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Corso di Laurea Magistrale in Ingegneria Gestionale

Tesi di Laurea Magistrale

Mathematical modeling of the Polish electricity supply with integration of large-scale wind power and use of energy storage

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Chapter 1:

Introduction

In recent years, the development of energy systems has been receiving considerable and increasing attention by scientists and policy makers.

The problem of modeling the development of energy systems is present in multi-disciplinary research since the first energy crisis in the early 1970's. Many countries and international organizations have taken part in the construction of tools for fore-casting and optimization of energy systems development.

1.1 Polish research on energy systems

In Poland research on the mid- and long-term development of the energy system was the subject of work published by Radovic et al. (2012) in which the MESSAGE model was used to analyze the investments plans for coal fired power plants.

Preliminary study on the long-term development of the power system in Poland was the subject of work of Pluta et al. (2012). Jaskolski (2012) used the MARKAL model to analyze the mechanisms to promote renewable energy sources and high-efficiency cogeneration. The role of hard coal and brown coal in the power sector in the time perspective up to 2050 was the subject of the study done with the use of the TIMES-PL model by Gawlik et al. (2013).

It should be emphasized that in Poland there is still a lack of comprehensive energy tool, which could be easily accessible for conducting the integrated energy system analysis.

1.2 Aim of the project

This project is the result of a four-month research internship at the AGH University of Science and Technology in Krakow, Poland, within the framework of the SMP (Student Mobility for Placement) Erasmus.

The purpose of this project was to develop two models: the first model was developed in GAMS language and the second one was developed using TIMES model generator - which is written in GAMS code. The General Algebraic Modeling System (GAMS) is specifically designed for modeling linear, nonlinear and mixed integer optimization problems. The two models considered in this project are both linear ones.

The goal of the first model (GAMS model) is to plan the construction of new electric capacity in Poland up to 2050, minimizing the total system cost considering two different cases: the first scenario without any climate policy initiative and the second one with carbon tax and emissions ceilings.

The second model (TIMES_STG_PL) has the purpose to make a sensitivity analysis, and thus to estimate the needed energy storage capacity to deal with the surplus of electricity produced by the supposed mass installation of wind power within the modeling horizon, considering 42 different wind profile.

Chapter 2:
The energy system

Present energy systems are the result of complex country dependent, multi-sector developments. Although each decision in this n-steps path may have provided rational answer based upon energy, engineering, economic or environmental reasons, it is hard to find rationality in the overall system. Furthermore, decisions take into account several other important dimensions that, are part of humanities or social sciences.

An energy system includes an energy supply sector and energy end-use. The energy supply sector consist of a sequence of elaborate and complex processes for extracting energy resources, converting these into more desirable and suitable forms of energy, and delivering energy to places where the demand exist. The end-use part of the energy system provides energy services such as cooking, illumination, comfortable indoor climate, refrigerated storage, transportation, and consumer goods. The purpose, therefore, of the energy system is to fulfill the demand for energy services.

The architecture of an energy system can be represented by a sequential series of linked stages, alternating commodities and processes, connecting various energy conversion and transformation processes that ultimately result in the provision of goods and services (see Figure 1). The technical means by which each stage is realized have evolved over time, providing a mosaic of past evolution and future options.

Primary energy is the energy that is embodied in resources as they exist in nature: the chemical energy embodied in fossil fuels or biomass, the potential energy of a water reservoir, the electromagnetic energy of solar radiation, the energy released in nuclear reactions. For the most part, primary energy is not used directly but is first converted and transformed into electricity and fuels such as gasoline, jet fuel, heating oil, or charcoal.

Final energy is the energy transported and distributed to the point of final use.

The next energy transformation is the conversion of final energy in useful energy, basically heat and work, by means of energy end-use devices, such as boilers, engines or motor drives.

In conjunction with non-energy end-use devices, useful energy provides energy

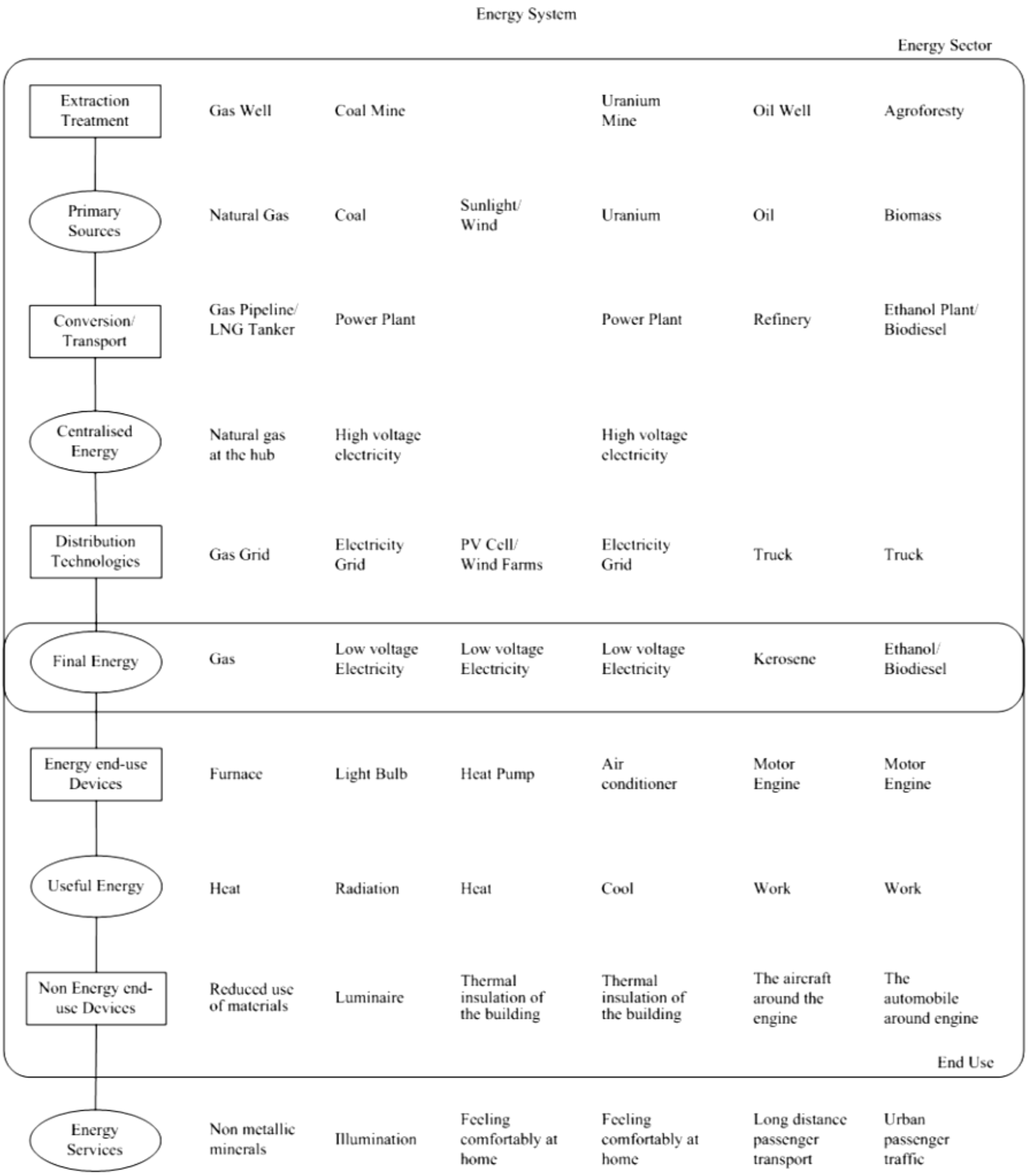


Figure 1. The energy system: schematic diagram with some illustrative examples of the energy sector and energy end-use and services.

services, such as moving vehicles, warm rooms, process heat, or light.

Energy services are the result of a combination of various technologies, infrastructures, labor, materials, and energy carriers. Clearly, all these input factors carry price tag and, within each category, are in part substitutable for one another. From the consumer's perspective, the important issues are quantity, quality and cost of energy services.

2.1 Environment and renewable sources

The damage to the environment is the major indirect cost caused by presence of energy system. Substance emitted into the atmosphere by energy technologies such as:

- power plants,
- refineries,
- incinerators,
- factories,
- fossil fuels extraction and production sites,
- distribution pipeline

are mainly responsible for:

- global warming and climate change,
- acidification,
- air quality degradation, and
- damage and soiling of building and other structures.

Nowadays conventional energy sources based on oil, coal, and natural gas are facing increasing pressure on a host of environmental fronts, with perhaps the most serious challenge confronting the future use of coal being the Kyoto Protocol greenhouse gas reduction targets. Renewable energy sources currently supply somewhere between 15 percent and 20 percent of world's total energy demand.

The renewable sources supply is dominated by traditional biomass, mostly fuel wood used for cooking and heating, especially in developing countries in Africa, Asia and Latin America. New renewable energy sources (solar energy, wind energy, modern bio-energy, geothermal energy, and small hydropower) are currently contributing about two percent.

A number of scenario studies have investigated the potential contribution of renewable to global energy supplies, indicating that in the second half of the 21st century their contribution might range from the present figure of nearly 20% to more than 50% with the right policies in place. The potential of renewable energy sources is enormous as they can in principle meet many times the world's energy demand.

Renewable energy sources such as small hydropower, wind, solar, biomass, and geothermal can provide sustainable energy services, based on the use of routinely available, indigenous resources. A transition to renewable-based energy systems is looking increasingly likely as the costs of solar and wind power systems have dropped substantially in the past 30 years, and continue to decline, while the price of oil and gas continue to fluctuate. In fact, fossil fuel and renewable energy prices, social and environmental costs are heading in opposite directions. Furthermore, the economic and political mechanisms needed to support the widespread dissemination and sustainable markets for renewable energy systems have also rapidly evolved. It is becoming clear that future growth in the energy sector is primarily in the new regime of renewable sources, and to some extent natural gas-based systems, and not in conventional oil and coal resources.

These systems can have dramatically reduced as well as widely dispersed environmental impacts, rather than larger, more centralized impacts that in some cases are serious contributors to ambient air pollution, acid rain, and global climate change; in fact environmental aspects and quality of life indicate that environmental pollution (of air, water, etc.) is largely linked to the increasing use of energy, actually the climate changes due to heavy use of fossil fuel with emissions of sulphur dioxide, nitrogen oxide and carbon dioxide become more and more a planetary problem and will influence the future. Air pollution is one of the aspects of the environmental problems. Air pollution is not the only aspect of the environmental problems created by the energy sectors: water pollution is another aspect of environmental problem. Water pollution includes any detrimental alteration of surface waters, underground waters or the marine environment with a thermal or material pollution. Water polluting agents can be solid, liquid, or gaseous that detrimentally alters the natural conditions of waters.

The environmental benefits due to the renewable energy systems are:

- reduced air pollution;
- lower greenhouse gas emissions;
- lower impacts on watersheds;
- reduced transportation of energy resource;
- preservation of natural resources for the long term.

Using renewable energy generates a wide variety of economic benefits, such as job creation that is a key part of economic development activity and healthy economies. When more people are working, the benefits extend beyond the income earned from those jobs.

Benefits occur when workers spend part of their income in the local economy, generating spin-off benefits known as the "multiplier effect." This increased spending creates economic activity (jobs and revenues) in other sectors such as retail, restaurant, leisure and entertainment. Renewable energy systems can create more jobs than conventional energy-supply projects.

Chapter 3:

Current energy situation and future perspectives for Europe and Poland

3.1 The EU's energy situation

The European Union is singularly responsible for 13,8% of energy consumed in the world in 2011. Petroleum was the most widely used energy resource, representing over 35% of the EU energy consumption (figure 2), followed by natural gas, which represent around 24%. In 2011 the EU-27 gross inland consumption was 1,700 Mtoe.

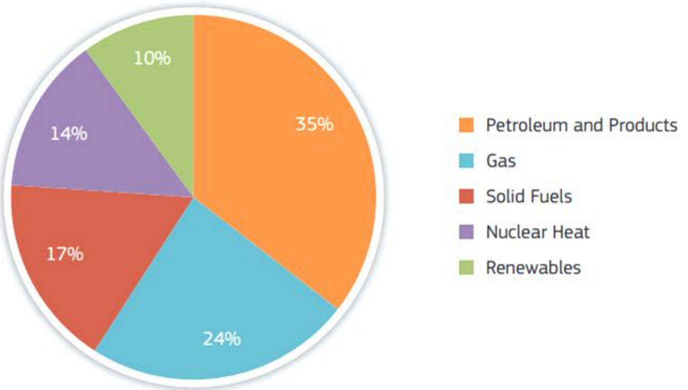


Figure 2: EU gross inland consumption by source in 2011 - Energy mix[1]

Because of its scarcity of primary energy resources, mainly petroleum and gas, the EU is forced to import heavily. In 2011, 940 Mtoe was imported, thus imports in 2011 were about 55% of the gross inland consumption (Figures 3,4).
In fact European countries, together, consume 13,8% of the world's energy and produce only 6.5% of it.
As a consequence of this huge import dependence current EU's energy prices are primarily determined by the global prices of fuels, over which the EU has very little control. In 2011 the EU's net import bill for fuels amounted to more than 3% of EU's GDP. Import routes are limited in number and exposed to an increased geopolitical risk which impact on both availability and price of fuels. Moreover, Europe has an ageing stock of generation capacity installed; by 2023 up to 110 GW

[1] Eurostat, April 2013

of plant capacity is due for retirement.

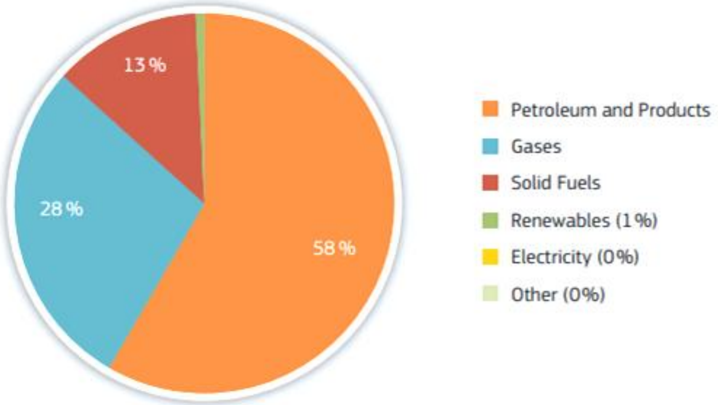
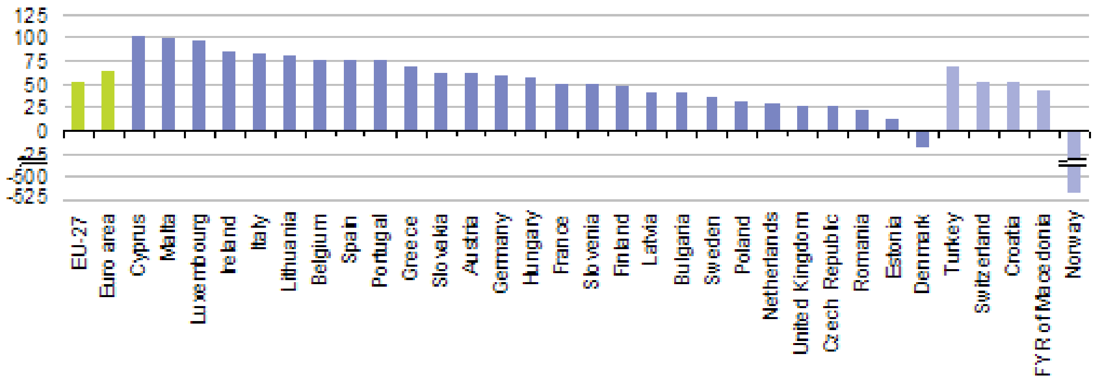


Figure 3: EU net imports by fuel in 2011[2]



Source: Eurostat (online data codes: tsdcc310 and nrg_100a)

Figure 4: Energy dependency rate in 2010, % of net imports in gross inland consumption and bunkers

Nowadays EU citizens' quality of life and EU's industrial competitiveness rely on external factors such as unstable oil and gas markets and volatile fossil fuels prices. Accordingly, a legally binding renewable energy target will reduce EU's exposure to volatile fossil fuels prices; moreover the continued deployment of renewable sources will allow long-term cost reductions in renewable energy technologies and will improve the EU's security of energy supply; finally, promote the use of renewable sources will be important to meet targets to combat global warming.

3.1.1 The "20/20/20" climate and energy package

Since the use of renewable sources is seen as a key element in EU's energy policy - reducing the dependence on fuel imported from non-EU countries, reducing emissions from fossil fuel sources and decoupling energy costs from oil prices- in

[2] Eurostat 2011

2009 the Renewable Directive, officially titled 2009/28/EC, set binding targets for all EU Member States, such that the EU will reach 20% share in energy from renewable sources by 2020 (part of the "20/20/20" climate/energy package). Figure 5 show the imposed targets for all the EU-27 Member States.
By 2011 the EU realized a 12.4% share of energy from renewable sources.

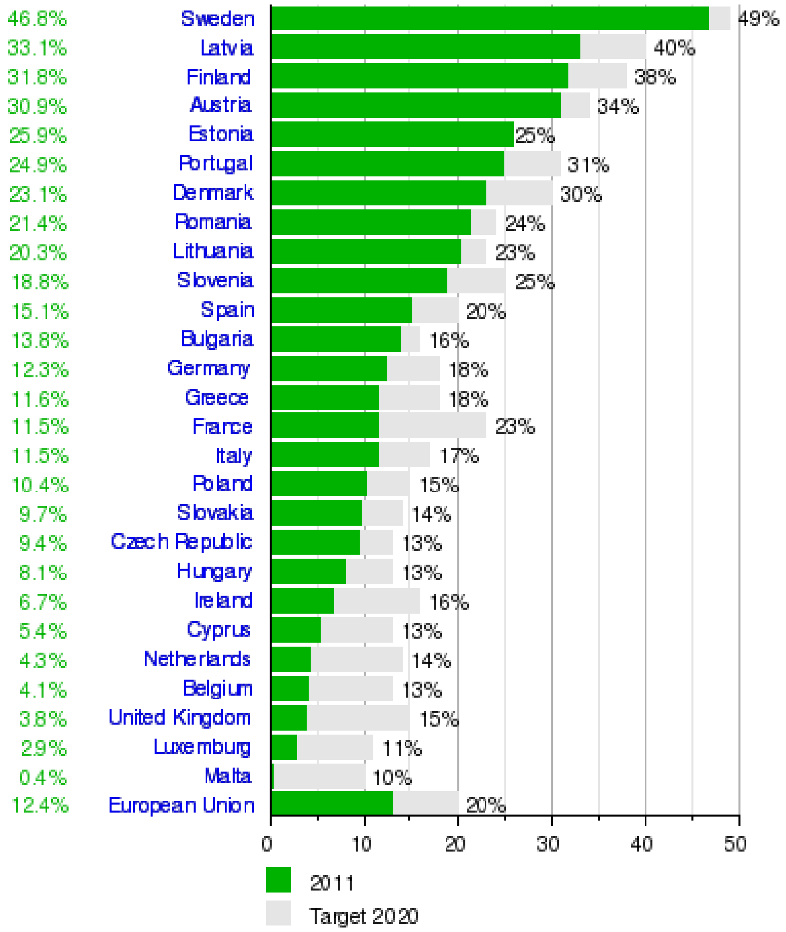


Figure 5: Share of RES in final energy consumption in EU-27 countries in 2011

Moreover, a regulatory framework was set up for CO_2 capture and geological storage (CCS), consisting on the capture of carbon dioxide from industrial installations, its transport to a storage site and its injection into a suitable underground geological formation for the purposes of permanent storage [Directive 2009/31].
Another target of the "Europe 2020" strategy is to reduce GHG emissions by, at least, 20% compared to 1990 levels and achieve a 20% increase in energy efficiency.
The control of European energy consumption and the increased use of energy from renewable energy sources, together with energy savings and increased energy

efficiency, constitute important parts of the package of measures needed to reduce greenhouse gas emissions and comply with the Kyoto protocol and with further European GHG emissions reduction commitments beyond 2013.

3.1.2 Air pollution

Green House Gases are emitted into the atmosphere from various sources but the main present-day contribution is associated with the combustion of fossil fuels.

The European Climate Foundation has recently proposed a new target for GHGs' emissions reduction, i.e. the cut by 2050 to the level of 80% of the GHGs emissions in 1990 - with the Roadmap 2050 project, discussed in the next section. The main burden of GHGs' emissions reductions will have to be incurred by energy-related sectors. It is expected that main directions until 2050 will be associated with fossil fuels substitution by renewable energy sources (RES), energy saving and energy efficiency measures as well as with deep decarbonization of power sectors.

Given the expected rise in energy demand until 2050, the ability to achieve the CO_2 emissions reduction target can largely be attributed to major declines in life cycle CO_2 intensities of energy across various energy commodities.

Despite the decreases in emissions that have occurred, energy sector remains an important source of key air pollutants, in particular SO_x, as illustrated in figure 6.

Large combustion plants (LCPs) have been a significant source of emissions of the acidifying air pollutants sulphur dioxide (SO_2) and nitrogen oxides (NO_X), and other air pollutants that potentially impact upon human health and the environment, including particulate matter (PM), carbon monoxide (CO) and non-methane volatile organic compounds.

Regarding the sulphur oxide actually all of the EU-27 Member States have reduced their national emissions below the level of the emissions ceilings set in the National Emissions Ceilings Directive (NECD) (Figures 7,8); indeed this is not true for the NO_x emissions as shown in figure 9.

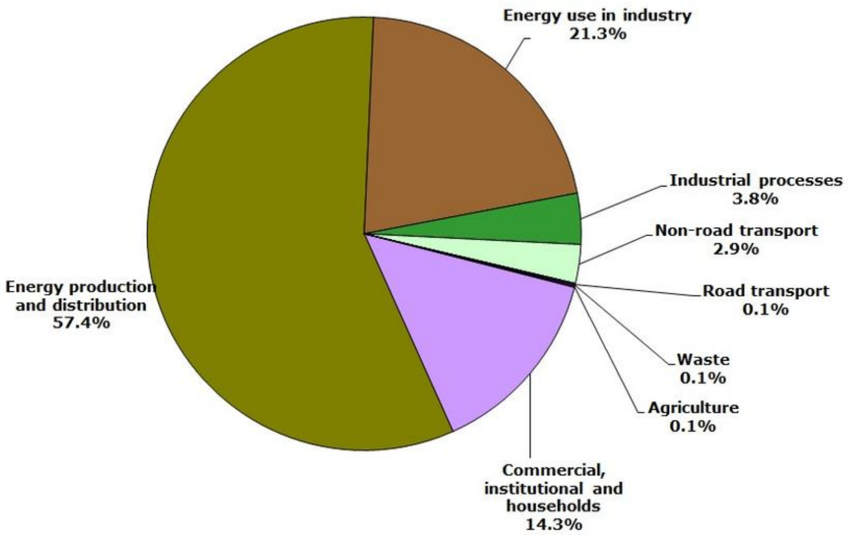


Figure 6: Sector share of sulphur oxides emissions - 2010 (EEA member countries)[3]

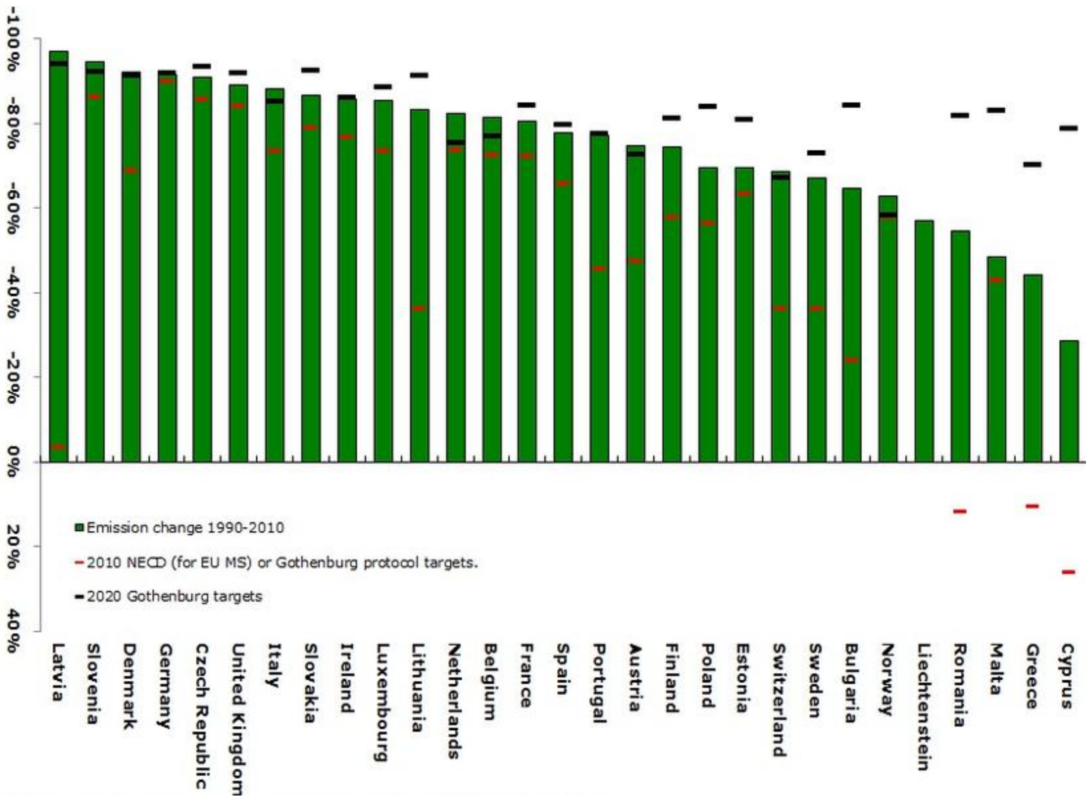


Figure 7: Reported change in sulphur oxide emissions (SOx) for each country, 1990-2010, in comparison with the 2010 NECD and Gothenburg protocol targets[4]

[3,4] National emissions reported to the Convention on Long-range Transboundary Air Pollution (LTRAP convention)

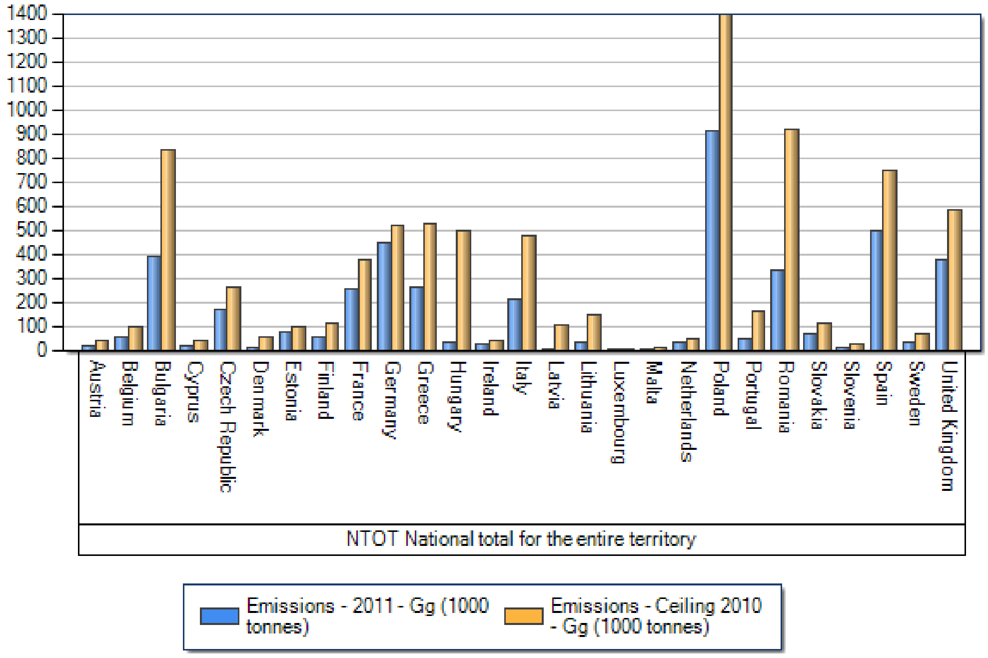


Figure 8: EU-27 SO2 emissions, year 2011[5]

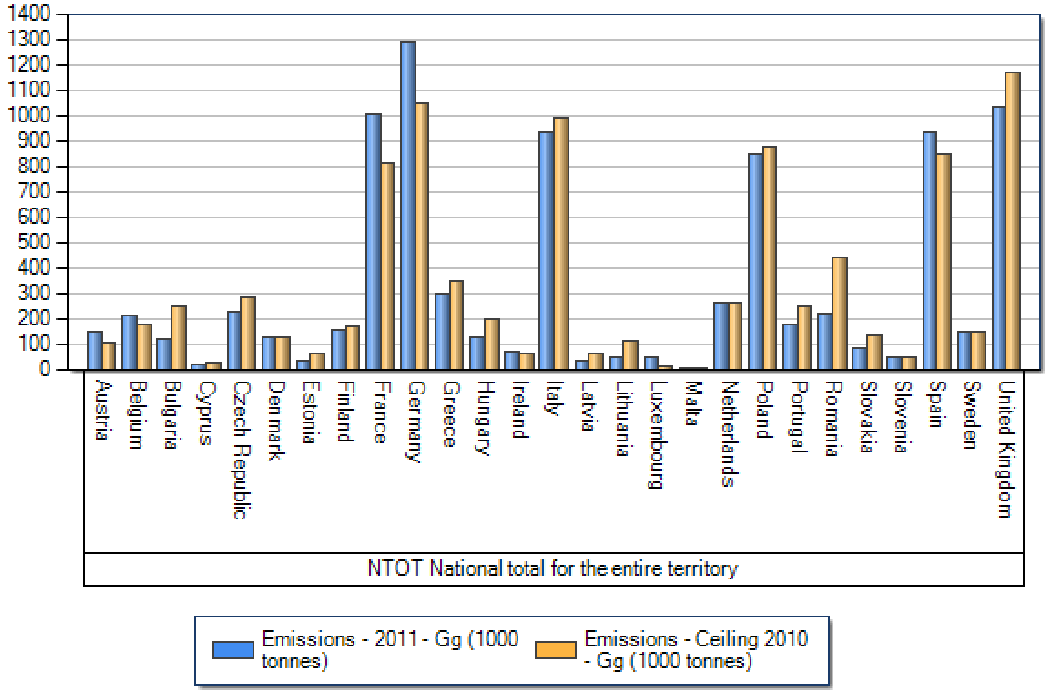


Figure 9: EU-27 NO_x emissions, year 2011[6]

[5,6] NEC 2011

3.1.3 Current energy system's indefensibility

The path towards the EU power sector's decarbonization will be difficult and it will take many years and many efforts, in particular by public organizations: in fact, nowadays, the European energy system and ways of producing, transforming and consuming energy are unsustainable. This is mainly due to:

1. high GHG emissions of which the great majority is directly or indirectly linked to energy which are not compatible with the EU and global objectives of limiting global climate change to a temperature increase of 2ºC to avoid dangerous impacts;
2. Security of supply risks, notably those related to:
   i) high dependence on foreign sources of energy imported from a limited number of suppliers, including supplies from politically unstable regions;
   ii) gradual depletion of fossil fuel resources and rising global competition for energy resources;
   iii) increasing electrification from more variable sources (e.g. solar PV and wind) which poses new challenges to the grid to ensure uninterrupted electricity deliveries;
   iv) low resilience to natural or man-made disasters and adverse effects of climate change;
3. Competitiveness risks related to high energy costs and underinvestment.

Thus, why is the shift to an energy system using low-carbon, more competitive and more diversified sources not, or too slowly, happening?
In fact there are several factors that hamper the shift:

- ✓ Energy market prices do not fully reflect all costs in terms of pollution, GHG emissions, resource depletion, land use, air quality, waste and geopolitical dependency (therefore, user and producer choices are made on the basis of inadequate energy prices that do not reflect true costs for society).
- ✓ Inertia of the physical system. The majority of investments in the energy system are long-term assets, sometimes requiring long lead times, and having life times of 30-60 years, leading to significant lock-in effects. Any change to the system materializes only gradually. Current market structure and infrastructures can discourage new technology development, since infrastructure, market design, grid management and development require adaptation and modernization which represent additional costs which face resistance from industry.
- ✓ Public perception and mindset of the users. General public perception of the

risks related to the construction of new power plants (large-scale renewable sources, nuclear, low-carbon fossil) and infrastructures needed to introduce large share of renewable sources (which additionally implies new grid lines and large energy storage technologies) or to store CO_2 can be more negative than expert judgments. Public acceptance was also acknowledged as important by many respondents in public consultation. It can also take a long time and require adequate incentives or regulation to persuade people to change the way they heat their houses, transport themselves, etc.

- ✓ Uncertainty concerning technological, demand, prices and market design developments: the energy system is characterized by a large proportion of long-term fixed costs that need to be recovered over several decades. Uncertainty about future technologies, energy demand development, market integration and rules, carbon and fuel prices, availability of infrastructures can significantly increase investor risks and costs, and make consumers and businesses reluctant to invest. Private investors can cope well with some categories of risks but policy makers and regulators can contribute to decreasing the uncertainties as regards political and regulatory risks.
- ✓ Imperfect markets. In some Member States, where markets are still dominated by incumbents, there is weak competition and lot of entry barrier for new entrants. Another factor is market myopia, i.e. the fact that long-term investments are not necessarily pursued by market actors who are generally drawn towards shorter-term gains.
- ✓ In some Member State developing markets for energy efficiency services and decentralized renewable sources are faced with a low number of actors on the supply side (lack of qualified labor force) as well as on the demand side (low levels of consumer awareness partly as a consequence of the ongoing rapid technological advances) and the lack of enabling regulatory framework.

Besides these factors there are problems specific to energy efficiency, infrastructure, security of supply and low-carbon generation technologies which are discouraging investments.

- *Energy efficiency*

Though a number of initiatives were undertaken at EU level since the mid-1990s, the European Energy Efficiency Action Plan created a framework of legislations, policies and measures with a view to realize the 20% energy efficiency and saving objective (see section 3.1.1). The projections indicate that with the rates of implementation of the current energy efficiency policies only half of the objective might be achieved by 2020. Furthermore, while the economic crisis contributed to this decrease in energy consumption, it has also negatively impacted energy efficiency investment decisions at all levels - public, commercial and private.

- *Tariff regulation and infrastructure*

Tariff regulation in most states has been based on the principle of cost-efficiency, allowing recovery of costs only for projects based on real market needs or cheapest available solutions, but some externalities, such as innovation, security of supply, solidarity aspects or other wider European benefits may not always be fully taken into account. For infrastructure networks that are entirely new, such as electricity highways or CO_2 transport infrastructure, it is likely to be of public interest to ensure that the first investments are compatible with later, more efficient network solutions.

- *Security of supply*

As we said EU's energy import dependency for all fuels is at 55%. More important, the EU is vulnerable to the increasing supply of some commodities by global oligopolies which can create internal and external imbalances. EU experiences of gas supply interruptions in early 2006, 2008, 2009 and 2010, as well as the EU's strong dependence on imports of petroleum products and the geopolitical uncertainty in many producer regions led to the adoption of the Regulation concerning measures to safeguard security of gas supply.

- *Low-carbon generation technologies*

All low carbon technologies are reliant upon a strong carbon price or other regulatory measures. As well as continuous R&D funding, long-term market or regulatory signals to investors are needed.

The conclusion is that relying on more low-carbon, domestic or more diversified sources of energy, produced and consumed in an efficient way, can bring significant benefits not only for the environment, competitiveness and security of energy supply but also in terms of economic growth, employment, regional development and innovation.

3.1.4 The Roadmap 2050 project

In July 2009, the leaders of the European Union and the G8 announced an objective to reduce greenhouse gas emissions by at least 80% below 1990 levels by 2050.

In support of this objective, the European Climate Foundation (ECF) initiated a study to establish a fact base behind this goal and derive the implications for

European industry, particularly for the electricity sector. The result is Roadmap 2050: a vision to a low-carbon Europe, a discussion of the feasibility and challenges of realizing an 80% GHG reduction objective for Europe. In addition to meeting the environmental target, the study was carried out with the energy security and economic goals of the EU at its core. It has created a fact-based analysis that illustrates why a zero-carbon power sector is required and how that can become a reality.

The message is clear: the decarbonization of Europe's power sector is achievable and affordable, with existing technologies - and high level of renewable energy are compatible with reliability and existing lifestyle.

As everybody knows energy that Europe consumes today is largely produced from fossil fuels; furthermore over the next few decades most of the power stations which generate this energy will be decommissioned as they will reach the end of their natural lives. The question concerning what should replace these old power stations lies at the centre of whether or not the EU will be able to meet its goal of reducing GHG emissions by 80% by 2050. Only by decarbonizing the power sector does EU stand a chance of coming close to achieving this goal.

The Roadmap 2050 project maps out four low- or zero-carbon pathways, using 40%, 60%, 80% or 100% renewable energy sources. In each case the difference is made up of a combination of fossil fuel with carbon capture and storage (CCS) and nuclear energy, and in each scenario the future cost of electricity is compared with the future cost of electricity under the current carbon-intensive infrastructure. Regardless of which pathway is chosen, the Roadmap 2050 study has established that the average cost to the economy over 40 years is not significantly different from the baseline. The baseline is defined as the current trend in technologies and policies for power, transport and buildings.

The project establish that to initiate the decarbonization transformation, current annual capital expenditure (capex) in the power sector needs to double to about €55 billion per year by 2020, depending on the share of renewable sources. Capital investments further peak towards 2035, after which the levels decline as the majority of the new power infrastructure is built.

Overall, the capex for the decarbonized pathways is 50-100% higher than for the baseline. This increase is mostly offset by lower operating expenditures due to a reduction in the demand for fossil fuels. The average cost of electricity over 40 years in the decarbonized pathways is similar to the cost in the baseline.

The decarbonized pathways would also affect other areas of the economy, reducing capital expenditure in oil and gas, as fossil fuels imports radically decline, as well as increasing capital investments for efficiency in buildings and industry and for electric vehicles and heat pumps.

The Roadmap 2050 analysis shows that Europe can significantly reduce its GHG emissions and meet the 80% target by 2050 with relatively little impact on the aggregate GDP.

Due to energy efficiency measures and a shift away from high cost fossil fuels, particularly in transportation, the energy bill per unit of output of the economy starts to fall by 2020 in all decarbonization pathways. In the longer-run the EU-27's low-carbon economy becomes more resilient against fossil fuels prices spikes and more competitive in terms of energy intensity, mostly thanks to the change in the structure of the economy and efficiency measures in industry, residential and transport sectors. As with all transitions, while technologies will become cheaper once they are deployed at large scale, the start-up phase will require more cash than the baseline.

The 2010-2050 average cost of electricity (COE) is roughly 10% higher in the decarbonized pathways than in the baseline, if no carbon tax is assumed. A carbon tax of 20-30 €/t CO_2 would make the COE in the decarbonized pathways comparable with the baseline, and this does not assume any technology breakthroughs, fossil fuels prices spikes or structural supply constraints, all of which would make the high-RES pathways more economical.

The Roadmap 2050 analysis shows clearly that the economic impacts themselves make the case in favor of the transition to a decarbonized power sector, including supply scenarios based on very high shares of RES.

Although the decarbonization pathways are feasible from a technical and economic viewpoint, political challenges remain. Installing the necessary solar panels, building the necessary transmission capacity, deploying up to 200 million electric vehicles around 100 million heat pumps for buildings and constructing the required backup generation capacity will all require careful political handling. Further challenges are presented by the potential increase in nuclear power generation and by the introduction of CCS capability not only to power plants but also to industry.

The transformation of all these energy-related sectors requires a step growth of supply chains for engineering, manufacturing and construction of power generation, transmission infrastructure, energy efficiency measures, new car type, etc. Funding requirements will need to shift substantially. Within the power sector additional funds are required for more capital intensive generation capacity and grid investments. Capital for oil, gas and coal supply in Europe may come down by 30%.

The challenges of implementation are considerable, but if European leaders are serious about achieving 2050 emissions targets, then a heavy burden falls upon policy-makers, in Brussels and in member state, to re-shape the energy landscape through enhanced markets and effective regulation.

Roadmap 2050 is a report which contains a vast amount of detail and suggested solutions, but three priorities sit at the heart of a successful implementation of its findings. The first is low carbon technologies.

As explained previously, its findings do not rely on technology breakthroughs, but they do rely on steady, in some cases dramatic improvements in existing technologies. Coordination of support for development and deployment of, e.g., CCS, PV, offshore wind, biomass, fuel cells, etc. will be critical. R&D support for potential breakthrough technologies will enable the transition faster and at lower cost. A key point to note here is that energy mix options are not limited by cost or technical capacity and that tomorrow's power mix is a question of policy priority not cost.

The second priority is an integration of grids and market operations. A large increase in regional integration and interconnection of electricity markets is key to transition in all pathways and is urgently required even for the level of decarbonization already mandated for 2020. It is also the key to reliable and economic integration of localized energy production.

The third priority are markets. A mass and sustained mobilisation of investment into commercial low-carbon technologies is needed, the vast majority of which will probably come from the private sector. Investors need greater certainty about future market conditions and future competitive landscape.

So, as Roadmap 2050 shows, if decarbonization fails, it will be a failure of policy.

The Roadmap 2050 project shows that the benefits of the low-carbon transition far outweigh the challenges and that a commitment now to a systemic low-carbon transformation of the energy sector is ultimately the winning economic strategy for competitiveness and low-carbon prosperity in Europe.

For more on Roadmap 2050 see www.roadmap2050.eu.

3.2 Poland

3.2.1 Country energy profile

Production of primary energy in Poland is based mainly on fossil fuels; first place belongs, and will most likely belong for a long time to hard coal and lignite, which cover 56% of its demand. Crude oil also has a significant share of 25% (figure 10).

