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WYDZIAŁ ENERGETYKI I PALIW

KATEDRA ZRÓWNOWAŻONEGO ROZWOJU ENERGETYCZNEGO

Praca dyplomowa

Integrated LCA and LCC analysis of hybrid district heating system in Poland

Zintegrowana analiza LCA i LCC hybrydowego systemu ciepłowniczego w Polsce

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Abstract

Our adorable planet is in the face of climate emergency, and Poland can’t keep aloof from that. In 2021, Polish energy cooperation, Tauron, collaborated with AGH to develop a project aiming to reform the ongoing district heating system. This study introduces life cycle thinking into project results to broaden the dimensions and discover valuable information. Through assessment, the properties of fuels and solar collector production are hot zone of the project. Besides, economic analyses validate the advantage of renewables implementation in the long run.

Streszczenie

Nasza urocza planeta stoi w obliczu kryzysu klimatycznego, a Polska nie może się od tego trzymać z daleka. W 2021 r. polska kooperacja energetyczna Tauron współpracowała z AGH nad projektem reformy funkcjonującego systemu ciepłowniczego. Badanie to wprowadza myślenie o cyklu życia do wyników projektu, aby poszerzyć wymiary i odkryć cenne informacje. Poprzez ocenę właściwości paliw i produkcji kolektorów słonecznych stanowią gorącą strefę projektu. Poza tym analiza ekonomiczna potwierdza korzyści płynące z wdrażania odnawialnych źródeł energii w dłuższej perspektywie.

1. Introduction

In this chapter, status quo of heating in Poland is introduced, followed by introducing on life cycle thinking. In the end, detail about Greening the heating, a cooperative project operated by AGH and Tauron, is provided.

1.1. Heating in Poland

Our living environment is facing tremendous challenge from climate emergency, which affect billions of people on Earth. The emission of greenhouse gas has been regarded as one of the contributors to this crisis; hence, not only the local authorities, but also the Intergovernmental organizations attempt to come up with countermeasures.

Paris Agreement, an international treaty, sought to combat the climate change through designing targets. Because of significant difference among countries, content of Paris Agreement is more principal. [1] EU is more ambitious, having an eye on reducing greenhouse gas emissions. By 2030, there are several targets, including decreasing at least 40% of greenhouse gas emissions in comparison to 1990 level, boosting the share of renewables in final consumption at least 27%. Furthermore, greenhouse gas emissions should be even further reached 80-95% reduction compared to 1990 level. [2] In addition to that, EU also provide long-tern vision of heating sector, electrification and district heating system ought to be primary pilar of district heating system. [3]

Poland is the largest and second largest producers in hard coal and lignite, respectively. As a consequence, more than 4 million Polish households are heated by solid fuels. [4] President Andrzej Duda also claimed that "there is no plan today to fully give up on coal" in COP24 in Katowice, Poland. [5] After the breakdown of iron curtain, Poland experienced economic growth. Subsequently, the energy demand also went up. [6]

Poland is also second largest producer of districting heating among European countries, following Germany and total length of the system is over 2000 km. [4], [6] Districting heating system is expected to share the burden of heating in more eco-friendly approach. There are several advantages; for instance, it allows integration of multiple energy to diminish costs and environmental impacts.

Thermal storage is able to combine so that energy arbitrage, capacity deferral and distribution deferral become possible. [7] Despite of that, districting heating in Poland was primarily fueled by coal, accounting for 72.5%. It connives carbon emission to stay high. [4] World Energy Trilemma Index 2021 Report gave Poland "C" in environmental sustainability. Mainstream of electricity generation is lack of diversity and has high carbon emissions. Besides, since energy storage and efficiency of public sectors are expected to thrive, Poland is graded in "B" in Energy security. [8] Especially, after Russian invasion of Ukraine, natural gas become counters of Russia. Natural gas consumed in Poland mostly comes from Russia; in 2021, the percentage was up to 50%. [9] Polish fossil fuel reserves, hard coal and lignite, is a solution to urgent matter, whereas improving energy diversity and executing energy transition is the idea for good.

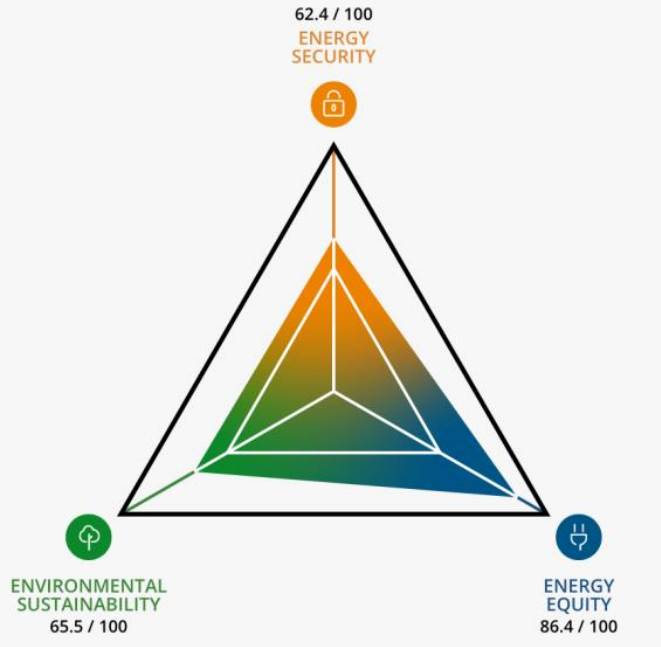


Figure 1 Polish profile in World Energy Trilemma Index 2021 *[8]*

With regard to economic conditions, 12% of the Polish population suffer from energy poverty, and 44% of them live in urban area. Furthermore, large scale districting heating systems have been proven to reduce the heating price in Poland. On the flip side, heat producers also encounter challenges. The price of heat from

coal is less competitive and deficits from heat generation comes up. [4] Moreover, modernization of the heating sectors becomes an urgent and critical issue.

1.2. Life Cycle Thinking

The concept of environmental protection is also evolved. Traditionally, governments confront risk and danger by command and control. Protection measures emphasize on production. Nonetheless, sustainability driven by society takes the place of existed notion, and the scope is not rigid in production processes. Processes shouldn't be single but integrated. In other words, the whole system, process network, is taken into consideration. Following the change of environmental protection concept, a new method is introduced for evaluation, life cycle assessment (LCA). [10]

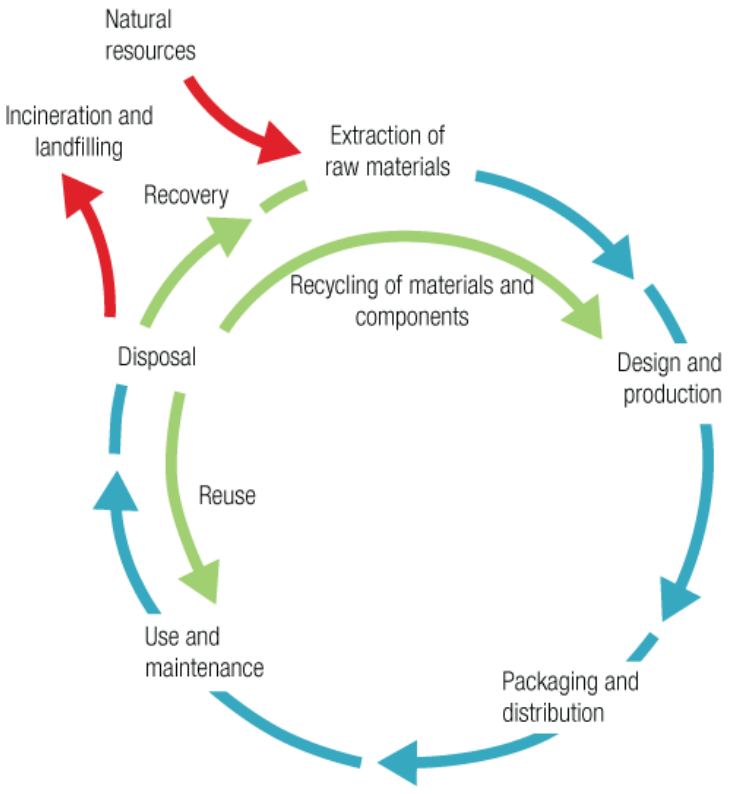


Figure 2 Concept of Life Cycle Thinking [11]

LCA is active in current society, because it takes all associated environmental impacts happened in life cycle into account, and it can be implemented on all kinds of products and services. Therefore, international standards, ISO 14040 and 14044, are ratified to formulize related activities. [10], [12] LCA results pinpoint the environmental effects and weak point of planned projects, offering exhaustive information for decision makers in planning, ongoing and completed phase. "Carbon footprint" and "water footprint" widely used recently are examples of applying life cycle concept, whereas they only reflect influence on ecology. That is to say, social reaction and financial concern also play an important role as environmental protection. As a consequence, life cycle costing (LCC) and social life cycle assessment (SLCA) are based on life cycle thing to harmonize with LCA to unveil more information in terms of momentary and social views.

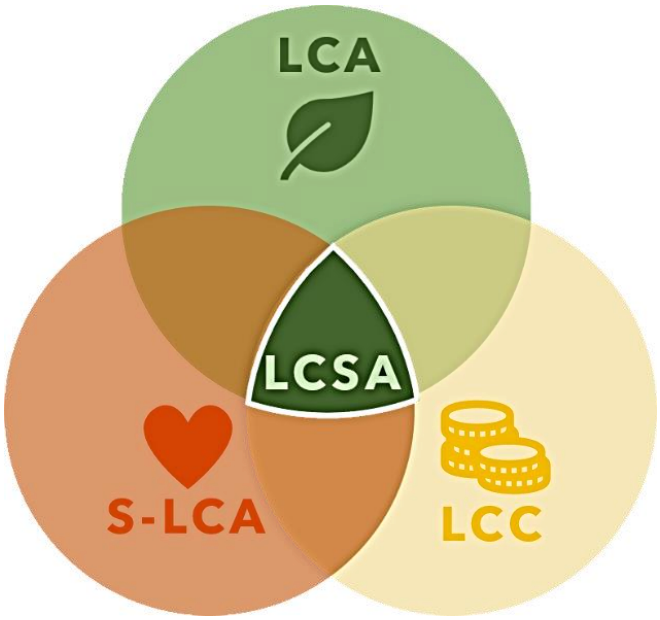


Figure 3 Composition of LCSA– LCA, LCA and S-LCA [13]

Doing energy transition is not excludable for future of Poland and the rest of world; as a consequence, some comprehensive research in energy and heating sectors have been carried out. LCA and LCC has also been employed in some studies.

Lelek et al. probed into heat and electricity generation in Poland via LCA approach. The concluded carbon emissions highly related to the fuel used in the sector, suggesting replacing increasing the share of renewables is one of keys to achieve GHG reduction. [14]

Paraschiv et al examined solar air heating system (SAHS) installed in a residential building in Romania in both technical and environmental aspects. They pointed out profitability is one critical point for investors to think over. [2]

Miro Ristimäki et al adopted life cycle management (LCM), combining life cycle assessment (LCA) and life cycle costs (LCC), to design residential district energy system in Finland. Heat pump and PV were considered in the study. Simulated results supported that cost and emission savings can be acquired with existed systems and investments lead to further enhanced. [15]

Jachura chose one single-family building fueled by a gas boiler, a heat pump in Czestochowa, Poland as analyzed target, to explore economic and ecological impacts. 11 % of financial saving can be acquired in a gas boiler compared to a heat pump. Heat pumps has negligible carbon emissions, whereas Polish electricity generation heavily relies on coal and fossil fuel. Therefore, taking energy generation into account makes heat pump less recommended. [16]

1.3. Greening of heating

Greening of heating is a collaborative project between Tauron Polska and AGH University of Science and Technology, which bridges industry and education institution. It offers pupils have a chance to handle issue from authentic world and gain beneficial experience. [17] Tauron is one of the major energy companies in Poland, operating in Lesser Poland, Silesian, Opole and Lower Silesian, southwestern part of Poland. Areas of activity include mining, producing, distribution, sales, etc. In other words, it covers vertical chain of energy industry. With the awareness of my living environment, energy company is expected to take more burdens and actions to break out of energy crisis. Tauron has reached 14.93% of renewables in their energy structure in 2021; in spite of that, coal and lignite accounted for 59.76% and 15.34%, respectively. [18] The aim of the

project is to attempt to revamp districting heating systems and contribute to long-run generation expansion planning.

