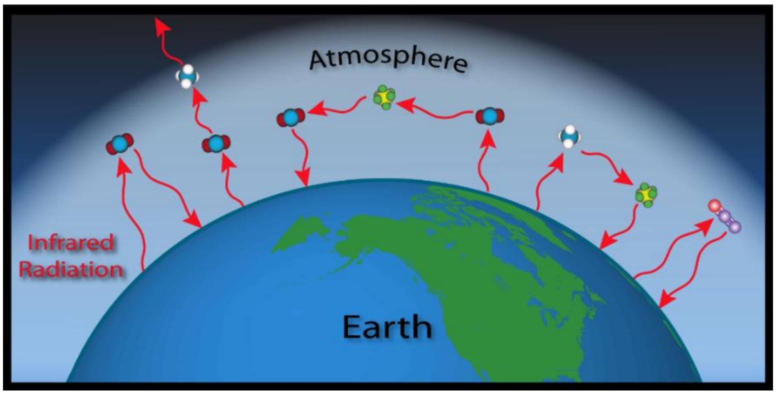


Fig. 2.1 Greenhouse Effect, *Basics of the Carbon Cycle and the Greenhouse Effect, ESRL Global Monitoring Division*

Pollutant gases have harmful effects which may not only impact air quality, but also contribute to the increase of the Greenhouse Effect.

We can attribute Greenhouse gases to two main sources: Natural and Human-related. Natural GHG sources may be volcanoes, decomposition of organic matter, respiration of animals and the release from oceans. Although nature itself sends GHG to the atmosphere, it also absorbs them in oceans and forests, maintaining a balance. This refuses the thesis that human's percentage of emissions are almost inexistent in comparison to nature's. The image below shows how carbon is sent to the atmosphere and absorbed by human activity and nature.

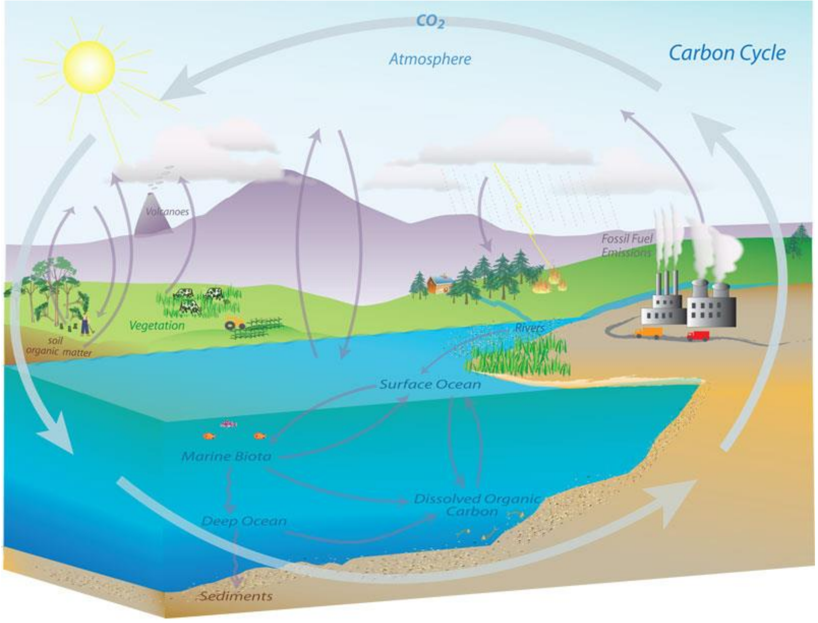


Fig. 2.2 The flux of carbon, *Basics of the Carbon Cycle and the Greenhouse Effect, ESRL Global Monitoring Division*

While the water absorbs CO_2, the oceans become closer to saturation from it. This slows the process of trapping carbon dioxide in the water, reducing its capacity, aggravating the global warming problem. It also turns the waters more acid, harming life beneath the oceans.

Within the human related activities – the ones that we can take actions on – the origin of GHG can be traced. In the figure 2.3 it is possible to compare each one of them and conclude which activity is polluting more.

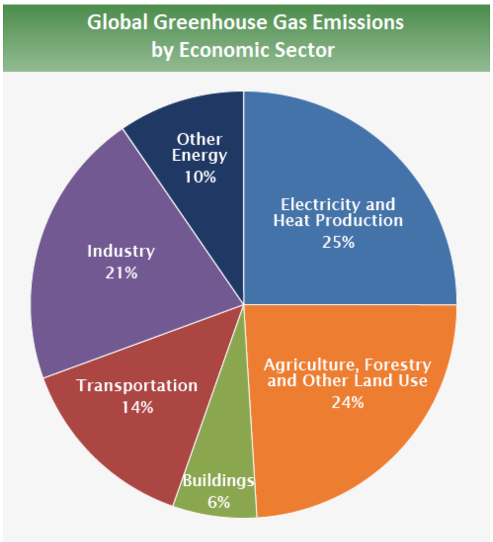


Fig. 2.3 GHG emissions per economic sector in 2010, *Global Greenhouse Gas Emissions Data, US EPA*

On the next subchapters, we will analyse the impact of the main pollutant economic activities on the global warming.

2.1. Electricity and Heat Production

The production of electricity and heat is mainly dependent on coal, gas and oil combustion. Efficiencies of modern power plants are around 40%. That means that 60% of the power released from the fuels is wasted. Their combustion releases mostly carbon dioxide, CO_2, but also sulphur, SO_2, and methane, CH_4, to the atmosphere. Coal is the most pollutant of these three and, for that reason, countries concerned about their CO_2 footprint have been moving their electricity production to an oil base and mostly natural gas base. On the other hand, because of the population and economic growth, the need for fuels have been increasing.

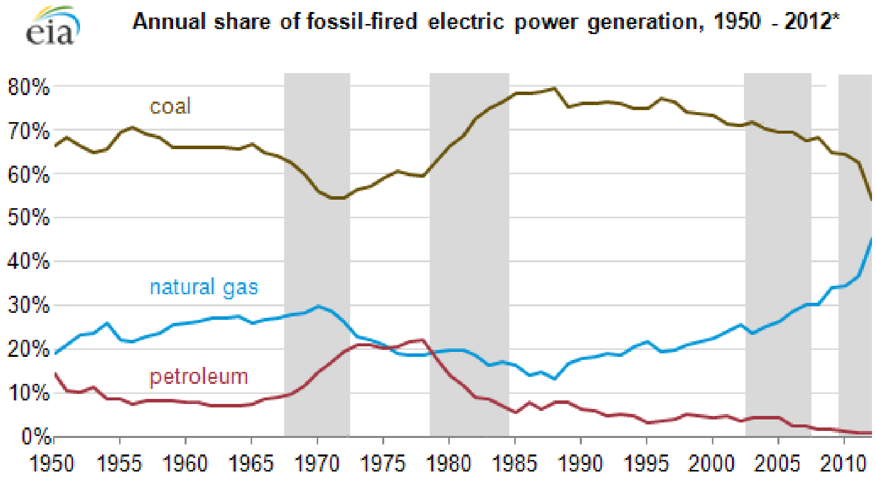


Fig. 2.4 Share of fossil fuel electric generation, *Competition among fuels for power generation driven by changes in fuel prices, US EIA*

2.2. Agriculture, Forestry and other Land Use

The primary economic sector has one main activity which causes a tremendous amount of pollutant gases emissions: cattle breeding. Beef is one of the most important causes to the tropical deforestation (for land use), which destroys an important way of absorbing CO_2. The other problem of breeding ruminant animals is that they produce methane, while eating. This gas is twenty times more harmful than CO_2. Beef production causes 37% of all human related methane emissions and 67% of human related nitrous oxide emissions. The chart below contains the amount of carbon dioxide emissions per kilograms of meat produced per animal:

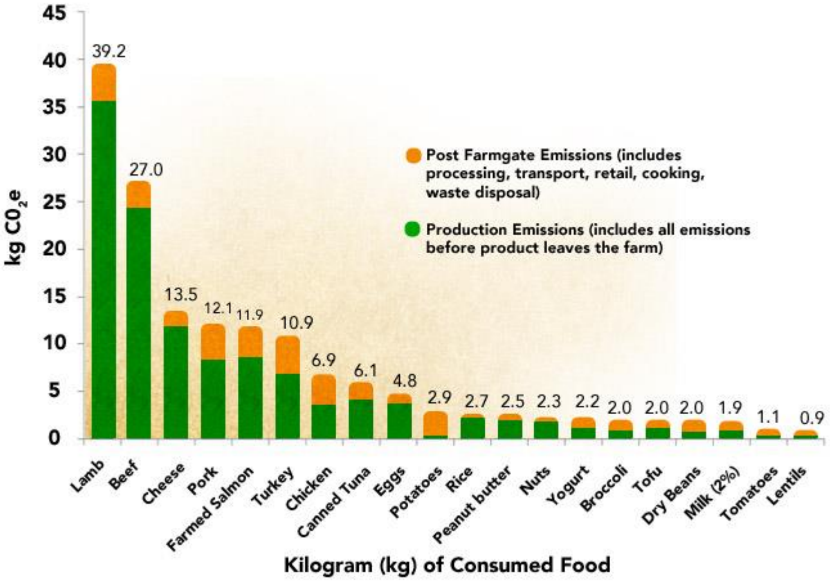


Fig. 2.5 Carbon dioxide emissions per kg of meat of an animal produced,
Climate and Environmental Impacts, EWG

Another source of GHG in the primary economic sector is agriculture. Agriculture is one of the main responsible of nitrous oxide emissions. This happens because of agriculture's dependency on nitrogen based fertilizers for its products. These compounds stimulate microbes which eventually produce nitrous oxide (N_2O) faster than usual. This gas is the third more potent for the greenhouse effect, comparing to methane and carbon dioxide, besides destroying the stratospheric ozone that filters UV rays from the sun. And above all that, since the 1750's the nitrous oxide levels rose from 270 parts per billions to 320 parts per billion. N_2O has a lifespan, on average, of 120 years. With the increase of the global population it is possible to assume that this number is likely to go up instead of decreasing, because fertilizers are essential in agriculture.

Tab. 1 GHG emissions in some primary economic sector activities in the USA, *EPA U.S. Inventory of Greenhouse Gas Emissions and Sinks (1990 – 2005), Trends in greenhouse gas emissions, Table 2-14*

Source	**Total emissions, %**	**Agrucultural emissions, %**
Agricultural soil management	5.0	61
Enteric fermentation	1.5	18
Manure management	0.7	9
CO_2 from fossil fuel consumption	0.6	7
Other	0.3	4
Total	8.2	100

On the other hand, agriculture has the advantage of sequestering CO_2 during the photosynthesis process – resulting in a sink for carbon – which brings some balance to the GHG flux, despite not being ideal.

Deforestation also holds a big responsibility in GHG emissions. This problem has two different and important fronts. First, it reduces the capacity of forests absorbing carbon dioxide in the atmosphere. Second, while destroying forests, large amounts of GHG gases are released from trees, like carbon dioxide, methane and nitrous oxide. Places like the amazons where deforestation are a mean to have space for cattle breeding represent a real destruction of the Earth's Lungs in order to assure a GHG emitter activity. There are other critical agriculture activities which cause deforestation such as palm oil production. Being an important ingredient in our diets, its production needs space which is taken by burning large forests, mainly in south Asia.

2.3. Industries, Household and Transportation

Industries need energy for manufacturing their products, which comes usually from fossil fuels. This includes powering its tools, heating materials for certain production processes and other industrial activities. Cement producing is one of the most impactful industry in terms of GHG emissions. Emerging countries have a key role in the industrial impact on global warming, mainly because the increase of the demand caused an increase on production. USA and China are the main emitters in this type of source. Some countries, because of legislation towards GHG, have been improving their manufacturing processes efficiency to achieve strict emission goals. In this point, Japan and Korea hold a high level of success. It is important to mention that implementing effectively efficient processes usually comes along with additional costs that aren't available to every country.

While one single house might not have a dangerous impact in global warming, the sum of all houses in the world certainly will. In homes, emissions of GHG exist because of combustion reactions to cook, to heat water and to warm the inside. Around three billion people all over the world use some form of coal or solid biomass to cook or to heat water. Nearly 85% of the black coal for these purposes is burned in developing countries. Also, the garbage produced is important to consider. While decomposing in a landfill, it creates greenhouse gases including methane.

Transportation is one of the main pollution causes in cities. The process of burning fuel releases GHG to the atmosphere, which, when considered that they come from millions of vehicles, are very impactful on the global warming problem. In Europe, it represents the source of almost 25% of all its greenhouse gases emissions.

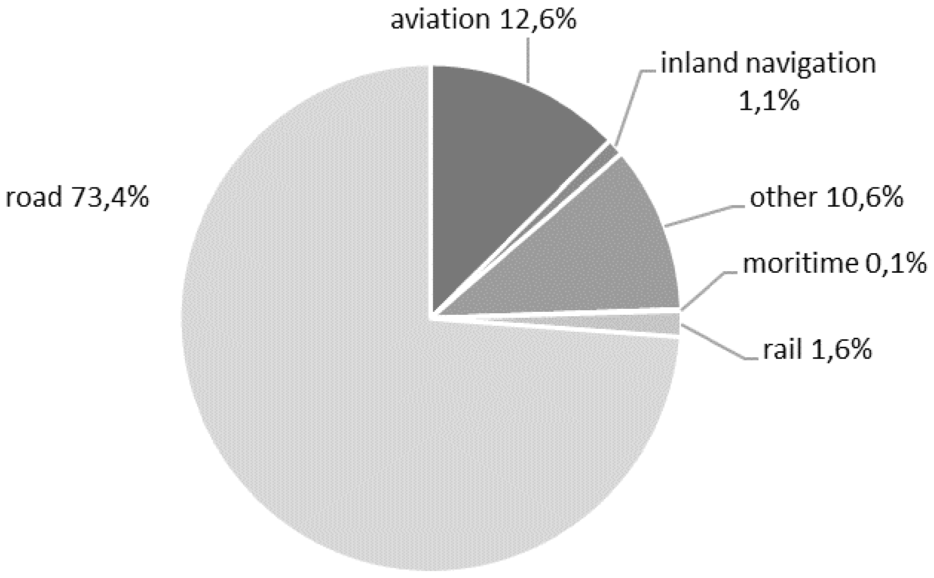
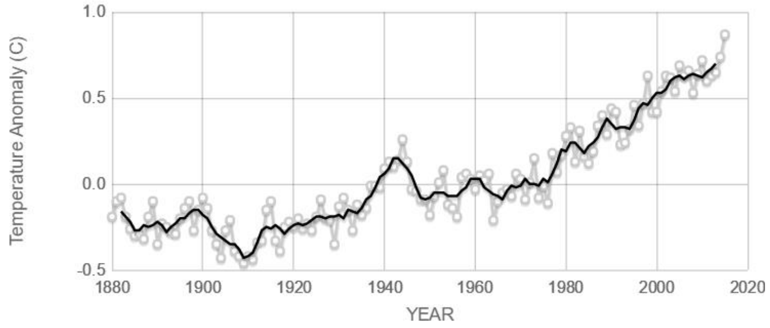


Fig. 2.6 Percentage of GHG emissions in the transportation sector per vehicle in 2014,
Reducing emissions from transport, Climate Action, European Commission

As presented in the pie chart above, road vehicles are the main contributors to GHG emissions. It is important to find alternatives which would reduce its impact.

3. Global Warming and the Rise of the Sea Level

In 1824, Joseph Fourier found that the atmosphere could trap heat from the sun. He stated that the Earth’s surface is warmer than it would be in vacuum, because of its atmosphere. In 1896, a Swedish scientist called Svante Arrhenius was the first to calculate the variation of temperature if the concentration of carbon dioxide in the atmosphere would increase. He realised that by doubling that concentration, the world’s average temperature would increase between 5 and 6ºC. Curiously, he thought that this would take thousands of years to happen and that it would benefit humanity. Detailed information about temperature have been recorded since 1850. From all these years to now, nine of the ten warmest years occurred in this millennium and 2015 was the warmest of them all. It is quite perceptible an abnormal increase of the world’s average temperature from the 70’s to now, comparing to the previous years. The graph below shows the average world’s temperature anomaly through time.



Source: climate.nasa.gov

Fig. 3.1 World’s average temperature anomaly through time, *Global Temperature, Climate NASA*

Today the temperature anomaly circulates around 0,85ºC. It is already possible to see some harmful consequences, such as climate changes and sea level rise. Reaching 2ºC, the world’s coral reefs would disappear, taking with them ecosystems important for tourism and fishing. At 3-4ºC heat waves would impact certain regions of the world making them impossible to live in. Also, it would be impossible to implement agriculture activities around the equator, which would leave a big part of humanity without food supply. If we compare the current temperature variations with a model for temperature behaviour since 1765, we realise that this kind of increase has no precedents:

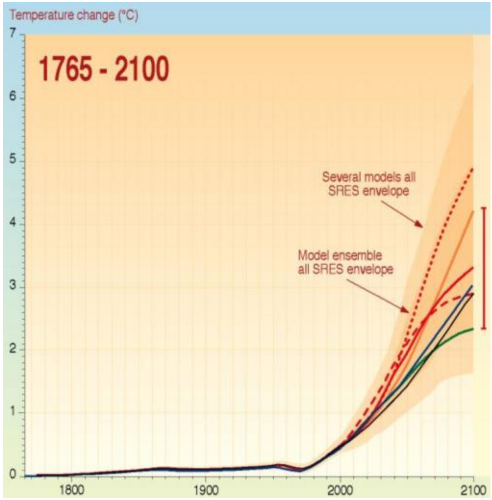


Fig. 3.2 Model For The Variation Of Temperature Since 1765, *Climate Change 2001: The Scientific Basis*

3.1. The Ice Poles

The biggest temperature anomalies happen in the North Pole and Greenland is the region where the impact is most visible, especially on its western coast. Every year, over 140 billion of ice are lost in the northern glaciers. According to NASA, until 1995 the Arctic's sea ice area circulated around 7 million square meters. Today it is possible to reach values below 4 million square meters. The sea ice minimum occurs, normally in September. Every year, around 13,3% of the sea ice melts.

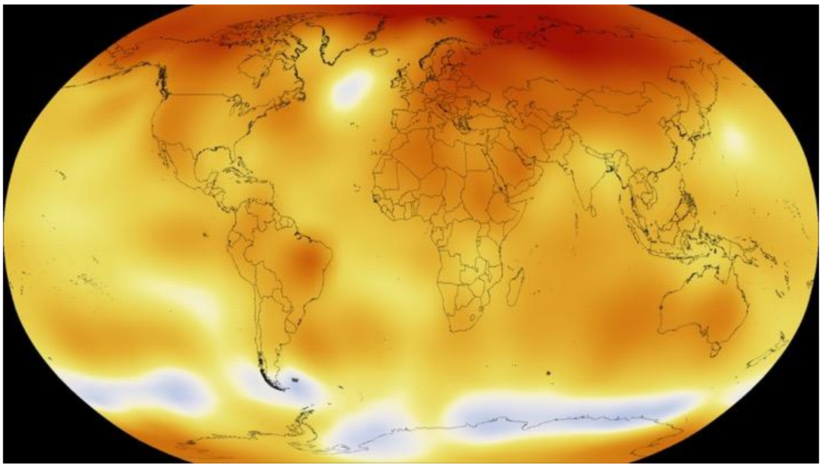


Fig. 3.3 Temperature anomalies around the world (red areas have a temperature higher than average), *Global Temperature, Climate NASA*

We can perceive sea ice as a not so thick layer (about 1 meter) of frozen water on the sea. Because liquid water is denser than ice, these layers cover the sea. Its formation and melting is very dynamic and it depends mostly on the season and winds. It covers around 7% of the Earth's surface. The difference between sea ice and glaciers, icebergs or ice sheets is that it is formed on sea with salty water, while the others are formed on land with fresh water or snow. Sea ice melting and frosting affects water movements in the ocean and the weather around the world as well. The glaciers and ice sheets in Greenland and Antarctica form the land ice. Sea ice does not influence the sea level, unlike land ice.

The poles have the characteristic of reflecting a high proportion from the sun's radiation, because of their colour. With the rise of the temperature, the ice melts and bare dark rock beneath is revealed. This only makes the process of melting quicker because darker colours absorb more radiation than brighter ones, thus it warms the region in a higher rate than expected. Besides land, also dark ice is revealed. Dark ice results from wild fires, volcanoes and pollutions products that sit on the ice and methane which is trapped in it as well. Because of that, melting rates of land ice in the arctic pole are higher than ever.

Fig. 3.4 Dark ice in southern Greenland, *Ice sheet melt factor, Dr. Jason Box, Meltfactor*

Glaciers can lose big portions which fall near the sea in its edge and cause noises similar to thunders. These chunks of ice can reach up to 60 meters of high and form icebergs. This process is called ice calving and has a direct impact to the rise of the sea level. It is also important to mention that the fall of this ice chunks makes the water more turbulent which promotes more heat exchanges between the rest of the glacier and the sea, accelerating the melting process of the ice poles. Another process that accelerates the melting of the poles is the hydrofracture. When the ice melts in the glacier, it forms water on it. Because water is denser than ice, it breaks it and goes under it to the sea. The water under the ice lubes it and causes it to drift away from the glacier, removing big blocks.

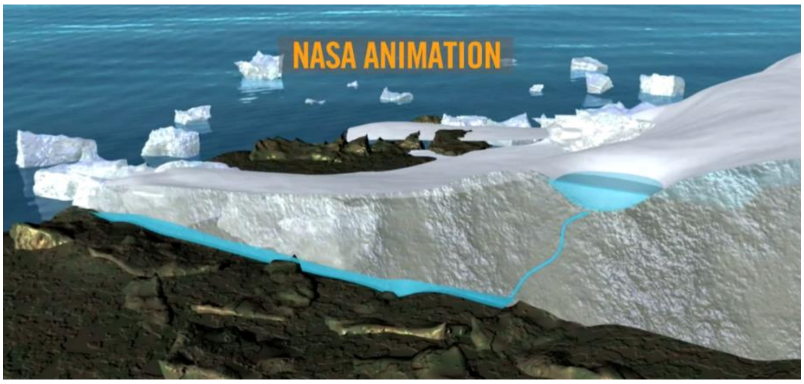


Fig. 3.5 Hydrofracture process, *Vice, HBO TV series, "Greenland Is Melting & Bonded Labor"*

If all Greenland melts, the sea level would increase 7 meters. This means that 80 of the world’s 100 biggest cities would drown.

According to Dr Jason Box, a researcher specialized on the melting of the Greenland ice sheet, it is possible to estimate a surface mass balance, knowing the precipitation and the amount of ice that melts or falls apart. Until 1990, the trends of this balance were not significant. On the other hand, between 1990 and 2008, the changes are quite visible. A 3% uniform increase of the melting and breaking apart of the ice sheet in relation to the values before this period. This is explained by the 7.59 kilograms per square meter per year of melting (with an error of +/- 1.75 $kg.m^{-2}y^{-1}$) and the 5.84 $kg.m^{-2}y^{-1}$ of ice runoff (with an error of +/- 1.17 $kg.m^{-2}y^{-1}$). Although the total precipitation increased by 2.3%, the surface mass balance was -7.01 $kg.m^{-2}y^{-1}$ (with an error of +/- 2.34 $kg.m^{-2}y^{-1}$).

Also, Antarctica is a very important region to analyse problems concerning the global warming. In fact, Antarctica is de biggest deposit of ice in the world. It holds around 90% of the Earth’s ice and 70% of its fresh water. If all Antarctica melts in the same rate as Greenland, sea level would rise much faster than expected.

Temperatures in the Antarctic Peninsula have risen 3ºC over the past 50 years. There and in the Western Antarctica is where the situation is the worst. In fact, in other regions of Antarctica the losses are not much significant.

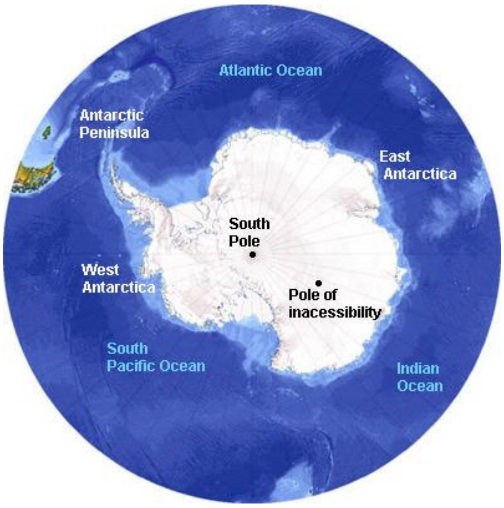


Fig. 3.6 Antarctica, *Antarctica Travel Guide - Page 1 – Basics, Cool Antarctica*

Over the last 40 years it is possible to observe a regime of westerlies stronger than the 1000 years before in West Antarctica. Westerlies are winds coming from the west to the east and tend to the poles. These winds, faster and stronger in West Antarctica, push subsurface warm water towards the glaciers. The water penetrates under them causing the glacier retreat in a high depth. The lines that define this retreat are called grounding lines and can move kilometres from their original position. Sometimes, it reaches a point when a fracture is created from the grounding lines to the surface of the glacier, causing it to drift away. The fastest grounding lines retreat rates are about 1 kilometre per year.

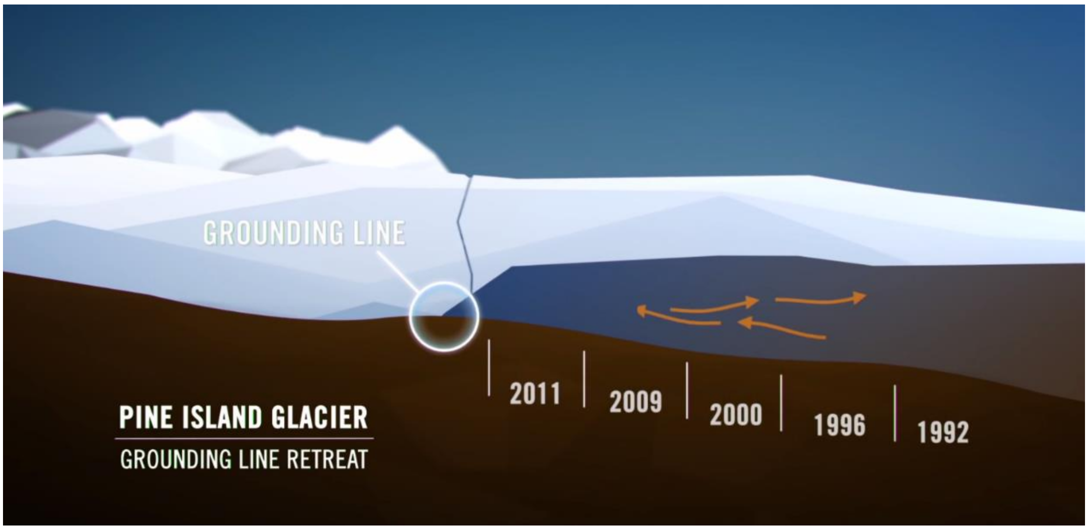


Fig. 3.7 Evolution of the grounding line under the Pine Island Glacier,
Vice, HBO TV series, "Our Rising Oceans"

According to NASA, Greenland’s ice sheet is losing 287 gigatons per year and Antarctica is losing 134 gigatons per year also.

3.2. Ice Measuring Mechanisms

There are several mechanisms which help us understand the volume and morphology changes of land ice and sea ice. The most important parameters to measure are height level changes, area changes and morphology.

One very simple way to measure the changes of height level in ice shelfs is the pole penetration. It consists on drilling a hole in the ice and placing a pole with a determined height in it. These poles are normally around 10 meters. Every year, the pole is measured to see how much of its height the melting revealed. In some regions, ice can melt 9 meters. The image below represents a real measure made in 2013 after one year of placing the pole in Greenland.

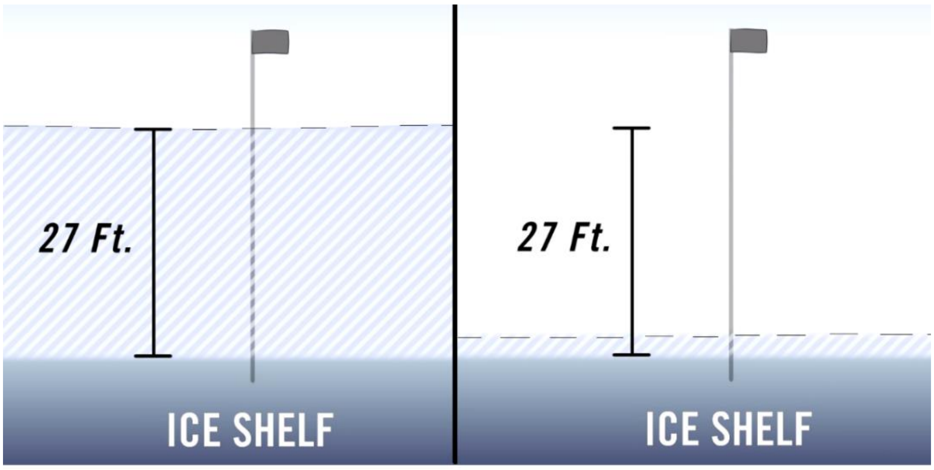


Fig. 3.8 Pole measure after one year of placing it, *Vice, HBO TV series,*
"Greenland Is Melting & Bonded Labor"

The Airborne Topographic Mapper (ATM), a laser altimeter, is a more technologically advanced measuring system. It requires a plane which must fly between 400 and 800 meters above the level of the ground. The ATM, as its name suggests, maps the topography of the ice shelfs and glaciers to better understand their evolution in the future. The technology consists in measuring the time for the reflection of a laser emitted to the ground to reach back. The ATM combines this data with information about the aircraft's position and altitude and inertial navigation systems. It is owned by NASA and it can measure height level changes from previous measures to a 5-centimetre precision. The ATM is also used to analyse sea ice, sea surface elevation and ocean waves characteristics.

Radioglaciology or ice-penetrating radar measures the thickness and morphology of a glacier or ice sheet. NASA uses the MCoRDS system which places the radar antenna under an aircraft's wing. It emits radar waves that hit the ice, penetrate it to the ground and come back up. Then, after months of filtering the data obtained, the measurements can be analysed. This technology helps scientists to understand what happens beneath the ice sheets, project models for future changes to the glaciers and analyse the water flow in the ice sheet's base.

The problem of the grounding lines retreat in Antarctica requests a measuring mechanism from under the ice, through the water. For that, the robot ocean gliders exist. Their function is to measure temperature, salinity, currents, turbulence and other data under water. In Antarctica's western coast, gliders often find strong Eddie currents. The increase the turbulence near the base of the glaciers promotes heat exchanges. Also, in those places temperature differences are found.

The land ice melting process is irreversible. Even if carbon dioxide emissions decreased by 80%, the sea level would rise. Even so, reducing GHG emissions would slow that process, maybe enough to keep life sustainable.

3.3. Rise of the Sea Level

20 000 years ago, the average sea level was 120 metres below the same parameter now. For that situation, the average global temperature was 4 to 7ºC lower too. Also, 3 million years ago, the average sea level was 25 to 35 metres higher for an average global temperature 2 to 3ºC above nowadays. Rough calculations say that the sea level changes 10 to 30 metres per Celsius degree. In the last one hundred years, global average sea level rose over 22 centimetres. For the next one hundred years, it is expected to rise to anywhere between 1 and 2 meters. Today, the sea level increases around 3,4 millimetres per year.

With this data, according to Dr. Stefan Rahmstorf, it is possible to approximate the initial velocity of the variation of the sea level (*dH/dt*) as a proportion of the difference between the average global temperature at a given time and the temperature in equilibrium. This is called the semi-empirical model for projecting future variations of the sea level.

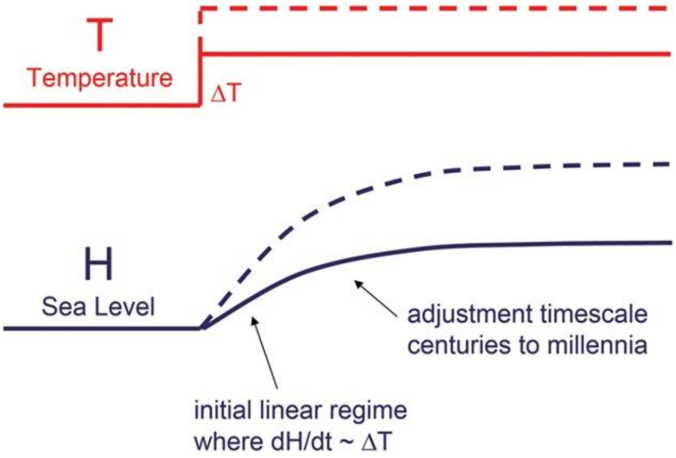


Fig. 3.9 Variation of the average sea level for a step variation in the temperature, *A Semi-Empirical Approach to Projecting Future Sea-Level Rise, Dr. Stefan Rahmstorf*

$$\frac{dH}{dt} = a \cdot (T - T_o) \tag{3.1.}$$

This means that:

$$H = a \cdot \int (T(t) - T_o) \cdot dt \tag{3.2.}$$

This approximation may be more effective assuming smaller periods of time. For example, for a period between 1980 and 2001 and a To equal to 0.5ºC (an average temperature for which the average sea level is zero), the proportion constant would be 3.4 millimetres per year per Celsius degree. This model's results are not much different for the existing estimations for the last 10 thousand years.

In the first figure below, the red line represents the model using the temperature stated below while the dark blue line represents the model using the mean global temperature in this period. The blue shade determines the accuracy. In the second figure, the red dots represent the annual sea level measures and the blue line was drawn using the mean global temperature in the semi empirical model.

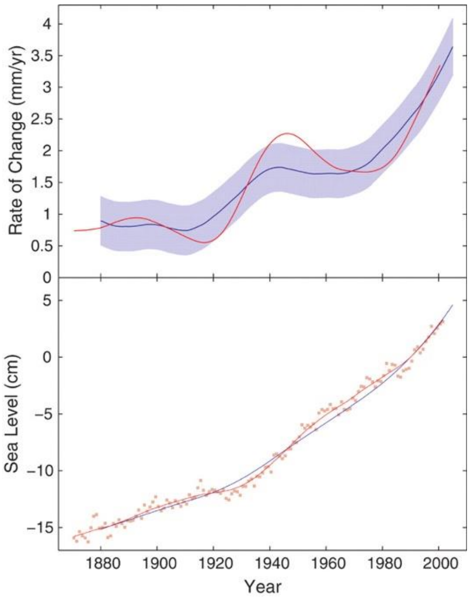


Fig. 3.10 Variation of the average sea level and rate of change per year, *A Semi-Empirical Approach to Projecting Future Sea-Level Rise, Dr. Stefan Rahmstorf*

Using the same model for a period between 1990 and 2100, the global average temperature would be 1.4 to 5.8ºC higher.

The rise of the sea level has two main causes that concern the global warming: the melting of the ice poles and the expansion of the water in the sea due to the temperature increase. From 1971 to 2010, per year, the sea level rose more 0,4 to 0,8 millimetres just because of the volumetric thermal expansion.

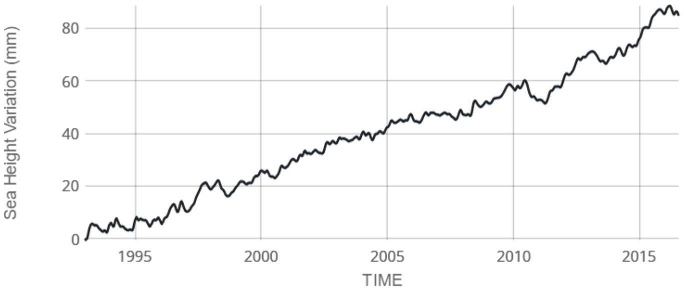


Fig. 3.11 Sea level variations through time, *Sea Level, Climate NASA*

Tides are especially aggravated by the rise of the sea level. The perfect example for that is Venice, Italy. In this city, flooding became the new normal. St. Mark’s Square is affected by high water about one hundred days per year. This might be amusing for tourists, but locals are very harmed by it. Local shops and small businesses need to close because of the floods. As much as they could, people tried to adapt.

Fig. 3.12 Flood in St. Mark’s Square on February 2015, *“Venice Carnival 2015: Revellers try to keep their costumes dry on flooded St Mark's Square”, International Business Times*

If the global average temperature rose 4ºC cities like Rio de Janeiro, New York, Shanghai, Sydney, Mumbai, Durban and London would suffer from similar floods. Almost all the main cities in the world are in regions near the sea and almost all the human population live there. Shanghai, which is around 3 meters above the sea level and other cities like Miami, Amsterdam and Bangkok, which are only 2 meters above the sea level are gravely endangered.

Small islands are particularly vulnerable to the rise of the sea. Some of them, like the Republic of Maldives already suffer the consequences. The Maldives are known as a tourism destination and receive over 600 thousand tourists per year. But besides the beautiful sand beaches and the long coral reefs, the Maldives are the flattest country in the world. The Maldives are never more than 2,5 meters above the sea level at its maximum. Reasonable scenarios say that by the end of this century, the ocean will rise more than a half of a meter, flooding 77% of Maldives’s whole land area. Events like the 2004 tsunami (unrelated to global warming) shown how fragile this country is. Through this century, the Maldives will not only face economic problems or resources scarcity, but it will also face a vast problem concerning climate changes refugees. It is questionable if the world is prepared for that.

Bangladesh is also a very vulnerable country to the average sea level increase. Today local economies are already harmed, specifically agriculture. Crops are already swallowed by the water. It is predicted by the Intergovernmental Panel on Climate Change that by the end of the century the sea level will rise around 1 meter, which means that 17% of the land area of Bangladesh will be covered by water.

4. Possible Solutions

The main solutions to this problem go through the reduction of the greenhouse gases. As the sources were identified earlier in this article, it is possible to address each one of them individually and even in a more personalized way. Alternatives such as protecting the forests, changing fertilizers methods of utilisation, developing more efficient energy technologies and power plants, developing renewables, applying strict laws and agreements to reduce emissions, creating a better organization for the public transportation, or even more personal solutions such as using public transportation more frequently, changing our diet and searching about the origin of our food and reducing waste. The biggest challenge of today might be using creativity to find alternatives of common emitters but needed processes that would be harmless.

There are solutions which turn to adapting to the consequences themselves. More resistant infrastructures, embankments and water breakers might be helpful. The disadvantage of this type of solutions is the fact that it would be impossible to implement them in a large amount of areas all over the world.

5. Summary

After having identified the main greenhouse gases emitters and possible solutions for their reduction, it is possible to have some hope for the future. Despite any possible efforts that humanity can make, the sea level will continue to rise. It is important to guarantee that it rises slowly enough to secure adaptation. Energy production, industries, primary economy activities and our habits must change in order to maintain this world sustainable

As the average global temperature continues to rise and, with it, the melting rates of the ice poles, it is important to innovate and create new and precise ways to measure the thaw and the rise of the sea level. That is essential to assess the current problems and act.

The impact of the rise of the sea level are already here and must not be ignored. Solving the problems of today might be avoiding problems for the future. What happens in the Maldives, Venice and Bangladesh is probable to happen in almost every big city in the world. The human and economic damages would be enormous.

No one benefits from the rise of the sea level and it is a problem that every country and every people should address their thoughts.

> “There is no Plan B, because there is no Planet B”
> - Mohamed Nasheed, former President of the Republic of Maldives

Acknowledgements

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Engineering Equation Solver in heat transfer problems heat exchanger with annular rectangular fins

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Abstract

Solution of heat transfer problems is a complex process and requires a lot of thermo-physical data of examined fluids and materials. Additionally, the calculations regarding convective part of overall heat transfer are based on empirical formulas, and the final results are obtained in the iterative way. Any analysis necessitate a repetition of sequence of operations, including the data from the tables and its interpolation. The Engineering Equation Solver software allows to perform the calculations basing on internal databases, built-in functions and mathematical tools, what improves the solving process. The model of annular rectangular fin heat exchanger has been programmed to carry out several analyses and to show their results in a graphical way.

Keywords: heat transfer, annular rectangular fin, Engineering Equation Solver (EES)

1. Introduction

The overall heat transfer between the fluid of higher temperature, through the wall to the fluid of lower temperature consists of three main types of heat exchange: convection, conduction and radiation. In practice (e.g. in heat exchangers), all of them take place simultaneously, but with different share of the total heat flux. The characteristic feature of conduction is the movement of particles limited to micro oscillations. The fundamental law has been defined by Fourier, introducing the thermal conductivity k, which is a physical property of a fluid or barrier [1].

$$\dot{\boldsymbol{q}} = -\boldsymbol{k}\nabla\boldsymbol{T} \tag{1.1}$$

Where $\dot{\boldsymbol{q}}$ is a heat flux, T stands for temperature and $\boldsymbol{k}$ – thermal conductivity (W/mK). The $\boldsymbol{k}$ coefficient is specific for a given substance and for simplification of calculations is assumed to be temperature-independent quantity.

What makes the major difference between the conduction and convection is the movement of particles, which in the case of convection can take a form of macro and micro movement of particles. Mathematical representation of convection heat flux has been developed by Newton [1].

$$\dot{\boldsymbol{q}} = \boldsymbol{h}(\boldsymbol{T_w} - \boldsymbol{T_{inf}}) \tag{1.2}$$

Where $\boldsymbol{h}$ represents the heat transfer coefficient, expressed in (W/m^{2}K), T_w and T_{inf} correspond to the values of temperatures on the external surface of the body and the fluid in long distance from the body's surface. The mechanism behind the convective and conductive heat transfer is the movement of particles, while in the radiation the heat is transferred by means of electromagnetic wave. The radiative heat flux can be calculated using the Stefan-Boltzman's law [1].

$$\dot{\boldsymbol{q}} = \boldsymbol{\sigma T^4} \tag{1.3}$$

Where the $\boldsymbol{\sigma}$ is the Stefan-Boltzman constant, equal to $5{,}67\times10^{-8}$ (W/m^{2}K^4) and T is a temperature of radiating surface. In the case when the heat flux from the one fluid of temperature T_1 to the second one of temperature T_2 crosses the solid wall/membrane, all three mentioned types of heat transfer take place. The overall rate of heat exchange between the fluids can be expressed by the Pectlet's equation [1]:

$$\dot{q} = U(T_1 - T_2) \tag{1.4}$$

where U represents the overall heat transfer coefficient (W/m^{2}K)

Heat exchangers are devices, which are designed to carry out the heat transfer between two or more fluids of different temperatures. Depending on the specific features of the heat exchange process, they can be divided into recuperators, regenerators and mixers. They can be also classified depending to flow direction, construction etc. [2]

In many cases, the thermal properties of fluids have fixed values, thus, adjusting the proper heat exchanger is necessary. In most of the cases, the possibly highest heat rate is an aim to achieve. Generally, there are two main ways to enhance the total power output of the heat exchanger: improving the heat exchange on the side of fluid characterised by lower value of heat transfer coefficient, or increase the total area of heat exchange. Since the first solution requires changes of parameters of fluid (e.g. increment of velocity or pressure), more commonly the expansion of heating surface is applied, by installing the fins [2].

The calculations regarding heat exchangers may have two approaches. The design approach calculates e.g. the necessary dimensions of the heat exchanger to fulfil the requirement of exchanged heat. On the other hand, the verification approach consists of calculations of heat rate in already existing device [1].

2. Definition of the problem

In this paper, the annular rectangular fin heat exchanger was taken under consideration. The reference for the solution of the problem is collection of heat transfer problems [1]. To simplify the problem's solution, several assumptions have been maintained:

- Steady state of the system,
- Thermal conductivity *k* doesn't depend on temperature,
- The problem is analysed as one-dimensional heat transfer, heat flux normal to the surface.

The geometry of the examined finned heat exchanger is presented in the Fig. 1 [2].

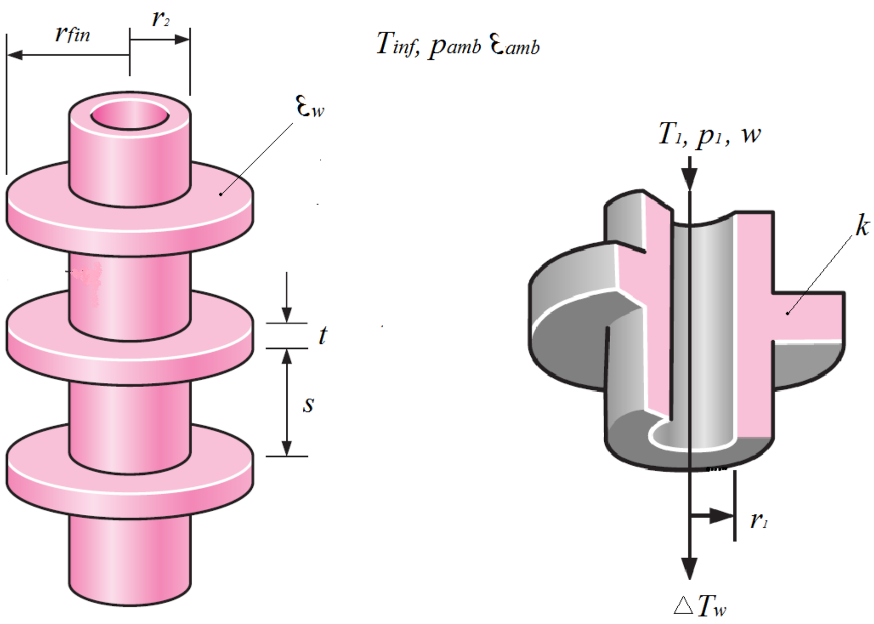

Fig 2.1. Geometry of annular rectangular finned tube and input data [2].

The situation of the heat exchanger is assumed to be horizontal. Inside the pipe flows heating water, while on the external side of heat exchanger is air. The flow inside a pipe is forced, thus the forced convection will be calculated. All the input data with symbols, their unit and explanation have been listed in the Table 1.

Tab. 1 Input data for the calculations [1]

Description	**symbol**	**value**	**unit**
Internal radius of pipe	r_1	0.0375	m
External radius of pipe	r_2	0.004	m
Radius of the fin	r_{fin}	0.075	m
Fin thickness	t	0.002	m
Distance between fins	s	0.008	m
External surface emissivity	ε_w	0.8	-
External fluid temperature	T_{inf}	291	K
Ambient pressure	p_{amb}	0.1	MPa
Emissivity of surroundings	ε_{amb}	1	-
Temperature of inlet water	T_1	353	K
Pressure of inlet water	p_1	0.5	MPa
Velocity of inlet water	w	0.3	m/s
Thermal conductivity of pipe	k_p	50	W/mK
Temperature drop of water	ΔT	20	K

3. Solution algorithm

The first step in calculations is to determine heat transfer coefficient of both fluids h_1 and h_2. In the forced flow of water in the pipe, the physical properties of the water are found for the arithmetic mean temperature of flowing water.

$$\boldsymbol{\mu, k, Pr = f(T)} \tag{3.1}$$

Where $\boldsymbol{\mu}$ stands for kinematic viscosity [m^2/s] and Pr is dimensionless Prandtl number. Then, the Reynolds and Nusselt dimensionless criterial numbers may be designated for the characteristic dimension equal to the internal diameter of the pipe. The heat transfer coefficient is then calculated from the following formulae:

$$\boldsymbol{h_1 = \frac{Nu*k}{d_1}} \left[\frac{\mathbf{W}}{\mathbf{m^2K}}\right] \tag{3.2}$$

In order to calculate the convective heat transfer coefficient from the heater to the air, the heat exchanger is assumed to be a cylinder of diameter d_{fin}. The main problem in calculating the natural convection outside the heat exchanger is the necessity of knowing the wall temperature at the surface. For this reason, this temperature is initially assumed to be T_w=*343K*. Similarly as in the case of internal flow of water, the physical properties of air are designated, but for the mean temperature between the wall surface T_w and external fluid temperature T_{inf} ***(eq.3.1)***. Having these properties, the computation of criterial dimensionless Rayleigh and Nusselt numbers is possible for the characteristic dimension equal to d_{fin}. The convective heat transfer h_{2c} coefficient is calculated analogously as in the equation (3.2).

$$\boldsymbol{h_{2c} = \frac{Nu*k}{d_1}} \left[\frac{\mathbf{W}}{\mathbf{m^2K}}\right] \tag{3.3}$$

As regards the radiation on the external surfaces, the emissivity of the surfaces between the fins $\boldsymbol{\varepsilon_{in}}$ is assumed to be equal to 1, because they create concave shape – the radiation is enclosed between them. For this purpose, the total weighted emissivity for the whole segment of heat exchanger is calculated.

$$\varepsilon_t = \frac{s-t}{s}\varepsilon_{in} + \frac{t}{s}\varepsilon_w \tag{3.4}$$

Similarly as in the case of determining the convection on the outer side of heater, for the calculation of radiative stream of heat, the area taken into consideration is the cylindrical shell of diameter d_{fin}. The area of one segment of the cylinder of length equal to s is obtained as follows:

$$A_{2cyl} = \pi d_{fin} s \left[\frac{\mathrm{m}^2}{\mathrm{segment}}\right] \tag{3.5}$$

The area of single fin:

$$A_{2fin} = 2\pi\frac{{d_{fin}}^2}{4} + \pi d_{fin} t - 2\pi d_2 [\mathrm{m}^2] \tag{3.6}$$

The area of pipe in one segment:

$$A_{2pipe} = \pi d_2 (s-t) \left[\frac{\mathrm{m}^2}{\mathrm{segment}}\right] \tag{3.7}$$

The area of one finned segment:

$$A_{2seg} = A_{2fin} + A_{2pipe} \left[\frac{\mathrm{m}^2}{\mathrm{segment}}\right] \tag{3.8}$$

The radiative heat transfer coefficient can be calculated from the following equation:

$$A_{2seg} h_{2rad} \left(T_w - T_{inf}\right) = A_{2cyl} \varepsilon_t \sigma \left({T_w}^4 - {T_{inf}}^4\right) \tag{3.9}$$

The total heat transfer coefficient equals the sum of the radiation and convection heat transfer coefficients.

$$h_2 = h_{2rad} + h_{2c} \left[\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}}\right] \tag{3.10}$$

Having the heat transfer coefficients, thermal conductivity of the pipe and the geometrical data of the finned tube, the efficiency of the fin η_{fin} can be read from the empirically developed charts [2].
The heat resistance of 1m of the finned pipe:

$$R_l = R_{l1} + R_{l2} + R_{l3} = \frac{1}{\pi d_1 h_1} + \frac{\ln(\frac{d_2}{d_1})}{2\pi k_p} + \frac{s}{h_2 (A_{2pipe} + \eta_{fin} A_{2fin})} \left[\frac{\mathrm{mK}}{\mathrm{W}}\right] \tag{3.11}$$

All the above calculations were carried out including the initially assumed temperature of the wall's surface T_w. Because of the linearity between the temperature and heat resistance, this temperature can be calculated from the following formulae:

$$\frac{R_{l1}+R_{l2}}{R_l} = \frac{(T_1 - T_{w-calc})}{(T_1 - T_{inf})} \tag{3.12}$$

Because the difference between previously assumed temperature of the wall and the calculated one is significant, the iteration process is necessary. Because the iteration is very convergent, after second iteration the final values of h_2 and have been R_l obtained.

After the iteration process, the heat flux related to 1m length of the exchanger and the total thermal power of the exchanger can be calculated:

$$\dot{q}_l = \frac{(T_1 - T_{inf})}{R_l} \left[\frac{\mathrm{kW}}{\mathrm{m}}\right] \tag{3.13}$$

$$\dot{Q} = w\frac{\pi {d_1}^2}{4}\rho_w \Delta T[\mathrm{W}] \tag{3.15}$$

Where ρ_w represents the density of water. Dividing the result of the eq. 3.15 by the result of the eq. 3.14, the necessary length of the heat exchanger to compensate the required heat power is calculated:

$$L = \frac{\dot{Q}}{\dot{q}_l}[\mathrm{m}] \tag{3.16}$$

The complete set of results of calculations based on initial data (Tab. 1) is presented in the Tab. 2.

Tab. 2 Results of calculations

Description	**symbol**	**value**	**unit**
Heat transfer coefficient on internal side	h_1	2019	$\frac{\mathrm{W}}{\mathrm{m^2K}}$
Convective heat transfer coefficient on external side	h_{2c}	3.14	$\frac{\mathrm{W}}{\mathrm{m^2K}}$
Weighted emissivity	ε_t	0.95	-
Area of cylindrical shell	A_{2cyl}	0.0037	$\frac{\mathrm{m^2}}{\mathrm{segment}}$
Area of single fin	A_{2fin}	0.026	[m^2
External Area of pipe in one segment	A_{2pipe}	0.001	$\frac{\mathrm{m^2}}{\mathrm{segment}}$
Area of one finned segment	A_{2seg}	0.027	$\frac{\mathrm{m^2}}{\mathrm{segment}}$
Radiative heat transfer coefficient	h_{2rad}	0.96	$\frac{\mathrm{W}}{\mathrm{m^2K}}$
Total heat transfer coefficient	h_2	4.1	$\frac{\mathrm{W}}{\mathrm{m^2K}}$
Fin efficiency	η_{fin}	0.85	-
Thermal resistance	R_l	0.08	$\frac{\mathrm{mK}}{\mathrm{W}}$
Calculated temperature of external surface	T_{w-calc}	361	K
After one iteration:			
Total heat transfer coefficient	h_2	4.43	$\frac{\mathrm{W}}{\mathrm{m^2K}}$
Thermal resistance	R_l	0.07	$\frac{\mathrm{mK}}{\mathrm{W}}$
Heat flux	q_l	4.72	$\frac{\mathrm{kW}}{\mathrm{m}}$
Power of the heater	$\dot{Q}$	108.5	kW
Necessary length of heat exchanger	L	23	m

4. Problem Analysis by means of Engineering Equation Solver (EES)

The EES software is designed to improve the process of solving engineering problems. One of the main advantages of this tool is solving complex sets of equations with subsequent finding the unknown values in the system. The only necessary condition is to have as many unknowns as equations to solve – in other case the solution can't be obtained, what limits the number of applicable problems significantly. Moreover, the inputs and outputs of internal functions are not commutable.