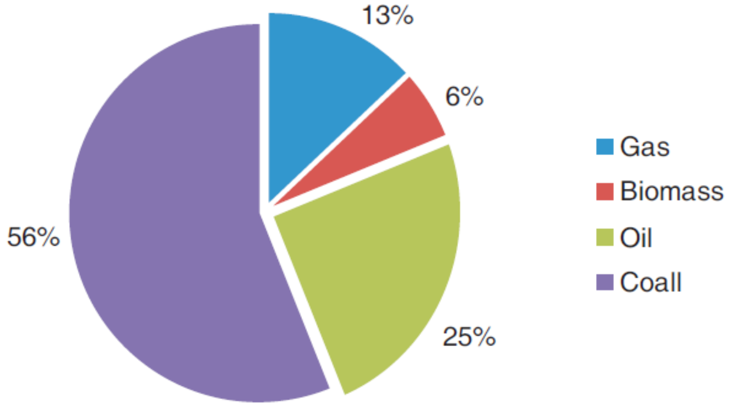


Figure 10: Demand of primary energy by source[7]

Generation subsystem encompasses power plants, industrial power plants, industrial heating plants, hydro-electric power pumps, wind power, biomass and biogas.

The gross national energy production volume in 2011 was 163.2 TWh. The domestic consumption of energy was 157.9 TWh (the difference was exported).

As explained the polish energy sector is historically based on fossil fuels, which occur abundantly in Poland (9th largest deposits in the world).

Regarding electricity production hard coal and lignite together produce nearly 90% of the Polish electricity supply- hard Coal 55.7%, lignite 32.9% (figure 11).

In 2012 installed capacity at the National Electricity System was up to 35 GW[8].

3.2.2 Current Polish energy sector challenges: shrinking coal reserve and excessive air pollution

<u>Shrinking coal reserve</u>

Poland's total coal reserves of close to 30,000 million tons would last some 300 years at today's level of consumption. This seems a fairly safe cushion for energy policy until one considers that the reserves which are currently or shortly to be operational amount to only around 3,000-4,000 million tons. With annual use in the range of 100 million tons, these reserves will be used up within 30 to 40 years.

[7] Energy mix 2050. Analysis of scenarios for Poland, Ministry of Economy, 2011
[8] Eia.gov statistics

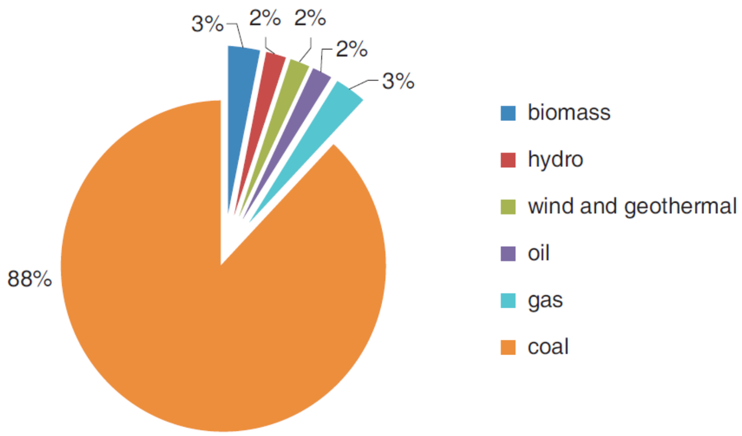


Figure 11: Electricity generation in Poland by source[9]

It's true that new technologies may come on line to make viable reserves out of ones which cannot be exploited today, but this cannot be relied to happen.

As the cost of exploitation rises thereafter, so the competitiveness of domestic coal falls - both compared to imported coal and domestic biomass. Within less than 20 years, therefore, domestic coal may no longer be competitive. If domestic reserves become uncompetitive and large amounts of import become unavoidable, then coal starts to become subject to some of the security of supply issues as imported gas, albeit much less so because of the multiple international resources.

Lignite reserves of around 4,800 million tons should last until the mid of 2070s at a rate of exploitation of around 70 million tons per year.

The presence of coal is a two edged sword. In a sense it is a bonus - while much of Europe is indeed highly dependent of Russian gas, Poland enjoys an enviable degree of self-sufficiency. Self-sufficiency means that security of fuel supply is for the time being less of an issue for Poland than its western counterparts.

On the other hand, the heavy dependence on coal means it is harder to delay the inevitable switch to a low-carbon economy.

The realization that domestic coal reserves could well be exhausted within the next twenty years at the current level of usage should make it politically easier to begin planning a power sector which is less coal dependent or which use coal in a more effective way.

Even if coal and lignite are not centre stage, they will continue to be a vital source of energy. But as precious resources, every efforts should be taken to ensure that they are utilized by the most efficient technologies.

The cost of reducing SO_x and NO_x emissions from LCP sector was estimated at over

[9] Poland Energy report, Enerdata, July 2012

€ 10 billion up to 2015.

Since 2001 the polish energy sector together with the National Administration have searched for the best solutions, minimizing costs of the emissions reduction through an introduction of the National Emissions Reduction Plan (NERP) and an Emissions Trading System (ETS) for SO_x, NO_x, and even dust.

The power sector of Poland is expecting to replace around 7 GW_e of total generating capacity between 2010 and 2020 but the current presumption that much of this replacement capacity will be coal-fired power plant is rather at odds with the imperative to dramatically reduce carbon emissions. Poland has however no simple alternatives for providing energy to its society because Poland has limited renewable energy capacity potential. Poland is a lowland country and hence it has limited hydro power potential, average wind speed is less favorable in Poland than in countries located in the vicinity of oceans while solar energy is less promising in Poland than in countries located in low latitude regions. Besides, deployment of nuclear power encounters various obstacles such as high investment costs, risks of uranium shortages after 2050, nuclear waste disposal or health and environmental concerns.

Air pollution

Among the top electricity producers worldwide, Poland has one of the highest CO_2 emissions per unit of electricity generated. Electricity generation in Poland is very dependent on hard coal and lignite and still has a significant share of relatively old and thus rather low-efficient power plants. Therefore, achieving ambitious CO_2 reduction targets might be particularly challenging for this country.

Poland is also one of the largest emitter of SO_x in Europe.

In 2011 the level of GHG emissions in Poland was 409.3 mln tons[10].

Figure 12 show the share of GHG emissions by gas, figure 13 show the share of GHG emissions by sector and finally figure 14 shows the share of GHG emissions relate to the polish energy sector.

[10] EEA 2011

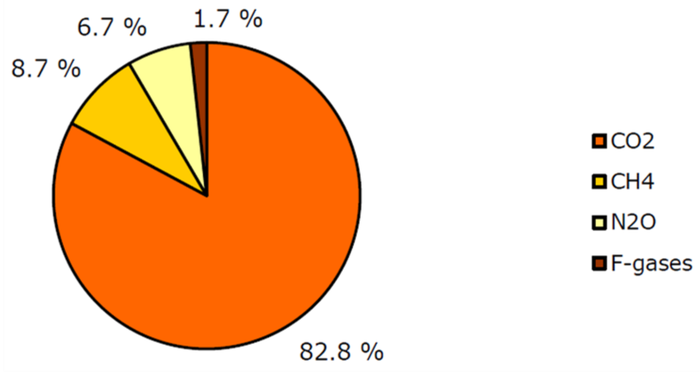


Figure 12. Poland's GHG emissions by gas[11]

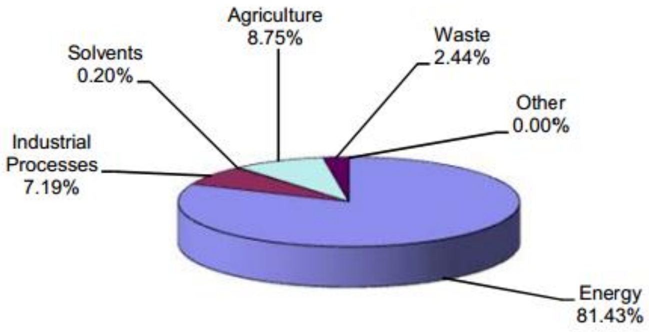


Figure 13. GHG emissions in Poland by sector in 2011[12]

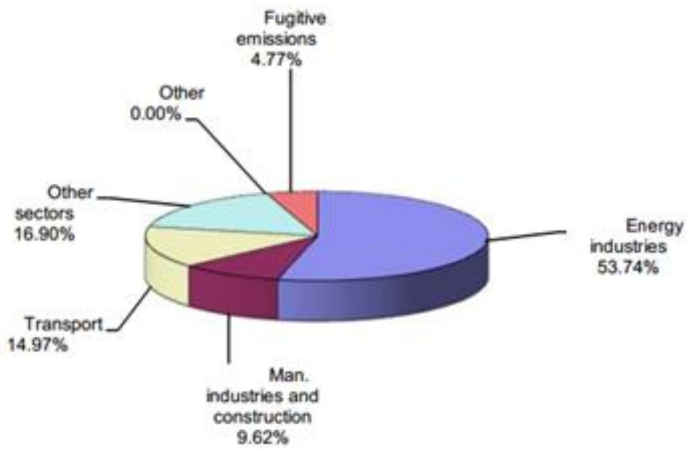


Figure 14: GHG emissions in Poland within the energy sector in 2011[13]

3.2.3 Renewable sources and their potential

Poland has untapped indigenous sources of fuels - wind along the Baltic Sea coast, biomass from its rich agricultural and forestry heritage, and domestic gas fields. Geothermal resources also remain quite unexploited.

[11] EEA 2011
[12,13] Summary of GHG emissions for Poland, United Nations-Climate change secretariat

Poland has an estimated 150 Gm^3 of natural gas, equivalent to about 10 years of current consumption, and 15 Mt of oil reserves. This relative poverty of hydrocarbon reserves leads to a considerable reliance on imports. Poland produces little oil – around 0.9 Mt – and imports 92–93% of its oil's needs, with about half its oil imports coming from the Russian Federation. Today the share of gas in power production is very low – it accounts for about 5%.

Nowadays the national production of natural gas covers 38% of gas demand, and the remaining share is primarily imported from Russia.

As, at a world level, the price of gas is expected to raise much faster than that of coal, and as the security of supply is highly uncertain, the development of power generation based on gas faces big obstacles.

Renewable sources could provide part of energy generation capacity as a viable alternative to that based on gas.

Table 1 shows the electricity generated from renewable sources from 2007 to 2012 in Poland:

RES type	2007	2008	2009	2010	2011	2012
Installed Capacity (MW)						
Biogas	45.70	54.61	71.62	82.88	103.49	131.247
Biomass	255.40	232.00	252.49	356.19	409.68	820.700
Wind	287.90	451.00	724.68	1180.27	1616.36	2496.748
Hydro	934.80	940.57	945.20	937.04	951.39	966.103
PV	0.00	0.00	0.00	0.00	1.12	1.29
Total	1523.80	1678.18	1993.99	2556.38	3082.04	4416.088

Table 1. MW of installed capacity from RES in Poland from 2007 to 2012

In the next sections each renewable source will be analyzed more in depth; giving first a brief introduction about the RES technology and then reporting its potential in Poland.

3.2.3.1 Hydropower

Hydropower is the principal source of electric power in over 30 countries, and provides about 17% of the world's annual electrical output. For the past 80 years technological development has largely centered in large-scale hydropower systems. Large hydropower systems are for the most part technically mature and already exploited.

There are different types of turbines with different areas of application, depending on the flow rate and the pressure of the water.
Small hydropower (SHP) systems, with an installed capacity of up to 10MW, have been widely used as an alternative energy source, especially in remote areas where other sources for electricity generation are not viable. SHP systems can be installed in small rivers or streams with little or no discernible environmental effects. SHP is based on a simple process, taking advantage on the kinetic energy of falling water. Nevertheless, they have been criticized because of the negative impacts on fish and other wildlife during SHP system's construction. It is important to note that drought, weather and seasonal water stream changes in many regions can cause serious problems with constant supply of electricity throughout the year. These constraints make it necessary to improve hydropower plants, such as a storage plant with enough capacity or pumped storage plants with reuse of water.
In Poland the ground is mostly lowland which is not favorable for construction of large hydropower plants. Nevertheless, among all the sources of renewable energy, hydropower provides the largest contribution to the generation of electricity in Poland today. The installed capacity in the hydropower plants is growing steadily, particularly in small-scale plants.
The highest concentration of existing medium size and large hydropower plants is in the western and southern parts of the country (figures 15 and 16). The lowest in central Poland, in the eastern part they are practically absent.
In Poland there are more than 700 hydropower plants, the most popular are SHP plants.
The potential of hydropower production in Poland are not evenly distributed. Most of it (about 68%) is present in the river Vistula basin. The rivers with high energetic potential are: Vistula, Dunajec, San, Bug and also Odra, Bóbr and Warta.
Regions in southern Poland, close to the mountains, are the most attractive for construction of small hydropower (SHP) stations in terms of water resources, but taking into account present hydro-technical infrastructure, the western and northern parts of the country are also regarded as very attractive.
According to NREAP hydroelectric potential in Poland is relatively small. The theoretical potential is estimated at 23 TWh per year, the technical potential at 12 TWh per year, and economic potential at 8.5 TWh per year, from which 45,3% comes from the Vistula river, 43,6% comes from Vistula basin, 9,8% comes from the Odra river and 14% from the rivers of the Pomorze Region.
Still according to NREAP, the planned installed power in 2020 is 1,152 MW, out of

which:

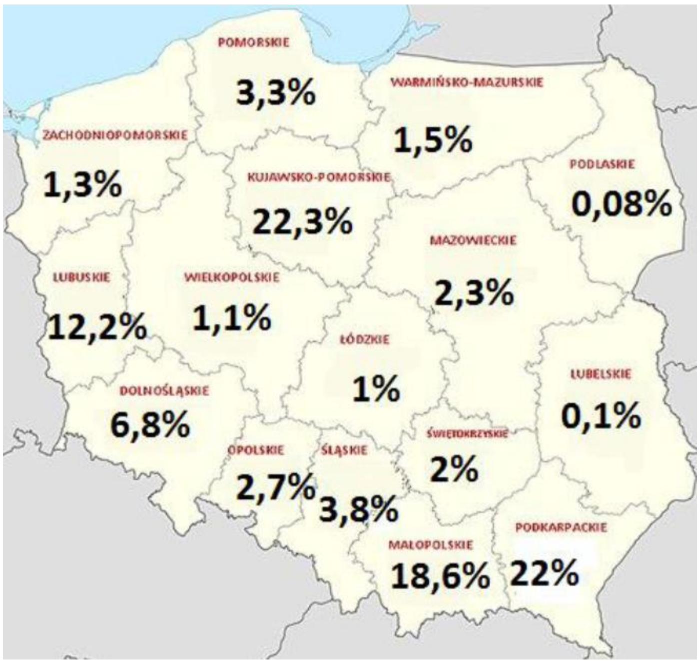


Figure 15: The distribution of energy produced by hydroelectric power plants in each region

- small hydro station: 142 MW;
- hydro stations from 1 MW to 10 MW: 238 MW;
- hydropower plants >10 MW: 772 MW.

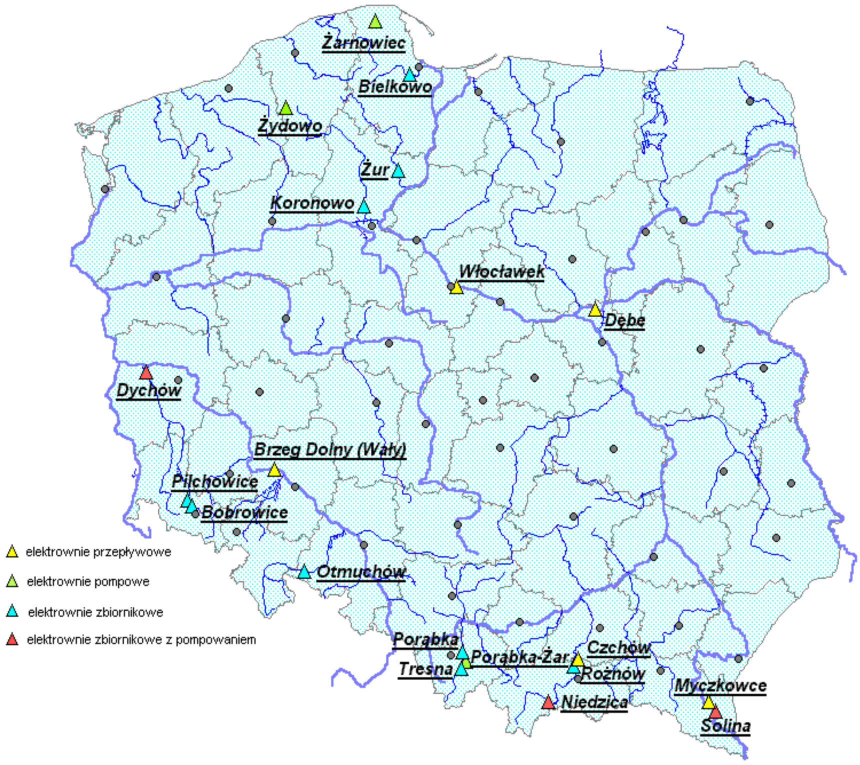


Figure 16: Location of the largest hydropower plants in Poland

3.2.3.2 Wind

Nowadays more than 58,000 wind turbines in the world are used for generating electricity.

The biggest producers of wind power in the world are Germany, Spain and USA. Electricity is generated when the wind's force turns the blades of a wind turbine, or wind energy conversion system, containing a generator. Most systems include a rotor with two or three blades, a transmission system, a control system, and an electrical generator, all mounted on a tower.

Wind turbines do not emit CO_2 and do not require water supplies unlike many conventional energy sources.

As we know, energy production in wind turbines depends mainly on wind speed in a place in which wind power plant is located. Depending on the wind speed, it is possible to differentiate between 4 phases of operation. At very low wind speed, the wind energy is not sufficient to overcome the system's moments of friction and inertia, and the rotors remain stationary. Starting at a certain wind velocity—about 3 m/s depending on the design—the wind turbine will turn. In this phase, the power output increases as a function of the wind speed to the power of 3, i.e. twice the wind velocity produces 8 times the electrical power. If the wind velocity increases further, then the maximum capacity of the generator will be approached, and the energy generation has also reached its maximum. The surplus energy from a further increase in wind velocity must be bypassed. The maximum power of the system is thus determined by the flow over the rotor area, and does not depend on the number of rotor blades. During a gale-wind speed of about 24–26 m/s, the mechanical load on the rotors is too high. Pitch-controlled turbines and active-stall systems are then taken off the grid and the entire rotor is turned out of the wind to protect the overall turbine structure. The rotor spins with no load. Nearly all the wind turbines installed today have 3 rotor blades, since the mechanical loads are easier to control with this design and because three-blade rotors are considered by most people as optically more harmonious than single or two-blade rotors. The blades themselves are usually made of glass-reinforced plastics and are more than 50m long for large turbines.

Depending on their rated capacity, modern large-size rotors turn at 10–30 revolutions/min.

The towers of the largest wind turbines today are more than 120m high, so that together with the rotor blades the wind turbines reach a height of up to 170 m. As a rule: the higher the tower, the less interference from air turbulence caused by ground roughness, and the mean wind velocities are higher.

Modern wind turbines can be divided into two basic configurations with respect to the turbine design: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs).

Wind energy is the most dynamically developing branch at the renewable energy market in Poland and through its intensive development Poland has a chance to achieve ecological and low emissions electricity generation as well as to meet the EU requirements regarding energy generation from renewable sources.

In fact the Polish wind potential is comparable to the wind potential of the ‟world wind giant”: Germany. It also compares favorably with countries where a significant share of energy is obtained from wind, such as Denmark or Sweden. Analyzes indicate a continue dynamic growth of wind power in Poland, as show in figure 17.

According to the Institute of Meteorology and Water Management about 30% of Polish territory has an average wind speed over 4 m/s. A preliminary estimate of the available wind sources is presented in Figure 18. The map shows that the north of Poland particularly experiences high wind speeds for a significant fraction of the year.

In accordance with the latest published data the total wind installed capacity in Poland amounts to 2644.9 MW[14] with 188 wind farms. Location of wind mills in Poland is shown in Figure 19.

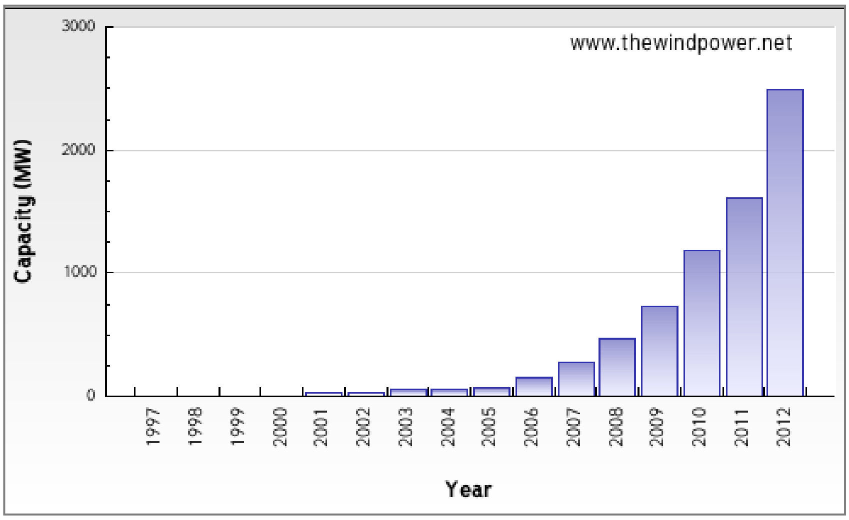


Figure 17: Installed wind capacity in Poland (1997-2012)

[14] As of 31.03.2013

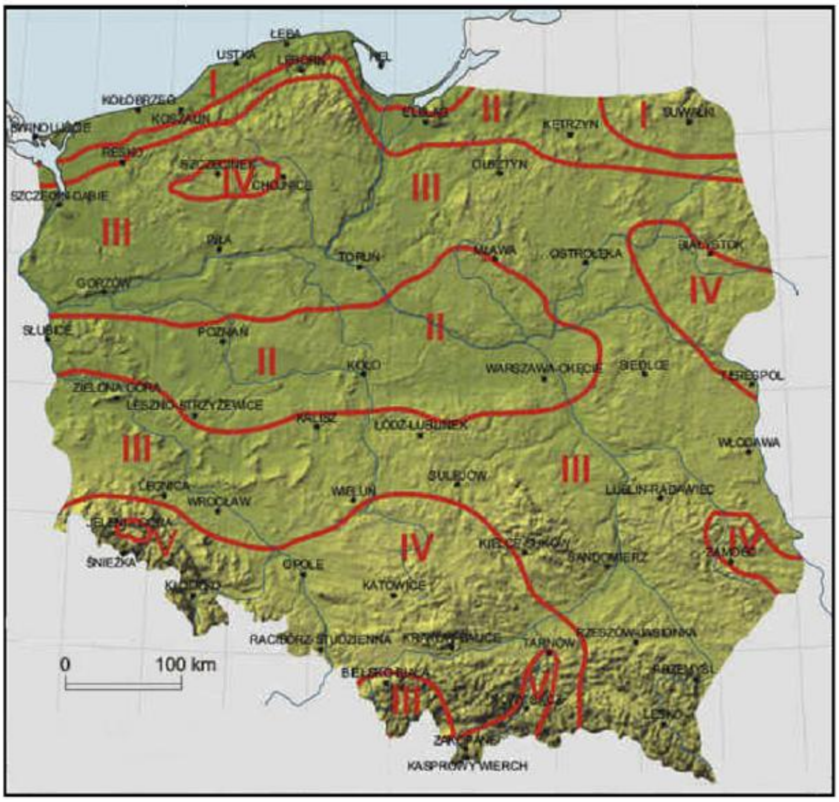


Figure 18: wind potential of Poland: I very favorable, II favorable, III sufficient, IV insufficient, V bad

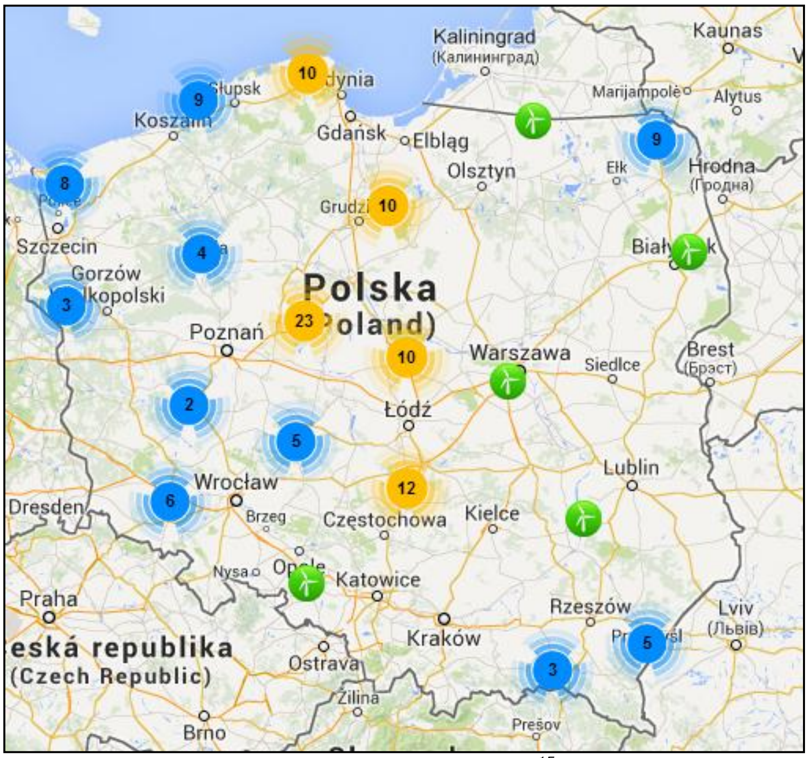


Figure 19. Location of wind farms in Poland, 2013[15]

[15] PSEW

3.2.3.3 Biomass and Biogas

The use of biomass for generating electricity and heat is a particularly attractive form of energy conversion from the climate point of view. Where growing, the biomass first removes the CO_2 from the atmosphere and binds the carbon in the biomass. This carbon is later released into the atmosphere again, i.e. as result of combustion or when the biomass is rotting. Therefore, when biomass is used for energy purposes, then only that CO_2 is released which was previously removed from the atmosphere when the plant was growing.

The sources of biomass for energy production and conversion methods are divided into four groups as shown in figure 20.

Included amongst the most important biogenous fuels are wood and leftover timber accumulating from forestry, in sawmills or as old timber. Fast-growing trees, e.g. poplars and willows, can be planted in so-called short turnaround plantations and be harvested within a few years. Reed is potentially a very high-yield regenerative raw material; however it requires high-quality fertile land and a good water supply. Residuary straw, as well as special grain plants such as e.g. the wheat-rye hybrid triticale, are also suitable for producing energy. Plants which contain sugar and starch, like corn and sugar beets, can be used for making bio-alcohol. Also included as biomass are those oil-containing plants, which, by pressing and subsequent processing, can be converted into liquid energy carriers. Organic residuals are also suitable energy sources. Liquid manure, bio-waste, sewage sludge, and municipal sewage and food leftovers can be converted into high-energy biogas. Biogas is also released from landfills.

Location of biomass plantations in Poland is shown in figure 21.

Also biogas is considered to be attractive and relatively cheap energy source. Biogas can be used in gas-driven electricity generators, gas boilers and CHP systems. In 2003, plants using agricultural biogas, as well as biogas from municipal sewage works, began to be built. A very promising alternative for burning is the gasification of biomass. Using gaseous biogenic fuels, it is possible to apply proven and efficient techniques like gas turbines and cogeneration units. The future use of biomass in fuel cells, which provide high yields of electricity even from small-power units, is possible with gasified wood.

Poland has a huge potential of biomass production as it has 1.6 million ha of agricultural land utilized for biomass production. Forestry biomass is also widely available as the forested area constitute 29.1% of Poland's territory (which is over 9 million ha).

In Poland, the different types of biomass are used for other purpose:

- Forestry biomass (e.g. fuel wood, wood wastes, pellets, briquettes) is used for heat production, both in households and power plants,
- Crops and rapeseed are used for bio-components production,
- Agricultural by-products (e.g. straw and other plant parts which cannot be used for food production) and energy crops are used for biogas production.

According to the data provided by the Institute of Renewable Energy, the real economical potential of biomass in Poland is estimated at the level of 600,168 TJ in 2020; however, the market potential is estimated at 533,188 TJ. This market potential is constituted from various types of biomass:

- solid waste (about 149,338 TJ), - wet wastes (designated for biogas production – about 72,609 TJ),
- firewood (24,452 TJ) and energy crops (286,718 TJ).

Regarding the biogas, this sector is developing fast in Poland. In Poland most of the biogas is produced sewage sludge (over 50 percent) and landfill gas (almost 40 percent). The remaining part of biogas is produced from other feedstock (e.g. energy crops, plant and animal wastes, animal production and plant production wastes).

In Poland biogas investments often encounter various protests. Many investments in biogas plants cannot be carried out as investors do not get permission for the construction. There is strong resistance from the society – local inhabitants and communities or ecologists. They claim the biogas investments will result in bad smell from biogas production, water and arable land contamination, decrease in the land prices or lowered chances for agro-tourism development.

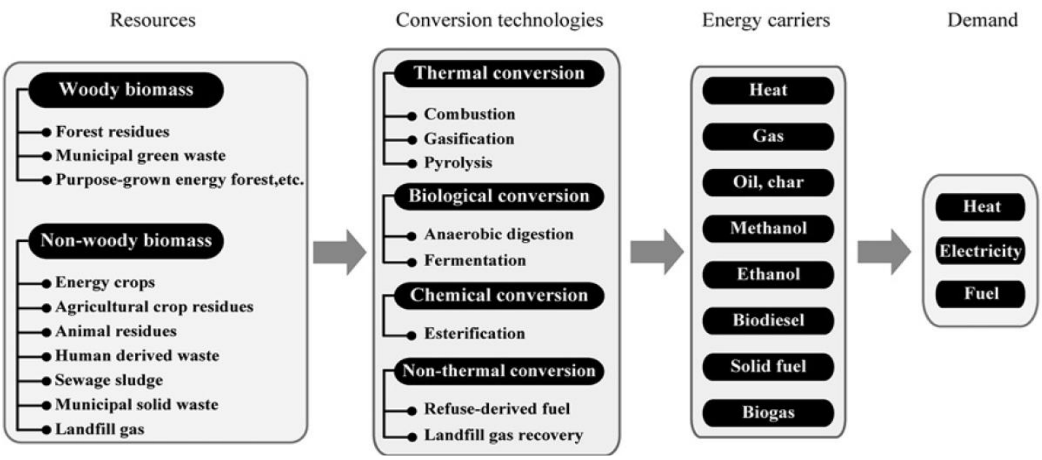


Figure 20: Biomass energy sources and conversion technologies

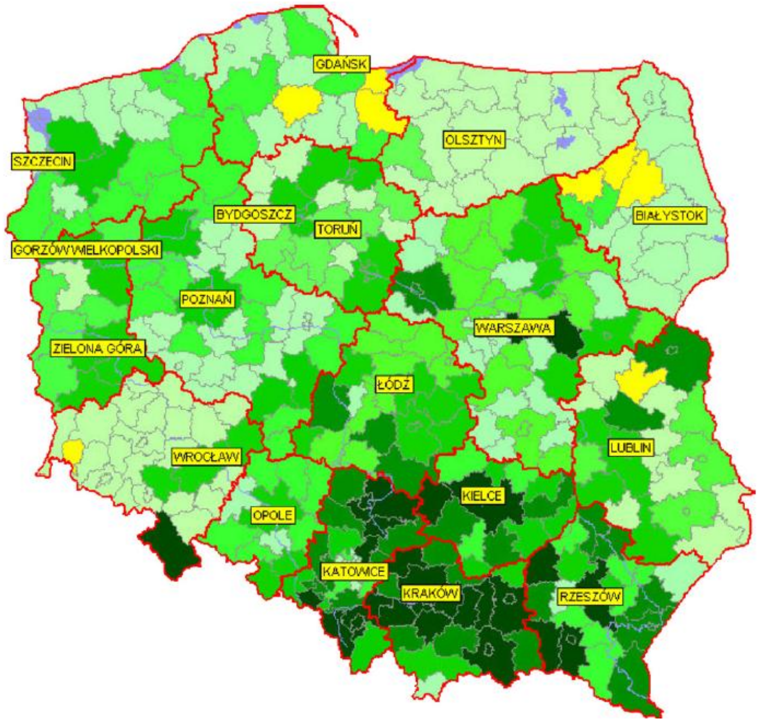


Figure 21: Location of biomass plantation in Poland

3.2.3.4 Solar

Solar radiation can be converted into useful energy using two types of technologies. The first is solar-thermal technology, which involves collecting and directly using solar radiation for space or water heating and for electricity generation in thermal engines.

The second type of solar energy technology is solar photovoltaic technology. PV technology involves the direct generation of electricity from light. The direct current thus generated can be used for powering electrical devices or stored in batteries. It can also be transformed into alternating current and fed into the national grid.

A PV system can also operate during winter and cloudy periods, but with significantly reduced energy output. PV generators are silent, clean in operation, highly reliable have few maintenance requirements, and are extremely robust.

Their useful lifetime performance is dependent on several factors such as, material ageing and outdoor condition, and typically based on 20 and 22 years limit.

Although there is less sunshine in Poland than in more southern countries, photovoltaic systems are also useful at our latitudes, since solar cells can also convert diffuse solar radiation into electrical energy. The annual average of solar radiation is higher in the south than in the north of Poland—see figure 22, amounting to between 990 and 1050kWh of incident energy/m^2 each year.

Approximately 80% of the total annual insulation is received during six months in spring and summer - from April to September. A modern solar cell can convert, on average, one-tenth of this solar energy into electricity. During recent years we could not only observe a drastic increase in demand for photovoltaic systems, but also a significant reduction in costs.

Currently, solar energy is used in Poland mainly as a source of heat through solar collectors. Solar installations are mainly small and located at the top of the buildings. Solar collectors are commonly used in houses or public buildings. The total area of solar panels is estimated at 904,000 square meters[16].

Direct production of electricity using photovoltaic panels in Poland is marginal at the moment. Photovoltaic panels, for economic reasons, are used only on a small scale. However, the National Renewable Energy Action Plan assumes an increase in installed power in photovoltaic up to 3 MW by 2020.

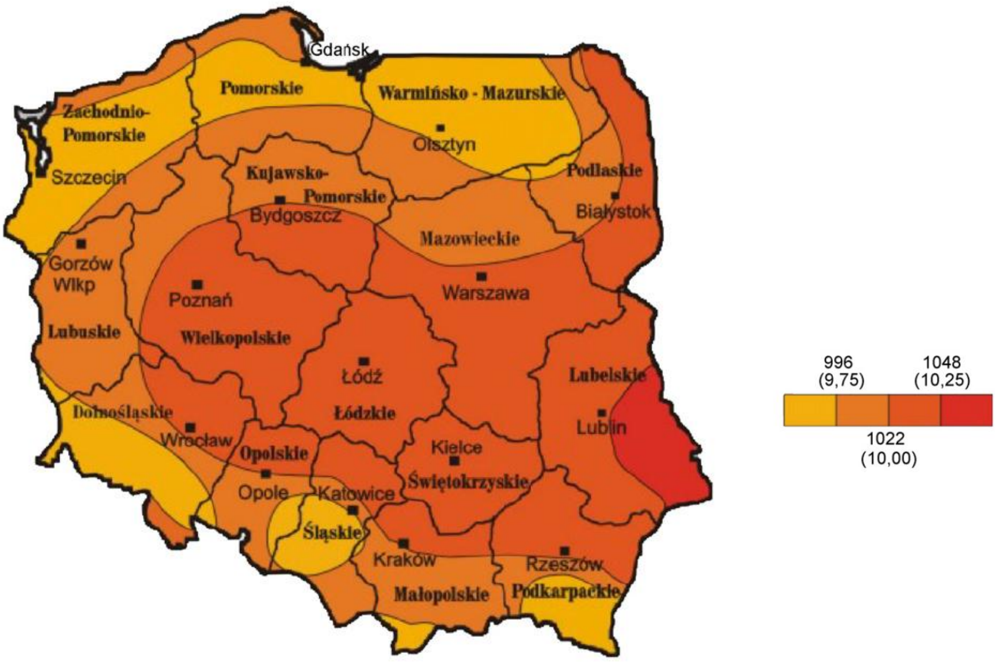


Figure 22: Distribution of solar radiation in Poland [kWh/m^2 per year]

3.2.4 Energy Storage Technologies

Hydro and geothermal renewable energy sources are similar to fossil fuels for what concerns the possibility to stockpile the fuel for immediate access to energy when needed, representing a concentrated, stable form of energy. A reliable source of power is vital to a stable grid. The supply of power must equal the demands of the consumers at every moment during the day. Fluctuations and unpredictable

[16] Pigeo.org.pl

variations of wind and solar energy can result in discontinuities in the power supply, which may last for a few seconds to a couple of hours. Moreover, the peak supply of wind may not coincide with the peak demand for energy.

Given these concerns, it may be a challenge to integrate wind and solar into the grid at a large scale. Energy storage technologies provide one solution to this problem.

There are several established and large number of developing technologies offering significant potential to enable energy storage for electricity production. Economically viable storage of energy requires conversion of electricity and storage in some other energy form, which can then be converted back to electricity when needed.

3.2.4.1 Pumped hydro

Pumped hydro is the most mature and widely used technology for large-scale energy storage. It accounts for 95% of the current storage capacity. Pumped hydro system consist typically of two reservoirs located at different elevations, a pump and a hydro turbine or a reversible pump turbine device. During low-demand periods (usually at night) excess low-cost electricity is used to pump water from the lower reservoir to the upper one. During peak-load periods, the system generates power just like a conventional hydro-power plant. Pumped hydro system based on artificial reservoirs can offer high power capacity (up to few GW) for short periods (6-10h). System based on large, natural water sources and dams are often used to provide daily and seasonal storage with power output of typically 200-400MW. In general, pumped hydro system can start operation and reach full power in a few minutes. The efficiency of the pumped hydro system is between 70% and 80%.

3.2.4.2 Compressed Air Storage Technology

CAES system use off-peak electricity to compress and store air into underground mines or caverns. Compressed air is then used in natural gas turbines to generate peak-load electricity. Usually simple-cycle gas turbines use almost two-thirds of the input fuel to compress air prior to combustion (efficiency of 37-38%). Using compressed air from CAES the turbine can save up to 40% of the input fuel used to generate electricity, and the typical efficiency of a CAES with a simple cycle gas turbine is about 50%. This efficiency can be increased using combined cycle gas turbines. CAES system can come online and react to power demand changes in 15 minutes. Compressed air is stored at pressure between 45 and 70 bars into 500-

800m-deep caverns.

At present, CAES systems in operation include the 290 MW Huntorf plant in Germany and the 110 MW McIntosh plant in Alabama. All the data for these plants are shown in the table below:

Location	Germany (Huntorf)	USA (McIntosh)
Maximum capacity (MW)	290	110
Geology	Salt	Salt
Number of caverns	2	1
Air cavern volume [m^3]	310,000	560,000
Ration hour Compression/Generation	4	1.6
Fuel	Gas	Gas/oil
Charging ratio MWin/MWout	0.82	0.75
Generation hours at max capacity	2	26
Normal start [min]	8	10-12
Starting reliability	99%	
Availability	90%	95%

Table 2. Existing CAES plants technical data[17]

Because air temperature increases during compression and the energy needed for compression increases with air temperature, air must be cooled during compression to reduce the compression energy and then re-heated prior to combustion. Therefore, CAES efficiency could be improved storing the heat extracted from air cooling and re-using it for air pre-heating (adiabatic CAES) but this technology is still under development.

3.2.4.3 Flywheels

Flywheels system store electrical energy as kinetic energy. During charging the flywheel rotation is driven by a motor-generator; during discharging, the rotation drives the generator to produce electricity. The rotational energy depends on flywheels diameter; therefore larger flywheels enable higher energy storage. Proper materials are needed to resist the centrifugal force.

Flywheels can be divided into three categories depending on power and time service: a few kW for a few hours service; a few hundred kW for 15 seconds to

[17] Modeling of an AA-CAES Unit and an Optimal Model-based Operation Strategy for its Integration into Power Markets, F. De Samaniego Steta, Prof. Dr. G. Andersson, Ing. A. Ulbig, Ing. S. Koch, EEH - Power System Laboratory, Swiss Federal Institute of Technology (ETH), Zurich, 2010

minutes service; and 600-1200kW for time service of 10-15 seconds. Compared with other form of electricity storage, flywheels offer a high power output for a short time, long lifetime, little or no maintenance.

3.2.4.4 Supercapacitors

Supercapacitors are high-capacitance electrochemical condensers. They can discharge their energy content in a short time, depending inversely on the output power and offer long lifetimes. Due to the short response time and the high power density supercapacitors can be used as instantaneous voltage compensator. For application with renewable power system supercapacitors are still under development and are often considered in combination with lead-acid batteries.

3.2.4.5 Vanadium Redox flow cells

VRB are electrochemical energy storage system based on the vanadium ability to exist at four different oxidation levels. During energy charging, vanadium ions in a diluted solution of sulphuric acid vary their oxidation, thus storing electricity in the form of electro-chemical energy. The process reverses during discharging. VRBs offer a storage efficiency of 65–80%, short time response to power demand and a lifetime of about 12,000 charge/discharge cycles (ten years). Unlike other rechargeable batteries, VRBs need little maintenance. The main disadvantages are the complexity of the system (unsuited for mobile applications) and the relatively low energy density by volume. Alternative flow battery concepts include Zn/Br flow batteries (commercial modular units with storage capacity of 50kWh and 500kWh) and other concepts still under development (Zn-Air, Al-Air, Fe-Cr, Zn-Cl).