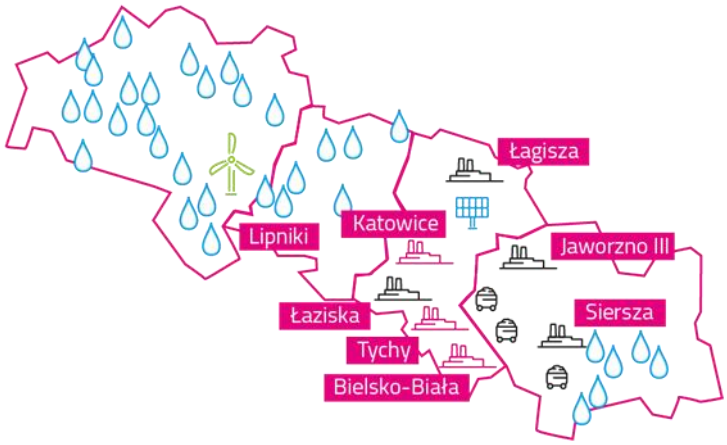


Figure 4 Production units of Tauron in southwestern Poland [18]

The proposed system composition includes large solar panels, a gas boiler, seasonal heat storage, which is far from being prevailing. Large flat solar panels integrated with seasonal storage system because of mismatch between peak season of energy usage and solar energy generation. Seasonal storage also enables to defer the transmission and distribution. Pit Thermal Energy Storage (PTES) tanks have the largest storage capacity, meeting the expectation of the project.

TIMES modelling tool gives insight into the optimized results of development and operation of district heating system through simulation. Two scenarios are set up, STAT and DYN. The distinguishment lies in price projection of gas and CO2—the former remains fixed, and the latter grows steadily. Useful heat and heat loss from solar collectors can be expounded from EU-JRC-PVGIS irradiance data. Thermal storage setup is calculated through water heat capacity.

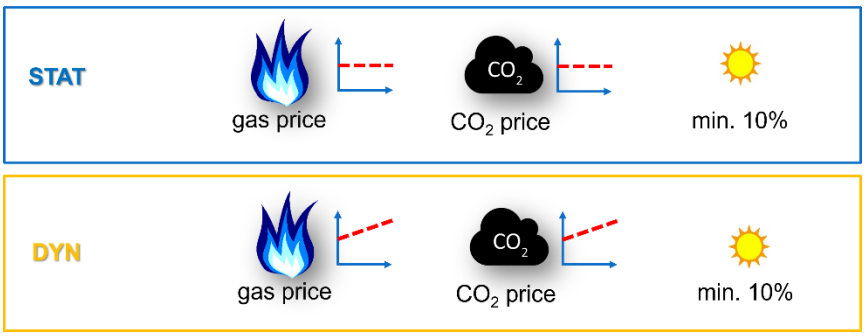


Figure 5 Distinguishment between STAT and DYN scenarios

The work fruitfully optimized size of solar collectors, gas boilers and heat storage systems. In other words, the optimal layout of entire system was acquired through TIMES model simulation. 20% of energy generation substituted by renewables reaches the crest of performance among different settings. On the other hand, regarding to heating costs, results in DYN had almost 1.5 folds higher than in STAT, 100 PLN/GJ and 62 PLN/GJ, respectively.

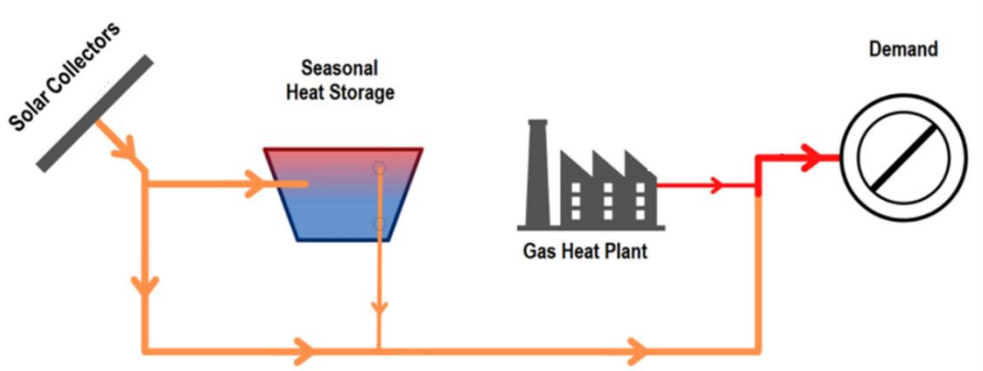


Figure 6 Layout of proposed system of Greening of heating

2. Aim and scope of the thesis

LCA and LCC have been extensively used to address issues in energy and heat sectors, whereas there is still a few research relating to Poland, showing potential for further development. This study is based on "Greening of heating", a collaborative project between Tauron and AGH. As a following research, life cycle concept is introduced to the project to offer another perspective and more information. As a result, this study is anticipated to bridge the gap in literature and to offer policymaker different vision in drawing up plans.

3. Methodology

This charter concentrates on the methodology adopted in this study, including the software, database, research method of performing LCA and LCC. The study attempts to discover the economic and environmental impacts from different heat source of district heating systems in Poland. It can be seen as extension of **Greening of heating**, which was done by my colleagues, illustrating the possibility of multiplying the source of district heating systems. The LCA and LCC analyses are conducted by openLCA equipped with selected database, Ecoinvent in version 371.

3.1. Software: GreenDelta and openLCA

GreenDelta is a consultancy and software developing company founded in Berlin, Germany in 2004, focusing on all services related to sustainability. In the former, they can offer enterprises, authorities, institutes practical suggestions to facilitate realization of sustainability. In the latter, several applications have been released, such as WARM for GHG emissions of waste management, CoEAT for food waste co-digestion, etc. [19]

Besides them, openLCA, iconic project of GreenDelta inaugurated from 2006, aims to trailblaze different application areas through coming up with LCA software. Nowadays, openLCA has a family of supporting software, like openLCA Nexus website (data repository), openLCA format converter (converting LCA data formats), Collaboration Server (enabling parallel collaboration). [19], [20]

openLCA is an open source freeware for LCA. This character allows users to access this product, share it with others and check the codes of system without any license cost, which means paywall barriers is demolished. openLCA also supports various data sets and databases, containing Ecoinvent, social hot spot, PSILCA, to name a few, bring significant convenience to users from different sectors of society, ranging from industry, consultancy, research and educational institutions. [20]

Figure 7 Surface of openLCA

With a flourish in evolution of life cycle concept, ecological effects are no longer the only indicators which the mass pay attention on. The concerns about economic and society rises correspondingly. Therefore, with continuous improvement of openLCA developers, LCSA become possible in openLCA. It refers to the social and economic aspects can be further expounded.

3.2. Database: Ecoinvent and Ecoinvent database

Ecoinvent, a NPO based in Switzerland, was created in 2013 as independent association by founding members coming from various institutions and laboratories. Furthermore, its history can be dated back to 1990s. At the moment, Ecoinvent was one project governed by Swiss Federal Institute of Technology (ETH), whose target was to create high-quality, consistent, transparent for sustainable assessment. After 25 years, Ecoinvent expanded from a project to an association, becoming a reliable partner and publisher of database named after the organization. Some countries have developed collaborative partnerships with them, including Brazil, Belgium, France, etc. [21]

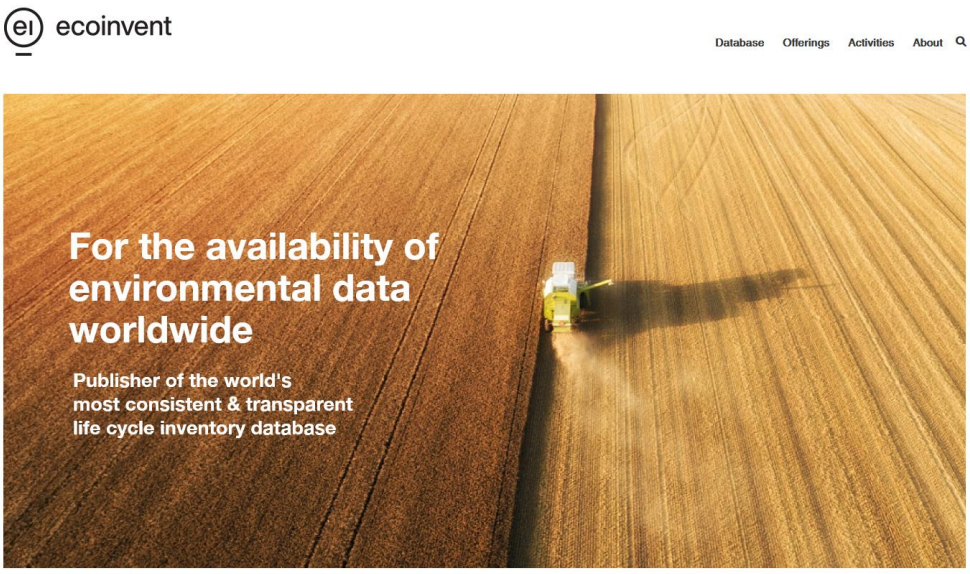


Figure 8 Official website of Ecoinvent [21]

Ecoinvent have dedicate themselves to publish excellent data for sustainable assessment. As mentioned in above paragraph, Ecoinvent database, administered by themselves, is one of the most popular databases in the world. In the latter of 2000s, it has been most commonly used database around the world. Ecoinvent database encloses over 18000 to formulize human activities and behaviors, comprising all around industries— such as energy, construction, metals, transportation, waste treatments, etc. [21] A myriad of activities is also collected, containing market, service, construction and operation.

The latest version of the database, Ecoinvent 3, was released in 2013, which broadened the geographic scope from Europe to other corners of the world. [21] In order to respond to rising global popularity of LCA, regional difference must be considered during the practicing LCA. Currently, the data are labelled as global, Europe, rest of the world.

Activities related to certain product or service are systematical and complex. However, model setting is the main pillar of database. There are three key concepts in life cycle thinking–subdivision, allocation and substitution. In the latest version, Ecoinvent 3, three different approaches are employed— "Allocation cut-off by classification" (cutoff), Allocation at the Point of Substitution (APOS) and

Substitution, consequential, long-term (Consequential). The difference between cutoff and APOS happens in how to address the pollutants— the former believes the responsibilities belong to polluters; on the other hand, all stakeholders involved in processes should take the burden mutually. In Consequential model, based on substitution principle, unnecessary burdens from the supply side are tackled by by-products generation. Additionally, the model can be used for projection of future changes. In this research, Consequential model is adopted, because it is in correspondence with the aim of in this research, results can give insight into future planning.

3.3. Research method

3.3.1. Scenario

The study continues Tauron project with its results. In an effort to reach the goal, several scenarios were examined. The first one is the recommended result in STAT scenario, 20% solar energy harmony with natural gas plant. As mentioned in introduction, using coal power is thorny and urgent issue in Poland. Hence, in another scenario, energy generation is from utilizing hard coal under same technical parameter settings. Besides that, 20% solar energy integrated with coal power is replaced by coal plant. Finally, the excavation activity is taken into account, which was excluded in Tauron project. The key distinguishments are listed in following table.

Table 1 Setup of scenarios

Scenario	Heat source	Seasonal Storge	excavation
I	Solar + Gas	Y	Y
II	Solar + Gas	Y	N
III	Solar + Coal	Y	Y
IV	Solar + Coal	Y	N
V	Coal	N	N

3.3.2. Parameter

Functional unit is served as the reference basis for calculation; in other words, it standardized quantitative results to make comparison possible. Based on the outcomes of Greening the heating, it is 1TJ of energy.

The chapter ahead briefly brings layout of Greening the heating up, whose further details are displayed below. In life cycle simulation, some critical parameters are picked up, including the area of solar collectors (1.2 km^2), output of solar collectors (1728 TJ), output of gas heat plant (6912 TJ). Apart from information on figure below, tank size is 0.2 km^2, and excavation volume is 1.2 times as tank size.

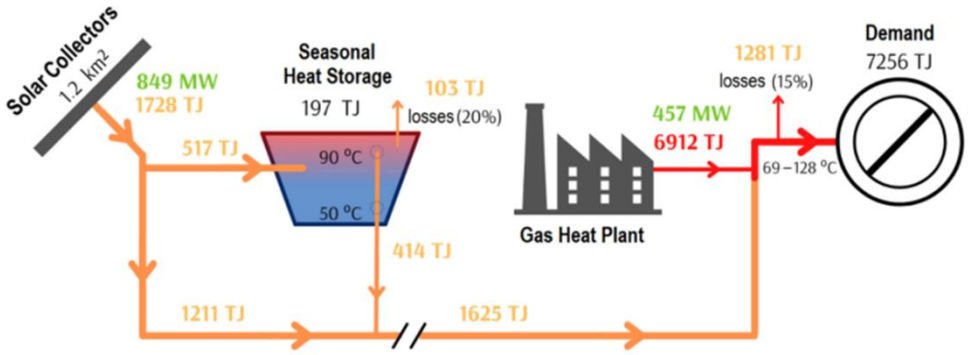


Figure 9 Detailed proposed system of Greening of heating

3.3.3. System boundary

The boundaries of analysis are defined as four stages— product phase, construction phase, use phase and end-of-life phase. Product phase is about acquiring the infrastructure involved in the projects, containing raw material extraction from earth, manufacturing of equipment, such as solar panels, water tanks, etc. Construction phase is associated with setting up and installing infrastructure, ranging from solar collector, coal planet, water tank for seasonal storage, etc. Operation and maintenance belong to the third stage, user phase.