Another feature improving, in particular, heat transfer problems is elaborate database containing numerous thermo-physical properties of the most commonly applied fluids and materials. The user may obtain exact values of these properties immediately, without interpolation as it is often necessary when using traditional tables with data. Additionally the EES program is equipped with the Heat Transfer Library containing the built-in functions regarding the most common issues [3].

The sequence of calculation presented in the section 3 results in only one particular solution. Moreover, in every single calculation of a given case the iteration process has to be repeated. In the ESS, after implementation of all the variables and equations, the calculations last seconds. This program also allows to perform series of calculations with respect to changing variables by means of parametric table. In other words, we can track the influence of varying one of the parameter on the other parameter or on the final result [3].

Exemplary analysis has been conducted and it shows the influence of the fin diameter on the quantities describing heat transfer (Fig. 4.1).

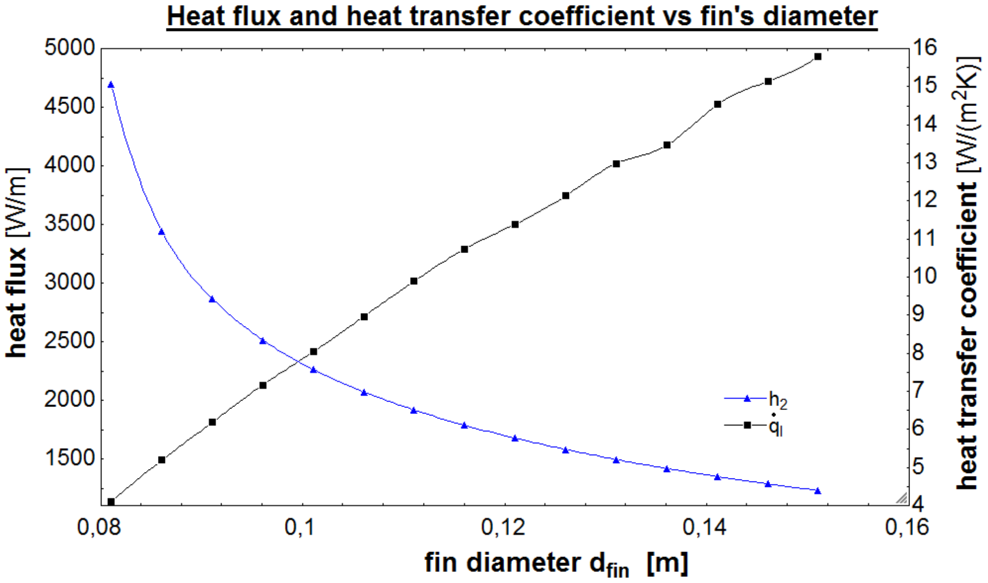

Fig. 4.1 Dependency of heat transfer coefficient and heat flux on the increasing fin's diameter

The main relation which can be read from the Fig. 4.1 is that despite the decreasing heat transfer coefficient, the expansion of heating surface by enlarging the fins intensifies the heat flux released from 1 m of the heater's pipe. Another proposed analysis regards the calculation of necessary length of the heat exchanger to release given amount of thermal power to the ambient. In this case, two variables have been changed simultaneously: the diameter of the fin and its thickness. The figure 4.2 shows how the necessary length of the heat exchanger varies within changing the geometry of the fin. The chart was generated for different set of data than the initial one.

From the e Fig. 4.2 it can be seen that the thinner the fin and the greater is its diameter, the smaller length of the heat exchanger's tube. The best solution would be to install very thin fins with possibly greatest diameter. Nevertheless, the final decision about the geometry of the fins is made on the basis of the cost of manufacturing and exploitation.

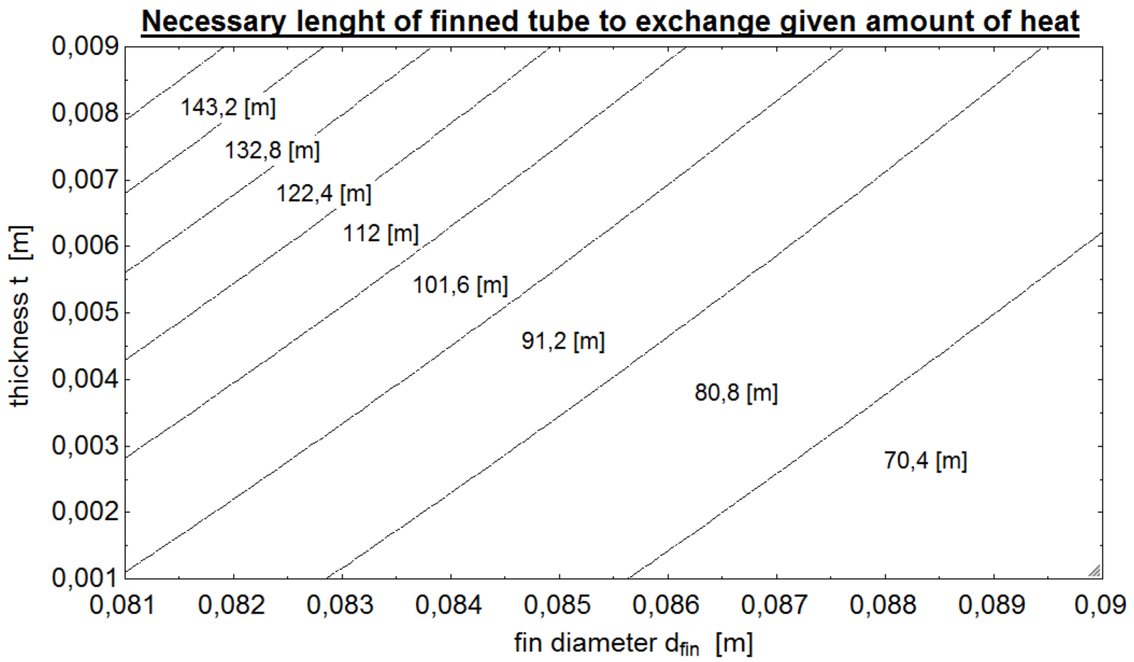

Fig. 4.2 Relation between varying dimensions of the fin and the necessary length of the heat exchanger

The last analysis regards the fin efficiency. As it was mentioned in the section 3 of this paper, the value of fin efficiency has to be read from specially created graphs. Repetition of this step is very time-consuming and may be burdened with a very high uncertainty. The EES software contains the internal procedures calculating the fin efficiency. For example, the code for the annular rectangular fin is determined as follows:

```
efficiency=eta_fin_annular_rect(t;d_2;d_fin;h_2;k_pipe)
```

After providing all the necessary input to the procedure (thickness, external diameter of pipe, diameter of fin, heat transfer coefficient, thermal conductivity of fin’s material), the user receives the values of the fin efficiency. In this paper, the relation between the fin’s diameter and its efficiency for different types of material has been examined (Fig. 4.3).

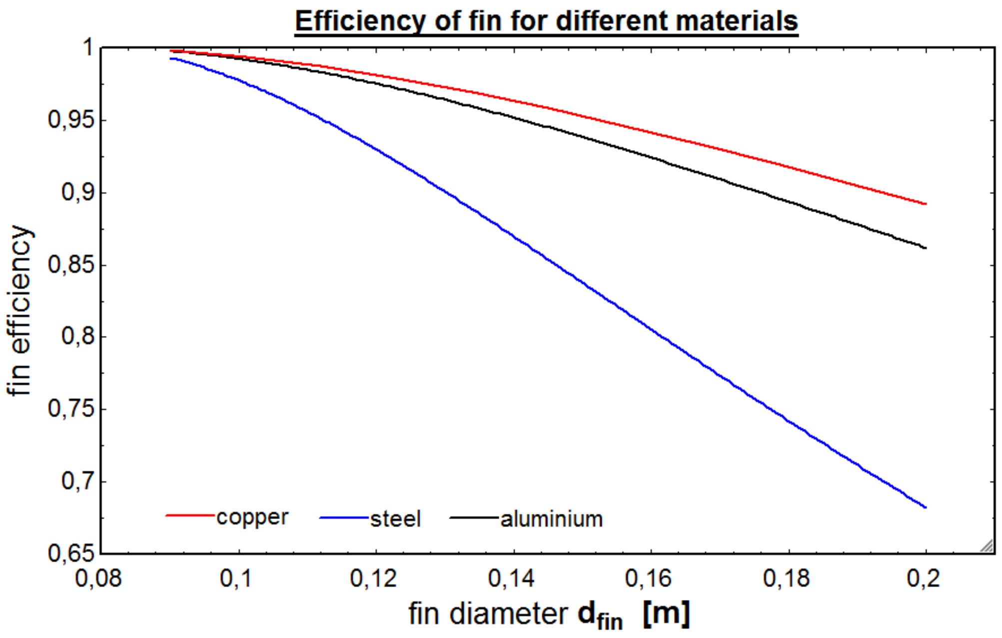

Fig. 4.3 Relation between fin’s diameter and its efficiency for materials characterised by different heat conductivity

The chart presented in the Fig. 4.3 shows that application of the material of higher heat conductivity allows to obtain higher efficiency of the fin for given diameter. The difference between the steel and copper may reach even 40% of efficiency. Also in this case, the following analysis should be supported by the economic one, which would include the prices of applied materials.

5. Summary

The calculation procedure of heat transfer problems, even very simplified, requires numerous steps containing reading the data from tables and graphs and iteration, what makes the process time-consuming. For this reason, the modelling of the problem in the EES software has been proposed. The program includes all the necessary data to solve the problem. The iteration process is run automatically, so the user obtains only the final, most accurate results. The internal functions allow to speed-up the process of calculation even more, because the user is not required to set-up e.g. complicated criterial equations.

The possibility of creation the parametric table and visualisation of the results graphically allows to track any required relation between quantities defined in the problem. The calculations are performed sequentially, and the charts may be auto-updated after any change in the provided input data. The creation of the charts is very effective and does not restrict the tracking only to input-output relation – any interdependency can be drawn, depending on the user's desire.

Even though the calculations performed in the EES are very exact and much more accurate that in comparison with manual solving, they are also based on criterial, empirical equations which are burdened with high uncertainty. The simplification of the problems to the one-dimensional makes it even more inaccurate. For this purpose, more complex approaches should be applied. Nevertheless, for the initial stage of designing, the application of EES in solving the heat transfer problems is very beneficial.

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Final disposal of spent nuclear fuel on the example of Sweden

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Abstract

Spent nuclear fuel is a material which is highly radioactive and emits significant amount of decay heat. To ensure its harmlessness to environment throughout the period of its activity, it needs to be isolated with no chance for leakage or water intrusion for many thousands of years. The paper explains characteristics of spent nuclear fuel as well as possible strategies for handling of it. It presents the means which various countries utilise to ensure safe storage of used nuclear material. Final disposal of spent fuel is a key issue for the present as well as the future and for this reason the programme of Spent Fuel Repository in Sweden is thoroughly examined. The aspects taken into consideration are technical issues, the means that were taken to obtain the level of knowledge needed, social attitude, additional research carried out at the Hard Rock Laboratory. Finally, the conclusions about overall condition of the back end of fuel cycle and its needs in the near future are drawn.

Keywords: spent nuclear fuel, final disposal, nuclear waste management, contamination protection, Sweden

1. Introduction

The problem of safe spent nuclear fuel storage and disposal is an important matter in every country producing energy from nuclear power plants (NPPs) or using nuclear reactors for research. Notably, there is a couple of factors that need to be taken into consideration to ensure proper safety of environment, among which two are particularly significant: high level of radiation and decay heat [1]. After the scheduled time, that material should operate, used fuel could be handled in a couple of possible ways. One of them is reprocessing and recycling of spent material before the waste is finally disposed. This treatment enables the country to use retrievable energy from the fuel. Other states choose open fuel cycle and develop storages for used fuel assemblies. There are also some countries which, using nuclear energy in domestic plants, still haven't decided what to do with the waste. However, one thing is common in all the strategies - High Level Waste (HLW) will finally need a disposal to get immobilised for between a couple of centuries to many thousands of years [2]. In the article, the process of site assessment, research, planning and building a final repository was presented. As a role model for the analysis, Sweden was chosen, being one of the leading countries in the world in terms of building a final repository for spent nuclear fuel.

2. Spent nuclear fuel

As a result of fission and neutron capture in reactor, nuclear fuel evolves from two components, to many different radioactive isotopes mixed together. Illustration of the fuel composition, before and after irradiation, is presented in Fig. 2.1 – spent nuclear fuel (SNF) not only contains unused Uranium and fission products (FP), but it also has some fraction of Plutonium created by neutron capture in Uranium-238 and various minor actinides such as Neptunium, Americium, Curium [2].

Activity of some isotopes, mostly fission products like Sr-90 and Cs-137 [3] [4], is very high, but they also have a short half-life, which means, that they become stable relatively quickly. However, other components of spent fuel are active for up to millions of years, which can be observed on the Fig. 2.2. [5] One of the objectives in disposing such a complex material is to ensure that the radiation of all the elements would not be harmful for the environment, either directly or indirectly, at any point of time, especially when the level of total emission is above the average radiation of a natural uranium ore. Spent nuclear fuel needs to be prevented from radiation to the surroundings, but its isolation must also minimise the chances of leakage and water access, the main purposes for corrosion of canisters and diffusion of nuclides.

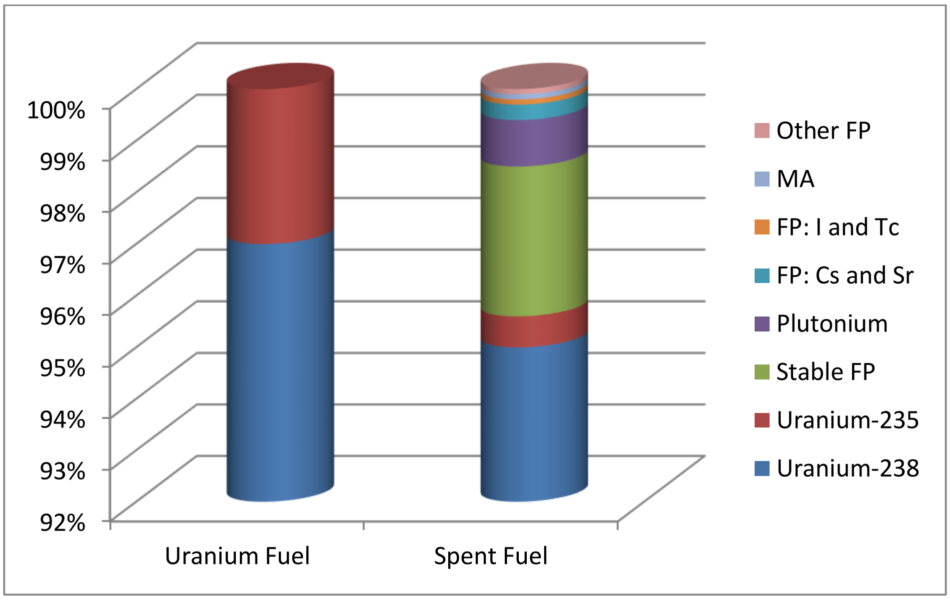
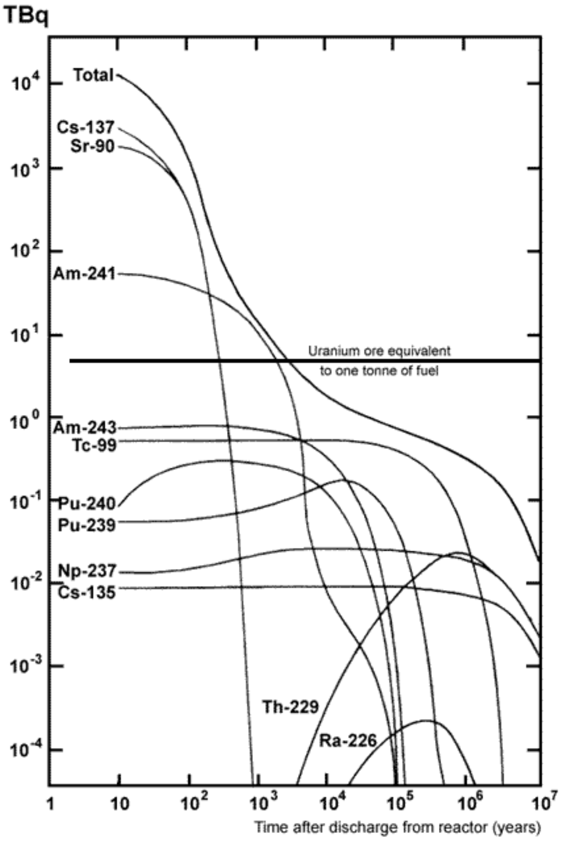


Fig.2.1 The content of the nuclear fuel at the beginning of operation in the reactor and at the beginning of cycle and at the end of cycle [3]



Activity of high-level waste from one tonne of spent fuel

Source: IAEA, 1992 - radioactive waste management.

Fig. 2.2 Activity of HLW in billions of decays per second from one tonne of spent nuclear fuel [4]

Among all the consequences of spent nuclear fuel being heavily radioactive, the fact that it produces decay heat is not to be omitted. Right after reactor shut-down it amounts around 10% of fuel thermal power and it decreases exponentially with time. This phenomenon is crucial when taking into account technologies used to store spent nuclear fuel. [2]

2.1. Spent nuclear fuel technologies in the back end of the fuel cycle

Obtaining used fuel from irradiation in NPP is one of the actions creating the fuel cycle as well as the beginning of so called back end of it (see Fig. 2.3) [2]. Discharging hot, radioactive used material is then followed by placing it in a temporary on-site pool, located next to the reactor, in order to provide proper heat removal. There are some countries which keep used fuel on-site for the whole period of power plant operation, with no possibility to transfer it to some other facility, but in most cases this process lasts only a couple of years [6]. Next, partly cooled assemblies are moved to an interim storage, built to serve all the NPPs in region or country. The design objectives of these facilities are heat removal and radiation protection. They are designed as extensive water pools, because water performs very well as a coolant and, when covering the assemblies with at least 4-meter-layer, eliminates the radiation. In case of older assemblies, where only little decay heat is generated, also dry, gas-cooled casks are used [7][8]. Importantly, this point is the last step in nuclear fuel cycle for most nuclear power plants in the world. Let us point out the numbers: in 2014 only around 5% of the global SNF amount was reprocessed and formed to MOX fuel and burnt for the second time to gain more energy from one portion of fuel. This strategy of SNF management is called Closed Fuel Cycle. By contrast, the rest of SNF on the world remained in interim storages with no intention of reprocessing, which is called Open Fuel Cycle or Once-through Fuel Cycle [9]. In the picture below, there is still final disposal as the last position in both open and closed fuel cycle, nevertheless it does not currently exist in any country in the world. There are many design ideas for this facility. The most far-fetched ones involve storage in cosmic space, glaciers or throwing canisters into subduction area of tectonic plates [10]. Nonetheless, when it comes to practically feasible solutions, mostly deep geological storage (400-1000 m under the ground) is studied and first final repository should be expected in 2020s. There are ten underground laboratories in the world carrying out intensive research on the technology of final repository. In one case the surroundings of the laboratory is clay, in second one – salt (see Fig. 2.4), another one –tuff, and the bedrock of remaining seven facilities is granite (see Fig. 2.5). These places may become future repositories. [5]

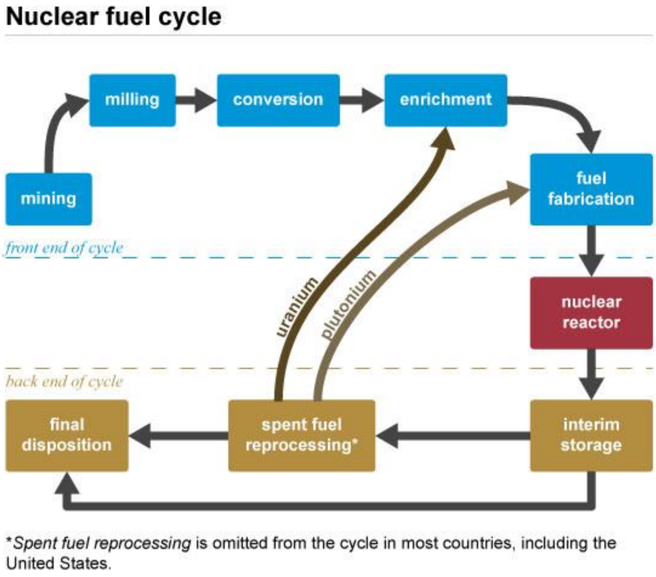


Fig. 2.3 Nuclear fuel cycle [11]

2.2. Spent nuclear fuel management in the world

As a matter of fact, countries manage spent nuclear fuel in various ways, which is a result of many factors, such as the extent to which government supports nuclear engineering, public acceptance as well as energy and global warming policies. The other important aspects are also geology of the country and the capacity for storing waste before action is required. [6]

Closed Fuel Cycle is implemented e.g. by France, Japan, United Kingdom, Russia, the Netherlands, Belgium etc. In these countries spent fuel is first stored in wet, than sometimes in dry storage to let it cool down and then it is transported to reprocessing and fuel manufacturing plant (located mostly in France, United Kingdom, India, Russia) [12], to be transformed into MOX (Mixed Oxide fuel) assemblies. Remaining waste tends to be vitrified, stored and awaiting for final disposal.

Other countries are not currently reprocessing their spent nuclear fuel, for instance Brazil, Hungary, Czech Republic, Taiwan, Germany, Sweden, Finland etc.. They currently depend on on-site pools as well as wet and dry storages.

Nonetheless, some of the states like Germany, Belgium, Canada, USA, Finland, France, Japan, UK, Sweden, Switzerland intend to build final repositories in the area of their country. French plans mention the year 2025 as the date of commissioning of the reversible deep geological facility. Next, Japan is to begin underground research around 2029 to store their wastes and maintain access to it at the same time. Moreover, Russia also plans to build a reversible geological storage in granite by 2035, the United Kingdom by 2040 and China by 2050. Czech Republic is considering construction of a repository after 2050. Canada also announced its interest in geological storage and currently waits for a volunteering location to start the site assessment [6]. The USA began its investigations already in 1986 in the tuff bedrock of Yucca Mountains, nevertheless, all the plans for construction were banned in 2008 by the President Barack Obama [5]. A different idea for geological storage has Germany, which decided to use the salt domes at Gorleben (see Fig. 2.4) to host spent fuel canisters. It is intended to start operation around 2030 [6].

Fig. 2.4 Salt domes are considered a proper environment for final storage in Germany [13]

The most outstanding states in this matter are Finland and Sweden. Finnish repository, presented on Fig. 2.5, will be located next to the Olkiluoto NPP on the west coast of the country. The license for construction was granted in November 2015 and operation is scheduled to begin around 2023 [14]

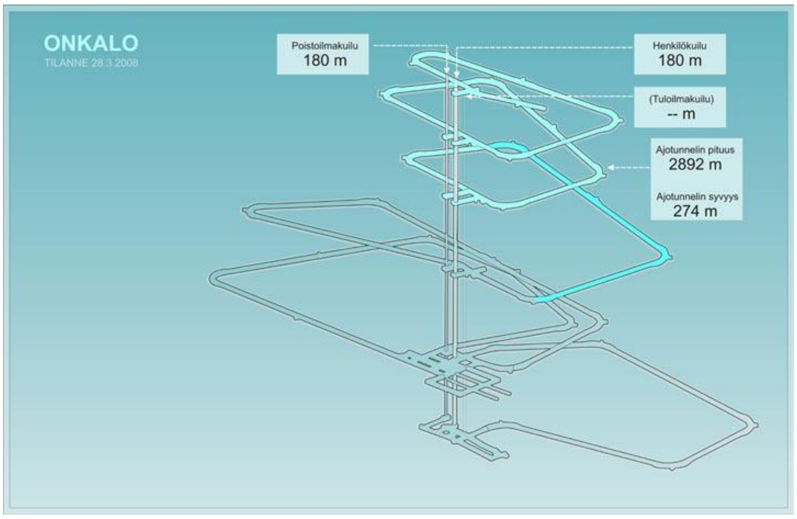


Fig. 2.5 Plan of the spent nuclear fuel repository in granite, Onkalo, Finland [14]

3. Spent fuel management in Sweden

Sweden is a country where 40% of electricity is provided by nine operating nuclear reactors. The country's official attitude to the back end is that once-through fuel cycle is implemented. NPP operators (currently Oskarshamms Kraftgrupp AB and Vattenfall, in the past also Barsebäck Kraft AB) are financially responsible for the proper waste management in the country. They are obliged to pay additional fee to the state to cover the expenses of waste management and decommissioning - since 2015 around 0.44 Euro cents/kWh. In 1977 the Swedish Nuclear and Waste Management Company (*swed. SKB*) was created to develop a design of disposal of the Swedish nuclear wastes. Its owners are Vattenfall (36%), Forsmark (30%), OKG (22%) and Barsebäck Kraft AB (12%). Since 1985 the country has also operated an interim repository for used fuel in Oskarshamn called CLAB. Its capacity is 8 000 tonnes, but SKB has already applied for extension to 11 000 tonnes to be able to store the fuel from all operating reactors. As all the nuclear power plants are located at the Baltic Sea, spent fuel is transported to CLAB by a dedicated ship M/S Sigrid [15]. According to the current plans, the wastes will cool down there for 30-40 years, till the radioactivity of the fuel will drop by 90%, and later on they will be transported to the deep geological repository.

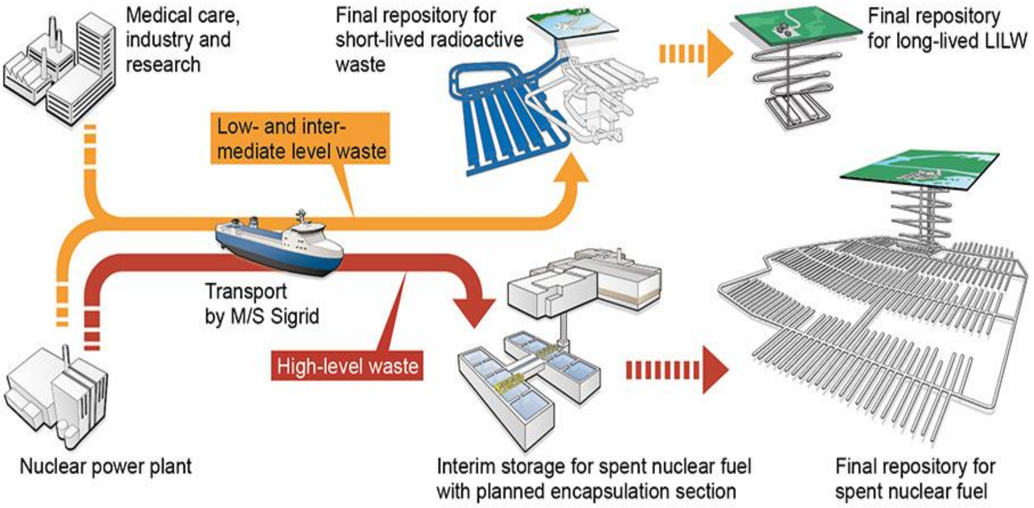


Fig. 3.1 Radioactive waste management in Sweden [16]

3.1. Spent Fuel Repository

The research on the siting and technology of the final repository, to deposit around 12 000 tonnes of spent fuel started in 1977 with the establishment of SKB. From 1977 to 1985 all the area of Sweden was analysed in terms of bedrock [17]. In 1995 Äspö Hard Rock Laboratory was created to estimate the expected conditions in the future final repository [18]. In the 1990s the bedrock in Sweden was categorised into suitable for a repository (green areas on Fig. 3.2) and non-suitable rock (grey areas). Between 1993 and 2002 feasibility studies in eight volunteering municipalities (see Fig. 3.2) showed, that only two of them have potentially suitable bedrock for an underground repository – these were Oskarshamn (Simpevarp and Laxemar) as well as Östhammar (Forsmark) [17]. Further research lasted for the next six years including also an independent poll carried out in April 2008, which resulted in societal support in both municipalities [15]. In June 2009 SKB announced the decision to build the repository at Söderviken near Forsmark, placing it in 1.9 billion years old rock [19]. The criteria of siting were plant and animal life, rainfall, mechanical and chemical stability of the bedrock, low hydraulic conductivity (low fracture frequency), high thermal conductivity, no valuable ores at the site. The means of investigation were for instance: geophysical measurements, rock sampling, water flow and borehole radars [18]

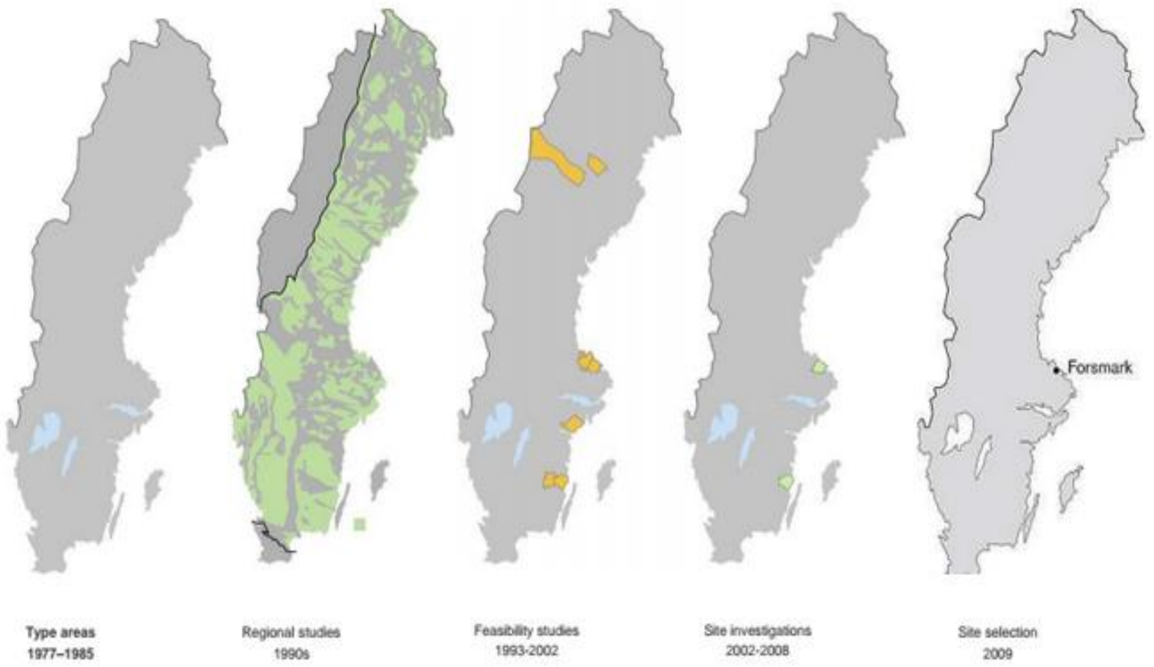


Fig. 3.2 Process of site selection for the final repository in Sweden [17]

The chosen method of deep geological storage developed by SKB in 1983 is called KBS-3. It involves storing of the fuel for at least 30 years and next, cooled assemblies should be encapsulated in copper canisters with iron cast insert, which is suited to the reactor type. One capsule weighs around 25 tons and the thickness of copper wall is 5 cm for long-lasting resistance against corrosion (copper is said to be one of the most corrosion-resistant metals) as well as mechanical forces caused by tectonic movements, due to ductility of the copper [18]. The canister will be surrounded by bentonite buffer and the corridors of the repository will also be backfilled with this material. It is a special type of clay, particularly suitable for the design, because it reacts for emerging water with expansion. Therefore it prevents the canisters from corrosion, radionuclide diffusion, as well as suffering from minor tectonic movements, as it fills the cracks in the bedrock. The final barrier of protection of the environment are the bedrock and the depth of the repository. The rock contains many micropores which help to absorb any leakages from the canisters. What is more, the depth of around 500 metres provides stable chemical environment as well as isolation from any conditions on the surface such as the layers of drinking water or even glaciations. Thanks to all these solutions, spent fuel is to be isolated from humans and environment for at least 100 000 years [19].

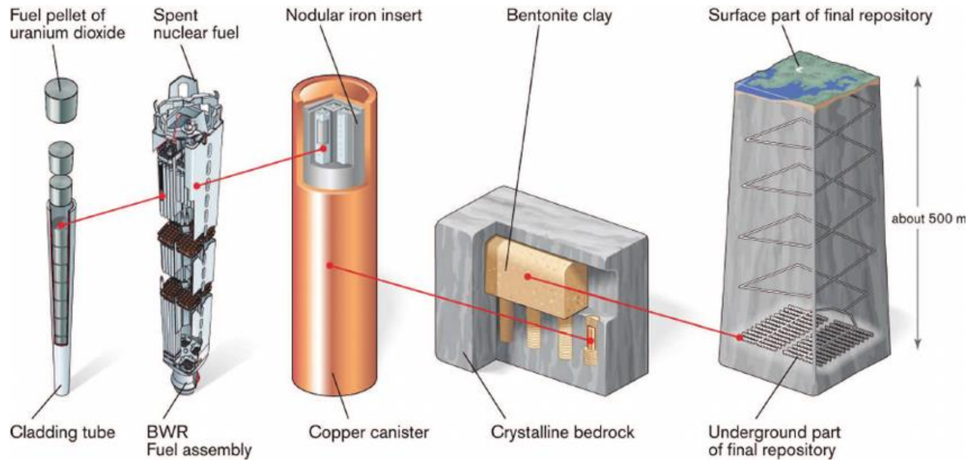


Fig. 3.3 Design of KBS-3 method of spent fuel storage [20]

3.2. Additional researches carried out at Äspö

Äspö Hard Rock Laboratory was built to enable and support researches on the repository technology in the depth similar to the real location and therefore it simulates real conditions of repository. It is located 500m under the ground and is used by both Swedish and international research groups. The experiments conducted on the site involve radionuclide path through the bedrock, interaction of bentonite and copper with underground conditions, transportation of the canisters using robots. Apart from this, new methods of geological studies are developed as well as environmental chemistry researches are carried out [21].

3.3. Societal aspects of Final Repository location

The key to success of the Swedish final repository programme is social support of local communities as well as the whole nation. Not to omit is the fact that the beginnings of site investigation were hard for SKB – not planning any social campaign it met with strong resistance on the part of locals (see Fig. 3.4) [22]

Fig. 3.4 Protests at Almunge test drilling site in 1985 [17]

After re-consideration of the strategy, new siting process was developed. It was said to be based on safety and democracy, voluntary participation and step-wise implementation. Societal research included for instance: current situation and future development of the locations, effects of siting on the local and regional economy, market, image of the region, tourism, property prices, as well as forecasts of demography. SKB started consultations with stakeholders such as municipalities, members of the public, NGOs connected with ecology, landowners as well as education of local communities. Set of benefits for the municipalities to host a repository was called Added Value Programme. The goods created have the common value of 1.5-2 billion SEK (around 200 million EUR). The Programme was divided into two stages: before and after the decision about location of repository. As a result of the siting, Oskarshamn acquired 75% of the money and the encapsulation plant, as the municipality which was not granted with the repository site. Östhammar got 25% of the assets and became an official place for building final repository. The money can be spent in a couple of areas like: education, support of innovation, infrastructure, visitors facility, further development of SKB laboratories, labour market expansion [17].

4. Summary

Sweden, as a country with high importance of nuclear energy in power system and once-through fuel cycle, considers development of spent fuel repository as a priority. Being a well-to-do state, it has little problem investing their assets, especially when they were collected beforehand, as a fee charged on generators for every kWh produced. Sweden has also developed its hydrogeological and geophysical knowledge as well as automation technology. Thanks to the programme of siting, local communities got a thorough education in nuclear waste storage, but also enhanced infrastructure and assets for development. Every country utilising nuclear energy will be obliged to build a repository sometimes in the future. Swedish experience will be an example for other them to lead a successful nuclear facility promotion and implementation.

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Review of selected renewable energies in Portugal

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Abstract

Renewable energies is a topic that has been taken under discussion for some years now. It started as something almost fictional, but with time it has taken bigger and bigger proportions and right now it is a topic everyone has heard about, knows about and cares about. There are global agreements setting targets for the countries in order to increase the growth of renewable energies. The purpose for this article is to make a follow-up of the European Union commitment regarding Portugal's progress. Since each country has its own characteristics, regarding topography, solar and wind exposure, the exploitation of the renewable sources is developed accordingly. In this article, it will also be discussed the main renewable sources of Portugal.

Keywords: Renewable energies, Portugal, European Union, hydro power, wind power, solar power, biomass

1. Introduction

In 2009 the European Union Renewables Directive set binding targets for all EU Member States, such that the EU will reach a 20% share of energy from renewable sources by 2020 and a 10% share of renewable energy specifically in the transport sector. By 2014 the EU realized a 16% share of energy from renewable sources with nine states already achieved its goals.

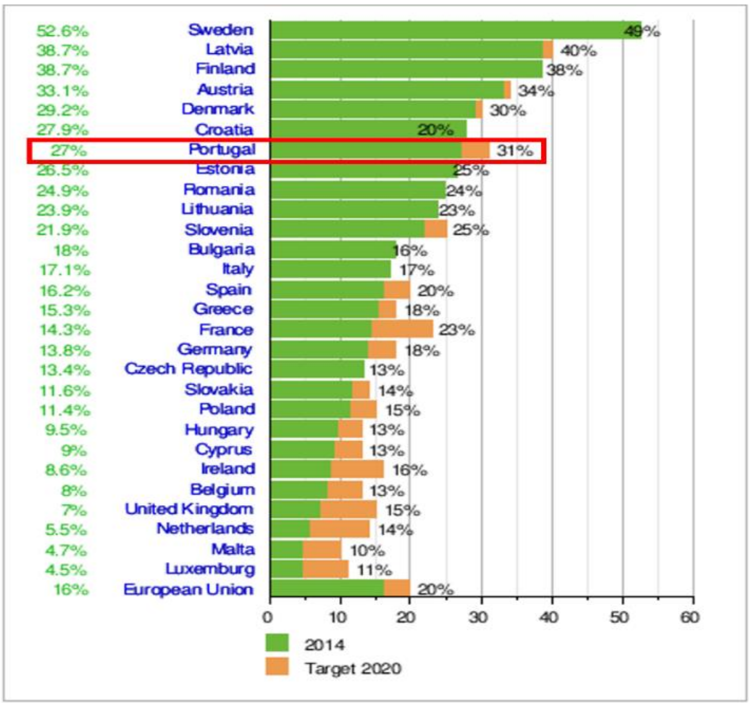


Fig. 1.1 Shares of renewable energies in different EU countries [2]

All EU countries have embraced national renewable energy action plans showing what steps they intend to take to satisfy their renewables targets. These steps involve sectorial targets for electricity, heating and cooling, and transport; proposed policy measures; the different mix of renewables technologies they want to employ; and the planned use of cooperation mechanisms [1].

In Portugal, in 2010, more than half of all the consumed electricity came from renewable sources. From these renewable sources, the most significant were hydroelectric with 30%, wind power with 18%, bioenergy 5% and finally solar power with just 0,5%. The next year the Portuguese government started a new energy policy instrument called the E4 Programme (Energy Efficiency and Endogenous Energies). The primary target of this programme is to rise the competition in the country's economy, update the country's social fabric while, at the same time, is reducing the gas emissions (especially CO_2) and promoting energy efficiency. For these targets were set several ways to measures to promote a consistent and complete strategy to energy supply and demand. As a result, in the five years between 2005 and 2010, energy production from renewable sources increased by 28%.

In January 2014, 91% of the monthly needed Portuguese electricity consumption was generated by renewable sources, although the real figure stands at 78%, as 14% was exported [2].

In Portugal, the main renewable energies are hydro power, wind power, biomass and solar power [3].

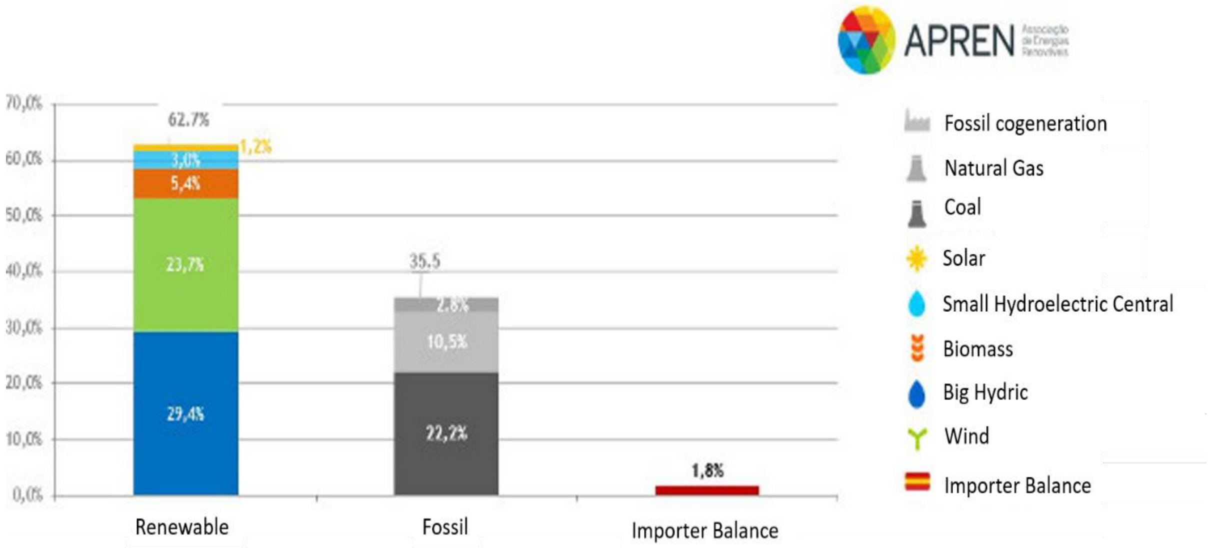


Fig. 1.2 Weight of different sources of electricity production in Portugal in 2014 [3].

One of the most important news from Portugal regarding this topic was reported by several national and international newspapers (like *Observador*, *The Guardian* and *National Geographic*) in May this year informing that Portugal has powered itself for 107h (4 days) in a row using only renewable energies: wind, solar and hydro power [4].

2. Hydro power

Hydropower is the electricity produced from machines that are run by moving water [5]. A hydroelectric power plant has 3 main components:

- Turbine
- Generator
- Dam

In the turbine, the energy from the falling water is converted into mechanic energy (kinetic energy). Afterwards, in the generator, that kinetic energy is converted into electric energy by electromagnetic induction where it is produced a high tension alternate current. This energy is finally transformed and transported to the customers.

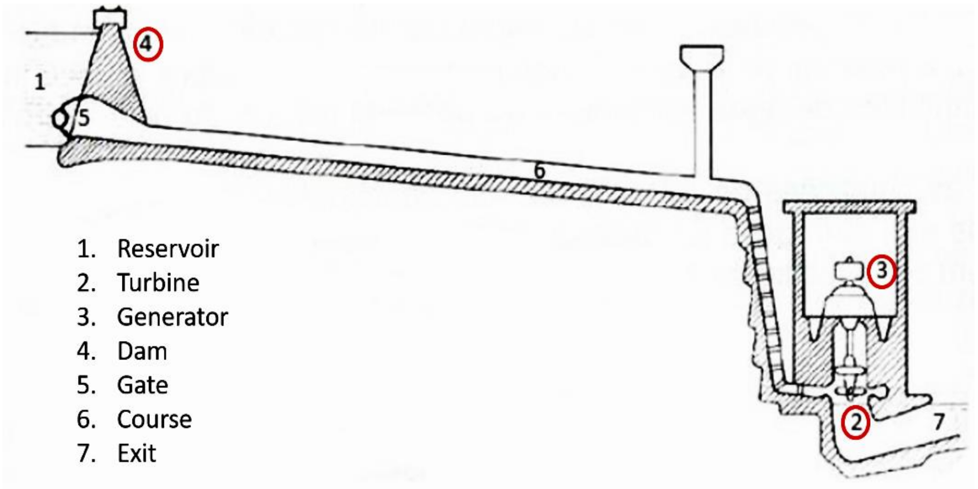


Fig. 2.1 Scheme of a hydroelectricity power plant [6]

During the day water falls into the lower reservoir but at night – when energy consumption falls – the turbine uses wind energy to pump water back into the upper reservoir so that the cycle can continue the next day without significant water loss [7].

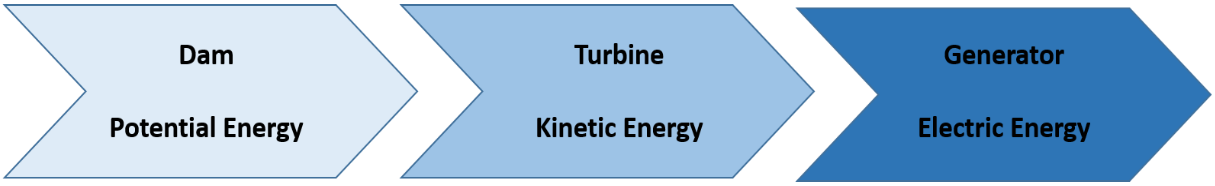


Fig. 2.2 Schematic explanation of the energy conversion in each component of the hydroelectric power plant

Tab. 1 Evolution of the existent in hydroelectric power plant in Portugal [6] [8]

Year	1950	2009	2012	2016	2020
Power	195 MW	4821 MW	5337 MW	6024 MW	8940 MW

The two biggest hydroelectric power plants in Portugal are:

- Alto Lindoso: is the biggest in the country with an installed power of 630 MW [6]
- Alqueva: is the biggest reservoir in Portugal and the biggest artificial lake in Europe with an installed power of 512 MW [6]

3. Wind power

Portugal is one of the top nations in Europe when it comes to wind power energy. Wind power is the second most developed renewable source, after hydropower [9].

Wind energy is using the air flowing through wind turbines and mechanically powering generators to generate electricity. The wind rotates the blades, which spin a shaft, which connects to a generator and generates electricity. Wind farms consist of many particular wind turbines attached to the electric power transmission network [10]. Wind farms are mainly located in the northern part of the country.

Three biggest wind farms are situated in the following districts:

- Viseu – 934.5 MW
- Coimbra – 599.5 MW
- Vila Real – 589.5 MW [11]

The following graph (Fig. 3.1) presents the production capacities of wind energy in Portugal from 1997 to 2015 [12].

Portugal started promoting research and development on renewable energy technologies in the early 1990s. Several new companies were created at this time to explore the country's wind power potential and develop wind energy technology.

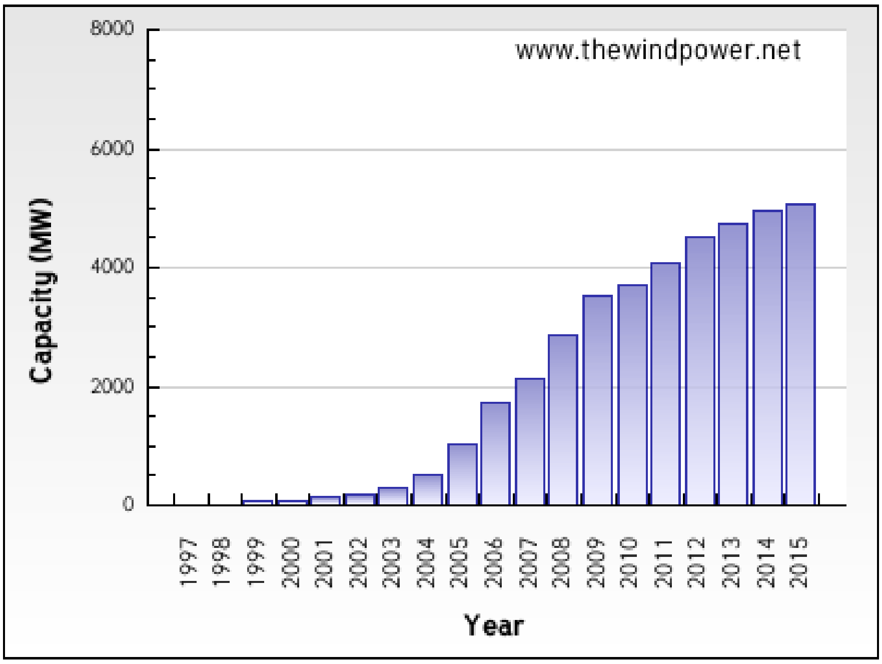


Fig. 3.1 The production capacities of wind energy in Portugal from 1997-2015 [12]

Between 2001 and 2003 a series of initiatives were launched to simulate the electricity market:

- A Decree-Law establishing a range of favorable feed-in tariffs for electricity produced from renewable energy sources
- A Decree-Law regulating the distribution of electrical energy to the low-voltage grid

Between 2001 and 2005, a significant source of investment support was the "Incentive Scheme for Rational Use of Energy" which provided capital grants for different types of renewable installations.

The most significant progress of wind power installed capacity in Portugal took place between 2004 and 2009. While this time more than 500 MW was established annually.

No new wind power capacity was attached from 2005 until 2012. The National Renewable Energy Action Plan (NREAP) was introduced to the European Commission in August 2010. The Plan covered 6 875 MW for wind power of which 75 MW was for offshore wind. To reach this goal, approximately 1 000 MW of new wind projects are required, which will need to be contracted by future tenders. In 2011, a Decree-Law was presented to define the conditions regulating the awarding and management of grid interconnection points for IPPs1 [9].

2016 has been an extraordinary year with new records. With 6024 MW capacity installed in hydro (5360 MW in big dams), 5033 MW in the wind, 566 MW in biomass, 474 MW of PV, and 29 MW in geothermal, a transition to 100% is already occurring in Portugal. In April 2016, renewable sources produced 95.5% of the electricity demand. Recently, Portugal broke the record for the most number of hours running straight on 100 percent renewable electricity energy sources [13].

By 2020, Portugal intends to be producing 60% of its electricity from renewable resources to meet 31% of its final energy consumption. Grid integration will be a critical element for improving wind power. [9] The target to reach in 2020 is 5300 MW in production capacity of wind energy [8].

4. Biomass

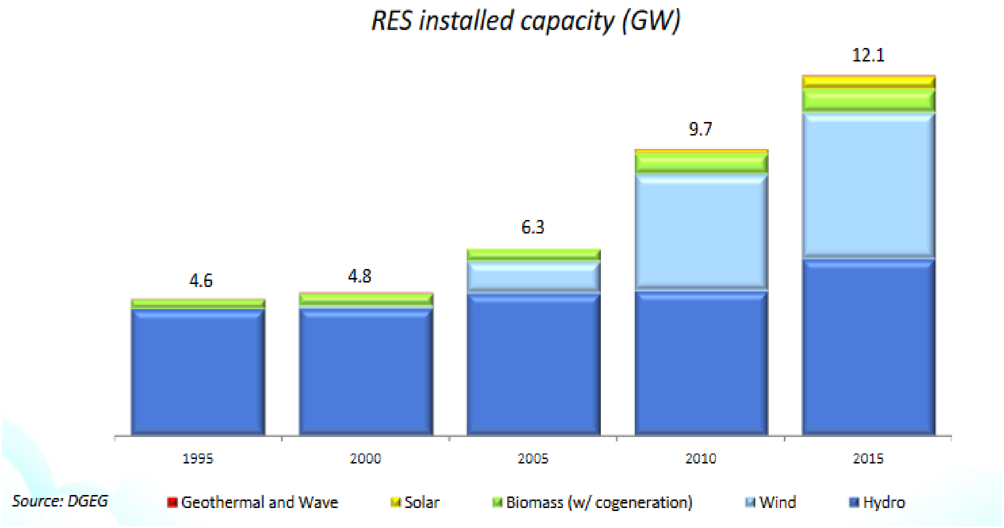
Biomass can be defined as the contemporaneous (non-fossil) biological material generated from the conversion of solar energy into vegetable matter and it is regarded as one of the most suitable ways of energy storage, thus being a real alternative to fossil fuels, as it is abundant, clean and carbon neutral.

Bioenergy is a form of energy obtained from biomass, and it is considered one of the most important renewable energy sources, as no other can be available in solid, liquid and gaseous forms via some processing [14].

Biomass relates to biological materials that can be used for industrial production or as biofuel. Biomass can likewise be used to produce heat or electricity. This diversity of applications has caused the production of biomass to become a growing industry in Portugal [15].

Presently Portuguese generation of energy from biomass stands for 556MW [13].

Portugal has a high biomass potential, especially in the form of forest residues and wood waste, which can be applied in energy generation, though it is already used by furniture industries and paper and pulp industries. The potential usage of biomass has a trend to increase. However, it is necessary to invest in the management and sustainability of the Portuguese forest.