3.2.4.6 Dry rechargeable batteries and Li-ion batteries

Traditional lead-acid batteries are the lowest-cost rechargeable batteries used in a number of commercial applications (e.g. vehicles), but they have low energy density and offer only short lifetimes if used for electricity storage service in power applications. Other types of batteries, such as advanced deep-cycle lead-acid batteries, NaS batteries and Lithium-ion batteries, are now entering the market of wind and PV electricity storage and grid support service. NaS batteries are based on the sodium-sulfur reaction and require high operating temperatures (300°C). They are suitable only for large-size applications, such as MW-size grid stabilization, load-leveling, utility-scale storage of wind and PV electricity. Lithium-ions batteries are perhaps the most promising technology for both small- and large-scale electricity storage in power generation. Li-ion batteries' applications to power generation require different types of Li-ion batteries, significantly lower costs and safer operation. Industry is currently in the process of improving capacity, power size, reliability and safety for applications to both electrical vehicles and power generation. A key issue relates to safety. The high energy density of Li-ion batteries, abnormal heating due to overcharging, possible short circuits due to lithium precipitation, heat produced at the anode and oxygen at the cathode can result in hazardous operation. In current portable devices, these issues have been solved by internal components and systems, All these systems ensure safe operation but add volume and complexity and increase costs. Li-ion batteries could have a wide range of applications in power generation, including renewable electricity storage for both distributed and centralized installations, grid support and load leveling.

3.2.4.7 Superconducting magnetic energy storage

SMES systems store energy in the magnetic field generated by superconducting magnets working at cryogenic temperature. An SMES system consists of a superconducting coil, a DC/AC converter, a quench protection system and a magnet cooling system. The AC/DC converter rectifies the grid alternate current (AC) to generate the magnetic field where energy is stored. The stored energy can be released back to the grid by discharging the coil through the AC/DC converter. The high cost of the superconductors is the primary barrier to commercial use of SMES for energy storage. Due to the energy needed for refrigeration, SMES is well-suited to short-term energy storage. Several demonstration SMES with power between 200 and 800 kW have been tested in Japan and the United States for distributed grid regulation and stabilization (D-SMES) and power-quality industrial voltage regulators.

The table above shows some characteristics for the explained technologies:

Technology	Energy cost ($/kWh)	Power cost ($/kW)	Operation and maintenance cost ($/kW)	Discharge time[k]	Eff (%)	Lifetime (years)
CAES	10[a]	450[g]	6[j]	3-10h	70[b]	30
Pumped hydro	12[d,e,f]	2000[h]	3[d]	10h	80[h]	40
Pb-acid (lead acid)	300[b]	450[b]	10[d]	10s-4h	75[d]	6
Sodium-Sulfur	534[c]	3000[b]	14[a]	4h	85[b]	15
Vanadium Redox	630[c]	3200[c]	28[a]	2-8h	80[b]	10
Lithium-ion	1500[b]	1500[b]	10[d]	15m-4h	93[b]	15
Flywheels	1000[d]	350[b]	18[a]	15s-15m	90[d]	15

SMES	10000[b]	300[b]	10[d]	1-100s/h	95[d]	20
Supercapacitors	30000[d]	300[b]	13[a]	<30s	95[d]	30

Table 3: summary of cost component data for energy storage technologies[18]

Note on table 3 references:

[a] EPRI (2003a),

[b] Chen et al. (2009),

[c] EPRI (2010),

[d] Schoenung and Hassenzahl (2003),

[e] Schoenung (2001),

[f] Schoennung and Hassenzahl (2007),

[g] Gordon and Falcone (1995),

[h] Ibrahim et al. (2008),

[I] Sels et al. (2001),

[j] EPRI (2003b),

[k] IEA-ETSAP and IRENA Technology Policy Brief, April 2012

[18] Evaluating energy storage technologies for wind power integration, Sandhya Sundararagavan, Erik Baker, 2012

Chapter 4:
System analysis, scenarios and energy-economic models

4.1 The System Analysis concept

Nowadays science and technology are playing an important role in helping policymakers to identify and chart sustainable pathways through complex and interlinked global processes.

The central purpose of the system analysis is to help private decision makers and public policymakers resolve the problems that they face in the short, medium, and long term.

System analysis has been the most helpful tool in addressing issues dominated by science and engineering.

Professor Leen Hordijk (Director of the International Institute for Applied System Analysis from 2002 to 2008) believes that it's possible to explain system analysis using a nine-step framework.

"First, we marshal all the information and scientific knowledge available on the problem in question; if necessary, we gather new evidence and develop new knowledge. Second, we determine what the goals of the stakeholders are, both of the people and the institutions.

Third, we explore different alternative ways of achieving those goals, and we design or invent new options, where appropriate. Fourth, we reconsider the problem in light of the knowledge accumulated. Fifth, we estimate the impacts of the various possible courses of action, taking into account the uncertain future and the organizational structures that are required to implement our proposals. Sixth, we compare the alternatives by making a detailed assessment of possible impacts and consequences. Seventh, we present the results of the study in a framework that facilitates choice by the stakeholders. Eighth, we provide follow-up assistance. Ninth, we evaluate the results."

To study the major global issues is required an understanding of the most relevant drivers of global transformation, including: development and urbanization, economic growth and globalization, population growth and demographic changes, and technological innovations and their diffusion.

In addition, analyses of solutions in these problem areas will need to consider a comprehensive set of impacts on human wellbeing (health and wealth); societal wellbeing (stability and sustainable development); and environmental quality (reduction of pollution, including CO_2 concentration, protection of species and biodiversity).

Problems , drivers, and impact are closely interlinked in system analysis.

While system analysis like any other human endeavor has its limitations and there are other means available to assist the decision maker, it does have a number of virtues. It introduces a certain objectivity into the subjective process of decision making and thus can help with acceptance and implementation of decisions; it can take uncertainty explicitly into account; it determines interactions and side effects; it may reveal unexpected consequences of policies and actions; it may provide insight into issues and suggest better alternatives.

It is more problematical where political, organizational, and social factors predominate and where goals may be obscure and authority diffuse and overlapping. As well as being used to craft good solutions, systems analysis can also be an art in terms of achieving an often delicate balance that satisfies multiple stakeholders.

Concerning energy system analysis, usually problem-driven analysis are conducted to yield new, policy relevant insights that inform energy and environmental planning. A key feature of these project is the use of computer models to analyze how different energy technologies operate together in a linked system that is subject to dynamic changes in energy prices, end-use demand as well as technology cost and performance characteristics. Since energy system models are used to shape energy technology deployment, emissions, and fuel commodity prices, the ability to characterize large future uncertainties is also critical.

These concepts will be analyzed more in deep in the following sections.

4.2 System methods and models to pursue a sustainable development

Since the early 1990s the concept of sustainable development has been receiving considerable and increasing attention by scientist and policy makers alike.

Many definitions of 'sustainable development' have been proposed. Many authors have undertaken initial steps towards concretization of the general concept by defining measurable indicators of sustainable development.

It has become common to look separately at three parts of the general concept. These are social, economic and environmental sustainability.

The modern concept of economic sustainability underscores the sustainability of the economic benefit from natural assets. The rationale behind this idea contends that the flow of economic benefit of natural assets should be preserved because it should be shared between the current and the future generations.

The notion of environmental sustainability goes even further and requires the maintenance of the 'physical property' of the environment. This view requires the preservation of the ecological function of the environment, which is defined in terms of scientific knowledge on ecological property of natural assets.

Concerning the social sustainability its most prominent indicator is of course social equity.

As to the global environment, climate change is the issue that dominates policy making and analysis alike, and many groups analyzing climate change embed this issue in the overall framework of sustainable development.

Energy use is central to climate change, but also to sustainability in general. Addressing both goals at the same time leads to the formulation and analysis of strategies that lead to environmentally compatible and sustainable energy systems.

Many studies have been made to specify and analyze a set of possible circumstances that are consistent with a sustainable path of future developments of the global energy-economy-environmental system.

Why most of studies use scenario to address the uncertainty surrounding the future development of the global energy-economy-environment system?

It is important to distinguish a scenario from forecasts and, even more clearly, from predictions; the most important difference is that forecasts and, to an even higher degree, predictions are meant to portray particularly likely future developments. In contrast, scenarios often include elements that may not be considered the most likely development. This is particularly true for sustainable-development scenarios, which have important 'normative' (prescriptive) elements. Rather, sustainable-development scenarios are meant to enrich the reader's imagination by portraying the possible and, in some instances, by exploring the limits of the plausible. In contrast, scenario that describe the consequence of assuming alternative future states of the world, which usually are meant to be particularly likely, are called 'descriptive'. These scenarios are those that begin in the present and explore trends into the future. By contrast prescriptive scenarios start with a prescribed vision of the future and then work backwards in time to visualize how this future could emerge.

Another distinction is between qualitative and quantitative scenarios. Qualitative scenarios describe possible futures in the form of words or visual symbols rather than numerical estimates. They can take the shape of diagrams, phrases, but more commonly they are made up of narrative texts, the so called 'storylines'. On the other hand, quantitative scenarios provide needed numerical information in the form of tables and graphs. One disadvantage is that quantitative methods are usually based on results of computer models, and these contain many implicit assumptions about the future.

Another useful way to classify scenarios is to distinguish between 'baseline' and 'policy' scenarios. Baseline scenarios are also known as 'reference' scenarios. They present the future state of the society and the environment in which environmental policies either do not exist or do not have a discernible influence on society or the environment.

But it is more difficult than one might think to conceive of a world completely without environmental policies because these policies already permeate society and act directly and indirectly on society and nature.

Whereas baseline scenarios portray a 'default' view of the future, policy scenarios depict the future effects of environmental protection policies. Policy scenarios are also sometimes known as 'pollution control' or 'mitigation' or 'intervention' scenarios.

Future energy systems need an optimized solution among emissions, supply security and the market economy.

A useful tool that can help managers taking decisions are models; they are simplified representations of the real world. In order for models to be useful in supporting decision-makers, they have to be simple to understand and easy to use. At the same time, they have to provide a complete and realistic representation of the decision environment by incorporating all the elements required to characterize the essence of the problem under study.

For example energy-economic models make information available to engineers to design specifications for efficiency, emissions and costs. Just as physical models can predict the impact of increasing CO_2 on climate, energy-economic models can show the economic and technical impact of alternative economic strategies for minimizing emissions.

Technological innovation and efficiency improvements are factors that should also be included in the model (figure 23).

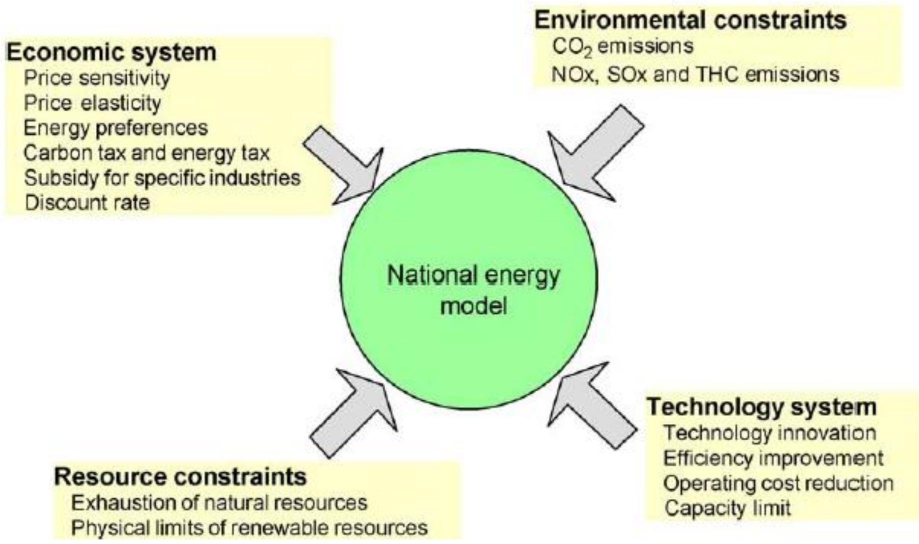


Figure 23: Scheme of national energy models

The main concept of energy-economic models is outlined in figure 24. There are two vectors, energy demand and supply, respectively. Each of these signals has two major factors such as energy quantity and energy price.

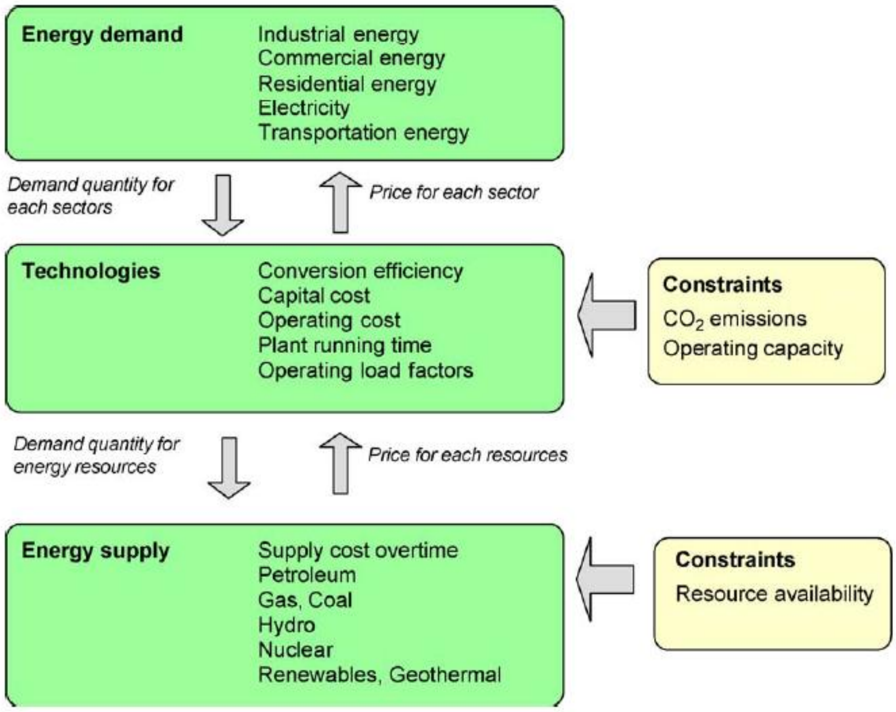


Figure 24: Component of energy-economic model

Top-down and bottom-up models are the two basic approaches to examine the linkages between the economy and the energy system. Top-down models evaluate the system from aggregate economic variables, whereas bottom-up models consider technological options or project-specific climate change mitigation policies.

The difference between their results are rooted in a complex interplay among the differences in purpose, model structure and input assumptions. The term 'top' and 'bottom' are shorthand for aggregate and disaggregate models. The top-down labels come from the way modelers apply macroeconomic theory and econometric techniques to historical data on consumption, prices, incomes, and factor costs to model the final demand for good services, and the supply from main sectors. Some critics complain, however, that aggregate models do not capture the needed sectoral details and complexity of demand and supply.

Macroeconomic models are also often detailed, but in a different way to bottom-up models.

The basic difference is that each approach represents technology in a fundamentally different way. The bottom-up models capture technology in the engineering sense: a given technique related to energy consumption or supply, with a given technical performance and cost.

In contrast, the technology term in top-down models, whatever the disaggregation, is represented by the shares of the purchase of a given input in intermediary consumption, in the production function, and in labor, capital, and other inputs.

Finally, the bottom up model tries to create a more disaggregated picture from the processes and the energy and emissions flows determining the energy system as well as to take relationship between them into account.

4.3 Existing energy-economic models

There are several modeling approaches available in energy economics, based on either equilibrium or optimization approaches.

Computable general equilibrium models construct the behavior of economic agents based on microeconomic principles. The models typically simulate markets for factors of production (e.g. labor, capital, energy), products, and foreign exchange, with equations that specify supply and demand behavior. The models are solved for a set of wages, prices, and exchange rates to bring all of the market in equilibrium.

CGE models examine the economy in different states of equilibrium and so are not able to provide insight into adjustment process.

Dynamic energy optimization models, a class of energy sector models, can also be termed partial equilibrium models. These technology-oriented models minimize the total cost of the energy system, including all end-use sectors, over a 40-50 year horizon and thus compute a partial equilibrium for the energy market. The costs include investment and operation costs of all sectors based on a detailed representation of factor costs. Early version of these models assess how energy demand can be met at least cost. Recent version allow demand to respond to prices. The rich technology information in the models is helpful to assess capital stock turnover and technology learning, which is endogenous in some models.

Integrated energy-system simulation models are bottom-up models that include a detailed representation of energy demand and supply technologies, which include end-use, conversion, and production technologies. Demand and technology development are driven by exogenous scenario assumptions often linked to technology vintage models and econometric forecasts. The demand sectors are generally disaggregated for industrial subsectors and processes, residential and service categories, transport modes, etc.

Table 4 provides a classification of the well-known and used applied energy economic models. They are classified in a different way according to their regional dimension, their bottom-up linear or non-linear programming (LP or NLP) nature, or their top-down input/output (I/O), macro-econometric, general equilibrium or integrated assessment framework.

	National	EU	Global
Input/output models	MIS MEPA		
LP/NLP models	MARKAL TIMES MESSAGE EFOM-ENV	HERMES MIDAS MARKAL TIMES PRIMES	
IA models		ESCAPE	DICE RICE PRICE SLICE CETA
CGE/AGE models	Conrad (D) Bovemberg-Goulder (USA) Jorgenson-Wilcoxen (USA)	GEM-E3 LEAN	
Econometric models	MDM (UK)	QUEST W ARM E3 ME	

Table 4: Existing energy-economic models[19]

The distinction between top-down and bottom-up can generally be typified as the distinction between aggregate and disaggregate models, respectively, or as the distinction between models with a maximum or minimum degree of endogenized behavior. The different aspects associated with top-down and bottom-up models are summarized in Table 5.

[19] Star RM. General equilibrium theory. Cambridge: Cambridge University Press, 1997

Top-down models	Bottom-up models
Use an economic approach	Use an engineering approach
Cannot explicitly represent technologies	Allow for detailed description of technologies
Reflect available technologies adopted by the market	Reflect technical potential
Most efficient technologies are given by the production frontier	Efficient technologies can lie beyond the economic production frontier suggested by market behavior
Use aggregated data for predicting purposes	Use disaggregated data for exploring purposes
Based on observed market behavior	Independent of observed market behavior
Disregard are technically most efficient technologies available, thus underestimate potential for efficiency improvements	Disregard market thresholds thus overestimate the potential for efficiency improvement
Determine energy demand through aggregate economic indices, but vary in addressing energy supply	Represent supply technologies in detail using disaggregated data, but vary in addressing energy consumption
Endogenize behavioral relationship	Assess costs of technological options directly
Assumes no discontinuities in historical trends	Assumes interactions between energy sector and other sector is negligible

Table 5: Characteristics of top-down models and bottom-up models[20]

The difference between top-down and bottom-up models is that the last one tries to create a more disaggregated picture of the processes and the energy and emissions flows determining the energy system as well as to take relationship between them into consideration.

Following a brief explanation of some typical energy-economic models[21]:

MESSAGE is a dynamic linear programming optimization model specifically suited for complex, multi-regional models; it has been developed at the IIASA. The model is typically used in long-term scientific applications, being a bottom-up technology-oriented model, which requires the provision of energy related demands as inputs. The MESSAGE modeling system is generally used for the optimization of energy

[20] Classification of energy models, Van Beeck N., Tilburg University, 1999

[21] Capros P, Vouyoukas EL. Technology evolution and energy modeling: overview of research and findings. Int J Global Energy Issues 2000

supply systems.

MARKAL is a widely applied bottom-up, dynamic linear programming (LP) model developed by the Energy Technology System Analysis Program (ETSAP), of the International Energy Agency (IEA). It was originally designed for the evaluation of the possible impacts of new energy technologies on national or regional systems. It can be applied to scenarios or cases which embody a variety of assumption or restrictions. The MARKAL is written in GAMS. The standard MARKAL-LP model has provision to model material flows within the energy system and to include uncertainties by a stochastic programming approach.

Bottom-up models, such as MESSAGE and MARKAL, are almost exclusively technology snapshot models that examine a suite of technological alternatives over time. They optimize a choice between different technologies using given abatement costs and carbon emissions targets. Both models account for the substantial uncertainty associated with the time of arrival and performance of new technologies by employing a stochastic rather than deterministic optimization technique.

The EFOM-ENV model is a national dynamic optimization model (employing linear programming), which represents the energy producing and consuming sectors in each member state. It optimizes the development of these sectors under given fuel import prices, and useful energy demand, over a pre-defined time horizon.

The TIMES (an acronym for The Integrated MARKAL-EFOM System) model is an economic model generator for local, national, or multi-regional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long term, multi-period time horizon. It is usually applied to the analysis of the entire energy sector, but may also applied to study in detail single sector.

The long-range energy alternatives planning system (LEAP) is a fixed coefficient model runs on EXCEL spreadsheet. It is based on comprehensive accounting of how energy is consumed, converted and produced in a given region under a range of alternative assumptions on population, economic development, technology, price, etc.

MIDAS is a large-scale energy system planning and forecasting model. It performs dynamic simulation of energy systems, represented by combining engineering process analysis and econometric formulations.

GEM-E3, the general equilibrium model for energy-economic-environment, is a multinational, multi-sector, general equilibrium model. It includes detailed representation of the energy supply, energy consumption, polluting emissions related to the latter and damages to environment generated by the emissions.

PRIMES is a price driven partial equilibrium model for energy-environment analysis within the context of market driven behavior. It focuses on market related mechanisms influencing the evolution of energy demand and supply and technology penetration in the market.

4.4 Language and Optimizers of the TIMES model generator

The two models developed under this project were built using TIMES model generator or directly writing GAMS code. In fact, the General Algebraic Modeling System (GAMS) is the computer programming language in which the TIMES Model Generators is written.

GAMS relies heavily on the concepts of sets, compound indexed parameters, dynamic looping and conditional controls, variables and equations.

GAMS integrates seamlessly with a wide range of commercially available optimizers that are charged with the task of solving the LP or Mixed Integer (MIP) that represent the desired model. This step is called the Solve or Optimization step. A solver is a software package integrated with GAMS which solves the mathematical programming problem produced by the Model Generator for a particular instance of the TIMES model. CPLEX or XPRESS are the optimizers most often employed to solve the LP and MIP formulations.

The following sections explain the general structure of the GAMS code first, then present the model developed in GAMS.

Chapter 5 reports the main features of the LP approach.

4.4.1 Structure of a GAMS model

Generally, the creation of GAMS entities involves two steps: a declaration and an assignment or definition. Declaration means declaring the existence of something and giving it a name. Assignment or definition means giving something a specific value or form.

The basic components of a GAMS models are:

Inputs:	Outputs:

`Sets`
Declaration
Assignment of members
Data (`Parameters`, `Tables`, `Scalars`)
Declaration
Assignment of values
`Variables`
	Echo print
	Reference Maps
	Equation listing
	Results

Declaration Assignment of type Assignment of bounds and/or initial values (optional) `Equations` Declaration Definition `Model` and `Solve` statements `Display` statement (optional)	

Table 6: Components of a GAMS model

<u>GAMS input</u>

Sets. Sets are the basic building blocks of a GAMS model, corresponding exactly to the indices in the algebraic representation of models.

Data. Three different formats are allowable for entering data: list, tables, direct assignment.

Variables. The decision variables (or endogenous variables) of a GAMS- expressed model must be declared with a `Variables` statement. Each is given a name, a domain if appropriate, and optionally text.

Once declared, every variable must be assigned a type. The permissible types are:

Variable type	*Allowed Range of Variable*
`free (default)`	-∞ to +∞
`positive`	0 to +∞
`negative`	-∞ to 0
`binary`	0 or 1
`integer`	0,1,…100 (default)

Equations. Equations must be declared and defined in separate statements. The format of the declaration is the same as for other GAMS entities. First comes the keyword, `Equations`, followed by the name, domain, and text of one or more groups of equations or inequalities being declared. Keep in mind that the word `Equations` has a broad meaning in GAMS. It encompasses both equality and inequality relationships, and a GAMS equation with a single name can refer to one or several of these relationships (if it's defined over a certain domain).

Objective function. GAMS has no explicit entity called the objective function. To specify the function to be optimized, you must create a variable, which is free and with no domain and which appears in an equation definition that equates it to the objective function.

Model and Solve statements. The word `model` has a very precise meaning in GAMS.

It is simply a collection of equations. Like other GAMS entities, it must be given a name in a declaration. The format of the declaration is the keyword `model` followed by the name of the model, followed by a list of equation names enclosed in slashes. If all previously defined equations have to be included, it's convenient to enter `/all/` in place of the explicit list.

The format of the solve statement is as follows:

- the keyword `solve`
- the name of the model to be solved
- the keyword `using`
- an available solution procedure. For example:

`lp`	for linear programming
`nlp`	for nonlinear programming
`mip`	for mixed integer programming
`minlp`	for mixed integer nonlinear programming

- the keyword `minimizing` or `maximizing`
- the name of the variable to be optimized

Display. The `solve` statement will cause several things to happen when executed. The specific instance of interest of the model will be generated, the appropriate data structures for inputting this problem to the solver will be created, the solver will be invoked, and the output from the solver will be printed to a file.

<u>GAMS output</u>

Echo Prints. Whether or not errors prevent your optimization model from being solved, the first section of output from a GAMS run is an echo, or copy, of your input file.

Error Messages. When the GAMS compiler encounters an error in the input file, it inserts a coded error message inside the echo print on the line immediately following the scene of the offense. These message always start with **** and contain a '$' directly below the point at which the compiler thinks the error occurred. The '$' is followed by a numerical error code, which is explained after the echo print.

Reference Maps. The next section of output, which is the last if errors have been detected, is a pair of reference maps that contain summaries and analyses of the input file for the purpose of debugging and documentation. The first reference map is an alphabetical list of all entities (sets, parameters, variables and equations) of the model. The second part of the reference map is a list of model entities grouped by type and listed with their associated documentary text.

Equation Listing. The equation listing shows the specific instance of the model that is created when the current values of the sets and parameters are plugged into the general algebraic form of the model.

Model Statistics. The last section of output that GAMS produces before invoking the solver is a group of statistics about model's size. The BLOCK counts refer to the number of generic equations and variables. The SINGLE counts refer to individual rows and columns in the specific model instance being created.

Status report. After the solve executes, GAMS print out a brief solve summary whose two most important entries are SOLVER STATUS and MODEL STATUS.

Solution report. The results are first presented in as standard mathematical programming output format; in this format, there is a line of printout for each row and column giving the lower limit, level, upper limit, and marginal. The single dots '.' in the output represent zeros.

4.5 The GAMS model: Multi-period planning of the electric capacity in Poland

4.5.1 Formulation

The formulation developed is a multi-period Linear Programming (LP) model that is able to realize the optimal mix of electricity supply sources which will meet current and future electricity demand of Poland minimizing the total cost of electricity generation expansion considering several constraint, such as: constraint on air pollution, constraint on the new installable capacity, and constraint on natural gas consumption; over a multi-period planning horizon given an existing reference energy system. The model's planning horizon is 38 years (2013-2050).

In this model system expansion decisions are made to select the type of power generation, such as coal, nuclear, solar, wind, natural gas, or hydro, where the new generation asset should be located, and in which time period expansion should take place.

The developed model was programmed and implemented using the GAMS 24.1.3 optimization package and solved using the IBM ILOG CPLEX 12.5.0.0 solver.

The complete GAMS code is reported in appendix A.

The topology for the existing Polish energy system considered in the model is shown in figure 25. It includes generation units consisting of different technologies: hard coal, brown coal, hydro, wind, natural gas, solar, and nuclear.

For the generation units that use natural gas as fuel it was supposed the possibility for them to draw the fuel from a reserve where the fuel from international natural gas supply system is stored; the storage process was necessary to cope with the uncertainty surrounding this supply system.

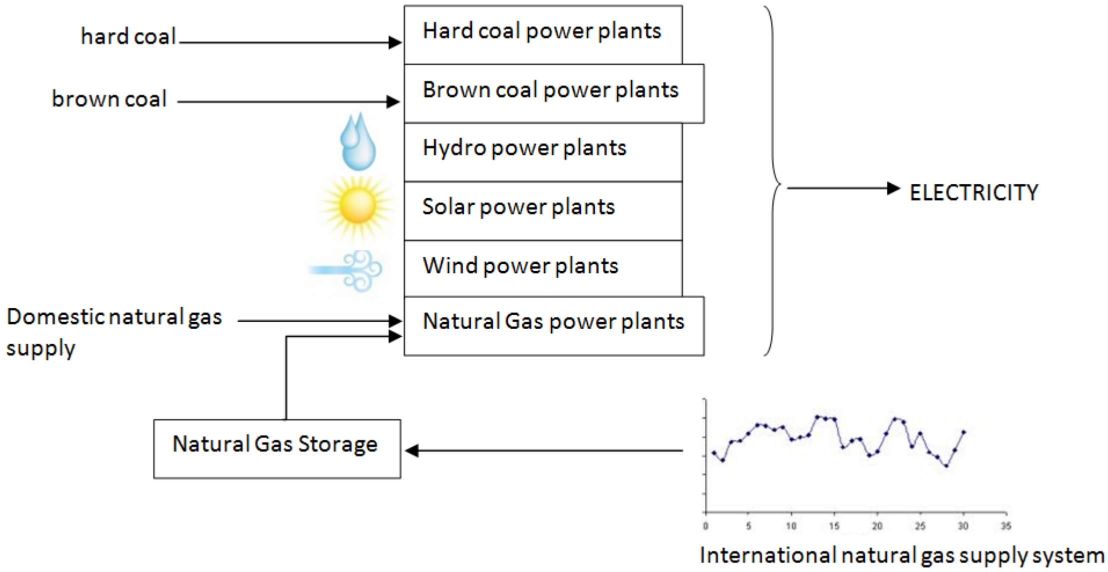


Figure 25: Topology of the existing system

The sets, parameters, scalars, and variables used in the planning model are the following:

<u>Sets</u>

t	Time period	$t \in T$, $T = \{1,2,\ldots,38\}$
tech	existing technologies	$tech \in \pi = \{1,2,..7\}$, where:

1. Hydro
2. Natural gas
3. Hard Coal
4. Brown Coal
5. Nuclear
6. Wind
7. Solar

<u>Parameters</u>

Dem_t	Demand forecast of electricity in MWh in year *t*, $t \in T$
Emi_Target_t	CO_2 emissions target in year *t*, $t \in T \backslash \{1\}$

- Parameters of the technology

$Installed\_CAP_{t,tech}$	Existing installed capacity in MW in year *t*, in technology *tech*, $t \in T$, $tech \in \pi$

Op_hrs_{tech}	Operating hours technology *tech* in hr per year, *tech* $\in \pi$
$Max\_Elc\_Production_{t,tech}$	Technology *tech*'s maximum electricity production in MWh in year *t*, $t \in T$, $tech \in \pi \setminus \{5\}$
CF_{tech}	Capacity factor of technology *tech*, $tech \in \pi$
Eff_{tech}	Efficiency of technology *tech* in fuel's use, $tech \in \pi$
$Lifetime_{tech}$	Lifetime of technology *tech* in years, $tech \in \pi$
crf_{tech}	Capital recovery factor of technology *tech*, $tech \in \pi$
$CO_2\_Emi_{tech}$	CO_2 emissions in ton per MWh produced of technology *tech*, $tech \in \pi$

- Cost parameters

$Inv\_Costs_{t,tech}$	Technology *tech*'s capital cost in € per MW in year *t*, $t \in T$, $tech \in \pi$
$Fix\_Costs\_Tech_{t,tech}$	Technology *tech*'s fix O&M costs, consisting in plant operating labor and regular and irregular maintenance work but also tax and insurance, in € per MW in year *t*, $t \in T$, $tech \in \pi$
$Var\_Costs\_Tech_{t,tech}$	Technology *tech*'s variable O&M costs due to constant maintenance contract and include periodic inspection, replacement, repair of system components, auxiliary materials, in € per MWh year *t*, $t \in T$, $tech \in \pi$
$Fuel\_Costs\_Tech_{t,tech}$	Technology *tech*'s, fuel costs in € per MWh produced year *t*, $t \in T$, $tech \in \pi$

- Natural gas storage parameters

$NGas\_Supply\_Limit_t$	Upper limit in international import of natural gas in m^3 in year *t*, $t \in T$
Initial_Stored_NGas	m^3 of natural gas stored in year 1

<u>Scalars</u>

r	Discount rate
Max_Nucl_Cap	Upper limit in nuclear capacity installation: max of 1500MW every 5 year
Emi_Cieiling_StartYr	CO_2 emissions ceiling for year 1
CO_2_Tax	Carbon tax in euro per tonCO_2
Base_NGas	Percentage of natural gas storage capacity that is intended as permanent inventory in a storage reservoir

	to maintain adequate pressure
Stg_Capacity	NatGas maximum storage capacity in m^3

Positive variables

$CAP_{t,tech}$	Technology *tech*'s total available capacity in MW in year *t* technology *tech*, $t \in T$, $tech \in \pi$
$NCAP_{t,tech}$	Technology *tech*'s new capacity brought online at the beginning of *t* in MW technology *tech*, $t \in T$, $tech \in \pi$
$Annual\_Elc\_Prod_{t,tech}$	Total electricity produced from technology *tech* in MWh in year *t*, $t \in T$, $tech \in \pi$
Tot_Emi_t	Total CO_2 emissions in ton year *t*, $t \in T$

- Natural gas storage process variables

$NGas\_Consumption_t$	Consumed natural gas for electricity production in m^3 year *t*, $t \in T$
$Domestic\_NGas\_Supply_t$	Natural gas domestic supply in m^3 in year *t*, $t \in T$
$International\_NGas\_Supply_t$	International supply of natural gas in m^3 in year *t*, $t \in T$
$Stored\_NGas_t$	m^3 of natural gas stored in year *t*, $t \in T$
$Stored\_NGas\_Consumption_t$	Consumption of stored natural gas in m^3 in year *t*, $t \in T$

- Cost variables

$Tot\_Inv\_Costs_{t,tech}$	Investment in new capacity in € in year *t* and technology *tech*, $t \in T$, $tech \in \pi$
$Tot\_Fixed\_Costs_{t,tech}$	Fixed O&M costs in € in year *t* and technology *tech*, $t \in T$, $tech \in \pi$
$Tot\_Var\_Costs_{t,tech}$	Variable O&M costs in € in year *t* and technology *tech*, $t \in T$, $tech \in \pi$
$Tot\_Fuel\_Costs_{t,tech}$	Fuel cost in € in year *t* and technology *tech*, $t \in T$, $tech \in \pi$
$Tot\_Ann\_Costs_t$	Total annual cost in year *t*, $t \in T$
$Carbon\_Tax_t$	Cost of CO_2 emissions in year *t*, $t \in T$

Free variable

Tot_Expansion_Costs	Total cost of capacity expansion in €

All the parameters used in the model are being specified by the programmer, except for some of them which have been derived from other parameters. They are:

- CF : the capacity factor of a power plant is the ratio of its actual output over a period of time, to its potential output if it were possible for it to operate at full capacity indefinitely considering an installed capacity of 1 MW. Having said that we define the CF as:

$$CF_{tech} = \frac{Op\_hrs_{tech}}{8760hr/year} \qquad \forall\, tech \in \pi$$

- Crf: the capital recovery factor is defined as the ratio between an uniform annual value and the present value of the annual stream. We define:

$$crf_{tech} = \frac{r*(1+r)^{Lifetime_{tech}}}{(1+r)^{Lifetime_{tech}-1}} \qquad \forall\, tech \in \pi$$

Technologies availability

The table below shows the technologies included in the existing system and their installed capacities, operating hours, efficiency, lifetime and CO_2 emissions characteristics:

Technology	$Installed\_CAP_{1,tech}$ [MW]	Op_hrs_{tech} [hr/yr]	Eff_{tech}	$Lifetime_{tech}$ [yr]	$CO2\_Emi_{tech}$ [ton/MWh]
HYDRO	1000	3000	1	80	0.004
NATURAL GAS	1500	5000	0.5	30	0.752
HARD COAL	18480	6000	0.4	40	0.9
BROWN COAL	14520	6000	0.4	40	0.341
NUCLEAR (III generation)	0	6500	0.34	50	0.016
WIND (onshore)	2500	2000	1	20	0.012
SOLAR (PV)	1.3	1400	1	20	0.046

Table 7: Technical data of the existing technologies

In the following pages are the graphs with the time course of the parameters previously declared.