After the designed lifespan, waste treatment and disposal are carried out, which are under the last categories.

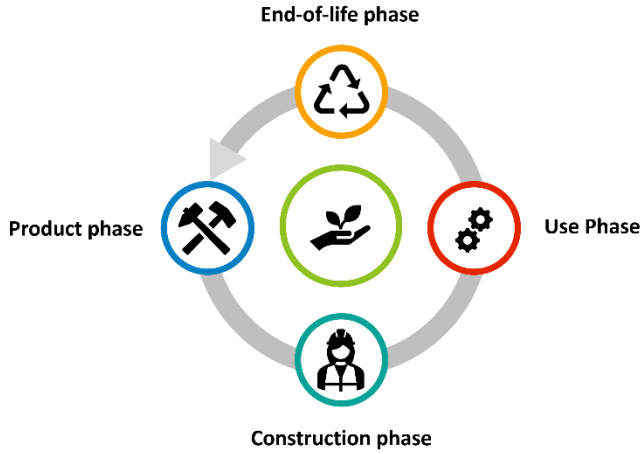


Figure 10 Boundaries of analysis

3.3.4. Impact indicator

Impact indicators are critical in LCA, since they comprise of hydrosphere, lithosphere, atmosphere and interactions. As a matter of fact, they enable us to have insight into the analyzed target. Our goal is to understand the influence from energy and heat generation. As a consequence, 8 relevant indicators are chosen to reveal the info— climate change (GWP100), fossil depletion (FDP), freshwater eutrophication (FEP), water depletion (WDP), natural land transformation (NLTP), terrestrial acidification (TAP100), particulate matter formation (PMFP), photochemical oxidant formation (POFP). The further information of indicators is manifested in following table.

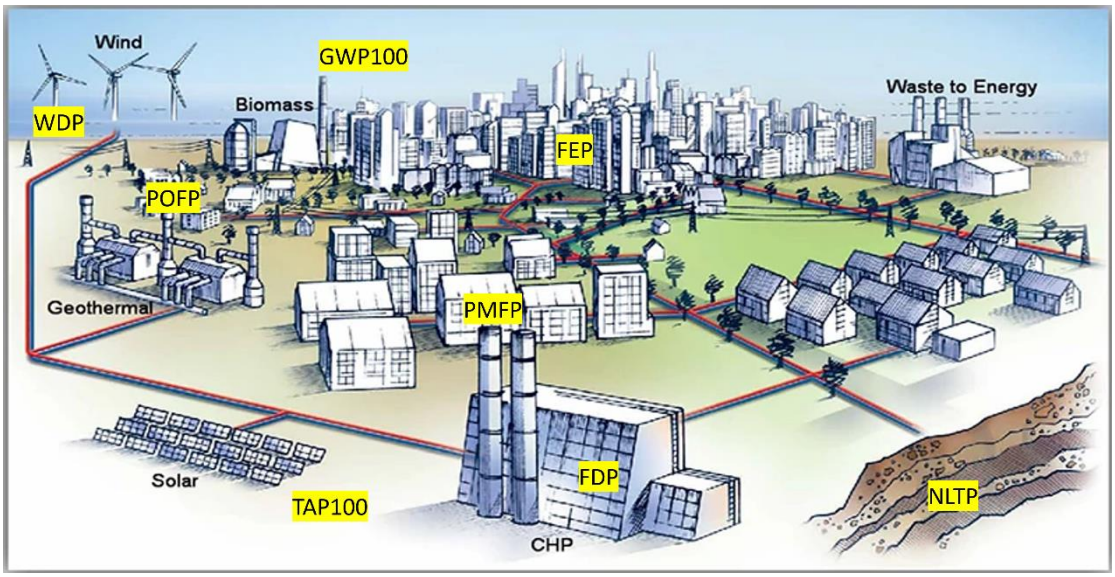


Figure 11 Selected indicators in the studies [22]

Table 2 Indicator categories and their units

Indicator	Unit
climate change - GWP100	kg CO2-Eq
fossil depletion - FDP	kg oil-Eq
freshwater eutrophication - FEP	kg P-Eq
water depletion - WDP	m3
natural land transformation - NLTP	m2
terrestrial acidification - TAP100	kg SO2-Eq
particulate matter formation - PMFP	kg PM10-Eq
photochemical oxidant formation - POFP	kg NMVOC

3.3.5. Economic index

When it comes to economic analysis, the importance of economic index is same as impact indicator. With the help of openLCA and Ecoinvent database, some indexes can be calculated. Net cost is chosen for measurement, whose meaning can be comprehended literally— the costs spent during the process.

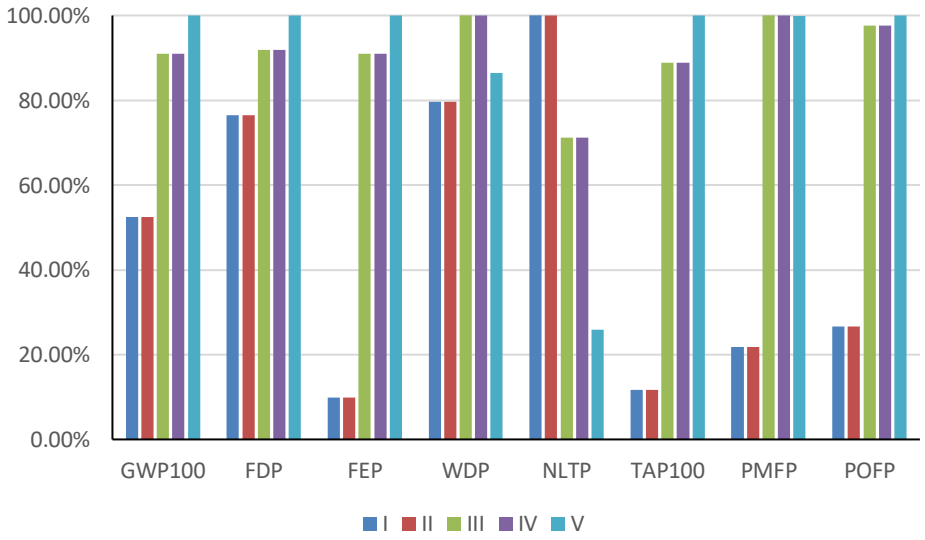
4. Result and discussion

In this chapter, life cycle simulation results are demonstrated and expounded. Initially, an overview of all impact categories is disclosed, followed by introduction to particular indicator. In the end, economic data are also embedded.

4.1. LCA: overview

Life cycle indicator results are listed in table and charts below. Generally, they follow the rule of thumb, coal is more less eco-friendly, and has positive correlation with environmental impacts. Thus, integrating renewables or utilizing natural gas can alleviate the impacts on environment. However, in some indexes, like NILTP and WDP, scenario V doesn't sink to the bottom. Apart from the heating source, excavation activity for seasonal storage tank is first time brought in discussion. Based on the results, there is no significant difference existed.

(a)



(b)

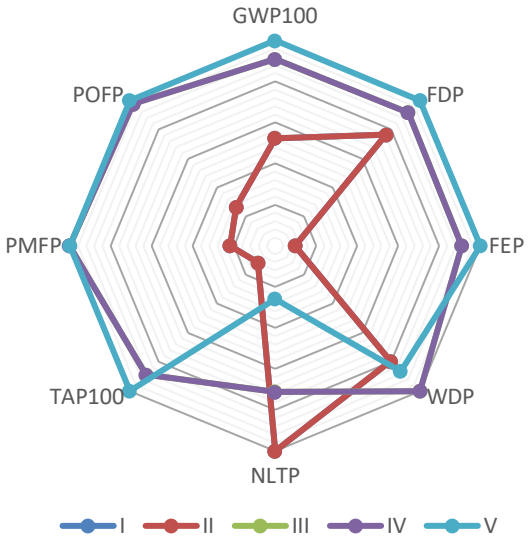


Figure 12 Relative LCA results (a) bar chart (b) radar chart

Table 3 LCA result table

Index	Scenario					Unit
	I	II	III	IV	V	
GWP100	160294.00	160309.00	278044.00	278059.00	305785.00	kg CO2-Eq
FDP	61074.00	61079.30	73284.20	73289.60	79811.80	kg oil-Eq
FEP	21.40	21.40	197.18	197.18	216.85	kg P-Eq
WDP	656.03	656.03	824.41	824.41	712.38	m3
NLTP	26.32	26.33	18.73	18.74	6.80	m2
TAP100	260.17	260.28	1987.01	1987.12	2237.58	kg SO2-Eq
PMFP	142.25	142.31	651.80	651.86	650.99	kg PM10-Eq

POFP	269.49	269.69	986.26	986.46	1010.52	kg NMVOC

For following discussion, 8 indicators are divided into 4 different groups, which are climate, water, land and air. The composition is shown in table below.

Table 4 Group composition of indicators

Theme	Indicator	
Climate	GWP100	FDP
Water	FEP	WDP
Land	NLTP	TAP100
Air	PMFP	POFP

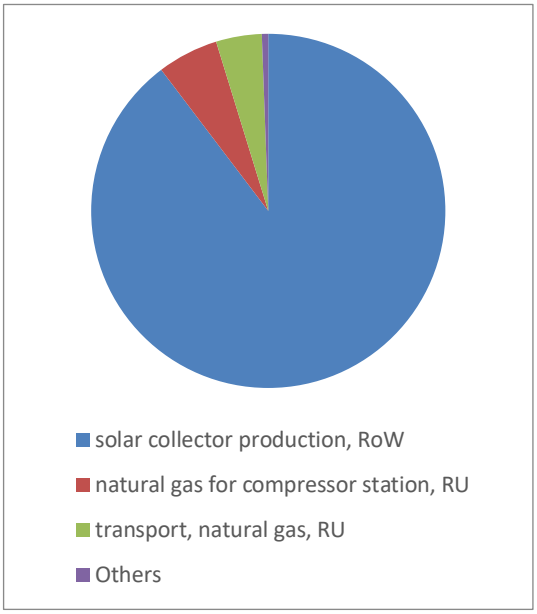
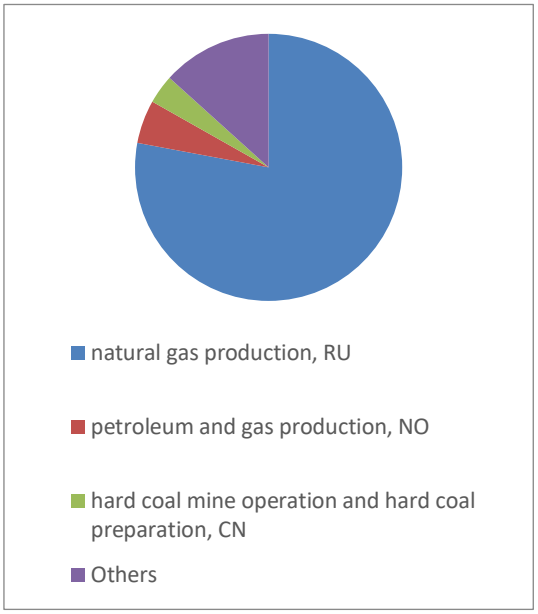
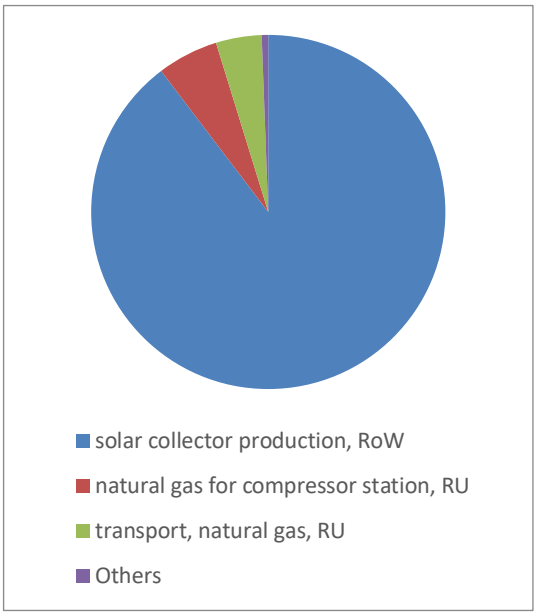
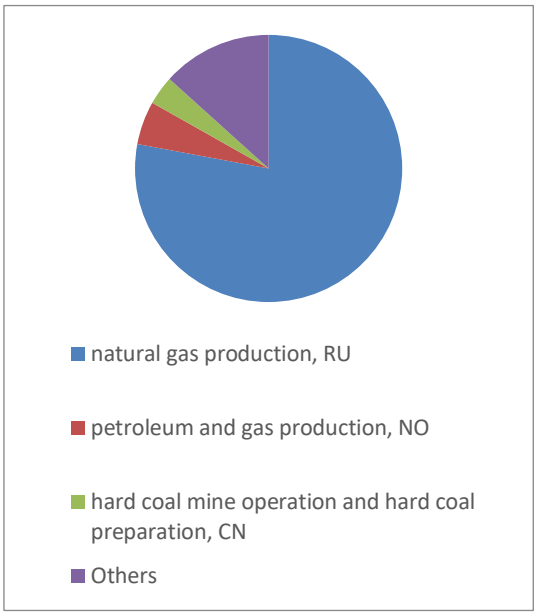
4.2. LCA: impact analysis