Source: DGEG

Fig.4.1 RES installed capacity in GW from 1995-2005 [16]

In 2006 the government started a public tender to award 15 licenses for forestry biomass power plants which represent a total of 100 MW at an estimated investment of around $330 million (€ 225 million), promoting linkages with forestry resources. Preference has been given to two types of biomass power plants; up to 12 MW permitting economies of scale in electricity generation and ensuring a larger forestry biomass collection area and up to 6 MW allowing the development of small local development units. [19] Five thermoelectric plants were installed between 2007 and 2009 with 78 MW of total installed power that uses biomass as main fuel [15].

The EDP power plant placed in Mortágua started working in 1999 with the potential of 9 MW, 63 GWh/year and it consumes 110kton of biomass per year. This installation allows avoiding 29 kton/y of CO2 emissions [18].

Another thermoelectric power plant connected to the national grid with biomass as the main fuel is Centroliva located in Bila Velha de Ródão. Apart from that, those there exist many cogeneration power plants installed in forestry sector industries such as Companhia de Celulose do Caima, Portucel, Amorim Revestimentos, Soporcel, Stora Celbi and SIAF which take advantage of biomass for heat production [19].

In 2013 Portugal remains to be one of four the largest wood pellet demander and producer. Solid biomass and especially wood pellets represent stable and cheap energy alternative for thermal energy or energy production. Portugal produces pellets essentially for exporting and since 2008 has expanded its production and exported its pellets to Netherlands, United Kingdom, Belgium and Denmark almost entirely [20]. To encourage the construction and operation of forest biomass power plants Decree-Law 5/2011, of 10 January 2011, provided a beneficial feed-in tariff calculus for power plants that start operating until 31 December 2016 [15].

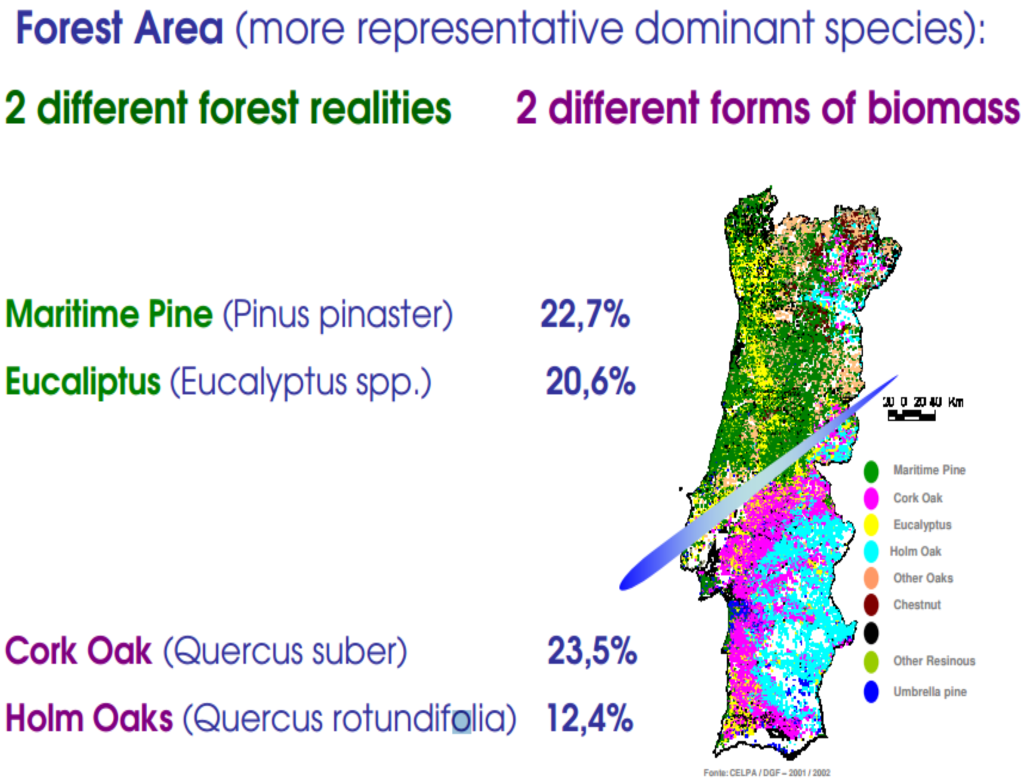


Fig. 4.2 Forestation in Portugal [17]

For future perspective biomass in the energy sector will increase in share. It means that large Dedicated Power Plants for over the country will create local Biomass Markets. [17] For 2020 stated target is 769 MW. [19] In 2017 new biomass power plant is going to be opened with the capacity of 14,75 MW with consumption 18 tonnes of forest biomass per hour – fuel will also come from residual organic matter generated by local wood processing business [21].

5. Solar Power

Portugal is characterized by best yearly solar radiation in Europe, with exception of Cyprus. Solar radiation values reach 70% more than in Germany, that means this type of electricity produced in Portugal can cost 40% less than in giant of Europe [22]. One of the oddest things about sunny Portugal is its lack of solar power – which is going to be changed.

The year 2016 has been impressive with records of renewable sources in electricity production. PV has 474 MW capacity installed [3]. In January, European Investment Bank (EIB) made public it had analysed grant funding for multiple Portuguese PV projects, containing one project by Expoentfokus featuring four PV installations with a combined capacity of 165 MW. The cost of the outline was measured at €130 million and EIB states on its website that it is in the phase of analysing grant funding for roughly €65 million [24].

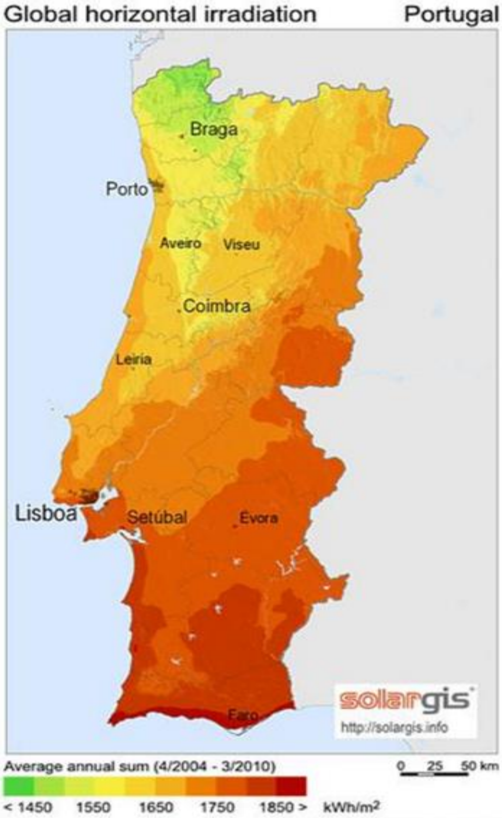
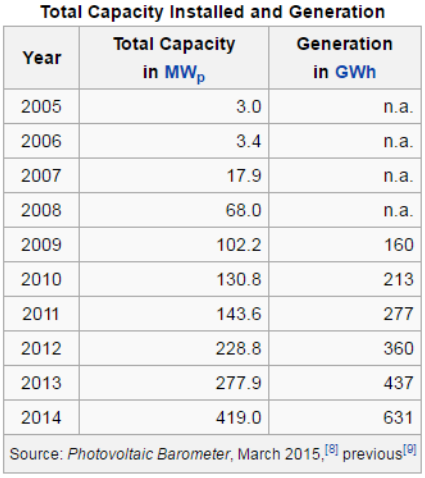


Fig. 5.1 Solar Radiation in Portugal [23]

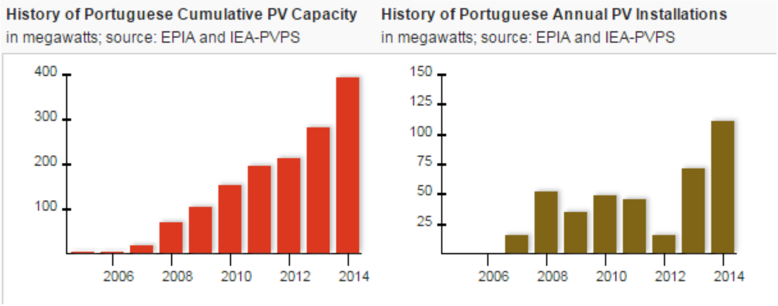
In 2005, Portuguese renewable electricity achieved only 16% of the total production of electricity – 8616 GWh, with the slight share of PV, only 3 GWh and 80% of this were off grid systems. Nonetheless, solar power contribution in Portugal energy sector was going only to rise.



Total Capacity Installed and Generation

Year	Total Capacity in MW_p	Generation in GWh
2005	3.0	n.a.
2006	3.4	n.a.
2007	17.9	n.a.
2008	68.0	n.a.
2009	102.2	160
2010	130.8	213
2011	143.6	277
2012	228.8	360
2013	277.9	437
2014	419.0	631

Source: *Photovoltaic Barometer*, March 2015,[8] previous[9]



History of Portuguese Cumulative PV Capacity
in megawatts; source: EPIA and IEA-PVPS

History of Portuguese Annual PV Installations
in megawatts; source: EPIA and IEA-PVPS

Fig. 5.2 Table of total capacity and generation of PV in Portugal from 2005-2014, Graph of history of Portuguese cumulative PV capacity in MW (red bars) and graph of history of Portuguese annual PV installations in MW [25]

In 2007 construction of 11MW Serpa solar power plant was completed. To produce more electricity, apart from using fixed-mounted conventional systems plant uses a specialist system to track the sun's daily pathway across the sky - PowerLight's PowerTracker system. The plant produces sufficient electricity to supply approximately 8,000 homes. The developer of The Serpa solar power plant was the Portuguese company Catavento which combines photovoltaic modules from Sharp, SunPower, Sanyo and Suntech. The financing of this investment was provided by General Electric Financial Services as part of its Ecomagination program. Generating electricity from the endless source - the sun, with no emissions or fuel costs, this power plant is situated on a 60-hectare hillside and is a model of clean energy production integrated with agriculture. As it allows to save more than 30,00 tonnes of greenhouse gas emissions a year compared to equivalent fossil fuel, this project supports a European Union initiative The EU agreed to cut by at least 20 percent greenhouse gas emissions by 2020, from 1990 levels [26].

Building Moura photovoltaic power station consisted of 2 stages – first ended in 2008, second in 2010. The power station is characterised by an installed capacity of 64 MW, with more than 376,000 solar panels. Approximately 190,000 panels (32 MW) are fitted on fixed structures, and 52,000 panels (10 MW) are fixed on single-axis trackers. Maora Power Plant represented half of a target for 2010 and big grid connected systems dominate the generation market in Portugal. From 2005 to 2010 power capacity of PV increased almost 45 times. [27].

In 2009 the Lisbon Region Supplier Market Plan has been opened with 6MW of installed power. It consists of 11 buildings with 28000 solar panels, 24 transformers and 59 inventors – with an investment 31 million Euro it enables to reduce the level of CO2 by 7000 t/year [13].

In 2010, Portugal crossed the origin of 50% of renewable sources in electricity production. This achievement was the result of government policies implemented at the beginning of the century. This policy led to PV power capacity increase almost 45 times from 2005 to 2010 [13].

In February 2014, a solar plant was opened in Coruche and it with a generation of 170 MWh per year. Society for Agroindustrial Development - the owner, expressed dissatisfaction in the Portuguese laws about the control in the production capacity for microgeneration and that resulted in installation only 1/10 of what they would like to invest. The power plant will save about 68 tonnes of carbon dioxide yearly [25].

Apart from investment in large PV systems, Portugal has a big share of residential PV systems. Not only households use such solutions to save money, but also Commercial buildings implement idea of producing green energy. More popular became BiPV – Built in PV, which allow to have special design, looking modern and smartly. [28] Future actions for Portugal consider an increase in PV installations – due to its potential in that country. It is essential to combine the hydro and wind generation (mostly during spring and winter) with PV (generally during summer), to achieve a higher average of renewable production along the year [13]. For 2020 Portugal has target to reach 720 MW from Solar Energy [19].

6. Summary

Answering the main target of this article, the presented results show that Portugal is having a great progress towards a greener country with less CO_2 emissions. These results also reveal that the policy measures taken 10-15 years ago had made a difference.

A good approach for even better results in the future, would be setting a new package of more ambitious measures for 2030. Also, knowing that, for example, the electricity price when it comes from renewable sources is lower than the electricity when it comes from fossil fuels, it could be a good way to push the local population to invest and even bigger effort to improve the renewable energies in the country.

Nowadays, Portugal is a great importer of energy, when it comes for fossil one, because it does not have petrol sources. However, that situation could change and Portugal would become an energy exporter, since there is a lot of renewable sources to exploit, but for that it would be crucial to improve the efficiency of the collection of energy.

Tab. 6.1. Comparison of renewable energy sources achievements in 2016 and goals for 2020 [8] [13]

Type of source	**Achieved in 2016, MW**	**Target to reach in 2020, MW**
Wind energy	5033	5300
Water energy	6024	8940
Solar energy	474	720
Biomass	566	769

As we can see by the results presented in Tab. 2, we can conclude that Portugal is in the right track, and if every country and everyone is focused in the same goal, it is possible to make Earth a better and healthier place to all of us.

Acknowledgements

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Enhancement in heat transfer of nano-engineered horizontal tubes

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Abstract

This thesis presents two studies with the aim of enhancing the heat transfer rate during condensation process of steam. First the effect of surface geometry was studied on three pure copper horizontal tubes. Integral fins and pin fins were produced. Condensation was performed on these tubes and their results were compared with an equivalent dimensional plain tube. The best results were obtained on pin fin tubes due to least condensate retention and highest surface area. Secondly, superhydrophobic nanostructures were coated on these tubes. Due to their remarkably low adhesion properties, increased droplet removal rate and reduced departing droplet size are seen. This will eventually increase the heat transfer over conventional film wise and dropwise condensation. This work investigates Al oxide nano-scaled coating with some Silicon oxide for binding purpose. The method adopted for this coating was vapour deposition (Modified Atomic Layer Deposition). Results obtained on superhydrophobic tubes were far better than uncoated copper tubes due to rapid shedding of condensate droplets.

Keywords: Condensation heat transfer; integral fin tube; pin f///in tube; condensate retention, superhydrophobic.

1. Introduction

Many common industrial systems such as power plants, desalinators and heat pipes rely on condensation. Condensation is a two-phase heat transfer process that utilizes the working fluids heat of vaporization. Latent heat transfer facilitates much larger heat flux than sensible heat transfer, which is important for two-phase thermodynamics systems.

Three different surface geometries were machined on tubes made of commercially available oxygen-free copper (99.9% pure). These geometries include plain tube, integral fin tube and pin fin tube. These tubes were tested near atmospheric pressure with downward flowing saturated steam for condensation results.

Nanostructures were imposed on these tubes with the aim of developing a surface that promotes robust dropwise condensation. Superhydrophobic surfaces, due to their remarkably droplet adhesion, were investigated for dropwise condensation.

1.1 Our Concern

Condenser is a major component in many engineering applications including power, process, air-conditioning, refrigeration and desalination plants. The aim is to reduce the initial and running cost while producing efficient and compact condensers. Apart from generation from renewable sources, improvement in the current generation system such as improving the condenser’s efficiency is still a massive benefit to be obtained

1.2 Energy Generation

Of a global install base of 4000 GWe that is set to double by 2030, 50% of that energy is produced by steam power cycles. These steam cycles rely on massive surface condensers to produce low pressures and temperatures at the outlet end of the steam turbines. The lower the pressure and temperature of the condenser, the higher the overall plant efficiency. However, these surface condensers are typically constructed from titanium tubes.

Condensation on these tubes occurs in a flimwise mode, which effectively creates an insulating layer of liquid around the metal pipe.

If the mode of condensation could be changed to the dropwise mode, the heat transfer coefficient has been shown to increase by up to a factor of more than 10.2 If this can be achieved, then overall plant efficiency increases of up to 5% may be attained, which translate into an overall energy savings of 100 GWe/yr.

1.3 Aims and Objectives

Following are the goals of this investigation:

- To study the effect of increased surface area on heat transfer rate.
- To examine the condensate retention on different tube geometries.
- To investigate the effect of superhydrophobicity on heat transfer.
- The main objectives of this project are:
- The main objectives of this project is to improve efficiency of condensers used in industry with very low cost.
- Manufacturing cost of condensers tubes is to be reduced to minimum value.

2. Literarature Review

2.1 Introduction

Different types of geometrically enhanced tubes are used with regard to enhanced condensation heat transfer for many years. These geometrically enhanced tubes are simple rectangular “integral-fin tubes” and three dimensional “pin-fin tubes”. It is often now realized that among the major aspects effecting the condensation heat transfer will be condensate retention. Surface tension effects also play the top role with condensation heat transfer. Heat transfer could possibly be enhanced simply by lowering the condensate retention or simply by increasing the active expanse of tube.

2.1.1 Condensation Heat Transfer on Horizontal Integral-Fin Tubes

The past few decades two dimensional “integral-fin tubes” are accustomed to increase heat transfer rate. Various investigators have got reported the enhanced heat exchange rate applying “integral-fin” tubes when compared to the simple plain tube. Important boundaries effecting condensation heat exchange rate had been spacing between fins, thickness regarding fins and also the condensate surface tension to density ratio.

Marto et al. [1] documented data for twenty-four different machined rectangular finned in addition to commercial integral-fin tubes with the condensation heat transfer rate using refrigerant R-113. The highest gain inside heat exchange rate ended up being about 7 with the integral-fin tubing having fin height, fin thickness and fin spacing of 1.0 mm, 0.5 mm in addition to 0.25 mm respectively. It was reported of which optimum fin spacing ought to be between 0.3 mm to 0.5 mm dependent on its fin height in addition to fin thickness.

Jung et al. [2] reported the study for the heat transfer coefficients by using low pressure refrigerants CFC11 and its alternative refrigerant HFC123 and medium pressure refrigerant CFC12 and its alternative refrigerant HFC134a on plain tube, low fin tube and Turbo-C tube. It was reported that the results of heat transfer coefficients of CFC11 outperformed its alternative refrigerant HFC123. While the results of heat transfer coefficients of HFC134a 4 outperformed its alternative refrigerant CFC12. Turbo-C tube showed the highest enhancement of almost 8 times greater than plain tube for all the refrigerants.

Kumar et al. [3] investigated steam and also refrigerant R-134a upon two various kinds of finned tubes which can be categorized integral-fin tubes (CIFTs) and also spine integral-fin tubes (SIFTs). With regard to both steam and also refrigerant R-134a, highest heat flux had been discovered being regarding spine integral-fin tubes (SIFTs).

A research has been completed by Briggs et 's. [4] to review the consequence associated with thermal conductivity on heat transfer rate for the condensation of steam and R-113 on the integral-fin tubes made of copper, brass in addition to bronze. The parameters varied were fin heights in addition to spacing between rectangular fins. Heat transfer was identified being much less evident on thermal conductivity for the low surface tension refrigerant R-113, however, for the case of steam, the effect of thermal conductivity was much prominent. While heat transfer enhancement was identified being centred highly with fin level in addition to fin spacing for R-113 but it was fairly much less prominent with the situation associated with steam.

Honda and Nozu [5] introduced the theoretical model for heat transfer results upon horizontal integral-fin tubes. They reported results associated with condensate retaining upon integral-fin tubes.

Rose [6] introduced the model pertaining for condensation heat transfer rates on horizontal integral fin tubes suggesting that ‘fin efficiency’ may have the crucial effect on heat transfer results which was afterwards incorporated by Briggs and Rose [7] into their theoretical model pertaining to rectangle-shaped fin tubes.

As per documented experimental studies, it has become observed in which integral-fin tubes showed the higher heat transfer enhancement for refrigerant R-113 of about 10.2 as reported by Honda et al. [8]. The highest gain heat transfer ratio for steam, found by Wanniarachchi et al. [9] had been around four. For ethylene glycol (which would be the medium surface tension fluid), highest heat transfer gain was 4.7 as reported by Briggs et al. [10].

2.1.2 Condensation Heat Transfer on Horizontal Pin-Fin tubes

Belghazi et al. [11] reported the study for the heat transfer rate of refrigerant R-134a on “Gewa-C” tube and found that the enhancement ratio was significantly improved compared to many of the integral-fin tubes.

Ali and Briggs [12] condensed ethylene glycol on eleven different three-dimensional pin-fin tubes by varying pin geometry systematically. The highest enhancement ratio of 5.5 was found for the pin-fin tube having pin thickness, pin spacing and pin height of 0.5 mm, 0.5 mm and 1.6 mm respectively. This enhancement found was about 24% higher than the equivalent two-dimensional integral-fin tube.

Ali and Briggs [13] condensed R-113 on five three-dimensional pin-fin tubes. The varied parameters were only circumferential pin thickness and spacing. The varied parameters showed effect on condensate retention. The highest gain in heat transfer rate was found to be about 6 for the pin-fin tube having 0.5 mm pin thickness and 0.5 mm circumferential pin spacing and 1.6 mm pin height respectively. This enhancement was about 13% more than the “equivalent’’ (i-e same longitudinal and radial dimensions) two-dimensional integral-fin tubes.

Briggs [14] reported the experimental study on the phenomenon of condensate retention of water, ethylene glycol and R-113 on twelve different pin-fin tubes and three integral-fin tubes. He found that retention angle was higher for the case of pin-fin tubes than equivalent integral-fin tube. It was also found that retention angle was higher for the case of R-113 than steam and ethylene glycol due to the lower surface tension to density ratio.

Ali and Briggs [15] further reported a semi-empirical model to predict condensate retention on pin-fin tubes. A systematic reported study of experimental data on three identical pairs of pin-fin tubes made of copper, brass and bronze using ethylene glycol and refrigerant R-113 as a fluid to study the effect of thermal conductivity has been given by Ali and Briggs [16]. Pin height was varied for each pair of test tubes. Copper tubes showed higher heat transfer enhancement than brass and bronze tubes due to higher thermal conductivity. Vapor-side, heat transfer enhancement ratio was relatively weakly dependent on tube thermal conductivity for refrigerant R-113 as copper is 18% and 28% higher than bronze at pin height of 0.9 mm and 1.6 mm respectively. Effect of thermal conductivity is strongly dependent for the case of ethylene glycol as heat transfer enhancement for copper is 34% and 66% higher than that of bronze at pin height of 0.9 mm and 1.6 mm respectively.

The best reported enhancement ratio for the case of steam, R-113 and ethylene glycol on pin-fin tubes are 4.1, 9.9 and 5.5 respectively (see Briggs [17], Baiser and Briggs [18] Ali and Briggs [12, 13]).

Based on the reported experimental data on pin-fin tubes, recently, Ali and Briggs [19] reported a semi-empirical model for condensation heat transfer on pin-fin tubes. Model showed agreement to data within ± 20%.

2.1.3 Condensation Heat Transfer on super hydrophobic materials

Superhydrophobic surfaces can cause water and even oils to roll off leaving little or no residue and carry away any resting surface contamination. Highly water-repellent surfaces (super-hydrophobic, ultrahydrophobic) are biologically inspired with the lotus leaf being the classic example. Surface texture, or roughness, is used to enhance the intrinsic hydrophobic chemistry of the surface, producing highly non-wetting surfaces.

Superhydrophobic surfaces exhibit extreme water-repellence, with water droplets resting on them with high contact angles, so water droplets shedding rate is extremely high so every time a new surface is available for heat transfer which enhances the heat transfer.

The principles of Superhydrophobicity were first outlined by Wenzel in 1936 and then by Cassie and Baxter in 1944.

Wenzel suggested that if liquid contact followed the contours of a rough surface then the effect of roughness should be to emphasize the intrinsic wetting tendency towards either film formation or enhanced contact angle. The contact angle observed on this type of surface is given by Wenzel's equation, $cos\Theta eW=rcos\Theta e$

Where the roughness factor r > 1 is the ratio of the true surface area of the solid to its horizontal projection and he is the equilibrium contact angle on a smooth flat surface of the same material. The involvement from the roughness is contained within r and the effect of surface chemistry in Θe, Fig. 1(a).

However, it can be energetically favourable for a liquid to bridge across the tops of surface features so that the droplet rests upon a composite surface of flat solid tops and flat air gaps between them, as described by the Cassie–Baxter relationship, Fig. 2.1.The contact angle is then given by a weighted average of the cosines of the contact angles on the solid and air using, $cos\Theta eC=(cos\Theta e)+(1-\varphi s)cos\Theta x$

Where φs < 1 is the fraction of the surface present at the tops of the surface protrusions, and $(1-\varphi s)$ is the fraction that corresponds to the air gaps, Θx is the contact angle on the gas in the gaps which is taken to be 180o. This always leads to an increase in contact angle when the droplet bridges the gaps. If they become filled with water Θx becomes 0o, and the contact angle decreases below that of a flat surface.

This second case is not the same as the Wenzel case as the roughness must be filled with liquid before the drop reaches it. This may occur on surfaces with contiguous pores, such as soils or sol–gels, where filling from below or rapid internal spreading (if contact angle allows) can occur. The two equations can be combined to produce a more general equation to cover the case when the contacting areas themselves are not flat (Fig. 2.1)

$$cos\Theta eCW=(cos\Theta e)+\varphi s-1$$

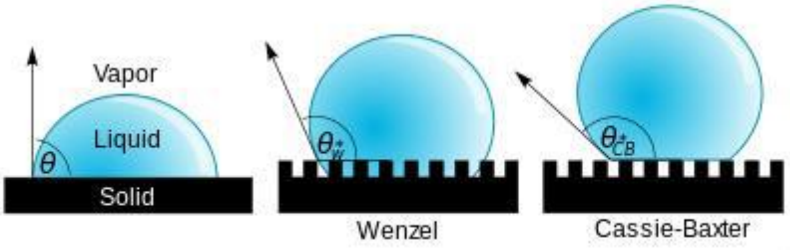

Fig. 2.1 Not flat contacting areas

Nicholus Dou [20] presented that superhydrophobic condensation does not showed much improvement than dropwise condensation and that is due to the merging of droplets pinned at the surface and increasing the thermal resistance. It is also believed that these results might have come due to silane layer which was used to functionalize the oxide.

Karlen E Ruleman [21] investigated condensation is hydrophobic surfaces created by silicon wafers, an findings showed that hydrophobic surfaces gave 70% larger heat transfer compared to hydrophilic surfaces.

Adam Paxon [22] found that two wetting states are possible. Wenzel state and Cassie Baxter state. In former one, the droplet is pinned and sometimes become difficult to shed off. While in state latter, the droplet contact angle is about 160-170 and therefore it creates superhydrophobic surfaces. Roughness of the surface decides which of above two state will be there.

3. Methodology & Experimental Setup

3.1 Apparatus

The apparatus (as shown in the Fig. 3.1) used for performing tests was made up of stainless-steel. It was consisted of an electrically heated stainless-steel boiler whose power was about 3 KW which was used for generating the steam for the condensation process. The capacity of the boiler was about 10 liters. There is a sight glass along-side of the boiler for indicating the boiler water level. The level of water inside the boiler insured the dipping of electrical heater completely. A well-insulated stainless-steel U-tube which has a bend of 1800 was attached to the boiler on one end. While the steam is being generated in the boiler, it does not have a uniform distribution.

To ensure the uniform distribution of steam, it passes through the U-tube. The U-tube was insulated by the glass wool covered by the aluminium tape to ensure the heat loss from the U-tube. The saturated steam was generated in the boiler and after passing through the U-tube moved vertically downward to the test section (primary condenser) by gravity. The other end of U-tube was attached to the test section. Test section is the primary condenser of the steam. A U-shaped glass manometer containing water present behind the test section is used for the pressure regulation of steam. It was ensured that the condensation of steam should be done on atmospheric pressure.

Test section contained a horizontally placed instrumented copper tube with coolant flowing inside it. The test tube could be viewed during condensation of steam through a 30 mm diameter circular glass window. A hair drier was used to remove the steam attached to the glass window for the clearer view of condensation on the test tube. All tests were performed at about atmospheric pressure with the steam flowing with a velocity of 0.48 m/s.

A portion of steam condensed on the instrumented tube and the remaining steam was then fed to the water cooled auxiliary condenser. The auxiliary condenser is tube in tube condenser whose purpose was to condense the excess vapour that was not condensed on the test tube. Water as a cooling medium passes through the outer tube while steam passes through the inner tube. Piping was done to circulate the coolant from the reservoir tank (capacity 400 gallons) to the primary condenser, auxiliary condenser and then to the drainage. After the final condensation of steam, the condensate returns back to the boiler through a 1 inch diameter tube having an overall length of 20 inches by gravity.

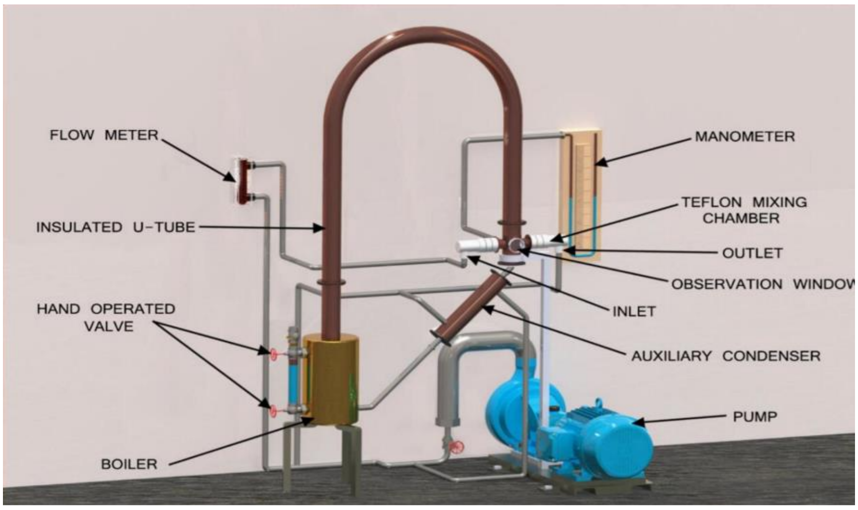

Fig. 3.1 3D schematic of experimental apparatus

3.1.1 Instrumented Plain Tube and Test Tubes

An instrumented tube used for the tests, was made of copper with an outside diameter of 14.7 mm and an inside diameter of 10.5 mm. The active length (condensing length) of the tube was kept 70 mm. Four K-type thermocouples (Omega, 0.5 mm diameter) were embedded inside the wall of the copper tube placed perpendicular to each other. To embed thermocouples, longitudinal slots (1 mm x 1 mm) were machined on the surface of tube, thermocouples were then placed into the slots keeping the tip of thermocouples at the midpoint of the active part of the tube and then longitudinal copper strips were forced fitted in the slots. The tube outer surface was then smoothly machined to 14.7 mm diameter (as shown in Fig. 3.2).

The test tubes were also made up of pure copper with internal diameter equal to 9.7 mm and the outer diameter is 12.6 mm. One tube is simple tube. One tube is integral fin with fin height 1 mm and width is also 1 mm. The longitudinal spacing between the integral fins was also 1 mm. The integral fins were generated on the mid of tube on a length of 70 mm.

The pin fin tube had the same pin dimensions as that of integral fin, with an additional circumferential spacing of 1 mm between the pin fins. The pins were 0.8 mm wide at the root, 1 mm at the pitch circle and 1.2 mm at the top.

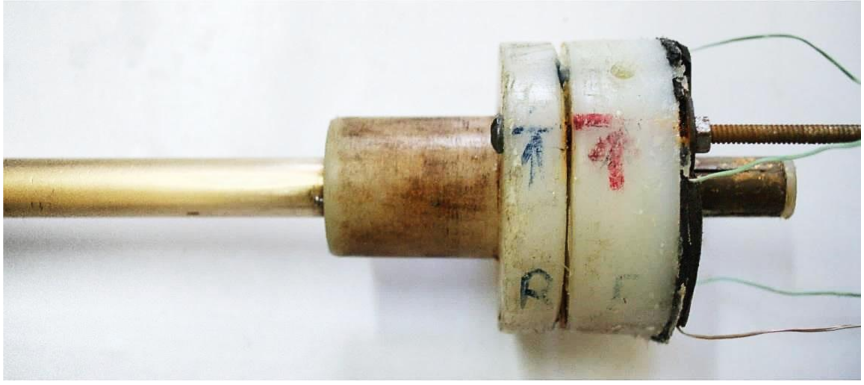

Fig. 3.2 Instrumented Copper Tube

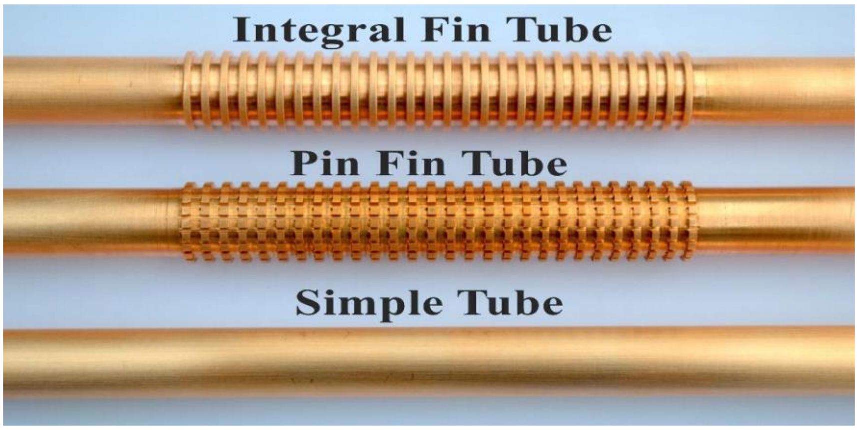

Fig. 3.3 Test Copper Tubes 12

3.2 Data Reduction

K-type thermocouples (having an accuracy of better than 0.1oC) were for the measurement off all temperatures. All temperatures were assessed accurately by directly linking thermocouples using the module associated with Agilent 34972A data logger (having the range of -100oC – 1200oC) as well as readings had been recorded using the pc through data acquisition system.

The vapor mass flow rate as well as vapour velocity was calculated through the power input towards the boiler heater. The equipment was well-insulated for the heat damage (boiler as well as test portion vapor temperatures were generally found to become within 0.1oC agreement). To stop heat loss from the test tube, Nylon inserts had been forced installed through both sides of the test tube towards the length up to active area.

The inside diameter connected with inserts ended up being kept 9.7 mm. On the lateral side of your tube, to stop heat transfer through the inactive subject of tube to test section, PTFE sleeves were used. PTFE blending chambers were placed at inlet as well as outlet to guarantee the proper blending of coolant to achieve a consistent temperature. The condensation heat flux ended up being measured through the difference connected with temperature connected with coolant coming from inlet as well as outlet on the test tube as well as the coolant movement rate.

The coolant movement rate ended up being varied inside range connected with 10 LPM in order to 24 LPM with all the difference connected with 2 LPM. A float-type movement meter (Omega) calibrated before experimentation having an accuracy of greater than ±2% was used for the h2o coolant movement rate measurement.

Test tube was inserted horizontally inside the test part keeping your thermocouples at angles connected with 22. 5o, 112.5o, 202.5o and 292.5o measured from the surface of the tube. This tube wall membrane temperatures were recorded right by information acquisition technique. The regular of a number of wall temps was and then used along with vapour temperature to acquire vapour-side temperatures difference.

3.2.1 Vapor-Side Temperature Difference

Vapor-side temperature difference was calculated by subtracting average of wall temperatures Tw from the saturated temperature Tsat and is given by:

$$dT = Tsat - Tw \tag{3.1}$$

Where,

dT = Vapor-side temperature difference; Tsat= Temperature of vapors at test section; Tw= Average of four wall temperatures of test tube.

3.2.2 Coolant-Side Temperature Rise

Coolant side temperature rise can be calculated by taking the difference of outlet temperature of coolant Tout and inlet temperature of the coolant Tin as:

$$\Delta Tc = Tout - Tin \tag{3.2}$$

Where,

ΔTc= Coolant temperature rise; Tout= Outlet temperature of coolant; Tin = Inlet temperature of coolant

3.2.3 Heat Transfer Rate through the Test Tube

Heat transfer through the test tube can be calculated from mass flow rate and coolant temperature rise as:

$$Q = m.Cp\Delta Tc \tag{3.3}$$

Where,

Q = Total heat transfer through the test tube; m. = Coolant mass flow rate; Cp= Coolant specific heat capacity; ΔTc= Coolant temperature rise.

3.2.4 Heat Flux

Heat flux can be calculated by dividing the total heat transfer through the tube to the active area of the tube:

$$\mathbf{q = Q/\lambda dl} \tag{3.4}$$

Where, q = Heat flux through the test tube Q= Total heat transfer through the test tube d = Outer diameter of the instrumented tube l = Active length of the test tube.

4. Results and discussion

4.1 General Results and Discussion:

The tests were performed with a vapour velocity of approximately 0.48 m/s at atmospheric pressure and saturation temperature. The validation of the experimental results were done by condensing steam on the plain horizontal instrumented tube. The results obtained from instrumented tube were in accordance with the Nusselt [23] theory on horizontal tubes for free convection condensation heat transfer rate can be seen in Fig. 4.1. The downward vapour velocity (0.48 m/s) cause the results obtained from instrumented tube to be 7% offset from the Nusselt line. Nusselt theory for the horizontal tubes is given by:

$$q = 0.729[g(\rho l-\rho v)hfgkl3\mu l(Tsat-Ts)D]14/\Delta T \tag{3.5}$$

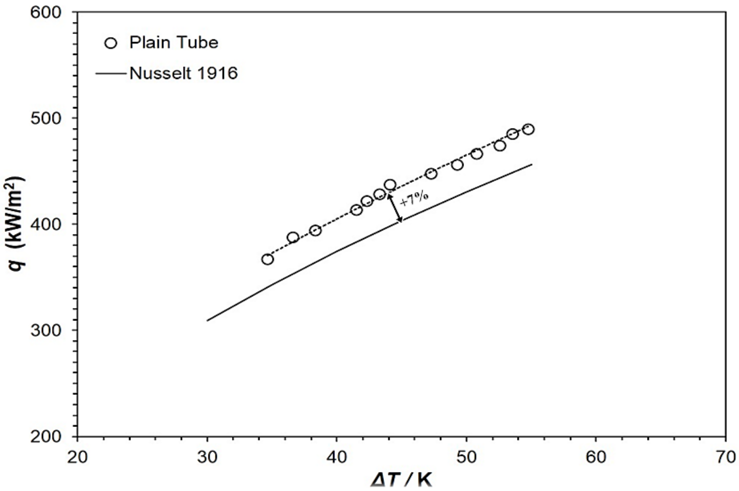

Fig. 4. 1 Validation of Nusselt [23] theory 16

Fig. 4.2 shows the graph plotted between heat fluxes on the horizontal axis while taking vapor side temperature difference on the vertical axis. Fig. 4.2 shows the condensation results of the plain tube, integral fin tube and the pin fin tube. The graph in Fig. 4.2 shows clear enhancement in heat transfer rate in case of integral fin tube and pin fin tube as compared to the results of plain tube. This is because of the increased surface area in case on integral and pin fin tube. The decrease in condensate retention also ease the process of condensation by offering less hindrance to heat transfer. The least condensate retention was observed for pin fin tube. The condensate retention for integral fin tubes and pin fin tubes can be seen from the Fig. 4.3 and Fig. 4.4.

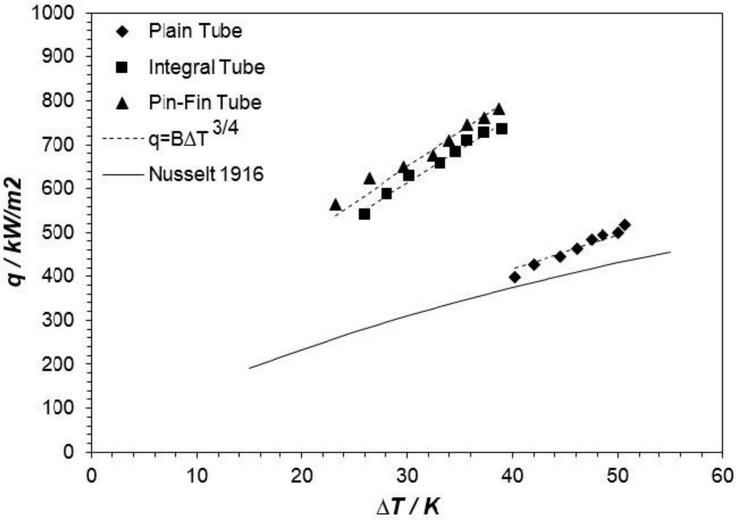

Fig. 4.2 Variation of Heat Flux with Vapour side temperature difference 17

The heat transfer is further increased due to the decrease in condensate retention for integral fin tube and pin fin tube. Pin fin tube shows the least condensate retention as seen in the Fig.. The condensate retention for Integral fin tube is also low as compared to plain tube.

This decreased condensate retention offers less hindrance to heat transfer. More surface area is available for heat transfer if less condensate sticks to the tube surface.

The superhydrophobic tubes were tested under the same environment as that for uncoated tubes. The results were highly increased due to less condensate retention and rapid droplet shedding. The heat transfer rates were enhanced dramatically. The superhydrophobic pin fin tube showed the highest heat transfer rate, whereas integral fin tube showed relatively lower heat flux. The enhancement for simple tube was found to be highest with respect to uncoated simple tube.

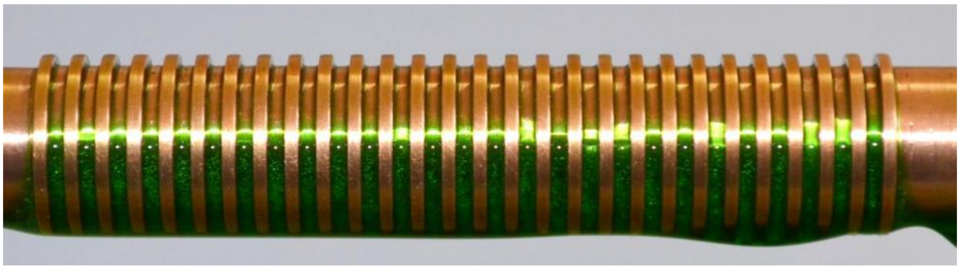

Fig. 4.3 Condensate retention on Integral Fin tube

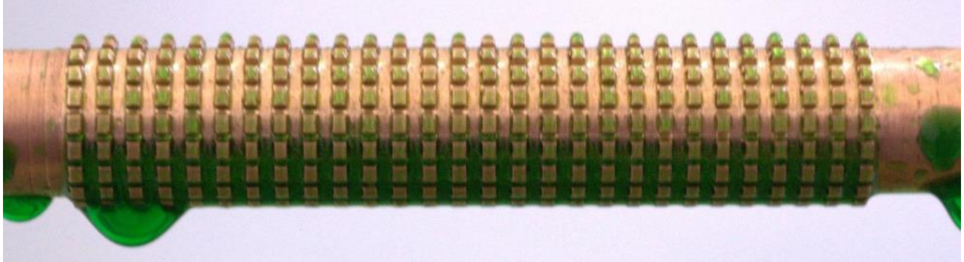

Fig. 4.4 Condensate retention on Pin Fin tube 18

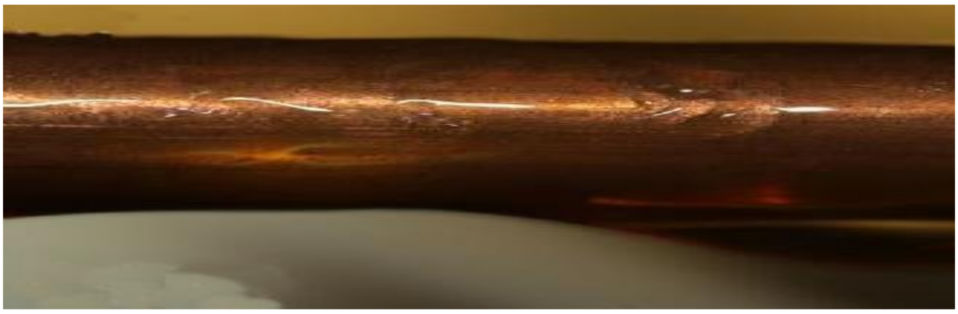

Fig. 4.5 Filmwise condensation on uncoated Plain Tube

Fig. 4.6 Drop-wise condensation on Nano structured Plain Tube

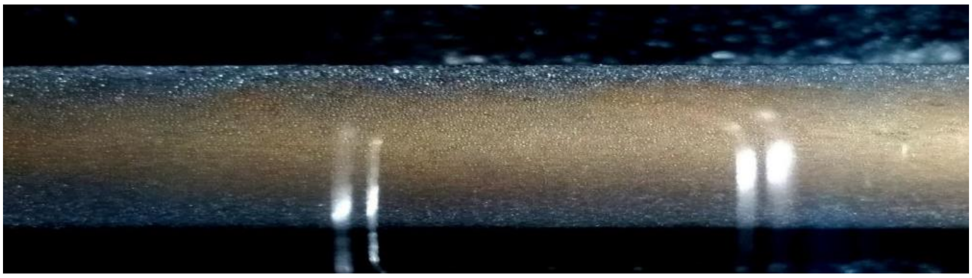

Fig. 4.7 Superhydrophobic condensation on Superhydrophobic Plain Tube

The increased heat transfer rate in case of superhydrophobic tubes is also due to the fact that rapid droplet shedding increases the active surface area available for heat transfer which further triggers the rate of heat transfer.

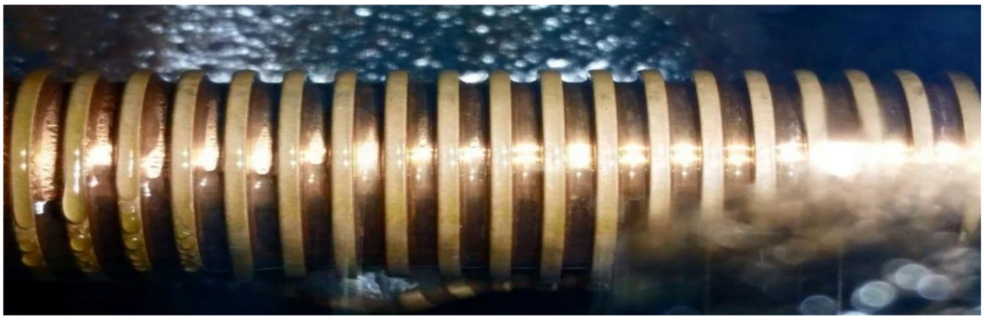

Fig. 4.8 Dropwise condensation on Superhydrophobic Integral Fin Tube

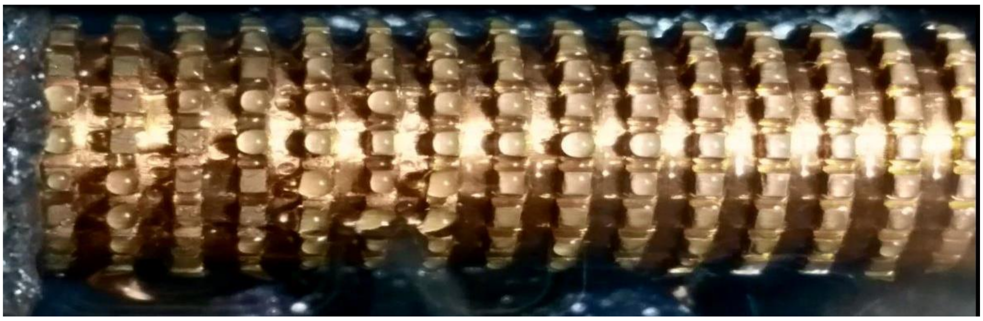

Fig. 4.9 Dropwise condensation on Superhydrophobic Pin Fin Tube

5. Conclusions

The present study gives accurate data for heat fluxes on horizontal copper tubes with variation in surface geometry and surface chemistry.

- With the uncoated surfaces, pin fin tube gave the highest heat flux among integral finned and plain tube. Enhancement in pin fin tube was found to be 92% from the plain copper tube. While for integral finned tube, it was found to be 83% of the plain tube. This was mainly due to the higher surface area than that exposed to the steam.
- Condensate retention on the lower half of the tubes causes thermal barrier. It was found that flooding/retention was more on integral finned tube than that of on pin fin tube.
- The super hydrophobic coating exceptionally increased the heat transfer due to least condensate retention on the tubes and thus larger surface area. This factor also reduced the thermal resistance caused by the condensate flooding on the lower side of the tubes.
- The enhancement in heat transfer for superhydrophobic plain tube with reference to uncoated plain tube is above 50%.
- The enhancement in heat transfer for superhydrophobic integral fin tube with reference to uncoated integral fin tube is 17%.
- The enhancement in heat transfer for superhydrophobic pin fin tube with reference to uncoated pin fin tube is 25%.

5.1 Future Recommendations

The future work proposed after this research includes:

- Replacing steam by low surface tension fluids like ethylene glycol or other refrigerants.
- Different dimensions for pin fins and integral fins can be applied to obtain different results.
- Superhydrophobic coating of oxides other than aluminum may also be applied to test.
- Coolant may also be changed, instead of water, to perform experiments.

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Nuclear Energy, ESBW Reactor

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Abstract

The ESBWRis a passively safe generation III+ reactor design derived from its predecessor, the SBWR and from the ABWR. The BWR has evolved over the years and now it has a very advanced technology, now called ESBWR. The reactor technology evolved and its containers have evolved at the same time. The ESBWR has a natural circulation of coolant and passive safety, so these aspects are really novel. The plant has a vessel and internal elements, a fuel, a system control rods and a boiler system gathers.The ESBWR is a reactor that is characterized forusing pasive security systems.The ECCS (Emergency Core Cooling Systems) of the ESBWR include a series of systems which transfer very efficiently the decay heat from the reactor to the water pools that are found out side the containment, main taining the nuclear fuel inmersed in water and properly cooled. All this makes the ESBWR one of the safest reactors in the market.

Keywords: ESBWR, Reactor, Passive Safety, Vessel, Rod

1. Introduction

The Economic Simplified Boiling Water Reactor, ESBWR, is the evolution later the Boiling Water Reactor (BWR). It was discover at first of december of 2005.The ESBWR program actually began in the 1990s, when GE developed the simplified boiling water reactor SBWR, but GE stopped it because the output power of the SBWR was too small.Taking advantage the test results of the original SBWR and the advanced construction and experience of ABWR boiling water reactors, the design team has produced a simplified and economically top-of-the-line reactor.The design of the ESBWR plant is based on the use of natural circulation and the use of passive safety to improve plant performance and reduce the cost of the reactor by eliminating several systems (The reactor construction has been reduced by 15% with With respect to the BWR).Natural flux is achieved by increasing the height of the vessel and thereby eliminating recirculation pumps, safety system pumps, safety systems of diesel generators, as well as valves and some engines.

ESBWR commercial attraction:

- Improves performance over BWR
- Passive safety system design (Reduce maintenance, minimizing exposure and radiation doses)
- Use of natural flow
- Increase in production
- Reduction in the use of materials for its construction (In contrast the materials used are more effective in case of natural disasters and reactor failures)

2. Technical and design aspects

The Simplified Economic Boiling Water Reactor, known as ESBWR, is an advanced third generation reactor still under development. It evolved from the Advanced Boiling Water Reactor (ABWR) and the Simplified Boiling Water Reactor (SBWR) technologies. All of them based on the previous design of the Boiling Water Reactor (BWR).Our reactor philosophy is based on simplicity. Due to the use of mechanisms of natural forces, it is possible to eliminate active components and mechanisms, resulting in a simpler design and, in turn, reducing its size.

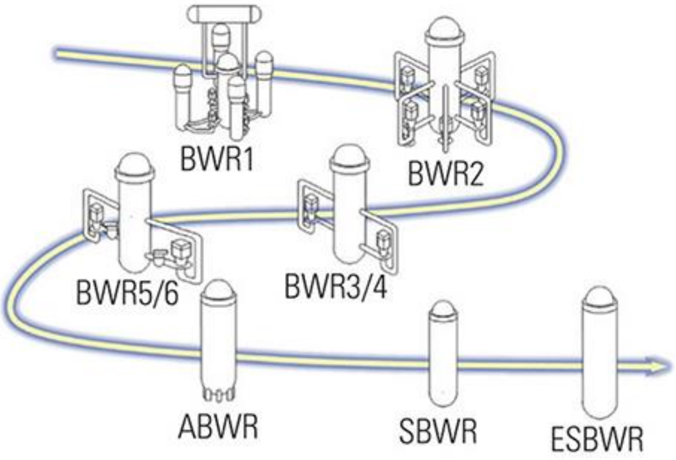


Fig. 2.1 Evolution of the reactor vessel of the BWRs [9]

Continuing with the design, the Fig. below shows the evolution of the containers of the boiling water reactors.

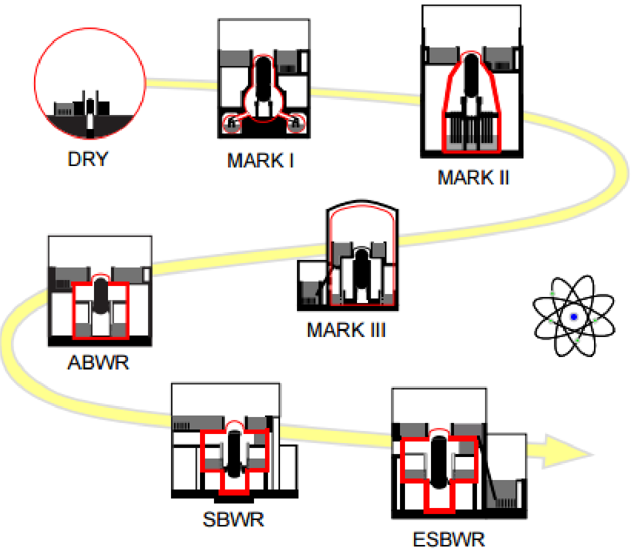


Fig. 2.2Evolution of BWR containers [9]

The first models were spherical in shape, coinciding with the current PWRs. However, the BWR quickly changed the design of the "pressure suppression" containment by a relaxation pool, obtaining several advantages:

- High heat transfer capacity.
- Lower design pressure.
- Superior ability to perform rapid depressurising.
- It allows filtering and retention of the products generated by fission.
- Large supplies to provide water in the event of an accident.
- Compact and simplified design.