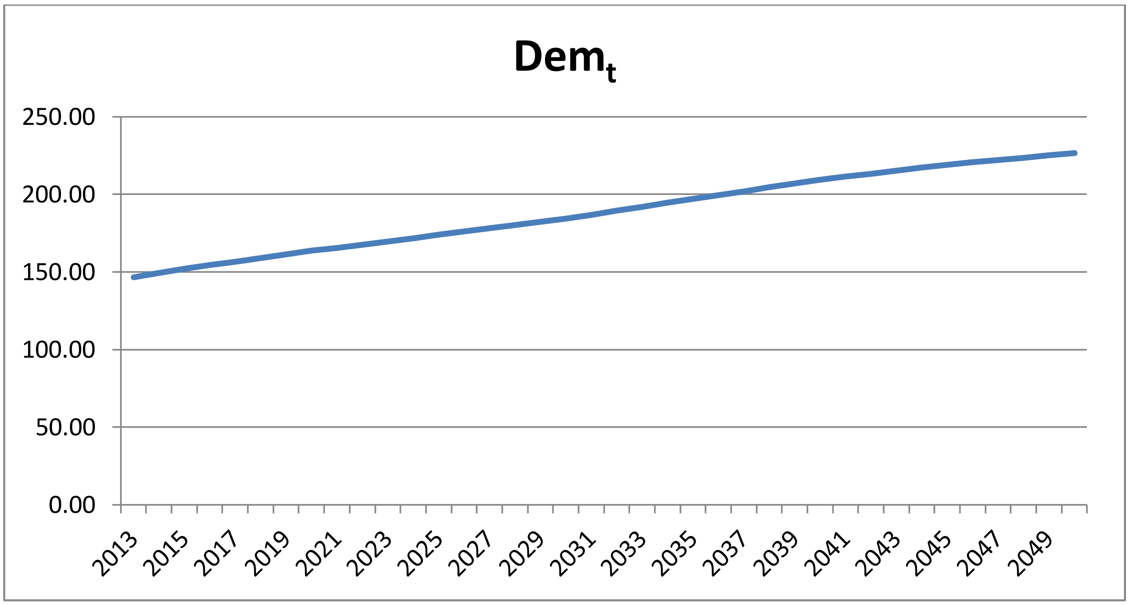


Figure 26: Demand forecast in TWh[22]

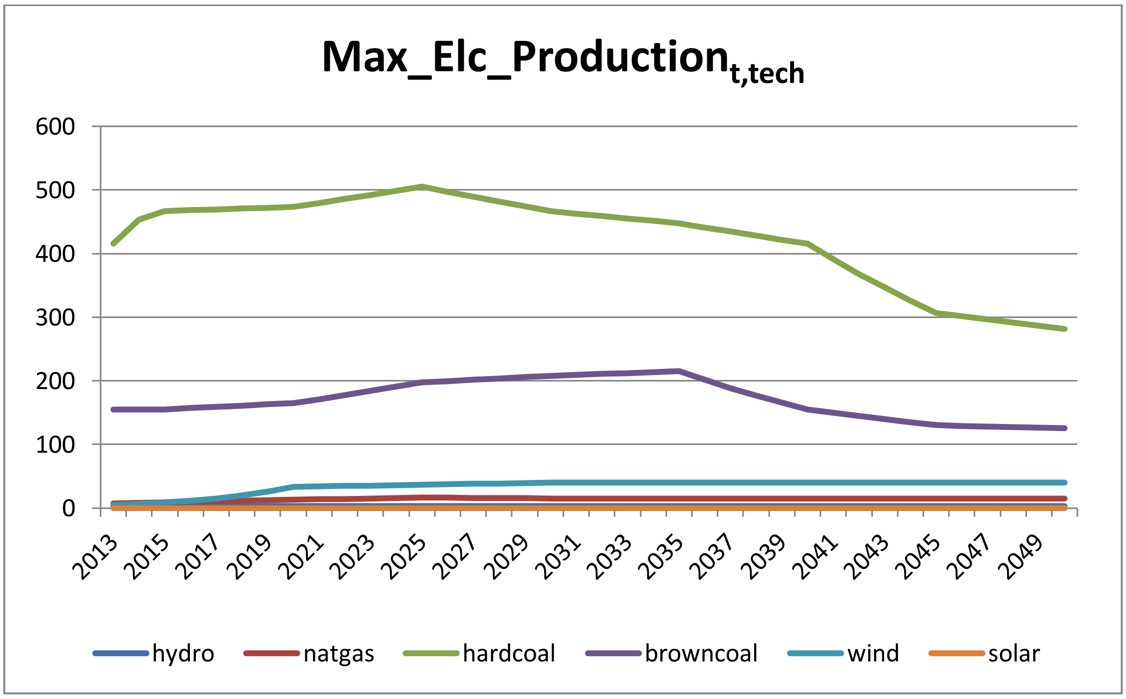


Figure 27: Maximum electricity production in TWh depending on the maximum installable capacity per year[23]

[22,23] EC BREC IEO, ARE SA, Wegiel dla polskiej energetyki w perspektywie 2050 roku analizy scenariuszowe, Katowice 2013

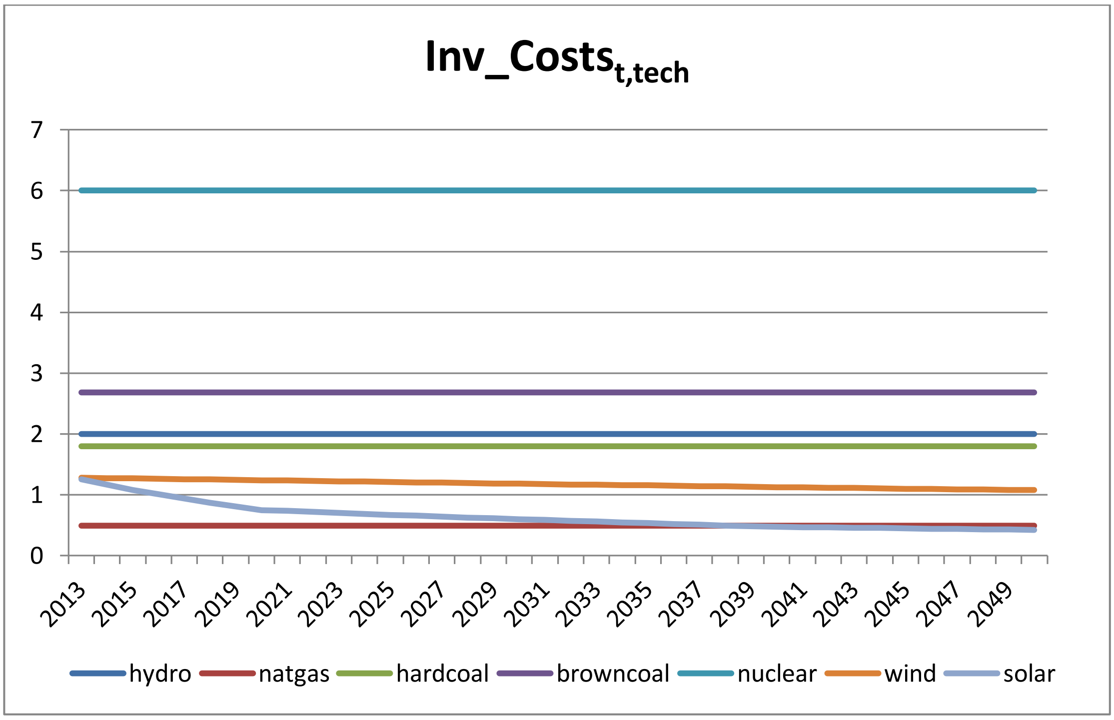


Figure 28: capital costs [€/TWh][24] source:

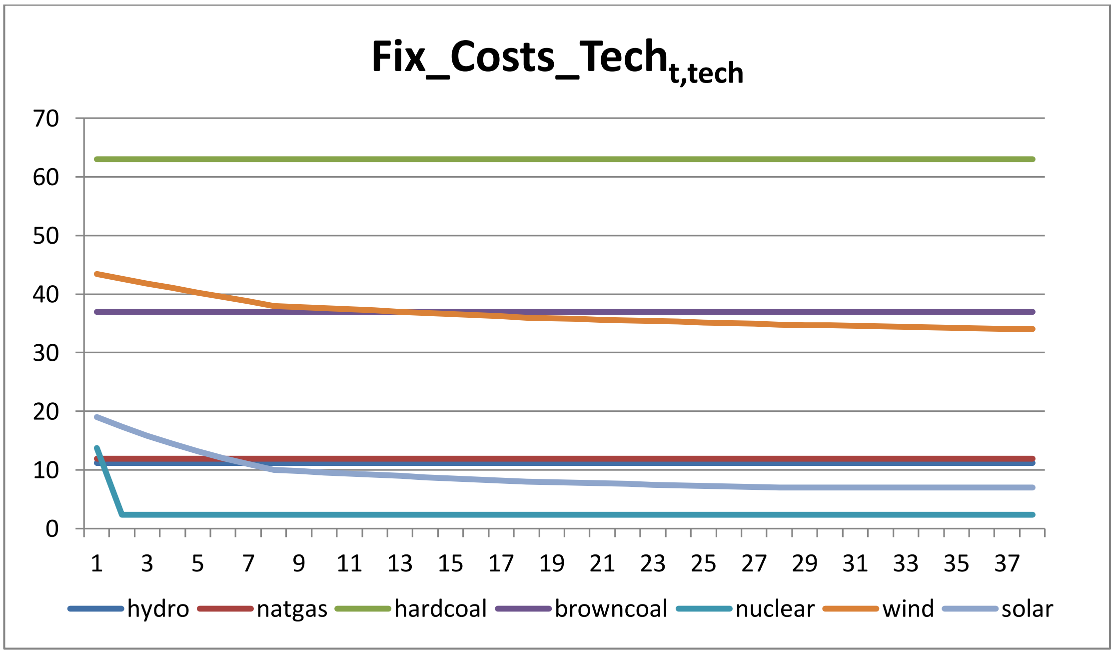


Figure 29: Fixed costs [€/GW][25]

[24,25] Current and Prospective Cost of Electricity Generation until 2050, DIW BERLIN 2013

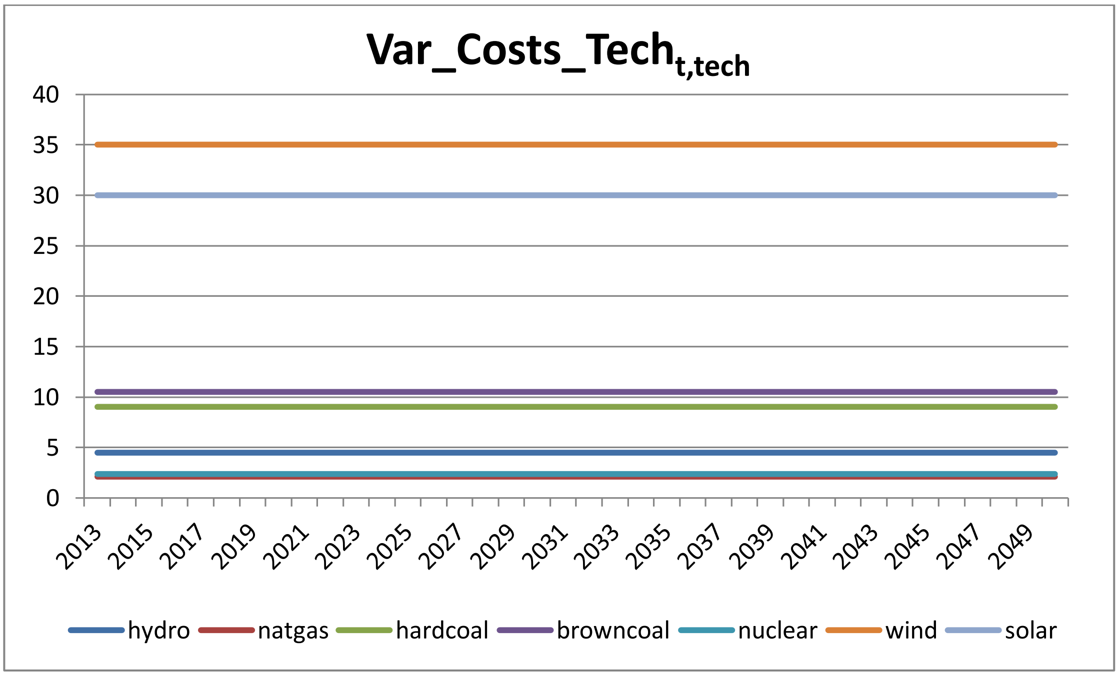


Figure 30: Variable costs [€/MWh][26]

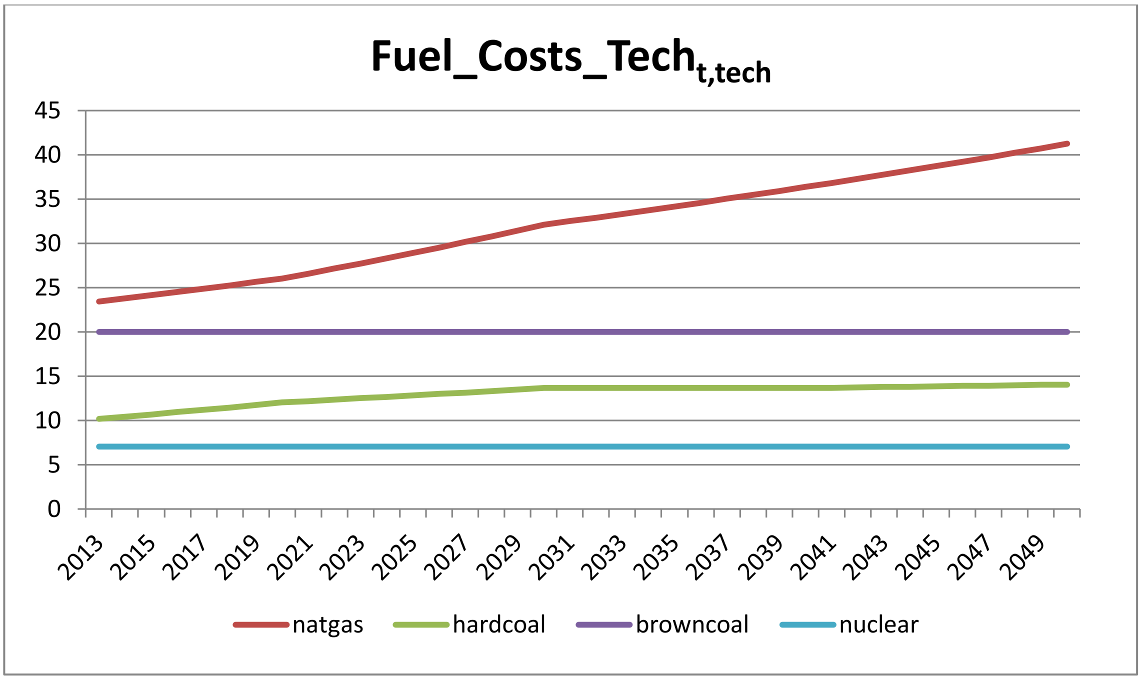


Figure 31: fuel costs [€/MWh][27]

[26] Current and Prospective Costs of Electricity Generation until 2050, DIW BERLIN 2013
[27] Roadmap 2050, part I

4.5.2 Assumptions

The main assumptions of the model are:

- The new capacity installed will be immediately available: this model doesn't take in account the lead time required to build the plant.
- The existing capacity will be decommissioned by annual 5% in the years following the start year.
- The discount rate is 3%.
- The existing natural gas storage capacity in Poland is 1,828mln cubic meters[28].
- The 'base' natural gas, as percentage of the maximum storage capacity, is the minimum request level of natural gas stored to maintain adequate pressure and it's 0.3 for salt formation, 0.5 for depleted reservoir and 0.8 for aquifer reservoir and; for this model it has been assumed 0.3.
- The initial natural gas stored is equal to the 'base' level.
- The cost of the natural gas supplied by the international grid is 5% higher than the domestic one.
- The maximum amount of domestic natural gas that can be supplied is fixed, we suppose that the international natural gas system will always provide enough natural gas to satisfy the power plants' need.
- The emissions ceiling for the start year is 270 mln tonCO_2.
- The carbon tax was considered 58€ per tonCO_2[29]

4.5.3 Objective function

The objective function of the planning model is to minimize the total cost of capacity expansion associated with meeting electricity demand while satisfying several constraints over a specific planning horizon.

The components associated with the objective function include: fixed and variable operating and maintenance cost, fuel cost, and capital cost for new power plants. Note that in the expression the total cost is not discounted because the used costs are already discounted.

The objective function for the deterministic multi-period LP model is as follows:

[28] Gas Infrastructure Europe: GSE Storage Map 2011

[29] Vivid Economics, Carbon taxation and fiscal consolidation: the potential of carbon pricing to reduce Europe's fiscal deficits, report prepared for the European Climate Foundation and Green Budget Europe, May 2012

$$\min f\ (t, tech) = \ min \sum_{t \in T} \sum_{tech \in \pi} (Tot\_Inv\_Costs_{t,tech} + Tot\_Var\_Costs_{t,tech} + \ Tot\_Fixed\_Costs_{t,tech} + \ Tot\_Fuel\_Costs_{t,tech}) + \sum_{t \in T} Carbon\_Tax_t$$

Where:

- $Tot\_Var\_Costs_{t,tech} = \ CAP_{t,tech} * Op\_hrs_{tech} * Var\_Costs\_Tech_{t,tech}$ $\quad \forall\ t \in T, \forall\ tech\ \in \pi$
- $Tot\_Fixed\_Costs_{t,tech} = \ CAP_{t,tech} * Fix\_Costs\_Tech_{t,tech}$ $\quad \forall\ t \in T, \forall\ tech\ \in \pi$
- $Tot\_Fuel\_Costs_{t,tech} = \frac{CAP_{t,tech} * Op\_hrs_{tech}}{Eff_{tech}} * Fuel\_Costs\_Tech_{t,tech}$ $\quad \forall\ t \in T, \forall\ tech\ \in \pi$

Concerning the capital, or investment, costs the user can choose between 2 option:

1. The investment costs are paid in a single amount in the year in which the investment in new capacity is done:

- $Tot\_Inv\_Costs_{t,tech} = \ NCAP_{t,tech} * Inv\_Costs_{t,tech}$ $\quad \forall\ t \in T, \forall\ tech\ \in \pi$

or,

2. The investment costs are annualized and spread over all the years within the lifetime of the technology

- $Tot\_Inv\_Costs_{t,tech} = \ CAP_{t,tech} * Inv\_Costs_{t,tech} * crf_{tech}$ $\quad \forall\ t \in T, \forall\ tech\ \in \pi$
- $Carbon\_Tax_t = \ CO_2\_Tax * Tot\_Emi_t$ $\quad \forall\ t \in T$

4.5.4 Constraints

The objective function discussed in the previous section is subject to the following constraints.

<u>Available capacity in year t</u>

The available capacity of technology *tech* in year *t* must include the existing capacity, the new capacity brought online at the beginning of t, and the new capacity built in the previous years such that the gap between *t* and the construction year is greater than zero.

$$CAP_{t,tech} = \ Installed\_CAP_{t,tech} + \sum_{j\ =\ max\{1, t-(Lifetime_{tech}-1)\}}^{t} NCAP_{j,tech} \qquad \forall t, \forall tech$$

<u>Annual electricity demand</u>

The annual electricity generated from the power system must be greater or equal to the annual electricity demand:

$$\sum_{tech \in \pi} CAP_{t,tech} * Op\_hrs_{tech} \geq Dem_t \qquad \forall t$$

<u>Maximum electricity production</u>

The total electricity production from a certain technology in year t must be lower or equal to the maximum electricity production potential, based on the maximum installed capacity potential of that technology in that year.

$$CAP_{t,tech} * Op\_hrs_{tech} \leq Max\_Elc\_Production_{t,tech} \qquad \forall t$$

<u>Decarbonization path</u>

The emissions target for a certain year have been calculated accordingly to the 'decarbonization path' under which the emissions ceiling decreases linearly over the years to reach 50% of the initial ceiling in the last year :

$$Emi\_Target_t = Emi\_Ceiling\_StartYr - (\frac{0.5*Emi\_Ceiling\_StartYr}{37}) * (t-1) \qquad \forall\, t$$

Thus, the total CO_2 emissions generated from the power system in the year t must be lower or equal to the emissions target, for each year:

$$\sum_{tech \in \pi} CO_2\_Emi_{tech} * Annual\_Elc\_Prod_{t,tech} \leq Emi\_Target_t \qquad \forall t$$

<u>Natural Gas storage process</u>

The consumption of natural gas for electricity production in year t must be satisfied by the domestic supply and, when it is not enough, by the natural gas from the reserve supplied by the international natural gas supply system:

$$Domestic\_NGas\_Supply_t + Stored\_NGas\_Consumption_t = NGas\_Consumption_t \qquad \forall t$$

The storage process is controlled by a dynamic equation, that is:

$$Stored\_NGas_t = Stored\_NGas_{t-1} + International\_NGas\_Supply_t - Stored\_NGas\_Consumption_t \qquad \forall t$$

<u>Maximum nuclear new capacity installed</u>

The overall nuclear installed new capacity within a period of five years, starting from 2025 - thus the period from 2025 to 2030, from 2030 to 2035, etc. - must be lower or equal to 1.5 GW. Since the nuclear technology will be available for installation from 2025 it was created a subset of *t* containing all the years that are multiples of 5; this subset, called *s,* will be:

s = {18, 23, 28, 33, 38}

and the constraint formulated as:

$$\sum_{i\,=\,j-4}^{j} NCAP_{j,5} \leq Max\_Nucl\_Cap \qquad \forall j, j \in s$$

4.5.5 Results

The results of this model are analyzed for two Cases: Case Study 1, the base case without any climate policy applied, and Case Study 2, the alternative case with CO_2 ceilings and carbon tax.

4.5.5.1 Case Study 1: Base Case

The base case represent a scenario in which no climate policy initiative are considered on the electricity sector. The table below illustrates the new capacity built in each year for each technology:

New capacity brought online at the beginning of t in MW				
t	Hydro	Natural Gas	Hard coal	Solar
2019	293.41	-	571.66	-
2020	41.58	-	1678.12	-
2021	34.91	-	1560.01	-
2022	33.17	-	1502.87	-
2023	31.51	-	1448.85	-
2024	29.93	-	1397.79	-
2025	28.44	-	1349.54	-
2026	27.02	-	1289.73	-
2027	25.66	-	1246.36	-
2028	24.38	-	1205.42	-
2029	23.16	-	1166.77	-
2030	22.006	-	1130.31	-
2031	20.91	-	1140.53	35.19
2032	19.86	-	1117.68	0.025
2033	18.86	-	1088.53	0.024
2034	17.92	-	1061.19	0.023
2035	17.03	-	1035.59	0.022
2036	16.18	-	967.67	0.021
2037	15.36	-	944.16	0.020
2038	14.60	-	922.13	0.019
2039	13.87	-	901.51	0.018
2040	13.17	-	882.24	0.017
2041	12.51	-	756.65	0.016
2042	11.89	-	737.58	0.015
2043	11.29	-	719.63	0.014
2044	-	-	708.12	0.014
2045	-	-	691.99	0.013
2046	-	153.54	463.34	0.012
2047	-	690.87	-	0.012
2048	-	673.24	-	-
2049	-	656.60	-	-
2050	-	640.91	-	-

Table 8:New capacity needed to meet the demand in MW in the Base Case

Figure 32 shows the total power allocated in MW from each supply technology. Total percentage of power allocated to each generating technology for years 2013, 2025,2035,2050 is given in figure 33.

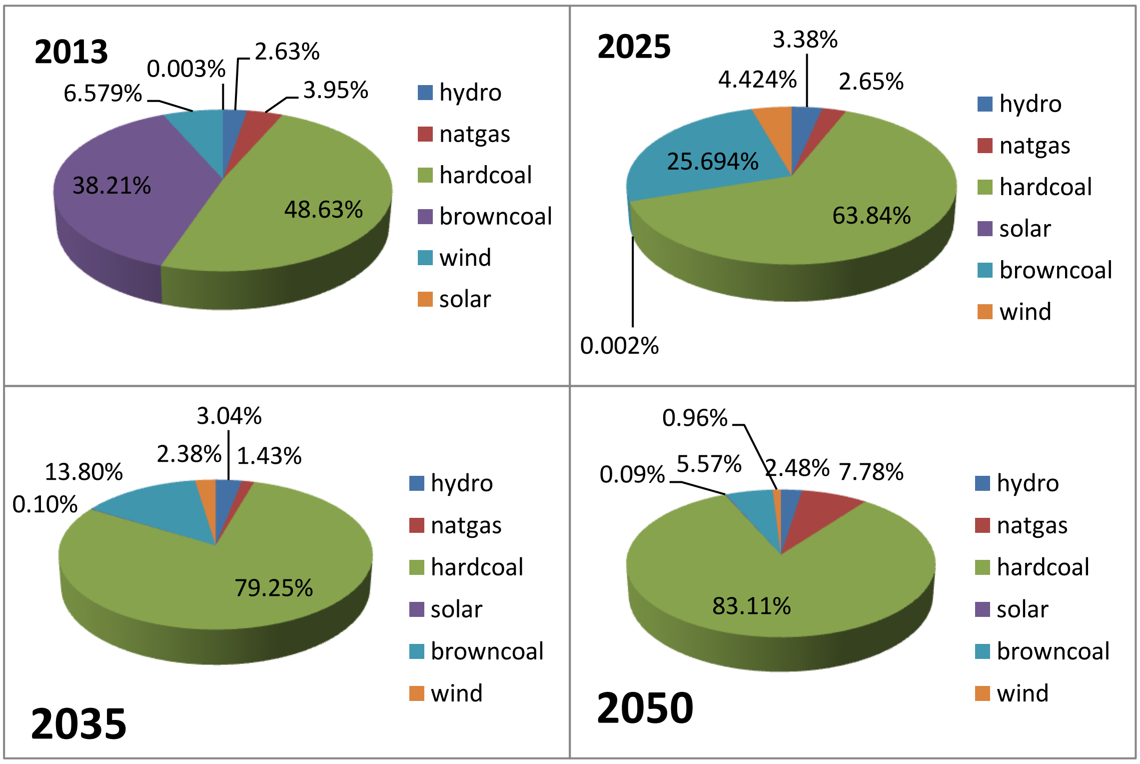
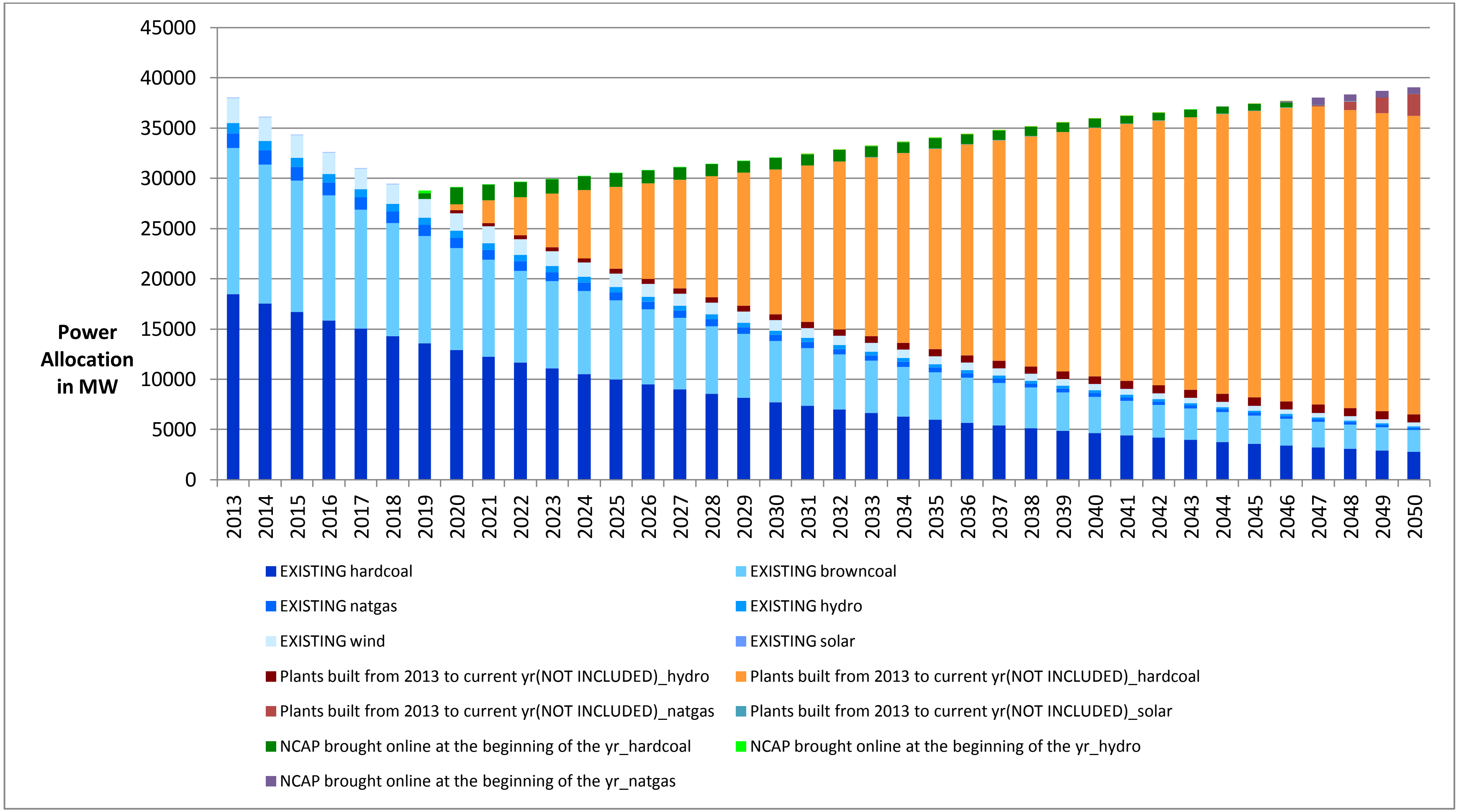


Figure 32: Percentage of power allocation by source for selected years in the Base Case

From figure 32 and 33 it can be seen that without constraint in CO2 emissions the most attractive source in terms of cost remains the hard coal. The role of renewable source is marginal in each year considered.

No nuclear or wind or brown coal power plants were constructed during the time horizon considered, and hence no power was allocated from these supply sources due to the high costs of fuel and/or capital costs.

Figure 33: Total power allocation in MW over the planning horizon



As shown in figure 34 the most of electricity in the base case will be generated from hard coal source.

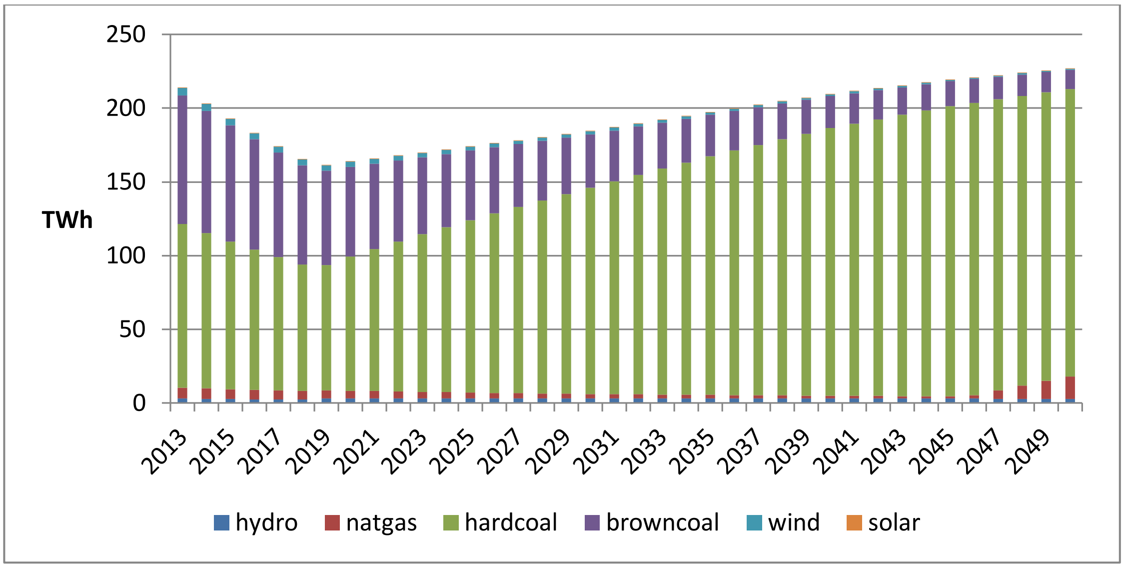


Figure 34: Base Case: electricity production in TWh by source

<u>Economic analysis</u>

The annual expenditure of the entire electricity sector is shown in Figure 28. The annual expense consist of: variable operational and maintenance costs, fixed O&M costs, capital or investment costs for construction of new power station.

As shown in figure 35 the major factors that contribute to the cost of generating electricity are fuel cost: hard coal, brown coal and natural gas.

Figure 36 illustrates the annual COE (Cost of Electricity) for the Base case. The COE values were obtained by dividing the total annual expenditure with the annual electricity production.

In this case the final cost of capacity expansion over the planning horizon considered amounts to:

463.294 bln €

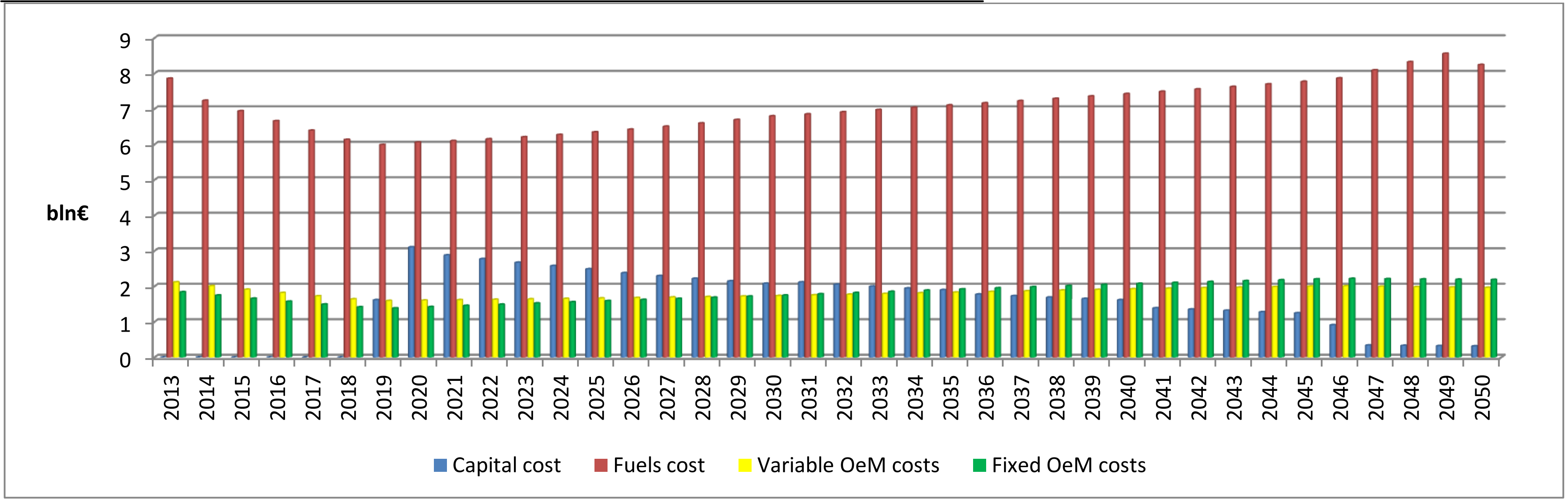


Figure 35: Annual expenditure by costs type in the Base Case

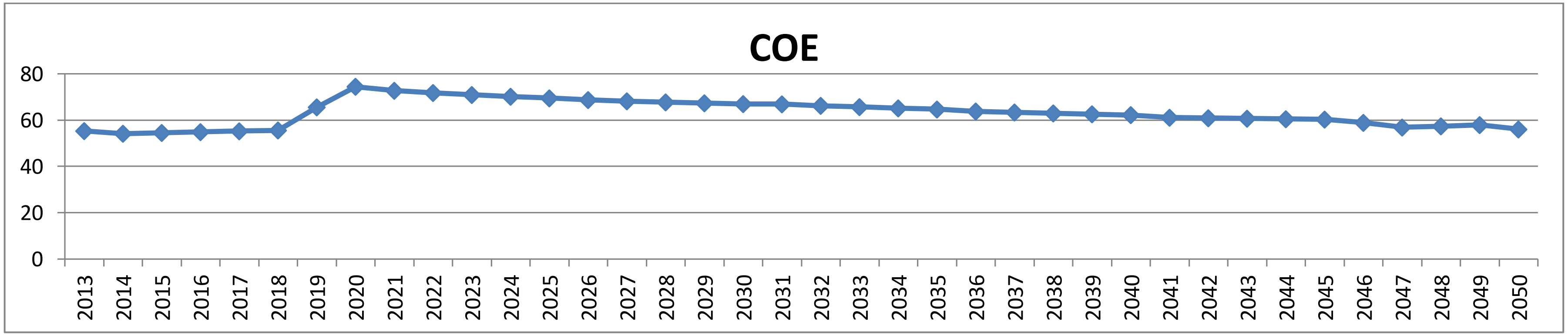


Figure 36: Cost of electricity in € per MWh

Carbon dioxide emissions

Annual CO_2 emissions from the entire fleet are presented in figure 37.

Note that no CO_2 emissions limits are imposed on the base case, and hence is expected that the base case will have the highest CO_2 emissions.

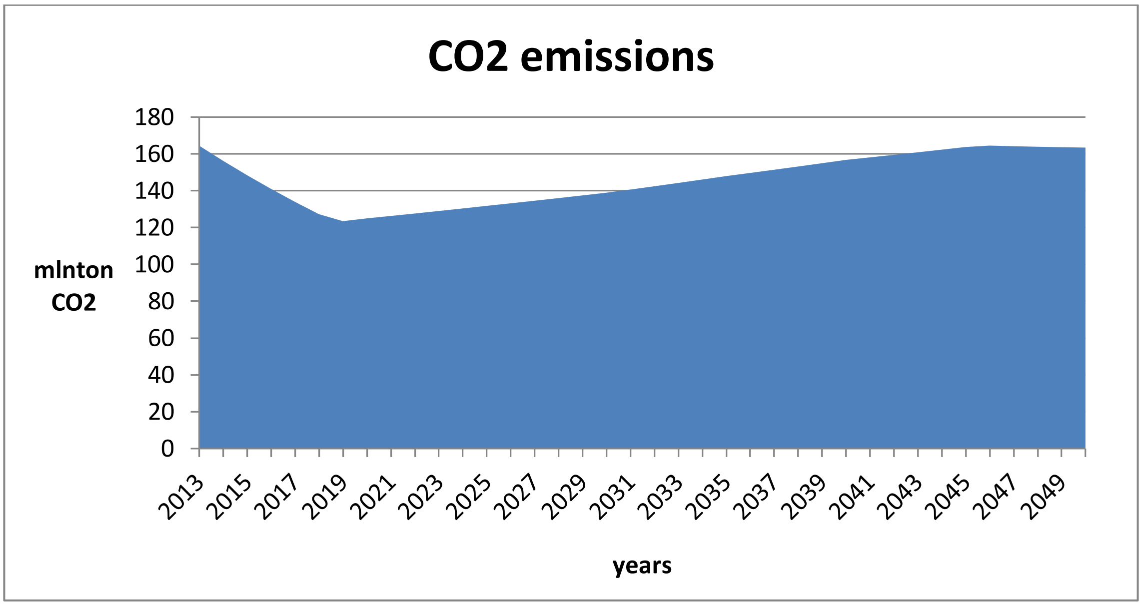


Figure 37: Annual CO_2 emissions for the Base Case

4.5.5.2 *Case Study 2: CO_2 emissions ceilings and carbon tax*

Case study 2 presents a scenario in which polish electricity sector must comply with annual CO_2 emissions below annual emissions ceiling, imposed by EU. Moreover, this case assumes the existence of carbon tax[30].

Table 9 illustrates the construction of new power stations for Case study 2.

New capacity brought online at the beginning of t in MW					
t	Hydro	Natural Gas	Hard coal	Wind	Solar
2019	293.41	-	-	1714.98	-
2020	41.58	-	278.27	4197.68	2.66
2021	34.91	1735.14	113.83	-	0.97
2022	33.17	186.56	1347.12	-	1.20
2023	31.51	190.92	1289.39	-	1.50
2024	29.93	61.63	1345.99	-	1.88
2025	28.44	-	1348.99	-	2.36
2026	27.018	-	1289.04	-	2.96
2027	25.66	-	1245.50	-	3.71

[30] A carbon tax is a tax levied on the carbon content of fuels, it's a form of carbon pricing.

2028	24.38	-	1205.42	-	-
2029	23.16	-	1166.77	-	-
2030	22.00	-	1130.31	-	-
2031	20.90	-	-	3433.69	17.93
2032	19.86	-	-	3353.04	0.025
2033	18.86	-	-	3265.59	0.024
2034	17.92	-	-	3183.59	0.023
2035	17.028	-	1021.40	42.57	0.022
2036	16.17	-	954.18	40.44	0.021
2037	15.36	-	931.35	38.42	0.019
2038	14.59	-	909.97	36.49	0.018
2039	13.86	-	889.96	1749.65	0.018
2040	13.176	-	871.26	4230.62	2.68
2041	12.51	-	746.22	31.29	0.98
2042	11.89	-	727.67	29.73	1.22
2043	11.29	-	710.22	28.24	1.52
2044	10.73	-	693.81	26.83	1.89
2045	10.19	-	678.40	25.48	2.37
2046	9.68	-	586.44	-	2.97
2047	-	-	575.72	-	3.72
2048	-	-	561.03	-	0.011
2049	-	-	547.16	-	0.010
2050	-	640.91	-	-	0.010

Table 9:New capacity needed to meet the demand in MW in the Case Study 2

Total percentage of power allocated to each generating technology for years 2013, 2025,2035,2050 is given in figure 38. Figure 39 shown the Total power allocated in MW from each supply technology.

From fig. 38-39 it can be seen that wind power plays an increasingly important role, while brown coal capacity will decrease over the time horizon due to its decommissioning and due to the fact that no new brown coal power plant have been built.

Notice that no nuclear power plants have been built, this is due to their high capital and fuel costs.

The capacity fluctuation among years is due to the decommissioning of the existing capacity, which decreases the installed capacity every year.

As shown in fig. 40 hard coal will continue to play a fundamental role in electricity production but this time another significant role is played by wind power. Indeed the wind capacity installed from 2035 will be the maximum available.

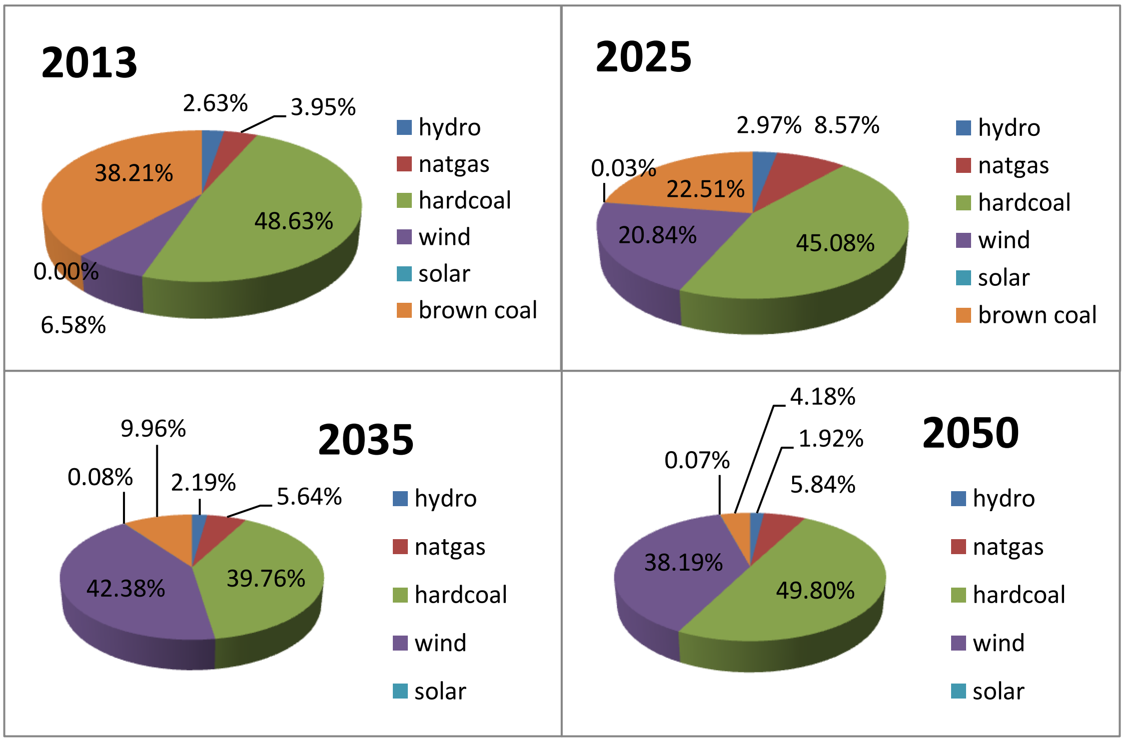


Figure 38: Percentage of power allocation by source for selected years in the Case Study 2

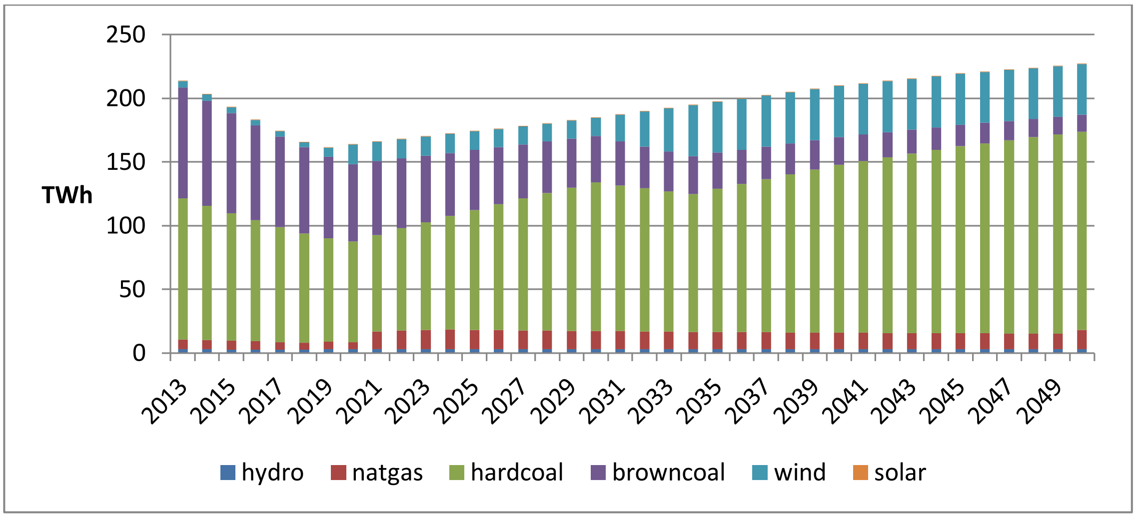
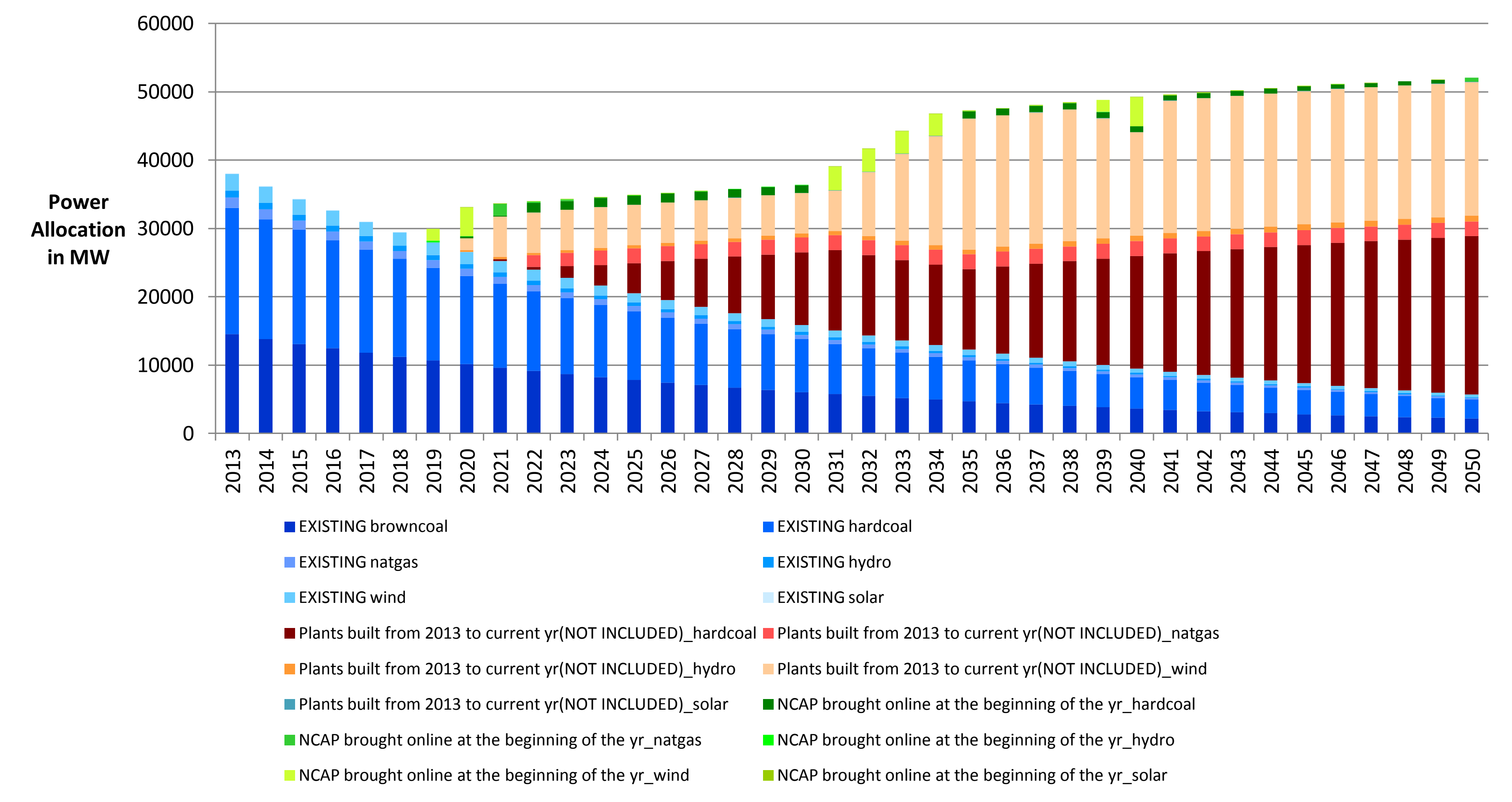


Figure 40: Case Study 2: electricity production in TWh by source

Figure 39: Total power allocation in MW over the planning horizon



Economic analysis

The annual expenditure of the entire electricity sector is shown in Figure 41. The annual expense consist of: variable operational and maintenance costs, fixed O&M costs, capital or investment costs for construction of new power station, and carbon tax.