4.2.1. Climate

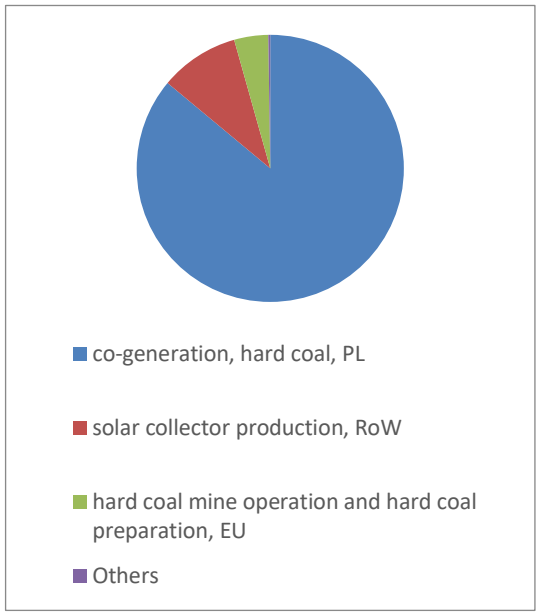
It goes without saying that fossil fuels have high correlation with climate emergency. GWP 100 can make projections on GHG's cumulative chronic effects on global climate, and fossil fuel depletion is related to its usage.

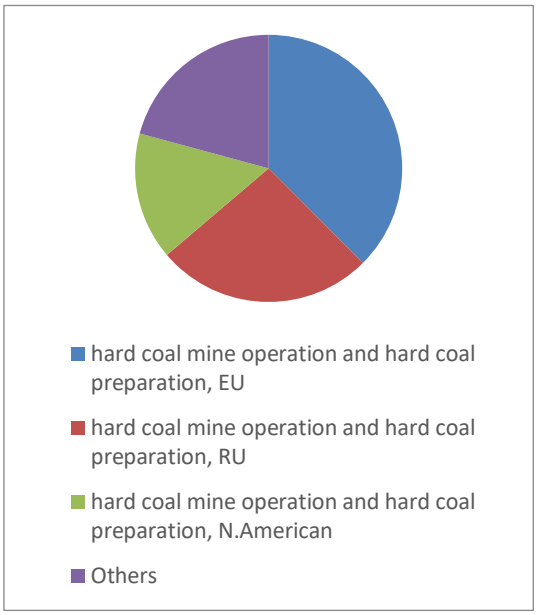
Without a surprise, S5, heating coming from coal entirely, received the worst score for this division. The score goes down with decreasing coal proportion. Once the fuel is shifted to natural gas, the condition can be further enhanced.

Generation of heat and energy is the main contributor, as well as solar panel production. Solar energy is placed high hopes to combat climate emergency, owing to its slight environment effects. Nonetheless, the center of solar energy, solar panels exist concern in production, which is still one of bottleneck to break through. One interesting fact is that coal is not the main energy source of S1 and S2; however, hard coal mining and preparation is still found on contributor list. It gives expression to the importance of life cycle thinking. The sustainability should take all phases into consideration.

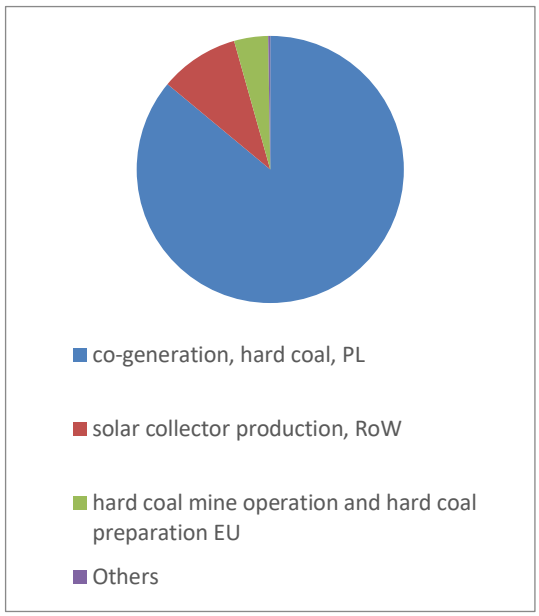
	GWP 100	FDP
I		
II		

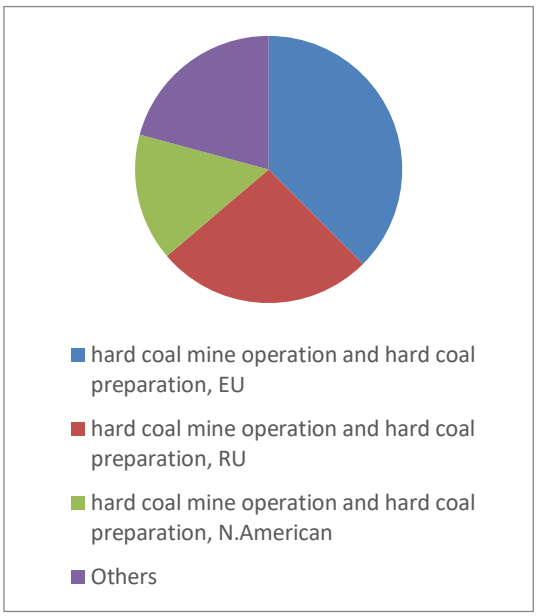
III


co-generation, hard coal, PL
solar collector production, RoW
hard coal mine operation and hard coal preparation, EU
Others


hard coal mine operation and hard coal preparation, EU
hard coal mine operation and hard coal preparation, RU
hard coal mine operation and hard coal preparation, N.American
Others

IV


co-generation, hard coal, PL
solar collector production, RoW
hard coal mine operation and hard coal preparation EU
Others


hard coal mine operation and hard coal preparation, EU
hard coal mine operation and hard coal preparation, RU
hard coal mine operation and hard coal preparation, N.American
Others

V

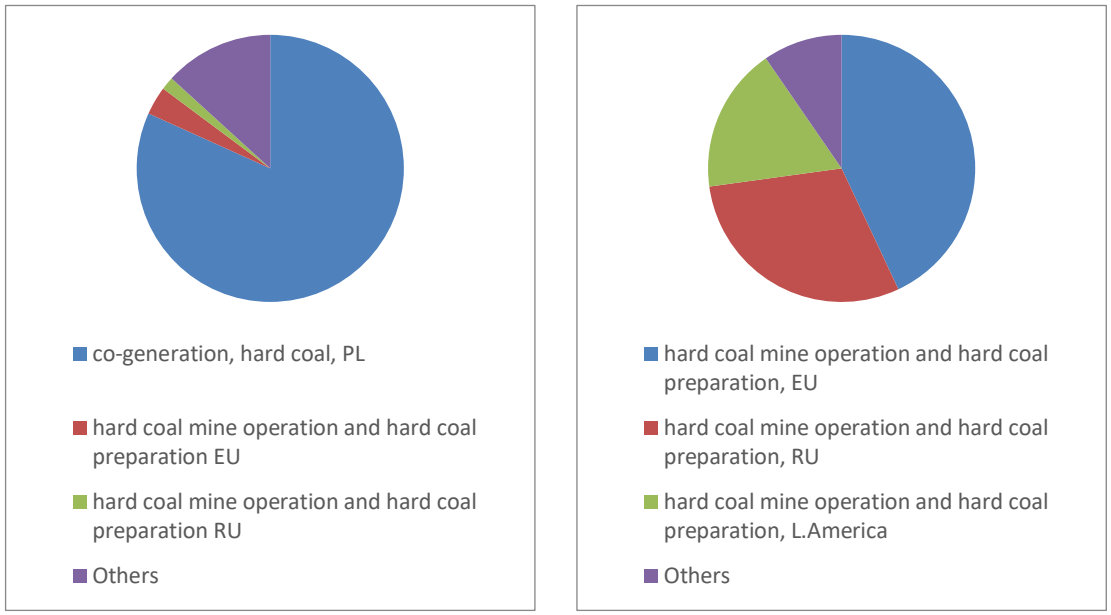
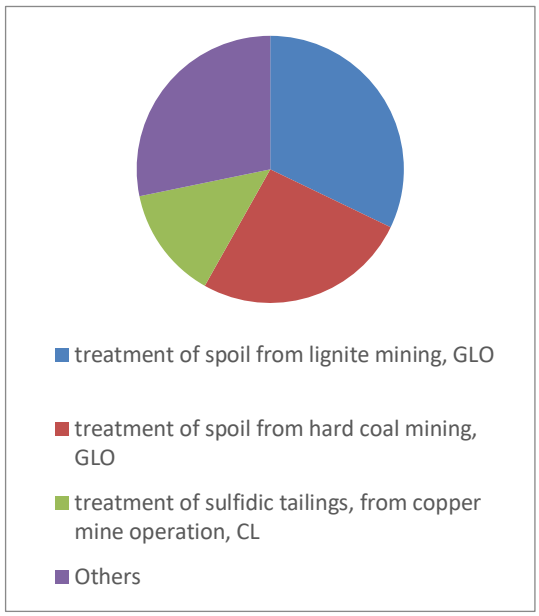
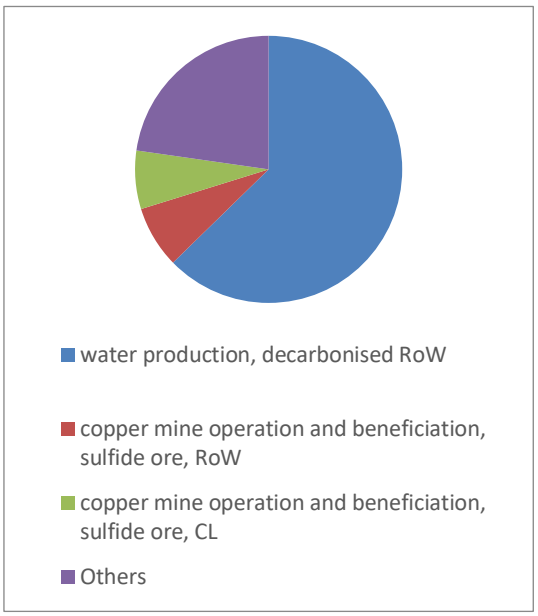
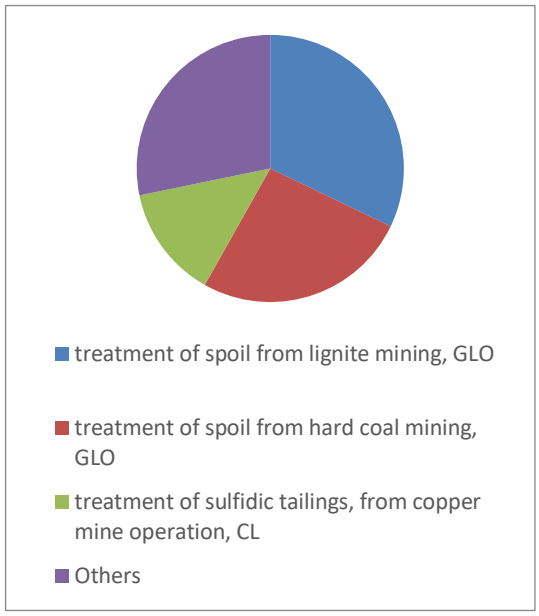
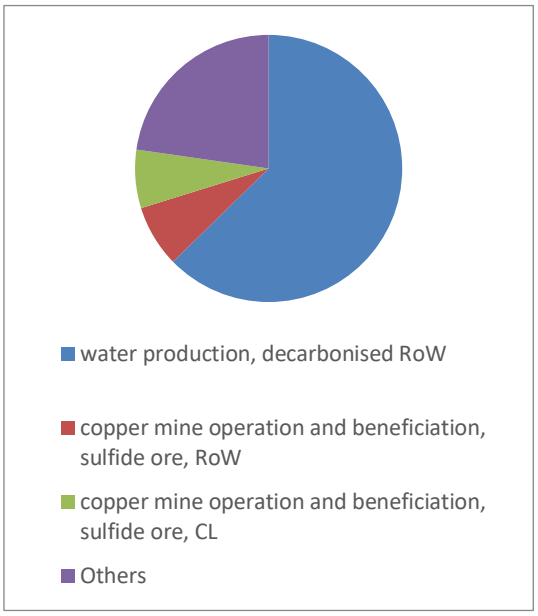