Reducing the design pressure in the containment together with the removal of the external recirculation circuits allows the containment to be more compact (and, by extension, the reactor building).Below is the difference between sizes of an SBWR plant and an ESBWR, which takes up less than half the space.

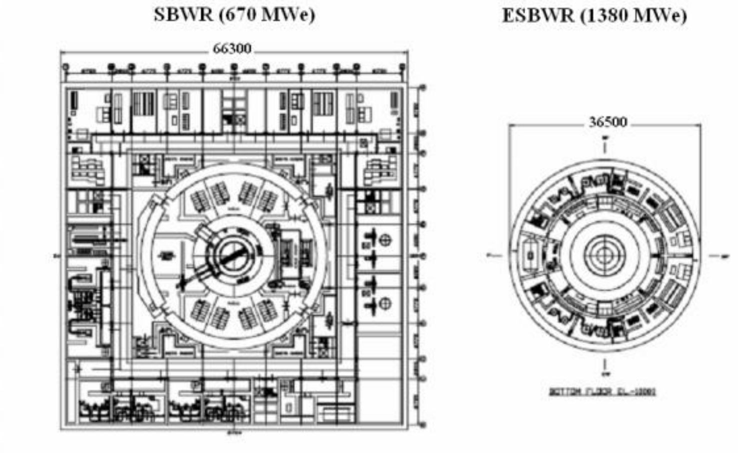


Fig. 2.3. Comparation between SBWR and ESBWR [11]

2.1. Design features

We will have to compare our ESBWR reactor with previous BWR designs.In terms of operation, an ESBWR plant is based on the use of natural circulation and passive safety features, in order to improve plant performance and simplify design.Natural circulation is achieved by an increase in the height of the reactor vessel. With regard to passive safety systems, they have the advantage of eliminating the need for various systems, such as recirculation pumps, safety system pumps, safety system of diesel generators as well as pipes, motor valves and controllers, in addition toAC power. All this implies a decrease in the volume of construction compared to the ABWR.In the last 10 years, it has evolved from the 670 MWe of the SBWR to the 1550MWe of the ESBWR.All this has led to economic benefits in the design, while the natural flow of recirculation in the core has been improved, retaining original features of the SBWR passive safety system, also improving safety.

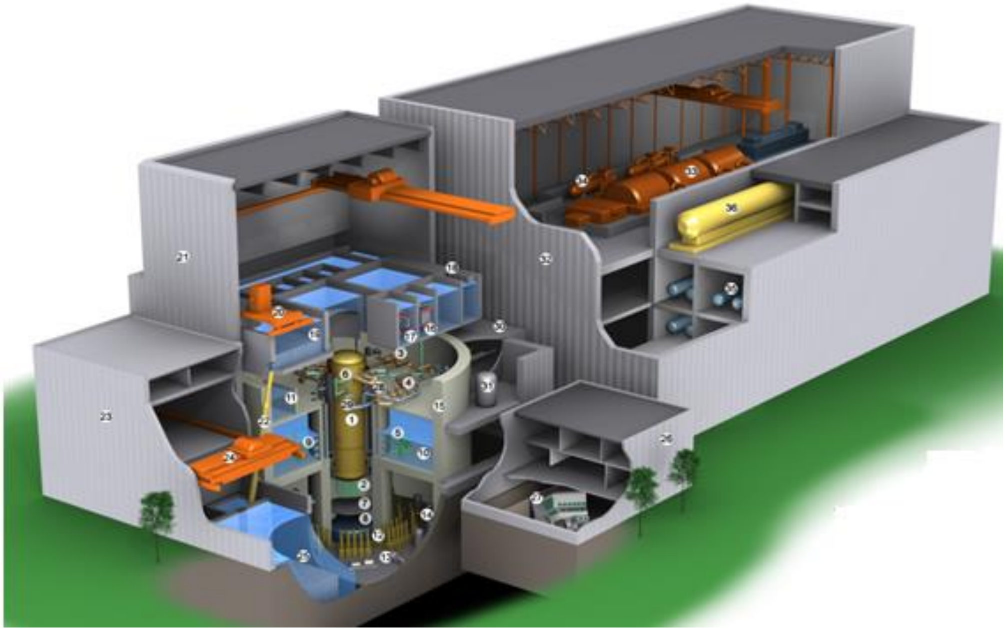
In summary, the advantages that this system brings with respect to its predecessors are:

- Improving overall plant performance
- Modular design of the passive safety system
- Natural circulation
- The increase in production and the reduction in quantities of material
- Shorter fuels, offering a reduction in Central pressure.
- Improved steam trap to reduce pressure drops.
- A high chimney to enhance the thermal conduction head for Natural circulation.

Tab 1. Benchmarking features between BWR designs

Parameter	**BWR/4**	**BWR/6**	**ABWR**	**ESBWR**
Power, MWt/MWe	3293/1098	3900/1360	3926/1350	4500/1550
Haight of the vessel/day, m	21.9/6.4	21.8/6.4	21.1/7.1	27.7/7.1
Number of containers of fuel	764	800	872	1132
Height of active fuel, m	3.7	3.7	3.7	3.0
Density of power, (kW/L	50	54.2	51	54
Recirculation pumps	2 (external)	2 (external)	10 (internal)	0
Number and kind of CRDs	185/LP	193/LP	205/FM	269/FM
Scurity system of pumps	9	9	18	0
Security of dissel generators	2	3	3	0
Alternative closing	2 SLC Pumps	2 SLC Pumps	2 SLC Pumps	2 SLC Accumul.
Control and intrumentation	One analogue	One analogue	Multiple digital	Multiple digital
Damage in the core	10^{-5}	10^{-6}	10^{-7}	10^{-8}
Security building, m^3/MWe	120	170	180	130

2.2. Scheme of the facilities



1. Reactor pressure vessel	2. Precise motion control bar units
3. Steam isolation valves	4. Safety valve
5. SRV deactivators	6. Depressurising valves
7. Lower platform of dry well equipment	8. BIMAC retention piece
9. Horizontal Vents	10. Suppression pool
11. Gravity cooling system	12. Hydraulic control units
13. Water Reactor Cleaning / Shutdown Cooling Pumps (RWCU / SDC)	14. RWCU / SDC Heat Exchanger
15. Containment vessel	16. Insulation Capacitors
17. Passive containment cooling system (PCCS)	18. Moisture Separators
19. Fuel Storage Pool	20. Recharging machine
21. Reactor building	22. Inclined fuel transmission machine
23. Fuel Building	24. Fuel Handling Machine
25. Spent Fuel Storage Pool	26. Control building
27. Main Control Room	28. Main steam lines
29. Water supply lines	30. Steam tunnel
31. Standby liquid control system	32. Building of turbines
33. Turbine Generator	34. Reheating Moisture Separator
35. Feed water heater	36. Open feed water heater and tank

Fig. 2.4. Scheme of the facilities [9]

2.3. Main Components of the ESBWR

Reactor vessel and internal elements: The main source of steam generation is the reactor core. This is inside the vessel. We are facing a security barrier against all those products that arise from fission.Both in the ABWR plant and in its evolution, ESBWR, the reactor pressure vessel (RPV) has the same diameter, 7.1m. However, they differ in length, with the ESBWR being 6 m (27.7 m) higher. This is because, in order to improve the thermal conduction head for the natural circulation flow, it has a high chimney.

The most important features that incorporate the RPV and its internal elements are the following:

- Steam nozzles with flow restrictors.
- Double feed water nozzle with thermal sleeve.
- Support of the vessel by sliding blocks.
- The floor is located below the head, relatively.
- Elimination of large nozzles located below the core.
- Use of a ring-shaped forged frame above and below the core.
- A large chimney to ensure natural circulation of the flow in the core.

Fuel: The core of the reactor consists of a vertical cylinder containing a large number of fuel groups, control rods and nuclear instrumentation. All of them are inside the reactor vessel. The refrigerant flows up through the core. The layout of the core and the lattice configuration are shown below:

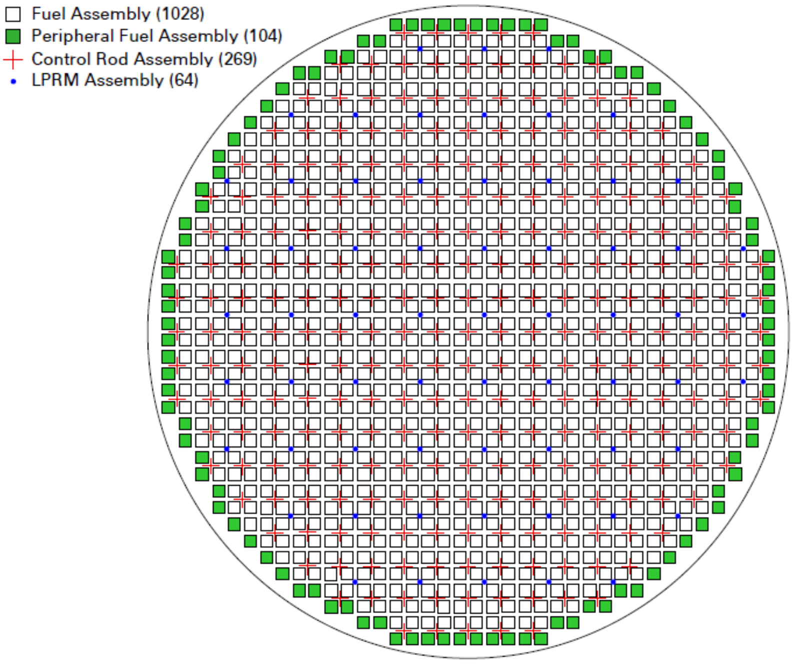


Fig. 2.5. ESBWR core configuration [9]

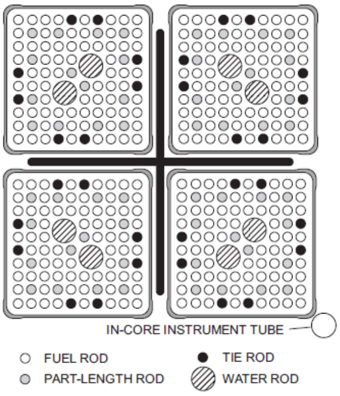


Fig. 2.6. Four fuel packing modules (cells) [9]

Mechanical designs of both fuels and control rods are basically identical to their predecessors, except for the first boiling water reactors. However, it should be noted that evolutionary improvements have been made throughout the history of the BWR.As shown in the image, the cells are distributed in groups of 10x10, fuel rods of about 3 meters in length, 14 bars of partial length that extend around two thirds of the active nucleus and two large bars of Water central.With respect to the fuel, it is possible to emphasize its support of 24 months of continuous cycle and the wide margin of cold stop.Control Rod Drive System, CRDS: Changes in core reactivity during power operation are controlled by CRDSs. This happens through the movement and positioning in small increments of these neutron absorbing rods within the nucleus. They act by means of the signals obtained from rod control and the information system (RC and IC).The amount of neutrons absorbed by the rods will depend on the location in which they are located. Thus, in turn, both the reactivity and the heat output obtained will vary. The CRDS also incorporates a rapid control of the rod against a respo nse of signals (manual or automatic) of the reactor protection system (RPS). When the RPS sends the emergency stop, the CRDS provides an essential negative reactivity to stop the reactor.

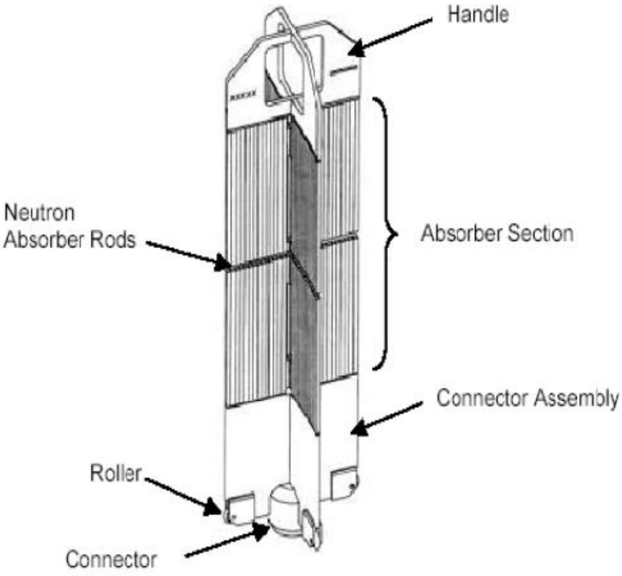


Fig. 2.7. Rod Control Drive System [11]

The CRDS consists of three main elements: Fine Motion Control Rod Drive (FMCRD), Hydraulic control unit (HCU) and Control Rod Drive Hydraulic System (CRDHS).

Nuclear Boiling System, NBS: The mission of the NBS is to direct the flow of steam from the steam outlet nozzles of the RPV to the main turbine. In each of the steam outlet nozzles is a throttle of the flow of the same, limiting it in case there would be a break in the steam line. This system incorporates provisions to relieve RPV from overpressure conditions. Also included in this system is a part of the nuclear island of the feed water system.Flow of natural circulation in the reactor: We will briefly describe what this process is, the fundamental pillar of our reactor, and the main differences that are incorporated in it with respect to other reactors. The natural circulation in a reactor is based on the fact that the refrigerant, generally water, circulates without pump, due to the different densities of its cold and hot sections.

As more significant improvements:

- The increase of water level by about 8.2 m.
- Increased driving head (due to increased driving of the circulation flow).
- Its design allows an acceptable flow band.
- Eliminates forced risks that occur in other plants.
- It has a large diameter vacuum tube, to be able to check the chimney in 2 phases of flow.

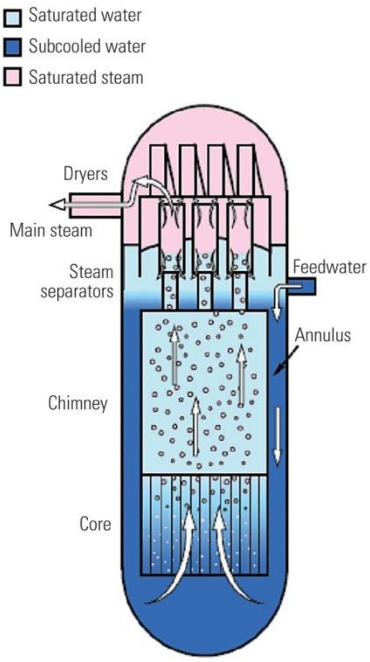


Fig. 2.8. Types of flow that run through the points of the reactor vessel [11]

The natural circulation flows can be driven either by gravity or by pressures of the same system, some of its characteristics being:

- The dependence of the central flow with respect to the direction of the water height.
- Losses through the circuit.
- The conduction of the water height is proportional to the height of the core and the chimney.
- Phase for losses in the core coefficients.
- Double phase to examine the data / correlation data of all flow events, in a smaller chimney.

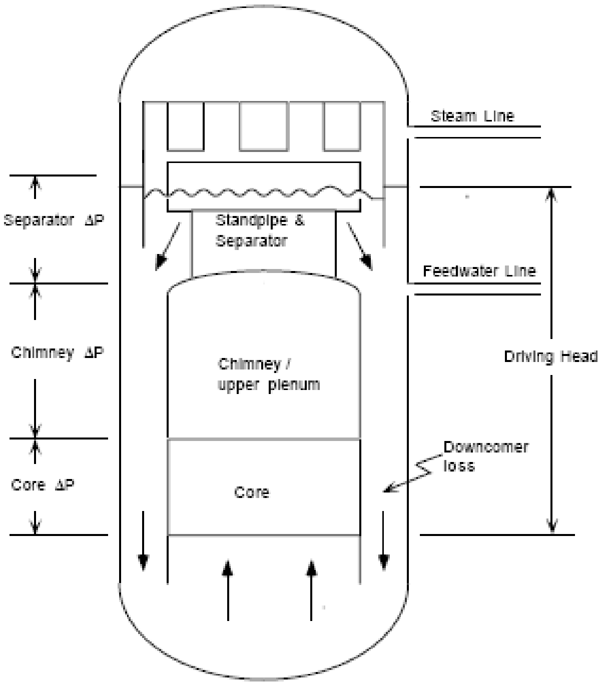


Fig. 2.9. Scheme of the flow [11]

The following image corresponds to a simple water level diagram. Through it, the importance of the pipes through which the water is lowered by means of gravity, the water feedback line, the increments in the sections of the chimneys and the direction of the flow inside the core are emphasized.The arrows refer to the direction of the natural circulation and the path of the water flow that runs throughout the reactor, as well as the main parts involved in this cycle. In short, using natural circulation in ESBWR is more effective than using jet pumps or internal plants and prevents anomalies in flow recirculation.

3. Security Issues

Emergency core cooling system (ECCS) constitute a technological safeguard whose function is to maintain adequate cooling of the core within the range of operational conditions, considering any possible breakages, including the design base accident (DBA). They have been designed to that the geometry of the core does not change after a loss of refrigerant, allowing its cooling and avoiding the release of fission products. These systems attempt to limit both the temperature and the oxidation of the fuel jacket to minimize its fragmentation and the generation of hydrogen produced by the oxidation of that jacket. All of it is to protect containment.

3.1. ESBWR reactor ECCS

The ESBWR is a reactor characterized by the use of passive safety systems. These systems operate without pumps, increasing design safety, integrity and reliability, while simultaneously reducing the total cost of the reactor. Only natural circulation, condensation and gravitational flow are used to safely cool the reactor, which allow the recirculation of the refrigerant inside the pressure vessel (RPV). By not relying on recirculation pumps, forced cooling, instrumentation and associated controls, the reactor can continue to be refrigerated for 7 days without the need for operator action or electronic feedback.

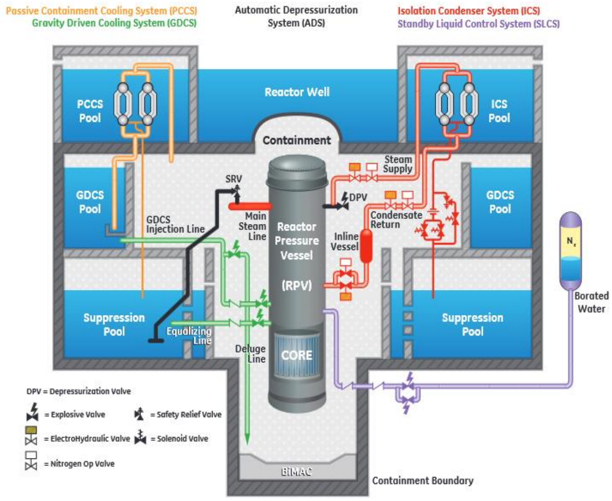


Fig. 3.1. ESBWR passive safety system [9]

ESBWR's ECCS include a serie of systems that efficiently transfer the decay heat from the reactor to the water pools that are outside the containment, keeping the nuclear fuel submerged in water and suitably cooled. These systems are: Gravity Forced Cooling System (GFCS), Automatic Depressurization System (ADS), Passive Containment Cooling System (PCCS), and Isolation Condensation System (ICS).

3.2. Gravity Forced Cooling System (GDCS)

The GDCS is a low pressure refrigerant injection system that starts with the reactor refrigerant inventory being reduced. It consists of separate pools located at the top of the containment (9.9 m above the fuel), and pipes connecting the pools to the reactor vessel, with the blast and check valves. The pools are isolated from the dry well, which is the part of the containment that surrounds the vessel and which has no water.When a LOCA

(Loss of coolant accident) is produced, the refrigerant is drained from the GDCS pools to the reactor vessel thanks to the depressurisation that occurs from the rupture of a flowing pipe from or to the vessel. With the gravity, is overcome the pressure difference between the wet well and the reactor vessel.The GDCS is a passive system that does not require electrical energy to operate or the intervention of an operator. Once the reactor is depressurized, the GDCS is capable of injecting large volumes of water into the reactor vessel and can keep the core submerged up to 72 hours after a LOCA. In the event that the core melts and damages the bottom of the vessel, allowing the molten fuel to reach the bottom of the dry well, the GDCS will drain water from its pools into the dry well.

3.3. Automatic Depressurization System (ADS)

The ADS is designed to release the vapor pressure of the main steam lines and the reactor vessel if conditions require it. This allows the GDCS to take action to recover the refrigeration.It consists of safety relief valves (SRV) and depressurising valves (DV), as well as their associated instruments and controls. During a LOCA, rapid depressurising of the vessel is required, a function performed by the ADS, which provides sufficient time for the GDCS to inject the refrigerant into the core allowing the PCCS and ICS to maintain the core temperature below the limits defined.

3.4. Passive Containment Cooling System (PCCS)

The PCCS is capable of maintaining the reactor refrigerated for 72 hours after a LOCA. It Kkeps containment below design pressure of 413.7 kPa without using active safety systems.The system consists of 4 low pressure condensers submerged in large pools located at the top of the containment. Steam and the mixture of steam and nitrogen enter in the PCCS capacitors through an inlet vapor line coming from the dry containment well. This vapor is condensed and drained to drainage tanks which are connected to the reactor vessel by means of check and explosion valves. The pool water removes heat and by this way condenses the steam, so that steam is produced which is vented to the atmosphere. The non-condensable gases are separated and sent to the suppression pool by means of a ventilation pipe, because they can reduce the efficiency to condense the steam.

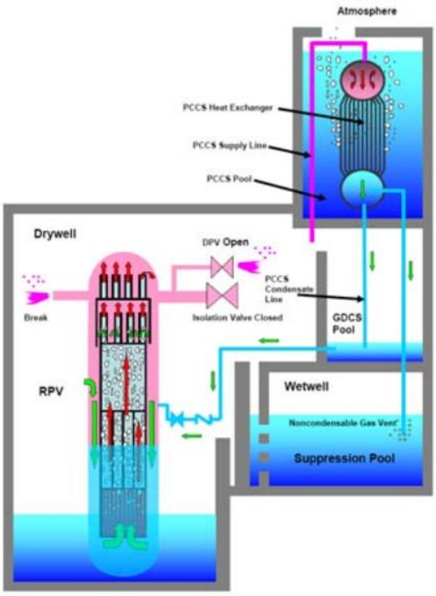


Fig. 3.2. Scheme of PCCS [10]

3.5. Isolation Condensation System (ICS)

When a SCRAM (Safety Control Rod Axe Man) is produced the ICS removes the decay heat to prevent reactor overheating. It is a passive high pressure system with 4 loops of insulated capacitors submerged in the pools that are at the top of the containment. It operates similarly to the PCCS, except that the ICS in normal operation is connected directly to the steam supply lines and the condensate is drained directly into the reactor vessel. It is a closed cycle.

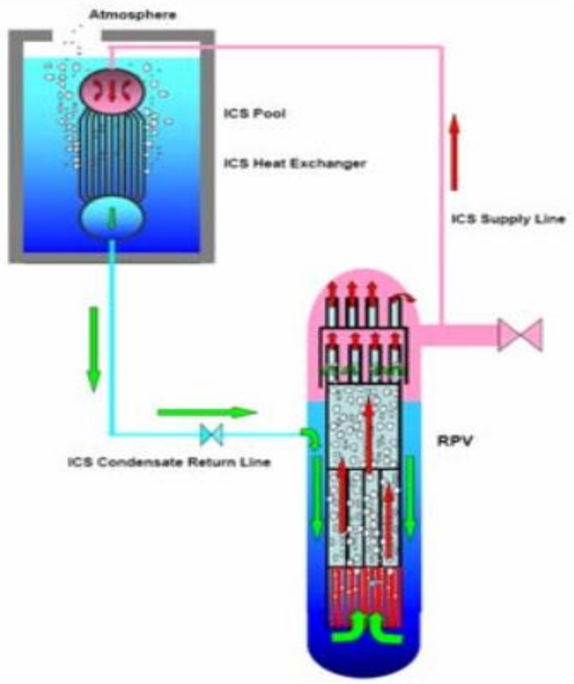


Fig. 3.3. Scheme of ICS [10]

3.6. Auxiliary Emergency System (AES)

Other support systems in case the ICS, ADS and GDCS are not in operation are: the Nuclear Fusion Cooling System (BiMAC) and the Standby Liquid Control System (SLCS). The BiMAC is located underneath the reactor vessel. It consists of a pipeline structure that allows the core to cool down during a very serious accident. These pipes facilitate cooling above and below the core by using water from GDCS swimming pools. The SLCS is a passive stop system that injects borated water into the reactor to control reactivity. Borated water is stored in a nitrogen tank.To recharge water from heat exchanger pools once it is running out, diesel pumps are used to collect water from storage tanks.The ESBWR is the safest reactor in the world. It has a lower rate of core damage (term used in the probabilistic risk assessment; CDF) than any other third generation reactor (Generation III or III +).

4. Economic Aspects

4.1. Conception and contruction

Design: ESBWR reactors use only natural circulation to cool the core. By this way, the reactor is simpler and cheaper. Like all the active safety injection systems of the PWR-type reactors are not needed, the design is simple. There are fewer pumps, pipes and valves, and also all associated instrumentation disappears, reducing construction costs. Between ESBWR and other types of plant there is a 25% reduction in the number of pumps, valves and motors. There are only 3 major systems, including emergency systems. Many less than in a PWR that contains many complicated and sensitive systems. According to GE-Hitachi (GEH) there are 11 systems less than in the other plants.

Materials and construction: The lower complexity of the plant makes the construction easier, reducing construction costs. In addition, having standardized components have a cost reduction, considering that it is easier to produce each element. Also, by simply using a smaller amount of material the construction of the plant is cheaper and also the dismantling. Simpler construction means faster construction, resulting in lower costs.

Research and development costs (R & D): The elements and technologies used are not new, they have been used for the construction of GE-Hitachi ABWR reactors, so there is no need to develop new or investigate. They are only modified versions of previous systems. From an economic point of view, this reduces the research and development costs of this type of reactor. GEH enjoys the previous experience gained from reactors already built to improve the concept, without having to start all over again.

4.2. Development

Maintenance: With fewer systems to maintain, operating costs decrease. The passive circulation works in any case, since it is maintained thanks to the laws of physics. In operation as in an accident situation, the plant can operate alone, which means less cost.

Fuel and recharge: The reactor uses a fuel enriched to 4.2%. A little more enriched than other reactors currently in operation, so the fuel will be more expensive. However, fuel does not represent a significant part of the total cost of the operation of the plant as to have a large influence on the final price. In addition, the refueling cycle of the plant is 2 years, longer than in other plants (year or year and a half) that compensates the higher price of fuel.

Center life: The reactor is designed for a life of 60 years, greater than that of the previous reactors that had been designed for a life of 40 years, this allows a better profitability of the investments. Also, the reactor is built in a modular way, the systems are independent and can be changed (except for the vessel), which makes it easy to replace poor equipment. With higher efficiency and power, ESBWR reactors are also more cost effective than ABWRs.

Accident: The use of natural circulation for cooling is also an advantage in the case of an accident because the reactor can be cooled only, without operator intervention, with pool water, without external electricity or diesel engines, and can last up to 7 days with all emergency systems. That is why the costs of emergency systems are lower. If passive circulation is not sufficient, the reactor is designed to be cooled only with water from the outside.

This type of reactor, as discussed in the safety aspects, has the lowest accident probability of all nuclear reactors. Thus, we can say that ESBWR reactors are very reliable, but we must keep in mind that there is currently no ESBWR in operation or under construction, so the final design can change if there are problems during construction or operation. Once the reactor is built, some problems can occur, changing the results of probabilistic analysis. From an economic point of view, it is imperative to have a very low accident probability, because any accident means additional costs, and therefore a loss of money. From this point of view, ESBWR reactors are very interesting.

Fig.s: For now, it is not possible to know precisely the costs of construction and operation of this type of reactor because, so far, none have been built in the world. But GEH wants ESBWR reactors to have the lowest operating, maintenance and maneuvering costs among all nuclear reactors, without giving precise Fig.s or estimates. There are currently two ESBWR reactor projects in the world, both in the United States, Virginia and Michigan. But they are only responses to tenders and cost Fig.s are not available.

Here, we can see the estimates of a study by SIA Partners for the construction costs of the different types of current nuclear power plants. We can see that, in fact, the costs of ESBWR plants appear to be lower than the others, in terms of construction and exploitation.

Tab 2. Benchmarking between different models

Manufacturer	**Model**	**Power MW**	**Price $/kWe**	**Development costs**
Areva	EPR	1600	1540-1740	Medium
Westinghouse	AP1000	1100	1100-1260	Medium
Mitsubichi	US-APWR	1700	1300-1400	Medium
GE-Hitachi	ABWR	1460	1270-1500	High
GE-Hitachi	ESBWR	1600	1190-1250	Low
Rosatom	VVER1200	1200	1000-1100	Unknown

5. Summary

Analyzing the third-generation ESBWR reactor, the years of experimentation and operation of the BWR (precursor of this reactor) reactor have proved to be one of the best technologies in the world for generating electrical energy through nuclear ways.

After the elimination of a series of components, but with the development of passive safety systems and natural circulation, we reached a generation of reactors with a great advance at operational levels.

The new design combines safety enhancements (in the event of an accident the ESBWR can remain 72 hours without any action by operators or external power supply) with a reduction in facilities to produce a safer nuclear power plant (probabilistic analysis of risk indicates that a core accident would happen once in 59 million years) and more productive with a lower cost.

In short, ESBWR reactors seem to be a very good alternative for nuclear reactors of the future. They are cheaper than other reactors, which is often a very important condition in choosing a new nuclear power plant project. But all this is just estimates. The first ESBWRs built will allow you to know more about the exact construction and operating costs of this new type of reactor.

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Geological CO_2 sequestration - a temporary solution for mitigation of climate change

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Abstract

In response to increasing amount of anthropogenic carbon dioxide emissions, carbon capture and sequestration technologies have emerged to mitigate power generation based CO_2 sources. Attempts to evaluate several CO_2 capture systems have been undertaken, as well as investigation of applicability of few essential sequestration concepts. Although, the methods for capture of CO_2 are well-developed and commonly used in industrial processes, selection of optimal economically and technically sequestration approach is still obscured and it's rigidly dependent on individual circumstances. Thus, crucial viable options for carbon dioxide storage have been described with main focus on dedicated geological storage and application in enhanced oil recovery process as CO_2 sequestration feasible technologies. The results of CCS implementation regarding potential impact for mitigation of carbon dioxide, have been examined.

Keywords: carbon capture and sequestration, enhanced oil recovery, CCS, carbon dioxide mitigation, CCT

1. Introduction

Indisputably, increase in anthropogenic greenhouse gas emissions has a harmful effect on the environment. One of the most significant factors that contribute to proceeding climate change are growing carbon dioxide emissions that mainly account for global warming. Moreover, recently researches were able to prove, that development of CO_2 mitigation technologies and adaptation to future greenhouse warming strategies is not of little importance. Not long ago, the results of investigation about the effect of growing amount of accumulated GHG in the atmosphere has been published, stating nonlinear climate sensitivity with tendency to more rapid climate change than predicted before [1]. In addition, as a part of Kyoto Protocol, many of developed and industrialized countries have agreed to legally binding limitations in emissions of GHG. Thus, the necessity of CO_2 mitigations technology implementation seems essential worldwide to efficiently introduce reduction of anthropogenic global greenhouse gas production to meet the binding requirements of emerged commitments.

According to the IEA statistics from 2012 (Fig. 1.1), two sectors that are mainly responsible for the highest rate of carbon dioxide emissions are electricity and heat production, and to the lesser extend transportation [2]. This publication is focusing mostly on managing the CO_2 emissions that correspond to power generation, as it accounts for the 41% of total anthropogenic CO_2 sources [2] and seems to have the most severe environmental impact.

The efficiency pathway' to reduce produced CO_2 plays an important role in the fossil-based power generation processes, as improved efficiency levels lower the amount of fuel that has to be used per single unit of energy produced. Only one percentage point of efficiency of a conventional pulverized coal-fired plant states for 2-3% difference in CO_2 emitted [3].

To face the escalating GHG problem and need for sustainable energy production, clean coal technologies are being developed. Fossil-fuelled power generation systems have received proper incentives to increase efficiency and decrease GHG emissions by development of advanced technologies, such as Integrated Gasification Combined Cycle (IGCC). Nowadays, to meet the requirements of clean coal concept, several technological methods are available: pre-combustion capture, as well as post-combustion capture or oxy-fuel combustion. Pre-combustion capture methods allow CO_2 to be economically separated and captured, then transported and somehow sequestrated [4]. Post-combustion capture method corresponds to separation of carbon dioxide from flue gases resulting from combustion. On the other hand, oxy-fuel combustion is a process in which fossil fuels are burned in pure oxygen and in recirculated flue gases (flue gas is necessary to control the combustion temperature), rather than in air. As a result, concentration of nitrogen in flue gases is decreased and relative economical CO_2 capture is viable [5].

Carbon capture and sequestration seems a key technology to mitigate CO_2 emissions, not only from burning coal, but also natural gas [3]. However, for this to be viable way to economically reduce GHG emissions, proper sequestration method for the purpose of utilizing captured carbon dioxide has to be established. Promising way for utilizing in context of storage is application of captured CO_2 in Enhanced Oil Recovery (EOR). Carbon Capture, Utilization and Storage (CCUS) and EOR offer means to meet crucial energy goals worldwide, such as reliable and cost-effective electricity from fossil fuelled power plants, simultaneously mitigating GHG emissions and increasing the amount of produced oil which will help to maintain national energy security.

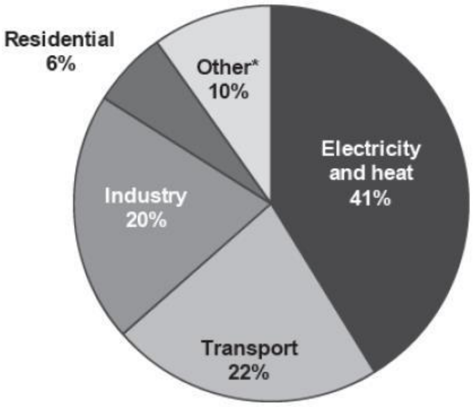

Fig. 1.1. Carbon dioxide emissions by sector [2].

2. Overview on carbon dioxide capture methods

To be able to geologically sequestrate carbon dioxide it requires to be captured and refined to meet conditions that will allow it to be economically stored or reused. In this chapter we shall focus on capture of CO_2 produced in large-scale industrial processes, with special focus on power generation facilities. Extracting CO_2 from ambient air would not be economically viable due to low (in technological, not ecological terms) concentrations of the greenhouse gas in the atmosphere, globally exceeding the point of 400 ppm [6]. Transportation and small scale building applications such as heating are also not a subject of this article as more demanding to be made useful in terms of a large-scale impact on the environment. The technologies for capture of carbon dioxide are mature and widely used in industrial processes such as urea production, steel and cement industries among others. In these applications however the greenhouse gas is usually not sequestrated and exhausted into the atmosphere. Methods and their basic principles are as shown on Fig. 2.1.

Regarding power plants, three main methods of capturing CO_2 may be distinguished. In the Oxyfuel combustion method carbon dioxide is not the gas that needs to be extracted. The combustion process is done in a mixture of pure oxygen and some recirculating CO_2; combustion in pure oxygen would lead to too high temperatures inside the chamber, which may damage the boiler. The oxygen is usually extracted from air using a very energy consuming cryogenic separation method. Combustion in oxygen environment causes flue gases to contain mostly CO_2, however to meet the requirements for storage it requires drying and usually removing some additional pollutants such as sulphur and nitrogen oxides. Pre-combustion separation methods involve the process of gasification of the fuel making it preferred capture process to be used in Integrated Gasification Combined Cycles. In such process, the fuel – usually coal or biomass, but it can be applied to waste to energy installations as well – is reacting with air or oxygen and steam under high temperatures producing so-called syngas – a mixture of mainly CO and H_2 among other gases present in the mixture.

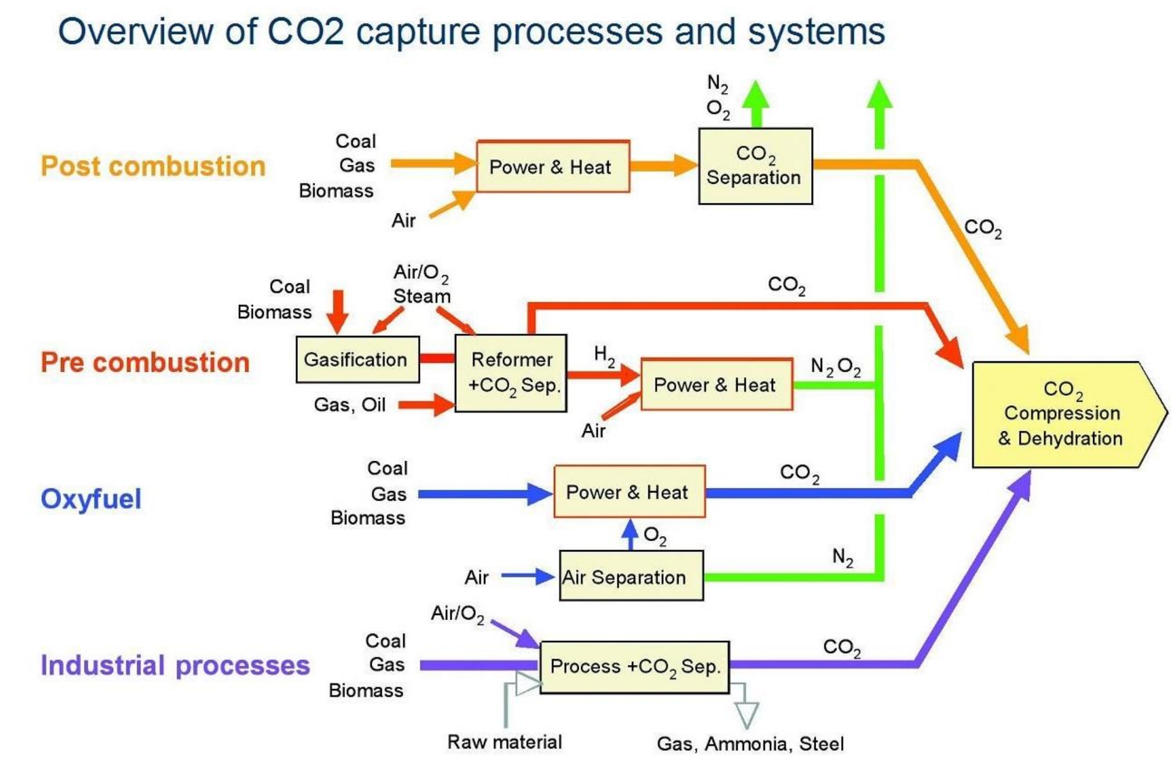

Fig. 2.1. CO_2 capture methods [2].

Carbon Monoxide is later reformed using water-gas shift reaction producing more hydrogen and CO_2. After separation hydrogen is used as a clean fuel and CO_2 is ready for further processing. However the most interesting methods concerning existing power plants are applied after the combustion process. The most mature and developed technologies use sorbents to capture the gas, which is later released in a stripper if the sorbent circulates, or in the vessel in which they are captured if the sorbent is not circulating. Post combustion capture stands out as the best method to integrate to existing power stations because it does not require any modification in the combustion or power generation processes, unlike other aforementioned methods. It can be retrofitted into any existing facility that has enough space to build the flue gas treatment installation. It is worth mentioning that the purity of CO_2 obtained this way is highest among all methods reaching as high as 99.9% which could be used in the food industry. The obvious drawback of all methods is a significant decrease in the plant efficiency. Each way of capturing requires vast amounts of energy in the process, either in form of electricity to run the absorbers, compressors, pumps, and other appliances or on form of heat delivered as steam, refrigeration of tanks etc. In post-combustion CO_2 capture approximately half of the energy is used to regenerate absorbing solvent and about a third to compress the gas. The decrease in efficiency leads to cost of increasing by 45-80% per kWh in PC power plants and increase in capital cost of building the plant by the same amount [2]. The values discussed in this section are estimated for new, high-efficiency plants, the costs of retrofitting already existing plants might increase cost of electricity by as much as 3 times. Considering gas-fired power plants increase in capital costs range between 40-70% however the increase in cost of electricity only ranges from 35 to 55% [2]. The most suitable for carbon capture seem to be the IGCC plants with capital cost increase from 20 to 65% and cost of electricity (COE) increasing by 20 to 55%. In all cases emissions of CO_2 drop by 80-90% [2], which is a significant drop and money saved on carbon emission taxes have to be taken into account when estimating costs of carbon capture installation. With the decrease in efficiency to produce the same amount of electric power one has to increase fuel consumption to meet the energy demand. For this reason in case of old power stations it might be a better idea to wait for the end of their life cycle and build new ones using the CCS technology instead. The missing power might also be generated using new renewable sources build to cover up the difference in power supply caused by capturing CO_2.

3. Large scale geological CO_2 utilisation methods

After the carbon dioxide has been captured it has to be utilized. There are numerous ideas on its application, but only two of these are mature, tested and worldwide used on a large scale. The concept is relatively simple. Captured carbon dioxide is pumped underground and trapped in rock formations to prevent it from reaching the atmosphere. Although at first it may seem as if the method is not reliable it is widely used and tested by the industry for many years. Basically geological sequestration can be divided into methods purely dedicated to store CO_2 and methods aimed to recover more fuel from the geological formation. The gas may be pumped to the deep saline aquifers, which sealed by cap rock will store carbon dioxide permanently or for the same purpose depleted oil and gas fields may be used. However CO_2 can also be pumped to fields that are not yet fully depleted, but economically or technologically not viable to continue extraction. Such methods include Enhanced Oil Recovery (EOR) which will be further explained in section 3.1. and Enhanced Coal Bed Methane Recovery (ECBM), which allow to capture methane in process of injection of carbon dioxide into source rock. This process however is usually too expensive to even cover the cost of pumping the gas, so this method is being researched to find out if pumping of unprocessed flue gas would be economical, as nitrogen in flue gases also allows to extract methane [7].

3.1. Enhanced Oil Recovery

Enhanced Oil Recovery is a process of implementing different techniques, that lead to increased amount of crude oil which can be obtained from extraction from an oil field. Among these techniques, some stand out in terms of potential for efficient CO2 sequestration. The basic idea of CO_2-EOR method is ilustrated on Fig. 3.1. At the moment, EOR is the only mature technology that uses carbon dioxide in significat amounts that have potential for considerable mitigation of anthropogenic GHG emissions from burning fossil fuels. The CO_2 EOR industry is an example of a succesful track record of safely injecting carbon dioxide into geologic formations [8]. CO_2 EOR technology and equipment is comparable for the one envisioned for sequestration, with infrastructure, wells, alike way of dealing with supercritical CO_2 in terms of low temperature and high pressure. In addition, similar subsurface simulation, characterization tools are used. The only differences are intentions (EOR cost-cutting purpose's is to minimalize amount of carbon dioxide used in opposition to sequestration goal) and concerns regarding monitoring and resposibility for stored CO_2 in long-term vision. EOR by CO_2 injection provide potential economic gain from increased oil production. According to IPPC special report for CO_2 capture and storage, 5% up to 40% of entire amount of original oil in place (OOIP) can be recovered during primary extraction. Secondary recovery allows to obtain addictional 10-20% of original oil in place using water flooding [2]. Among other miscible agents, CO_2 application for EOR resulted in an incremental oil recovery of average 13,2% of OOIP [2].

For enhanced CO_2 storage through EOR process to be viable, oil reservoirs have to fulfil certain criteria. Reservoir's depth has to be more than 600m, immiscible agents used in injection have to be sufficient enough for gravity oil in range of 12-25° API(heavy and medium oil gravity). Furthermore, generally preferred miscible flooding is avaible for light oils(25-48°API) with small viscosity [2]. In case of miscible floods, required pressure in the reservoir has to exceed the minimum miscibility pressure (10-15 MPa) [2]. Other kind of requirements that has to be meet for miscible and immiscible flooding include thickness of reservoir lower than 20m, appropriate angle of the storage place, homogenous character of formation, as well as low vertical permeability. Regarding more horizontal reservoirs, absence of flow of natural water is desired and prefference for major gas cap and natural fractures occurs. However, permeability, along with thickess are not crucial in that case [2].

IPCC Special Report regarding CCS contain estimation how much CO_2 would be stored in reservoirs suitable for EOR. According to the source, global capacity for CO_2EOR possibilities is evaluated to have geological sequestration potential for 61-123 $GtCO_2$. However, if CO_2-EOR would be engineered to optimize carbon dioxide storage in future, those numbers would increase. In order to make this happen, CO_2 storage has to gain more economical value [2].

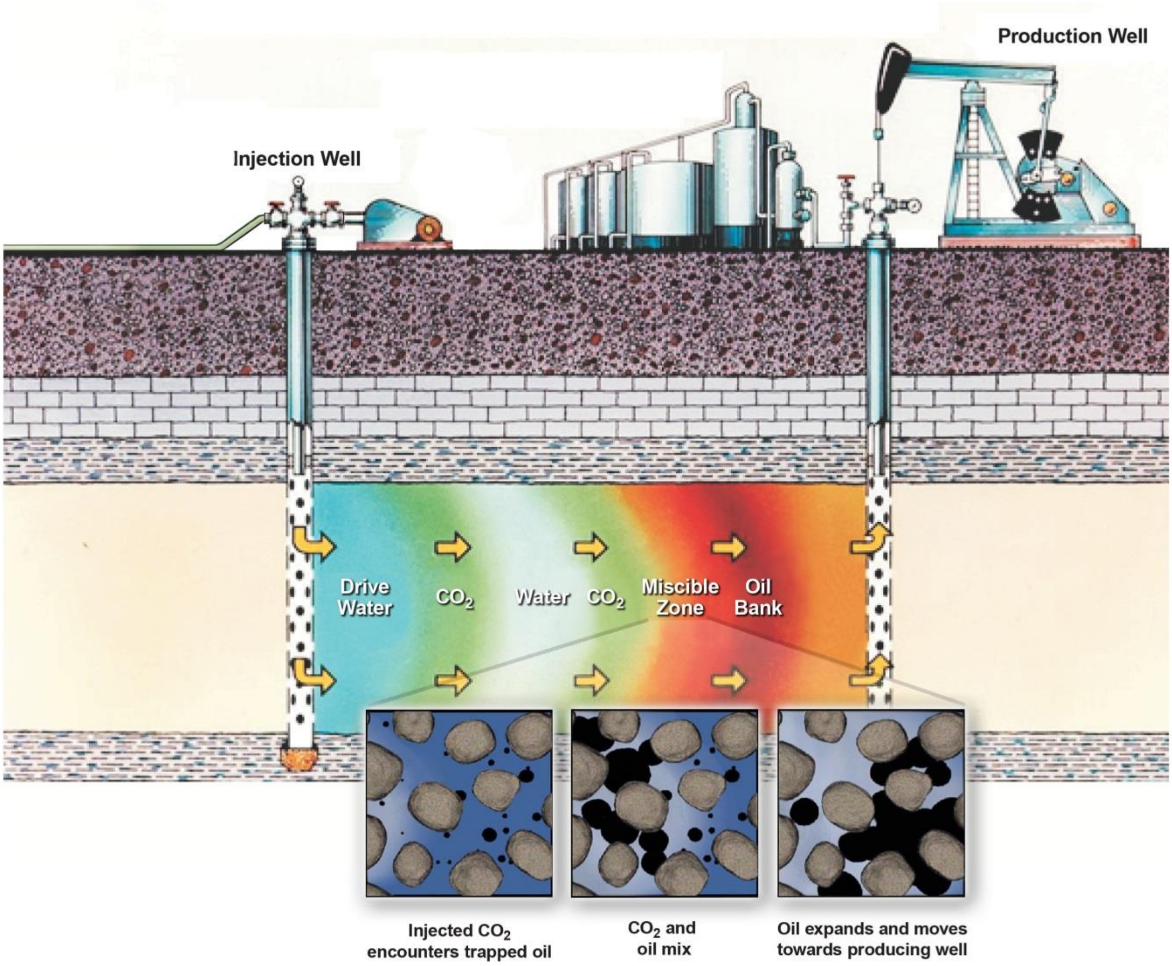

Fig. 3.1. CO_2 and water application for flushing residual crude oil from a subsurface rock formation [8]

3.2. Dedicated Geological Storage

Geological storage traps CO_2 underground using several mechanics. The main idea is to pump the carbon dioxide under impermeable rock layers, so they cannot escape, however there is a number of things that can help store the greenhouse gas including conversion into solid minerals or adsorbed on the micropores on surfaces of coal either physically or chemically. This has a huge influence of safety of geological storage as displayed on Fig. 3.2.

The longer injected CO_2 is kept underground, the bigger amount is becoming tapped into the surroundings. That process takes thousands of years to contribute into safety of storage, so the sites chosen for injection should not be as seismically passive as possible, since possible tectonic movements may result in leakage that would lead to release of carbon dioxide back to soil, water and finally atmosphere, diminishing all the efforts undertaken to prevent the pollution. However dangerous that sounds, there are numerous applications around the globe which, after years of operation prove that injected CO_2 indeed stays in the geological formation. This experience is further supported by a number of natural CO_2 deposits and widespread experience in storing gaseous fuels in geological formations for sake of national energy security, a practice extensively used all over the world. In terms of industrial geological sequestration of CO_2, 14 out of 38 existing CCS projects use Dedicated Geological Storage as their way of storage [9]. Only three of them, however are fully functional and operating on a commercial scale right now (2016), the rest being in evaluation or construction phase.

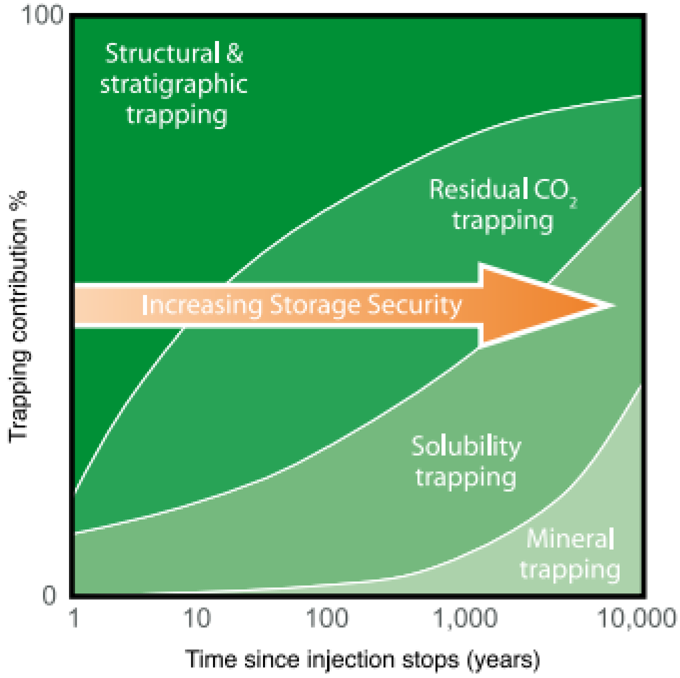

Fig. 3.2. Trapping mechanics dependence on time of injection [2].

Together they would be able to capture and permanently utilize up to 27.3Mt of CO_2 each year [9]. This amount is still insignificant – it could sequestrate about 0,76‰ in comparison to worldwide anthropogenic emissions in 2014 of CO_2 equal to 35.9 Gt [10] or 1,77‰ if we take into account that about 41% of the emissions were connected with electricity and heat generation. However this is one of very few technologies that are mature and tested enough to be used on a large scale at this very moment. Estimates from 2005's IPCC report on CCS estimate earth's capacity to be able to store 2 trillion tonnes of CO_2 [2], though Global CCS institute states that this might be underestimated, and the potential might be greatly higher. Based on this data we can see that if we hypothetically stored 100% of carbon dioxide produced by humans, we will run out of storage space in about 50 years. With current CCS capacity we have enough reserves for roughly another 70 millennia.

4. Conclusions

Carbon dioxide sequestration is by no means a sustainable method of mitigation of the climate change. However with rapid increase of global temperature it is the best method we can use right now to drastically cut the emissions in newly build power plants or retrofit the existing ones, allowing us to meet the energy demand and provide enough relatively clean energy. However desired, full transmission to renewable sources will not be soon technologically possible or economically viable worldwide, clean technologies such as sequestration and storage of carbon dioxide can directly help humanity today to keep the energy supply at desired levels, while radically cutting greenhouse gases emissions. Transition phase from fossil based energy sources to renewable has already begun but will most probably not finish for many years to come. Carbon capture methods can also be utilized in power plants fired by biomass, or naturally-derived gas where flue gases may be used as i.e. feedstock for energy-rich algae for production of biogas, contributing to creation of renewable, sustainable and reliable energy supply system.

Nowadays, the only mature, well-tested application that consider significant amount of CO_2 usage – and simultaneously storage – is Enhanced Oil Recovery. However, CO_2-EOR is optimized to maximize revenues from secondary oil extraction, which prevailingly result in minimizing the amount of CO_2 used in the process. In order to improve the effectiveness in terms of CO_2 emission mitigation, CO_2 storage process has to gain more economic value. Thus, the development that accounts for co-optimizing CO_2 storage and EOR would proceed more fluently. Nevertheless, CO_2-EOR still remain a considerable asset to improvement in mitigation greenhouse gas emissions.