Figure 41 shows also that the major factors that contribute to the cost of generating electricity are fuel cost and emissions taxation.

Figure 42 illustrates the annual COE for the CO_2 restriction case. The CoE values were obtained by dividing total annual expenditure with the annual electricity production.

In this case the final cost of capacity expansion over the planning horizon considered amounts to:

764.936 bln €

Carbon Dioxide Emissions

Annual CO_2 emissions from the entire fleet are presented in figure 43.

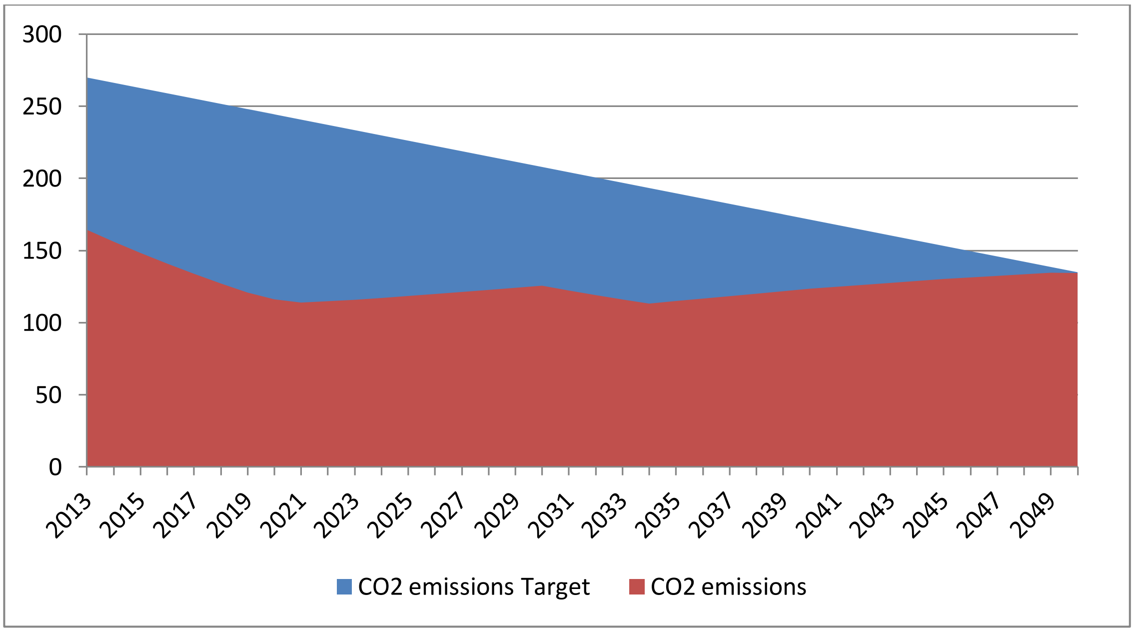


Figure 43: annual CO_2 emissions for the Case Study 2

As we can see in this case CO_2 emissions are lower than in the first case and the system maintains always the emissions under the ceiling imposed.

Due to the lack of accurate data on the potential installable capacity from renewable resources the model fulfill the total available renewable capacity by 2035; after that time the model has to build coal plants to meet the growing

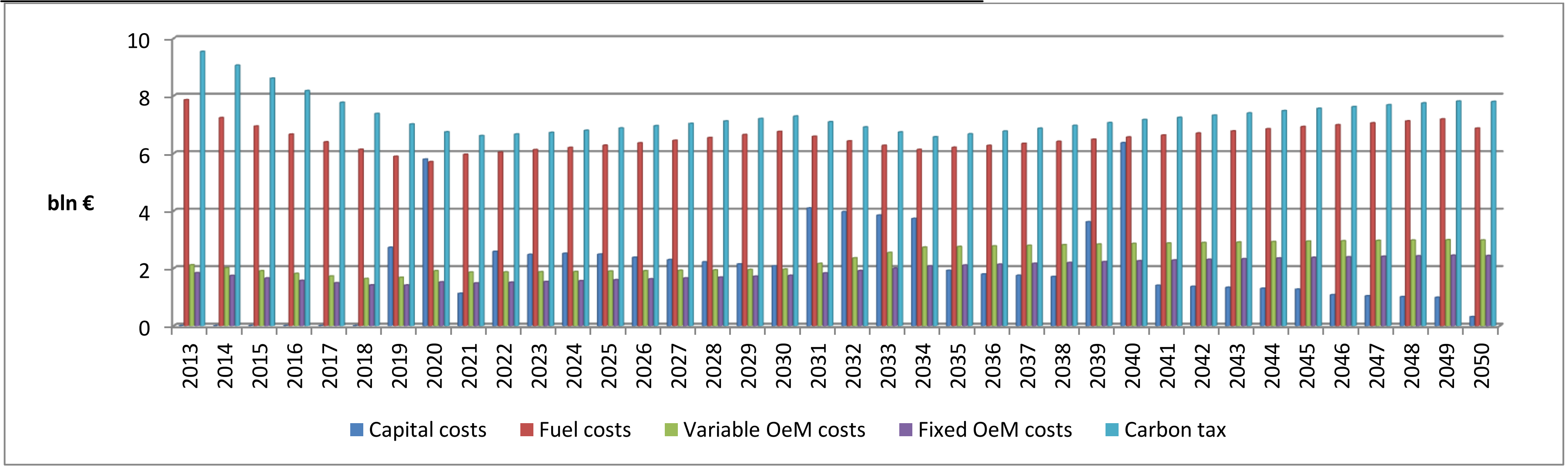


Figure 41: Annual expenditure of the entire electricity sector in the Case Study 2

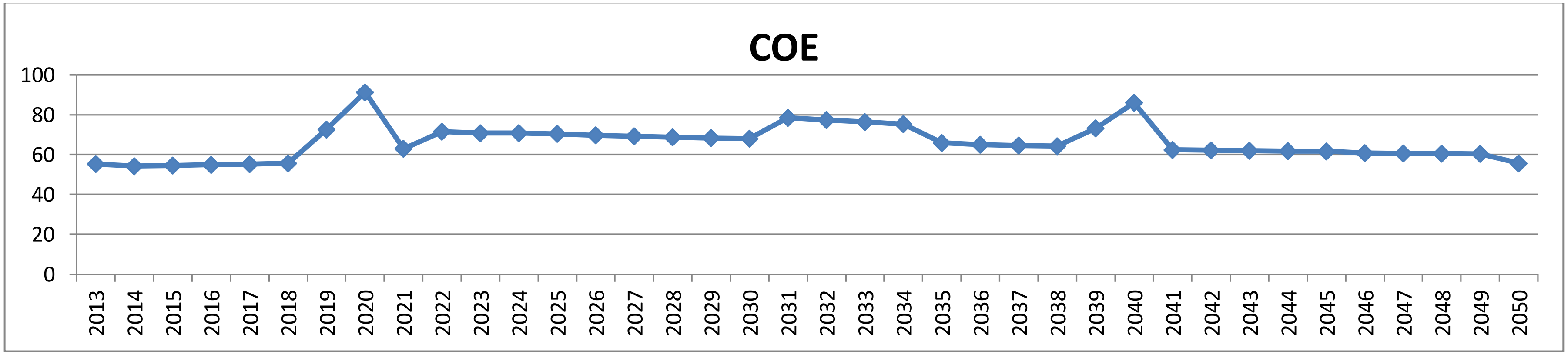


Figure 42: cost of electricity in € per MWh for the Case Study 2

demand of electricity. That's why the model results infeasible when the parameter Emi_Cieiling_StartYr is set lower than 270mln ton. When new data about renewable potential will be available the user can update the excel file contains the value of all parameters and solve again the model with a lower Emi_Cieiling_StartYr.

Natural gas storage process

With the intention to show how the natural gas storage process works the graph of its dynamics is displayed in figure 44.

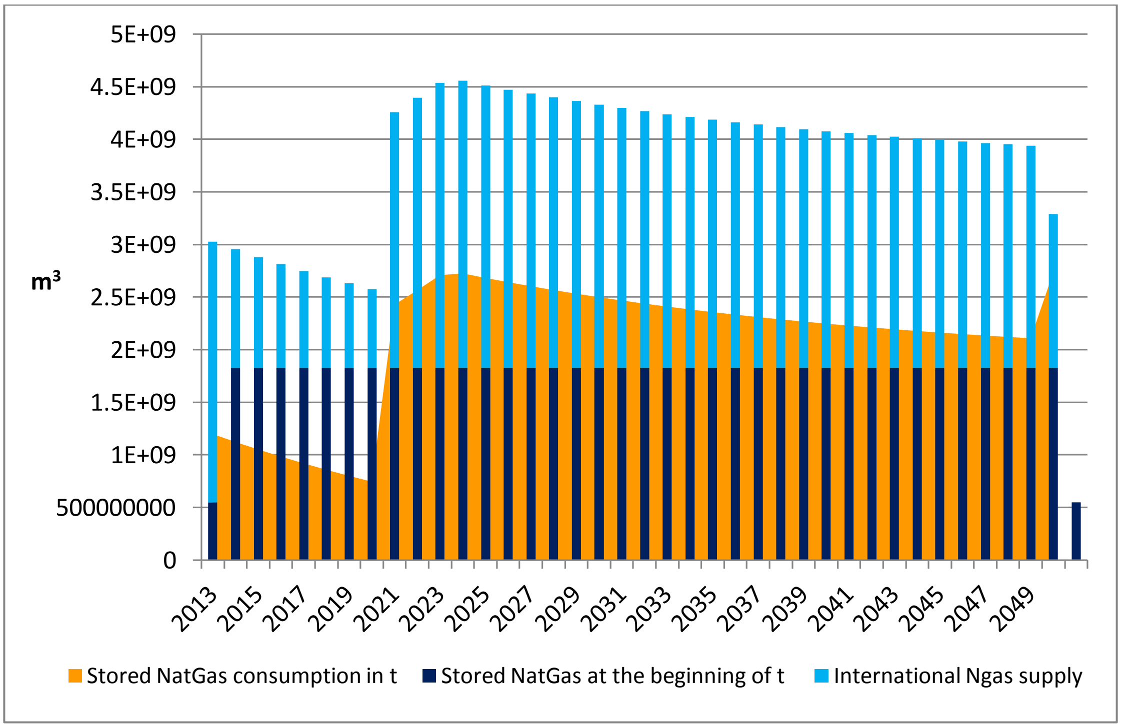


Figure 44: Storage process dynamics in the Case Study 2

As we can see the model will fulfill always the maximum storage capacity because a 'storage cost', depending on the m^3 of natural gas stored, have not been implemented in this model.

The amount of natural gas stored at the beginning of the planning horizon is equal to the 'base gas' and it have to be the same at the end of 2050.

Chapter 5:

Linear Programming optimization method

Since, as explained in the previous chapter, the GAMS code, and thus the TIMES model generator, uses the Linear Programming (LP) approach, and in particular the Simplex algorithm, to find the optimal solution in terms of system cost the following sections have the purpose to explain the foundation and the main theorems of this method.

5.1 LP as a branch of operational research

Operational research is characterized by a scientific approach to managerial decision making.

Generally mathematical programming concerns the optimum allocation of limited resources among competing activities, under a set of constraints imposed by the nature of the problem being studied. When the mathematical representation uses linear functions exclusively, we have a linear-programming (LP) model.

Mathematical programming and especially linear programming is one of the best developed and most used branches of operational research.

In 1947, George B. Dantzig, a member of a research group of the U.S. Air Force developed the Simplex method for solving the general linear-programming problem. The extraordinary computational efficiency and robustness of the Simplex method, together with the availability of high speed digital computers, have made linear programming the most powerful optimization method ever designed and applied.

Since mathematical programming is only a tool of the broad discipline known as operational research, let us first attempt to understand the operational research approach and identify the role of mathematical programming within that approach.

"Operational research is characterized by the use of mathematical models in providing guidelines to managers for making effective decisions within the state of the current information, or in seeking further information if current knowledge is insufficient to reach a proper decision."

There are several elements of this statement that are deserving of emphasis. First, the essence of operational research is the model-building approach—that is, an attempt to capture the most significant features of the decision under consideration by means of a mathematical abstraction.

Second, through this model-design effort, operational research tries to provide guidelines to decision-makers or, in other words, to increase their understanding of the consequences of their actions. There is never an attempt to replace or substitute for decision-makers, but rather the aim is to support their actions. Decision-makers should formulate the basic questions to be addressed by the model, and then interpret the model's results in light of their own experience and intuition, recognizing the model's limitations.

Finally, it is the complexity of the decision under study, and not the tool being used to investigate the decision-making process, that should determine the amount of information needed to handle that decision effectively.

5.2 LP model formulation

In mathematical terms, a linear programming model can be expressed as the maximization (or minimization) of an objective function, subject to a given linear constraints. Specifically, a linear programming problem can be described as finding the values of n decision variables, $x_1,x_2,...x_n$, such they maximize the objective function z where

$$z = c_1x_1+c_2x_2+....+c_nx_n, \tag{1}$$

subject to the following constraints:

$$\begin{aligned} &a_{11}x_1+a_{12}x_2+.....+a_{1n}x_n \le b_1 \\ &a_{21}x_1+a_{22}x_2+.....+a_{2n}x_n \le b_2 \\ &\quad\vdots \\ &a_{m1}x_1+a_{m2}x_2+.....+a_{mn}x_n \le b_m \end{aligned} \tag{2}$$

and, usually,

$$x_1 \ge 0, x_2 \ge 0, \quad ...., \quad x_n \ge 0, \tag{3}$$

where c_j, a_{ij}, and b_i are the given constants.

Values of the decision variables $x_1,x_2,...,x_n$ that satisfy all the constraints of (2) and (3) simultaneously are said to form a feasible solution to the linear programming model. The set of all values of the decision variables characterized by constraints (2) and (3) form the feasible region of the problem under consideration. A feasible solution that in addition optimizes the objective function (1) is called an optimal feasible solution.

Generally, solving a linear problem can result in three possible situations:

i) the linear program could be infeasible, meaning that there are no values of the decision variables $x_1, x_2, .. x_n$ that simultaneously satisfy all the constraint of (2) and (3).

ii) it could have an unbounded solution, meaning that, if we are maximizing, the value of the objective function can be increased indefinitely without violating any of the constraints (if we are minimizing, the value of the objective function may be decreased indefinitely).

iii) it will have at least one finite optimal solution and often it will have multiple optimal solutions.

The Simplex method, which will be discussed below provides an efficient procedure for constructing an optimal solution, if one exist, or for determining whether the problem is infeasible or unbounded.

Note that in linear programming formulation, the decision variables are allowed to take any continuous value. An important extension of this linear programming model is to require that all or some of the decision variables be restricted to be integers. Another fundamental extension of the above model is to allow the objective function, or the constraints, or both, to be non linear function. But these topics will not be discussed in this thesis.

5.3 The Simplex method

5.3.1 Generality

The Simplex method for solving linear programs is just one of a number of methods, or algorithms, for solving optimization problems. By an algorithm, we mean a systematic procedure, usually iterative, for solving a class of problems.

The Simplex method is an algorithm for solving the class of linear-programming problems. Any finite optimization algorithm should terminate in one, and only one, of the following possible situations:

- by demonstrating that there is no feasible solution;
- by determining a optimal solution; or
- by demonstrating that the objective function is unbounded over the feasible region.

We will say that an algorithm solves a problem if it always satisfies one of these three conditions. As we shall see, a major feature of the Simplex method is that it solves any linear-programming problem.

The simplex algorithm is iterative, in the sense that it moves from one decision point $x_1, x_2, \ldots, x_n$ to another. Generally for these type of algorithms, we need:

I. a starting point to initiate the procedure;
II. a termination criterion to indicate when a solution has been obtained; and
III. an improvement mechanism for moving from a point that is not a solution to a better point.

The Simplex method is a systematic procedure for solving linear programs, it proceeds by moving from one feasible solution to another, at each step, improving the value of the objective function. Moreover, the method terminates after a finite number of such transitions.

Two characteristics of the Simplex method have led to its widespread acceptance as computational tool.

First, the method is robust. It solves any linear program; it detects redundant constraints in the problem formulation; it identifies instances when the objective value is unbounded over the feasible region; and it solves problems with one or more optimal solutions. The method is also self-initiating. It uses itself either to generate an appropriate feasible solution, as required, to start the method, or to show that the problem has no feasible solution.

Second, the Simplex method provides much more than just optimal solutions. As byproducts, it indicates how the optimal solution varies as a function of the problem data (cost coefficients, constraint coefficients, and right-hand-side data). This information is intimately related to a linear program called the dual to the given problem, and the Simplex method automatically solves this dual problem along with the given problem.

These characteristics of the method are of primary importance for applications, since data rarely is known with certainty and usually is approximated when formulating a problem. These features will be discussed in detail in the section to follow.

5.3.2 The Simplex Algorithm

First, before running simplex algorithm the problem must be in the canonical form. It satisfied the following:

- ✓ All the decision variables are constrained to be non-negative.
- ✓ All constraints, except for the non-negativity of decision variables, are stated as equalities (adding slack (≤ constraint) and surplus (≥ constraint) variables).
- ✓ The right-hand side coefficient are all non-negative.
- ✓ One decision variable is isolated in each constraint with a +1 coefficient. The

variable isolated in a given constraint does not appear in any other constraint, and appears with a zero coefficient in the objective function.

This formulation might appear to be quite limited and restrictive but any linear programming problem can be transformed so that is in canonical form.

Given a canonical form for any linear program, all the solutions that satisfy the constraints are called basic feasible solutions. Generally, a basic feasible solution is given by setting the variable isolated in constraint j, called the j-th basic-variable, equal to the right-hand side of the j-th constraint and by setting the remaining variables, called non-basic, all to zero. Collectively the basic variables are termed as basic.

Consider this criterions:

Optimality criterion. Suppose that, in a maximization problem, every non-basic variable has a non-positive coefficient in the objective function of a canonical form. Then the basic feasible solution given by the canonical form maximizes the objective function over the feasible region.

Unboundedness criterion. Suppose that, in a maximization problem, some non-basic variable has a positive coefficient in the objective function of a canonical form. If that variable has negative or zero coefficients in all constraints, then the objective function is unbounded from above over the feasible region.

Improvement criterion. Suppose that, in a maximization problem, some non-basic variable has a positive coefficient in the objective function of a canonical form. If that variable has a positive coefficient in some constraint, then a new basic feasible solution may be obtained by pivoting. Notice that, after pivoting the form of the problem has been altered, but the modified equations still represent the original problem and have the same feasible solutions and the same objective value when evaluated at any given feasible solution.

Ratio and Pivoting criterion. When improving a given canonical form by introducing variable x_s into the basis, pivot in a constraint that gives the minimum ratio of right-hand-side coefficient to corresponding x_s coefficient. Compute these ratios only for constraints that have a positive coefficient for x_s. In other words we chose the constraint to pivot in (and consequently the variable to drop from the basis) by determining which basic variable first goes to zero as we increase the value of the non-basic variable.

The simplex algorithm, in the *maximization* form, is writable as following:

STEP (0) The problem is initially in canonical form and all $\bar{b}_i \geq 0$.

STEP (1) If $\bar{c}_j \leq 0$ for j = 1, 2, . . . , n, then stop; we are optimal.

If we continue then there exists some $\bar{c_j} > 0$.

STEP (2) Choose the column to pivot in (i.e., the variable to introduce into the basis) by:

$\bar{c_s} = max_j\{\bar{c_j}|\bar{c_j} > 0\}$.

If $\bar{a}_{is} \leq 0$ for i = 1, 2, . . . ,m, then stop; the primal problem is unbounded.

If we continue, then $\bar{a}_{is} > 0$ for some i = 1, 2, . . . ,m.

STEP (3) Choose row r to pivot in (i.e., the variable to drop from the basis) by the ratio test:

$\frac{\bar{b}_r}{\bar{a}_{rs}} = min_i\left\{\frac{\bar{b}_i}{\bar{a}_{is}} \mid \bar{a}_{is} > 0\right\}$

STEP (4) Replace the basic variable in row r with variable s and re-establish the canonical form (i.e., pivot on the coefficient $\bar{a}_{rs}$).

STEP (5) Go to step (1).

The data $\bar{a}_{ij}$, $\bar{b}_i$, $\bar{z}_0$, $\bar{w}_0$, and $\bar{c}_j$ are known. They are either the original data (without bars) or that data as updated by previous steps of the algorithm. We have assumed (by re-indexing variables if necessary) that x_1, x_2, . . . , x_m are the basic variables. Also, since this is a canonical form, $\bar{b}_i \geq 0$ for i = 1, 2, . . . ,m.

The steps above are the essential computations of the Simplex method.

The only computation to be specified formally is the effect that pivoting in step (4) has on the problem data. Recall that we pivot on coefficient a_{rs} merely to isolate variable x_s with a +1 coefficient in constraint *r* . The pivot can be viewed as being composed of two steps:

I. normalizing the *r*-th constraint so that x_s has a +1 coefficient, and
II. subtracting multiples of the normalized constraint from the order equations in order to eliminate variable x_s .

These steps are summarized pictorially in figure 45.

The last tableau in figure 38 specifies the new values for the data. The new right-hand-side coefficients, are given by:

$\bar{b}_r^{\,new} = \frac{\bar{b}_r}{\bar{a}_{rs}}$ and $\bar{b}_i^{\,new} = \bar{b}_i - \bar{a}_{is} * \left(\frac{\bar{b}_r}{\bar{a}_{rs}}\right) \geq 0$ for $i \neq r$

Observe that the new coefficient for the variable x_r being removed from the basis summarize the computations. For example, the coefficient of x_r in the first row of the final tableau is obtained from the first tableau by subtracting $\frac{\bar{a}_{is}}{\bar{a}_{rs}}$ times the row from the first row. The coefficients of the other variables in the first row of the third tableau can be obtained from the first tableau by performing this same calculation. This observation can be used to partially streamline the computations of the Simplex method.

x_1	$\cdots$	x_r	$\cdots$	x_m	x_{m+1}	$\cdots$	x_s	$\cdots$	x_n	
1					$\bar{a}_{1,m+1}$	$\cdots$	$\bar{a}_{1s}$	$\cdots$	$\bar{a}_{1n}$	$\bar{b}_1$
	$\ddots$				$\vdots$				$\vdots$	$\vdots$
		1			$\bar{a}_{r,m+1}$	$\cdots$	$\boxed{\bar{a}_{rs}}$	$\cdots$	$\bar{a}_{rn}$	$\bar{b}_r$
			$\ddots$		$\vdots$				$\vdots$	$\vdots$
				1	$\bar{a}_{m,m+1}$	$\cdots$	$\bar{a}_{ms}$	$\cdots$	$\bar{a}_{mn}$	$\bar{b}_m$
					$\bar{c}_{m+1}$	$\cdots$	$\bar{c}_s$	$\cdots$	$\bar{c}_n$	$-\bar{z}_0$

↓Normalization

1					$\bar{a}_{1,m+1}$	$\cdots$	$\bar{a}_{1s}$	$\cdots$	$\bar{a}_{1n}$	$\bar{b}_1$
	$\ddots$				$\vdots$				$\vdots$	$\vdots$
		$\left(\frac{1}{\bar{a}_{rs}}\right)$			$\left(\frac{\bar{a}_{r,m+1}}{\bar{a}_{rs}}\right)$	$\cdots$	1	$\cdots$	$\left(\frac{\bar{a}_{rn}}{\bar{a}_{rs}}\right)$	$\left(\frac{\bar{b}_r}{\bar{a}_{rs}}\right)$
			$\ddots$		$\vdots$				$\vdots$	$\vdots$
				1	$\bar{a}_{m,m+1}$	$\cdots$	$\bar{a}_{ms}$	$\cdots$	$\bar{a}_{mn}$	$\bar{b}_m$
					$\bar{c}_{m+1}$	$\cdots$	$\bar{c}_s$	$\cdots$	$\bar{c}_n$	$-\bar{z}_0$

↓ Elimination of x_s

1		$-\left(\frac{\bar{a}_{1s}}{\bar{a}_{rs}}\right)$			$\bar{a}_{1,m+1} - \bar{a}_{1s}\left(\frac{\bar{a}_{r,m+1}}{\bar{a}_{rs}}\right)$	$\cdots$	0	$\cdots$	$\bar{a}_{1n} - \bar{a}_{1s}\left(\frac{\bar{a}_{rn}}{\bar{a}_{rs}}\right)$	$\bar{b}_1 - \bar{a}_{1s}\left(\frac{\bar{b}_r}{\bar{a}_{rs}}\right)$
	$\ddots$				$\vdots$				$\vdots$	$\vdots$
		$\left(\frac{1}{\bar{a}_{rs}}\right)$			$\left(\frac{\bar{a}_{r,m+1}}{\bar{a}_{rs}}\right)$	$\cdots$	1	$\cdots$	$\left(\frac{\bar{a}_{rn}}{\bar{a}_{rs}}\right)$	$\frac{\bar{b}_r}{\bar{a}_{rs}}$
			$\ddots$		$\vdots$				$\vdots$	$\vdots$
		$-\left(\frac{\bar{a}_{ms}}{a_{rs}}\right)$		1	$\bar{a}_{m,m+1} - \bar{a}_{ms}\left(\frac{\bar{a}_{r,m+1}}{\bar{a}_{rs}}\right)$	$\cdots$	0	$\cdots$	$\bar{a}_{mn} - \bar{a}_{ms}\left(\frac{\bar{a}_{rn}}{\bar{a}_{rs}}\right)$	$\bar{b}_m - \bar{a}_{ms}\left(\frac{\bar{b}_r}{\bar{a}_{rs}}\right)$
		$-\left(\frac{\bar{c}_s}{\bar{a}_{rs}}\right)$			$\bar{c}_{m+1} - \bar{c}_s\left(\frac{\bar{a}_{r,m+1}}{\bar{a}_{rs}}\right)$	$\cdots$	0	$\cdots$	$\bar{c}_n - \bar{c}_s\left(\frac{\bar{a}_{rn}}{\bar{a}_{rs}}\right)$	$-\bar{z}_0 - \bar{c}_s\left(\frac{\bar{b}_r}{\bar{a}_{rs}}\right)$

Figure 45: Algebra for a pivot operation

Note also that new value for z will be given by:

$$\bar{z}_0 + \left(\frac{\bar{b}_r}{\bar{a}_{rs}}\right) * \bar{c}_s$$

By our choice of the variable x_s to introduce into the basis, $\bar{c}_s > 0$. Since $\bar{b}_r \geq 0$ and $\bar{a}_{rs} > 0$, this implies that $\bar{z}^{new} \geq \bar{z}^{old}$ new.

5.3.3 Convergence of the algorithm

As we said, simplex algorithm should solve any linear program.

We assume that the linear program has n variables and m equality constraints.

First note that there are only a finite number of bases for a given problem, since the basis contains m variables (one isolated in each constraint) and there are a finite number of variables to select from. A standard result in linear algebra state that, once the basic variables have been selected, all the entries in the tableau, including the objective value, are determined uniquely. Consequently, there are only a finite number of canonical forms as well. If the objective value strictly increases after every pivot, the algorithm never repeats a canonical form and must determine an optimal solution after a finite number of pivots.

This argument shows that the Simplex method solves linear programs as long as the objective value strictly increases after each pivoting operation. As we have just seen, each pivot affects the objective function by adding a multiple of the pivot equation to the objective function. The current value of the z-equation increases by a multiple of the right-hand-side coefficient; if this coefficient is positive, not zero, the objective value increases. With this in mind we introduce the following definition:

A canonical form is called non-degenerate if each right-hand-side coefficient is strictly positive. The linear-programming problem is called non-degenerate if, starting with an initial canonical form, every canonical form determined by the algorithm is non-degenerate.

In these terms we have shown that the Simplex method solves every non-degenerate linear program using a finite number of pivoting steps. When a problem is degenerate, it is possible to perturb the data slightly so that every right-hand-side coefficient remains positive and again show that the methods works. A final note is that, empirically, the finite number of iterations mentioned here to solve a problem frequently lies between 1.5 and 2 times the number of constraints.

Conclusion the Simplex method solves any given linear program in a finite number of iterations. That is, in a finite number of iterations, it shows: that there is no feasible solution; finds an optimal solution; or shows that the objective function is unbounded over the feasible region.

5.4 Shadow prices

Solving a linear program usually provides more information about an optimal solution that merely the values of the decision variables. Associated with an optimal solution are shadow prices (also referred to as dual variables or marginal values) for the constraints.

Def. The shadow price associated with a particular constraint is the change in the optimal value of the objective function per unit increase in the right-hand-side value for that constraint, all other problem data remaining unchanged.

Def. The reduced cost associated with the non-negativity constraint for each variable is the shadow price of that constraint (i.e. the corresponding change in the objective function per unit increase in the lower bound of the variable).

Notice that the shadow prices are associated with the constraint of the problem and not the variables. They are in fact the marginal worth of an additional unit of a particular right-hand-side value.

The shadow price for the non-negativity constraint on a variable is the objective coefficient for this variable in the final canonical form. For basic variables, these reduced costs are zero.

Alternatively, the reduced costs for all decision variables can be computed directly from the shadow prices on the structural constraints and the objective-function coefficients. In this view, the shadow prices are thought of as the opportunity costs associated with diverting resources away from the optimal production mix.

This operation of determining the reduced cost of an activity from the shadow price and the objective function is generally referred to as *pricing out* an activity. This is an important observation, since it implies that the shadow prices provide a mechanism for screening new activities that were not included in the initial model formulation. In a maximization problem, if any new activity prices out negatively using the shadow prices associated with an optimal solution, it may be immediately dropped from consideration. If, however, a new activity prices out positively with these shadow prices, it must be included in the problem formulation and the new optimal solution determined by pivoting.

Consider a problem in initial canonical form:

		shadow price
$a_{11}x_1+a_{12}x_2+....+a_{1n}x_n+x_{n+1}$	$= b_1$	y_1
$a_{21}x_1+a_{22x2}+....+a_{2n}x_n+x_{n+2}$	$= b_2$	y_2
:	:	:
$a_{m1}x_1+a_{m2}x_2+....+a_{mn}x_n+......+x_{n+m}$	$= b_m$	y_m
$(-z)+c_1x_1+c_2x_2+..+c_nx_n+0x_{n+1}+0x_{n+2}+..+0x_{n+m}$	$= 0$	

The variables x_{n+1}, x_{n+2},...,x_{n+m} are either slack variables or surplus variable that have been introduced in order to transform the problem into canonical form.

Assume that the optimal solution to this problem has been found and the corresponding final form of the objective function is:

$(-z)+\bar{c}_1x_1+\bar{c}_2x_2+..+\bar{c}_nx_n+\bar{c}_{n+1}x_{n+1}+\bar{c}_{n+2}x_{n+2}+..+\bar{c}_{n+m}x_{n+m} = -\bar{z}_0$ (4)

$\bar{c}_j$ is the reduced cost associated with variable x_j. Since (4) is in canonical form, c_j = 0 if x_j is a basic variable. Let y_i denote the shadow price for the i-th constraint. The arguments from the example problem show that the negative of the final objective coefficient of the variable x_{n+i} corresponds to the shadow price associated with the i-th constraint. Therefore:

$\bar{c}_{n+1} = -y_1,\quad \bar{c}_{n+2} = -y_2,\quad .....,\quad \bar{c}_{n+m} = -y_m.$ (5)

Note that this result applies whether the variable x_{n+1} is a slack variable (i.e. the i-th constraint is a less-than-or-equal-to constraint), or whether x_{n+1} is a surplus variable (i.e. the i-th constraint is a greater-than-or-equal-to constraint).

We now shall establish a fundamental relationship between shadow prices, reduced costs, and the problem data. Recall that, at each iteration of the Simplex method, the objective function is transformed by subtracting from it a multiple of the row in which the pivot was performed. Consequently, the final form of the objective function could be obtained by subtracting multiples of the original constraints from the original objective function. Consider first the final objective coefficients associated with the original basic variables $x_{n+1},x_{n+2},...,x_{n+m}$. Let π_1, π_2, ..., π_n be the multiples of each row that are subtracted from the original objective function to obtain its final form (4). Since x_{n+1} appears only in the i-th constraint and has a +1 coefficient, we should have:

$\bar{c}_{n+i} = 0 - \pi_i.$

Combining this expression with (5), we obtain:

$\bar{c}_{n+i} = -\pi_i = -y_i.$

Thus the shadow prices y_i are the multipliers π_i.

Since these multiples can be used to obtain every objective coefficient in the final form (4), the reduced cost $\bar{c}_j$ of variable x_j is given by:

$\bar{c}_j = c_j - \sum_i^m a_{ij}y_i$ (j = 1,2,...,n),

and the current value of the objective function is:

$$\bar{z}_0 = \sum_i^m b_i y_i$$

The first expression links the shadow prices to the reduced cost of each variable, the second one establishes the relationship between the shadow prices and the optimal value of the objective function; this expression can also be viewed as a mathematical definition of the shadow prices. Since $\bar{c}_j$ = 0 for the m basic variables of the optimal solution, we have:

$0 = \bar{c}_j - \sum_i^m a_{ij}y_i$ for j basic.

This is a system of m equations in m unknowns that uniquely determines the values of the shadow prices y_i.

5.5 The duality theory

As it was explained that the shadow-price interpretation of the optimal simplex multipliers is a very useful concept. First, these shadow prices give us directly the marginal worth of an additional unit of any of the resources. Second, when an activity is "priced out" using these shadow prices, the opportunity cost of allocating resources to that activity relative to other activities is determined.

Duality in linear programming is essentially a unifying theory that develops the relationships between a given linear program and another related linear program stated in terms of variables with this shadow-price interpretation. The importance of duality is twofold. First, fully understanding the shadow-price interpretation of the optimal simplex multipliers can prove very useful in understanding the implications of a particular linear-programming model. Second, it is often possible to solve the related linear program with the shadow prices as the variables in place of, or in conjunction with, the original linear program, whenever there are advantages to doing so. For example, if the number of constraints of a problem is much greater than the number of variables, it is usually wise to solve the dual instead of the primal since the solution time increases much more rapidly with the number of constraints in the problem than with the number of variables.

Definition of the dual problem

Let the primal problem be:

$$Maximize\ z = \sum_j^n c_j x_j$$

subject to:

$\sum_j^n a_{ij} x_j \le b_i$ (i = 1,2,...., m),

$x_j \ge 0$ (j = 1,2,....,n).

Associated with this primal problem there is a corresponding dual problem given by:

$$Minimize\ v = \sum_i^m b_i y_i$$

subject to:

$\sum_i^m a_{ij} y_i \ge c_j$ (j = 1,2,..., n),

$y_i \ge 0$ (i = 1,2,....,m).

The optimal values of the objective function of the primal and dual solutions are equal. Furthermore, an optimal dual variable is non-zero only if its associated constraint in the primal is binding. This should be intuitively clear, since the optimal dual variables are the shadow prices associated with the constraints. These shadow prices can be interpreted as values imputed to the scarce resources, so that the value of these resources equals the value of the primal objective function. To further develop that the optimal dual variables are the shadow prices discussed in above.

In the final tableau of the Simplex method, the reduced costs of the basic variables must be zero. For non-basic variables, the reduced cost in the final tableau must be non-positive in order to ensure that no improvements can be made.

Since any linear program can be put in the primal form by making simple transformations, then any linear program must have a dual linear program. In fact, since the dual problem is a linear program, it must also have a dual. It can be shown that, for completeness, the dual of the dual is the primal.

It could be interesting to investigate the duality relationship when the primal problem is cast in minimization, rather than maximization form:

$$Minimize\ z = \sum_j^n c_j x_j$$

subject to:

$\sum_j^n a_{ij} x_j \leq b_i$ (i = 1,2,...., m'),

$\sum_j^n a_{ij} x_j \geq b_i$ (i = m'+1,m'+2,...., m''),

$\sum_j^n a_{ij} x_j = b_i$ (i = m''+1,m''+2,....,m).

$x_j \geq 0$ (j = 1,2,....,n).

Associated with this primal problem there is a corresponding dual problem given by:

$$Maximize\ v = \sum_{i=1}^{m'} b_i y_i + \sum_{i=m'+1}^{m''} b_i y'_i + \sum_{i=m''+1}^{m} b_i y''_i \quad ,$$

subject to:

$$\sum_{i=1}^{m'} a_{ij} y_i + \sum_{i=m'+1}^{m''} a_{ij} y'_i + \sum_{i=m''+1}^{m} a_{ij} y''_i \geq c_j$$

$y_i \leq 0$ (i = 1,2,...,m')

$y'_i \geq 0$ (i = m'+1, m'+2,...,m'').

Observe that now the sign of the dual variables associated with the inequality constraints has changed, as might be expected from the shadow price interpretation. In a cost-minimization problem, increasing the available resources will tend to decrease the total cost, since the constraint has been relaxed. As a result, the dual variable associated with a less-than-or-equal-to constraint in a minimization problem is non-positive. On the other hand, increasing requirements could only generate a cost increase. Thus, a greater-than-or-equal-to constraint in a minimization problem has an associated non-negative dual variable.

The primal and dual problems that we have just developed illustrate one further duality correspondence.

It's now possible to summarize the general duality relationships. Basically we note that equality constraints in the primal correspond to unrestricted variables in the dual, while inequality constraints in the primal correspond to restricted variables in the dual, where the sign of the restriction in the dual depends upon the combination of objective-function type and constraint relation in the primal. These various correspondences are summarized in the table below.

Primal (Maximize)	Dual (Minimize)
i-th constraint ≤	i-th variable ≥ 0
i-th constraint ≥	i-th variable ≤ 0
i-th constraint =	i-th variable unrestricted
j-th variable ≥ 0	i-th constraint ≥
j-th variable ≤ 0	i-th constraint ≤
j-th variable unrestricted	i-th constraint =

Table 10: Correspondences in the sign of the restrictions between primal and dual problem

5.5.1 Fundamental properties

Let the primal problem be:

$$Maximize\ z = \sum_j^n c_j x_j$$

subject to:

$$\sum_j^n a_{ij} x_j \leq b_i \qquad (i = 1,2,...., m),$$

$$x_j \geq 0 \qquad (j = 1,2,....,n).$$

The corresponding dual problem is given by:

$$Minimize\ v = \sum_i^m b_i y_i$$

subject to:

$$\sum_i^m a_{ij} y_i \geq c_j \qquad (j = 1,2,..., n),$$

$$y_i \geq 0 \qquad (i = 1,2,....,m).$$

The first property is referred as "weak duality" and provides a bound on the optimal value of the objective function of either the primal or the dual. Simply stated, the value of the objective function for any feasible solution to the primal maximization problem is bounded from above by the value of the objective function for any feasible solution to its dual. Similarly, the value of the objective function for its dual is bounded from below by the value of the objective function of the primal.