Figure 13 Pie charts of climate impact indicators

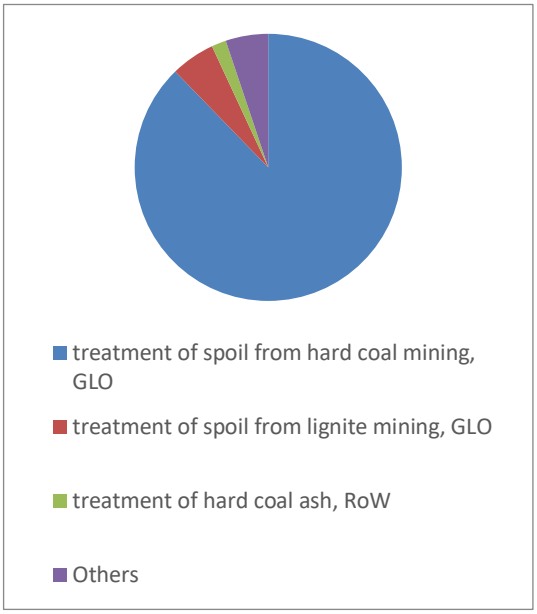
4.2.2. Water

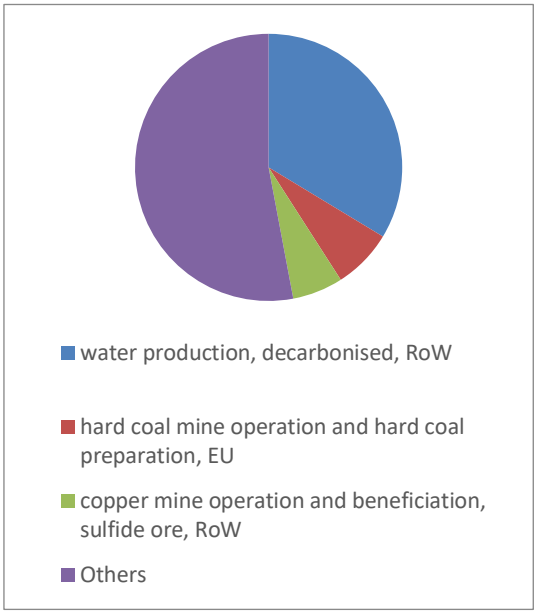
Over 70% of the Earth is covered by water, and water is essential compound for us. Water is circulated continuously, while the quantity of fresh water faces an ordeal. FEP and WDP can measure the influence on water in this study— FEP can tell the circumstance when chemical with nitrogen or phosphorus discharged into water body; WDP gives water usage during project operation.

The result of FEP reflects the difference between coal and natural gas. Since coal is richer in nitrogen, the higher contribution to eutrophication can be expected. Regarding to WDP, unique outcomes are granted. The sequence of WDP index is S3&S4, S5, S1&S2, which refers to all coal group is better than the combination of coal and solar panels. When we look into the contributors, water production and copper mine operation and beneficiation have critical effect here. They may have something with solar panels either in production or operation.

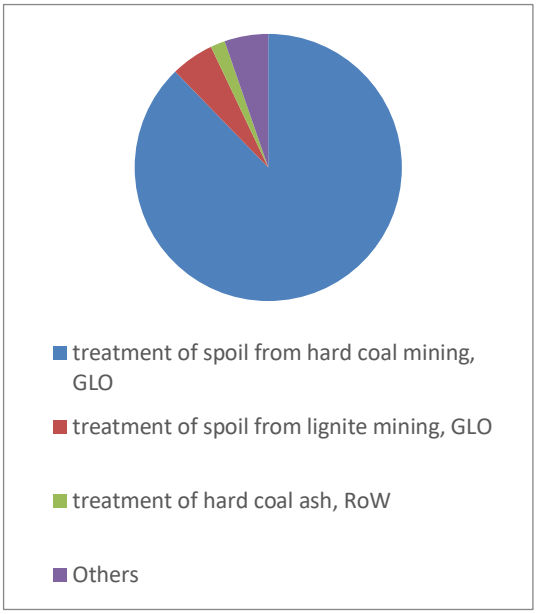
	FEP	WDP
I	 treatment of spoil from lignite mining, GLO treatment of spoil from hard coal mining, GLO treatment of sulfidic tailings, from copper mine operation, CL Others	 water production, decarbonised RoW copper mine operation and beneficiation, sulfide ore, RoW copper mine operation and beneficiation, sulfide ore, CL Others
II	 treatment of spoil from lignite mining, GLO treatment of spoil from hard coal mining, GLO treatment of sulfidic tailings, from copper mine operation, CL Others	 water production, decarbonised RoW copper mine operation and beneficiation, sulfide ore, RoW copper mine operation and beneficiation, sulfide ore, CL Others

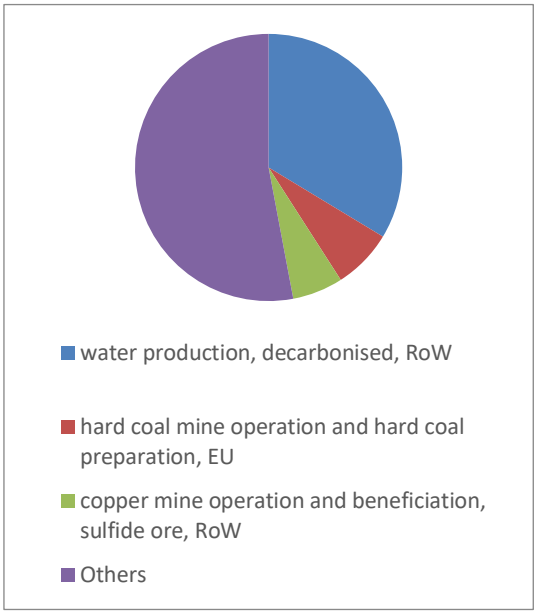
III


treatment of spoil from hard coal mining, GLO
treatment of spoil from lignite mining, GLO
treatment of hard coal ash, RoW
Others


water production, decarbonised, RoW
hard coal mine operation and hard coal preparation, EU
copper mine operation and beneficiation, sulfide ore, RoW
Others

IV


treatment of spoil from hard coal mining, GLO
treatment of spoil from lignite mining, GLO
treatment of hard coal ash, RoW
Others


water production, decarbonised, RoW
hard coal mine operation and hard coal preparation, EU
copper mine operation and beneficiation, sulfide ore, RoW
Others

V

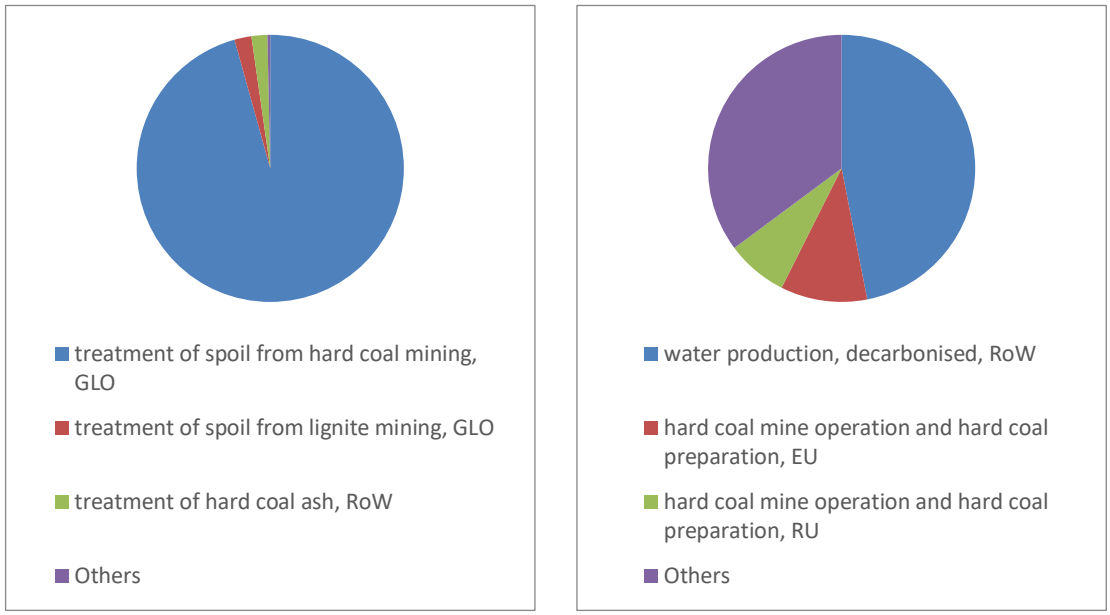


Figure 14 Pie charts of water impact indicators

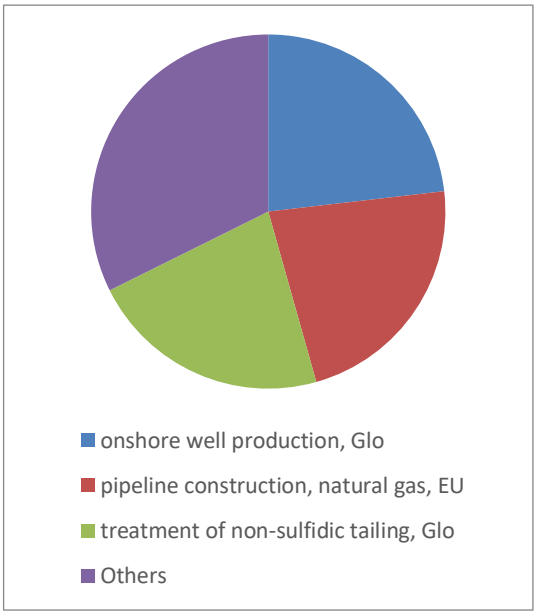
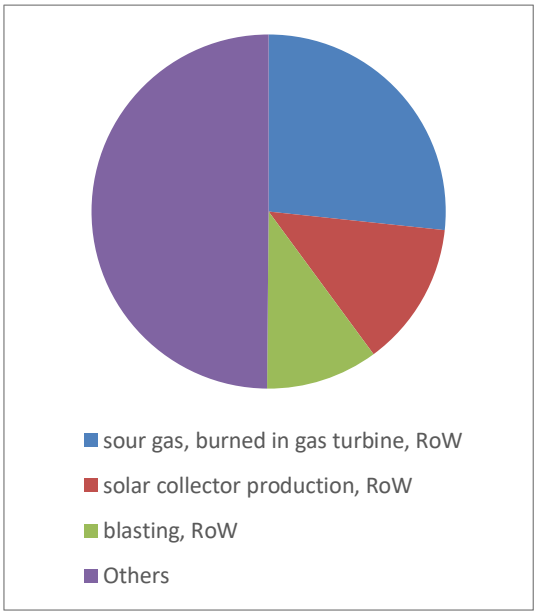
4.2.3. Soil

Human being is one of terrestrial animals; accordingly, soil is indispensable for our lives. However, soil is under the threat of human activities. In this situation, NLTP and TAP100 are chosen to unveil the influence. Our project requires broad area, which has been justified. Therefore, it is likely to transform natural land. Furthermore, the exhausted gas from energy and heat generation is likely to reach soils via precipitation.

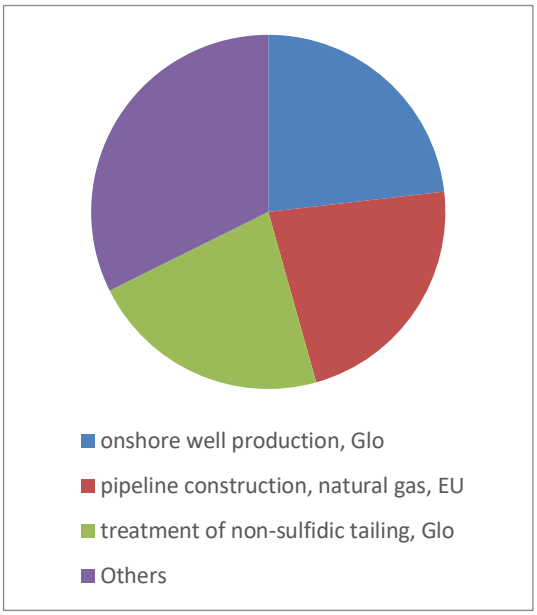
The outcome of NLTP reveals different picture, S5 occurs least natural land transformation. Moreover, natural gas is less friendly than coal. The potential reason is properties of the fuels; that is to say, the difference between solid fuel and gas fuel. Moving to TAP100, the tendency is similar to FEP. Coal can generate more acidic substances than natural gas. When the composition of coal usage is changed, moving from S5 to S3, 20% of reduction on coal can lower the TAP100 value by 10%.