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General overview of rechargeable battery technologies in particular Li-ion and Na-ion solutions in energy storage

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Abstract

This paper includes a comprehensive overview of rechargeable battery technologies, specifically focusing on lithium-ion as a current leading solution as well as sodium-ion as its possible replacement. A simplified mechanism of cell work was presented along with its current performance parameters and cost of production. A basic comparison between lithium and sodium cell and several emerging technologies was presented, based on widely available popular science sources. According to the given statistics the main applications were described as a prospective for rechargeable cells.

Keywords: Lithium-ion battery, Sodium-ion battery, Rechargeable battery

1. Introduction

A breakthrough moment that took place in early 1990s when Sony company introduced a new generation of lithium-ion batteries began the revolution in energy storage at a large scale. General improvements of cathode materials in comparison with earlier tryouts in 1970s brought lithium-ion batteries to portable electronics and consequently to larger applications such as vehicles or renewable energy storage. A market of lithium-ion battery is expected to rise from $30 billion in 2015 to $77 billion in 2024, with a relatively high CAGR (Compound Annual Growth Rate) of 11.6% [1,2,3]. Currently the automotive industry is what accelerates the demand for rechargeable batteries mostly. While technologies of Ni-Cd and Ni-MH are no longer thought to be innovative in this area, Li-ion as well as the other promising solutions like Sodium-ion batteries are about to spread in world of technology. Unfortunately there is still a major disadvantage for Li-ion – their price. At $7,475 per metric ton in 2016, a major growth by 13% towards 2015, the price of lithium in future does not seem to be promising [24]. Also the availability of this element is limited to only 4-5 countries, what poses the question if we can retain the price of lithium and the sustainable management at the acceptable level for next decades or we have to replace lithium with something more available and cheap [15].

2. Rechargeable lithium-ion batteries

Technology of Li-ion rechargeable batteries is generally based on the reaction of intercalation of lithium as charge carriers to D-block elements. Batteries store energy in chemical bonds of the electrode which reach a level of several eV/atom enable them to store energy above 100 kWh/kg. While charging the battery ions are transported from the cathode to anode. This migration cause the consequent effect in which electrons are passed by the external circuit from the cathode to the anode. A reverse process is simply discharging the battery – the electrons are passed back by external circuit to cathode and ions are embedded into cathode material again without permanent changes in solid structure of electrode [1,2,4]. Each of the element of battery is responsible for given parameters - voltage, capacity, density of stored energy depends on properties of cathode and anode. Number of working cycles and lifespan is a result of processes between electrode and electrolyte while stability of used materials provides a safety [2].

2.1 Basic properties of Li-ion and their performance

Batteries performance differs from each other due to processes of production used by manufactures. One has to remember that application and consequently an optimization can significantly influence a battery's performance [5]. Cathode materials are made of lithium compounded with d-block metals, the most popular are oxide $LiCoO_2$ as well as $LiFePO_4$ or $LiMn_2O_4$. Electrolytes are mainly solutions of lithium salts in organic solvent. Anode consists of graphite. Parameters of cathode materials are not sufficient enough for today's demand, which requires long cycle life, high specific capacity and energy. In the Tab. 1 properties and comparison of cathode materials' examples were presented [6].

Tab. 1 Gravimetric properties of materials used for cathode materials [6]

Material (Abbreviation)	**Specific capacity, mAh/g**	**Specific energy, Wh/kg**
$LiCoO_2$ (LCO)	140	546
$LiMn_2O_4$ (LMO)	100-120	410-492
$LiFePO_4$ (LPF)	150-170	518-587

Those materials are not lacking in disadvantages therefore industry challenges researches to find an improvement, a nanoscale approach can be very beneficial in terms of materials engineering. $LiFePO_4$ for instance has a relatively small conductivity, what can be increased by thin nano-plates of materials instead of thick layer. $LiMn_2O_2$ on the other hand is instable towards electrolyte and need a substitution of other elements or modification of a surface of electrode. While comparing cathode materials as well as whole cell a focus on the specific energy among various technologies gives a clear view how the batteries have developed. Li-ion for instance with its density of energy as a parameter had a major growth across the last 20 years, completely outclassing technologies of nickel-cadmium and nickel-metal hydride. Nowadays Li-ion batteries are capable of holding twice as much energy within weight and volume then first commercial batteries sold by Sony in 1991. Unfortunately many scientists claim that in next decade Li-ion batteries may reach their limitations. Even improvement by 30% enhanced specific energy cannot reach the level of, for instance, petrol engines in terms of the range. Currently specific energy values for Li-ion batteries varies from 130 Wh kg^{-1} to most impressive 243 Wh kg^{-1} – by reviewing these figures one has to consider bare cell dimensions. The Fig 2.1 depicts the current established technologies like Li-ions or Ni-MH (Nickel Metal Hydride) with its specific energy and specific energy. The current target for Li-ion is to reach over 300 Wh kg^{-1} [7,8].

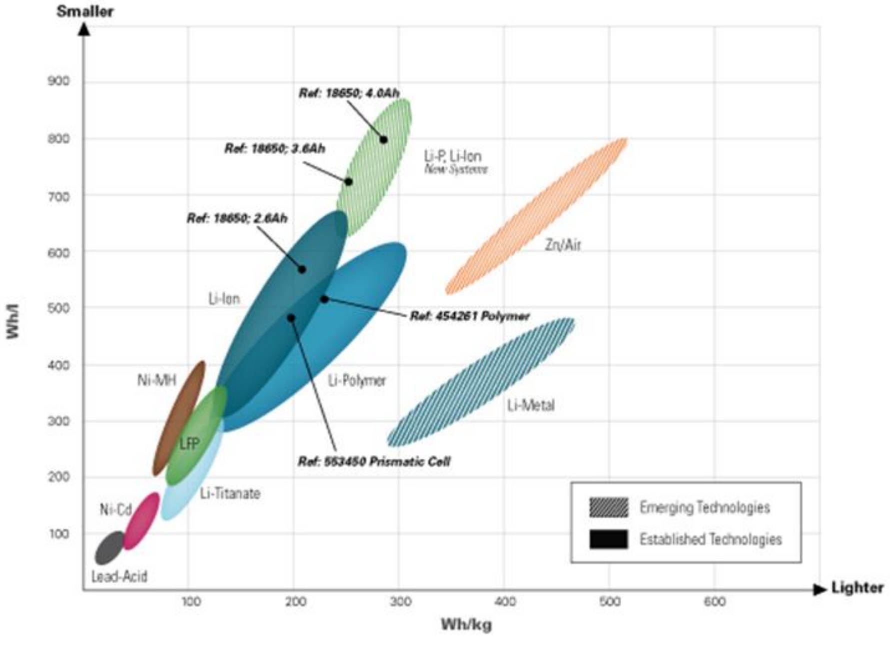

Fig. 2.1 Performance properties of emerging and established technologies of rechargeable batteries [7,8]

2.2 Review of overall price and cost breakdown of Li-ion

The main blocking point for lithium-ion batteries to increase the share of usage in automotive industry is the price. For a smartphone OEM (original equipment manufacturer) a lithium-ion battery cost is about 2% of an entire price of a device, while for the electric vehicle can reach 40% of price. The cost, despite the growth in lithium prices, continues to decline, today it is between \$200-\$500 per kWh. It is imperative to bear in mind that cost structure especially among EVs (electric vehicles) suppliers vary from one to another manufacturer and additionally may be counted as whole battery pack or bare cell cost. Announcement of General Motors stated that cost of their EVs batteries will decline first to \$145/kWh while the goal is \$100/kWh quoting lone cell cost. Unsurprisingly it is hard to get the accurate insight to cost structure due to confidential politics, it is possible though to assess the cost breakdown for consumer-grade batteries and divide it into three basic categories of cost: material, labour and manufacturing overhead and profit [9,10]. The result was depicted on Fig. 2.1.

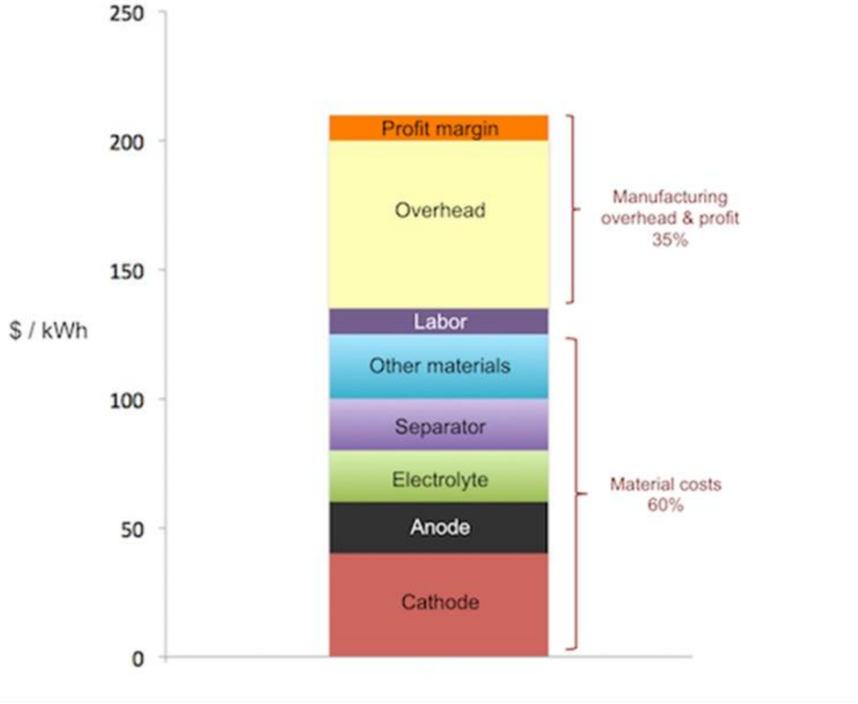

Fig. 2.2 Cost breakdown of example Li-ion cell [9]

The material cost is a major contributor with a share of 60% of costs and again the cathode is likely to be an area of possible improvement. Only raw material for lithium-cobalt oxide cathodes and nickel-cobalt aluminium can reach the level of up to S15/kWh, adding overall processing and manufacturing, cathode can costs over \$40/kWh. The labour cost itself is a rather minor component overall, mainly due to automation and concentration of manufacturing plants in countries with low labour cost like China [9]. Since the overhead exceeds 30% of the price, decisions like this made by Tesla about building its own Gigafactory in Nevada, US are not a surprise and could be major step towards price reduction. The goal is to reduce material cost, study the influence of the supply chain and assess the efficiency of manufacturing by implementing innovative ways to production management. All of these actions just to reach \$100/kWh taking into consideration the weight of whole battery pack. This is the only way to compete with petrol engines. According to some analysts Tesla can reach this target by eliminate so called "dead weight" which is the weight of the inactive layer – the solution is to make them thicker yet stronger, this can be done by adopting nanoscale approach. The price \$100/kWh can be a major step towards other mass-scale applications, rechargeable batteries was mainly used in portable electronic devices and electric vehicles (EVs) but lower price can bring them to renewable energy storage [9,10].

2.3 Carbon footprint and approach of closed loop lifecycle management

Some of the materials used while producing Li-ion batteries are concerned as energy consuming. A review of each kind of Li-ion batteries in terms of energy consumption while manufacturing can give an average of 105 MJ/kg battery. Components like silicon and cobalt are the most pricy to include in supply chain, batteries that use cobalt in cathode materials may reach values even above 150 MJ/kg battery. Phospho-olivines like PFP and LMO seem to be the most sustainable being the lightest ones and each battery produced consumes below 85 MJ/kg. Wrought aluminium is responsible regardless of technology for about 25-35% of energy consumption [11]. What is interesting is the approach in which one is able to assess contribution of batteries to life-cycle energy use and CO_2 emissions in greenhouse gases emission (GHG). The calculations in Tab.2 has been conducted in order to illustrate the CO_{2e} emission regarding Nissan Leaf's LMO battery which can reach energy consumption of 75 MJ/kg [11, 22].

Tab. 2 Calculation of CO_{2e} of Nissan Leaf's LMO battery production [11, 21, 22]

Weight of single cell, g	**Total number of cells**	**Total weight, kg**
799	192	153.4
Average energy consumption for LMO		
MJ/kg battery	kWh	kg
11505.6	3196	2246

This roughly estimated final figure of kilograms of CO_{2e} per one battery pack could be equivalent to 8663 kilometres driven by an average passenger vehicle or energy used in average house during 2-3 months. Further estimations can show how single batteries contribute to overall life-cycle CO_{2e} emissions. On the basis of US grid, available calculations shows that manufacturing battery in primal plant made up less than 20% for battery electric vehicle (BEV) cars and 18% in plug-in hybrid (PHEV) of GHC emission per kilometer [g Co_{2e}/km]. This contribution is surely constant across the range of vehicles and only fuel cycle can have a major impact on emissions, so one has to assess the environmental friendliness of each drive system in terms of well-to-pump and pump-to-wheels fuel cycle. First cycle begins with the fuel feedstock and by production and distribution ends with the fuel available for customer, second one represent cycle of fuel in vehicle. It is imperative though to acknowledge direct and indirect emission and base the calculation on sources of energy in each country.

The reuse and recycling of lithium batteries is also a new challenge for OEMs. Despite the fact that lithium can be easy recycled, it does not always make economic sense to do so. The individual lithium fraction is so insignificant and inexpensive in secondary market that recycling almost only focuses on more valuable metals like cobalt or nickel (Tab.3). Process of extraction of lithium from slag would be five times more expensive than actual market price of recycled metal. Nevertheless as more and more countries starts to adapt closed loop lifecycle for any products, Li-ion recycling will play the role in the value chain. It definitely needs a more feasible reprocessing technologies as future materials will be probably devoided of cobalt or nickel (like $LiFePO_4$) and net negative value for recycling will effectively drive away manufactures from recycling [19]. This net negative value comes also from lack of the regulations regarding Li-ion recycling and difficult removal from applications like EVs [20].

Tab. 3 Prices of recovered constituents from several types of cathodes [20]

Cathode	**Constituents price, $/kg**	**Cathode price, $/kg**
$LiCoO_2$	3.76	6.35
$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$	2.22	5.22
$LiMn_2O_4$	0.77	2.04
$LiFePO_4$	0.32	4.08

In case of batteries that contain cobalt or nickel the most commercialized process is pyrometallurgical recycling (smelting). Dismantled modules are placed in a furnace with slag-forming agent and smelted, the goal is to acquire an alloy of coper, cobalt, nickel and iron what can be leached in order to separate them into each components. Recovery of metals like lithium or aluminium is not economical nor energy efficient in this case. Nonetheless the process in which we can efficiently recover all materials is direct recycling, cells are treated with supercritical CO_2 which separates electrolyte and the next step is a pulverization of cells and subsequent separation of other parts using techniques based on electronic conductivity or density differences between each element. Question is however, if the recovered materials would perform as good as primal one – that can cause a reluctance in purchasing recycled materials. Even if the properties would be slightly worse, batteries consisting of reprocessed materials should be researched in less demanding applications. Reluctance towards recycling is also a lack of improvements of battery and package design. Approach of closed loop lifecycle and circular economy should impose several enhancements making recycling easier like:

- Labelled cells to enable identification for proper treatment;
- Policy according to which recovered batteries are returned to manufacturer or manufacturer is responsible for recycling;
- Standardization of cells formats and packages;
- Avoidance of various toxic materials that can be released in gases while smelting [20].

3. Sodium-ion and possible alternatives

Sodium-ions batteries represent analogical process of conversion chemical energy to electricity. Nevertheless technical parameters are mainly worse because of the ion radius which is 116 pm, lithium ion radius in comparison is 90 pm [12]. Salts of sodium on the other hand are attractive in terms of price or abundancy. Earth's crust is far more rich in sodium (2.6% of earth's crust) than lithium (0.005%), consequently price of sodium carbonate is less than 10% of the price of lithium salts and this finally contributes to 50% saving in cathode and electrolyte costs. There is possibility of introducing them to applications where the importance of weight and specific energy is not a most relevant factor like renewable energy storage. Energy storage is vital in making grid more stable. Shipping is also easy, batteries can be stored and transported while being drained to zero charge and what is even more optimistic, can deliver its 93% of original capacity after 1000 cycles. Another advantage is that the process of manufacturing remains the same so a switch from production of lithium-ion to sodium-ions could be easy and cost-efficient. Recent years brought several technologies that may hit the market in not so distant time. Funded by Danish company Haldor-Topsøe and Japanese Sharp, British start-up Faradion has optimize a sodium-ion battery with an quite impressive specific energy of 140 to 150 Wh kg^{-1} which can theoretically compete with cells based on lithium cobalt oxide cathodes as they can reach 170 Wh kg^{-1}. The company aims though in densities above 200 Wh kg^{-1} [17, 16, 15]. This can be done by using of special technology of a layered oxide cathode, what has already made sodium more competitive in comparison of cathodes listed in Tab. 1 reaching 500 Wh kg^{-1}. [15, 16].

Year 2015 brought a sodium-ion battery that were packed into a very popular 18650 format used in laptops, LED flashlights or even vehicles like Tesla. The number "18650" refers the dimensions of the battery which is a cylinder, with a diameter of 180 millimeters and a height of 650 millimeters. The RS2E - French network on electrochemical energy storage presented a new sodium-ion 18650 battery and claimed a density of 90 Wh kg-1 as well as a great lifespan with over 2000 recharging cycles, what outclass average Li-ion with its 1200 recharge cycles. Despite rather poor density today, it gives a positive outcome. RS2E managed to create battery prototype packed into one of the most commercialized formats, still reaching 90 Wh kg-1 what is comparable with the first lithium-ion batteries introduced in 1991. This poses a question whether sodium-ion are really about to replace lithium-ion in next decade, even if they will reach a level of specific energy of modern batteries it is unknown if the market would be eager to commercialize them. Sodium-ion batteries need to prove their properties in applications like storage of renewable energy off-peak hours or back up power which can regulate and optimize consumption. This technology in a form of mural battery like Powerwall is now available but relatively expensive, therefore using cheap but still efficient Na-ions can bring them into general use [13, 14].

Research conducted in Lawrence Berkeley National Laboratory in Berkeley, California shows possibility of using lithium-sulphur (Li-S) technology as a very cheap one and according to predictions it can enhance the specific energy of standard lithium-ions. The major change in technology is the replacement of graphite by a sliver of pure lithium metal which works on two levels, it is an electrode and the supplier of lithium ions. Sulphur is in this case replacement of metal oxide, which can bond two lithium atoms what was not possible in case of previously used metals. Unfortunately as the charging and discharging goes, Li-S compounds can get through the electrolyte and that cause the loss of charge. Advanced nanotechnology and electrolyte chemistry on the other hand offers a solution in graphene oxide binders adulterated in Sulphur but despite good parameters on relatively small laboratory scale, the usage of Li-S in commercial applications is questionable due to temperatures of work, and the danger that battery will gum up. Although future does not seem to be optimistic, company which is called Oxis Energy, based in UK, started working with Lotus Engineering to reach 400 Whkg^{-1} Li-S battery capable of powering a vehicle [15, 23]. Another emerging technology is battery which realize concept of cathode reaction with oxygen. Those Lithium-oxide or Sodium-ion batteries are expected to reach specific energy on the level of respectively 1300 $\mathrm{Wh\ kg}^{-1}$ and 650 $\mathrm{Wh\ kg}^{-1}$ but at the same time lose to 10% of capacity in every charge-recharge cycle, what actually means being useless in most of applications. Regardless of technology, researchers constantly review new ideas and possible solutions in the field of Li-ions [25].

4. Summary

Lithium-ion batteries played a great role in commercializing electronic devices in last 20 years and for sure will be significant technology in energy storage in future. As price per kWh of battery will drop alongside with enhanced parameters and possible entrance of new technologies like sodium-ion, rechargeable batteries are serious alternative for petrol and diesel cars. Scientific research that has to be done is to evaluate possible development of cathode material with possible nanoscale approach and overall standardized production in terms of management and design and package what can simplify process of recycling. As for renewable energy and from environmental point of view there could be a major step towards applications like energy storing system based on renewable sources. Those systems could be available for every household and enable householders to manage the power supply whatever it is needed. This somehow would be a major improvement in sustaining stability of the grid in smart cities or in small scale power generation – both elements are significant fundamentals of intelligent energy and sustainable energy development.

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Wind energy in Małopolska voivodeship – short case study

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Abstract

This paper presents an overview of the regulatory framework for wind energy in Poland, environment – related issues and short case study of small wind farm. In 2015 there have been major changes in law which terminates the old support scheme based on green certificates and replaces it with the auction model. In recent years, wind energy has climbed to the first place in alternative sources of energy in terms of the installed capacity and the number of installations in Poland. Małopolska holds one of the last places among all voivodeships in terms of number of wind turbines and in installed capacity. This may be due to generally not favourable geographical position in terms of wind force. But it turns out that even in not favourable conditions, there are people who have decided to take brave and forward - looking steps and invested their capital in wind turbines, even in the vicinity of Kraków. At a distance of 30 km from Kraków, in the vicinity of the town Miechów, three wind turbines are operating. Author managed to talk to the owner [1], and conclusions from the interview are written in this paper.

Keywords: wind energy, wind farm, Poland, Małopolska voivodeship

1. Introduction

Main source of electricity in Poland are Power Plants fueled by coal or lignite. According to the Polish Energy Policy a key raw material in generating energy until 2030 will be coal, but its participation in electricity production will fall. In recent years wind energy has climbed to the first place in alternative sources of energy in terms of the installed capacity and the number of installations. More and more investors acknowledge Poland's potential in renewable energy sources. Over the last four years the installed capacity in wind power has risen, reaching 5,000 MW at the end of 2015. The share of energy from wind in the total energy production has reached 6.21% [2].

2. Legal acts in Poland

In Poland an act, which regulates all issues related to energy policy is *Energy Law Act*. This act was adopted on April 10, 1997. Due to Poland’s membership in European Union, country has been obligated to respect new laws, also in renewable energy sources. The main regulation in this matter is the *Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from the renewable sources* (*RES Directive*). One of the main assumptions of the *RES Directive* is setting individual targets for particular European Union member states with regard to the share of renewable energy sources in the overall energy balance. For Poland this target is to reach 15% of the renewable energy sources share in the gross final energy consumption in 2020. The *RES Directive* refers to direct support of renewable energy sources but it also regulates prioritizing renewable energy sources in the European Union countries. Amendment of the *Energy Law Act*, which came into force on October 1, 2005, introduced support mechanism based on the guarantee of the possibility to sell all energy generated by renewable energy source. Producers of energy from renewable sources usually sell it to the so – called ex officio supplier at price equivalent to sales price of energy on a competitive market announced by the President of the Energy Regulatory Office. Additionally, for each produced unit of electrical energy, the producer is obtaining certificates of origin, the so - called green certificates, which are transferable and can be traded on the market. These certificates are bought by suppliers of electricity. They must reach a minimum level of share of energy from renewable sources. In 2015 this was 14%, new law sets minimum to 20% of the total electricity supply to end users, but for 2016 it has already been lowered to 15%. If supplier has not produced energy from renewable sources, he must fulfil the obligation by either making up the difference by purchasing certificates on the market, or pay a compensation fee determined by the President of the Energy Regulatory Office. So apart from the revenues obtained from the sales of energy itself, the owner of a renewable energy source installation obtains additional profit from the sales of certificates of origin. The possibility of acquiring additional income from the sale of certificates is the basic condition of profitability of investments in most renewable energy source types, including wind energy. The market value of green certificates is decided on the Polish Power Exchange and their maximum value is the compensation fee because its payment releases a particular entity from the duty to buy certificates. The green certificate system had worked well until 2010. The rapid increase in biomass co-firing and in installed capacity of wind turbines lead to an enormous oversupply of green certificates in 2012 – 2014 period. This caused significant drop of their value (from around PLN 280/MWh in early 2012 to less than PLN 100/MWh by February 2013). The *RES Act* cut subsidies for co-firing with biomass by a half. Along with the decrease of green certificates value, prices of an electric energy also dropped. This situation increased the operational risk in the sector.

To ensure complete implementation of the *RES Directive* to Polish law, an amendment to *Energy Law Act* was submitted on July 26, 2013. This amendment is referred to as *Little Energy Three – Pack*. Meanwhile, some of the provisions of the *RES Directive* were not transposed into the *Little Energy Three – Pack*. No streamlining of administrative procedures, and no non - discriminatory criteria of access to the grid for renewable energy sources was ensured. Therefore, before the entry into force of the *Little Energy Three* - *Pack*, the government has announced that the work on act will be continued. In order to stabilize the market and implement the *RES Directive*, on February 20, 2015, Sejm (lower chamber of Polish Parliament) adopted the *Act on Renewable Energy Sources* (*RES Act*). *The RES Act* moves away from the support based on certificates of origin and introduces a new system for sources with capacity exceeding 40 kW based on contract for differences model in which projects have to compete in an auction in order to receive a contract to sell energy. The application of the auction mechanism is the consequence of Poland implementing the recommendation of the *European Commission included in the document European Commission guidance for the design of renewables support schemes*. This does not mean complete shutdown of the certificate of origin system. Sources, which started production of energy before January 1, 2016, could stay in old support system or migrate to new auction system voluntarily. Whereas renewable energy sources installations that started generating electricity on or after January 1, 2016 have no choice, and have to compete in an auction system. The owner of a source will be able to receive support through auctions and from other sources, to the value of the reference price (the maximum value of the offer which can be submitted in an auction). First auctions will take place no earlier than in the 4th quarter of 2016.

Auction system is a support based on a type of *contract – for* - *difference* (*CfD*) granted through auctions organized by the President of the Energy Regulatory Office. Shortly, it works like reverse auction, prices are bid down instead of increasing through an auction. The producers participating in auctions make offers of sales of electrical energy which they will produce for the period of 15 years. The offer has to include the price at which the energy will be sold for the period of 15 years and the quantity of energy they will produce in the particular source during that period. Offers with the lowest price are winning. Support will be granted up to the limit of the annual auction budget, the state will offer support up to a specific volume and value of renewable electricity to be generated within the 15 years. These volume and value budgets will be published for each auction year by the Council of Ministers. The main goal of the auction system is to ensure fair competition of all renewable energy technologies. Within each auction pool different renewable energy technologies will directly compete with each other for support. Auctions will be organized separately for units with the capacity below 1 MW and for larger installations. Such solution is expected to give an impulse to develop technologies, which are the most efficient in terms of economy. It may occur, that some technologies will not be able to compete witch others, more cost – efficient ones. In situation like this more expensive technologies will stop its expansion in the country. It may also turn out, just like it was in other European countries, where the auction system has been implemented, that the prices offered in auctions were below the investment profitability. *The RES Act* does not provide penalties or other negative consequences for producers who make deflated offers. In the new system investors also take the risk of not receiving any support in a particular year if the Council of Ministers sets too low amount of energy which will be purchased at auctions in comparison with the amount of energy participating. On the other hand, the auction system will guarantee the winner investors financial stability for the period of 15 years. From the point of view of stability and predictability, the auction mechanism is definitely more beneficial than the system of certificates of origin, even that the certificate of origin system was more generous. Continued development of renewable energy sources projects, especially wind, may be expected in Poland as it will be possible to rely on long term support mechanisms.

Country's law is one of the key factors which decreases the investment attractiveness in Poland in terms of renewable energy sources because of its instability. Until the adoption of the *RES Act*, the *Energy Law* had been amended 66 times. What is more, the *RES Act* delegates the key rights e.g. specifying the most important parameters of the auction, such as reference prices or the auction budget, to the Prime Minister or the Minister of the Economy. In addition, the Energy Minister can decide which renewable technologies are preferred in each new calendar year by determining how much electricity is allocated between the various auctions. Government has also severely limited growth in wind generation recently by passing *The Act on Investments Concerning Wind Turbines* (*WT Act*), which was adopted by the Sejm on May 30, 2016. This act makes the minimum distance between the wind turbine and households or mixed - use buildings at least equal to ten - times the total height of the wind turbine measured from ground level to the top of the structure. It rules out 99% of land. In terms of time consumption the administrative procedure from the time of the decision to construct a wind power plant to its launch is similar to that in all the European Union. Poland has been considered to be one of the most attractive markets from all around the world from the perspective of risk by financial institutions [2 – 14].

3. Environment – related conditions

Picture 3.1 shows map of a wind resources in Poland. As we can see this map is not very detailed and only gives a general view on wind conditions in the country.

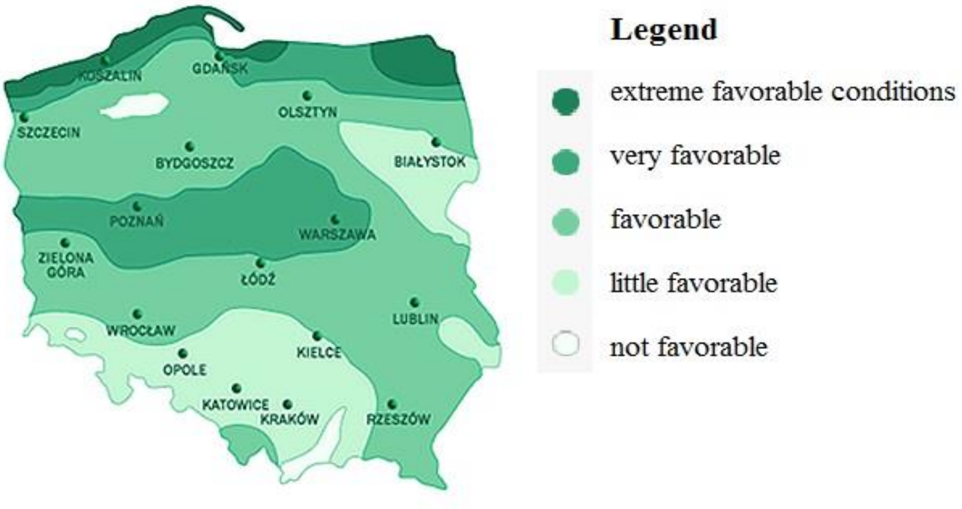

Fig. 3.1 Wind energy zones in Poland [13]

According to the map it is clear that wind can constitute a source of clean energy in Poland. Certainly this is not true for all regions due to geographic and climatic factors. The best conditions for onshore wind power industry are in the northern part of the country. That reflects in installed capacity, which is the largest there. Moving north, to the open sea, there are perfect and stable wind conditions, which definitely improves the predictability of that type of generation source and enables to compensate much higher investment costs as compared to onshore wind sources. Poland has one of the highest potential for offshore wind farms on the whole Baltic Sea. Going back to the land, the weaker wind conditions are getting the more we move south, excluding only part of the central range of the country. The least favorable conditions are on the south – western end, including Małopolska voivodeship. That is seen in installed capacity, which is one of the smallest among all voivodeships. But one should remember that available maps of the wind resources are not very detailed, and all across the country, even in the less favorable regions, there could be spots with excellent wind conditions. Investor can always buy an analysis of energy yield based on study of wind conditions for the selected location. Despite the fact that in some locations there may be available some data concerning the wind (e.g. from a neighbouring weather station, an airport or a wind farm), they may turn out to be useless. Measurements should be conducted using certified measuring equipment at the appropriate height adjusted to planned type of turbines and for the period of minimum 1 year. One of the first steps that investor should take to know whether to invest in particular project or not should be seeking for potential barriers. The most frequently listed investment barriers in the whole European Union are the procedures connected with obtaining the environmental impact assessment and with the zoning plan. Environmental protection regulations, e.g. protection against noise, influence of the electromagnetic field, plant, animal or soil protection, often become, due to unclear regulations, a major barrier for investors, also because of environmental organizations which are often protesting. The diagnosis of the most important barriers in the opinion of the players on the Polish market is largely similar to those in Europe. Newly adopted *WT Act* introduces rule that new wind turbines may only be located on the basis of a local zoning plan, which is another obstacle. It means, that when particular place has already been signed to another purpose, e.g. agricultural, wind turbine cannot be built there. This mechanism can be overused to forbid setting new wind farms, when local community or authority does not want them to arise. Experience of the recent years shows the growing number of protests of local communities against locating wind farms on their territories. The protesters fear the decreased comfort of life, lower prices of real estate, loss of health, etc. The research shows that one of the most frequently mentioned factors hindering the execution of wind projects are such social protests [2-5;13;15-17

4. Case study

In Małopolska voivodeship, on the outskirts of Miechów town, which is 30 km from Kraków, small wind farm is located. Author of current paper always wondered if producing energy from wind in such not favourable area is profitable. To find out author managed to talk to wind farm owner. Wind turbines are property of Mr. Stanisław Dróżdż, local entrepreneur. He also owns couple other businesses, like vehicle control station, gas station, national and international transport services, building materials store and others.

Mr. Dróżdż has always been interested in renewable energy sources, and he has been developing his knowledge from long time, but rather as a hobby. He never took any special education in field of energy. As a big fan of 'green energy' he wanted to have his own 'green energy factories' not only to gain income, but also to protects environment in his beloved country.

Outskirts of Miechów town, where Mr. Dróżdż lives, are rather rural sides, majority of the land is cultivated and residential buildings are rare. Businessman has a house and quite large uncultivated field there. He decided to had a wind force measurements conducted on his land. Measurements were lasting for 1 year, and results were satisfactory. After this tests, he started efforts to achieve building permit. The land has no zoning plan, so it was not an obstacle. Businessman claimed that there were no legal problems and procedure was quite easy but, as an entrepreneur, he got some experience in that matter and probably that helped him. Neighbours also made no problems back then.

Wind turbines were bought in secondary market. They had been working for almost 20 years in Denmark before they arrived to Poland in 2008. Now they are 28 years old and they are still working pretty well. Owner did not have any help in choosing them, he was relying only on his knowledge. Turbines were produced by Nordtank. Their capacity is 300 kW each. Towers of turbines are 31,5 m high. They start generating electricity when wind speed excess 4,5 m/s. On average, they work 10% of the time. Turbines are maintained by specialized Polish company. To this day, there has not been any major failures, occasionally some parts have to be repaired in Denmark, e.g. electronic parts, because Polish firms do not want to do that,. Mr. Dróżdż claims that cost of maintenance and repairs are not high. Building work of the wind farm were conducted by Mr. Dróżdż's employees, who have been previously trained.

The turbines were purchased with own funds, the entrepreneur did not try to get any form of financial support from the European Union or a bank, because such help comes with a price of different kind of obligations, and they could be really expensive. Owner uses amortization of costs. Produced energy is transferred to the grid and sold, total annual profit is PLN 200 000, including all kind of income and outcome.

The entrepreneur tried to get permission to build new turbines, but this this time he faced protests of community, and project failed. Their main argument was that the neighbouring fields would have lover value on the market.

The house of Mr. Dróżdż is 300 metres away from nearest turbine. When windows are closed, one do not can hear any noise. Outside of the house noise can be heard, it is similar to mild wind. This house is nearest building to the turbines, owner have not noticed any health impact.

Fig. 4.1 Wind farm and its surrounding [photo made by Paulina Drach]

5. Conclusions

As we can see, small wind farm can be profitable, even in places where nobody would at first expect them to. In Poland there still could be many spots like this near Kraków, with really good wind conditions and which now are waste lands, like Mr. Dróżdż's land was. Opportunity to make money out of natural, limitless energy source awaits to be explored but this could never happen due to fear and lack of knowledge among people. Moreover, new regulations could make renewable energy sources investments too risky. Only time will tell what new law will do with wind energy sector in Poland. The new auction system is competitive and more challenging for renewable energy sources owners, especially for new ones with little or no experience with stock exchange

When asked if running a wind farm is problematic, Mr. Dróżdż claims that it is not. Even when society has rather negative attitude to the renewable energy sources and government is slowly shutting down their help owner thinks that it is worth to invest in wind energy, because it could be really profitable and it helps in restoring an environment. Such activity nowadays is no longer reserved only for the few. However, having own capital and the act of ownership of a land where it is windy makes things easier.

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Multi-criteria analysis of natural gas combined system located in Poland

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Abstract

The main goal of this article is description of working NGCC installation. Here have been presented types of this kind of installations with different solution of gas and steam-water-cycles. Economic analysis has been done to show profitability of building gas combine cycle unit and compare installation with and without carbon dioxide reduction. Thermo analysis show how much electrical energy can be produced with different parameters of working fluids. By exergy analysis there have been shown the biggest losses of exergy and fuel-product analysis. The results obtained can be used for initial analysis of building this kind of unit.

Keywords: NGCC combined system

1. Introduction

Nowadays, humanity is struggling with depletion of natural sources. It is not known exactly how much sources are still on Earth, but most of the analysis say that in several decades our planet will be out of the most important energetics natural resources. Therefore can be found a lot of warnings for the people about saving electricity, fuels and water. There are plenty of indicators which are showing the problem of natural sources depletion but usually we forgot about exergy. What is an exergy and how it is connected to the ecology? According to definition, exergy is the minimum work necessary to produce a substance with a specific structure and concentration from a common materials in the environment. What is more extraction and usage of natural sources can be defined by increasing of entropy, which is connected to exergy. Every time we are producing different types of substances we need huge amount of exergy to switch it from environment state to final product. That is why exergy is the best indicator to estimate natural sources. In addition to this, exergy recognizes irreversibility of thermal processes, which is not contained in energy efficiency analysis. [1, 2].

There is also a lot of legal restriction which are forcing industrial units including power plants to reduce their emissions of harmful elements like sulfur, nitrogen or carbon compounds. Currently, ecological aspects are very important if we are considering to build a new unit. Companies have to invest in very expensive technologies like CO_2 capture or No Selective Catalytic Reduction (NSCR) installations in order to build modern power plants. These kind of methods sometimes have got even the negative impact on total efficiency of producing electricity, which from the thermodynamic point of view should be the major target.

It can be seen significant rise of interest of renewable sources of energy but total amount of energy which they are producing is not enough to cover demand of modern energetic network with their picks especially in Poland. This is the reason why we have to search technologies which are using fossil fuels but did not have so big negative impact on environment. The great solution seems to be the Natural Gas Combine Cycle (NGCC). Burning gas fuel do not causes so high amount of NO_x in compare with burning hard coal. This kind of installation has got also much higher efficiency.

This article shows a simplified example of natural gas combined cycle with the demonstration of exergoecology and economic analysis. There have been presented details about emissions of harmful substances to the environment and methods of their reduction. There is also described impact of carbon dioxide reduction installation on financial cost of investment in this kind of unit.

2. Natural Gas Combined Cycle

NGCC installations are connecting two cycles. The first one is an open cycle of gas turbine and the second one is a traditional Clausius-Rankine CR steam-water cycle. Exhaust gases which are flying out from gas turbine has got still high temperature so throwing this to environment generate a huge loss. To cover it, gases can be used to in Heat Recovery Steam Generator (HRSG) to generate steam with comparatively high temperature.

We can divide this kind of cycles in a lot of ways:

- Number of generators
  - One generator to both cycles
  - Two generators, each one for gas and steam cycle
- Type of HRSG
  - Vertical
  - Horizontal
  - With or without reheat
  - With or without afterburning
- Number of pressure stages in HRSG
  - One pressure
  - Two pressure
  - Three pressure
- Type of fuel
  - Natural gas
  - Gas from the degassing other fossil fuels
  - Oil fuel
- Type of produced energy
  - Electrical energy
  - Electrical energy and heat
- With or without CO_2 capture installation

2.1 Natural Gas Combined Cycle in Poland

Fig. 2.1 NGCC power plants located in Poland

The NGCC power plants located in Poland are presented in Fig. 2.1.

1. CHP Lublin-Wrotków -235 MWe, 150 MWt
2. CHP Rzeszów- 101 MWe, 76 MWt
3. CHP Zielona Góra- 198 MWe, 135 MWt
4. CHP Siedlce- 14,6 MWe, 22,4 MWe
5. CHP Gorzów- 55 MWe, 64 MWt
6. CHP Nowa Sarzyna- 116 MWe, 70 MWt

3. Exergy Analysis

At the very beginning of each exergoecology analysis, we have to extract components and flows of our system. A set of components is presented in Fig. 3.1. In this analysis, gas turbine system is treated as one component.

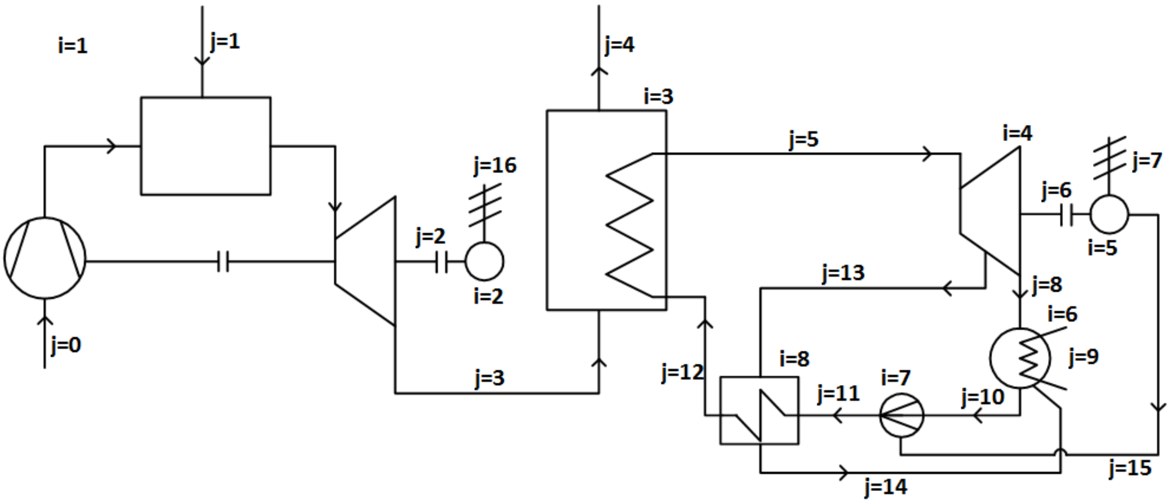


Fig. 3.1 Scheme of analyzed NGCC power plant

Tab. 1 Components of NGCC power plant

i	Component
1	Gas turbine system
2	Gas turbine generator
3	HRSG
4	Steam turbine
5	Steam turbine generator
6	Condenser
7	Pump
8	Heat exchanger

At this point there is needed to calculate exergy of each stream in the system. Exergy is definied by:

$$\dot{B} = \dot{m}\left(b_f + b_{ch}\right) \tag{3.1}$$

$$b_f = i - i_0 - T_0(s - s_0) \tag{3.2}$$

$$b_{ch} = T_0 \sum g_i R_i ln \frac{z_i}{z_{i\,n}} \tag{3.3}$$

where:
$\dot{B}$- exergy stream,
$\dot{m}$- mass flow,
b_f- physical exergy,
b_{ch}- chemical exergy,
i- enthalpy,
T_0- ambient temperature,
s- entropy,
g_i- mass fraction,
R_i-individual gas constant,
z_i- molar fraction.

Values of entropies, enthalpies and exergies were calculated by Engineering Equation Solver. The exergy of the streams is presented in Tab. 2.

Tab. 2 Exergy of flows in a system

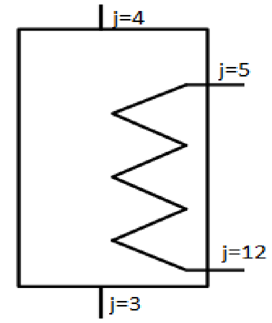
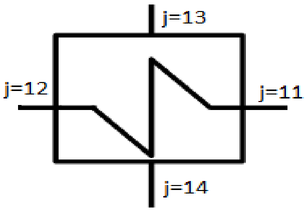
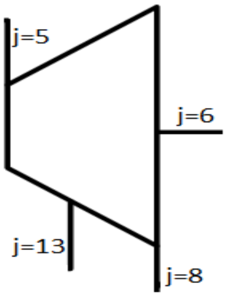
Flow j	**Exergy, kW**	**Flow j**	**Exergy, kW**
1	154 227	9	248
2	37 156	10	45
3	71 570	11	370
4	19 236	12	2 911
5	57 933	13	4 021
6	46 758	14	618
7	46 406	15	339
8	266	16	32 140

Next step is to create three matrixes: system matrix, fuels matrix and products matrix. There are three rules, each of them refer different matrix.

- Rule 1: In System Matrix, each flow which is defined as inlet of the component has value “+1”. The flow which is defined as outlet of the component has value “-1”. If there is no connection between stream and a component it has value equal zero.
- Rule 2: In Fuels Matrix only fuels are considered. Each flow which is defined as inlet of the component has value “+1”. The flow which is defined as outlet of the component has value “-1”. If there is no connection between stream and a component it has value equal zero.
- Rule 3: In Products Matrix only products are considered. Each flow which is defined as inlet of the component has value “-1”. The flow which is defined as outlet of the component has value “+1”. If there is no connection between stream and a component it has value equal zero.

To clarify the concept of fuels and products there are presented examples of few components in Tab. 3.

Tab. 3 Example of three component with division for fuel and product

Component	Fuel	Product
	$\dot{B}_3 - \dot{B}_4$	$\dot{B}_5 - \dot{B}_{12}$
	$\dot{B}_{13} - \dot{B}_{14}$	$\dot{B}_{12} - \dot{B}_{11}$
	$\dot{B}_5 - \dot{B}_{13} - \dot{B}_8$	$\dot{B}_6$

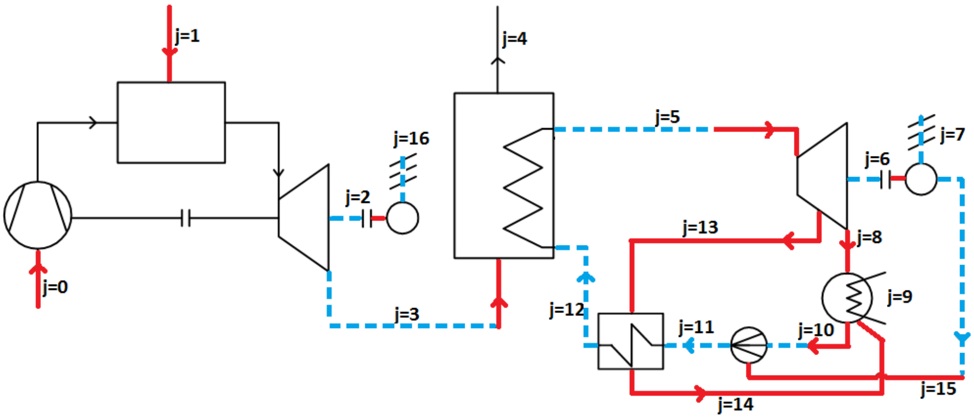


Fig. 2.2 Fuel and products in NGCC power plant.

To make it more understandable in Fig. 3.2 is presented a scheme which shows a division of streams for fuel and products. The solid line means fuel while the dashed line means product.

Tab. 4 System Matrix

System Matrix																
Component i/Flow j	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	-1
3	0	0	1	-1	-1	0	0	0	0	0	0	1	0	0	0	0
4	0	0	0	0	1	-1	0	-1	0	0	0	0	-1	0	0	0
5	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	-1	0
6	0	0	0	0	0	0	0	1	-1	-1	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	1	0
8	0	0	0	0	0	0	0	0	0	0	1	-1	1	-1	0	0

Tab. 5 Fuels Matrix

Fuels Matrix																
Component i/Flow j	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	1	0	0	-1	0	0	0	0	-1	0	0	0
5	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	1	0	-1	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
8	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0

Tab. 6 Products Matrix

Products Matrix																
Component i/Flow j	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
3	0	0	0	0	1	0	0	0	0	0	0	-1	0	0	0	0
4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
6	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	0

Last step of this analysis is to multiply matrix of exergies (presented in Tab. 2) by Fuels Matrix and Products Matrix to obtain the final results. Tab.7 presents comparison of exergy in every single component of the system.

Tab. 7 Vector exergy values of fuel, product and irreversibility.

Component i	**F_b, kW**	**P_b, kW**	**I_b, kW**
1	154 227	108 726	45 502
2	37 156	32 140	5 017
3	71 570	55 022	16 548
4	53 646	46 758	6 888
5	46 758	46 744	14
6	839	0	839
7	339	325	14
8	3 403	2 541	862

Value F_b shows fuel which is needed to produce substances with required parameters, which are marked as P_b. Factor I_b characterizes losses in each component. The loses may be internal, due to irreversibility of thermodynamic processes and external like exhaust gases and cooling water which are released to the environment .

4. Emission of Pollution

According to growing limits regarding emission of harmful substances, power plants need to use a cleaning system of flue gasses. The main chemical substances, which are, carbon dioxide, sulfur and nitrogen compounds, and also dust (PM10 PM2,5). Excessive emissions of this harmful compounds can be very dangerous for the human's health, this is the reason why this emission must be controlled and reduced in industry installations especially in power plants. These sulfur and nitrogen compounds affect negatively on human health. Namely, they can cause cardiovascular and respiratory diseases. These emissions are also causing negative effects to the environment, they are responsible for acid rain, smog and ozone hole.

The directive, which refers to the environment protection has been introduced by the European Parliament, and it is called IED 2010/75/UE (The Industrial Emissions Directive). This document is a guideline, which also Poland as the EU country have to realize. It replaces a few of pre-existing directives on pollution issues, which were created from industrial processes. On 22 November 2014 came into force to the Polish legal order regulations related with IED, according to the most important IED issue “Regulation of the Minister of Environment of 4 November 2014 related to emission standards for some types of installations, combustion plants, and equipment of firing or co-firing of waste”.[5] The legislation defines limits of many substances such as SO_2, NO_x, CO_2, and dust. For the installation, which power is more than 300 MW, which as fuel we used natural gas they are as follows $SO_2 < 35$ mg/m^3 , $NO_x < 100$ mg/m^3 (3% of O_2 in flue gases) or $NO_x < 50$ mg/m^3 (15% of O_2 in flue gases), $CO_2 < 100$ mg/m^3 (3% of O_2 in flue gases), dust < 5 mg/m^3.

4.1 Methods of Nitrogen Oxides Removal

Nitric oxide and nitrogen dioxide interact as acidifiers elements in atmospheric conditions. It can be said that they influence on the human organism in a destructive way. If the concentration is higher than some limits Tab. 8 [7,8], they can be poisonous. Regarding the formation of nitrogen oxides, that nitrogen reacts with oxygen at different stages of oxidation to form mainly nitric oxide NO (concentration in the flue gasses from the boiler 100-1000 mg/m^3), nitrogen dioxide NO_2 (10-100 mg/m^3) and nitrous oxide N_2O (1-10 mg/m^3).

Depending on combustion temperature, the concentration of O_2 and the nitrogen compounds we can identified two mechanisms of nitrogen oxides formation. These mechanisms are fuel (related to the nitrogen compounds in fuel) and air (thermal and prompt). As is mentioned the formation of fuel NOx is associated with the presence of nitrogen, which is chemically connected with the fuel, only in the case of gaseous fuels nitrogen is not associated with the structure of the fuel and therefore the fuel NO_x are not created. Emission of fuel NO_x increase as the combustion air factor λ is increased, and achieve minimal value for λ (0,65-0,85).

As regards the second group is the air NO_x, we can mention here two types: thermal NO_x and prompt NO_x. The reactions of formation of thermal NO_x have been described by Zeldowicz. The main factor that determines formatting of thermal NO_x is of course temperature, we can observe very significant increase of these type of NO_x above 1400°C, others factor are concentration of O_2 and N_2, also the length of stay in high zone temperature. Second types of air NO_x are prompt NO_x, they are formed in the front of combustion processes. They weakly depend on the temperature, the main factor determining their formation is high concentration of N_2 and $\lambda<1$. To sum up, some nitrogen oxides are associated with parameters such as combustion air factor, the temperature in the flame, fuel properties, length of stay in temperature areas and turbulence.

As it was mentioned at the beginning in relation to harmful effects of nitrogen oxides is a necessity to reduce them from flue gasses. There are two main groups of nitrogen oxides reduction methods (1) primary methods – all the operation related to the combustion process, (2) secondary methods – reduction of NO_x in the flue gasses.