The sequence of properties to be developed will lead us to the "strong duality" property, which states that the optimal values of the primal and dual problems are in fact equal. Further in developing this result, we show how the solution of one of these problems in readily from the solution of the other.

Weak Duality Property: If $\bar{x}_j$, j = 1,2,...,n is a feasible solution to the primal problem and $\bar{y}_i$, i = 1,2,...,m is a feasible solution to the dual problem, then:

$$\sum_{j}^{n} c_j \bar{x}_j \leq \sum_{j}^{n} b_i \bar{y}_i$$

There are a number of direct consequences of the weak duality property. If we have feasible solutions to the primal and dual problems such that their respective objective functions are equal, then these solutions are optimal to their respective problems. This result follows immediately from the weak duality property, since a dual feasible solution is an upper bound on the optimal primal solution and this bound is attained by the given feasible primal solution. The argument for the dual problem is analogous. Hence, we have an optimality property of dual linear programs.

Optimality property. If $\hat{x}_j$, j = 1,2,..,n is a feasible solution to the primal problem and $\hat{y}_i$, i = 1,2,..,m is a feasible solution to the dual problem, and, further,

$$\sum_{j}^{n} c_j \hat{x}_j = \sum_{j}^{n} b_i \hat{y}_i$$

then $\hat{x}_j$, j = 1,2,..,n is an optimal solution to the primal problem and $\hat{y}_i$, i = 1,2,...,m, is an optimal solution to the dual problem.

Furthermore, if one problem has an unbounded solution, then the dual of that problem is infeasible. This must be true for the primal since any feasible solution to the dual would provide an upper bound on the primal objective function by the weak duality theorem; this contradicts the fact that the primal problem is unbounded.

Again, the argument for the dual problem is analogous. Hence, we have an unboundedness property of dual linear programs.

Unboundedness Property. If the primal (dual) problem has an unbounded solution, then the dual (primal)problem is infeasible.

We are now in a position to give the main result of this section, the ‘‘strong duality’’ property. The importance of this property is that it indicates that we may in fact solve the dual problem *in place of* or in conjunction with the primal problem .

Strong duality property. If the primal (dual) problem has a finite optimal solution, then so does the dual (primal) problem, and these two values are equal. That is, $\hat{z} = \hat{v}$ where:

$\hat{z}$ = Max $\sum_j^n c_j x_j$ $\hat{v}$ = Min $\sum_i^m b_i y_i$

subject to:

$\sum_j^n a_{ij} x_j \le b_i$ $\sum_i^m a_{ij} y_i \ge c_j$

$x_j \ge 0$ $y_i \ge 0$

It should be pointed out that it is not true that if the primal problem is infeasible, then the dual problem is unbounded. In this case the dual problem may be either unbounded or infeasible.

The last but not least property is called of complementary slackness.

Complementary Slackness Property. If, in an optimal solution of a linear program, the value of the dual variable (shadow price) associated with a constraint is nonzero, then that constraint must be satisfied with equality. Further, if a constraint is satisfied with strict inequality, then its corresponding dual variable must be zero.

For the primal linear program posed as a maximization problem with less-than-or-equal-to constraints, this means:

if $\hat{y}_i > 0$, then $\sum_j^n a_{ij}\hat{x}_j = b_i$;

if $\sum_j^n a_{ij}\hat{x}_j < b_i$, then $\hat{y}_i = 0$.

For the dual linear program posed as a minimization problem with greater-than-or-equal-to constraints, the complementary-slackness conditions are the following:

if $\hat{x}_j > 0$, then $\sum_i^m a_{ij}\hat{y}_j = c_j$;

if $\sum_i^m a_{ij}\hat{y}_i > c_j$, then $\hat{x}_j = 0$.

the complementary slackness conditions of the primal problem have a fundamental economic interpretation. If the shadow price of the i-th resource (constraint) is strictly positive in the optimal solution $\hat{y}_i > 0$, then we should require that all of this resource be consumed by the optimal program; that is,

$$\sum_j^n a_{ij}\hat{x}_j = b_i$$

if on the other hand, the i-th resource is not fully used; that is

$$\sum_j^n a_{ij}\hat{x}_j < b_i$$

then its shadow price should be zero, $\hat{y}_i = 0$.

The complementary-slackness conditions of the dual problem are merely the optimality conditions for the simplex method, where the reduced cost c j associated with any variable must be non-positive and is given by

$\bar{c}_j = c_j - \sum_i^m a_{ij}\hat{y}_j \le 0$ (j = 1,2,...,n).

If $\hat{x}_j > 0$ then $\hat{x}_j$ must be a basic variable and its reduced cost is defined to be zero. Thus,

$$c_j = \sum_{i}^{m} a_{ij}\hat{y}_j$$

If, on the other hand,

$$c_j - \sum_{i}^{m} a_{ij}\hat{y}_j < 0$$

then $\hat{x}_j$ must be non-basic and set equal to zero in the optimal solution; $\hat{x}_j = 0$.

Is shown that the strong duality property implies that the complementary-slackness conditions must hold for both the primal and dual problems. The converse is also true. If the complementary-slackness conditions hold for both problems, then the strong duality property holds.

5.6 Mathematical programming in practice

Since operational research basically aims to improve the quality of decision-making by providing decision-makers with a better understanding of the consequences of their decisions, it is important to spend some time reflecting upon the nature of the decision-making process and evaluating the role that quantitative methods, especially mathematical programming, can play in increasing managerial effectiveness.

There are several ways to categorize the decision faced by decision-makers. In this thesis it will be discussed one framework in particular, since it has proved to be extremely helpful in generating better insights into the decision-making process.

This framework was proposed by Robert N. Antony. He classified decisions in three categories: strategic planning, tactical planning, and operations control.

Strategic planning

Strategic planning concerns mainly with establishing managerial policies and with developing the necessary resources that the system (firm, country's Public Administration) needs to satisfy its external requirements in a manner consistent with its specific goals. Examples of strategic decision are major capital investments in new production capacity and expansion of existing capacity, merger and divestiture decisions, determination of location and size of new plants and distribution facilities, and issuing of bonds and stocks to secure financial resources.

These decisions are extremely important because they are responsible for maintaining the competitive capabilities of the system, determining its rate of growth, and eventually defining its success or failure. An essential characteristic of these strategic decisions is that they have long-lasting effects, thus mandating long planning horizons in their analysis. This, in turn, requires the consideration of uncertainties and risk attitudes in the decision-making process.

Tactical planning

Once that physical facilities have been decided, the basic problem to be resolved is the effective allocation of resources (e.g. production, storage, distribution capabilities, etc) to satisfy demand and technological requirements, taking into account the costs and revenues associated with the operation of the resources available to the system. This decision usually involve the consideration of a medium-range time horizon divided into several periods, and require significant aggregation of the information to be processed.

Operations Control

After making an aggregate allocation of the resources of the firm, it is necessary to deal with the day-to-day operational and scheduling decisions.

5.6.1 Stages of formulation, solution and implementation

Having seen where mathematical programming might be most useful and having indicated its interplay with other managerial tools, now it will be described an orderly sequence of steps that can be followed for a systematic formulation, solution, and implementation of a mathematical-programming model. These steps could be applied to the development of any operational-research model.

Although the practical applications of mathematical programming cover a broad range of problems, it is possible to distinguish five general stages that the solution of any mathematical-programming problem should follow.

A. Formulating the model
B. Gathering the data
C. Obtaining an optimal solution
D. Applying sensitivity analysis
E. Testing and implementing the solution

Obviously, these stages are not defined very clearly, and they normally overlap and interact with each other. Nevertheless we can analyze, in general terms, the main characteristics of each stage.

A) Formulating the Model

The first step to be taken in a practical application is the development of the model. The following are elements that define the model structure:

1. Selection of the Time Horizon

One of the first decisions the model designer has to make, when applying mathematical programming to a planning situation, is the selection of the time horizon (also referred to as planning horizon, or cutoff date).

The time horizon indicates how long we have to look into the future to account for all the significant factors of the decision under study. Its magnitude reflects the future impact of the decision under consideration.

Sometimes it is necessary to divide the time horizon into several time periods. This is done in order to identify the dynamic changes that take place throughout the time horizon.

2. Selection of Decision Variables and Parameters

The next step in formulating the mathematical-programming model is to identify the decision variables, which are those factors under the control of the decision-maker, and the parameters, which are beyond the control of the decision-maker and are imposed by the external environment.

The decision variables are the answers the decision-maker is seeking.

On some occasions, a great amount of ingenuity is required to select those decision variables that most adequately describe the problem being examined. In some instances it is possible to decrease the number of constraints drastically or to transform an apparent nonlinear problem into a linear one, by merely defining the decision variables to be used in the model formulation in a different way.

The parameters represent those factors which affect the decision but are not controllable directly (such as prices, costs, demand, and so forth). In deterministic mathematical-programming models, all the parameters are assumed to take fixed, known values, where estimates are provided via point forecasts. The impact of this assumption can be tested by means of sensitivity analysis.

3. Definition of the Constraints

The constraint set reflects relationships among decision variables and parameters that are imposed by the characteristics of the problem under study. These relationships should be expressed in a precise, quantitative way. The nature of the constraints will, to a great extent, determine the computational difficulty of solving the model.

It is quite common, in the initial representation of the problem, to overlook some vital constraints or to introduce some errors into the model description, which will lead to unacceptable solutions. However, the mathematical programming solution of the ill-defined model provides enough information to assist in the detection of these errors and their prompt correction. The problem has to be reformulated and a new cycle has to be initiated.

4. Selection of the Objective Function

Once the decision variables are established, it is possible to determine the objective function to be minimized or maximized, provided that a measure of performance (or effectiveness) has been established and can be associated with the values that the decision variables can assume. This measure of performance provides a selection criterion for evaluating the various courses of action that are available in the situation being investigated.

The definition of an acceptable objective function might constitute a serious problem in some situations, especially when social and political problems are involved. In addition, there could be conflicting objectives, each important in its own right, that the decision-maker wants to fulfill. In these situations it is usually helpful to define multiple objective functions and to solve the problem with respect to each one of them separately, observing the values that all the objective functions assume in each solution. If no one of these solutions appears to be acceptable, we could introduce as additional constraints the minimum desirable performance level of each of the objective functions we are willing to accept, and solve the problem again, having as an objective the most relevant of those objective functions being considered. Sequential tests and sensitivity analysis could be quite valuable in obtaining satisfactory answers in this context.

B) Gathering the Data

Having defined the model, we must collect the data required to define the parameters of the problem. The data involves the objective-function coefficients, the constraint coefficients (also called the matrix coefficients) and the right-hand side of the mathematical-programming Model. This stage usually represents one of the most time-consuming and costly efforts required by the mathematical-programming approach.

C) Obtaining an optimal solution

Because of the lengthy calculations required to obtain the optimal solution of a mathematical-programming model, a digital computer is invariably used in this stage of model implementation. Today, all the computer manufacturers offer highly efficient codes to solve linear-programming models. These codes presently can handle general linear-programming problems of up to 4000 rows, with hundreds of thousands of decision variables, and are equipped with sophisticated features that permit great flexibility in their operation and make them extraordinarily accurate and effective. Instructions for use of these codes are provided by the manufacturers; they vary slightly from one computer firm to another.

D) Applying sensitivity analysis

One of the most useful characteristics of linear-programming codes is their capability to perform sensitivity analysis on the optimal solutions obtained for the problem originally formulated.

In general, the type of changes that are important to investigate are changes in the objective-function coefficients, in the right-hand-side elements, and in the matrix coefficients. Further, it is sometimes necessary to evaluate the impact on the objective function of introducing new variables or new constraints into the problem.

Although it is often impossible to assess all of these changes simultaneously, good linear-programming codes provide several means of obtaining pertinent information about the impact of these changes with a minimum of extra computational work.

E) Testing and implementing the solution

The solution should be tested fully to ensure that the model clearly represents the real situation. If the solution is unacceptable, new refinements have to be incorporated into the model and new solutions obtained until the mathematical-programming model is adequate.

When testing is complete, the model can be implemented. Implementation usually means solving the model with real data to arrive at a decision or set of decisions.

Care must be taken to ensure that the model is flexible enough to allow for incorporating changes that take place in the real operating system.

Chapter 6:

The TIMES model generator

Based on 'Documentation for the TIMES Model' Part I and II

Full documentation available at http://www.etsap.org

6.1 Description of the model generator

6.1.1 Brief overview

As explained in chapter IV TIMES (an acronym for The Integrated MARKAL-EFOM System) is an economic model generator for local, national or multiregional energy systems, which provides a technology-rich basis for estimating energy dynamics over a long-term, multi-period time horizon.

Reference case estimates of end-use energy services demands (heat, electricity, etc.) are provided by the user for each region. In addition the user provides estimates of the existing stock of energy related equipment in all sectors, and the characteristics of available future technologies, as well as present and future sources of primary energy supply and their potentials.

Using these as input, the TIMES model aims to supply energy services at minimum global cost (more accurately at minimum loss of surplus) by simultaneously making equipment investment and operating, primary energy supply, and energy trade decisions, by region. The choice made by the model regarding the generation equipment (type and fuel) is based on the analysis of the characteristics of alternative generation technologies, on the economics of the energy supply, and on the environmental criteria. TIMES is thus a vertically integrated model of the entire extended energy system.

In TIMES the quantities and prices of the various commodities are in equilibrium, i.e. their prices and quantities in each time period are such that the suppliers produce exactly the quantities demanded by the consumers. This equilibrium has the property that the total surplus is maximized.

The TIMES model is particularly suited to the exploration of possible energy futures based on contrasted scenarios.

In TIMES a complete scenario consists of four types of input: energy services demands, primary resource potentials, a policy setting, and the descriptions of a set of technologies.

6.1.2 The demand components of a TIMES scenario

In the case of the TIMES model demand drivers are obtained externally, via other models or from accepted other sources. Usually the main drivers are: Population, GDP, GDP per capita, number of households.

Once the drivers for a TIMES model are determined and quantified the construction of the reference demand scenario requires computing a set of energy service demands over the horizon. This is done by choosing elasticity of demands to their respective drivers, in each region, using the following general formula:

$$\text{Demand} = \text{Driver}^{\text{Elasticity}}$$

As mentioned above, the demands are provided for the reference scenario. However, when the model is run for alternate scenarios, it is likely that the demands will be affected. TIMES has the capability of estimating the response of the demands to the changing conditions of an alternate scenario. To do this, the model requires still another set of inputs, namely the assumed elasticity of the demands to their own prices. TIMES is then able to endogenously adjust the demands to the alternate cases without exogenous intervention. In fact, the TIMES model is driven not by demands but by demand curves.

6.1.3 The supply components of a TIMES scenario

The second constituent of a scenario is a set of supply curves for primary energy and material resources. Multi-stepped supply curves can be easily modeled in TIMES; each step represents a certain potential of the resource available at a particular cost. In some cases, the potential may be expressed as a cumulative potential over the model horizon (e.g. reserves of gas, crude oil, etc), as a cumulative potential over the resource base (e.g. available areas for wind converters differentiated by velocities, roof areas for PV installations) and in others as an annual potential (e.g. maximum extraction rates, or for renewable resources the available wind, biomass, or hydro potentials). Note that the supply component also includes the identification of trading possibilities, where the amounts and prices of the traded commodities are determined endogenously (within any imposed limits).

6.1.4 The policy components of a TIMES scenario

Insofar as some policies impact on the energy system, they may become an integral part of the scenario definition. For instance, a No-Policy scenario may perfectly ignore emissions of various pollutants, while alternate policy scenarios may enforce emissions restrictions, or carbon tax, etc.

6.1.5 The techno-economic components of a TIMES scenario

The fourth and last constituent of a scenario in the set of technical and economic parameters assumed for the transformation of primary resources into energy services. In TIMES, these techno-economic parameters are described in the form of technologies (or processes) that transform some commodities into others (fuels, materials, energy services, emissions). In TIMES, some technologies may be imposed and others may simply be available for the model to choose. The quality of a TIMES model rests on a rich, well developed set of technologies, both current and future, for the model to choose from. The emphasis put on the technological database is one of the main distinguishing factors of the class of Bottom-up models, to which TIMES belongs. Other classes of models will tend to emphasize other aspects of the system (e.g. interactions with the rest of the economy) and treat the technical system in a more succinct manner via aggregate production functions.

6.2 The structure of the TIMES model

It is useful to distinguish between a model's structure and a particular instance of its implementation. A model's structure exemplifies its fundamental approach for representing and analyzing a problem—it does not change from one implementation to the next. All TIMES models exploit an identical mathematical structure. However, because TIMES is data driven, each (regional) model will vary according to the data inputs. For example, in a multi-region model one region may, as a matter of user data input, have undiscovered domestic oil reserves. Accordingly, TIMES generates technologies and processes that account for the cost of discovery and field development.

Due to this property TIMES can also be called a model generator that, based on the input information provided by the modeler, generates an instance of a model.

The structure of TIMES is ultimately defined by variables and equations determined from the data input provided by the user. This information collectively defines each TIMES regional model database, and therefore the resulting mathematical representation of the reference energy system for each region. The database itself contains both qualitative and quantitative data. The qualitative data includes, for example, lists of energy carriers, the technologies that the modeler feels are applicable (to each region) over a specified time horizon, as well as the environmental emissions that are to be tracked. This information may be further classified into subgroups, for example energy carriers may be split by type (e.g., fossil, nuclear, renewable, etc). Quantitative data, in contrast, contains the technological and economic parameter assumptions specific to each technology, region, and time period.

The TIMES energy economy is made up of producers and consumers of commodities such as energy carriers, materials, energy services, and emissions. TIMES, like most equilibrium models, assumes competitive markets for all commodities. The result is a supply-demand equilibrium that maximizes the net total surplus (i.e. the sum of producers' and consumers' surpluses) as will be fully discusses in the next sections.

TIMES may, however, depart from perfectly competitive market assumptions by the introduction of user-defined explicit constraints, such as limits to technological penetration, constraints on emissions, exogenous oil price, etc. Market imperfections can also be introduced in the form of taxes, subsidies and hurdle rates.

Operationally, a TIMES run configures the energy system (of a set of regions) over a certain time horizon in such a way as to minimize the net total cost (or equivalently maximize the net total surplus) of the system, while satisfying a number of constraints.

TIMES is run in a dynamic manner, which is to say that all investment decisions are made in each period with full knowledge of future events. The model is said to have perfect foresight (or to be clairvoyant). In addition to time-periods (which may be of variable length), there are time divisions within a year, also called time-slices, which may be defined at will by the user (figure 46). Time-slices are especially important whenever the mode and cost of production of an energy carrier at different times of the year are significantly different. This is the case for instance when the demand for an energy form fluctuates across the year and a variety of technologies may be chosen for its production. The production technologies may themselves have different characteristics depending on the time of year (e.g. wind turbines or run-of-the-river hydro plants).

6.2.1 Time horizon

The time horizon is divided into a user-chosen number of time-periods, each model period containing a number of years. For TIMES each year in a given period is

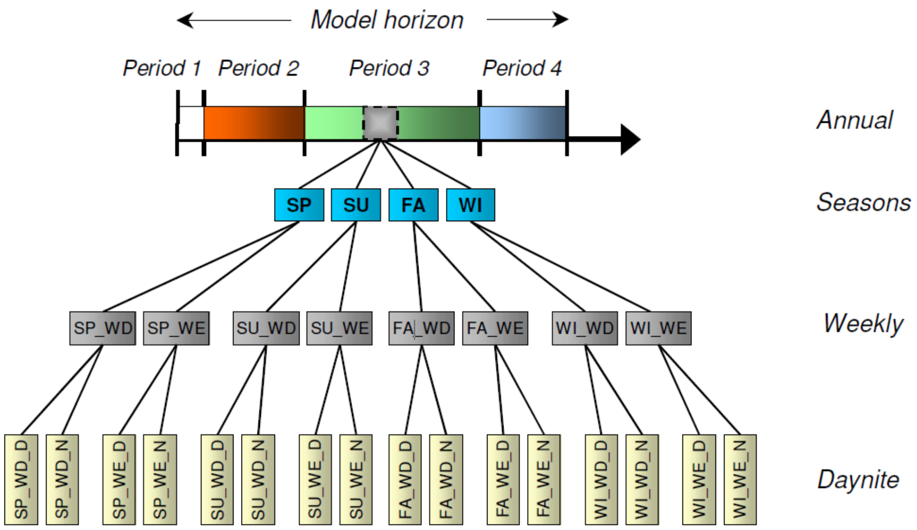


Figure 46: Example of a time-slice tree

considered identical, except for the objective function which differentiates between payments in each year of a period. For all other quantities (capacities, commodity flows, operating levels, etc) any model input or output related to period t applies to each of the years in that period, with the exception of investment variables, which are usually made only once in a period.

The initial period is usually considered a past period, over which the model has no freedom, and for which the quantities of interest are all fixed by the user at their historical values. It is often advised to choose an initial period consisting of a single year, in order to facilitate calibration to standard energy statistics. Calibration to the initial period is one of the more important tasks required when setting up a TIMES model. The main variables to be calibrated are: the capacities and operating levels of all technologies, as well as the extracted, exported, imported, produced, and consumed quantities for all energy carriers, and the emissions if modeled.

In TIMES years preceding the first period also play a role. Although no explicit variables are defined for these years, data may be provided by the modeler on past investments.

6.2.2 The Reference Energy System concept

The TIMES energy economy consist of three types of entities:

1. Technologies (or processes) are representations of physical devices that transform commodities into other commodities, or transformation activities such as conversion plants that produce electricity, energy-processing plants such as refineries, end-use demand devices such as lamps, heating system,

etc.

2. Commodities consisting of energy carriers, energy services, materials, monetary flows, and emissions. A commodity is generally produced by some processes and/or consumed by other processes.
3. Commodity flows, that are the links between processes and commodities. A flow is of the same nature as a commodity but is attached to a particular process, and represent one input or one output of that process.

It is helpful to picture the relationship among these various entities using a network diagram, referred to as a Reference Energy System (RES).

In TIMES, the RES processes are represented as boxes and commodities as vertical lines. Commodity flows are represented as links between boxes and lines.

Using graph theory terminology, a RES is an oriented graph, where both the processes and the commodities are the nodes of the graph. They are interconnected by the flows, which are the arcs of the graph. Each arc (flow) is oriented and links exactly one process node with one commodity node. Such a graph is called bi-partite, since its set of nodes may be partitioned into two subsets and there are no arcs directly linking two nodes in the same subset.

Figure 47 depicts a small portion of a hypothetical RES containing a single energy service demand, namely residential space heating. There are three end-use space heating technologies using the gas, electricity, and heating oil energy carriers (commodities), respectively. These energy carriers in turn are produced by other technologies, represented in the diagram by one gas plant, three electricity-generating plants (gas fired, coal fired, oil fired), and one oil refinery. To complete the production chain on the primary energy side, the diagram also represents an extraction source for natural gas, an extraction source for coal, and two sources of crude oil (one extracted domestically and then transported by pipeline, and the other one imported). This simple RES has a total of 13 commodities and 13 processes. Note that in the RES every time a commodity enters/leaves a process (via a particular flow) its name is changed (e.g., wet gas becomes dry gas, crude becomes pipeline crude). This simple rule enables the interconnections between the processes to be properly maintained throughout the network.

To organize the RES the various technologies, commodities, and flows may be classified into sets. Each set regroups components of a similar nature. The entities belonging to a set are referred to as members, items or elements of that set. The same item may appear in multiple technology or commodity sets. While the topology of the RES can be represented by a multi-dimensional network, which

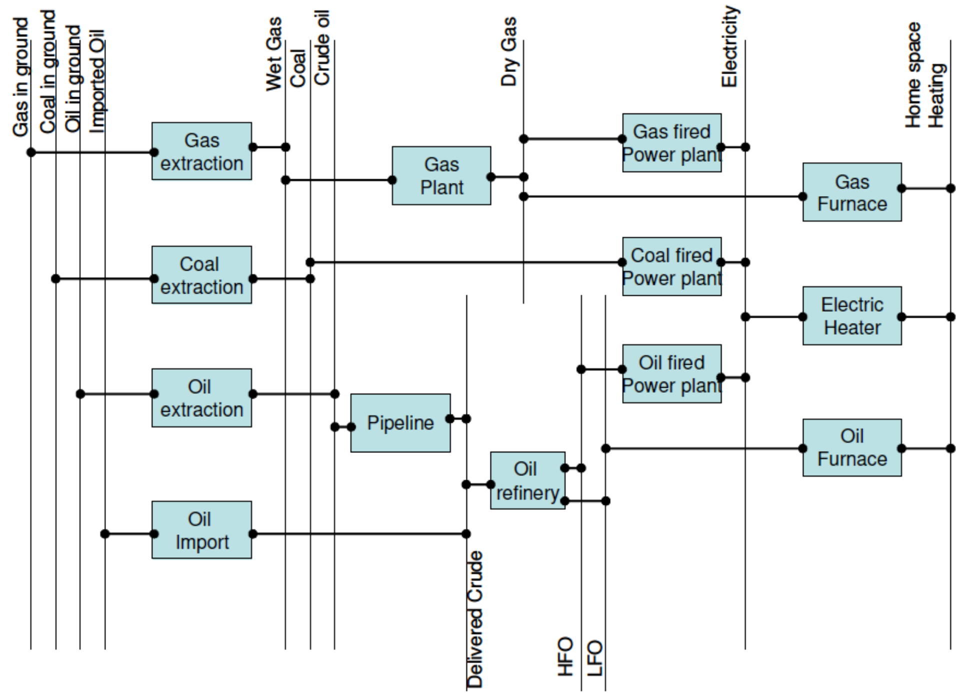


Figure 47: Partial view of a simple RES (all arcs are oriented left to right)

maps the flow of the commodities to the various technologies, the set membership conveys the nature of the individual components.

The TIMES commodities are classified into several Major Groups. There are five such groups: energy carriers, materials, energy services, emissions, and monetary flows.

6.2.3 TIMES attributes

Attributes may be cardinal (e.g. numbers) or ordinal (e.g. sets). The cardinal attributes are usually called parameters. The types of parameters available in TIMES are:

1) Parameters associated with processes: TIMES process oriented parameters fall into three general categories. First are technical parameters that include efficiency, availability factor, commodity consumption per unit of activity, technical life of the process, construction lead time, contribution to the peak equations. Second are economic and policy parameters that include a variety of costs attached to the investment, dismantling, maintenance, and operation of a process but also the economic life of a process and the process specific discount rate both of which are needed to calculate the annualized payment on the process investment cost. Finally, the modeler may impose a variety of bounds (lower, upper, equality) on the investment,

capacity and activity of a process.

2) Parameters associated with commodities: commodity oriented parameters fall into three categories. Technical parameters associated with commodities include overall efficiency, and the time-slices over which the that commodity is to be tracked; for demand commodities, in addition the annual projected demand and load curves can be specified. Economic parameters include additional costs, taxes and subsides on the overall or net production of a commodity; in the case of a demand service, additional parameters define the demand curve, they are: the demand's own-price elasticity, the total allowed range of variation of the demand value, and the number of steps to use for the discrete approximation of the curve. Policy based parameters include bounds on the overall or net production of a commodity, or on the import or export of a commodity by a region.
3) Parameters attached to commodity flows into and out of process. A commodity flow is an amount of a given commodity produced or consumed by a given process. Some processes have several flows entering or leaving it, perhaps of different types (fuels, materials, emissions). Technical parameters permit full control over the maximum or minimum share a given input flow may take within the same commodity group. Other parameters and sets define the amount of certain outflow in relation of certain inflows. Economic parameters include delivery and other variable costs, taxes and subsides attached to an individual process flow.
4) Parameters attached to the entire RES. These parameters include currency conversion factors, region specific time-slice definitions, a region-specific general discount rate and reference year for calculating the discounted total cost (objective function).

6.2.4 Processes and commodities classification

Although TIMES does not explicitly differentiate process or commodities that belong to different portions of the RES there are some ways in which some differentiation does occur.

First, TIMES does require the definition of Primary Commodity Groups (pcg), i.e. subset of commodities of the same nature entering or leaving a process for those processes that require more than one commodity as input or output. TIMES uses the pcg to define the activity of the process, and also its capacity.

As noted previously TIMES does not require that the user provide many set memberships. However, we will see that the TIMES report step does pass some set declaration to the VEDA-BE shell to facilitate construction of results analysis tables. These includes process subset to distinguish demand services, energy processes, material processes, electric production plants, heating plants, storage technologies and distribution technologies; and commodity subset for energy, energy demands, environmental indicators and materials.

6.3 Economic rationale of the TIMES modeling approach

This section provides a detailed economic interpretation of the TIMES and other partial equilibrium models based on maximizing total surplus.

TIMES is a technology explicit, or bottom up, partial equilibrium model that uses optimization techniques to compute a least cost path for the energy system.

Partial equilibrium models have one common feature: they simultaneously configure the production and consumption of commodities and their prices. The price of producing a commodity affects the demand for that commodity, while at the same time the demand affects the commodity's price. A market is said to have reached an equilibrium at price p* and quantity q* when no consumer whishes to purchase less than q* at price p* and no producer whishes to produce more than q* at price p*. When all markets are in equilibrium the total economic surplus is maximized.

A brief description of TIMES would express that it is a:

- ✓ Technology explicit;
- ✓ Multi-regional;
- ✓ Partial equilibrium model;

that assumes:

- ✓ Price elastic demand;
- ✓ Competitive markets;
- ✓ Perfect foresight.

<u>Technology explicit model</u>

Since each technology is described in TIMES by a number of technical and economic parameters. Thus each technology is explicitly identified and distinguished from all others in the model. Furthermore, the number of technologies and their relative topology may be changed at will, purely via data input specification, without the user having to modify the model's equations. The model is thus data driven.

<u>Multi-regional feature</u>

The number of regions in a model is limited only by the difficulty of solving LPs of very large size. The individual regional modules are linked by energy and material trading variables, and by emissions permit trading variables.

Partial equilibrium properties

TIMES compute a partial equilibrium on energy markets. This means that the model computes both the flows of energy forms and materials as well as their prices, in such a way that, at the prices computed by the model, the suppliers of energy produce exactly the amounts that the consumers are willing to buy. This equilibrium feature is present at every stage of the energy system: primary energy forms, secondary energy forms, and energy services. A supply-demand equilibrium model has as economic rationale the maximization of the total surplus, defined as the sum of suppliers and consumers surpluses.

The mathematical method used to maximize the surplus must be adapted to the particular mathematical properties of the model; in TIMES these properties are as follows:

- Outputs of a technology are linear functions of its input;
- Total economy surplus is maximized over the entire horizon;
- Energy markets are competitive, with perfect foresight.

As a result of these assumptions the following additional properties hold:

- The market price of each commodity is equal to its marginal value in the overall system;
- Each economic agent maximize its own profit or utility.

Linearity

A linear input-to-output relationship first means that each technology represented may be implemented at any capacity, from zero to some upper limit, without economies or diseconomies of scale. In a real economy a given technology Is usually available in discrete size, rather than in a continuum. In particular, for some real available technologies, there may be a minimum size below which the technology cannot be implemented (or else a prohibitive cost). In such case in may happens that the model's solution shows some technology's capacity at an unrealistically small size. However in most applications, such a situation is relatively infrequent to and often innocuous, since the scope of application is at the country or region's level, and thus large enough so that small capacities are unlikely to occur. On the other hand, there may be situations where the plant size matters, for instance when the region being modeled is very small. In such case, it is possible to enforce a rule by which certain capacities are allowed only in multiples of a given size, by introducing integer variables. This approach should, however, be used sparingly because it greatly increases solution time. Alternatively and more simply, a user may add user-defined constraints to force to zero any capacities that are clearly too small.

It is the linearity property that allows the TIMES equilibrium to be computed using Linear Programming techniques. The fact that TIMES's equations are linear, however, doesn't mean that production functions behave in a linear fashion. Indeed, the TIMES production functions are usually highly non linear, representing non linear functions as a stepped sequence of linear functions.

Maximization of total surplus: price equals marginal value

The total surplus of an economy is the sum of the suppliers' and the consumers' surpluses. The term supplier designates any economic agent that produces (and sells) one or more commodities. A consumer is a buyer of one or more commodities. In TIMES the suppliers of a commodity are technologies or demands that consume a given commodity.

It is customary in microeconomics to represent the set of suppliers of a commodity by their inverse production function, that plots the marginal production cost of the commodity as a function of quantity supplied.

In TIMES, as in other linear optimization models, the supply curve of a commodity is not explicitly expressed as a function of aggregate factor inputs such as capital, labor and energy.

However, it is a standard result of Linear Programming theory that the inverse supply function is step-wise constant and increasing in each factor (see figure 48).

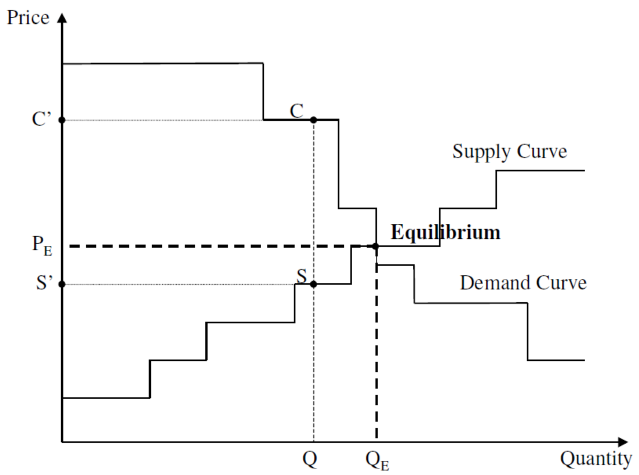


Figure 48: Equilibrium in the case of an energy form: the model implicitly builds both the supply and the demand curves

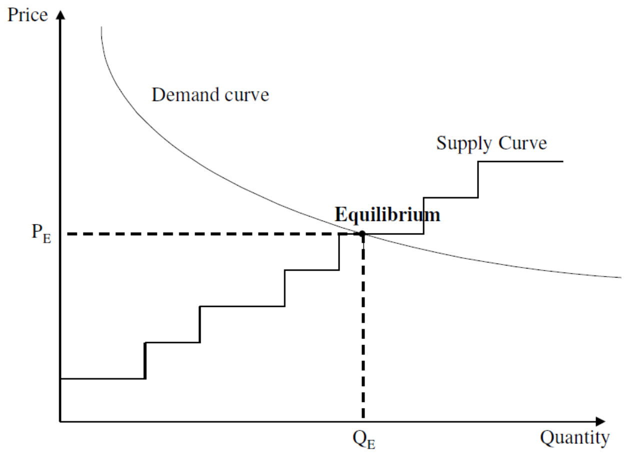


Figure 49: Equilibrium in the case of an energy service: the user, explicitly provides the demand curve

Each horizontal step of the inverse supply function indicates that the commodity is produced by a certain technology or set of technologies in a strictly linear fashion. As the quantity produced increases, one more resource in the mix is exhausted, and therefore the system must start using a different (more expensive) technology or set of technologies in order to produce additional units of the commodity, albeit at higher unit cost. Thus, each change in production mix generates one step of the staircase production function with a value higher than the preceding step. The width of any particular step depends upon the technological potential and/or resource availability associated with the set of technologies represented by that step.

In a similar manner, each TIMES instance defines a series of inverse demand functions. In the case of demands, two cases are distinguished. First, if the commodity is an energy carrier whose production and consumption are endogenous to the model, then its demand function is implicitly constructed within TIMES, and is a step-wise constant, decreasing function of the quantity demanded. If, on the other hand, the commodity is a demand for an energy service, then its demand curve is defined by the user via the specification of the own-price elasticity of that demand, and the curve is in this instance a smoothly decreasing curve. In both cases the supply-demand equilibrium is at the intersection of the supply function and the demand function, and corresponds to an equilibrium quantity Q_E and an equilibrium price P_E. At price P_E, suppliers are willing to supply the quantity Q_E and consumers are willing to buy exactly that same quantity Q_E. Of course, the TIMES equilibrium concerns many commodities, and the equilibrium is a multi-dimensional analog of the above, where P_E and Q_E are vectors rather than scalars.

Using figure 48 as an example the definition of the suppliers' surplus corresponding to a certain point S on the inverse supply curve is the difference between the total revenue and the total cost of supplying a commodity. In figure 48 the surplus is thus area between the horizontal segment SS' and the inverse supply curve. Similarly, the consumers' surplus for a point C on the inverse demand curve is defined as the area between the segment CC and the inverse demand curve. This area is a consumer's analog to a producer's profit; more precisely it is the cumulative opportunity gain of all the consumers who purchase the commodity at a price lower than the price they would have been willing to pay. For a given quantity Q the total surplus is simply the area between the two inverse curves situated at the left of Q. It should be clear from fig. 48 that the total surplus is maximized exactly when Q is equal to the equilibrium quantity Q_E. Therefore, we may state the following Equivalence Principle:

"The supply-demand equilibrium is reached when the total surplus is maximized".

Competitive energy markets with perfect foresight

Competitive energy market are characterized by perfect information and atomic economic agents, which together preclude any of them from exercising market power. That is, neither the level any individual producer supplies, nor the level any individual consumer demands, affects the equilibrium market price (because there are many other buyers and sellers to replace them). It is a standard result of microeconomic theory that the assumption of competitive markets entails that the price of a commodity is equal to its marginal value in the economy.

In TIMES the perfect information assumption extends to the entire planning horizon, so that each agent has perfect foresight. Hence, the equilibrium is computed by maximizing total surplus in one pass for the entire set of periods.

Marginal value pricing

Given that the TIMES equilibrium occurs at the intersection of the inverse supply and inverse demand curves, it follows that the equilibrium prices are equal to the marginal system values of the various commodities. From a different angle, the duality theory of LP (see chapter V) indicates that for each constraint of the TIMES linear program there is a dual variable. This dual variable (when an optimal solution is reached) is also called the constraint's shadow price, and it's equal to the marginal change of the objective function per unit increase of the constraint's right-hand-side (RHS). For instance, the shadow price of the balance constraint of a commodity represent the competitive market price of the commodity. The fact that the price of a commodity is equal to its marginal value is an important feature of competitive markets. Duality theory does not necessarily indicate that the marginal value of a commodity is equal to the marginal cost of producing that commodity. For instance, in the equilibrium shown in figure 49 the price does not correspond to any marginal supply cost, since it's situated at a discontinuity of the inverse supply curve. In this case the price is precisely determined by demand rather than by supply, and the term marginal cost pricing is incorrect. The term marginal value pricing is a more appropriate term to use.

It is important to note that marginal value pricing does not imply that suppliers have zero profit. Profit is exactly equal to the suppliers' surplus.

In TIMES the shadow prices of commodities play a very important diagnostic role. If some shadow prices are clearly out of line this indicate that the model's database may contain some errors.

Profit maximization: the Invisible Hand

An interesting property may be derived from the assumption of competitiveness. While the avowed objective of the TIMES model is to maximize the overall surplus, it is also true that each economic agent in TIMES maximizes its own profit. This property is akin to the famous 'invisible hand' property of competitive markets, and may be established rigorously by the following theorem that we state in an informal manner:

Theorem: Let (p*,q*) be the pair of equilibrium vectors. If we now replace the original TIMES linear program by one where the commodity prices are fixed at value p*, and we let each agent maximize its own profit, there exists a vector of optimal quantities produced or purchased by the agents that is equal to q*.

This property is important inasmuch as it provide an alternative justification for the class of equilibrium models based on the maximization of total surplus. It is now possible to shift the model's rationale from a global, societal one to a local, decentralized one. Of course, the equivalence suggested by the theorem is valid only insofar as the marginal value pricing mechanism is strictly enforced - that is neither individual producers' nor individual consumers' behaviors affect market prices - both group are price takers.

Clearly, many markets are not competitive in the sense the term has been used here.

6.4 Description of the TIMES optimization program

This chapter contains a simplified formulation of the TIMES Linear Program.

As we saw in chapter V a Linear Programming problem consist in the minimization (or maximization) of an objective function defined as a mathematical expression of decision variables, subject to constraints (also called equations) also expressed mathematically.

6.4.1 Indices

The model data structures (set and parameters), variables and equations use the following indexes:

r region

t or v time period; t corresponds to the current period, and v is used to indicate the vintage year of an investment

p process (technology)

s time-slice; this index is relevant only for user-designated commodities and processes that are tracked at finer than annual level.

c commodity (energy, material, emissions, demand).

6.4.2 Decision variables

The decision variables represent the choices to be made by the model, i.e. the unknowns. The various kinds of decision variables in a TIMES model are:

NCAP(r,v,p): new capacity addition (investment) for technology p, in period v and region r. For all technologies the v value corresponds to the vintage of the process, i.e. year in which it's invested in. Typical units are PJ/year for most energy technologies.

CAP(r,v,t,p): installed capacity of process *p*, in region *r* and period *t*. It represents the total capacity in place in period *t*, considering the residual capacity at the beginning of the modeling horizon and new investments made prior to and including period *t* that have not reached their technical lifetime.

CAPT(r,t,p): total installed capacity of technology *p*, in region *r* and period *t*. The CAPT variables are only defined when some bound or user-constraint are specified for them.

ACT(r,v,t,p,s): activity level of technology *p*, in region *r* and period *t*. Typical units: PJ for all energy technologies. The s index is relevant only for processes that produce or consume commodities specifically declared as time-sliced.

FLOW(r,v,t,p,c,s): the quantity of commodity *c* consumed or produced by process *p*, in region *r* and period *t*. Typical units: PJ for all energy technologies.

SIN(r,v,t,p,c,s)/SOUT(r,v,t,p,c,s): the quantity of commodity *c* stored or discharged by storage process *p*, in time-slice *s*, period *t* and region *r*.

TRADE(r,t,p,c,s,imp) and TRADE(r,t,p,c,s,exp): quantity of commodity *c* sold or purchased by region *r* through export or import process.