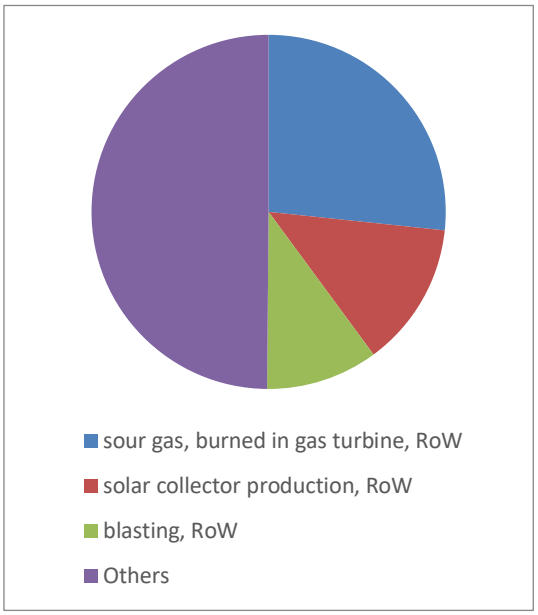
Concerning the contributors, in NLTP, there is no absolute majority existed. In the meantime, most activities are related to infrastructure, such as well production, pipeline construction, mine construction. Nevertheless, the condition

in TAP100 is another story. Following the statement in last paragraph, the leading role belongs to energy generation by gas or coal. There is one point worth paying attention, solar panel production appears to the ranking once again. Although the ratios in different scenarios made up 7-13%, it still has a room for further improvement.

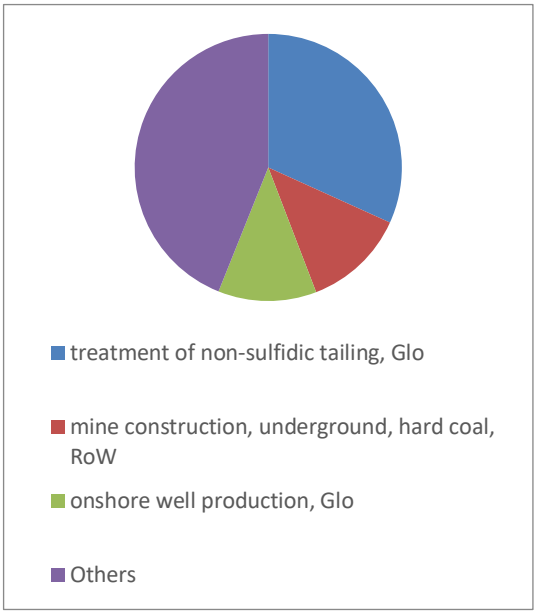
	NLTP	TAP100
I		

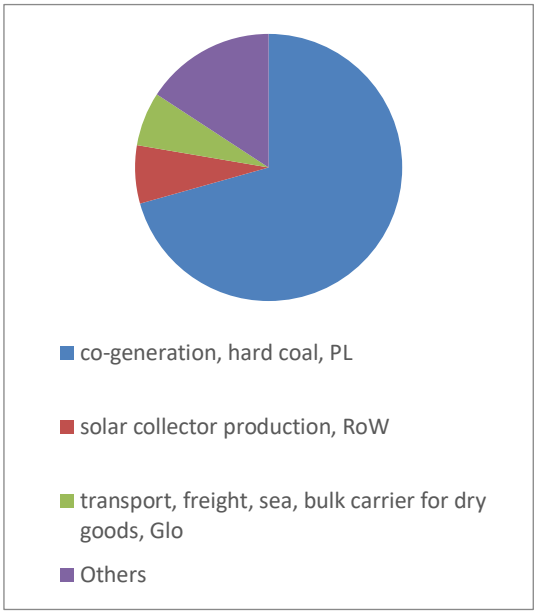
II


onshore well production, Glo
pipeline construction, natural gas, EU
treatment of non-sulfidic tailing, Glo
Others


sour gas, burned in gas turbine, RoW
solar collector production, RoW
blasting, RoW
Others

III


treatment of non-sulfidic tailing, Glo
mine construction, underground, hard coal, RoW
onshore well production, Glo
Others


co-generation, hard coal, PL
solar collector production, RoW
transport, freight, sea, bulk carrier for dry goods, Glo
Others

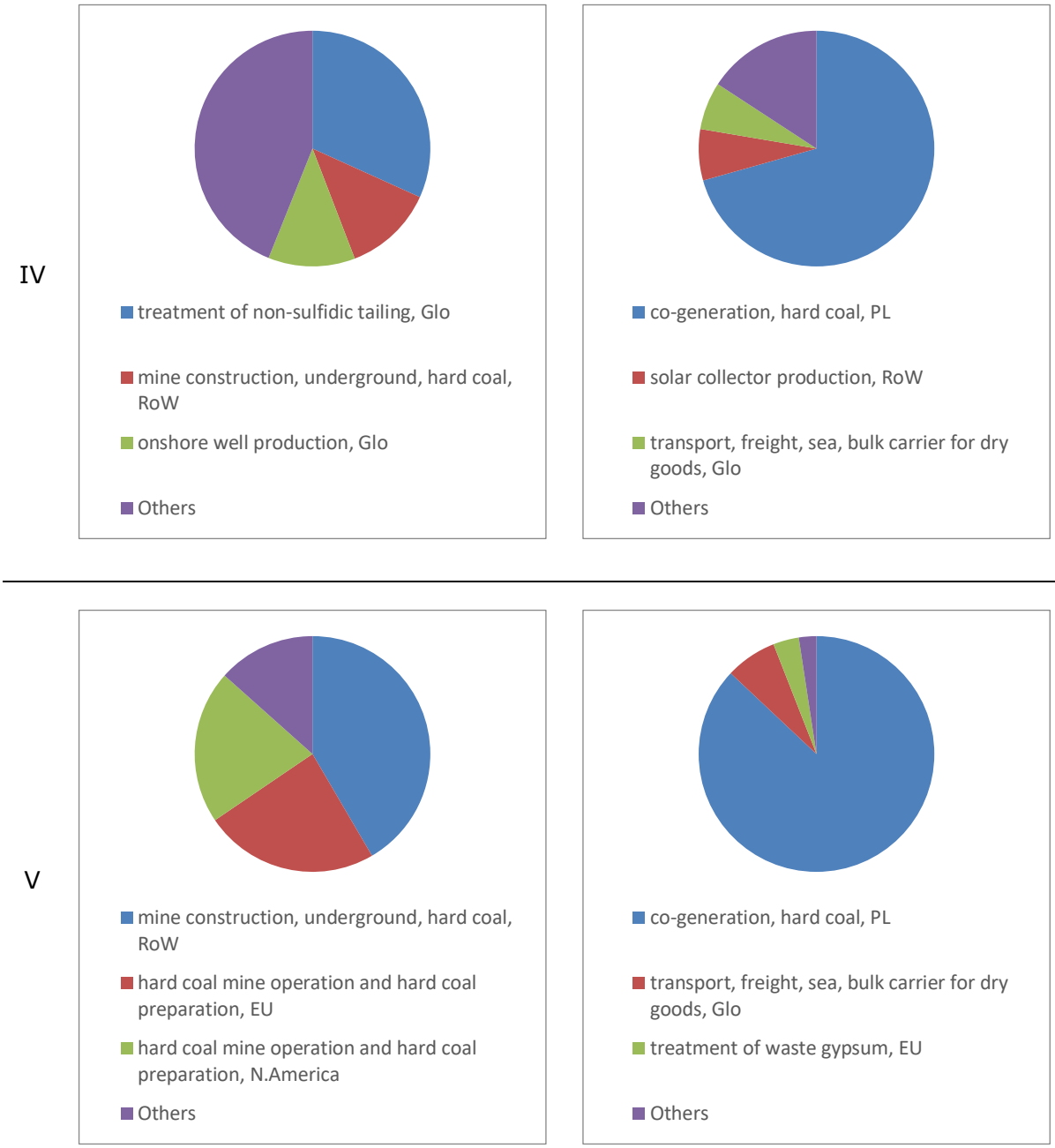


Figure 15 Pie charts of soil impact indicators

4.2.4. Air

Owing to resilience on fossil fuels, especially on coal, air pollution is one of primary environmental pollution in Poland. Therefore, two indicators, PMFP and POFP, are employed to assess air quality. The former corresponds to nitrogen

oxides (NOx) and volatile organic compounds (VOC), and the latter represents particulate matters, having close relationship with coal.

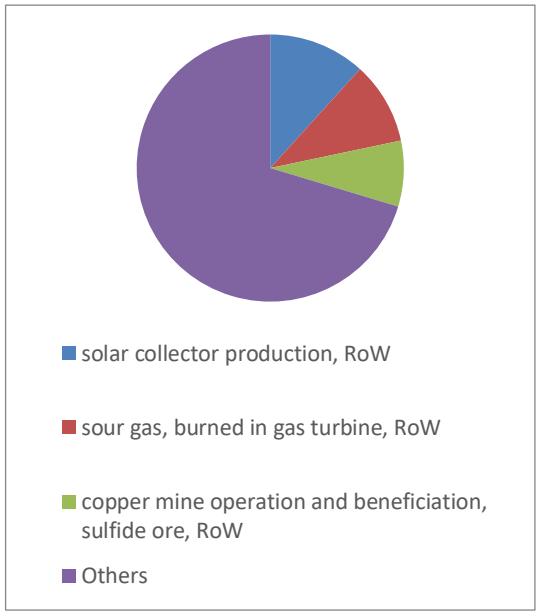
For both indexes, as previous genre, S5 has highest environmental impacts among all. However, for S3 and S4, coal partially replaced by solar panels, have almost the same contribution to the environment. S1 and S2 have the best performance, which only account for around 22% and 27% in PMFP and POFP, respectively.

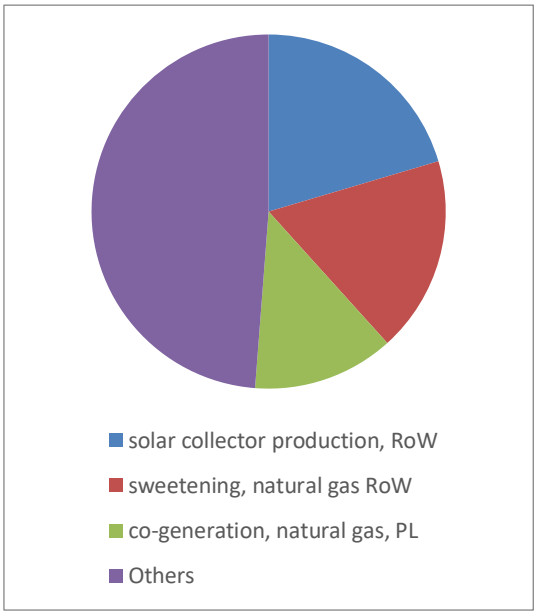
Hard coal is the black sheep in S3, S4 and S5 without a doubt. On the other hand, generation from gas reach the third place in S1 and S2. Despite of that, it reduces particulate matters effectively. Solar panel production has been proved as one of the roots of problems. Based on simulation, solar panel production contributes accounts for 12% in PMEP and 13% in POFP, which make itself in leading position.

Besides, sweetening in natural gas power plant and coal transport can’t be ignore, since sweetening is only behind solar panel production and coal transport made up 11-13% in last three scenarios.