The first group includes operation such as regulation of combustion air factor λ, gradation supply of air and fuel to the combustion process, recirculation of exhaust gasses and reducing of flame temperature. Mentioned operation can be by made using the system like Overfire Air System (OFA), Separated Overfire Air (SOFA), Low NO_x Concentric Firing System (LNCFS), as well as low-emission burners. When we are using primary methods may appear negative effects such as incomplete combustion, high and low temperature corrosion, slagging of combustion chamber, also the exhaust gas temperature increase and at the same time drop in produced steam temperature.[6]

The second group is secondary methods, SNCR and Selective catalytic reduction (SCR) can be distinguished. SNCR system is to reduce NO_x by injecting the reagent into right place of the combustion chamber, thereby producing amino radical, which reduce nitrogen oxides to the nitrogen. As reagent, ammonia NH_3 or urea $CO(NH_2)_2$ can be used. The range of temperature in which the reagent should by injected is 700-1100°C. This method is very sensitive to temperature, and also when we used as reagent ammonia the emission of this compound increase. The efficiency of this method ranges between 30-60%, and is affected by the type and amount of reagent, time of process and temperature. Power consumption consist of using this system is about 0,2% of generating capacity. The second of the method is SCR, here as well as in the SNCR two typical reagent NH_3 and $CO(NH_2)_2$ are used, with the additional element such as catalyst. The catalysts are usually vanadium oxide V_2O_5 or tungsten oxide WO_3. Temperature range of the process 170-500°C is lower than SNCR; the system is placed behind the combustion chamber. The efficiency of this method can achieve 95%. Also, as in the SNCR, the problems with ammonia emission appears, but the amount is lower. The main disadvantages of this method are a high investment and operational costs.[6]

4.2 Methods of Sulfur Dioxide Removal

The desulfurization methods can be divided due to the type of waste as follows:

a) Simply waste solutions

In these methods, the product is put entirely in a landfill or dumped into the sea, and used to fill in coal mine. Storage in the depths of the sea in special containers is the most environmentally friendly method. The main processes occurring in this method is the absorption and neutralization of sulfuric acid. The basic chemical reactions are as follows:

- Absorption $\mathrm{SO_2}$ and dissolution $\mathrm{CaCO_3}$

$$\mathrm{SO_2 + H_2O \rightarrow HSO_3^- + H^+}$$
$$\mathrm{CaCO_3 + H^{2+} \rightarrow Ca^{2+} + CO_2 + H_2O}$$

- Oxidation

$HSO_3^- + \frac{1}{2}O_2 \rightarrow SO_4^{2-} + H^+$

$Ca^{2+} + SO_4^{2-} + 2H_2O \rightarrow CaSO_4 \cdot H_2O$

Nowadays there are two the most popular waste desulfurization methods. The first one is wet scrubbing (gases are reacting with a suspension of limes). And the second one is lime method (exhaust gases are washed by milk of lime).

b) Packed bed scrubbers

Similar to simply waste methods, a process of absorption is used in packed bed scrubbers. Furthermore, additional processes which occur in this method include neutralization with lime or limestones as well as the separation and oxidation of calcium sulfite to sulfate. The product of this method is gypsum, which has properties similar to natural gypsum. It can be used in the construction industry as well as stored in landfills, because it is environmentally friendly. Below are presented packed bed scrubbers methods with their basic chemical reactions [4].

- Carbonate of lime manufacturing the gypsum**:**

$CaSO_3 \cdot \frac{1}{2}H_2O + \frac{1}{2}O_2 + 1\frac{1}{2}H_2O \rightarrow CaSO_4 \cdot 2H_2O$

- Limestone with manufacturing of gypsum:

$Ca(OH)_2 + 2HCl \rightarrow CaCl_2 + H_2O$

$CaCl_{2+}2SO_2 + 2H_2O \rightarrow Ca(HSO_3)_2 + 2HCl$

- Double catalytic methods with manufacturing of gypsum
- Absorption in a solution of sulfuric acid method
- Dry scrubbing

c) Waste-Free method:

This method assured SO_2 binding reagent from the flue gases is regenerated and freed concentrated sulfur dioxide is fed conversion to sulfuric acid, elemental sulfur or condensed. The method comprising the desulfurization of a waste-free [4]:

- Wellmann-Lorda method:

$Na_2SO_3 + SO_2 + H_2O \rightarrow 2NaHSO_3$

$2NaHSO_3 \rightarrow Na_2S_2O_5 \downarrow + H_2O$

- Magnesium oxide method:

$MgO + SO_2 + 6H_2O \rightarrow MgSO_3 \cdot 6H_2O$

$MgO + SO_2 + 3H_2O \rightarrow MgSO_3 \cdot 3H_2O$

$MgSO_3 + \frac{1}{2}O_2 + 7H_2O \rightarrow MgSO_4 \cdot 7H_2O$

- Walther's company ammonia method:

$SO_2 + 2NH_3 + H_2O \rightarrow (NH_4)_2SO_3$

$(NH_4)_2SO_3 + \frac{1}{2}O_2 \rightarrow (NH_4)_2SO_4$

In addition, methods of flue gas desulfurization can be divided also on:

- Absorption, adsorption, catalytic
- Regenerating, no regenerating

- Wet, dry, semi-dry
- Calcium, sodium, ammonia, magnesium, etc.

One of the most popular desulfurization methods is wet scrubbing using lime as a sorbent . In this process suspension of lime, which is dissolved in water, is reacting with exhaust gases causing absorption. The final product of this reaction is gypsum. It has got cleanliness very similar to gyps which occurs in natural environment. After dehydration of gypsum it can be stored in landfills or used to fill in uneven of terrain, and also sell for construction purposes.

The desulfurization unit consists of parts: absorption, preparation and transport of suspension absorption, oxidation and separation of sludge and heating the cleaned gas. The advantages of this technology are: low investment costs, availability of absorbent, possibility to sell the waste, high efficiency desulphurization and dust removal of exhaust gases - especially in coal-fired boilers, high degree of automation and instrumentation installation. Additional advantage is avoidance of fees for emissions of SO_2. In contrast, the disadvantages can: the need for heating exhaust, susceptibility for clogging and erosion which is caused by products of desulfurization. This kind of installation needs large building area, and has got a necessity to remove water from the product. [3]

Poland's first wet scrubbing method using lime as a sorbent were used in Jaworzno III in 1996. Gases from 4 power units of 200 MW boilers type RAFAKO OP-650, fired with coal were desulfurized.

Tab. 8 Limits of emissions

Emission	**Limits**
PM10	40 μg/m^3 (allowable annual level, average concentration) 50 μg/m^3 (allowable level, average for 24h) 300 μg/m^3 (alarm level average for 24h)
PM2.5	25 μg/m^3 (allowable annual level, average concentration)
SO_2	125 μg/m^3 (allowable level, average for 24h) 350 μg/m^3 (allowable level, average for 1h)500 μg/m^3 (alarm level, average for 1h)
NO_2	40 μg/m^3 (allowable annual level, average concentration) 200 μg/m^3 (allowable level, average for 1h) 400 μg/m^3 (alarm level, average for 1h)
CO_2	1000 pm (allowable concentration) 5000 pm (maximum concentration)

5. Economic Analysis

In this point economic analysis of building new 600MW NGCC unit is described. As a first thing in this case of analysis there had been assumed some financial details like investment costs, discount rate or amortization. Time of operation of this theoretical unit is 20 years. Cost of investment has been estimated on 700 million PLN. The most important things for profitability analysis are costs of production and sale of energy. The cost of production of 1 MWh is 300 PLN [9]. To make this installation profitable the cost of sale energy has to be on level of 500 PLN per MWh.

There are a lot of payments which power plant has to manage like operation and maintenance costs or environmental fees. Company has to pay for an emission of each component of exhaust gases or heavy metals like mercury and lead. In Poland for emission mercury to environment, owners of the units are obligate to pay 190.68 PLN/kg [10]. In this analysis there were considering only the most important compounds of exhaust gases, it means CO_2, SO_2 and NO_x. Price of using gas was adopted from actual price on fuel exchange and is equal to 10.37 $/MWh [11]. It means that for 600 MW NGCC power plant it is cost over 23.8 million PLN per year.

In calculations as an expenses considered operation and maintenance costs. It means consumptions of materials, tools, repairs, transport and service subcontractors. As a value which will show that this investment is profitability is used NPV. For this kind of power plant is the need to employment over 100 workers. In this analysis adopted number of employee as 120 people. Their average wage is 4 700 PLN per month [12].

There have been compared two variants of NGCC plant, with and without CO_2 capture installation. Obviously additional installation means that investments cost are much higher. It was estimated as 1.19 hundred millions. But in this case environmental fees are lower and 90% efficiency of Carbon Dioxide Reduction (CDR) installation provides to savings of costs. In a Tab. 9 there are showed more details which were used to analysis the first case without CDR installation.

Tab. 9 Data for economic analysis

Variable	**Value**	**Unit**
Investment cost	700 000 000	PLN
Price of sale of energy	400	PLN/MWh
Price of energy produce	300	PLN/MWh
Expenses		
Operating costs	25 650 000	PLN/y
Maintenance costs	5 130 000	PLN/y
Costs of fuel	236 932 018	PLN/y
Payments to employees	7 752 672	PLN/y
Environmental fees	80 943 144	PLN/y
Discount rate	0,05	%
Time of building	30	Months
Time of operating	20	Years
Liquidation rate	15	%
Amortization	8,5	%

6. Summary

In this article were showed exemplary installation of natural gas combined cycle power plant. Exergy analysis showed where are the values of exergy for products and fuels. It can be used to estimate the biggest losses in this cycle. There is presented limits of emission compounds which are emitted to atmosphere. To reduce this amounts there are described special installations which are used in this unit. By economic analysis we proved that this kind of unit is not profitable in polish actual conditions. Prices of fuels are much bigger than prices of selling energy. Specially carbon dioxide reduction installation has got a huge impact on investments and operation costs

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The way of improving energy efficiency in steel industry TRT Turbines

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Abstract

Paris Agreement with its main aim on keeping a global temperature rise this century well below 2 degrees Celsius shows the political will to prevent global warming. Strong emphasis is put on CO_2 abatement. In the article a cutting edge technology of TRT turbine is described. Turbines of this type are capable of cutting carbon dioxide emissions in very energy intensive industry – steel making. Simultaneously they are very interesting in terms of economic. The article presents TRT turbine's advantages, design features and principle of operation.

Keywords: TRT, energy efficiency, blast furnace, BFG, steel

1. Introduction

TRT (Top-Pressure Recovery Turbine) is a machine used to generate electrical energy from employing blast furnace top gas. Blast furnace is a heart of nowadays iron making plant. From the whole steel-making industry, the most energy-consuming process is iron making, responsible for about 70% of the consumption. Taking a deeper insight into energy flow of an iron making process the most energy consuming activities are:

- blast furnace – 39 %,
- coking – 11.9 %,
- power – 12.5 %,
- electric furnace – 17.5 %.

These statistical data show that blast furnace is the highest energy consumption unit in the industry. On the other hand, there is the greatest opportunity for energy saving in blast furnace [1]. One of the effects of blast furnace work is a production of blast furnace gas.

Tab. 1 Typical Blast Furnace Gas Composition

Compound	Chemical formula	Typical value	Range of deviation	Unit
Carbon dioxide	CO2	18	+/- 2	Vol %
Carbon oxide	CO	24	+/- 2	Vol %
Hydrogen	H2	2.5	+/- 2	Vol %
Nitrogen	N2	54.5	+/- 2	Vol %
Oxygen	O2	0.6	+/- 0.5	Vol %
Methane	CH4	0.4	+/- 0.5	Vol %

That gas has usually the pressure of 0.2-0.236 MPa and temperature of approximately 200°C at the furnace top. Lower Heating Value of BGF is in the range of 3.3 to 3.5 MJ/m^3. Thanks to its chemical energy BFG is desired to feed other steel making processes or to be utilized by plant's CHP unit to produce electricity and steam. For this purpose it needs to be cleaned and expanded.

BFG (Blast Furnace Gas) is exhausted from the top of a blast furnace and is thereafter treated in wet or dry cleaning process. Dry BFG purification method uses the dry-type dust collector while the main equipment in wet process are Venturi scrubbers.

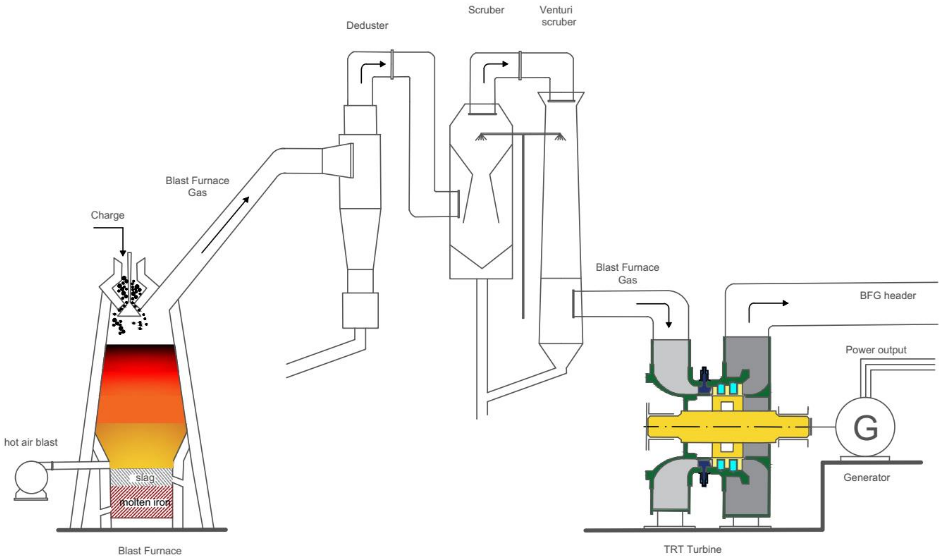

Fig. 1.1 TRT turbine arrangement with wet BFG cleaning process

Cleaning method applied is reflected by blast furnace gas physical parameters, namely temperature, pressure and water content.

Tab. 2 Dry and wet BFG cleaning methods comparison [2]

Parameter	**Dry process**	**Wet process**
Clean gas dust content	≤ 3 mg/Nm3	≤ 5 mg/Nm3 in combination with TRT
Temperature drop	Max. 5 °C (no cooling of top gas)	Gas temp. goes down to water temperature
Pressure drop	10–20 mbar	250 mbar
Energy recovery at TRT	+ 20–30 % higher	Basis

Wet BFG purification method has been implemented in older steel plants while dry method can be found in any new or modernised plant. Method applied has a strong influence on TRT turbine potential to generate power.

To lower the pressure of blast furnace gas to the level required by burners usually a septum valve (special valve used in steel-industry to expand and control pressure level of gases) is used. Even if throttling was ideally isentropic, the change of pressure is a loose of exergy. TRT turbine allows to recover this exergy.

2. Top-Pressure Recovery Turbine

TRT turbines at a first glance are simple expanders but their construction is complicated when investigated deeper. Solutions of design are known just for a few companies and protected by patents and know-how. The reason for this are hard working conditions (high dust content, water droplets presence, toxicity and explosiveness of BFG).

TRT turbines are most popular in Japan and China. Main Suppliers of TRT Turbines are:

- Mitsui,
- ShaanGu,
- Hitachi,
- Kawasaki.

1.1. TRT Configurations

There are variant configurations possible:

- Single Flow (BFG is introduced from one side of the turbine and the generator is connected by a shaft or a gearbox from the other.)
- Double Flow (BFG is parallelly flowing through two sides of turbine, each consisting of its own blades sets. Generator in this configuration is placed in the middle)
- Dual Duty (Design is similar to Double Flow but BFG can be coming independently from two separate blast furnaces with own pressure control)

1.2. TRT Design

Main design features are:

- Revolution (usually 1500/1800 RPM or 3000/3600 RPM) – Slower rotational speed prolongs life of the blades thanks to smaller velocity of the blades which suffer from erosion caused by dust carried by BFG. On the other hand the need of installing the switchgear lowers efficiency and availability.
- labyrinth seals + gas sealing (utilising N2) – Gas-tightnes is one of the most important features of TRT turbine as the BFG is highly toxic (carbon monoxide) and explosive (air cannot be utilized).
- Fixed or adjustable angle of stator blades (first, all) – Amount of BFG produced, thus it's velocity, and pressure varies with time. The optimal angle of stator blades for any load case gives a result in higher efficiency.
- type of inlet (side, radial, bottom),
- type of outlet (side, radial, axial),
- Number of stages (1 to 4) – Usually blast-furnaces gases have similar pressure no matter in which plant a blast furnace is installed. The need of expansion to the same pressure appears for majority of burners. Number of stages is therefore increasing investment costs but efficiency as well.
- Coating on blades (special paints, gum or glass) – Dust particles accumulating on blades not only interfere with the flow but may cause vibrations or accelerated wear.
- Water-blowers – As dust accumulation is impossible to be reduced to zero level, special cleaning systems are being used. They are able to clean inlet and outlet as well as blades of a turbine.

3. Economic Evaluation

Construction of TRT turbine is a very effective way of cost optimization in steel-industry what has been proven around the work by different companies. Some examples from the market are presented below:

- New Energy and Industrial Technology Development Organization:

Tab. 3 Evaluation of investment in TRT turbine in Japanese conditions[3]

Investment	Equipment and construction cost (approx.)	800 million ¥
	Generating capacity	7 MW
Economic assumptions	Price of power	18 ¥/kWh
	Annual savings (approx.)	900 million ¥
Investment payback time	Equipment only (approx.)	1.4 years
	Equipment + construction costs (approx.)	1.8 years

- Tata Steel Ltd [4]:

According to Tata Steel experience from constructing and running 3 TRT turbines payback time is in the range of 4 to 5 years.

4. Potential of development in Poland

In this year the Board of Tameh (joint-venture of ArcerolMittal and Tauron) have decided to build a TRT turbine in Huta Katowice – a steel-making plant in Dąbrowa Górnicza. Turbine is said to be able to reach power of 25 MW. This is a perfect example of energy efficiency increase which is now obligatory by the latest Energy Efficiency Law Act (May 20, 2016). Beside savings in energy, the ecological effect will be achieved thanks to avoided emissions in conventional power plant. Main emissions components are carbon dioxide CO2, nitrous oxides NOx and sulphur oxides SOx [5,6].

Power generation by the TRT requires a blast furnace with pig iron production of 1 million ton/year or higher. This limitation makes possible to install a TRT turbine only in biggest steel-plants. Beside the plant in Dąbrowa Górnicza, only in Huta Sędzimira, located in Krakow, blast furnaces have capacity high enough.

5. Conclusions

TRT Turbine is a state-of-the-art solution for energy recovery from blast furnace gas expansion process. Ability to save energy and decrease greenhouse gases emissions should mean that TRT turbines are present in every major steel-plant as technology is known for years. The reason they are not is not behind their economy as they have short payback time. The answer to this puzzle is common for every industrial plant. The risk connected with impacting the production while improving energy efficiency deters owners and investors. This attitude should be changed if humanity wants to slow down climate changes. These should be government and citizen to push the industry

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Feasibility study and exergy study of supercritical power plant

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Abstract

This article is focused on the analysis of energy, exergy and economy for the steam power plant with supercritical parameters. The whole article is divided into four integral parts. The first part of the article is the introduction which realized recipient about the technological solutions of modern coal power unit. The second part shows the analysis of energy and exergy on the 550 MW supercritical carbon unit, which is a tool to optimize the process. In the third part, the economic analysis was done to define the basic indicators of economic efficiency of investment. Finally, the conclusion will be find, which contains the results and interpretations of the analysis.

Keywords: Supercritical power plant, energy, exergy, economy

1. Introduction

Nowadays electric power is an integral part of life. It is also the most useful form of energy. The most popular and general method of power generation is based on the Rankine cycle. Working fluid is a steam which is a result of the conversion of primary energy into thermal energy. The standard power plant consists of a boiler where the steam is the effect of water evaporation; steam turbine converts the energy contained in steam into rotary motion of the driveshaft. The turbine is connected to generator which produces electricity. The last element is condenser closing the steam cycle where the steam is condensed to water and then feed the boiler again.

The most popular and widespread fuel in Poland is coal. Poland is one of the largest coal producers in the European Union. Figure 1 shows the coal mining in selected European countries [1]. In addition, coal is a strategic resource in Poland because it provides 60% of the total electricity requirement of the whole country. Coal market seems to guaranty high stable electricity cost. For that reason, coal-fired power units can be modified and improved. The basic method to improve the thermal efficiency increases the operating pressure and temperature.

Modern thermal power plants operate at very high pressures greater than the critical pressure of steam. This kind of units is called supercritical power plants. The operating pressure is in the range of 24 to 26 MPa and temperature 500 to 600°C. The effect of a higher pressure operation and the temperature is the increase thermodynamic efficiency up to 45%. Another reason of power units improvement are ecological aspects which require reduction of emission. High values pressure and temperature are possible to achieve as a result of progress in material engineering. Special high-grade materials are used for the boiler tubes and turbine blades.

Another aspect of improvement power plants is optimization of cycle process. Therefore, exergy analysis in steam power units can be carried out. The exergy efficiency is determined as a perfect cycle of the power plant. To define this value must be made exergy balance. Every value in an exergy balance of device working in the steady state should be found in one of the three groups: drive exergy group, useful effect group and loss exergy group.

Drive exergy is only on the input side of the balance while the exergy losses are only on the output side. The useful effect is a result of difference between output and input data. In the exergy balance of power unit the input values are fuel exergy, exergy water replenishing the circulating factor loss and water which replenish losses in cooling systems. For this reason, exergy replenishing water should be the rate to drive exergy of the process.

Exergy is the maximum theoretical useful work (shaft work or electrical work) obtainable from a thermal system as it is brought into thermodynamic equilibrium with the environment while interacting with the environment only [3]. Alternative definition of exergy is the minimum theoretical work (shaft work or electrical work) required to form a quantity of matter from substances present in the environment and to bring the matter to a specified state [3]. Therefore exergy is a measure of the departure of the state of the system from the state of the environment.

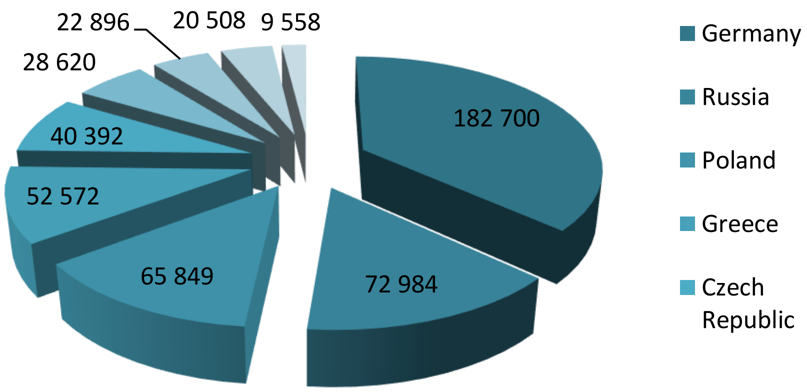


Fig.1.1 Coal mining in 2013, thousand tonnes

The environment is defined as big balanced system wherein state variables (T_o , p_o) and chemical potential from chemical components stayed constant during exchange heat and mass between another system and environment. The exergy of elements and compounds at the environment conditions is equal zero [2]. Apart from electrical, magnetic, nuclear and surface tension effect, total exergy E_{sys} is sum of four kind of exergy: physical exergyE_{sys}^{PH}, kinetic exergy E^{KN}, potential exergy $E^{PT}$and chemical exergyE^{PH}. The physical exergy can be obtained from equal:

$$E_{sys}^{PH} = (U - U_0) + p_0(V - V_0) - T_0(S - S_0) \tag{1.1}$$

Where U, V, S are represented as internal energy, volume, entropy of the system.

The chemical exergy E^{PH} (more information can be find in article [4]) is the maximum work which can be achieved as the system at parameters: temperature T_o and pressure p_o occurring in chemical balance with environment.

For calculating chemical exergy besides specified temperature and pressure, chemical components of environment have to be specified. Tabulated standard chemical exergies for substances contained in the environment at standard conditions ($T_{ref} = 298.15K \; and \; p_{ref} = 1{,}013 \; bar$) are used in order to calculate chemical exergy.

The standard chemical exergy of substance which is not present in environment can be calculated using reversible reaction of substances with another substances for which chemical exergy are known. It shows that calculation for energy-conversion processes is especially important.

The Figure 2 shows exemplary reversible, isotermic and isobaric reactor in which fuel reacts with oxygen in steady state [2]. Products of reaction are CO_2, H_2O, SO_2, N_2.The assumption is that all of them are enter and exit unmixed at T_o, p_o.

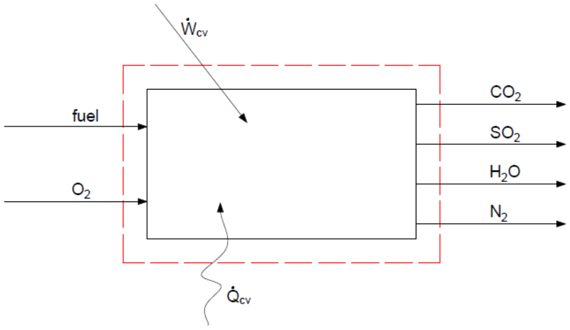


Fig. 1.2 Hypothetical, reversible isotermic and isobaric reactor for evaluating the chemical exergy of a fuel [2]

For the reversible reaction the chemical exergy on a molar basis of fossil fuel can be derived from balance of energy, exergy and entropy [2].

$$e_f^{-CH} = \left(\Delta\bar{h}_R - T_0\Delta\bar{s}_R\right) + \Delta e^{-CH} = -\Delta\bar{g}_R + \Delta e^{-CH} \tag{1.2}$$

$$\Delta\bar{h}_R = \sum_i v_i\bar{h}_i \;;\; \Delta\bar{s}_R = \sum_i v_i\bar{s}_i \;;\; \Delta e^{-CH} = \sum_k v_k e_k^{-CH} \tag{1.3}$$

$$i = H_2O, SO_2, CO_2, O_2, N_2$$
$$k = H_2O, SO_2, CO_2, O_2, N_2$$
$$v_i \text{ and } v_k \geq 0: H_2O, SO_2, CO_2, N_2$$
$$v_i \text{ and } v_k < 0: O_2$$

Where $\Delta\bar{h}_R$,$\Delta\bar{s}_R$, $\Delta\bar{g}_R$ are molar enthalpy, entropy and Gibbs function, accordingly for reversible combustion reaction of the fuel with oxygen, $v_i \text{ and } v_k$ is the stoichiometric coefficient of the kth(ith) substance in this reaction, e_f^{-CH} is the molar chemical exergy of a fossil fuel.

2. Exergy

Thermodynamic processes are depended on the law of energy and mass conservation. Therefore, the overall mass and energy cannot be created and destroyed in the same process. In fact, exergy is destroyed because of irreversibility of the process. What is more loss of exergy is the result of dispersion of energy flow to the environment.

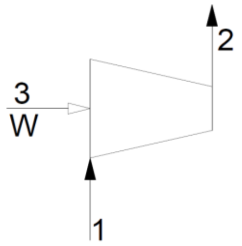
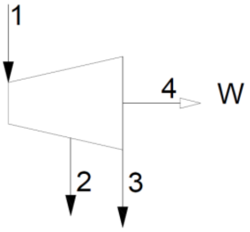
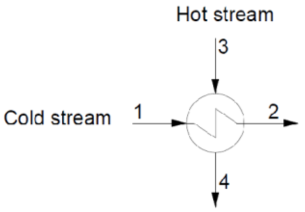
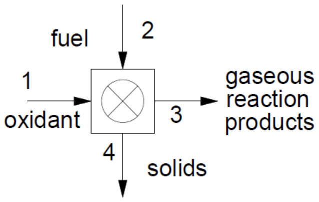
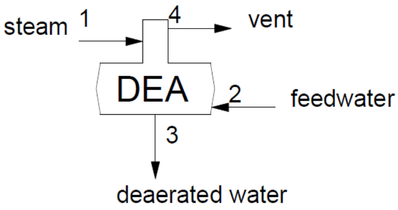
The change in total exergy of a closed system is the result of transfers of energy by work and heat between the system and its surrounding.

$$E_{sys2} - E_{sys1} = E_q + E_w - E_d \tag{2.1}$$

Where $(E_{sys2} - E_{sys1})$, E_q, E_w, E_d are respectively change in total exergy, exergy transfer related to heat transfer, exergy transfer related to transfer of energy by work, exergy destruction.

Selected components in steady state are presented in Tab.1. In order to define exergy efficiency each component, exergy rates of product and fuels have to be known. Exergy rate of product E_p is a desired results which are produced by the system, exergy rate of fuel E_f is a resource which generates the product. It cannot be conventional fuels such as coal, oil and natural gas. The fuel can be represented by work or heat.

Tab. 1 Exergy rates of fuel and product for selected components at steady-state. [2]

Component	**Schematic**	**Exergy rate of product E_p**	**Exergy rate of fuel E_f**
Compressor, pump		$\dot{E}_2 - \dot{E}_1$	$\dot{E}_3$
Turbine or expander		$\dot{E}_4$	$\dot{E}_1 - \dot{E}_2 - \dot{E}_3$
Heat exchanger		$\dot{E}_2 - \dot{E}_1$	$\dot{E}_3 - \dot{E}_4$
Combustion chamber		$\dot{E}_3 - \dot{E}_2$	$\dot{E}_1 - \dot{E}_4$
Deaerator		$\dot{m}_2(e_3 - e_2)$	$\dot{m}_1 - (\dot{m}_3 - \dot{m}_2)e_1 - \dot{m}_4 e_4$

For the cycle shown in the diagram was made energy and exergy analysis for values of pressure, temperature and flow of steam and condensate. The results of calculations were presented in the Table 2.

3. Energy and Exergy Analysis of Supercritical Power Plant

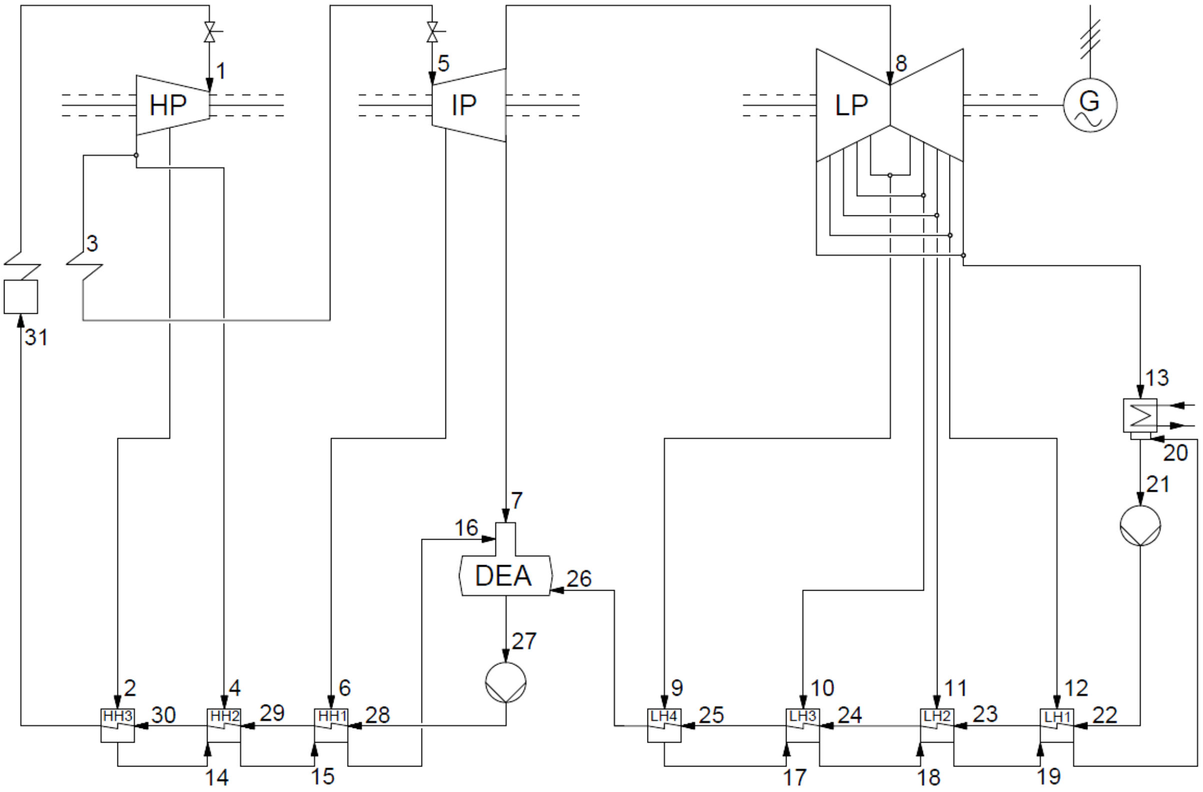


Fig. 2.1 Supercritical steam cycle

Tab. 2 Calculation results

Variable	**m**	**P**	**T**	**h**	**s**	**e**
unit	kg/s	kPa	C	kJ/kg	kJ/kg-C	kJ/kg
1	439.9	26 000	630	3 573	6.437	1 675
2	32.08	7 500	416.4	3 194	6.472	1 285
3	401.2	5 000	357.4	3 089	6.483	1 177
4	38.62	5 000	357.4	3 089	6.483	1 177
5	401.2	4 806	630	3 738	7.359	1 568
6	27.12	1 994	479.5	3 423	7.376	1 248
7	8.897	895	360.5	3 182	7.392	1003
8	365.2	895	360.5	3 182	7.392	1003
9	24.19	483	281.4	3 027	7.410	841.3
10	12.29	145	152.2	2 778	7.448	581.3
11	10.97	55	83.71	2 619	7.476	414.2
12	13.45	21	61.12	2 481	7.502	268.5
13	304.3	5	32.87	2 300	7.540	75.73
14	32.08	5 143	265.7	1 163	2.937	299.4
15	70.7	2 337	220.4	945.4	2.521	204.2
16	97.82	1 172	186.9	793.6	2.206	145.6
17	24.19	138	108.9	456.6	1.406	44.8

18	36.48	62	86.77	363.5	1.155	25.78
19	47.45	28	67.52	282.7	0.925	13.11
20	60.9	5	32.87	137.8	0.476	0.6848
21	333.1	5	32.87	137.8	0.476	0.6848
22	333.1	1 806	33	139.9	0.477	2.507
23	333.1	1 731	60.6	255.1	0.838	11.21
24	333.1	1 662	81.1	340.9	1.088	23.25
25	333.1	1 593	103.9	436.7	1.350	41.58
26	333.1	1 531	147.8	623.4	1.818	89.88
27	439.9	910	167.2	706.9	2.014	115.6
28	439.9	30 000	171.9	743.9	2.025	149.3
29	439.9	29 000	215	930.4	2.427	217
30	439.9	28 000	260	1 134	2.829	302.3
31	439.9	27 000	290.6	1 283	3.102	370

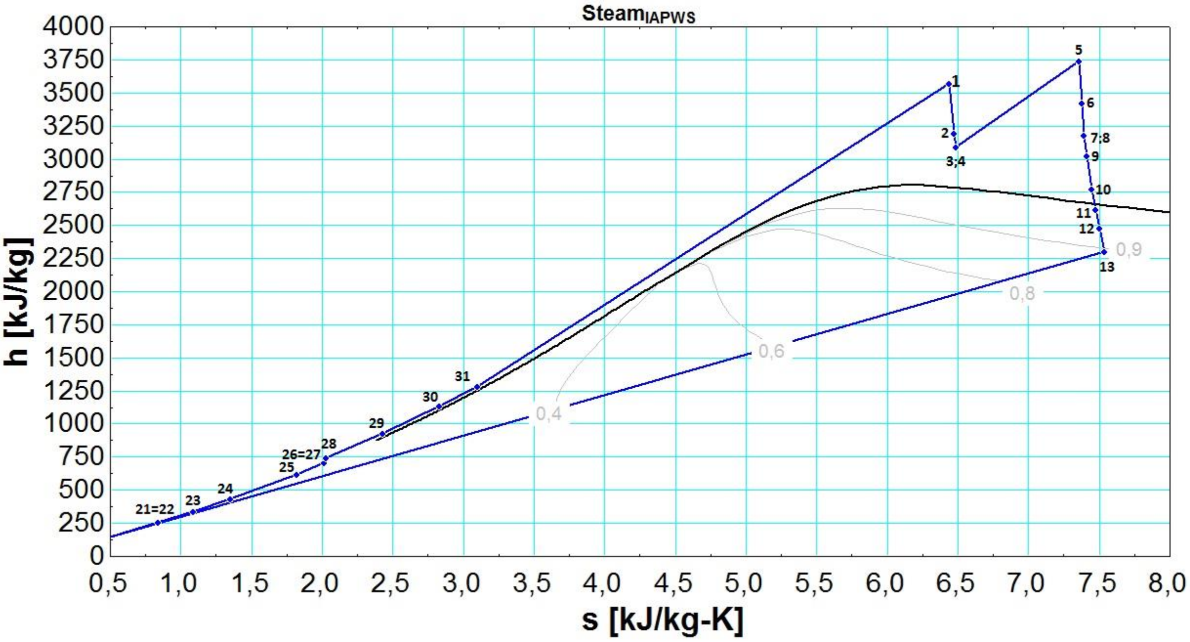


Fig. 3.1 Supercritical steam cycle in h-s diagram

Balance of substance

$$\dot{m}_{in} = \sum_i \dot{m}_{out.i} \tag{3.1}$$

Balance of energy

$$m_{in} \cdot h_{in} = \sum_i (\dot{m}_{out.i} \cdot h_{out.i}) + N_{iT} \tag{3.2}$$

Balance of exergy

$$\dot{m}_{in} \cdot e_{in} = \sum_i (\dot{m}_{out.i} \cdot e_{out.i}) + N_{iT} + \delta E \tag{3.3}$$

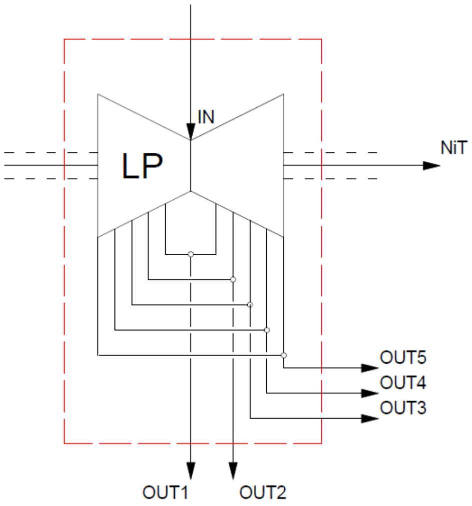


Fig. 3.2 Mass and energy balance

Tab.3 Results of exergy analysis

No.	**Element of Power Plant**	**Absolute exergy losses**	**Relative exergy losses**
		kW	%
1	Boiler	692 491	48.66
2	Highpressure Turbine	67 187	4.721
3	Intermediatepressure Turbine	3 830	0.2691
4	Lowpressure Turbine	14 375	1.010
5	Shaft and Generator	24 792	1.742
6	Condenser	24 809	1.743
7	Pomp of Condesate	16 139	1.134
8	Lowpressure Heat Exchanger 1	1 290	0.09065
9	Lowpressure Heat Exchanger 2	852	0.05987
10	Lowpressure Heat Exchanger 3	1 181	0.08296
11	Lowpressure Heat Exchanger 4	3 182	0.2236
12	Deaerator	1 629	0.1144
13	Pomp of Feed Water	1 925	0.1353
14	Highpressure Heat Exchanger 1	1 878	0.1320
15	Highpressure Heat Exchanger 2	3 114	0.2188
16	Highpressure Heat Exchanger 3	4 267	0.2998

Tab.4 Results of exergy analysis

	Gross	Net
Energy efficiency	44.50%	41.86%
Exergy efficiency	41.81%	39.46%

4. Economical analyse

Net Present Value is a formula, which is used to determine the present value of investment by the discounted sum of all cash flows received from this project. The formula for the discounted sum of all cash flows can be rewritten as

$$NPV = \sum_{t=0}^{N} \frac{CF_t}{(1+r)^t} \tag{4.1}$$

When a company or investor takes on project or investment, it is important to calculate how profitable the project or investment will be. Considering that the money going out is subtracted from the discounted sum of cash flows coming in. the net present value would need to be positive in order to be considered a valuable investment. Cash flow is the net amount of cash and cash-equivalents moving into and out of a business. Discount rate is the interest rate charged to commercial banks and other depository institutions for loans received from the Federal Reserve Bank’s discount.

Real discount rate $r = \frac{1+n}{1+i} - 1$

n – nominal discount rate. i – inflation rate

NPV takes account of time value of money. placing emphasis on earlier cash flows and looks at all the cash flows involved through the life of the project. Use of discounting reduces the impact of long-term. less likely cash flows. NPV has a decision-making mechanism – reject projects with negative NPV. NPV calculations are very sensitive to the initial investment cost. The higher NPV is the better for the project from the economic point of view.

4.1 Technical assumptions

For the purpose of cost-benefit analysis, the project was based on the assumptions and calculation carried out in the program ESS (Engineering Equation Solver). Additionally, adopted availability rate of 92% assuming the need for annual shutdowns for repair with a length of 30 days. For the emission, the limit values of basic concentrations of gases in the exhaust gas such as: SO_2, NO_x and dust were adopted on the basis of the BAT reference document [5] assuming that the newly built power plant must meet these guidelines. Designed Power Plant does not produce the heat for sale and was not qualified in 2011 for the National Investment Plan. Since the power plant was not qualified on a basis of the EU ETS Directive will not receive free allowances for CO_2 emissions and the whole emissions will have to buy on the market. All described and needed technical data summarized in the Table 5.

Tab.5 Technical basic data

Technical basic data		
Electrical power net	MW	561.508
Efficiency net	%	41.85%
Availability	%	92%
Type of fuel	Coal	
Lower Heating Value	GJ/Mg	20.289
Fuel Stream to Boiler	kg/s	66.12
Ash content	%	19.50%
Amount of dry flue gasses	m_n^3/s	412.9
The mass of CO_2 in the exhaust gas	kg/s	133.3
Allowable concertation of SO_2 in the exhaust gas	mg/m_n^3	75
Allowable concertation of NOx in the exhaust gas	mg/m_n^3	85
Allowable concertation of ash in the exhaust gas	mg/m_n^3	5

4.2 Price assumptions

The financial model was based on current price levels in 2016. The basic prices are:

- electricity price calculated on the basis of the Power Exchange [6] relating to transactions concluded on the market the next day during 1-10.2016:
- the price of coal on the basis of data from the Polish coal market [7] as the average period between 1-9.2016
- EUA price of the trading day on EUA Secondary Market 2013-2020 (EEX) in 15.11.2016 [8] and the average exchange rate of NBP for day 11.15.2016.
- fees for emissions adopted in ordinance of the Council of Ministers[9]

Tab.6 Prices and rate of payments

Prices and rate of payments		
Price of energy	PLN/Mg	160.50
Coal price	PLN/Mg	194.9
Price of EUA	EUR/Mg	5.4
Rate	PLN/EUR	4.4136
The rate of emission charges for No_x	PLN/Mg	530
The rate of emission charges for SO_2	PLN/Mg	530
The rate of emission charges for ash	PLN/Mg	350
Unit cost for waste utilization	PLN/Mg	16.2

4.3 Capital Expenditures - CAPEX

CAPEX was determined on the basis of media reports [10] regarding the costs of building block 910 MW Power Plant Jaworzno III amounting 5.4 mld. PLN and taking into account the proportion of power i.e.545 MW/910 MW in the analysed project.

Tab.7 Investments Outlets

Investments Outlets		
Investment	mln. PLN	3 239.13
Depreciation rate	%	5.00%

For the purposes of cash flow analysis premised the share of expenses in each year and it is shown in the table below.

Tab.8 The share of expenses in the following years

The share of expenses in the following years			
1	**2**	**3**	**4**
10%	30%	35%	25%

4.4 Fixed Costs

The model assumes fixed costs included in the 3 main categories i.e.: employee costs, costs of materials and services, taxes and fees. According to [11-12], employee cost was based on the projected level of employment. The level of employment was adopted on the level of 0.2 per. /MW which corresponds to the level of employment in the power plant Drax [13] and the employment level in the designed that time power plant Opalenie [14]. The level of the cost of materials and services depends largely on the level of resources allocated for repairs. The model assumes an annual level of these costs in the amount of 2% of the expenditures for the construction. Those costs are taking into account both the costs of current repairs and capitalized costs of the capitalize devices. In practice every 7-8 years, overhaul of the turbine which is more expensive than standard repair is performed, and it is raising the cost of materials and workers. The main component in taxes and charges position is property tax of 2% of the gross value of construction and the product of usable buildings and the tax rate per m2. It was posited that “the value of the building will be approximately 25% of total expenditures which in turn gives value of 0.5% in a tax connected with the costs of construction.

Tab.9 Fixed costs

Fixed costs		
Employment rate	per/MW	0.2
Employment	person	109
Average gross wage	PLN/per/m-c	4 500
Social security contribution	PLN/per/m-c	900
Costs of materials and services	mln.PLN	65
Taxes and fees	mln.PLN	16

4.5 Other assumptions

It was also assumed that the inflation rate over the entire period will be constant at 1.5% and this value was used to index all prices and costs. This value corresponds to the last National Polish Bank (NBP) inflation forecast for 2018[15]. Discount rate for calculating the NPV adopted in the amount of 6.6% what gives risk premium of 3.3% compared to the average profitability from the last 11 treasury bonds of 3.289% [15].

Tab.10 Other financial assumption

Other financial assumption		
Inflation	%	2%
Discount rate	%	6.6%

4.6 Analysis of the profitability of the project

Analysis of the profitability of the project was based on the NPV. In order to determine the NPV cash flows were translated in the period of 24 years taking into account four years period of investment and 20 years period of power plant exploitation. The basis for calculating the flows was to determine the maximum value of annual electricity sales of 4.5 TWh, coal consumption of 1.9 million Mg and CO2 emissions of 3.9 million Mg. The project did not include loss of production efficiency over the years. All calculated flows didn’t change during exploitation period Based on these values, the value of revenues, fixed and variable costs allowed to calculate EBITDA. EBITDA is a shortcut which means “Earnings before interest: taxes, depreciation, and amortization” and it is widely used in many areas of finance when assessing the performance of a company, such as securities analysis. Figure 4.1 shows the resulting flow for the entire analysed period.

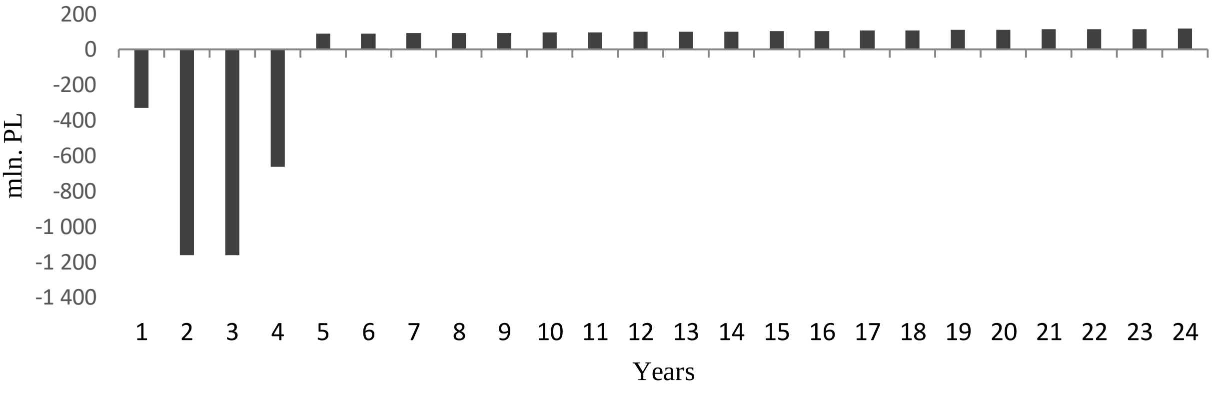


Fig. 4.1 Cash flow

Taking into account the established discount rate of 6.6% the discounted cash flows can be seen in the chart below.

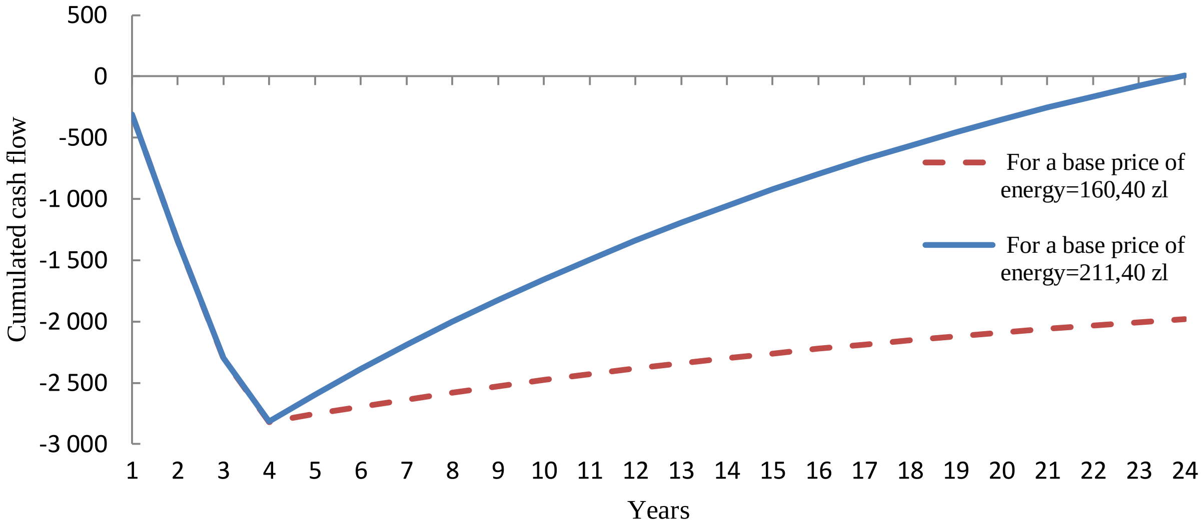


Fig. 4.2 Cumulated Cash Flow

Figure 4.2 shows that NPV = sum of discounted cash flows is negative and amounts to - 1 980 million PLN. On the basis of the calculated NPV, it can be stated that the analysed project for the accepted assumptions is unprofitable. After analysing the sensitivity of selling price of electricity received a basic price in the amount of 211.40 PLN (which is 31.7 % higher than the price amount in the project) for which the NPV is positive and has a value of 10 mln. PLN. The new NPV value is also shown on the figure 4.2.

5. Conclusions

The value of gross energy efficiency is 44.35%, which is typical for new build coal power plants. The quality of steam before the condenser (at 13th point) is 0.8922 this value of quality confirmed that the assumptions for the turbine are correct because it should be in the range between 0.8 and 0.9. The greatest loss of exergy are located in the boiler, almost half of exergy of coal is lost there. This loss can be reduced only by raising the parameters of live steam and lowering the temperature of the exhaust gas.

Financial analysis shows that the current market structure considered power plant with supercritical parameters is unprofitable (NPV project less than zero). The main reasons for this situation are the low electricity prices, the cost of CO_2 emissions and the high cost of investment. The project will become profitable if there are real reasons for the increase in electricity prices that indicates the calculated value of NPV for higher energy prices, which exceeds 10 billion.

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The influence of heavy metals on *Phaeodactylum tricornutum* growth – a preliminary study

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Abstract

Heavy metals pollution is the ever rising problem, as these elements may cause serious harm to many organisms, including humans. This apprehensiveness is visible especially in developing countries, where the industry relies heavily on, for example, mining. The toxic heavy metals may also come from industrial wastewaters, fertilizers or batteries. One way of removing these pollutants from waters is the use of bioremediation techniques, based on the special capabilities of microorganisms. We tested if the marine diatom species *Phaeodactylum tricornutum* is able to thrive in cadmium(II), chromium(VI), lead(II), mercury (II) and thallium(I)-contaminated mediums. We found that these diatoms can grow in culture media containing these heavy metals and that the scope of *P. tricornutum*'s resistance depends on the metal and its concentration. Moreover, we describe the observation of a putative adaptation mechanism.

Keywords: diatom growth, heavy metals, *Phaeodactylum tricornutum*, phytoremediation, wastewaters

1. Introduction

Heavy metals are ubiquitous environment pollutants in both soil and water, where they can be highly toxic to many different organisms including humans. Contamination of water and soil with heavy metals is common problem worldwide. An often described example is a problem of drinking water contamination in India, where arsenic is frequently detected in wells [1]. Heavy metals may be easily introduced to environment during mining activity [2], or using phosphate fertilizers and, by its prevalence, it is serious problem [3]. Mechanisms of heavy metals toxicity in humans and other animal species are well described in literature [4,5]. Despite of that, for some poisonings with metallic compounds, such as dimethylmercury, there are no efficient specific treatments [4,6]. Reported metals poisoning can be the source of broad spectrum of symptoms affecting different systems of human body, such as nervous, digestive and excretory system [4,6,7]. Heavy metals are also toxic for plants and algae, however some of them show tolerance for certain amounts of different extremely toxic metals. There exist species of bacteria [8], fungi [9], plants [10] and algae [11], which demonstrate not only a tolerance to heavy metals, but also the ability of metals accumulation or the ability to remove heavy metals from their environment. Due to described properties of heavy metals, pollution with those elements should be concerned as extremely dangerous for marine ecosystem, especially in coastal areas where heavy metals are frequently found. Heavy metals pollution in such areas is of particular importance due to the fact that organisms living in those areas are commonly utilized as a source of food [12,13].

Due to simplicity of their culturing, low price and effectiveness against relatively broad spectrum of metals, algae are very promising remediating factors in bioremediation of water contaminated with heavy metals [9]. One of the most interesting algal species is *Phaeodactylum tricornutum* (Fig. 1). Belonging to diatoms, *P. tricornutum* is frequently found in marine environments across the world, living in different conditions.

Moreover, marine diatoms fix 20 billion tons of carbon per year which corresponds to 40% of the marine and 20% of the global net primary production. This immense carbon fixation is even higher than that of the most productive terrestrial ecosystem, the tropical rainforests [14]. These facts indicate a major role of diatoms in the functioning of marine ecosystems and regulation of the conditions of Earth life. *P. tricornutum* as a genome-sequenced diatom species can be used as model organism, also in studies on heavy metals pollution effect on marine ecosystems [15]. In this work the resistance of *P. tricornutum* to selected heavy metals, commonly described as toxic, was examined. Obtained results can be beneficial for future application of *P. tricornutum* in bioremediation of contaminated waters.