D(r,t,d): demand for end-use energy service *d* in region *r* and period *t*. In this simplified formulation we do not show the variables used to decompose *D(r,t,d)* into a sum of step-wise quantities.

Moreover, TIMES has a number of commodity related variables that are not strictly needed but are convenient for reporting purposes and/or for applying certain bounds to them. Examples of such variables are: the total amount produced of a commodity (COMPRD), or the total amount consumed of a commodity (COMCON).

6.4.3 Objective function: discounted total system cost

The surplus maximization objective is first transformed into an equivalent cost minimization objective by taking the negative of the surplus, and calling this the total system cost.

The TIMES objective is therefore to minimize the total cost of the system, properly augmented by the cost of lost demand. All cost elements are appropriately discounted to a selected year.

While the TIMES constraints and variables are linked to a period, the components of the system cost are expressed for each year of the horizon. This choice is meant to provide a smoother, more realistic rendition of the stream of payments in the energy system.

Each year, the total cost includes the following elements:

- Capital costs incurred for investing into and/or dismantling processes;
- Fixed and variable annual Operation and Maintenance costs, and other annual cost occurring during the dismantling of technologies;
- Cost incurred for exogenous imports and for domestic resource production;
- Revenues from exogenous export;
- Delivery costs for required commodities consumed by processes;
- Taxes and subsides associated with commodity flows and process activities or investments;
- Revenues from recuperation of embedded commodities, accrued when a process' dismantling releases some valuable commodities;
- Salvage value of processes and embedded commodities at the end of the planning horizon;

- Welfare loss resulting from reduced end-use demands.

As already mentioned, in TIMES, special care is taken to precisely track the monetary flows related to process investments and dismantling in each year of the horizon. Such tracking is made complex by several factors:

- ✓ First, TIMES recognizes that there may be a lead-time between the beginning and the end of the construction of some large processes, thus spreading the investment installments over several years;
- ✓ Second, TIMES also recognizes that for some other processes (e.g. new cars), the investments in new capacity occur progressively over several years of a time period, rather than in one lump amount;
- ✓ Third, there is the possibility that a certain investment decision made at period t will have to be repeated more than once during that same period (this will occur if the t^{th} period is long compared to the process life);
- ✓ Fourth, TIMES recognizes that there may be dismantling capital costs at the end of life of some processes (e.g. a nuclear plant), and these costs, while attached to the investment variable indexed by period t, are actually incurred much later, and
- ✓ Finally, TIMES assumes that the payment of any capital cost is spread over an economic life that may be different from the *technical life* of the process, and annualized at a different rate than the overall discount rate.

These various TIMES features, while adding precision and realism to the cost profile, also introduce complex mathematical expressions in the objective function.

In this simplified formulation, we do not provide much detail on these complex expressions, which are fully described in section 5.1 of the document 'Documentation for the TIMES Model - Part II' available on iea-ETSAP website.

This description ha the purpose to give general indications on the cost elements composing the objective function. Before reporting the objective function some model's assumption that affect its expression must be taken into account:

- ✓ The investment and dismantling costs are transformed into streams of annual payments, computed for each year of the horizon (and beyond, in the case of dismantling costs and recycling revenues), along the lines suggested above;
- ✓ A salvage value of all investments still active at the end of the horizon (EOH) is calculated and its value is assigned to the (single) year following the EOH;
- ✓ The other costs listed above, which are all annual costs, are added to the annualized capital cost payments, minus salvage value, to form the

ANNCOST quantity (below), and

- ✓ TIMES then computes for each region a total net present value of the stream of annual costs, discounted to a user selected reference year. These regional discounted costs are then aggregated into a single total cost, which constitutes the objective function to be minimized by the model in its equilibrium computation.

$$\mathrm{NPV} = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR-1} \cdot ANNCOST(r,y)$$

Where:

- NPV is the net present value of the total cost for all regions (the objective function);
- ANNCOST is the total annual cost in region r and year y;
- $d_{r,y}$ is the general discount rate;
- REFYR is the reference year for discounting;
- YEARS is the set of years for which there are costs, including all years in the horizon, plus past years if cost have been defined for past investments, plus a number of years after EOH where some investment and dismantling costs are still being incurred, as well as the salvage value;
- R is the set of regions in the area of study.

6.4.4 Constraints

While minimizing total discounted cost the TIMES model must satisfy a large number of constraints (the so-called equations of the model) which express the physical and logical relationship that must be satisfied in order to properly depict the associated energy system. TIMES constraints are of several kinds. We list and briefly discuss the main type of constraints. A full description is given in the document 'Documentation for the TIMES Model - Part II'. If any constraint is not satisfied the model is said to be infeasible, a condition caused by data error or an over specification of some requirement.

<u>Capacity transfer (conservation of investments)</u>

Investing in a particular technology increases its installed capacity for the duration of the physical life of the technology. At the end of that life, the total capacity for this technology is decreased by the same amount. When computing the available capacity in some time period, the model takes into account the capacity resulting from all investments up to that period, some of which may have been made prior to the initial period but are still in operating condition, and others that have been decided by the model at, or after, the initial period, up to including the period in question.

The total available capacity for each technology p, in region r, in period t, is equal to the sum of investments made by the model at past and current periods, and whose physical life has not yet ended, plus capacity in place prior to the modeling horizon that is still available.

EQ_CPT(r,t,p)

$$CAPT(r,t,p) = \sum_{t\prime = max\{1, t-LIFE(r,p)\}}^{t} \{NCAP(r,t',p)\} + RESID(r,t,p)$$

Where *RESID(r,t,p)* is the capacity of the technology *p* due to investments that were made prior to the initial model period and still exist in region *r* at time *t*.

Definition of process activity variables.

Since TIMES recognizes activity variables as well as flow variables, it is necessary to relate these two types of variables. This is done by introducing a constraint that equates an overall activity variable, *ACT(r,v,t,p,s)*, with the appropriate set of flow variables, *FLOW(r,v,t,p,c,s)*, properly weighted. This is accomplished by first identifying the group of commodities that defines the activity of the process. In a simple process, one consuming a single commodity and producing a single commodity, the modeler simply chooses one of these two flows to define the activity, and thereby the process normalization (input or output). In more complex processes, with several commodities (perhaps of different types) as inputs and/or outputs, the definition of the activity variable requires first to choose the primary commodity group (pcg) that will serve as the activity-defining group.

EQ_ACTFLO(r,v,t,p,s)

$$ACT(r,v,t,p,s) = \sum_{c \in pcg} \frac{FLOW(r,v,t,p,c,s)}{ACTFLO(r,v,p,c)}$$

Where *ACTFLO(r,v,p,c)* is a conversion factor (often equal to 1) from the activity of the process to the flow of a particular commodity.

<u>Use of capacity</u>

In each time period the model may use some or all of the installed capacity according to the Availability Factor (AF) of that technology. Note that the model can decide to use less than the available capacity during certain time-slices, or even throughout one or more whole periods, if such a decision contributes to minimizing the overall cost. Optionally, there is a provision for the modeler to force specific technologies to use their capacity to their full potential.

For each technology *p*, period *t*, vintage *v*, region *r*, and time-slice *s*, the activity of the technology may not exceed its available capacity, as specified by a user defined AF.

EQ_CAPACT(r,v,t,p,s)

$$ACT(r,v,t,p,s) \le AF(r,v,t,p,s) * CAPUNIT(r,p) * FR(r,s) * CAP(r,v,t,p)$$

Here *CAPUNIT(r,p)* is the conversion factor between units of capacity and unit of activity (often equal to 1, except for power plants). The *FR(r,s)* parameter is equal to the duration of time-slice s. The AF also serves to indicate the nature of the constraint as an inequality or an equality.

Note that the *CAP(r,v,t,p)* variable is not explicitly defined in TIMES. Instead it is replaced by a fraction of the investment variable *NCAP(r,v,p),* a sum of past investment that are still operating.

The *s* index of the AF coefficient in the equation indicates that the user may specify time-sliced dependency on the availability of the installed capacity of some technologies. This is especially needed when the operation of the equipment depends on the availability of a resource that cannot be stored, such as wind and sun, or that can be only partially stored, such as water in a reservoir.

Concerning the storage processes, the capacity describes the volume of the storage and the activity the storage content. For storage processes between time-slices parameter RS_STGPRD is used instead of FR. This coefficient equals the number of storage periods for the time-slice s in a year multiplied with the duration of its parent time-slice ts, which is the duration of one storage period. RS_STGPRD is equal to (1) 1 for seasonal storage, (2) 365/7*FR(r,ts) for weekly storage, (3) 365*FR(r,ts) for daily storage.

<u>Commodity balance equation</u>

In each time period, the production by a region plus import from other regions of each commodity must balance the amount consumed in the region or exported to other regions. In TIMES, the sense of each balance constraint (≥ or =) is user-controlled, via a special parameter attached to each commodity. However the constraint defaults to an equality in the case of materials and to inequality in the case of energy carriers, emissions and demand.

For each commodity *c*, time period *t*, region *r*, and time-slice *s* this constraint requires that the disposition of each commodity balances its procurement.

EQ_COMBAL(r,t,c,s)

$$\left[\sum_{p}\sum_{c\in TOP(r,p,c,\text{out})}\{FLOW(r,v,t,p,c,s)+SOUT(r,v,t,p,c,s)*STG\_EFF_{(r,v,p)}\}\right.$$
$$+\sum_{p}\sum_{c\in RPC_{IRE(r,p,c,\text{imp})}}\{TRADE(r,t,p,c,s,"imp")\}$$
$$\left.+\sum_{p}\{Release(r,t,p,c)*NCAP(r,t,p,c)\}\right]*COM\_IE_{(r,t,c,s)}$$

$$\geq \ or \ =$$

$$\sum_{p}\sum_{c\in TOP(r,p,c,"in")}\{FLOW(r,v,t,p,c,s)+SIN(r,v,t,p,c,s)\}$$
$$+\sum_{p}\sum_{c\in RPC\_IRE(r,p,c,"exp")}\{TRADE(r,t,p,c,s,"exp")\}$$
$$+\sum_{p}\{Sink(r,t,p,c)*NCAP(r,t,p,c)\}+FR(c,s)*DM(ct)$$

Where:

- *TOP(r,p,c,"in/out")* identifies that there is an input/output flow of commodity *c* into/from process *p* in region *r*;
- *RPC_IRE(r,p,c,"imp/exp")* identifies that there is an import/export flow into/from region *r* of commodity *c* via process *p*;
- *STG_EFF(r,v,p)* is the efficiency of storage process *p*;
- *COM_IE(r,t,c)* is the infrastructure efficiency of commodity *c*;
- *Releaser(r,t,p,c)* is the amount of commodity *c* recuperated per unit of capacity of process *p* dismantled;
- *Sink(r,t,p,c)* is the quantity of commodity *c* required per unit of new capacity of process *p*.
- *FR(s)* is the fraction of the year covered by time-slice *s*.

Defining flow relationship in a process

A process with one or more commodity flows is essentially defined by one or more independent input and output flow variables. In the absence of relationship between these flows, the process would be completely undetermined, i.e. its outputs would be independent from its inputs. We therefore need one or more constraints stating that the ratio of the sum of some of its inputs flows to the sum of some of its input flows is equal to a constant. In the case of a single commodity in and a single commodity out of a process, this equation defines the traditional efficiency of the process.

EQ_PTRANS(r,v,t,p,cg1,cg2,s)

$$\sum_{c \in cg2} FLOW(r,v,t,p,c,s) =$$
$$FLOFUNC(r,v,cg1,cg2,s) * \sum_{c \in cg1} COEFF(r,v,p,cg1,c,cg2,s) * FLOW(r,v,t,p,c,s)$$

Where *COEFF(r,v,p,cg1,c,cg2,s)* takes into account the harmonization of different time-slice resolution of the flow variables, which have been omitted here for simplicity, as well as commodity-dependent transformation efficiencies.

Transform input to output for the time-slice storage processes

Generally the model allows two kinds of storage: inter-period storage (IPS), and storage across time-slice (TSS). A special type of the TSS storage is a night-storage device which may have an input commodity being different from its output commodity. Storage processes are special, as they have the same commodity as input and output. Also, all other processes transform energy within their time-slices and time-periods. Since topology does not determine in/out, different variables have to be used for this purpose. Similarly, since the transformation is special, EQ_PTRANS is replaced by new equations for the two types of storage.

For the purpose of this thesis it's enough to explain only the TSS storage equation.

EQ_STGTSS(r,t,p,s)

$$\sum_{v \in vintyr(r,v,t,p)} VAR\_ACT(r,v,t,p,s) * PRC\_ACTFLO(r,v,p,pcg)$$
$$=$$
$$\sum_{v \in vintyr(r,v,t,p)} \Bigg\{ VAR\_ACT(r,v,t,p,s-1) * PRC\_ACTFLO(r,v,p,pcg) + VAR\_SIN(r,v,t,p,c,s-1) - VAR\_SOUT(r,v,t,p,c,s-1) - \left[\frac{(VAR\_ACT(r,v,t,p,s) + VAR\_ACT(r,v,t,p,s-1)}{2} * PRC\_ACTFLO(r,v,p,pcg) \right] * STG\_LOSS(r,v,p,s) * G\_YRFR(r,s) \Bigg\} + STG\_CHRG(r,t,p,s-1)$$

Where:

- The parameter *PRC_ACTFLO(r,v,p,pcg)* contains the conversion factor from the activity unit to the commodity unit of the primary commodity group. The variable *VAR_ACT(r,v,t,p,s)* in this case indicates the storage level (amount of energy stored) in the time-slice s.
- The parameter *STG_LOSS(r,v,p,s)* is the annual energy loss of a storage process per unit of average of energy stored and *STG_CHRG(r,t,p,s)* is the annual exogenous charging of a storage technology in a particular time-slice s.

<u>Peaking Reserve constraint</u>

This constraint imposes that the total capacity of all processes producing a commodity at each time period and in each region must exceed the average demand in the time-slice where peaking occurs by a certain percentage. This percentage is the Peak Reserve Factor, *RESERV(r,t,c)*, and is chosen to insure against several contingencies, such as: possible commodity shortfall due to uncertainty regarding its supply; unplanned equipment down time; and random peak demand that exceeds the average demand during the time-slice when the peak occurs. This constraint is therefore akin to a safety margin to protect against random events not explicitly represented in the model.

For each time period *t* and for region *r*, there must be enough installed capacity to exceed the required capacity in the season with largest demand for commodity *c* by a safety factor E called the peak reserve factor.

EQ_PEAK(r,t,c,s)

$$\sum_{\substack{p\ producing\ c\\ c=pcg}} \{CAPUNIT(r,p) * Peak(r,v,p,c,s) * FR(s) * CAP(r,v,t,p) * ACTFLO(r,v,p,c)\}$$

$$+ \sum_{\substack{p\ producing\ c\\ c\neq pcg}} \{FLOW(r,v,t,p,c,s) * Peak(r,v,p,c,s) + TRADE(r,t,p,c,s,i)\} \geq$$

$$[1 + RESERV(r,t,c,s)] * \sum_{p\ consuming\ c} \{FLOW(r,v,t,p,c,s) + TRADE(r,t,p,c,s,e)\}$$

Where:

- *RESERV(r,t,c,s)* is the region-specific reserve coefficient for commodity *c* in time-slice *s*, which allows for unexpected down time of equipment, for demand at peak, and for uncertain resource availability;
- *Peak(r,v,p,c,s)* specifies the fraction of technology *p*'s capacity in a region *r* for a period *t* and commodity *c* that is allowed to contribute to the peak load in slice *s*; many types of supply processes are predictably available during the peak and thus have a peak coefficient equal to 1, whereas others (such as wind turbines) are attributed a peak coefficient less than 1, since they are on average only fractionally available at peak.

Remark: to establish the peak capacity, two cases must be distinguished in equation EQ_PEAK.

For production processes where the peaking commodity is the only commodity in the primary commodity group (denoted c=pcg), the capacity of the process may be assumed to contribute to the peak.

For processes where the peaking commodity is not the only member of the pcg, there are several commodities included in the pcg. Therefore, the capacity as such cannot be used in the equation. In this case, the actual production is taken into account in the contribution to the peak, instead of the capacity.

Constraints on commodities quantities

In TIMES variables are optionally attached to various quantities related to commodities, such as total quantity produced. Therefore it is quite easy to put constraints on these quantities, by simply bounding the commodity variables at each period. It is also possible to impose cumulative bounds on commodities over more than one period.

A specific type of constraint may be defined to limit the share of a certain process in the total production of a specific commodity.

User constraint

In addition to the standard TIMES constraints discussed above, the user interested in developing reference case projections of energy market behavior typically introduces additional constraints to express these special conditions.

6.5 Elastic demand and the computation of the supply-demand equilibrium

In the preceding sections, it was explained that TIMES does more than minimize the total cost of supplying energy services. Instead, it computes a supply-demand equilibrium where both the supply options and the energy service demands are computed by the model. The equilibrium is driven by the user-defined specification of demand functions, which determine how each energy service demand varies as a function of the market price of that energy service. The TIMES code assumes that each demand has constant own-price elasticity in a given time period, and that cross price elasticity are zero.

Economic theory established that the equilibrium thus computed corresponds to the maximization of the net total surplus, defined as the sum of the suppliers and of the consumers' surpluses[31].

The TIMES model is normally run in two contrasted modes: first to simulate some reference case, and then to simulate alternate scenarios, each of which departs in some way from the reference case assumptions and parameters.

In TIMES demands self-adjust in reaction to changes of their own price, and therefore the model goes beyond the optimization of the energy sector only.

[31] Samuelson 1952, Takayama and Judge 1972

In this section I explain how Linear Programming computes the equilibrium.

6.5.1 Mathematics of the TIMES equilibrium

The computational method is based on the equivalence theorem presented in section .3, which restate here:

"A supply/demand economic equilibrium is reached when the sum of the producers and the consumers surpluses is maximized".

For each demand category, define a demand curve, i.e. a function determining demand as a function of price. In TIMES, a constant elasticity relationship is used, represented as:

$$DM_i(p)=K_i*p_i^{Ei} \qquad (1)$$

Where DM_i is the i^{th} demand, p_i is its price, taken to be the marginal cost of procuring the i^{th} commodity, and E_i is the own price elasticity of that demand. Note that although the region and time indexes *r,t* have been omitted in this notation, all the above quantities are region and time dependent. Constant K_i may be obtained of one point of the reference curve is known. Thus equation may be rewritten as:

$$DM_i/DM_i^0 = (p_i/p_i^0)^{Ei} \qquad (2)$$

Or its inverse:

$$p_i = p_i^0 * (DM_i/DM_i^0)^{1/Ei}$$

where the superscript '0' indicates the reference case, and the elasticity E_i is negative. Note also that the elasticity may have two different values, one for upward changes in demand, the other for downward changes.

With inelastic demands, the TIMES model may be written as the following Linear Program

$$\text{Min}\, c \cdot X \qquad (3)$$

s.t.

$$\sum_k CAP_{k,i}(t) \geq DM_i(t) \qquad i = 1,2,..I; t = 1,..,T \qquad (4)$$

$$B \cdot X \geq b \qquad (5)$$

Where X is the vector of all variables and I is the number of demand categories.

With elastic demands the role of TIMES is to compute a supply/demand equilibrium where both the supply side and the demand side adjust to changes in prices, and the prices charged by the supply side are the marginal costs of demand categories. A priori it seems to be a difficult task, because the prices used on the demand side are computed as part of the solution to equations (3),(4),(5). The equivalence theorem, however, states that such an equilibrium is reached as the solution of the following mathematical program, where the objective is to maximize the net total surplus:

$$Max\ \sum_i \sum_t \left(p_i^0(t) \cdot [DM_i^0(t)]^{-1/E_i} \cdot \int_a^{DM_i(t)} q^{1/E_i} \cdot dq\right) - c \cdot X \qquad (6)$$

s.t.

$$\sum_k CAP_{k,i}(t) \geq DM_i(t) \qquad i = 1,2,..I; t = 1,..,T$$

$$B \cdot X \geq b$$

Where X is the vector of all TIMES variables with associated cost vector c, (6) expresses the total net surplus, and DM is now a vector of variables rather than fixed demands.

The integral (6) is easily computed, yielding the following maximization program:

$$Max\ \sum_i \sum_t \left(p_i^0(t) \cdot [DM_i^0(t)]^{-1/E_i} . DM_i(t)^{1+1/E_i} \Big/ 1 + 1/E_i\right) - c \cdot X \qquad (7)$$

s.t.

$$\sum_k CAP_{k,i}(t) \geq DM_i(t) \qquad i = 1,2,..I; t = 1,..,T \qquad (8)$$

$$B \cdot X \geq b \qquad (9)$$

6.5.2 Linearization of the mathematical program

The mathematical program embodied in (7),(8),(9) has a non-linear objective function, because the latter is separable and concave in the DM_i variables, each of its items is easily linearized by piece-wise linear functions which approximate the integral in (6). By so doing, the resulting optimization problem becomes linear. The linearization proceeds as follows:

For each demand category *i*, the user selects a range within which it is estimated that the demand value $DM_i(t)$ will always remain, even after adjustment for price effects. The smallest range value is denoted $DM(t)_{min}$.

Select a grid that divides each range into a number n of equal width intervals. Let $\beta_i(t)$ be the resulting common width of the grid, $\beta_i(t)=R_i(t)/n$. The number of steps, n, should be chosen so that the step-wise constant approximation remains close to the exact value of the function.

For each demand segment $DM_i(t)$ define n step-variables, denoted $s_{1,i}(t)$, $s_{2,i}(t)$,…,$s_{n,i}(t)$.

Each s variables is bounded below by 0 and above by $\beta_i(t)$. One may now replace in the equations (6) and (7) each $DM_i(t)$ variable by the sum of the n-step variables, and each non-linear term in the objective function by a weighted sum of the n step-variables, as follows:

$DM_i(t) = DM(t)_{min} + \sum_{j=1}^{n} s_{i,j}(t)$

And

$DM_i(t)^{1+1/Ei} \approx DM(t)_{min}^{1+1/Ei} + \sum_{j=1}^{n} A_{j,s,i} \cdot s_{i,j}(t)/\beta_i(t)$

The resulting linear program is now fully linearized.

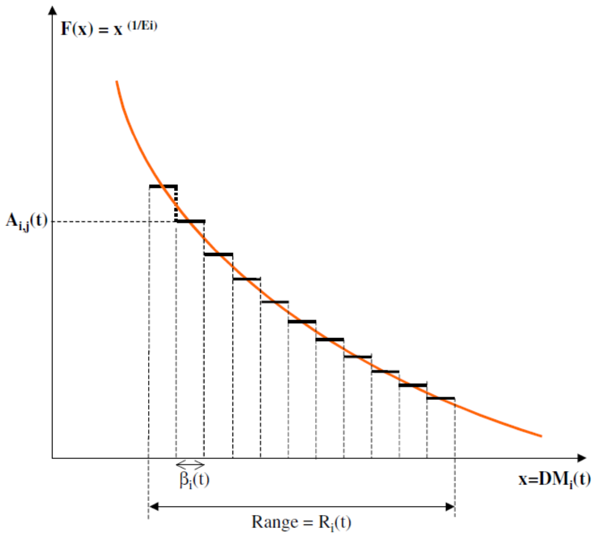


Figure 50: step-wise approximation of the non-linear terms in the objective function

Chapter 7:

The TIMES model: TIMES_STG_PL

The TIMES model developed takes into account a scenario-building path defined by the European Environmental Agency. This path is based especially on activities of the Intergovernmental Panel on Climate Change, World Water Commission and other groups. Based on the experience of these and other groups the EEA built a 'story and simulation' approach to develop scenarios. This approach combine qualitative and quantitative information and consist of two main elements: a storyline and a set of model calculation. The storyline describes in story form how relevant events unfold in the future, while the model calculations complement the storyline by presenting numerical estimates of future environmental indicators and helping to maintain the consistency of the storyline.

7.1 Model's storyline

Based on the decarbonization path scenario showed in the EU's RoadMap2050 project (Figure 51) according to which in 2050 at least 40% of the total production of Primary Energy should come from renewable sources, it has been defined the storyline of TIMES_STG_PL: in 2050 Poland will achieve at least 40% of electricity produced by renewable sources through a mass installation of wind power plants. Since the solar potential is negligible in Poland (70 MW maximum potential in 2030) and the available hydro potential is almost exhausted we focused our attention on wind onshore potential.

Note that the EU target concerns the production of Primary Energy that includes also the energy that will be consumed by the industry and the transport sector while we're considering only the production of electricity.

The model has a time horizon of 39 years (2011-2050) in 9 unequal time periods. The intra-annual time-slices are depicted at seasonal, weekly and hourly level: 4 season, 7 weekdays and 8 hourly time-slice were considered, for a total of 224 time-slices.

Based on ARE SA studies about economic potential of all resources in Poland it was fixed the amount of wind capacity that has to be built in each time period, from 2015 to 2050 (Table 11 and Figure 52). The intention is to have 30 GW of installed wind capacity in 2050 (note that based on ARE SA studies the overall wind economic potential for Poland is about 52 GW).

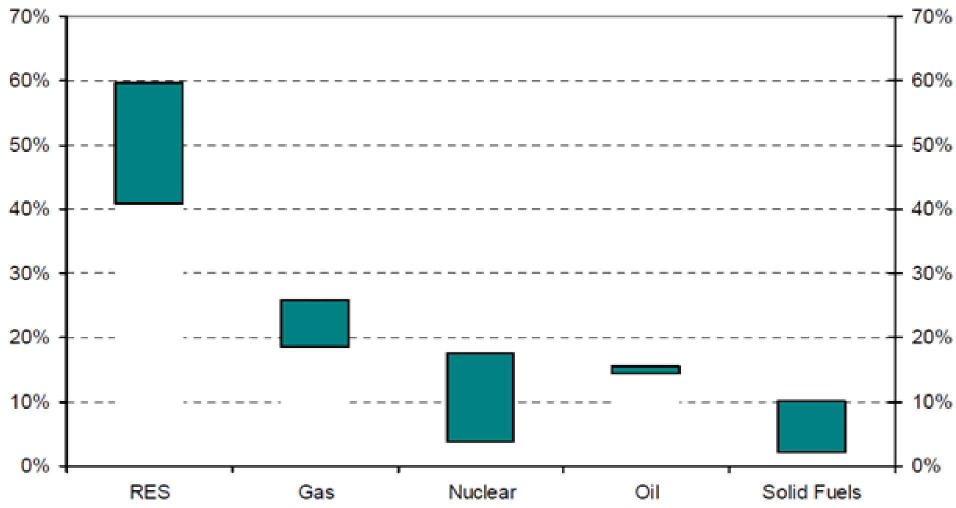


Figure 51: Range of Fuel Shares in Primary Energy in 2050[32]

Table 11: Fixed amount of wind power that has to be built within the time horizon

Year	2011	2015	2020	2025	2030	2035	2040	2045	2050
Existing CAP_wind onshore	1.62	1.62	1.62	1.62	1.62	0.50	0	0	0
NCAP_wind onshore	0	3	3	3	3	5	5	7	10

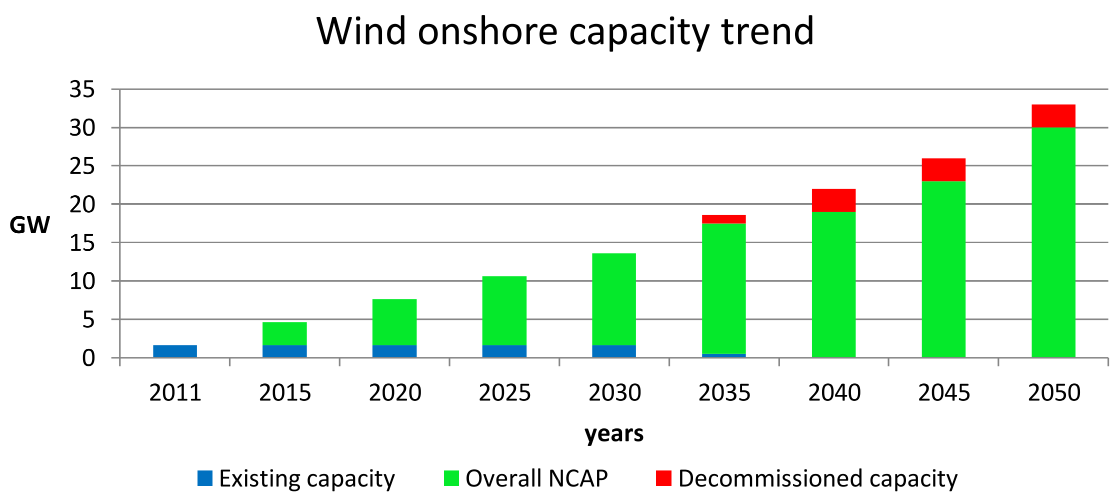


Figure 52: Wind power allocation fixed trend within the time horizon

Since the production of electricity from wind based technologies is subject to uncertainty a storage system was modeled to store the surplus of electricity and re-use it in peak demand situations.

[32] RoadMap2050, Part 2

Assuming this storyline, the question is: how much storage capacity Poland needs to deal with over production of electricity from wind power plants?
With the intention to provide a possible range of values for this quantity, and thus to make a sensitivity analysis, TIMES_STG_PL was run and thus the results were collected, considering 42 different wind profiles.

7.2 Which storage technology?

Figure 53 shows the comparison between the existing energy storage technologies (treated in chapter III) considering their rated power and organizing them in three different groups. The technologies with a rated power of 1-100kW form a first group that works as uninterrupted power sources as well as to keep the power quality of the grid. The second group considers technologies with a rated power of 0.1-10 MW and a discharge time from seconds to hours, which support the grid as a buffer and emergency storage. Finally, the third group considers the utility-scale technologies. This last group has the highest rated power and discharge times, which implies that the energy output of these systems is the highest one.

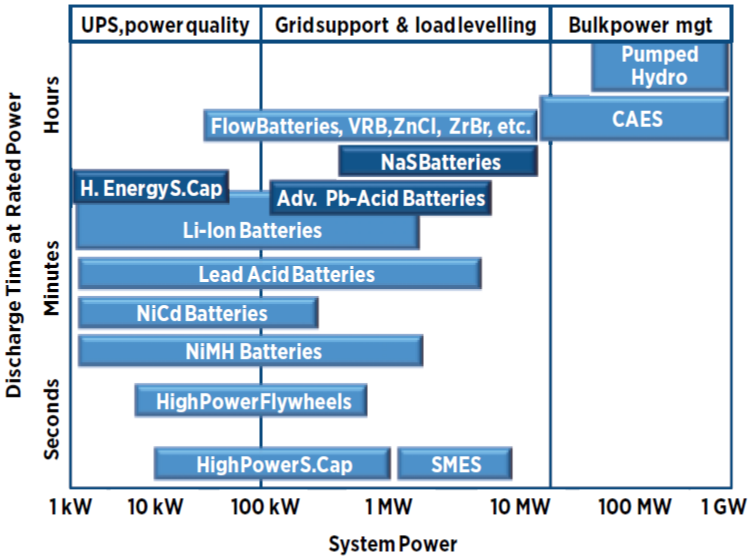


Figure 53: Typical power output and discharge time of electricity storage technologies[33]

The inclusion of a properly chosen energy storage system can improve the technical and economic competitiveness of wind electricity to a great extent providing at the same time higher system flexibility to cover the electricity demand.
Large-scale electricity storage systems, such as CAES or PHS, are able to optimize the consumption of wind electricity through load leveling, which means to store the

[33] IEA-ETSAP and IRENA Technology Policy Brief, 2012

electricity during low-demand periods and supplying it on peak demand periods, transforming non-scheduled low-value electricity into a high-value product.
The storage technology suitable for this project has to store the electricity surplus from 30 GW of wind power plants, thus it must be a large-scale technology able to store a wide amount of electricity from one to several hours.
Since the PHS potential is very low and almost completely saturated in Poland it was decided to consider the CAES technology to store energy surplus from wind turbines, furthermore considering that the construction of the storage plants can be done near high quality wind zones in Poland (Figure 54).

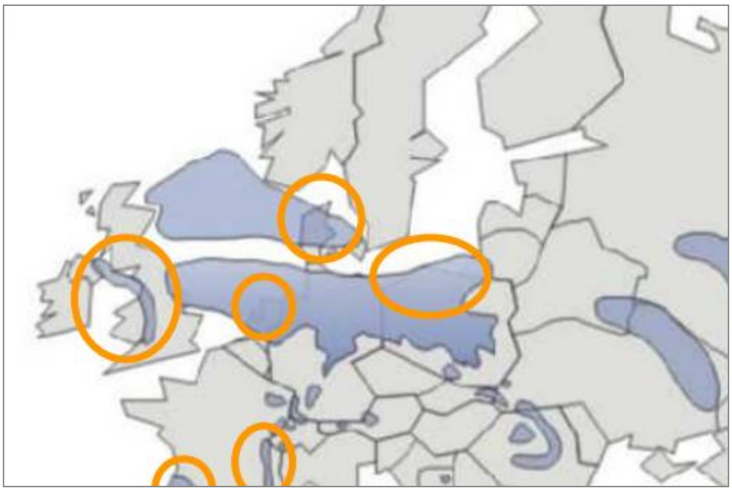


Figure 54: Correlation between salt domes and high quality wind: the circles denote areas investigated for CAES development (salt domes availability) and the light blue zone depict some high quality wind regions[34]

7.2.1 Compressed Air Energy Storage technology can be the solution?

First, let's explain how the CAES technology works.
In principle, a CAES system operates very similarly to a conventional gas turbine, except that clutches are added so that the compression and expansion stages are separately connected to the generator, thereby taking place at different times. This system can be understood as interrupting the Joule thermodynamic cycle; the compressed air is injected into a cavern instead of sending it directly to the combustor. When electricity is needed, the pressurized air is extracted from the underground reservoir and the cycle is then completed. Figure 55 shows the basic configuration of a CAES plant, which mainly consist of a compressor train (1), motor-generator unit (2), expansion train (3) and underground insulated reservoir

[34] B. Calaminus. Innovative Adiabatic Compressed Air Energy Storage System of EnBW in Lower Saxony. In 2nd International Renewable Energy Storage conference (IRES II), Bonn, Germany, 2007

(4). During the compression stage, surplus electricity of the grid powers a compressor train to compress air to high pressure levels. The storage stage involves the injection of the pressurized air into an insulated reservoir (cavern). While the air is being compressed, it passes through inter-coolers and after-coolers to reduce its temperature thereby enhancing the compression efficiency, reducing the storage volume requirement and minimizing the thermal stress on the storage volume walls. However, cooling down the air poses a problem at the moment of expansions since the efficiency of the turbines depends on the air temperature and pressure. Thereby, in the expansion stage, fuel is combusted inside the turbines to increase the temperature of the air. The combustion products are then expanded through the turbine train, thus re-generating part of the stored electricity.

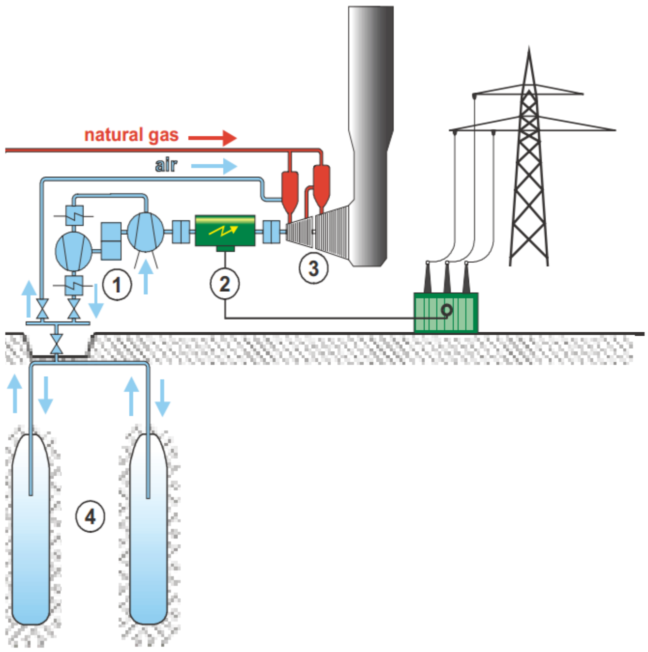


Figure 55: main component of CAES plant[35]

7.2.1.1 Energy density

For an estimation of the energy density of the CAES system it was considered air as an ideal gas with constant specific heat capacities. Its state equation is called the ideal gas equation, which is given by

$$p \cdot V = n \cdot R \cdot T \qquad (1)$$

Where p is the pressure of the gas, V the volume, T the temperature, n the number of moles and R is the universal gas constant.

[35] Huntorf CAES: more than 20 years of successful operation, F. Crotogino, Orlando, 2001

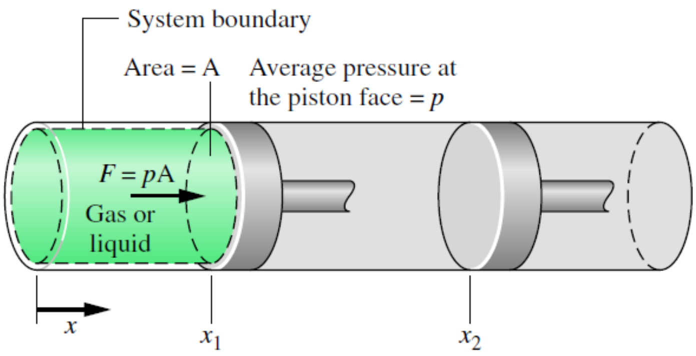


Figure 56: Expansion or compression of an ideal gas

To evaluate the amount of energy that is stored whilst compressing the gas it was considered a closed system, which consist of a piston-cylinder assembly with area A where the gas is compressed (see figure 56). During the compression, the gas exerts a normal force F on the piston, given by

$$F = p \cdot A \qquad (2)$$

Thus, the work δW done by the system as the piston is displaced by a distance dx is

$$\delta W = p \cdot A \cdot dx \qquad (3)$$

Since the product $A \cdot dx$ in the latter equation equals the change in the volume of the system δV, we can write the work expression as

$$\delta W = p \cdot dV \qquad (4)$$

When the gas expands, the work at the moving boundary is positive, since dV is positive when the volume increases. However, when the gas is being compressed, dV is negative, and so is the work given by equation (4).

For a volume change from V_1 to V_2, we can obtain the work W by integrating equation (4)

$$W = \int_{V_2}^{V_1} p \, dV \qquad (5)$$

We will assume an isothermal compression process to calculate the volumetric energy density of compressed air. This assumption transforms the ideal gas equation into the Boyle-Mariotte's law, given by

$$p \cdot V = n \cdot R \cdot T = constant$$

Hence

$$W = -\int_{V_2}^{V_1} p \, dV = -n\,R\,T \int_{V_2}^{V_1} \frac{dV}{V} = n\,R\,T\,ln\left(\frac{V_1}{V_2}\right)$$

If we consider that the gas is being compressed in an isothermal process from an initial state with volume V_0 1 m^3 and pressure p_0 1 bar to a final state with volume V_1 0.0167 m^3 (Boyle law for perfect gas) and pressure p_1 60 bar the amount of stored energy is

$$\frac{W}{V_0} = -\frac{nRT}{V_0}\int_{V_0}^{V_1}\frac{dV}{V} = \frac{p_0V_0}{V_0}\int_{V_1}^{V_0}\frac{dV}{V} = p_0 ln\left(\frac{V_0}{V_1}\right) = 0.409 \ \ [\text{MJ/m}^3]$$

This means that if we want to store 250 MWh the cavern size should be about *2,700,000 cubic meters*.

7.2.1.2 Suitable cavern geologies

In large-scale CAES system the reservoirs where the compressed air is injected are always underground because of the required volumes. The main requirement that needs to be fulfilled by the cavern is that the geologic formation must have sufficient depth to allow safe operation at the required air pressure. The classification for the suitable geologies for these caverns is divided in three categories: salt, porous rock, and hard rock.

Salt cavern are the most straightforward to develop and operate. The elasto-plastic properties of salt pose a minimal risk of air leakage in these underground reservoirs. These caverns are created by solution of mining or dry mining, with cost of USD 1 and USD 10 per kWh of storage capacity respectively. The first one is a technology based on fresh water dissolving salt and becoming saturated with it.

Underground rock caverns are an option for compressed air storage although the cost of mining a new reservoir is USD 30 per kWh of storage capacity created. These caverns are created by excavating comparatively hard and impervious rock formations. As an alternative to these high cost there are some existing mines that might be used as a reservoir and in this case the cost would typically be of USD 10 per kWh. An advantage of this high cost reservoirs is the possibility to maintain a constant pressure inside the cavern by using water-compensation ponds. However, this water/air system has a potential hazard called the "champagne effect", which is related to water flow instabilities resulting from the release of dissolved air in the upper portion of the water shaft.

Porous rock formations like sandstone or fissured limestone are found in rock aquifers or depleted gas fields. This geology has the potential to be the least costly storage option for large-scale CAES since it typically costs USD 0.10 per kWh produced.

7.2.1.3 Advanced Adiabatic CAES

The AA-CAES is a promising concept in a carbon-constrained future, since it's free of carbon emissions during its operation and it does not depend on any fossil fuel to recover the stored electricity. The basic idea of this concept is to recover the energy expelled as heat during compression and reuse it later to reheat the stored air during the expansion stage, eliminating the combustor from the conventional cycle. A Thermal Energy Storage (TES) stores the heat recovered from the compression stage, where it works as an inter-cooler, reducing the temperature of the compressed air, hence enabling the using of low-cost underground reservoir. During the discharge regime, the air is reheated to the required temperature by the high pressure turbine inlet.