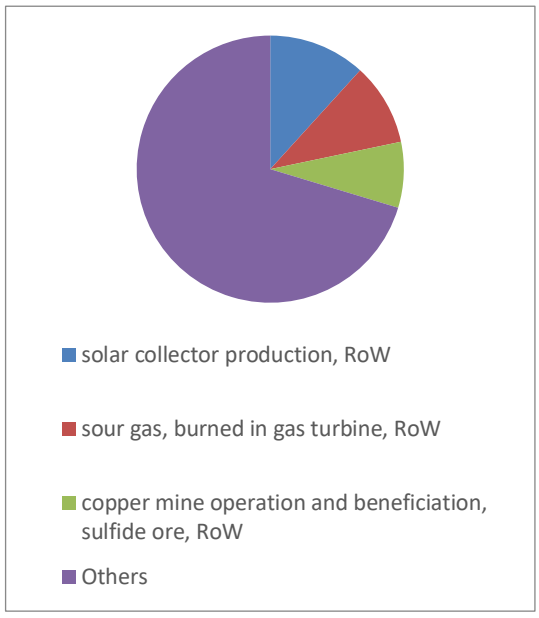
PMEP	POFP

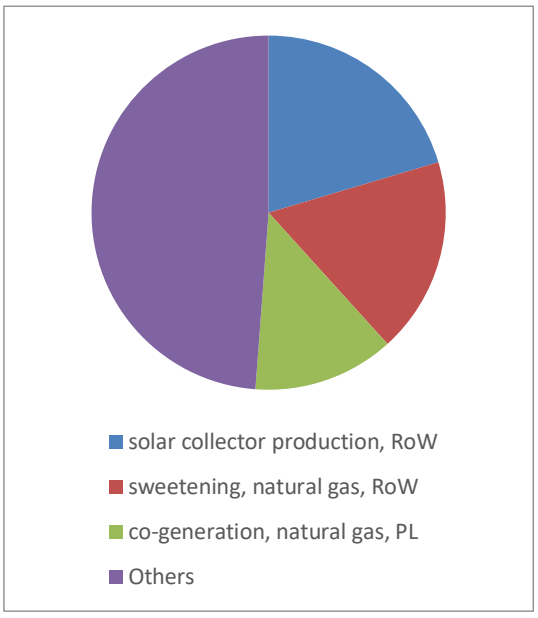
I


solar collector production, RoW
sour gas, burned in gas turbine, RoW
copper mine operation and beneficiation, sulfide ore, RoW
Others

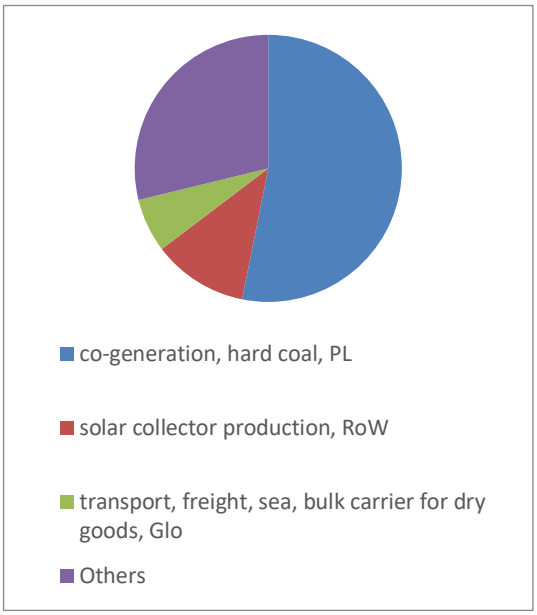

solar collector production, RoW
sweetening, natural gas RoW
co-generation, natural gas, PL
Others

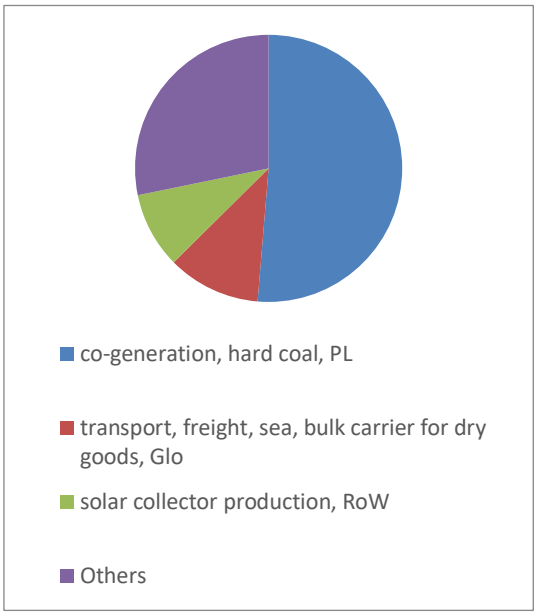
II


solar collector production, RoW
sour gas, burned in gas turbine, RoW
copper mine operation and beneficiation, sulfide ore, RoW
Others

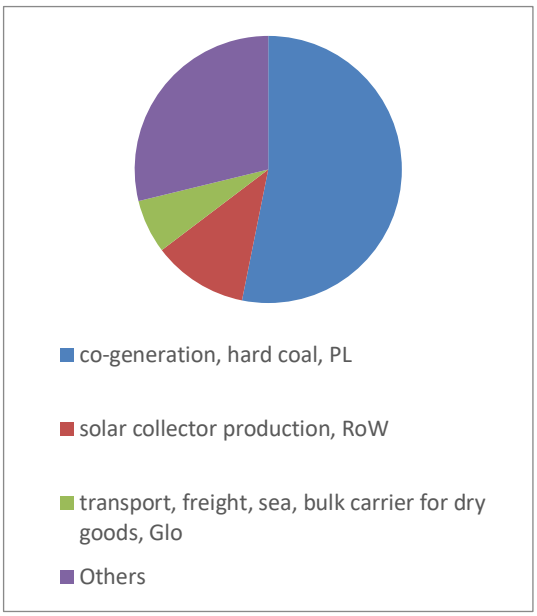

solar collector production, RoW
sweetening, natural gas, RoW
co-generation, natural gas, PL
Others

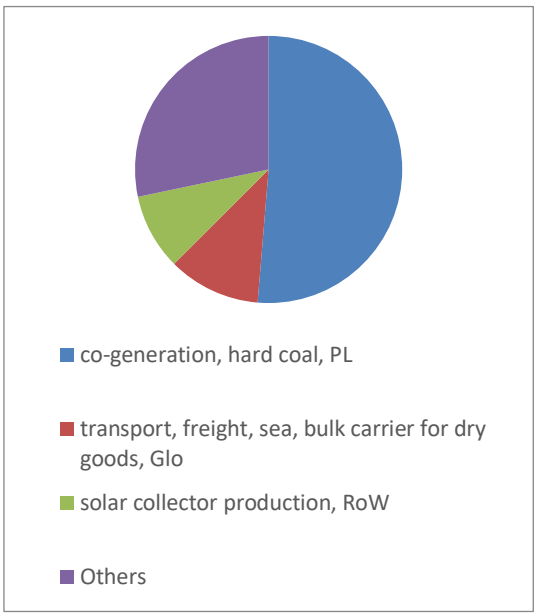
III


co-generation, hard coal, PL
solar collector production, RoW
transport, freight, sea, bulk carrier for dry goods, Glo
Others


co-generation, hard coal, PL
transport, freight, sea, bulk carrier for dry goods, Glo
solar collector production, RoW
Others

IV


co-generation, hard coal, PL
solar collector production, RoW
transport, freight, sea, bulk carrier for dry goods, Glo
Others


co-generation, hard coal, PL
transport, freight, sea, bulk carrier for dry goods, Glo
solar collector production, RoW
Others

V

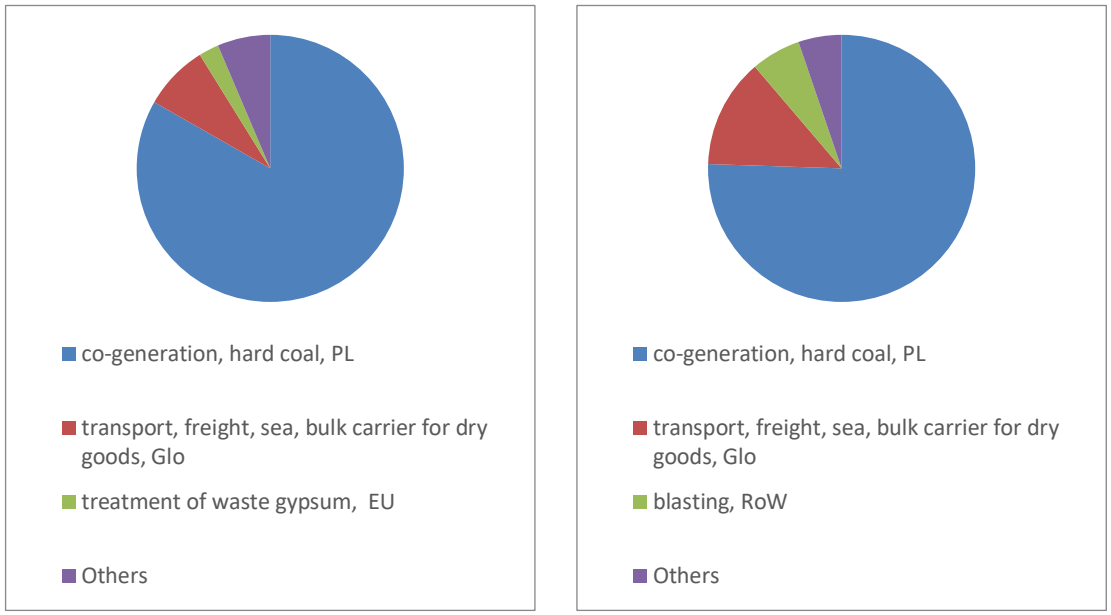


Figure 16 Pie charts of air impact indicators

4.3. LCC

Net costs of 5 scenarios are shown in Table below. From this table, it's easy to realize the benefits of energy transition. S1 and S2, most sustainable among all in LCA, crest in the rankings. It happens that there is a similar case. S5 falls to the bottom owing to its worst outcome.

Table 5 results of net costs

	Net cost
I	-121295
II	-121309
III	-1001930
IV	-1001940
V	-1039300

Following the same approach in LCA, it starts from figuring out the contributors. The five scenarios are spilt into two sides based on the fuel they use. For S1 and S2, fueled by natural gas, energy generation and local emission

requirement hold the majority. On the contrary, for S3-S5, local emission requirement is not as important as in former scenarios, and electricity production matters in their cost structures.

5. Conclusion

The iron curtain has fallen down for more than 30 years, Poland becomes a thriving country. However, the road of Polish energy transition is long and bumpy. In recent years, with rising awareness of environment, the condition gradually changes.

Staring from Greening to this research, the results of this study unveil more messages of original project, Greening the heating, clearly indicating the significance of solar panel production and co-generation in life cycle. In addition, market tools are efficacious to increase the cost of life cycle, implying the feasibility of altering behaviors in markets.

Energy policy can cause chronic and wide influence on society. Consequently, detailed assessment is necessary. However, the ball is still in decision makers' court. The crucial global annual meeting targeting on climate issues, COP 27, was taken placed in Egypt in November this year. Before the opening, United Nations Secretary-General António Guterres expressed his concern. He pointed out the inadequate progress since COP26 in Glasgow and insufficient efforts coming from greenwashing, fake movers or late movers. He also reminded that we already have straightforward suggestions, but we need to take immediate actions before it becomes too late. [23]

6. Future work

This work validates the results of previous work, Greening of heating, can reduce the negative externality during energy generation of fossil fuel, provide more information to look into the black box. A feasible solution can be taken into account. Despite of that, it is believed that there is still a room for further improvement.

First, there is two scenarios in Greening of heating project, SYN and DYN. However, only SYN scenario is investigated in this study. DYN Scenario can be taken into consideration.

Second, using first-hand data is always am merit for exercising LCA and LCC. Indeed, database is filled with a myriad of well-constructed data and information, some of which even have taken regional differences into account. However, LCA and LCC should be tailor designed to analyzed goods or services. This is to say, more first-hand information employed in simulations can significantly enhance precision and accuracy of results.

Third, although impacts of excavation behavior are not magnificent, whereas using out-of-use landfills may be a promising idea. It can revitalize the area with greener approach. Undoubtedly, a thorough assessment is indispensable.

Fourth, every long-term planning faces the same problem— uncertainty. In recent years, our living environment is experiencing black swan and gray rhino, pandemic of COVID and Russian invasion of Ukraine. Fluctuation and recession can be detected in global markets. Hence, even detailed research is necessary.

7. References

[1] United Nations Environment Programme, *The Emissions Gap Report 2017: A UN Environment Synthesis Report*. UN, 2017. doi: 10.18356/1cf881fb-en.

[2] S. Paraschiv, N. Bărbuţă-Mişu, and L. S. Paraschiv, "Technical and economic analysis of a solar air heating system integration in a residential building wall to increase energy efficiency by solar heat gain and thermal insulation," *Energy Reports*, vol. 6, pp. 459–474, Nov. 2020, doi: 10.1016/j.egyr.2020.09.024.

[3] "EU to fight energy waste with the first Heating and Cooling Strategy," *European Commission - European Commission*. https://ec.europa.eu/commission/presscorner/detail/it/MEMO_16_311 (accessed Nov. 27, 2022).

[4] "Heating in Poland | 2019 edition - Forum Energii." http://forum-energii.eu/en/analizy/cieplownictwo-2019 (accessed Nov. 27, 2022).

[5] H. Brauers and P.-Y. Oei, "The political economy of coal in Poland: Drivers and barriers for a shift away from fossil fuels," *Energy Policy*, vol. 144, p. 111621, Sep. 2020, doi: 10.1016/j.enpol.2020.111621.

[6] D. Chwieduk, W. Bujalski, and B. Chwieduk, "Possibilities of Transition from Centralized Energy Systems to Distributed Energy Sources in Large Polish Cities," *Energies*, vol. 13, no. 22, Art. no. 22, Jan. 2020, doi: 10.3390/en13226007.

[7] M. de Guadalfajara, M. Lozano, and L. Serra, "Analysis of Large Thermal Energy Storage for Solar District Heating," Mar. 2014. doi: 10.13140/2.1.3857.6008.

[8] "World Energy Trilemma Index | 2022," *World Energy Council*. https://www.worldenergy.org/publications/entry/world-energy-trilemma-index-2022 (accessed Nov. 25, 2022).