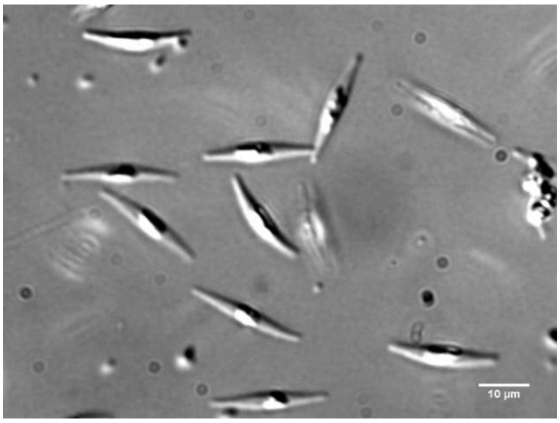

Fig 1.1. *Phaeodactylum tricornutum* cells (fusiform morphotype), visible under the light microscope. The diatoms were grown in f/2 medium with no heavy metals added. The picture was taken by Dr. Weronika Krzeszowiec-Jeleń.

2. Materials and methods

Diatoms were cultured in Guillard's f/2 medium [16]. When heavy metals effect on diatoms was studied, medium was contaminated with one of five heavy metals at a given metal ion concentration (final ones: Cd^{2+} - 0.1, 1, 2 mg/L; CrO_4^{2-} - 1, 5, 50 mg/L; Hg^{2+} - 0.01, 1, 10 mg/L; Pb^{2+} - 1, 5, 25 mg/L; Tl^{+} - 0.5, 5, 50 mg/L). The ion concentrations were chosen in a way that the lowest one would be in a range of a sewage disposal norms [17] or the concentrations found in waters contaminated with a gives heavy metal [18]. The other concentrations exceed these values. Potassium chromate(VI) and chloride salts of other heavy metals were obtained from Sigma-Aldrich. For each ion concentration as well as for medium without metal addition (control), three repetitions were prepared. *P. tricornutum* strain 1055/1 diatoms (obtained from Culture Collection of Algae and Protozoa (CCAP); UK) were inoculated into the prepared media and grown at 12°C under the 14/10 hours light/dark regime [19]. The intensity of light used to illuminate cultures (measured with Skye PAR Quantum light meter) was 48 $\mu mol \cdot m^{-2} \cdot s^{-1}$. After each 2-3 days, the samples were taken from each shaken culture flasks (2 times 1 mL) and the optical density (absorbance) at 600 nm (OD_{600}) was measured using Jasco V-650 spectrophotometer. The samples taken from the culture flasks containing chromate(VI) anion were blanked using the f/2 medium with the chromate(VI) anions added to the corresponding concentration. For all other samples, the f/2 medium with no additions was used to the blank samples.

3. Results and discussion

Diatoms grown in control samples readily increased in number, reaching OD_{600} value of around 2 after a month of growth (Fig. 3.2.1). The absolute OD_{600} value increased by 1.69 (Fig. 3.2). Growth of diatom cultures treated with cadmium(II) was handicapped only at the highest tested concentration (20 mg/L). Starting from day 7, the OD_{600} values were approximately equal to half of the values measured for control (Fig. 3.3). However, even at this concentration, a limited growth could be observed, as OD_{600} value reached ~1 after the entire culture period (absolute increase by 0.862). The lower tested concentrations of Cd^{2+} (0.1 and 1 mg/L) did not greatly affect the growth characteristics obtained by absorbance measurements (Fig. 3.2.1). In these two instances, the mean OD_{600} values recorded between days 5 and 16 were higher than the mean values obtained for the control samples (Fig. 3.3). However, the absolute increase in mean OD_{600} value during the entire experiment was comparable with the control (Fig. 3.2).

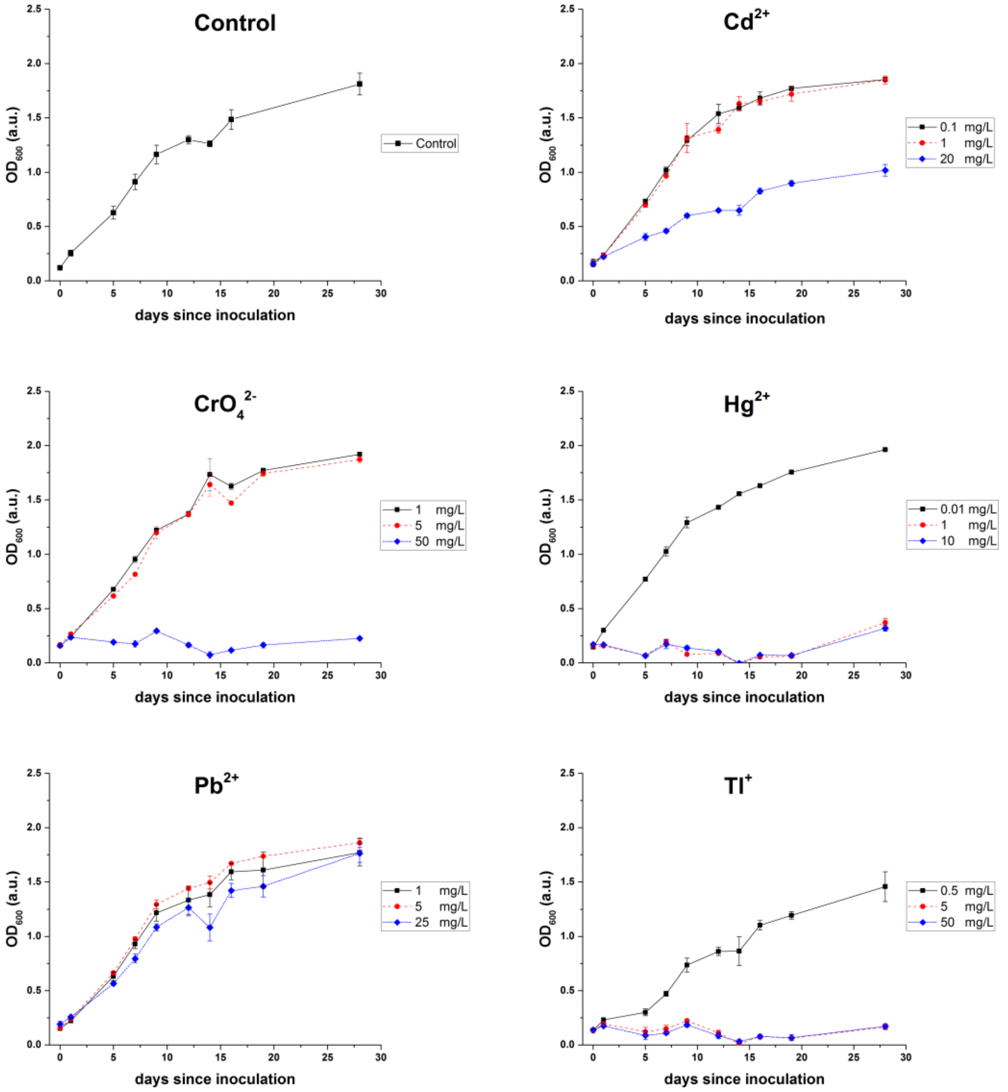

Fig. 3.1. *Phaeodactylum tricornutum* growth curves in different conditions. Each line represents the mean OD_{600} values of three independent culture flasks; error bars represent the standard deviation.

As for the chromate(VI) anions, two lowest tested concentrations (1 and 5 mg/L) also did not cause any great change in the diatom growth curves. The mean OD_{600} values recorded for each day were generally comparable with those obtained for the control, especially after 9 days of growth. The only major increase in these values, in comparison to the control, was observed on 14th day of the experiment. The growth characteristics, expressed as the percentage of OD_{600} value compared with the control and the absolute increase in the mean OD_{600} value was slightly better for the lowest tested concentration. In this instance, the mean OD_{600} value increased by 1.761 during the entire experiment, while the mean value in the case of the middle chromate(VI) concentration increased by 1.706, which is closer to the control (Fig. 3.2). However, the middle concentration was much higher (5 mg/L) than the Cd^{2+} middle concentration, which suggests that *P. tricornutum* diatoms may be less susceptible to chromate anions in comparison to the cadmium(II) cations. The highest chromate(VI) concentration (50 mg/L) seriously handicapped the growth of these diatoms, as no clear log phase can be seen and the final OD_{600} values are comparable to the ones just after the inoculation (absolute increase of only 0.066) (3.1, 3). Starting from day 5, the OD_{600} values obtained for this concentration never exceeded 25% of the values recorded for control (Fig. 3.3).

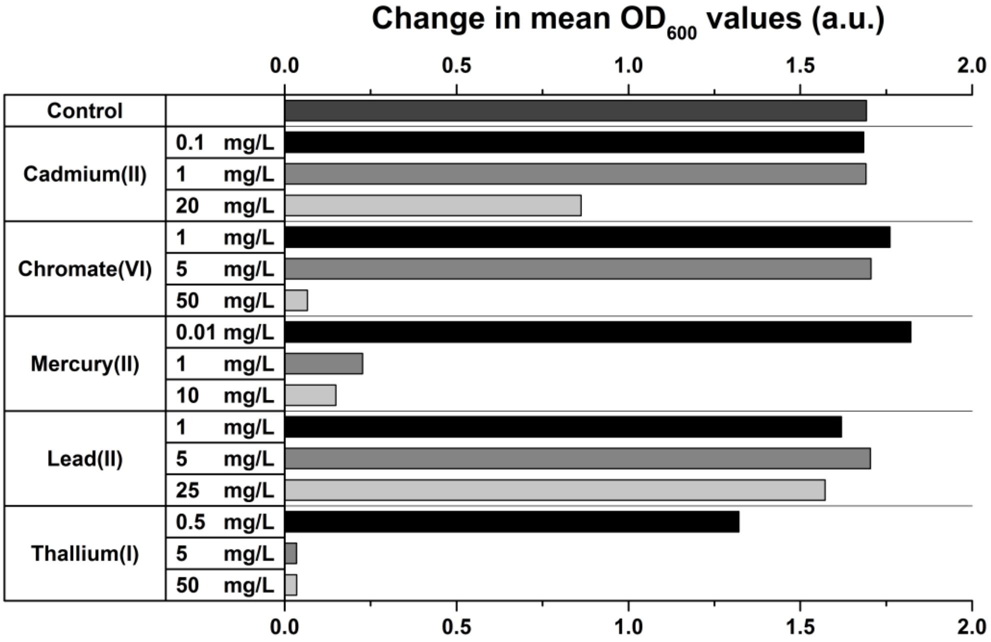

Fig 3.2. The absolute change in mean OD_{600} values (between the beginning and the end of the experiment) obtained for a given growth condition.

Lead(II) cations did not greatly influence the growth characteristics of *P. tricornutum*, even at the highest tested concentration (25 mg/L). In this case, the OD_{600} values were only slightly lowered in comparison with control, as the mean OD_{600} values reached ~80-90% of the values recorded for the control (Fig. 3.3) The greatest absolute increase in mean OD_{600} values was observed for the middle concentration (5 mg/L), while this increase observed for the other concentrations was lesser than that of control samples (Fig. 3.2.2). This implies that these diatoms are more resilient to the cations of this metal, than the cadmium(II), mercury(II) and thallium(I) cations.

Thallium(I) cations handicapped the growth of *P. tricornutum* even at the lowest tested concentration (0.5 mg/L; in this case the final OD_{600} value reached only 1.321), which was not observed for other heavy metal ions (3.1, 3). The OD_{600} values for this concentration decreased to about 45% of the control values during the first 5 days, and this percentage was steadily increasing since then, reaching 80% of the control values at the end of the experiment (Fig. 3.3). The middle and highest tested concentrations (5 and 50 mg/L) were the same as in the case of chromate(VI) anions. Thallium(I) at 5 mg/L significantly influenced the growth curve of *P. tricornutum* and this effect was comparable to the effect exerted by this metal cations at 50 mg/L, which was not observed in the case of chromate(VI) anion. The OD_{600} values obtained for these two concentrations did not significantly increased after the initial decrease and, starting from day 5, did not exceed 20% of the control (Fig. 3.3). The absolute mean OD_{600} values increase was equal to 0.034 and 0.035 respectively for middle and the highest concentration (the lowest increase observed during the entire experiment; Fig. 3.2). The data suggests that thallium(I) cations are more toxic to *P. tricornutum* than cadmium(II), chromate(VI) and lead(II) ions.

Mercury(II) cations shown to be even more harmful to *P. tricornutum* than cadmium(II) cations (3.1). At the lowest tested concentration (0.01 mg/L), the growth characteristics were slightly better than those of control samples. The absolute increase in the OD_{600} value in this instance was the highest among all recorded ones (1.822; Fig. 3.2). Moreover, the OD_{600} values for particular days were consistently higher than those obtained for the control (Fig. 3.3). The middle tested concentration was the same for these two metals (1 mg/L), yet Hg^{2+} limited the diatom growth to the greater extent. Starting from day 5, the OD_{600} values recorded in the cases of the middle (1 mg/L) and the highest (10 mg/L) mercury(II) concentration never exceeded 20% of the control, while these values in the case of cadmium(II) were always above 40%, even at the highest tested concentration of this metal (Fig. 3.3). Furthermore, the absolute change in mean OD_{600} values obtained for the middle and the highest tested mercury(II) concentration was equal to, respectively, 0.227 and 0.149 (Fig. 3.2). This implies that mercury(II) is toxic to *P. tricornutum* even below the concentration of 1 mg/mL, which complies with the previous findings [20].

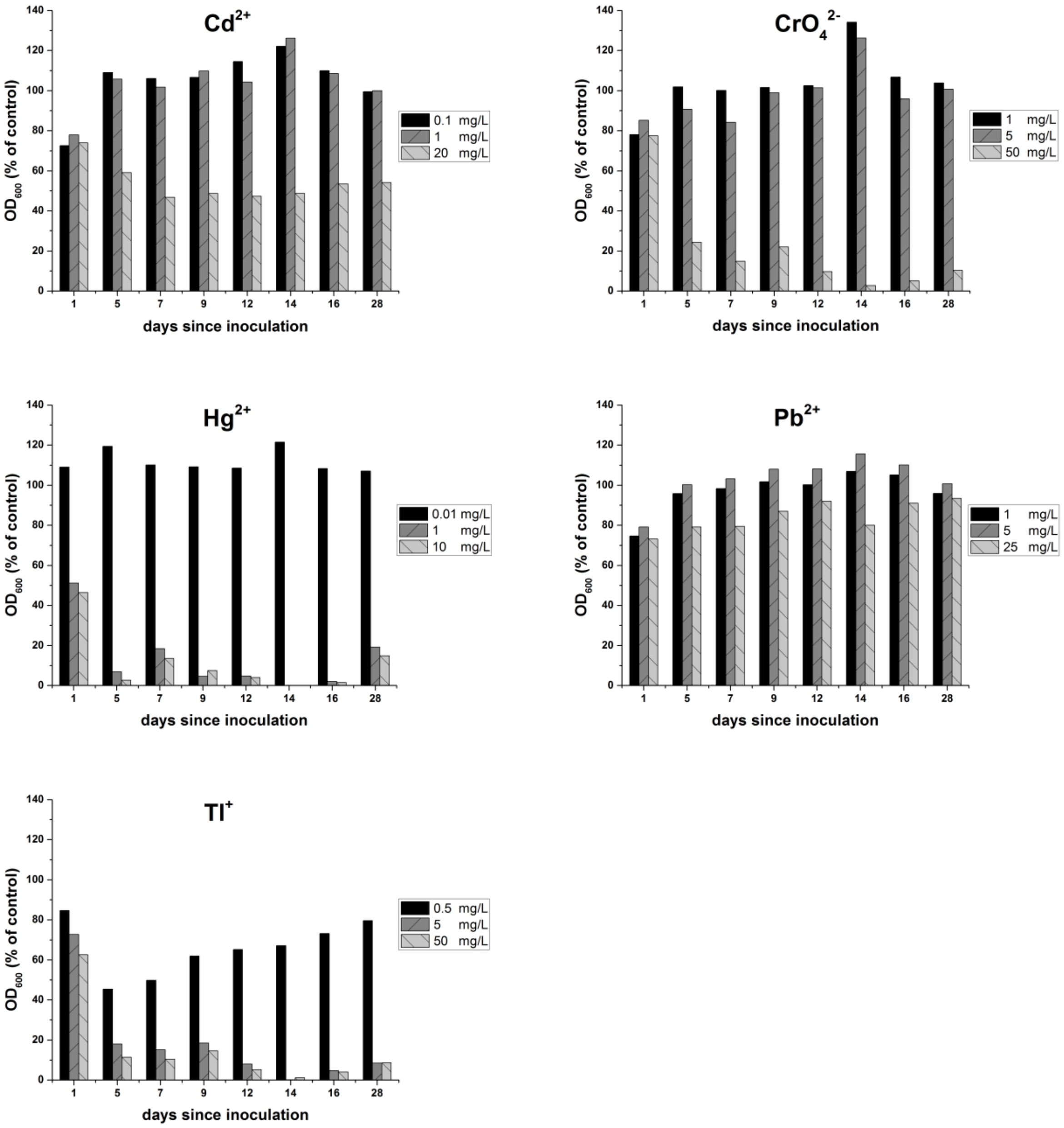

Fig. 3.3. *Phaeodactylum tricornutum* growth characteristics (mean OD_{600} values for a given heavy metal ion concentration) expressed as a percentage of mean OD_{600} values obtained for control.

Nevertheless, the increase in OD_{600} values, which began after the 20th day since inoculation (3.1) was observed. This may imply that these diatom species possesses one or more adaptive mechanisms that need time to be switch on in the cells and then allow them to thrive in mercury(II)-containing medium. The similar phenomenon, although not as clear, was also observed in the case of chromate(VI) and thallium(I)-containing media. This can comply with the results obtained for arsenic-treated *P. tricornutum* diatoms [21]. However, longer incubation periods are necessary to fully understand the scope of this phenomenon and its implications on *P. tricornutum* resistance to selected heavy metal ions.

4. Conclusions

Taken together, the data suggests that *P. tricornutum* diatoms show the ability to grow in heavy metal-contaminated media. The scope of diatom response to these contaminants depend on the type and concentration of heavy metal cations. Obtained results also indicate the existence of potential resistance mechanism that makes it possible for *P. tricornutum* to increase in number after the initial adaptational period. This suggest the possible future utilization of *P. tricornutum* in bioremediation of sea waters contaminated with heavy metals. Further studies are necessary to fully elucidate the mechanisms of *P. tricornutum*'s response to the heavy metal contamination. Should it involve the removal of heavy metal ions from the culture medium, this diatom species will become an interesting starting point for the future developments in the bioremediation industry. Moreover, the diatoms of this species may be utilized as bioindicators, given that they survive the exposure to selected heavy metals. More detailed follow-up experiments are required to assess, whether the contact with heavy metal ions induces any morphological or physiological changes in *P. tricornutum* cells. In such instance, these diatoms may be potentially used to monitor the contamination levels of sea waters.

Acknowledgements

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Thermodynamic equilibrium analysis of methane reforming as a prospective process for synthesis gas production

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Abstract

Thermodynamic equilibrium calculations were performed for dry reforming of methane (DMR), steam reforming of methane (SRM), partial oxidation of methane (POM), and tri-reforming of methane (TRM). The analyses assumed the volumetric ratios of feed compositions according to the stoichiometry of each of reforming reaction, except for the TRM where the feed: $CH_4/CO_2/H_2O/O_2/Ar = 1/0.5/0.5/0.1/7.9$ was assumed as suggested in literature. The calculations were carried out using HSC5 software for pressure of 1 atm, and temperature range of 550-900°C. The aim of this study is to check a new feed composition in tri-reforming of methane process, which may be applied in a coal-based power plant. The proposed molar relations are as follows: $CO_2/H_2O = 1.5$, $O_2/CH_4 = 0.33$, and $(CO_2+H_2O+O_2)/CH_4= 2.5$. 1.05 mol of CH_4 is added to the proposed new feed composition. The satisfactory results were obtained already at temperatures from 580 to 680°C. The possible maximum equilibrium conversions of CH_4 and CO_2, as well as H_2/CO molar ratio, and carbon deposit formation are presented as a function of temperature.

Key words: thermodynamic equilibrium, reforming of methane, Gibbs free energy, synthesis gas

1. Introduction

Synthesis gas, which is a mixture of hydrogen and carbon monoxide, is used as feedstock in fuels production processes. Syngas is produced in industry in steam methane reforming process. An important issue is the appropriate molar ratio of H_2/CO, which for methanol production or in Fisher-Tropsch synthesis is in the range of 1.5 - 2.0) [1].

Syngas formation from methane may be realized with three different reacting gases. Dry methane reforming (DRM), also called CO_2-reforming, has long been considered as one of the prospective operation for the valorization of carbon dioxide ($CH_4 + CO_2 = 2CO + 2H_2$, $\Delta H^0 = 247.3$ kJ/mol). However, it does not give a satisfactory H_2/CO molar ratio for fuel production, therefore is it recommended to perform dry reforming in the company of steam reforming (SMR) [2], which is the currently used commercial method and produces synthetic gas with a H_2/CO ratio of 3.0 ($CH_4 + H_2O = CO + 3H_2$, $\Delta H^0 = 206.3$ kJ/mol). The partial oxidation of methane (POM) is a slightly exothermic reaction which already produces a H_2/CO ratio equal to 2.0 ($CH_4 + \frac{1}{2} O_2 = CO + 2H_2$, $\Delta H^0 = -35.6$ kJ/mol). For this reason, the POM is very advantageous from the application point of view. Although, a new process, which is a combination of DRM, SMR and POM, has been proposed in literature [2]. This process is called tri-reforming of methane and allows CO_2 utilization and the production of synthesis gas with molar ratio of $H_2/CO=1.5 - 2.0$. The presence of H_2O and O_2 in the process improves stability of a catalyst by removal of carbon deposits [2].

The model calculations carried out by Song and Pan, 2008 [2] showed that high conversions of CH_4 and CO_2 conversions (over 95, and ca. 80 % at 850°C) may be obtained, with molar ratios of $CO_2/H_2O = 1.0$, $O_2/CH_4 = 0.1$ and $(CO_2+H_2O+O_2)/ CH_4=1.05$. There are some experimental catalytic studies of TRM for gas feeds the same and/or very close to those proposed in literature calculations [2]. Majewski et al. [3] and Gracia et al. [4] studied TRM process with the feed of $CH_4/CO_2/H_2O/O_2 = 1/0.5/0.5/0.1$. Pino et al. [5] worked under $CH_4/CO_2/H_2O/O_2 = 1/0.46/0.46/0.1$ gas feed composition; while Lan-jie et al. [6] studied catalysts at

$CH_4/CO_2/H_2O/O_2$ = 1/0.5/0.375/0.25, and Lau-Zhi et al. [7] applied in their study $CH_4/CO_2/H_2O/O_2$ = 1/0.45/0.45/0.1.

The presence of oxygen may improve catalytic performance of the reforming process. However, it has to be stressed that possible methane ignition should be prevented. Thus, upper and lower flammability limits (UFL, LFL, respectively) have to be taken into account. Above the upper flammability limit the CH_4 concentration is too high, thus in the presence of spark methane will not combust. The flammability limits are obtained through calculations, and from methane and oxygen mixture UFL is: 1.57, while for methane in air it is 0.94. Conversely, when CH_4 concentration is below the LFL its too low to start the process of ignition. The lower flammability limits are: CH_4/oxygen = 0.22, and for CH_4/air: 0.05 [8].

2. Thermodynamic equilibrium analysis method

2.1. Minimization of Gibbs free energy

The Gibbs free energy analysis was used in order to obtain the equilibrium of multiphase system containing several species. The total Gibbs free energy is expressed as [9, 10]:

$$G_{total} = \sum_{i=1}^{N} n_i \left[G_i^0 + RT \ln\left(\frac{f_i}{f_0} \right) \right] \tag{2.1}$$

Where the number of moles is assigned to n_i of species i. The standard-state of Gibbs free energy of species i is G_i^0. Standard-state stands for 25°C and 1 atm, while f_i^0 is a fugacity at this state of species i, and f_i refers to operating state. In view of equation (2.1.1.), n_i moles of species has to fulfill the following relation

$$\sum_{i=1}^{N} a_{ji} n = b_j \tag{2.2}$$

Where the number of element j expressed in grams or atoms of molecule i is assigned to a_{ji}. b_{ji} is a total number of moles of element j in the feed. Additionally, the following equality: $1 \leq j \leq M$, where M is the number of elements in the mixture, has to be fulfilled.

3. Experimental

Thermodynamic calculations were carried out by using software HSC Chemistry 5 software. The calculations were based on minimization of Gibbs free energy method. The influence of temperature and feed gas composition were considered to calculate equilibrium conversions of CH_4, CO_2, carbon deposition and H_2/CO molar ratios. The following reactions, presented in Table 1, were considered as possible reactions in methane reforming processes.

Tri-reforming of methane may be considered as a sum of DMR, SMR and POM, and thus be written as: $3CH_4 + CO_2 + H_2O + \frac{1}{2}O_2 = 4CO + 7H_2$. Here some inaccuracy is included, as the complete oxidation of methane (reaction number (4)) is not considered. The latter is highly probable and thermodynamically improves the TRM process. Therefore, the calculations of tri-reforming process were made using the molar ratio proposed in the literature: $CH_4/ CO_2/H_2O/O_2$ = 1/0.5/0.5/0.1 [3, 4], which fulfills the main assumptions made by Song and Pan, 2008 [2].

Based on reactions in Table 1, and their possible products, the following gases were considered as reactants in the thermodynamic calculations: $Ar_{(g)}$, $CH_{4(g)}$, $CO_{2(g)}$, $CO_{(g)}$, $H_{2(g)}$, $H_2O_{(g)}$, $O_{2(g)}$, $C_{(s)}$. As the substrates were assumed: $CH_{4(g)}$, $CO_{2(g)}$, $H_2O_{(g)}$, $O_{2(g)}$, and $Ar_{(g)}$. The oxygen presence was consider only in calculations of POM and TRM processes. All calculations were performed for constant pressure equal to 1 bar.

Tab. 1 The list of reactions of methane reforming processes HSC [2]

Number	**Name**	**Reaction**	**ΔH^0 (kJ mol^{-1})**
1	Dry reforming of CH_4	$CH_4 + CO_2 = 2CO + 2H_2$	247
2	Steam reforming of CH_4	$CH_4 + H_2O = CO + 3H_2$	206
3	Partial oxidation of CH_4	$CH_4 + ½O_2 = CO + 2H_2$	-36
4	Oxidation of CH_4	$CH_4 + 2O_2 \rightarrow CO + 2H_2O$	-880
5	Oxidation of CH_4	$CH_4 + O_2 = CO_2 + 2H_2$	-319
6	Reverse water gas shift	$CO_2 + H_2 = CO + H_2O$	41
7	Methane decomposition	$CH_4 = C_{(s)} + 2H_2$	75
8	Boudouard reaction	$2CO = C_{(s)} + CO_2$	-172
9	Hydrogenation of CO_2	$CO_2 + 2H_2 = C(s) + 2H_2O$	-90
10	Hydrogenation of CO	$CO + H_2 = C + H_2O$	-131
11	Methanation of CO_2	$CO_2 + 4H_2 = CH_4 + 2H_2O$	-165
12	Methanation of CO	$CO + 3H_2 = CH_4 + H_2O$	-206
13	Oxidation of CO	$CO + ½O_2 = CO_2$	-283
14	Oxidation of H_2	$H_2 + ½O_2 = H_2O$	-242
15	Decomposition of CO	$2CO = C_{(s)} + CO_2$	-176
16	Partial oxidation of C	$C(s) + ½O_2 = CO$	-110
17	Steam on C	$C(s) + H_2O = CO + H_2$	131
18	Hydrogen oxidation	$H_2 + ½O_2 = H_2O$	-58

3.1. Calculation methods

In order to obtain conversions of CH_4, $CO_2$and the molar ratio of H_2/CO, the following equations were used:

$$CH_{4\,conversion}[\%] = \frac{n_{CH_4,initial} - n_{CH_4,final}}{n_{CH_4,initial}} \cdot 100 \tag{3.1}$$

$$CO_{2\,conversion}[\%] = \frac{n_{CO_2,initial} - n_{CO_2,final}}{n_{CO_2,initial}} \cdot 100 \tag{3.2}$$

$$H_2 / CO = \frac{n_{H_2,final}}{n_{CO,final}} \tag{3.3}$$

Where $n_{CH4,initial}$ and $n_{CO2},_{initial}$ are the inlet numbers of moles of methane and carbon dioxide, respectively. And $n_{CH4,final}$, $n_{CO2,final}$, $n_{H2,final}$, $n_{CO,final}$ state for outlet number of moles of methane, carbon dioxide, hydrogen and carbon oxide, respectively.

3.2. Feed gas composition during methane reforming reactions

Table 2 shows the feed compositions which were proposed for calculations. The following compositions refer to the volumetric ratios of the components, such as: (1) DRM: $CH_4/CO_2/H_2O/O_2/Ar$ = 1/1/0/0/8, (2) SRM: $CH_4/CO_2/H_2O/O_2/Ar$ = 1/0/1/0/8, (3) POM: $CH_4/CO_2/H_2O/O_2/Ar$ = 1/0/0/0.5/8.5, and (4) TRM: $CH_4/CO_2/H_2O/O_2/Ar$ = 1/0.5/0.5/0.1/7.9.

Tab. 1 The feed gas compositions used for thermodynamic calculations

Number	**Process**	**Feed gas composition**					
		CH_4	CO_2	H_2O	O_2	Ar	CH_4/O_2 ratio
(1)	DRM	1	1	0	0	8	-
(2)	SRM	1	0	1	0	8	-
(3)	POM	1	0	0	0.5	8.5	2
(4)	TRM	1	0.5	0.5	0.1	7.9	10

The second part of the paper describes thermodynamic calculations which were proposed based on the assumption that tri-reforming process may be introduced on the industrial scale. A typical flue gas composition from coal-fired power plant was used, in the temperature range from 550 to 900°C, in order to check the feasibility of the TRM.

Typical exhaust gas from coal-fired power plant includes 12-14% vol.% CO_2, 8-10 vol.% H_2O, 3-5 vol.% O_2, 72-77 vol.% N_2 [2]. Based on above, the ratio of flue gases may be expressed as: $CO_2/H_2O/O_2/N_2$ = 1.4/0.95/0.35/7.3, The calculations were carried out assuming the addition of 1.05 moles of methane, thus giving the volumetric feed gas composition of $CH_4/CO_2/H_2O/O_2/N_2$ = 0.95/1.3/0.9/0.3/6.6, with Ar instead of N_2. The molar ratio of CH_4/O_2 is equal to 3. Consequently, the new proposed molar relations are: CO_2/H_2O = 1.5, O_2/CH_4 = 0.33, and $(CO_2+H_2O+O_2)/CH_4$= 2.5 and thus they differ from these which are presented in the work of Song and Pan [2].

4. Results and discussion

4.1. The influence of temperature on equilibrium conversions of CH_4 and CO_2

The influence of temperature was checked for four feed gas compositions, presented in Table 2. Figure 1 shows CH_4 equilibrium conversion versus temperature. As it is observed, all outcomes are relatively high (above 65% in the temperature range from 550 to 900°C). For all methane reforming processes a significant increase in CH_4 conversion may be observed in the range of 550 to 720°C, with smaller increase over 720°C. In the temperature range from 850-900°C CH_4 conversion was almost 100%.

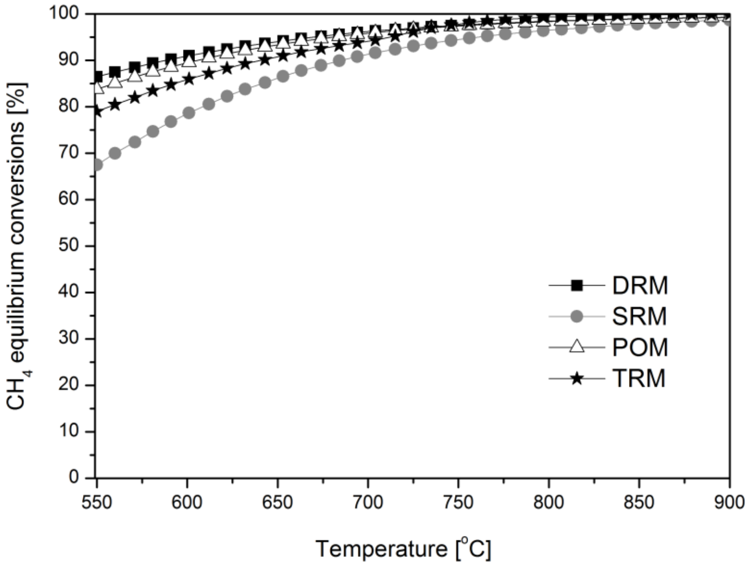

Fig. 1 The influence of temperature on the equilibrium concentration of methane

Figure 2 presents the changes in CO_2 content as a function of temperature. The results originate from CO_2 conversion, as well as take into account the occurrence of the side reactions mentioned in Table 1, where CO_2 is a product. The equilibrium carbon dioxide content declines with the increase in temperature.

Only negligible amounts of CO_2 were observed for SMR and POM over 800°C. For these reactions carbon dioxide did not play any role as the reactant, therefore it may be assumed that in case of SMR the amount of CO_2 in the system at lower temperature range was related to water gas shift process, i.e. the reverse of reaction (6) in Table 1. In POM the carbon dioxide was produced through CH_4 oxidation (reaction (5)), or CO oxidation – (reaction (13)).

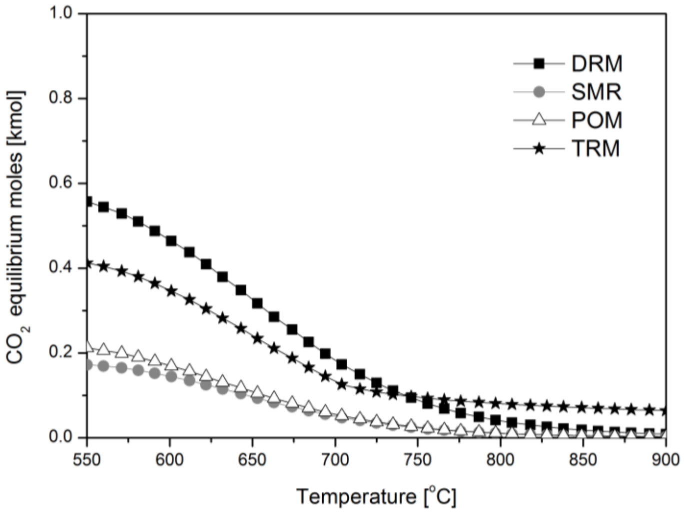

Fig. 2 The influence of temperature on the reformation of carbon dioxide.

Carbon dioxide was present as a reactant in dry reforming and tri-reforming of methane. Hence, it is possible to calculate CO_2 conversion based on the equation assigned as (3.1.2.). Figure 3 represents carbon dioxide equilibrium conversion for SMR and TRM. For both processes conversion increased with the temperature growth. For DRM process CO_2 conversion was always higher than for TRM, in the whole temperature range. The best results were obtained at temperature of 850°C and 900°C, where CO_2 conversion was close or equal to 100%, respectively. Nevertheless, the TRM outcomes are relatively good, since more than 80% of CO_2 may be converted in temperatures higher than 750°C.

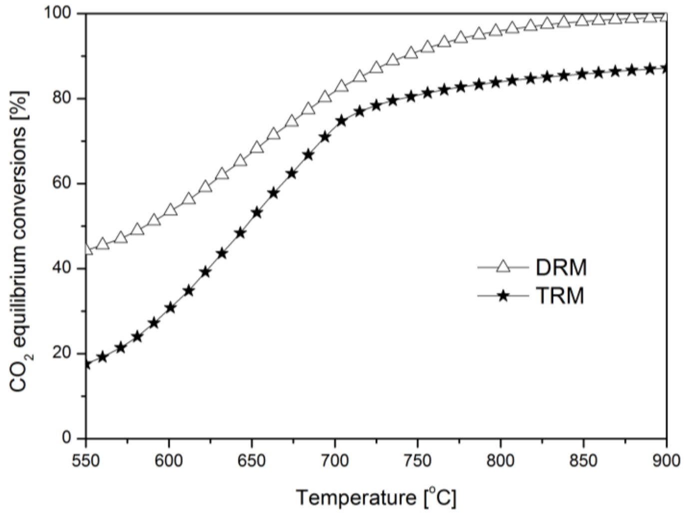

Fig. 3 The influence of temperature on the equilibrium concentration of carbon dioxide.

4.2. The influence of feed gas composition on H_2/CO molar ratio as a function of temperature

The synthesis gas may be used directly in the fuels production (e.g. Fisher Tropsch or methanol synthesis) when the H_2/CO ratio is in the range of 1.5-2.0. According to the calculations performed by HSC5 the desired ratio may be received for POM and TRM feed gas compositions presented in the Figure 4 at temperatures 700 to 900°C. Steam reforming of methane and dry reforming have, respectively, too high or too low molar ratios of the considered gaseous components. Therefore, the idea of combination of these two reforming reactions may be promising in terms of receiving desired H_2/CO ratio.

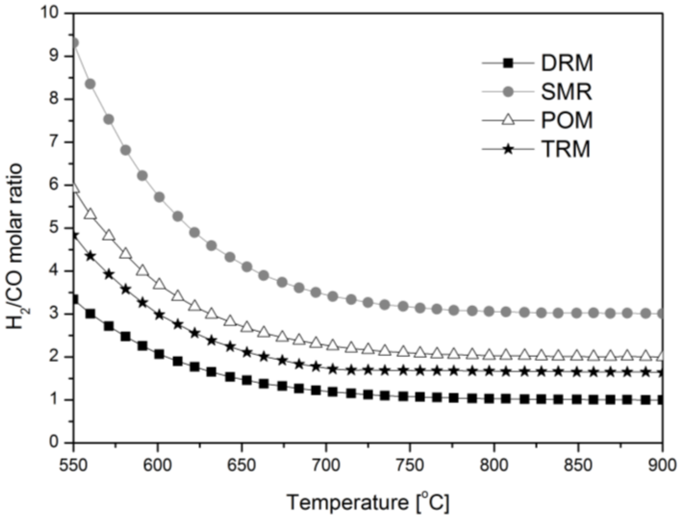

Fig. 4 The influence of temperature on the H_2/CO molar ratio.

4.3. The influence of feed gas composition on carbon deposition

Figure 5 presents equilibrium carbon content as a function of temperature. Almost no carbon formation was observed over 900°C, at 850°C, 830°C or 715°C for DRM, POM, SMR or TRM, respectively. This proves the positive influence of H_2O and O_2 in the feed on carbon formation, in good agreement with conclusions drawn by Song et Pan, 2004. At their study, there was no carbon formation at ca. 650°C for the molar ratio of $CH_4/CO_2/H_2O/O_2$= 1/0.25/0.5/0.5, while the molar ratio of $CH_4/CO_2/H_2O/O_2$= 1/1/0/0 was characterized by zero carbon formation at temperature close to 1000°C.

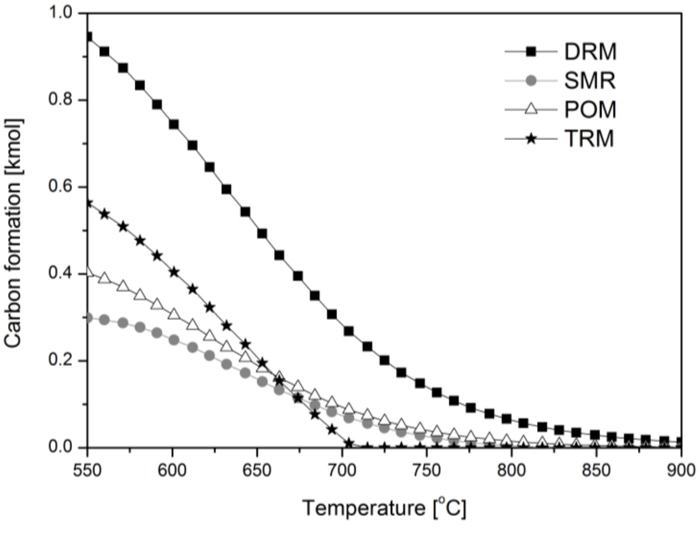

Fig. 5 The influence of temperature on the carbon formation.

5. The influence of temperature on TRM performance for the flue gas from coal-fired power plant

In order to check feasibility of tri-reforming of methane process, a calculation was carried out for a typical flue gas composition from coal-based power station with 1.05 mol of methane added. Figure 6 presents equilibrium conversion of CH_4 and CO_2 versus temperature. Over 600°C a significant increase in methane conversion is observed- from around 80% to almost 100% at 675°C. At the higher temperatures CH_4 conversion stays stable at 100%. For CO_2 around 20% of conversion was observed at 675°C. This proves the feasibility of TRM process and the possibility of direct utilization of CO_2 from flue gases from coal combustion. The highest CO_2 conversion, assuming this feed gas composition is 40% at 900°C.

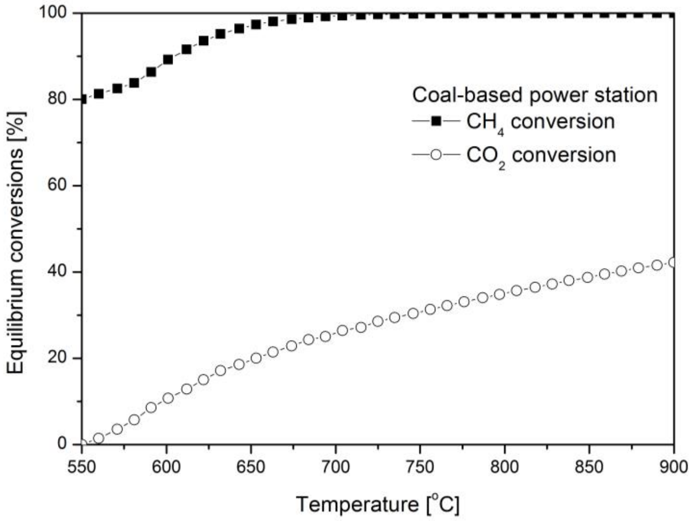

Fig. 6 The influence of temperature on equilibrium conversion of CH_4 and CO_2 for TRM as applied to flue gas from coal-fired power plant.

Figure 7 shows H_2/CO molar ratio for flue gas from power plant processed in TRM. A significant decrease in H_2/CO ratio may be observed with the increase in temperature. The most desired ratio, from range of 2.0-1.5, is observed at temperatures from 580 to 685°C. At 900°C it reaches 1.13.

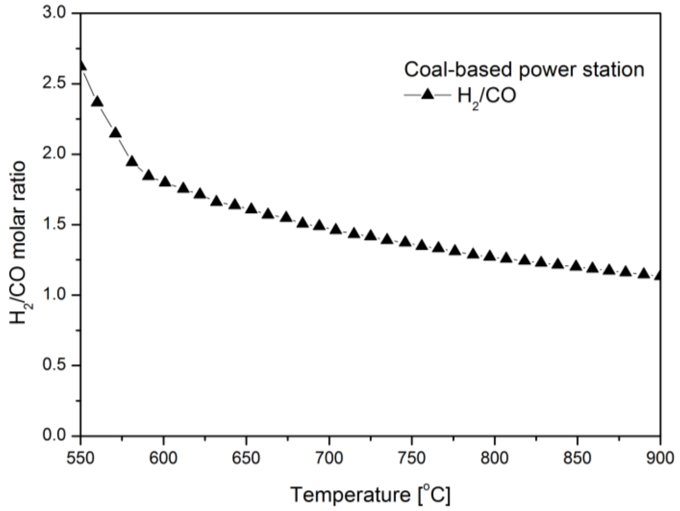

Fig. 7 The influence of temperature on H_2/CO molar ratio for TRM applied to coal-fired power plant.

Figure 8 represents carbon formation during TRM process. Above 590°C no carbon formation was observed for the studied gas feed composition.

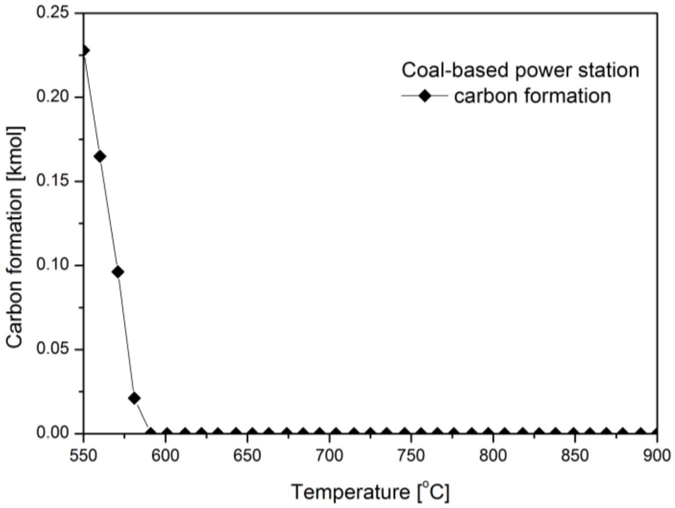

Fig. 8 Carbon formation for TRM applied for flue gas from coal-fired power plant.

6. Conclusions

Thermodynamic equilibrium analysis was performed to test the possibility of conversion of selected flue gas components to synthesis gas. The processes considered were: dry reforming of methane (DRM), steam reforming of methane (SRM), partial oxidation of methane (POM), and tri-reforming of methane (TRM). The calculations were carried out by using HSC5 software, and by assuming the following gases in the system: $Ar_{(g)}$, $CH_{4(g)}$, $CO_{2(g)}$, $CO_{(g)}$, $H_{2(g)}$, $H_2O_{(g)}$, $O_{2(g)}$, $C_{(s)}$.

The thermodynamic analysis on tri-reforming of methane for flue gas composition showed that it is possible to receive high conversions of CH_4 (from 80 to 100%), reasonable conversion of CO_2 (from 6 to 24%) and no carbon formation at low temperature range (590 - 680 °C), under the following assumptions: $CO_2/H_2O = 1.5$, $O_2/CH_4 = 0.33$, and $(CO_2+H_2O+O_2)/CH_4= 2.5$. Additionally, in this temperature range the most desired H_2/CO molar ratio (2.0-1.5) is obtained. Comparing the CO_2 conversion results with calculations based on assumptions for TRM (Figure 3), the results at 590 - 680°C would be higher (27% - 66%) with considerable amount (0.4 - 0.08 kmol) of formed carbon. On the other hand, for the feed composition proposed in this paper, containing low amounts of added methane (1.05 mol), the conversion of CO_2 is lower but the used catalysts should be more stable, because there is no deactivation connected with carbon deposition.

Acknowledgments

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The main parameters controlling heat transfer during infant's hypothermic treatment – experimental and computational setup

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Abstract

Human infants are very susceptible to various diseases, some of which are results of the difficult delivery. Among such health complications, hypoxic-ischemic encephalopathy (HIE) could be distinguished. In order to prevent its negative medical consequences, hypothermic therapy has been developed. Such treatment could be applied in different ways – for example, the Olympic CoolCap medical system could be used. The aim of this work is to present the experimental and computational setup which will be used in order to gather more information about heat transfer between the infants' head and the coolant during such treatment. All measurements will be performed in cooperation with the medical staff of the Regional Health Center located in Opole.

Key words: bioengineering, experimental setup, neonates, heat transfer, mathematical modeling, CFD

1. Infants' health problems and hypothermic treatment

Some newborns during delivery can be stricken with perinatal hypoxemia which may result in hypoxic-ischemic encephalopathy (HIE). According to the data provided by the World Health Organization, each year about 2 millions of neonates either die due to such affliction or survive and suffer substantial neurological consequences. Such high rate of serious medical consequences is the result of the temperature fluctuations in the newborn's body after difficult delivery [1].

Under normal conditions, human body loses heat in a couple distinct ways: through radiation (about 55-65% of total heat loss), evaporation which can also be associated with breathing (around 12-15% of total heat loss) as well as by conduction. Maintenance of a constant body temperature, which is a very high energy consumption process, is absolutely crucial for proper functioning of the whole organism. It is assumed that the normal expected level of deep (core) temperature is close to circa 37°C. If the individual variations from the normal expected state and environmental influences are taken into account, it could be stated that this temperature ranges from 36°C to 38°C. Any unattached with thermoregulation deviations of this temperature cause malfunctions of any and all parts and organs constituting the human organism. Sphere of influence of these undesired dangerous consequences of such state depend on four crucial factors:

- level of deep temperature lowering (how much it is lower than the normal expected value);
- rate of this process;
- causes leading to the process;
- general condition of the organism [2].

In general, two states differing from the normal state can be distinguished based on the level value of deep/core temperature: hypothermia and hyperthermia.

Hypothermia is a state in which core temperature of human body decreases below 35°C. Such state could be further divided into three sub-states: mild hypothermia which occurs when core temperature is in the range of 32°C and 35°C; moderate hypothermia which occurs when deep temperature is in the range of 28°C and 32°C; and strong hypothermia which occurs when deep temperature is lower than 28°C. Some authors introduce hypothermia classification scale consisting of four different levels. In such scale, either total hypothermia or strong hypothermia is introduced and it corresponds to the deep temperature value lower than 20°C. In such scenario, patients do not show any signs of life. Hyperthermia is a contrary state in which core temperature rises over 38°C due to external influences [3,4].

Human brain and nervous system are particularly susceptible to heightened temperature values. When temperature of nerve cells rises over 37,5°C, their excitability is significantly affected and further increase of their increase to 40-41°C may lead to their progressive damage even up to ablation. What is more, such situation is very complicated due to huge amounts of metabolic heat generated in the brain. Even though human brain constitutes only 2% of total body mass, it consumes about 20% of inhaled oxygen. Relatively small brain mass also leads to modest heat transfer surface which can result in local overheating. Among different causes of hyperthermia, for example there are intensified intellectual activity (temperature could rise by even 1-2°C) or intensified physical activity (temperature may rise by even 1-3°C) [5-7].

In both cases of hyperthermia and hypothermia, every significant deviation from the normal value of deep body temperature is potentially harmful for the whole organism. In extreme cases, such deviation may result in patient’s death. Nevertheless, it should be stated that targeted thermal therapy may be applied with high success rate in treatment of very dangerous cases of either hypo- or hyperthermia.

For example, for many years the advanced studies on hyperthermia’s application in cancer treatment have been carried. Affected cells have particularly high excitability for high temperature. Additionally, this effect can be fortified by application of nanoparticles [8-10].

Furthermore, intense research on forced hypothermia application in treatment of patients with blood circulation stoppage has been carried out [11]. Clinical tests conducted by a group of scientists led by M. Holzer have shown that if targeted hypothermia treatment is applied, it causes both upswing in patients’ survival rate and downswing in the number of neurological consequences [12]. Moreover, conducting such researches have resulted in vital results in reality as in many countries therapeutic hypothermia has been introduced as a standard treatment for patients after restoration of blood circulation [13,14]. Nonetheless, there are still many question marks connected with the way of carrying the targeted thermal therapy, its’ efficiency and even about the therapy itself [15,16].

The goal of this project is to broaden the knowledge about the targeted thermal therapy and hopefully to answer some of those question. Due to very high level of complexity of the analyzed problem, it is a difficult yet significant task. With better understanding of the mechanisms affecting the treatments’ efficiency, it may be possible to lead the treatment in a more effective way.

However, such improvements must be introduced very carefully, because the therapy must be carried in not only efficient, but also safe way. Furthermore, they must be easy to apply. Harmless development of these refinements is possible with the methodology proposed in this article.

Also, better, deeper understanding of the bioheat transfer will hopefully result in some new ideas about how to mathematically describe such phenomena. In the future that knowledge could be used in order to develop new, enhanced mathematical models of bioheat transfer. Such models could be applied in order to describe other medical treatments and therefore, to save lives of many people.

In order to achieve the intended goal, some measurements will be performed in the Regional Health Center in Opole. Moreover, mathematical model of the process will be developed and computations will be performed.

Specifically, the research will be focused on the hypothermic treatment applied with the Olympic CoolCap medical system.

It is also important to note that this project is the continuation of the work carried by Joanna E. Łaszczyk, PhD and Prof. Andrzej J. Nowak which resulted in the publication of the defended PhD thesis – “The Analysis of a Newborn's Brain Cooling Process” [1].

2. Experimental setup

In order to gather the necessary experimental data, the measurement stand will be built in the regional health center in Opole. The stand will consist of a couple of elements:

- the Olympic CoolCap medical station owned by the health center;
- temperature sensor and flow meter;
- additional medical drains.

The CoolCap system consists of a main station, some medical drains and the cooling cap. The main station’s tasks include general maintenance and control of the whole therapy. In the main station, there are not only electronic components, but also a pump which forces the flow of cooling water. The coolant flows from the main station to the cooling cap by medical tubes made specifically for the task and then returns to the station [17].

The necessary measurement equipment will be placed in the near proximity of the CoolCap station. The water will flow from the main station through the original medical drains to the compact measurement station consisting of the temperature sensor and the flow meter. Then, the coolant will be transferred to the cooling cap by additional medical tubes. The water leaving the cap will flow through some additional tubes back to the measurement station and then back to the main station.

This way, three significant sets of pieces of information will be gathered – the values of water volume flow rate and temperatures of the coolant on the inlet and the outlet of the cap. This data will then be used in order to calculate heat flux between the head and the cooling water.

The measured data will be recorded by the measurement station and then transferred to the computer. The resulting pieces of information will be used in the next step of the project in order to validate the proposed mathematical model of heat transfer during the analyzed therapy.

All the measurements will be performed during the actual treatments. The whole process will be supervised by the highly qualified medical personnel working in the Regional Health Center in Opole.

Figures below present various elements of the measurement station and were taken in the hospital in Opole.

Fig. 1. The cooling cap placed on the infant’s head

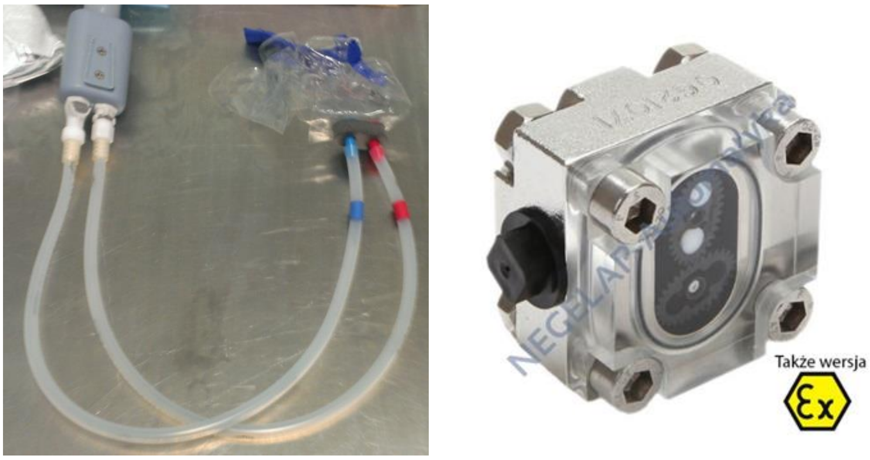

Fig. 2. The medical drains connected with the CoolCap and meter of volume flow rate

At this moment, the authors are still in the process of obtaining all the equipment necessary for the construction of the measurement station.

3. Computational setup

While the measurements will be performed and recorded, a parallel part of the project will be carried out. The mathematical model of the heat transfer between the infants’ head and the coolant will be developed in order to provide appropriate mathematical description of the physical phenomena taking place during the therapy. This will not only be helpful in better understanding of the whole process, but also it will hopefully be crucial in optimizing the way in which such therapy is applied.

In the first approach, the mathematical model will be based on the Pennes equation. This equation is commonly referred to as the oldest equation describing heat transfer in medical applications, therefore describing bioheat transfer [18].

In nature, heat transfer within tissues is transient. When such process is considered, internal heat generation should be accounted for. Therefore, energy equation representing transient heat transfer within tissue could be described as:

$$\rho_t c_{p,t} \frac{\partial T_t}{\partial \tau} = \nabla(k_t \nabla T_t) + \dot{q}_{source} \tag{2.1.}$$

where ρ_t stands for tissue's density, $c_{p,t}$ is the specific heat of the tissue, T_t represents tissue's temperature, τ expresses time, k_t represents tissue's thermal conductivity and q_{source} stands for the internal heat source term [1].

Due to the fact that analyzed tissues are blood-perfused, it could be noted that the internal heat source is a result of both metabolic processes and heat exchange between tissues and blood. Perfusion could be described as the process of pouring either through or over – for example, when blood perfuses a tissue, it flows through and over the blood vessels of a specific organ [19].

Thus, the equation (2.1.) could be expanded:

$$\dot{q}_{source} = \rho_b c_b \omega_j (T_a - T_t) + \dot{q}_{met,j} \tag{2.2.}$$

$$\rho_t c_{p,t} \frac{\partial T_t}{\partial \tau} = \nabla(k_t \nabla T_t) + \rho_b c_b \omega_j (T_a - T_t) + \dot{q}_{met,j} \tag{2.3.}$$

The equation (2.2.) represents the aforementioned definition of the internal heat source while the equation (2.3.) presents the basic equation combines both the equations (2.1.) and (2.3.). The first addend in the equation (2.2.) stands for the perfusive term while the second one is the metabolic heat term. Blood perfusion of the *j* tissue is represented by ω_j, the $_b$ subscript refers to blood, T_a is arterial blood temperature and $q_{met,j}$ represents the metabolic heat rate of tissue number *j*.

The calculations will be performed in the twofold way. First, the calculations will be carried using the commercial software ANSYS Fluent. Next, the developed mathematical model will be recreated using the open source code OpenFOAM. This way, the gathered results will be compared – such comparison could provide crucial pieces of information about both the models' strengths and weaknesses. Furthermore, it will provide a valuable way of assessing performance of the two computational software packages.

In order to carry the computations, the material data gathered from the literature will be applied. Exemplary values of characteristic properties of various tissues is presented below [1].

Tab 1. Exemplary values of thermal conductivity and specific heat for chosen tissues

Tissue	**k, W/(m*K)**			**c, J/(kg*K)**		
-	min	max	mean	min	max	mean
blood	0.488	0.500	0.494	3600	4200	3900
bone	0.116	1.163	0.640	1500	2300	1900
brain	0.200	0.800	0.500	3643	4160	3901.5
brain gray matter	0.490	0.566	0.528	3680	3700	3690
brain white matter	0.490	0.503	0.497	3600	3700	3650
CSF	0.490	0.566	0.528	3800	3800	3800
muscle	0.420	0.600	0.510	3500	3768	3634
skin	0.174	0.594	0.384	2495	4000	3247.5
viscera	0.530	0.547	0.539	3697	3697	3697

Tab 2. Exemplary values of density and perfusion rate for chosen tissues

Tissue	**ρ, kg/m^3**			**perfusion, $m^3_b/(m^3_{ts})$**		
-	min	max	mean	min	max	mean
bone	1030	1990	1510	0.000	0.052	0.026
brain gray matter	1030	1050	1040	0.000	0.031	0.016
brain white matter	1030	1050	1040	0.000	0.024	0.012
eye	1030	1050	1040	0.000	0.009	0.005
fat	850	1483	1166.5	0.000	0.076	0.038
lung	550	1050	800	n/d	n/d	n/d
muscle	1040	1085	1062.5	0.000	0.001	0.001
skin	1000	1483	1241.5	0.000	0.012	0.006
viscera	1000	1050	1025	0.004	0.004	0.004

Some of the particularly significant phenomena that will be included in the expanded versions of the mathematical model will cover such aspects of heat transfer as:

- heat transfer by conduction and blood perfusion in human brains' soft tissues;
- mechanisms of thermoregulation – particularly, shrinking of blood vessels due to temperature changes, perfusion and metabolic heat generation;
- heat transfer in bone tissue placed in the nearest proximity of the brain (in the skull);
- conduction and convection in cerebrospinal fluid.

4. Conclusions

In this article, the problem of infant's hypothermic therapy has been described. Careful analysis of such treatment is a crucial yet difficult task. This difficulty is the result of the complexity of the analyzed problem. Nevertheless, it is a significant goal, because with better understanding of both the mechanisms controlling the therapy and the treatment itself, it will be possible to provide newborns with safe and more efficient health care.

Furthermore, in the publication the proposed measurement and computational methodology has also been described. Hopefully, with application of the aforementioned methods it will be possible not only to deepen the knowledge about this particular treatment, but also to develop some new ways of mathematical description of bioheat transfer.

Due to the equipment being acquired and the preliminary computations still being performed at the moment of publication, it is not yet possible to draw more specific conclusions. Nevertheless, the results of this project will be presented in the future publications.

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Vermicomposting of organic waste and sewage sludge

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Abstract

In this paper possibilities of using earthworms for the waste processing and sewage deposits treatment by vermicomposting method were described. Furthermore environmental requirements of that process were presented, its advantages and disadvantages were shown. Moreover examples for vermicomposting using earthworms were recalled in form of so-called "eco-friendly boxes" at schools as a subject of research in environmental education. Regardless of the direction of using earthworms – whether for the production of fertilizers or the sewage sludge treatment, the ecological issue of their operation is invaluable. Apart from its ecological importance as an integral part of ecosystem - earthworms are performing an essential role in production of fertilizers, sewage processing - they can be taped to objectives of education.

Keywords: vermicomposting

1. Introduction

Vermiculture stands for inbreeding of earthworms at high congestion - led on organic waste, sevage sludge etc. The process of waste treatment is being called vermicomposting. With the main purpose of meant process a production of natural fertilizers is meant. Moreover it is also possible to use it in the waste management for processing biodegradable fraction of municipal waste or sewage deposits. Additionally produced fertilizers may be applied for cultivation of earthworms which next are applicable at the production of medicines, detergents and as cosmetic or fodder ingredients[1]. This process conducted by earthworms along vermicomposting is possible to use for the soil quality improvement, implementing them to relegated areas. *Eisenia fetida* (Sav.) is estimated to be the type of earthworms that find the best fulfilment while waste vermicomposting. In contrast to species living in soil, a greater fertility, longer life and higher resistance to negative environmental factors are characterizing these group of animals. During the vermicompost production it should be remembered that earthworms could accumulate the heavy metals in their bodies. This phenomenon is often used in the so-called bioindication of environmental pollutions.

2. Vermicomposting of waste matter

Earthworms are of importance in the natural environment. They are contributed to soil aeration and its layers shuffle. Additionally they are processing the deteriorating of organic matter what is leading to rapid decomposition of organic matter and an increase of hummus content. On account of that earthworms application for the production of natural fertilizers from waste was started. Coprolite, an excrement produced by earthworms, is characterised of a high fertilizer maximum value, thanks to the high content of assimilable forms of macro- and microelements, enzymes, vitamins and the participation of microorganisms which are decomposing entirely the organic matter. Earthworms itself can be used in production of medicines, beauty products, detergents or also as fodder for animals (subspecies in most cases of demsticated genuas). Moreover earthworms are contributing to the refinement of the degraded soil by vermicomposting. Out of three types of earthworms at compost targets only epigeic (living in surface layers which are rich in the organic matter) earthworms are performing this function well. They are marked by intensive dark coloration and a slight build. Compared with other species, they are moving more quickly as well as they are giving more prolific offspring which is being envolved more quickly. To representatives of epigeic species mainly belong: *Lumbricus rubellus* and *Eisenia fetida*. The latter kind are characterized by a long vitality (16 years) and with a frequent cocoons production (every 7 days). Specimens are able to survive in difficult environmental conditions.

Production of vermicompost is a process requiring steady scrutiny. In order to acquire a satisfying activity of earthworms, appropriate conditions should be fulfilled - so as the amount and the quality of organic substance, the adequate humidity, temperature, nourishment relaxation and the number of earthworms. Animal manure or organic waste - thats the matrix supporting the development of earthworms after the preliminary fermentation. The pH of food should be in range of 6.5-7.5. The nourishment acidity may be adjusted through adding chalk, however alkaline reaction can be neutralized by applying peat and leaves of coniferous trees. The C/N relationship should achieve 25:1. In order to raise the carbon content cardboard or straw are being added. Earthworms are taking food in the semifluid form, therefore the recommended humidity of the nourishment amounts to 75-80%. Too dry medium trigger a dropp in their vital processes intensity. However a wet medium surface exhibits a limited access of oxygen, and as a consequence putrefactive processes occure which are adversely affecting their activity of earthworms. In order to provide appropriate water amount a drainage in the medium should be applied. The regulation of the humidity consists of sprinkling the medium with water - the organic matter becomes soaked (without scouring) what facilitates to preserve valuable ingredients incurred vermicompost. The adequate temperature influencing the effectiveness of compost earthworms should be hold in range of 12-28°C. Earthworms resistance to low temperatures depends on the season and is changing stepwise. In order to adapt them to changes of temperature, in autumn vermicompost may be covered with an additional layer of manure, straw or leaves. It is possible to monitor the humidity and the temperature by overshadowing a nourishment or applying protective shield. Relaxed bed is facilitating migration and is ensuring higher oxygen content. Earthworms living in lax base are distinguished by higher activity and a better tinge. The population distribution of earthworms should cross 20 000 itm / cubic meter - , amount below that limit can lead to the vermicompost quality downgrade. In medias, in which appropriate conditions aren't ensured, earthworms can migrate to more organic matter-rich medium. Then they are wasting the energy, are less active, grow more slowly as well as produce fewer cocoons what is adversely affecting the vermicompost production [1].

2.1. Vermicomposting of sewage sludge

In Poland vermicomposting of sewage sludge by earthworms settlements was started since mid-nineties on a wide scale. The groundbreaker who has started the production of vermicompost a bit earlier was a sewage treatment plant at Pyrzyce, that began the use of this vermicompost as fertilizer for agricultural targets [1].

Vermiculture is being conducted in appropriate emplacements. It is also limited from sides with boards or concrete elements. Side walls and the bottom of vermicomposting bed must adhere strictly to each other (Fig. 1).

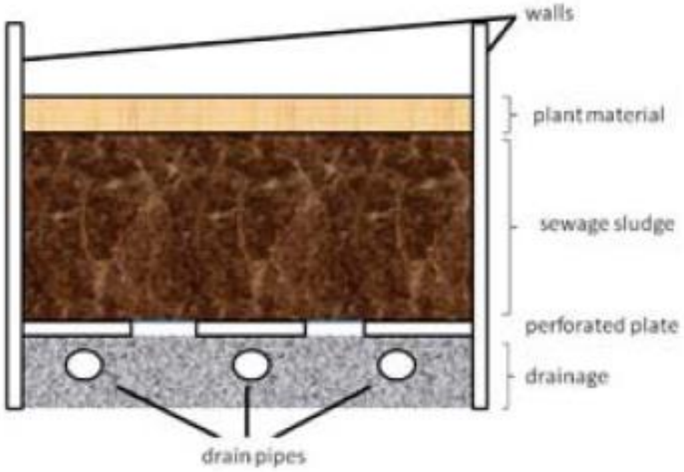

Fig. 1. Scheme of sewage deposits vermicomposting test-stand

Therefore the farm is separated from environmental conditions, including natural predators so as the mole. Earthworms belonging to *Eisenia fetida* show immunity to environmental conditions. However as all earthworms, they are sensitive to the presence of ammonia in vermicomposte [1]. All sewage sludge rich in this substance can lead in a direct contact to population distribution losses. Therefore before implementing earthworms, preliminary processing of sewage sludge is applied to the organic material.

Vermicomposting of sevage sludge is hold in phases. The deposit is firstly apportioned in thin layers alternately with green waste (straw, hay). Thanks to that the requirement on lifting the compost mass out it is not a routine treatment during standard composting in prisms. Besprinkling of earthworms settlements and their regular feeding are the most important parts of conditional treatment. The participation of water in that medium must be controlled and supervised. Too high hydrating level, e.g. during the rain, may perhaps cause putrefactive processes and dying of the population of earthworms. Therefore good drainage under the test –stand for vermicomposting is of importance. Distributing of chosen earthworms nourishment can be held by hand or in an automated way. Process of vermicomposting usually runs since April until October. Before the winter comes the inbreeding-positions are being specially secured with a thick layer of straw. Vermicompost's quality depends initial on sewage sludge composition, on pollutants content or conducted care processes. Due to the ability of metals accumulation by earthworms, vermicomposting of sewage sludge is being given as the most fitting processing on the countryside or for the Waste Water Treatment plants in small towns. So then getting valuable fertilizer and avoiding of contamination with metals are possible, and both: the product, and its producers, earthworms. Another threat of running a vermiculture on sewage sludge is the possibility of fertilizer production from sewage medium contaminated by the digestive tract parasites. It turns out, that the technology of waste processing by vermicomposting, does not let on full hygienization of polluted raw material due to vital requirements of earthworms. The temperature of nourishment rarely exceeds 40ºC – it doesn't ensure full material hygienization [1-3, 4-6]. Therefore vermicompost, that will be exploited at agricultural targets should meet the requirements concerning content of heavy metals and biological pollutants, according to the ruling law[7]. Vermicomposts from sewage sludge are at most applied for fertilizing plants and in the remediation of degraded areas.

3. Using earthworms in ecological education

Process of vermicomposting is possible to use in households by processing kitchen waste and at schools to objectives of education. For that purpose so-called "earthworms eco-friendly boxes" are being built [1]. The educational effect of using earthworms cannot be overestimated. In the ecological education the facility of using earthworms and theirs universality is an advantage as well as small environmental requirements and the ease to observe their activity. Children are directly involved in the care and safekeeping about earthworms. Young people are studying liabilities for life forms and simultaneously meet knowledge about environment. Often teachers during lessons of biology use glass containers, in which school-age students are observing waste processing and the migration of earthworms in the soil. Therefore the promotion of that kind of activities which are teaching and developing ecological attitudes at children are promotion-worth. The description of the use of earthworms in the ecological education is defined and substantiated on many official websites of schools. Apart from that earthworms around school-vermicompost may be useful during biology lessons: at discussing the morfology and functions of *Annelidas* in the environment.

4. Summary

Vermicomposting of waste is usually leading in order to the production of valuable natural fertilizer. It is possible also to apply the process for processing municipal waste or sewage sludge. Advantages of this process include:

- production of rich-in-nutrients-compost,
- reduction of volume of wastes
- homogenization and decomposition of organic matter,
- improvement in its structure,
- reduction of odours.

The method has also drawbacks from which the most important is its lack of full-hygienization ability of processed waste. Therefore recommended is vermicomposting of waste uncontaminated biologically. Vermicompost of sewage sludge cannot always be applied for the cultivation of plants, especially vegetables - due to the viable possibility of crops deterioration. For the purpose of supplementing missing ingredients it is advised to apply simultaneously: vermicompost and fertilizing mineral[1].

Regardless of direction of earthworms exploitation: for the production of fertilizers or the waste processing, the ecological effect is invaluable To sum up it is possible to state, that apart from its ecological important role, earthworms are presenting also a major contribution in the production of natural fertilizers and in waste processing as well as they are applied to objectives of education.

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Hydrogen production from wood waste by mean of dark fermentation

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Abstract

The utilization of wood wastes in clean and green chemistry method like by mean of dark fermentation, is a highly desired solution of waste management. In the article model for the estimation hydrogen potential of wood waste is given. The model has been used to calculate the potential theoretical hydrogen mass that can be produced from wood wastes in Pomerania and Silesia: pine, spruce, fir, beech and oak. In the introduction, there describes the process and background of the model and the parameters are explained. In model description the formulas of a model are given with reaction schemes and variables description. In the results and discussion there are calculations of hydrogen potential mass from wood waste in Pomerania and Silesia. The potential hydrogen production from wood waste of these two regions fulfil near 8 times the recent demand of Poland.

Key words: dark fermentation, beech, pine, oak, spruce, fir

1. Introduction

Proper management of forests needs to overcome the problem of wood waste utilization - it can be used directly as a source of heat of some household but it pollutes environment shifting greenhouse effect and some dioxins. Therefore, there is necessary to project a new way of wood waste management, more friendly to the environment. On the other hand, the best strategy of utilization of waste is to transfer it for renewable source of energy or efficient raw material of green chemistry. One of the potential methods of such an utilization considers to be dark fermentation. Dark fermentation is a microbial anaerobic conversion of simple carbohydrates to hydrogen, carbon dioxide, butyric acid or acetic acid. The most desired substrate is hydrogen ‘fuel of the future’. Therefore, in the article there has presented a model of potential hydrogen production from wood waste. Lignocelluloses wastes like wood waste can be considered as the raw material. Thus the model for hydrogen production estimation from different lignocelluloses wastes has been developed. In the models two of biopolymers of lignocelluloses are taken into account: cellulose and hemicellulose. The model gives possibility to estimate potentiality of the selected kind of wood to be hydrogen source. The presented equation can calculate potential hydrogen volume production from selected parts of the plant, all plants and group of plants. Let assumes that the model follows: that plant waste in the range of kind are from the same part of the plant and the origin of the same growth area. Other assumptions of the model follows Bartacek et al [1] and Pradhan et al [2] - maximal yield calculations for hexoses is 0.33 and for pentoses 0.32. The model estimations include parameters: yield of reactions Y_{tg} (dark fermentation of hexoses) or Y_{th} (dark fermentation of pentoses) mass of waste, fraction of biopolymer in the plant (f_c – of cellulose) and (f_h - of hemicelluloses) The hydrolysis of polysaccharides are considered as perfect. The model was used for calculation theoretical hydrogen volumes of selected lignocelluloses wastes taken of selected wood waste data from the report 2015[3], Ropińska[4], Jasiulewicz [5] for pine wood (Pinus sylvestris), spruce (Picea abies), fir (Abies alba), beech (Fagus sylvatica) and oak (Quercus robur).

2. Model description

Let's assume that model follow: plant waste in the range of kind are in the same age and origin from the same cultivation area. The model estimations include parameters: yield of reactions Y_{tg} (dark fermentation of hexoses) or Y_{th} (dark fermentation of pentoses) mass of waste, fraction of biopolymer in the plant (f_c of cellulose) and (f_h of hemicelluloses). In the model, perfect hydrolysis of polysaccharides into simple carbohydrates (glucose, rhamnose fructose xylose, maltose and lactose) are assumed, and dark fermentation undergoes only in acetic way. The process undergoes in two reactions (1 or 2) with a maximal theoretical yield of hydrogen 0.32 – 0.33 [1,2]. Dark fermentation of carbohydrates can undergo in 2 reactions:

$$C_6H_{12}O_6 + 4H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \tag{2.1}$$

$$C_5H_{10}O_5 + 2.67H_2O \rightarrow 1.67CH_3COOH + 1.67CO_2 + 3.33H_2 \tag{2.2}$$

Equation 3 has been developed to calculate optimal potential hydrogen production availability M_{Hij} (mass of hydrogen produced) of the same random waste part of age 'j' of plant 'i' of mass m_{ji}:

$$M_{Hij} = \left(\frac{Y_{tg}\, f_{cji}\, m_{ji}\, M_{GluH2}}{M_{GLU}} + Q_{hji}\, m_{ji}\right) \approx \frac{Y_{tg}\, f_{cji}\, m_{ji}\, M_{GluH2}}{M_{GLU}} + \left(\frac{Y_{th} f_{h6ji}\, M_{hekH_2}}{M_{hek}} + \frac{Y_{tp} f_{h5ji}\, M_{penH2}}{M_{pen}}\right) m_{ji} \tag{2.3}$$

where:

M_{Hij} - theoretical hydrogen mass from random part of age 'j' of plant 'i' [kg];

Y_{tg} - theoretical optimal hydrogen yield from glucose 0.33 according to reaction 1 [1];

m_{ji} - mass of random part of age 'j' of plant 'i';

f_{cii} - fraction of cellulose in part 'j' of plant 'i';

Y_{th} - theoretical optimal hydrogen yield from hexoses in hemicelluloses: (glucose, fructose, lactose,) via reactions (1 and 2) - 0.33 [2];

Y_{tp} - theoretical optimal hydrogen yield from pentoses: glucose, fructose, lactose, xylose, rhamnose) via reactions (1 and 2) - 0.32 [2];

M_{GluH2} - molar mass of hydrogen in glucose – 12 g/mol;

M_{Glu} - molar mass of glucose – 180 g/mol;

M_{hekH2} - molar mass of hydrogen in hexose – 12 g/mol;

M_{Glu} - molar mass of hexose – 180 g/mol;

M_{penH2} - molar mass of hydrogen in pentose – 10 g/mol;

M_{pen} - molar mass of pentose – 150 g/mol;

Q_{hji} - polymerization and fraction of hemicellulose factor in random age 'j' of the plant 'i' via equation (2.4)

$$Q_{hji} = \frac{Y_{th} f_{h6ji}\, M_{hekH_2}}{M_{hek}} + \frac{Y_{tp} f_{h5ji}\, M_{penH2}}{M_{pen}} \tag{2.4}$$

where:

f_{h6ji} - fraction of hexoses in fraction of hemicelluloses;

Y_{th} - theoretical optimal hydrogen yield from hexoses in hemicelluloses: glucose, fructose, lactose via reaction (1 and 2) - 0.33[2];

Y_{tp} - theoretical optimal hydrogen yield from pentoses in hemicelluloses: glucose, fructose, lactose, xylose, rhamnose via reaction (1 and 2) - 0.32 [2];

f_{h5ji} - fraction of pentoses in fraction of hemicelluloses.

In case of calculation of theoretical maximal hydrogen production from the bark of different random 'j' age of plant 'i' (for example, fir wood of different age group) equations (5) and (6) have been designed. Overall mass M_i of 'j' parts of the plant 'i' equals equation (5):

$$M_i = \sum_j m_{ij} \tag{2.5}$$

where: m_{ij} - mass of ‘j’ age of plant ‘i’ (for example age 21-40 and age 41-60 give j=2).

If the plant ‘i’ belongs to spermatophytes group then ‘j’ age includes (1-20 years, 21-40 years, 41-60, 61-80 and 81-100, thus j=5). Optimal potential hydrogen production availability of plant ‘i’ from all parts ‘j’ was shown in equation (2.6):

$$M_{Hi} = \sum_j m_{ij} \left(\frac{Y_{tg}\, f_{cij}\, M_{GluH2}}{M_{GLU}} + Q_{hij}\right) \tag{2.6}$$

For analysis wood of 5 different group age ‘j’ of pine are chosen: 1-20 years, 21-40 years, 41-60 years, 61-80 and 80-100. The parameters for optimal theoretical hydrogen volume are given in Table 1.

Tab 1. Values of parameters of wood waste.

Kind of wood	**Age years**	**f_c, %**	**f_h, %**	**f_{h5}, %**	**f_{h6}**	**ref**
Pine wood	1-20	47	16.8	44%f_h=7.5%	58%f_h=18.5%	[6–9]
	21-40	48.9	16.8	43%f_h=7.2%	57%f_h=16.1%	
	4160	40.8	25.9	40%f_h=10.4%	60%f_h=14.5%	
	60-81	42	25	38%f_h=9.5%	62%f_h=15.5%	
	81-100	42.5	24.8	37% f_h=9.3%	63% f_h=15.5%	
Spruce wood	41-60	40.4	32.3	42%f_h=14%	58%f_h=18,3%	[10]
Fir wood	1-20	40.7	35.2	38%f_h=13.5%	62%f_h=21.7%	[11]
	21-40	41	35.1	38.3%f_h=13.4%	61.7%f_h=21.7%	
	41-60	42.1	34	39.2%f_h=13.4%	60.8%f_h=20.6%	
	60-81	42.9	33.5	39.3%f_h=13.2%	60.7%f_h=19.7%	
	81-100	43.5	33.1	39.7%f_h=13.1%	60.3%f_h=20%	
Beech wood	41-60	46.4	22.4	47% f_h=10.5%	53%f_h=21.9%	[9]
Oak wood	21-40		39 20	43% f_h=9%	57%f_h=11%	[12]
	41-60	39.4	21	40% f_h=8%	60% f_h=13%	
	60-81	41.3	23	38%f_h=9%	62% f_h=14%	
	81-100	42	22.4	36%f_h=8%	64% f_h=14.3%	

3. Results and discussion

The model presented in the article equations (3-10) is used for estimation of potential hydrogen production by dark fermentation in Pomerania region and Silesia region. The results are given in tables (Tables 2 and 3).

Table 2. Potential mass of hydrogen produced by dark fermentation from pine, spruce, fir, beech and oak wood waste at Pomerania Region according to [3,4].

Material	**Age**	**Annual mass of wastes at Pomerania Region, 10^3 tonnes**	**Estimated hydrogen mass at Pomerania Region,·tonnes**
Pine wood	1-20	43,684	577,714
	21-40	10,593	144,264
	41-60	27,521	365,933
	60-81	25,009	337,653
	81-100	40,954	555,985
Sum Pine wood	1-100	109,210	1981,549
Spruce wood	41-60	5,379	17,645
Fir wood	1-20	652	7,696
	21-40	158	1,878
	41-60	411	4,931
	60-81	373	4,532

	81-100	611	7,984
Sum fir wood	1-100	1,630	18,826
Beech wood	41-60	15,974	63,914
Oak wood	1-20	1,304	4,638
	21-40	316	4,681
	41-60	821	12,792
	60-81	747	11,661
	81-100	1,223	19,339
Sum oak wood	1-100	3,260	33,771
Total waste wood		133,823	2115,526

Table 3. Potential mass of hydrogen produced by dark fermentation from pine, spruce, fir, beech and oak wood waste at Silesian Region according to [3,4].

Material	Age	Annual mass of wastes at Silesian Region, 10^3 tonnes	Estimated hydrogen mass at Silesian Region ·tonnes
Pine wood	1-20	18,200	307, 497
	21-40	4,414	76,576
	41-60	11,466	182,039
	60-81	10,420	167,283
	81-100	17,063	225,697
Sum Pine wood	1-100	45,500	733,395
Spruce wood	41-60	11,375	43,317
Fir wood	1-20	728	8,593
	21-40	177	2,097
	41-60	459	5,506
	60-81	417	5,067
	81-100	683	8,358
Sum fir wood	1-100	1,820	21,021
Beech wood	41-60	10,010	40,051
Oak wood	1-20	2,912	32,921
	21-40	706	10,451
	41-60	1,835	25,959
	60-81	1,667	42,910
	81-100	2,730	43,298
Sum oak wood	1-100	7,280	153,149
Total waste wood		74,165	567,429

The model presented in equations (3-10) assesses profitability of hydrogen production by dark fermentation. They show an upper limit of hydrogen masses that can be obtained from selected part, kind, and set of different plant wastes. The model collects parameters and data taken from literature [3,7,12]. Shown potential volumes of hydrogen are obtained under the assumption of perfect hydrolysis (all parts of the biopolymers are converted into simple sugars). From the 1 kg of selected wood wastes can be obtained maximally: from: pine wood 1-20 years 16.9g of hydrogen, pine wood 21-40 years 17.4 g of hydrogen, from pine wood 41-60 years 15.9g of hydrogen, pine wood 61-80 years 16.1g of hydrogen, pine wood 81-100 years 13.2 g of hydrogen; spruce wood 41-60 years 16.6 g of hydrogen; fir wood 1-20 years 11.8g of hydrogen, fir wood 21-40 years 11.9g of hydrogen, fir wood 41-60 years 12 g of hydrogen, fir wood 61-80 years 12.1g of hydrogen, 81-100 years 12.2 g of hydrogen, beech wood 41-60 years 17.5 g of hydrogen, oak wood 1-20 years 14.7 g of hydrogen, oak wood 21-40 years 14.8g of hydrogen, oak wood 41-60 years 15.6 g of hydrogen, oak wood 61-80 years 15.7 g of hydrogen, 81-100 years oak wood 16 g of hydrogen. The amount of hydrogen obtained from wood is smaller than from textile wastes cotton or linen. From 1 kg of cotton wastes 21g of hydrogen, from 1 kg of linen wastes 19 g of hydrogen[16]. The highest mass of hydrogen can be obtained by dark fermentation of wood wastes from beech wood of 41-60 years, pine wood and spruce wood. Dark fermentation can optimally produce hydrogen from the above mentioned annual wood waste in masses: 2 115,526 tonnes of hydrogen from Pomerania region and 567,426 tonnes of hydrogen from Silesia region. The Lotos, the greatest consumer of hydrogen in Pomerania Region in 2014 used $45.9 \cdot 10^3$ tonnes of hydrogen per year [17,18]. Recent consumption of hydrogen in Poland that is

290.6·10^3 tonnes. Therefore, potential masses of hydrogen from Pomerania wood waste are 46 times more than Lotos demand and Silesian 12 times more than Lotos demand. Pomerania potential hydrogen mass is 7 times more than Poland demand and Silesian potential hydrogen mass is 1.95 of Poland demands of hydrogen. Therefore, however wood wastes are less efficient raw material for the hydrogen source than textile waste due to widespread of waste they can fulfill better Polish demand for this element [1,19]. The world recent demand for hydrogen is 356 ·10^7 tonnes and Pomerania potential hydrogen from wood waste fulfill it in 0.06% and Silesia in 0.02%. Pomerania and Silesia wood waste could fulfill world demand in 0.08%. The difficulty in recent technique is efficiency up to 15% and low hydrolysis level from softwood [20,21].

4. Conclusions

The article is an analysis of potential of source of hydrogen other than beet or corn waste –wood waste [22,23]. The model presented in the article allow to assess availability of hydrogen source without empirical works. The model allows to design process with high efficiency and is a useful device in scale-up of dark fermentation from lab scale into industrial wastes. The wood wastes from Pomerania and Silesia are enough to fulfil Lotos demand for hydrogen and overall recent consumption of Poland for hydrogen. The best sources of hydrogen from pine wood, spruce wood, fir wood, oak wood and beech wood are beech wood and pine wood. The potential production of hydrogen from wood waste are lower than production for textile waste, but higher than from corn waste [24]. However, textile wastes mass is lower 288,593 tonnes are smaller than wood wastes of 207,988·10^3 tonnes, therefore wood waste are more widespread material and enough high hydrogen potentiality[16,25,26]. Assessing hydrogen production from different plant waste is an important step for efficient selection of proper source for hydrogen production. The data are hints for designing industrial process, where hydrogen is used, how many renewable sources can be applied for replacing of conventional processes.

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Reducing the environmental footprint: Processing of organic waste for vegetable and mushroom growing, integrated with a new greenhouse technology

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Abstract

Processing of clean organic wastes into new food can be performed in one system - production of biogas and greenhouse production of vegetables and mushrooms. Biogas production provides electricity for lighting of plants, CO_2 for their feeding and thermal energy for heating and greenhouse, and organic waste is converted into biogas, and digester residue is converted into substrate for vegetable and mushroom production. This system allows year round production, even in winter. New type of semi-closed greenhouse with reduced ventilation and double walls, and soap foam technology as thermal insulation, "bubble greenhouse" is used. The aim of this article is presentation of the pilot scale integrated system, and the use of digester residue for production of vegetables and mushrooms.

Key words: closed greenhouse system, digestate, biogas, food waste, vegetables, mushrooms

1. Introduction

Growth of world population and rising demand for food has led to evolution in agriculture, by increased use of capital and other inputs. Its intensification increased potential for material losses and environmental degradation. Whereas traditional agriculture was cyclical by nature (produce crops, livestock, use manure for fields fertilization to grow crops), "modern" or "industrialized" agriculture transformed cyclical into linear process; great amounts of raw materials consumed and huge amounts of waste produced (Allenby and Graedel 1995). However, food waste generation is different between regions: in high-income countries it is dominated by consumer waste, whereas in developing countries it is generated mostly at the post-harvest and processing stages because of spoilage. Roughly one third of the food production in the world for human consumption gets lost or wasted, yearly approximately 1.3 billion tones (Gustavsson et. al. 2011). This accounts for 6-10% of human-generated greenhouse gas emissions (Vermeulen et. al. 2012). In Europe and North America people waste 95-115 kg of food per person each year, when in Sub-Saharan Africa and South Asia the loss is only 6-11 kg (Gustavsson et. al. 2011). This wastage has great negative impact on global economy, food availability and major environmental impacts.

Source separation of household bio-waste was introduced as a strategy to reduce the amount of organic waste deposited in landfills, stimulated by European ban on land filling of wastes containing more than 100 g/kg^{-1} total organic carbon. The organic waste should be recycled on agricultural land. Anaerobic digestion (AD) is a good way of utilizing organic wastes including food waste; this treatment reduces CO_2 emissions from landfills and the biogas can be used in power production (Weiland 2000, 2010). Moreover AD extracts the nutrients available for use in agriculture, and reduces odors by a closed process (Singh et al. 2010).

The greenhouse horticulture sector is the ideal sector to convert local organic waste into food. It is in average an energy intensive industry. The difference with other sectors is that horticulture needs CO_2 to stimulate plant growth, while other industries emit CO_2. There is a big opportunity for the greenhouse sector to obtain local organic waste, and put this into use with good businesses advantage. However, greenhouses often have poor energy and water performance as well as a high carbon footprint. Most heat is lost from greenhouse at night by conduction through glass, and by air infiltration and airing. To reduce this losses, modern greenhouses were designed and built hermetic, which increased humidity inside and condensation on the glass surface. Condensation can reduce the solar light absorption by plants, and extend of heat reduces the photosynthesis. Hence, in summer greenhouse overheats and requires ventilation and shading, in winter – this causes heat losses. The "Food to Waste to Food" project - F2W2F - develops an integrated system aimed at greatly improving this situation. The project demonstrates a closed cycle organic waste to energy and food system, which is the integration of food waste treatment, biogas digestion, growing crops with the digester residue and a new semi-closed dynamic greenhouse technology. In this system, organic waste is converted into biogas and digester residue is converted into substrate for vegetable and mushroom crops, and liquid fertilizer for fertigation. Biogas production provides electricity for lighting of plants, CO_2 for their feeding and thermal energy for heating, allowing year round production, even in winter. In the process it is possible to control the mass and energy flow and model the carbon, nitrogen and phosphorus cycles.

Return to self-sustainable agricultural system is not a revolutionary idea. All the components have been more or less well documented before, but the combination is unique (Hardy et al. 2000, Todd et al 2003, Gan 2008, FAO 2013, Specht at al. 2014). The integration makes it possible to exploit all products from the digester in an optimal way. The complete small scale system has been built in Norway and is the basis for the overview article presented here.

1.1. Waste processing, anaerobic digestion and growing using the digester residue

Source separated household and commercial food waste is received in plastic bags or consumer packaging. The pre-treatment plant grinds, separates plastics and makes slurry ("substrate") out of the food. Precipitating (e.g. sand) and floating solids (e.g. plastic) are separated. The slurry is pasteurized at 70°C. The presented stream is fairly clean and can be used in organic farming. The standard in the biogas production is to have quality control of the input stream at all times. To ensure the foodwaste does not contains pathogens the stream is sanitized according to European standards. Study performed by Govesmark et al. (2011) shows the foodwaste digestate contained rather low amounts of heavy metals, pesticides and organic pollutants such as phthalates and is considered as a potential beneficial biogas input product. However, the amounts of chemical contamination should be controlled, for it might perform minor seasonal variations. This is also important for the digestate composition in terms of stability in nutrients which can vary seasonally (as the input source separated from households changes through year).

The substrate is digested to biogas and digestate. The biogas is burnt (in CHP generator or in simple burner heating water) at correct temperature enabling flue-gas to be released in the greenhouse environment directly for fertilizing atmosphere with CO_2. The digestate is separated using a decanter centrifuge. Both the dewatered digestate (the fibrous part) and the reject water have been investigated in terms of how to convert it most efficiently into a selective plant growth substrate and nutrient solution.

The dewatered part was used for mixing with straw and paper waste to produce mushroom compost. Fibrous fraction is rich in nitrogen (N) and phosphorous (P) which comprise a great part of demand for those elements both for plants and for mushrooms. Dewatered fraction was also mixed with green waste compost and used directly as plant substrate. The dewatered digestate fraction has also been converted by means of vermicomposting into worm casts. The spent mushroom compost was used as a potting substrate for plants. Mushrooms (heat-loving species) were grown under plants in the greenhouse. The spent mushroom substrate was transformed into potting substrate for plants production by process of vermicomposting. Also some parts of dry fibrous fraction of dewatered digestate were vermicomposted without producing mushrooms first. For the reason the digestate contains a lot of organic nitrogen (N) but also ammonium (NH) in high concentration it was composted or stored before it was used in order to dispose of extend ammonium.

The liquid fraction of the digestate was conditioned to change its microbial and chemical composition, the final product is rich in nitrogen and potassium, and used after dilution, by controlling its electrical conductivity, for irrigation and fertilisation of plants in the greenhouse.

1.2. The bubble greenhouse system

The bubble greenhouse comprises a double plastic layer cover with the cavity between. Insulated tanks contain soap liquid which can be pumped and converted by generators to bubbles/foam to fill in the cavity. The foam has favourable properties in terms of insulation, shading, light reflexion and transmission properties. The greenhouse also has a large thermal mass as water tanks. One mass is kept warm and one cold for different purposes. The system also includes heat exchangers between the soap liquid and the thermal mass, and between the internal air and thermal mass, as well as the thermal mass and the outside air. An advanced sensor and monitoring system enables online control of the system. It has been stated the cavity convective heat transfer coefficient increases with the bubble diameter and porosity however decreases with the increase of cavity width, which is compatible with research made by Gan (2008).

2. Mass and Energy Balance of our solution

The mass balance model shows that when the amount of food waste fed to the system is based on the amount of nitrogen in the liquid digestate (after separation) needed for plant crops, the energy from the produced gas will be 70-80% of the energy usually supplied by fossil fuels for heating in conventional Nordic greenhouses. Our gas energy is however evenly produced through the year, while the fossil fuels in conventional greenhouses are normally burnt in the winter months only, especially during night. But since the F2W2F-installation is in orders of magnitude better in terms of thermal performance than conventional greenhouses, and since heat will still be added from electrical lighting (a great deal of the necessary heat during daytime comes from growing lights in Nordic greenhouses), it can still be managed without adding fossil fuel. In fact, when operating the growing lights as the only source of heat, while having the cavity completely filled with foam/bubbles, the temperature inside kept rising towards 30°C despite an outside temperature of -20°C. There is also heat generated from the degradation of the fiber fraction, and thermal heat in the digestate adding to the supply during periods when lights are off. Thus, in terms of heat and nutrient mass there is a highly useful match. No gas is required for heating the greenhouse, only for pasteurization of the food waste slurry. Energy from gas produced can be exported from the system as gas (e.g. for cooking, for upgrading to vehicle fuel etc.) or as electricity to the grid. Detailed information, including the complete mass and energy balance of the system, "bubble greenhouse" operation procedures are described in separate paper, and will not be the subject of further discussion (Fig. 2.1)

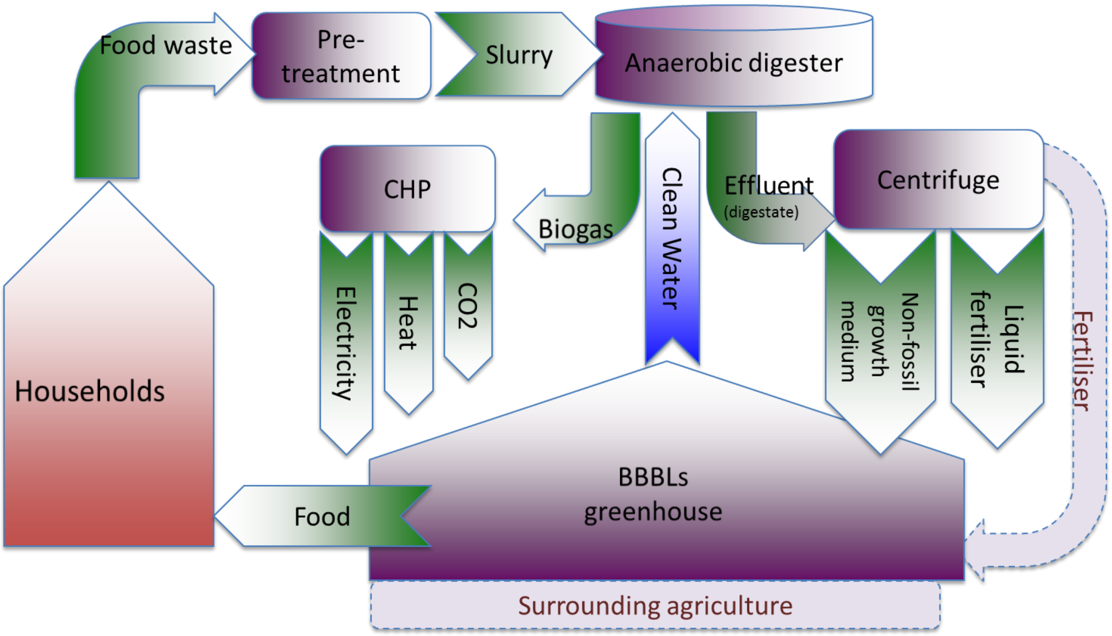

Fig. 2.1 Flow diagram for a *balanced* F2W2F community scale system

3. Mushroom production

As shown in Fig. 2 the solid fraction was used after dewatering as a high nitrogen component of substrate in mushroom cultivation. The mushroom compost was prepared according to Stoknes et al. (2013). In these experiments increasing amounts ranging from 0 to 40% (DW/DW), with intervals of 10% were used. All compost types supported growth and produced mushrooms. Yield of three species investigated: *Agaricus arvensis, Agaricus bitorquis and Agaricus subrufescens* depend on the amount of digestate which was added to the cultivation substrate. Increasing amount of digestate resulted in increased yield. The yields differed between investigated species. For *Agaricus bitorquis* the highest yield was obtained on substrate with addition of 30 and 40% of digestate. *Agaricus subrufescens* yielded best on substrate with addition of 30% of digestate. Those results are comparable with findings of Stoknes et al (2013).The lowest yield was obtained from the substrate with the addition of 20 and 10% of digestate. The highest amount of digestate (40%) performed with significantly lower yields for *A. subrufescens* and *A. arvensis,* which performed on digested with the lowest yield. Solid fraction of digestate from anaerobic biogas production seems to be a good alternative source of nitrogen for mushroom cultivation. Presented data have been described in details in the separate paper, where additional information can be found, therefore will not be discussed here (Jasińska et al. 2016).

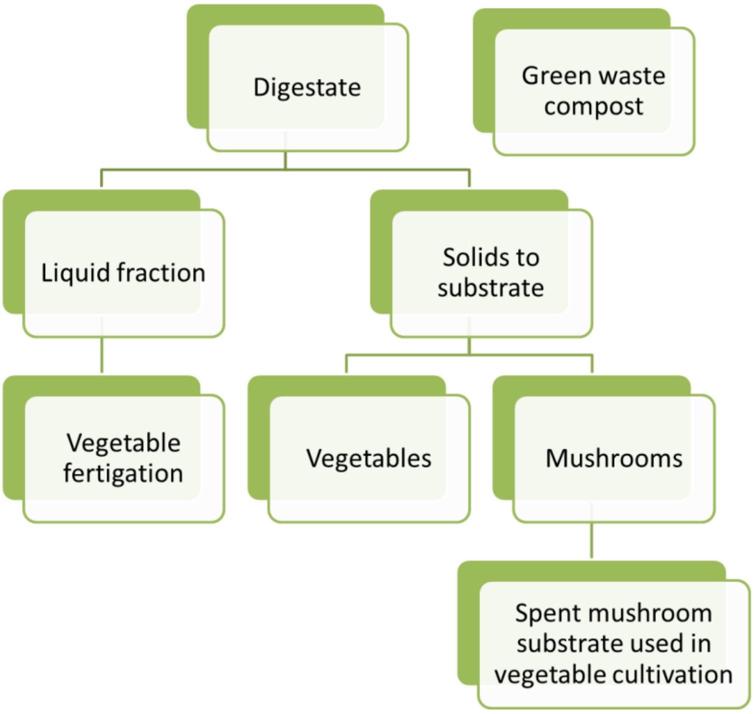

Fig. 3.1 Utilization of food waste digestate from anaerobic digestion in closed greenhouse system

4. Plant cultivation

Solid fraction and liquid fraction were successfully used in herbal plant cultivation (melissa, coriander). AD food waste was separated by filtration into solids and liquid. The liquid had pH=8.1 and EC=12.4 mS/cm. pH was lowered to pH 6,5 by adding nitric acid (65%): 5.7 ml per liter. By adding this amount of nitric acid EC raised up to 13.4 mS/cm. Melissa (*Melissa officinalis* L.) and coriander (*Coriandrum sativum* L.) were cultivated in organic peat based substrate and were fertigated with different dilutions of liquid, with EC 0.5; 1.0; 1.5; 2.0; 2.5. Multicomponent mineral fertilizer EC 0.5 was used as control. The experiment was conducted in two cycles. Each treatment had four repetitions.

Herbs were cultivated in peat based substrate and fertigated with different concentrations of liquid fraction. In an experiment with Melissa, yield was 32 – 59 g per pot and with coriander 34-81 g per pot. In Melissa cultivation, in both cycles increasing liquid concentration caused higher yield. The lowest yield was in the control treatment and with a liquid concentration of EC 0.5 mS/cm. The experiment with coriander showed inconsistency in yield. In the first cycle there was no significant influence of concentration used for fertigation. In the second cycle there was significant influence. The highest yield was in the treatment with EC 2.0 mS/cm and the lowest in the control and in the treatment with EC 0.5 mS/cm. Increasing concentration caused higher yield up to EC 2.0 mS/cm. In the experiment with bentgrass and bluegrass Michitsch et al. (2008) found that clipping yields were comparable up to the recommended N application. Higher EC in treatments with increased concentration of wastewater caused poor plant growth. Makádi et al. 2008 suggest that plants can be divided into two groups of sensitivity to digestate application – sensitive like alfalfa, soybean and sunflower, and a second non-sensitive group– like silage maize, sweet corn, triticale and winter wheat. Sensitivity to digestate also depends on growth stage. Liquid fraction from anaerobically digested food waste can be used alternatively as an organic fertilizer in melissa and coriander cultivation but further investigations according to biological and chemical influence on herbs need to be done.

5. Conclusions

The overall goal of the project was to increase the use of organic waste as valuable raw material for producing a closed-loop process with production of food (vegetables, herbs, mushrooms), energy and fuel crops. This is strongly related to concept of circular economy, where products do not quickly become waste and are reused to extract their maximum value before safety and productively returning to the biosphere. What is important for business, those products can deliver economy growth.

Some F2W2F applications will be scaled up from just waste treatment and a higher requirement for gas (high volume of waste), meaning that there will be more excess gas, CO_2 and nutrient exported as fertiliser from the system. Other projects will be scaled from a greenhouse growers need (smaller volume of waste), meaning that the primary goal will be a steady supply of substrate, nutrients and CO_2 for plant growth, while local waste treatment and cooking gas will be regarded as additional benefits. In some climates and contexts there will be better balance between these two needs than in others. Also, there is large variation between countries in terms of political instruments, such as feed-in tariffs etc. meaning the implementation will depend on the context. In any situation there will be benefits of the F2W2F system, it is just the inputs, outputs and internal scaling of components that has to be adjusted, by means of a good quantitative model, which will be further developed through the project (Fig. 5.1).

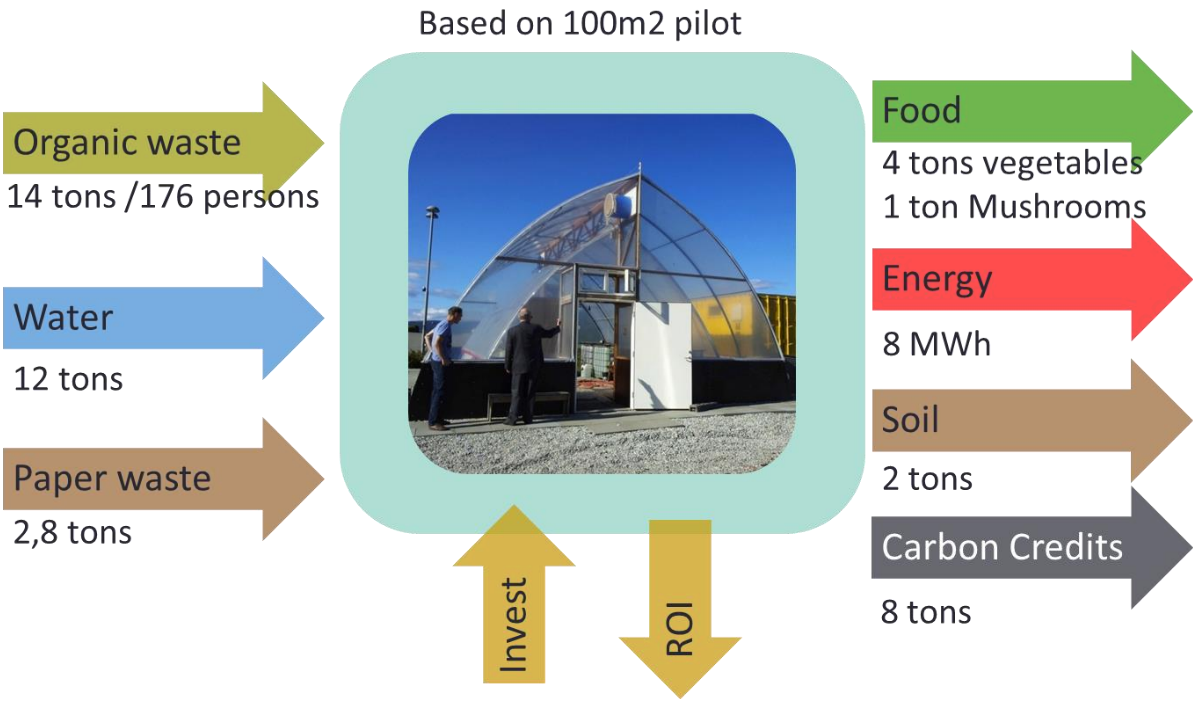

Fig. 5.1 F2W2F system performance based on $100m^2$ pilot BBBL Systems greenhouse

The energy consumption for heating can be lowered up to 70% (heat emitted by high pressure sodium lamps used for lightning of plants - 80 W/m2 - was enough to keep temperature at 20°C inside the bubble greenhouse with an outside temperature of -20°C.

The bubble insulated greenhouse worked as a semi-closed greenhouse and drastically reducing the need for ventilation. By including heat exchange systems the temperature could be precisely controlled during both winter and summer conditions.

A closed system of water circulation will reduce amount of used water

Utilization of liquid and solid food waste digestate fractions as fertilizers can eliminate petrochemical fertilizers.

Direct utilization of digestate as a fertilizer in vegetable or mushroom substrate components will lower costs of digestate storage and transport from AD plants.

Increased output i.e.: food product, energy, soil/substrate, carbon credits, of 35% by integrated production.

Assist the production of fresh vegetables and mushrooms throughout the year

“Clean” electric energy or biogas-fuel production

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Authors Index

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