[9] "Dependence on Russian gas by European country 2021," *Statista*. https://www.statista.com/statistics/1201743/russian-gas-dependence-in-europe-by-country/ (accessed Nov. 27, 2022).

[10] M. Finkbeiner, E. M. Schau, A. Lehmann, and M. Traverso, "Towards Life Cycle Sustainability Assessment," *Sustainability*, vol. 2, no. 10, Art. no. 10, Oct. 2010, doi: 10.3390/su2103309.

[11] "What is Life Cycle Thinking? - Life Cycle Initiative," Dec. 07, 2012. https://www.lifecycleinitiative.org/starting-life-cycle-thinking/what-is-life-cycle-thinking/, https://www.lifecycleinitiative.org/starting-life-cycle-thinking/what-is-life-cycle-thinking/ (accessed Nov. 25, 2022).

[12] B. Corona and G. San Miguel, "Life cycle sustainability analysis applied to an innovative configuration of concentrated solar power," *Int J Life Cycle Assess*, vol. 24, no. 8, pp. 1444–1460, Aug. 2019, doi: 10.1007/s11367-018-1568-z.

[13] "Contactica | Life Cycle Sustainability Assessment." https://contactica.es/en/life-cycle-sustainability-assessment-lcsa/ (accessed Nov. 25, 2022).

[14] L. Lelek, J. Kulczycka, A. Lewandowska, and J. Zarebska, "Life cycle assessment of energy generation in Poland," *Int J Life Cycle Assess*, vol. 21, no. 1, pp. 1–14, Jan. 2016, doi: 10.1007/s11367-015-0979-3.

[15] M. Ristimäki, A. Säynäjoki, J. Heinonen, and S. Junnila, "Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design," *Energy*, vol. 63, pp. 168–179, Dec. 2013, doi: 10.1016/j.energy.2013.10.030.

[16] A. Jachura, "Environmental-economic analysis of the heating system for a single-family building," *E3S Web Conf.*, vol. 44, p. 00054, 2018, doi: 10.1051/e3sconf/20184400054.

[17] A. Wyrwa *et al.*, "Greening of the District Heating Systems—Case Study of Local Systems," *Energies*, vol. 15, no. 9, Art. no. 9, Jan. 2022, doi: 10.3390/en15093165.

[18] "Tauron." https://www.tauron.pl/ (accessed Nov. 25, 2022).

[19] "GreenDelta | Sustainability Consulting + Software." https://www.greendelta.com/ (accessed Nov. 25, 2022).

[20] "openLCA.org | openLCA is a free, professional Life Cycle Assessment (LCA) and footprint software with a broad range of features and many available databases, created by GreenDelta since 2006." https://www.openlca.org/ (accessed Nov. 25, 2022).

[21] "Home - ecoinvent." https://ecoinvent.org/ (accessed Nov. 25, 2022).

[22] B. G. E. News, "District heating as the future of urban heating in Europe – Novi Sad Heating Plant leads by example," *Balkan Green Energy News*, Mar.

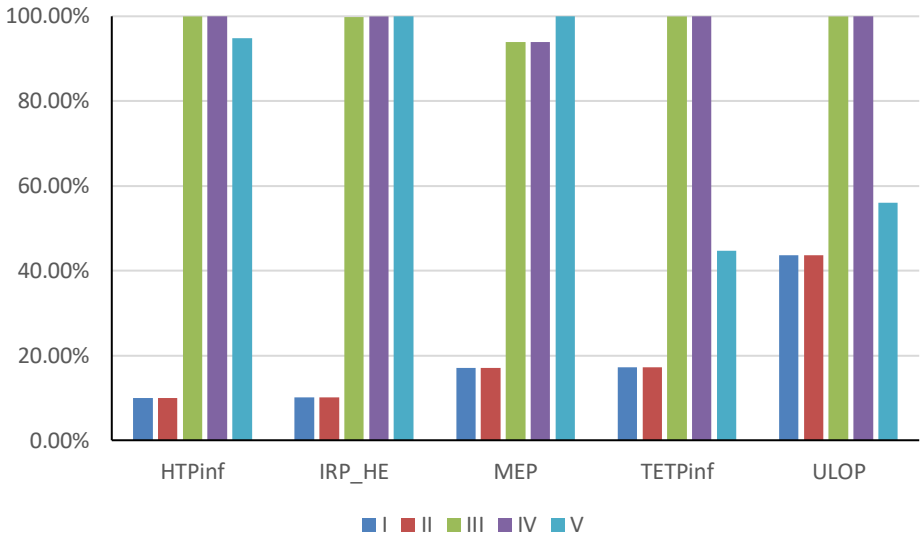
12, 2019. https://balkangreenenergynews.com/district-heating-as-the-future-of-urban-heating-in-europe-novi-sad-heating-plant-leads-by-example/ (accessed Nov. 25, 2022).

[23]"World headed for climate catastrophe without urgent action: UN Secretary-General," *UNEP*, Oct. 27, 2022. http://www.unep.org/news-and-stories/story/world-headed-climate-catastrophe-without-urgent-action-un-secretary-general (accessed Nov. 25, 2022).

[24]"Tauron – Strategia i model biznesowy Grupy TAURON w kontekście wymagań dla ochrony klimatu." https://raport2020.tauron.pl/strategia/strategia-i-model-biznesowy-grupy-tauron-w-kontekscie-wymagan-dla-ochrony-klimatu/ (accessed Nov. 26, 2022).

8. Appendix 1: Other indicators

(a)



(b)

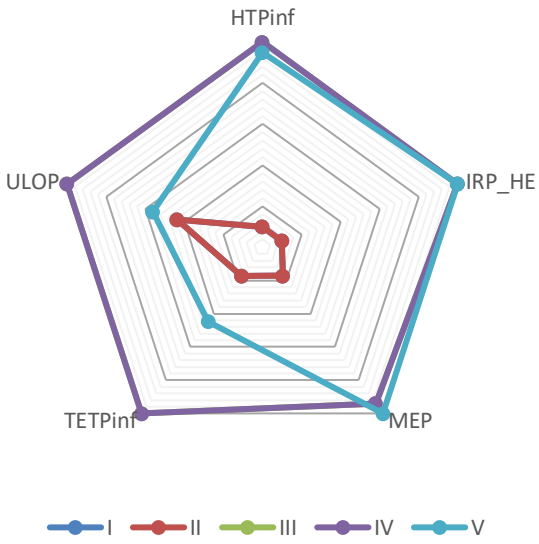


Figure 17 Relative LCA results (a) bar chart (b) radar chart

Table 6 LCA result table

Index	Scenario					Unit
	I	II	III	IV	V	

HTPinf	15796.70	15797.70	157636.00	157637.00	149555.00	kg 1,4-DCB-Eq
IRP_HE	257.37	258.14	2556.97	2557.75	2560.30	kg U235-Eq
MEP	64.94	65.01	358.27	358.33	381.28	kg N-Eq
TETPinf	1.21	1.21	7.01	7.01	3.13	kg 1,4-DCB-Eq
ULOP	2310.21	2310.25	5292.44	5292.47	2966.33	m2a

9. Appendix 2: Business analysis of Tauron

9.1. Tauron Group's strategy on climate change

Social pressure and regulations result in increasingly stringent environmental standards and increasing taxation of CO2 emissions. Continuous increase in the price of CO2 emission allowances is also related to the use of regulatory mechanisms, resulting in a reduction in the supply of emission allowances. Adapting coal-fired units to the stricter emission standards may prove technologically impossible for older sources or very costly and, consequently, economically unjustified. In response to the above, the TAURON Group already today envisages the gradual phasing out of old coal-fired units. The first of such steps was the permanent retirement of coal-fired units with a total capacity of 970MW at the turn of 2020 and 2021. In line with the Strategy, further coal units will be phased out by 2030. [24]

9.2. Business model about

9.2.1. SWOT analysis

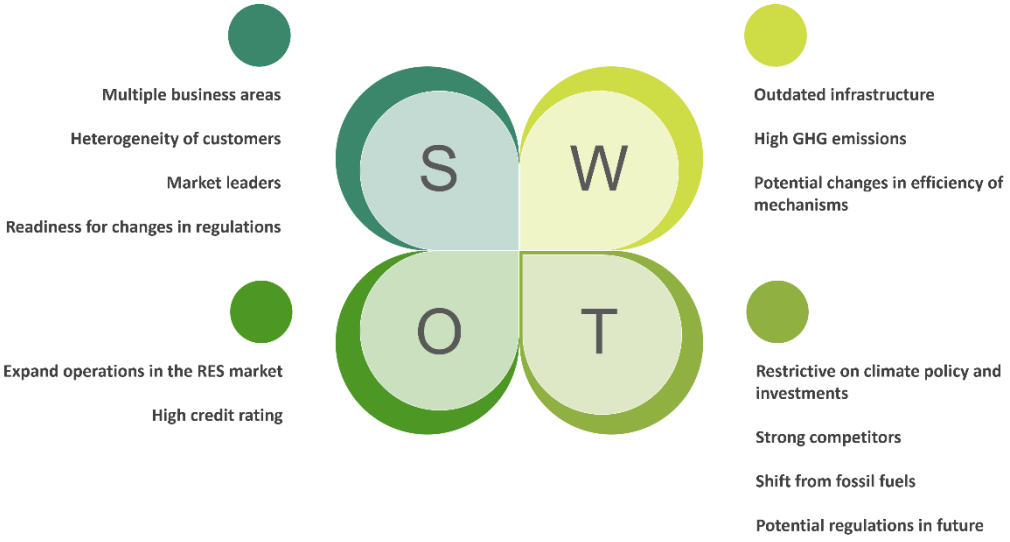


Figure 18 SWOT analysis on energy tranisition action for Tauron

- Strengths:

1. operating in multiple business areas
2. diversity of fuels used (conventional and renewable sources)

3. one of the market leaders
4. readiness for changes in regulations related to energy production (increase of installed capacity in RES)

- Weaknesses:

1. need to modernise infrastructure

2. high GHG emissions

3. potential changes in efficiency of mechanisms

- Opportunities:

1. expand operations in the RES market
2. high credit rating

- Threats:

1. restrictive climate policy
2. formal and legal restrictions on investments
3. strong competition on the market, e.g. PGE
4. departure from fossil fuels
5. potential regulations in future

9.2.2. Value Proposition Canvas

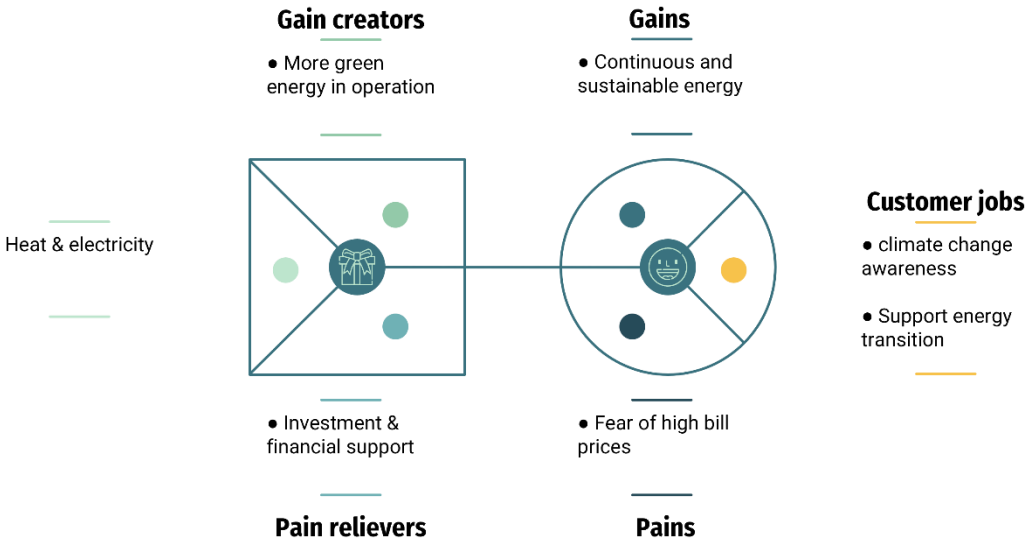


Figure 19 Value Proposition Canvas of energy tranisition action for Tauron

- **Customer Profile:**
  - Customer Jobs: Customers should understand the status quo of climate change and its relationship with fossil fuels. Besides, customers should encourage energy compant to take more actions to combat the predicament.
  - Gains: Customers access to energy continuously and sustanably.
  - Pains: Fear of high bill prices

- **Value map:**
  - Gain Creators: Installation of renewables relies on goverments and energy company. Therefore, a well-constructed energy transition plan is required.
  - Pain Relivers: Cooperations and goverments ought to investment more on renewable energy. Besides, goverments should provide more financial support to energy transition. When fossil fuel industry developed, it also recevied magnificent help from authroities.
  - Product&Services: The final products for customers are remained the same, heat and electrity. However, the generation method is less detrimental to the ecology.