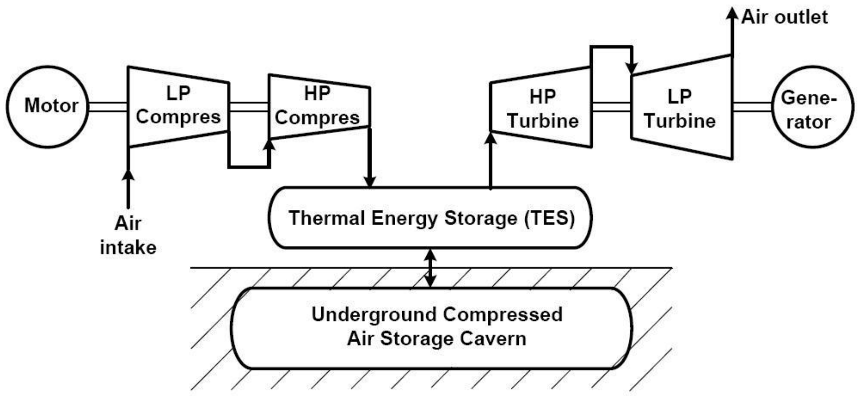


Figure 57: Function diagram of AA-CAES plant[36]

One such AA-CAES concept with high efficiency turbine and high capacity TES, achieves round trip *efficiency of approximately 70%* with no fuel consumption.

7.2.1.4 Gas storage facilities operating in Poland

Currently in Poland are operating 8 underground gas storage facilities (UGS), with a total active capacity of 1,821 billion m^3:

- ✓ 1 warehouse methane gas created in salt cavern, Mogilno;
- ✓ 5 magazines methane gas created in depleted gas fields: Wierzchowice , Swarzów, Brzeźnica, Husów, Strachocina;
- ✓ 2 magazines methane gas created in the partially depleted Daszewo and Bonikowo.

In addition a cavern for UGS is under construction in Kosakowo. By the end of 2020 is planned to expand its storage capacity to 250 million m^3. Figure 58 shows the location of underground storage facilities in Poland.

[36] ALSTOM power

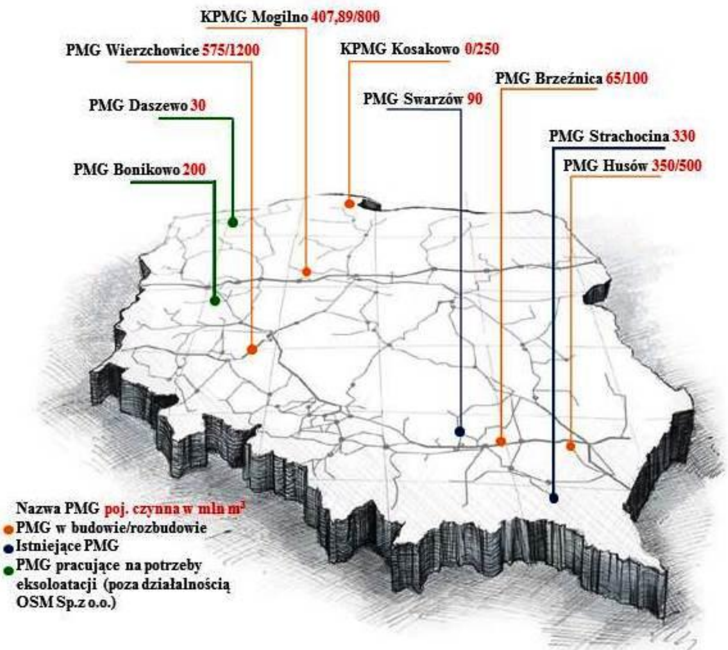


Figure 58: Distribution of underground storage facilities in Poland

Table 12: Basic parameters of UGS operating in Poland

UGS	Capacity *mln* m^3	Max flow injection *mln* m^3*/day*	Max flow out *mln* m^3*/day*
Mogilno	407.89	9.60	18.00
Wierzchowice	575	3.60	4.80
Husów	350	2.80	5.76
Strachocina	330	2.4	3.36
Swarzów	90	1.00	1.00
Brzeźnica	65	1.10	0.93
Sum:	1,821.89	20.50	33.85

Nowadays these storage facilities are reserved for natural gas storage but is shown that natural gas is stored under very similar condition to those needed for CAES. Consequently, consideration of natural gas storage potential and future development in Poland provides a valuable starting point to evaluate an hypothetical storage potential for CAES.

7.2.1.5 Polish Underground Gas Storage construction potential

Poland is a country very rich in salt. Figure 59 shows a map of the documented deposits of salt and potassium-magnesium in Poland, while figure 60 shows the distribution of the major diapir-type salt structure and airborne salt deposits in Poland.

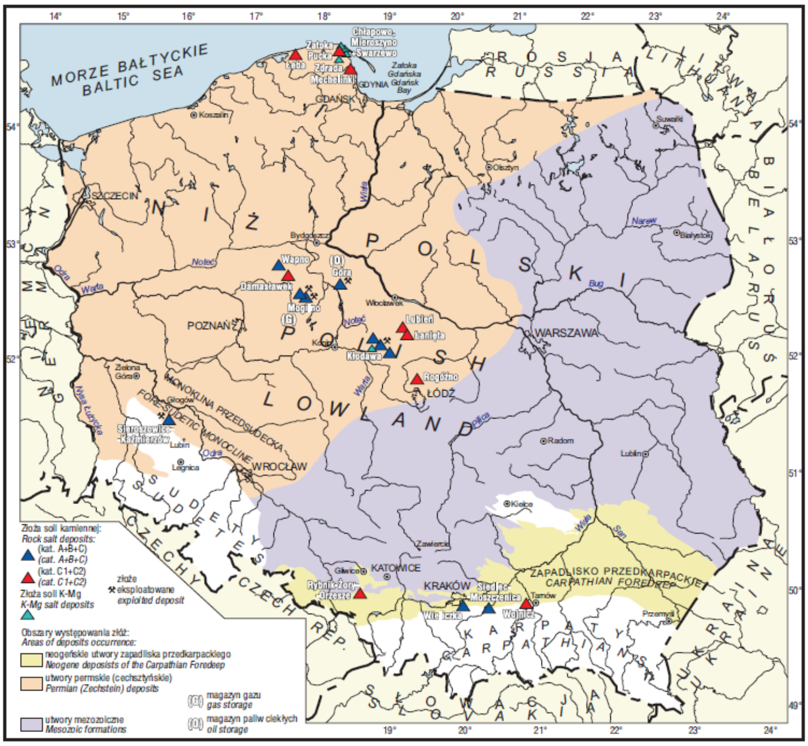


Figure 59: distribution of documented salt and potassium deposits in Poland

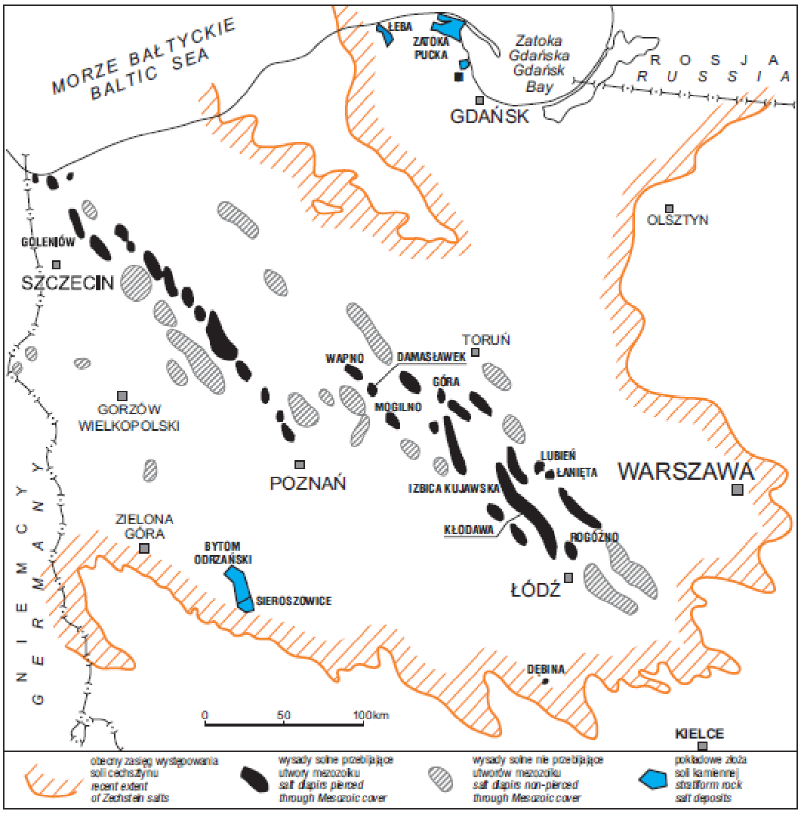


Figure 60: Distribution of diapir and stratiform types of salt deposits in Poland

Table 13 presents relevant data for the construction of warehouse in salt deposits deemed useful for UGS.

<table>
<tr><th>Deposit name</th><th>Deposit composition</th><th>Composition category</th><th>Estimated capacity of the deposit</th><th>Water leaching</th><th>Ability to discharge the brine</th></tr>
<tr><td colspan="6">Region I – Sudetic Monocline</td></tr>
<tr><td>Bytom Odrzański</td><td>P.</td><td>C2</td><td rowspan="6">For each of the fields min. dozens of cavern of 50-150 thousand m3</td><td rowspan="6">Easy for each deposit</td><td rowspan="6">Difficult for each deposit</td></tr>
<tr><td>Głogów</td><td>R.</td><td>A+B+C1</td></tr>
<tr><td>Głogów II</td><td>P.</td><td>C2</td></tr>
<tr><td>Głogów III</td><td>P.</td><td>C2</td></tr>
<tr><td>Sieroszowice</td><td>R.</td><td>A+B+C1</td></tr>
<tr><td>Nowa Sól</td><td>N.R.</td><td>lack</td></tr>
<tr><td colspan="6">Region II – Central Poland</td></tr>
<tr><td>Damasławek</td><td>P.</td><td>C2</td><td rowspan="8">For each of the fields min. A dozen-tens of caverns 300-500 thousand m3</td><td rowspan="8">Easy for each deposit</td><td rowspan="8">Difficult for each deposit</td></tr>
<tr><td>Kłodawa (cz. Płd)</td><td>P.</td><td>A+B+C1</td></tr>
<tr><td>Kłodawa (cz. Płn)</td><td>P.</td><td>A+B+C1</td></tr>
<tr><td>Lubień</td><td>R.</td><td>C1</td></tr>
<tr><td>Łanięta</td><td>R.</td><td>C2</td></tr>
<tr><td>Rogoźno</td><td>P.</td><td>C2</td></tr>
<tr><td>Izbica Kujawska</td><td>N.R.</td><td>lack</td></tr>
<tr><td>Dębina-Bełchatów</td><td>N.R.</td><td>lack</td></tr>
<tr><td colspan="6">Region IV – Northern Poland – Gdańsk area</td></tr>
<tr><td>Łeba</td><td>P.</td><td>C2</td><td rowspan="4">For each of the fields min. more than a dozen caverns 100-300 thousand m3</td><td rowspan="4">For each of the possible field</td><td rowspan="4">For each of the possible field</td></tr>
<tr><td>Mechelinki</td><td>R.</td><td>C1</td></tr>
<tr><td>Zatoka Pucka</td><td>R.</td><td>C1</td></tr>
<tr><td>Chłapowo - Mieroszyno</td><td>R.</td><td>C1</td></tr>
</table>

Table13: UGS construction potential in salt deposits in Poland

Notes

P. - deposit covered by a pre-identified (C2)

R. - deposit of resources identified in detail (A + B + C1)

N. R. - unrecognized resources

Domes salt structures in the NW and central area of Poland (31 identified domes) were considered as potential object for UGS location since 1970. So far, warehouse were built in two cavities: Mogilno and Kujawach Mount. Excluding few structures already developed and unsafe structures, 10 diapir structures remain undeveloped, spacing from the area of Swinoujscie to the area of Lodz and Berchatow.

Taking into account the exploration of the deposit, geological and mining conditions, location, and favorable wind conditions the best locations are Mechelinki and Zatoka Pucka.

The selection of other potential locations of warehouse salt deposits in not obvious. It can be said with certainty that in the north-western, central and lower Silesia there are lots of attractive locations. However, each of them requires additional work, treatments and thus investments. Clarification of these issues require previously the demonstration of the works feasibility and the adequacy of the caves.

<u>Conclusion</u>

From the calculation made earlier about the storage density of the CAES technology we can deduct that to have a storage capacity of 1 GW we need about 10,800,000 cubic meter of caves. Since we suppose to not have a single centralized CAES system but to have several CAES systems spread on Polish territory, from table 13 we can see that this storage capacity need can be satisfied, also because we can take into account that part of the caves dedicated to natural gas storage or CO_2 storage can be converted.

7.3 Model data

7.3.1 Reference Energy system

The model of the national energy system used in TIMES_STG_PL is based on the one developed at AGH UST[37] and is showed in figure 61. The difference is that in this RES only electric power plants were considered, thus the CHP plants and then the heat production were not considered. Regarding the costs, the relative bibliography is the [22] that is the same used for the GAMS model except for the investment costs that take into account additional capital costs incurred during construction.

This subsystem covers all existing professional power plants (PP) with the net electric capacity equal to about 24 GW in 2011. These PP were considered as base-load power plant, they were mainly hard coal and brown coal fired units. The model includes existing renewable energy technologies such as wind turbines and hydro plants. These PP, together with the natural gas ones were considered peak load plants. The total power of these technologies in the base year was about 4 GW.

Since the base-load plants produce a constant amount of energy during each period it was supposed that they don't need to be shut down, thus we don't consider their

[37] A. Wyrwa, M. Pluta, S. Skoneczny, T. Mirowski, LNCS, 2014, Springer-Verlag Berlin Heidelberg 2014 - not yet published, FORTHCOMING 2014

start-up time. On the contrary, the gas power plants can be very flexible and the start-up time is negligible. Unfortunately the natural gas plants start-up costs were not implemented in this model, but their presence make the storage use even more attractive.

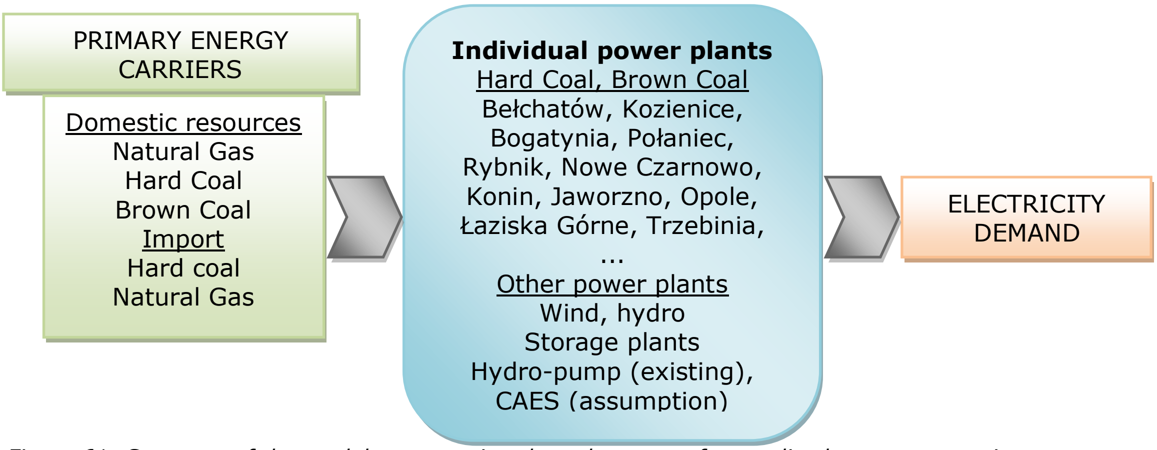


Figure 61: Structure of the model representing the subsystem of centralized power generation

7.3.2 Simulation settings

The model was developed in GAMS 24.1.3, generated by TIMES V346 and the data were gathered and managed through VEDA 4.3.45 shell. Finally the IBM LOG CPLEX solver was used to solve the model and to find the optimal solution.

Modeling horizon in this study covered the period from 2011 to 2050. As explained in the 'storyline' each modeling year was split into 224 time slices in order to improve the temporal characteristics of demand and supply side. For instance R_MO_01 covered the total demand for electricity in all Mondays of the year during the Spring in the period 00:00 - 03:00. Note that the duration of each time slice within a year is different depending on the season of which is member (e.g. winter time slices are shorter than the summer or spring ones).

Data about the variability of wind turbines' electricity generation were taken from the meteorological data provided by the European Centre for Medium-range Weather Forecasting (ECMWF) for the location in West Pomeranian Voivodeship. Since the data about the wind speed were provided hourly it was necessary to develop some Microsoft Office Excel™ macros to manage the data to obtain the availability of wind capacity for each time slice.

The locations for which the hourly wind speed was available are shown in figure 62.

In this thesis just the areas very advantageous in terms of wind potential were considered, as following:

- Baltic shore (A zone)
- North-eastern Poland (vicinity of Suwałki and Gołdap) (G3-I1 zone)
- Open areas of Warmia, Mazury and Pomerania (B1,B2,F1)

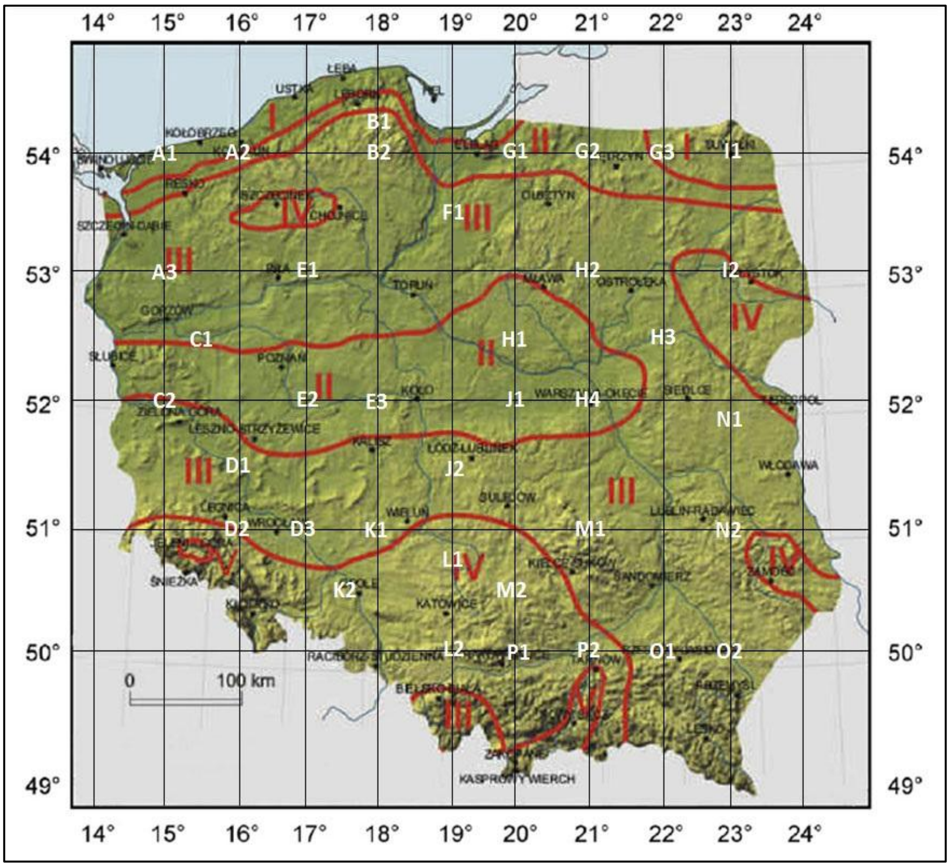


Figure 62: Location for which wind data were available
(I - very favorable, II - favorable, III - sufficient, IV - insufficient, V - bad)

- Sub-montane areas of southern Poland – primarily Podkarpacie and Lower
- Silesia region (L-P)

These locations were selected based on the 'Wind power development in Poland by 2020 – a vision' document.

Since the goal was to make a sensitivity analysis, six different wind profiles have been extrapolated from the data about the hourly wind speed for the years from 2000 to 2005 and for 2008s - for a total of 42 profiles analyzed. The profiles were built considering different week of each season in each year and selecting the wind availability every 3 hours (thus for 2000_1 we selected the wind data for the first complete week - from Monday to Sunday - of each season of the year 2000 considering wind availability every 3 hours - 0.00, 3.00 am, 6.00 am, etc). As an example in figure 63 are given the three different profiles for the year 2000.

Since TIMES uses internal logics to manage the storage parameters not fully known

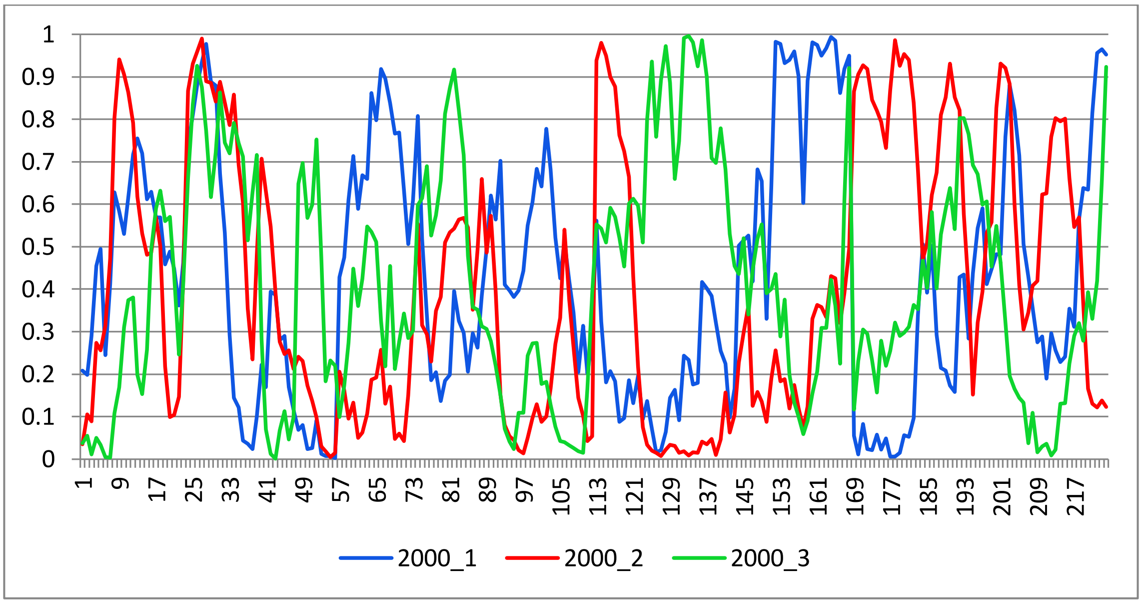


Figure 63: Three of the six wind profile for the year 2000

to the user some loopholes were necessary:

- all the time slices are at 'Daynite' level;
- one change was made to the source code in order to obtain correct storage behavior:

  File 'eqcapact.mod', code lines:

  […] storage: parent time slice fraction of the number of storage cycles in a year*

  SUM(PRC_TS(R,P,TS)$RS_FR(R,TS,S),%VAR%_ACT(R,V,T,P,TS%SOW%)*R S_FR(R,TS,S)/RS_STGPRD(R,TS))$RP_STG(R,P) = […]

  the denominator of the ratio *RS_FR(R,TS,S)/RS_STGPRD* was put equal to 1.

7.3.3 Declaration of the model through VEDA-FE user interface

Data and assumptions for the TIMES model generator are fed into the VErsatile Data Analyst-Front End that provides input to the TIMES code. VEDA-FE accepts input from a variety of Excel files with different (flexible) structures that are tailored to work efficiently with data intensive models. The TIMES code works in the GAMS environment and produces text output that is read by VEDA-BackEnd.

VEDA-BE produces numerical and graphical (mainly via Excel) output for the user.

7.3.3.1 VEDA-FE workbooks and internal syntax

VEDA-FE relies totally on templates, a collection of Excel workbooks, for all input data. The VEDA templates permit the user to organize the information in flexible

schema. In the following section I'm going to report the basic concepts of VEDA and the data gathered on VEDA-BE associated with TIMES_STG_PL.
Full details of VEDA are described at www.kanors.com/vedasupport.

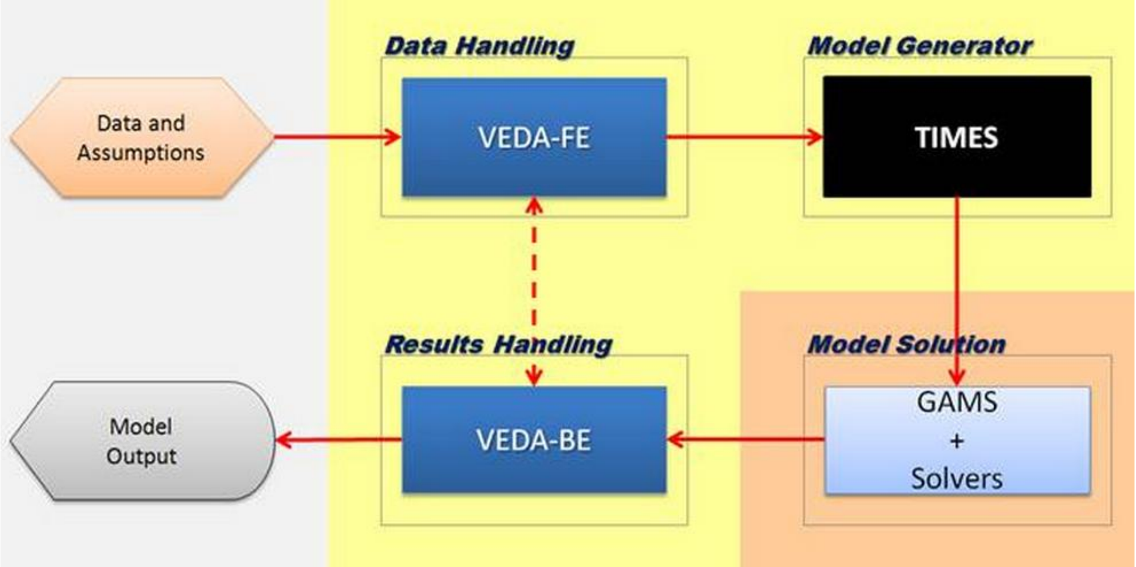


Figure 64: scheme of the VEDA system for TIMES modeling[38]

VEDA template controls

Inside the templates special characters "~" and "\I:" are reserved and indicate to VEDA-FE what to do with the information that follows. The VEDA-FE import program reads each sheet in a workbook in sequence, line-by-line from left to right. The basic type of codes are:

- Flexible Input codes (~FI_**:) that establish the nature of the information to follow, they are declared above a table and are valid for the whole table;
- Flexible Input Table (~FI_T) is the main data input indicator, and is placed in the row immediately above the table headers and in the column before the first column containing values;
- Ignore codes (\I:**) are declared in a table to ignore the rows and/or the columns where they are specified, and
- Special codes (~T**) are used to declare special tables, whose processing is different from simple parameter insertion.

VEDA workbooks

Templates are Excel spreadsheet workbooks that lay down the basic structure of the model and hold the fundamental data and assumptions. These templates provide information about the base year, demand projections, future technology

[38] support.kanors-emr.org

possibilities and scenario assumptions that collectively describe the entire energy system to be studied. The templates are:

- SysSettings: this is one of the three files in VEDA with a fixed name, which stands for System Settings. It is used to declare the very basic model structure like regions, time-slices, start year, etc. It also contains interpolation rules for various attributes and some settings for the synchronization process.
- Base Year Templates: these are meant to set up the base-year technology stock and demand levels such that the overall energy flows respect the energy balance. In these files the user creates processes, commodities, the reference energy system connections and we add the basic attributes for processes and commodities. By default, all declarations hold for all the regions that map to the super region indicated by the file name; but all above declarations can be made region-specific by introducing a region column in any of the table.
- BY_Trans_<anything>: this file supports all tables and works just like a scenario file, with one important difference: the process and commodity filters see only those elements that come from the B-Y templates.
- SubRes_<application>, Data/Transformation file: new technology and sub-RES definition, data specification, and regional transformation. Declarations in SubRES files are identical to the B-Y templates with one important difference: all of them are completely region independent. Region-specificity is introduced via the process availability and transformation tables in the related transformation file.
- Scen_<scenario designator>, scenario files: contains data specifications and transformation for any part of the reference energy system.

7.3.3.2 SysSettings: Model Setup Template

The SysSettings file contains comprehensive information about the model's basic structure (regions, time-periods and time-slices), along with the default interpolation and extrapolation user input definition. This workbook is made up of various sheets, each of them will be elaborated in the following lines.

The first sheet is named Region-Time Slices. In this sheet regions and time-slices are defined as shown in table 14.

~BookRegions_Map		~TimeSlices		
BookName	Region	Season	Weekly	DayNite

TIMES_STG_PL	PL			1R1MO1
				1R1MO2
				1R1MO3
				1R1MO4
				1R1MO5
				1R1MO6
				...

Table 14: Declaration of regions and time-slices

The second sheet is named TimePeriods (Table 15). In this sheet the start year and the time periods are defined, as explained below:

- The workbook control ~StartYear is used to define the start year of the model.
- The workbook control ~ActivePDef is used to define the set of active periods. Alternate period definitions can be made and the active one is declared under this tag.
- The workbook control ~TimePeriods is used to define the time horizon of the model for all the ActivePDef.

~StartYear		~TimePeriods
2011		Pdef-1
		2
		5
~ActivePDef		5
Pdef-1		5
		5
		5
		5
		5
		5

Table 15: Declaration of the start year and the number of period within the time horizon

In the third sheet, named Interpol_Extrapol_Defaults, users declare the rules for inter/extrapolating input parameters that are time dependent, and other data manipulation options. To define the inter/extrapolations options the workbook control ~TFM_UPD is used. This workbook is used to declare a table in a scenario file which is a simple transformation to pre-existing data in a rule-based manner. In this sheet the 1st block deals with setting the default interpolation rules for various parameter. The 2nd block sets default prices for the "backstop" options for fuels (dummy IMPort technologies ending with Z) and demands (a dummy IMPDEMZ process that can feed any demand).

The fourth sheet, named 'Import Settings' contains some settings for the

synchronization process. The user can control the creation of dummy import or prohibit the investments in processes when a newer vintage becomes available.
The fifth sheet, called 'Constants' is used to define some overall parameters of the model (Table 16). The only workbook control used here is ~TFM_INS (transformation insert table), to assign an absolute value for parameters that are based on rules.
The column headers used in this sheet are:

- TIMESLICE indicating the particular time-slice for which the data is provided;
- ATTRIBUTE, indicating that a VEDA-TIMES parameter names appear in this column. In this project these parameters are: *G_Dyear*, discount year, *Discount*, overall discount rate, *YRFR*, fraction of year for time-slices;
- Year, indicating the years for which the attribute is set (if empty the attribute is set for all the years in the time horizon);

~TFM_INS

TimeSlice	Attribute	Year	AllRegions
	G_Dyear		2011
	Discount		0.075
1R1MO1	YRFR		0.0045682
1R1MO2	YRFR		0.0045682
1R1MO3	YRFR		0.0045682
...	...		..
2S1MO1	YRFR		0.0045316
2S1MO2	YRFR		0.0045316
2S1MO3	YRFR		0.0045316
...	...		..
3F1MO1	YRFR		0.0044031
3F1MO2	YRFR		0.0044031
3F1MO3	YRFR		0.0044031
...	...		..
4W1MO1	YRFR		0.0043542
4W1MO2	YRFR		0.0043542
4W1MO3	YRFR		0.0043542
...	..		..

Table 16: Constants declaration

7.3.3.3 Commodities and process definition in the base year

<u>Supply template</u>

In general the supply template (SUP) describes fossil fuel extraction, renewable potentials, and various fuel transformation processes including petroleum refineries and gas pipelines. For this project this is done in a single file, VT_TIMES_STG_PL_SUP_V01 , but more robust model may have multiple base year templates.

In this particular file there are four sheets, each discussed in the following sections. The 'SUP_comm' sheet identifies the individual commodities found in the workbook (Table 17). The commodity type indicates the nature of a commodity (energy-NRG, material-MAT, demand service-DEM, emissions-ENV, and financial-FIN). It determines as well the default type of constraint of the commodity balance equation: for NRG, ENV, and DEM the supply has to be greater than or equal to consumption, while for MAT and FIN equality holds.

~FI_Comm

Csets	CommName	CommDesc	Unit
NRG	HARD_COAL	Hard Coal	PJ
	BROWN_COAL	Brown Coal	PJ
	NAT_GAS	Natural Gas	PJ
	URAN	Uranium	PJ
	HYDRO	Water	PJ
	WIND_ON	Wind Onshore	PJ

Table 17: Commodities definition for the supply template

The workbook control ~FI_Comm is used to declare the following column headers:

- Csets: the sets to which commodities belong; the commodity sets indicates the type of a commodity;
- CommName: commodity name, which need to be unique;
- CommDesc: commodity description;
- Unit: the commodity unit throughout the model;

The second sheet, called 'SUP_Process', identifies the individual processes found in the workbook. In VEDA templates all processes must be declared and the type defined (Table 18).

~FI_Process

Sets	TechName	TechDesc	Tact	Vintage
MIN	MIN_HARD_COAL	Hard Coal Domestic Extraction - Located Reserves	PJ	NO
	MIN_BROWN_COAL	Brown Coal Domestic Extraction - Located Reserves	PJ	NO
	MIN_HYDRO	Hydro Potential	PJ	NO
	MIN_WIND_ON	Wind Onshore Potential	PJ	NO
IMP	IMP_NATURAL_GAS	Import Natural Gas	PJ	NO
	IMP_HARD_COAL	Import Hard coal	PJ	NO
	IMP_URANIUM	Import Uranium	PJ	NO

Table 18: Process definition for the supply template

The workbook control ~FI_Process is used to declare the following column headers.

- Sets: the sets to which the processes belong; the process sets indicate the nature of a process (thermal electric power plant (ELE), combined heat and power (CHP), heating plant (HPL), pump storage (STGTSS), pump storage IP (STGIPS), generic process/technology (PRE), demand device (DMD), import process (IMP), export process (EXP), mining process (MIN) and renewable potential technology (RNW).
- TechName: name of the process, which need to be unique.
- TechDesc: description of the process;
- Tact: activity unit of the process;
- Vintage: electricity vintage tracking (YES/NO).

The sheet named 'MIN' is used to characterize the domestic resource supply and the domestic renewable potential in terms of resources while the 'IMP-EXP' sheet is used to characterize the IMPORT and EXPORT facilities. In these sheet, to characterize the supply processes, the "~FI_T" workbook control is used (Tables 19,20,21).

Non renewable energy reserves ~FI_T

TechName	TechDesc	Comm-OUT
MIN_HARD_COAL	Hard Coal Domestic Extraction - Located Reserves	HARD_COAL
MIN_BROWN_COAL	Brown Coal Domestic Extraction - Located Reserves	BROWN_COAL

TechName	COST~2011	COST~2015	COST~2020	COST~2025	COST~2030	COST~2035	COST~2040	COST~2045	COST~2050
*	MzI/PJ	MzI/PJ	MzI/PJ	MzI/PJ	MzI/PJ	MzI/PJ	MzI/PJ	MzI/PJ	MzI/PJ
MIN_HARD_COAL	12.80	11.53	11.30	11.10	11.08	11.06	11.04	11.01	10.99
MIN_BROWN_COAL	7.11	6.40	6.19	6.01	5.93	5.86	5.77	5.68	5.60

Tech Name	BNDACT~2015~UP	BNDACT~2020~UP	BNDACT~2025~UP	BNDACT~2030~UP	BNDACT~2035~UP	BNDACT~2040~UP	BNDACT~2045~UP	BNDACT~2050~UP
*	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ
MIN_HARD_COAL	1804	1804	1628	1232	1100	1012	1012	1012
MIN_BROWN_COAL	588	542	617	617	617	608	608	608

Table 19: Non renewable sources technologies characterization for the supply template

Renewable potentials ~FI_T

TechName	TechDesc	Comm-OUT	COST	BNDACT~UP
\I: Unit			MzI/PJ	PJ
MIN_HYDRO	Hydro Potential	HYDRO	0.00	1000

MIN_WIND_ON	Wind Onshore Potential	WIND_ON	0.00	1000

Table 20: Renewable sources *technologies characterization for the supply template*

Exogenous Import		~FI_T	
TechName	TechDesc	Comm-OUT	BNDACT~UP
*			PJ
IMP_NATURAL_GAS	Import Natural Gas	NAT_GAS	2000
IMP_HARD_COAL	Import Hard coal	HARD_COAL	2000
IMP_URANIUM	Import Uranium	URAN	1000

TechName	COST~2011	COST~2015	COST~2020	COST~2025	COST~2030	COST~2035	COST~2040	COST~2045	COST~2050
*	MzI/PJ	MzI/PJ	MzI/PJ	MzI/PJ	MzI/PJ	MzI/PJ	MzI/PJ	MzI/PJ	MzI/PJ
IMP_NATURAL_GAS	28.00	34.27	33.43	32.31	31.91	31.11	30.55	30.21	29.78
IMP_HARD_COAL	15.32	12.17	11.92	11.74	11.72	11.71	11.70	11.67	11.67
IMP_URANIUM	1.94	1.94	1.94	2.02	2.10	2.16	2.24	2.46	3.01

Table 21: Import processes characterization

The column headers used in these sheets are explained below:

- TechName - defines the technology name.
- TechDesc - description of the technology.
- Comm-out - identifies the name of the output commodity from a process. Note that mining processes are usually processes that don't have an input commodity.
- COST - assign the annual resource cost per unit of production (extraction).
- BNDACT - specifies a bound on the annual activity of a technology. It must be combined with the limtype (UP,LO or FX) and optionally with the year.

<u>Electric power plants template</u>

In general the electricity template (ELC) describes processes (electric power plants) that generate electricity consuming one or more commodities as input. For this project the file is named VT_TIMES_STG_PL_ELC_V01; in this file there are seven sheets, each discussed in the following lines.

The 'ELC_comm' sheet identifies the commodities used in the ELC template. The commodity type indicates the nature of a commodity (energy-NRG, material-MAT, demand service-DEM, emissions-ENV, and financial-FIN).

All the commodities used in this template are shown in table 22.

Csets	CommName	CommDesc	Unit	CTSLvl	Ctype
NRG	ELC_HV	Electricity - High Voltage WITHOUT Grid Costs	PJ	DAYNITE	ELC
	HARD_COAL	Hard Coal	PJ		
	BROWN_COAL	Brown Coal	PJ		
	NAT_GAS	Natural Gas	PJ		
	HYDRO	Water	PJ		
	URAN	Uranium	PJ		
	WIND_ON	Wind Onshore	PJ		
ENV	CO2	Carbon Dioxide - Combustion (ELC)	kt		
	SO2	Sulphur Dioxide - Combustion (ELC)	kt		
	NOX	Nitrogen Oxides - Combustion (ELC)	kt		
	TPM	Total Particulate Matter - Combustion (ELC)	kt		
DEM	ELC_LV	Total LV electricity	PJ	DAYNITE	ELC

Table 22: Commodity definition for the elc PP template

In this sheet the following column headers are used:

- Csets: the sets to which commodities belong; the commodity sets indicates the nature of a commodity;
- CommName: commodity name, which need to be unique;
- CommDesc: commodity description;
- Unit: the commodity unit throughout the model;
- CTSLvl: the commodity time-slice tracking level;
- CType: electricity (ELC) commodity indicator.

The second sheet, called 'ELC_Process', identifies the individual processes found in the workbook. All the processes used in this template for this project are report in table 23.

Sets	TechName	TechDesc	Tact	Tcap	Tslvl	Vintage
ELE	EX_PP_HC_CLASS_A	Power Plants Hard Coal - CLASS 1	PJ	GW	ANNUAL	NO
ELE	EX_PP_HC_CLASS_B	Power Plants Hard Coal - CLASS 2	PJ	GW	ANNUAL	NO
ELE	EX_PP_HC_CLASS_C	Power Plants Hard Coal - CLASS 3	PJ	GW	ANNUAL	NO
ELE	EX_PP_BC_CLASS_A	Power Plants Brown Coal - CLASS 1	PJ	GW	ANNUAL	NO
ELE	EX_PP_BC_CLASS_B	Power Plants Brown Coal - CLASS 2	PJ	GW	ANNUAL	NO
ELE	EX_PP_BC_CLASS_C	Power Plants Brown Coal - CLASS 3	PJ	GW	ANNUAL	NO

ELE	EX_GT	Gas turbine	PJ	GW	DAYNITE	NO
ELE	EX_PP_HYDRO	Power Plants Hydro	PJ	GW	DAYNITE	NO
ELE	EX_PP_WIND_ON	Power Plants Wind Onshore	PJ	GW	DAYNITE	NO
DMD	ELC_TRANSF_HV_LV	Electricity transmission and distribution network and transformers	PJ	PJ	DAYNITE	NO
ELE.STGTSS	CAES_STG	Compressed Air Energy Storage technology	PJ	GW	DAYNITE	NO

Table 23: Process definition for the elc PP template

The following column headers are used:

- Sets: the sets to which the processes belong; the process sets indicate the nature of a process (thermal electric power plant (ELE), combined heat and power (CHP), heating plant (HPL), pump storage (STGTSS), pump storage IP (STGIPS), generic process/technology (PRE), demand device (DMD), import process (IMP), export process (EXP), mining process (MIN) and renewable potential technology (RNW).
- TechName: name of the process, which need to be unique.
- TechDesc: description of the process;
- Tact: activity unit of the process;
- Tcap: capacity unit of the process;
- Tslvl: the process time-slice operational level (ANNUAL, SEASON, WEEKLY, DAYNITE);
- Vintage: electricity vintage tracking (YES/NO).

To characterize the processes used in the ELC template four sheets were created:

- 'PP' - that describes the existing power plants (Table 24);

TechName	*TechDesc	Comm-IN	Comm-OUT	EFF	Peak	Cap 2 Act	AFA	LIFE
				%	%	PJ/GW	%	years
EX_PP_HC_CLASS_A	Power Plants Hard Coal - CLASS 1	HARD_COAL	ELC_HV	0.35	1	31.54	0.85	40
EX_PP_HC_CLASS_B	Power Plants Hard Coal - CLASS 2	HARD_COAL	ELC_HV	0.45	1	31.54	0.85	40
EX_PP_HC_CLASS_C	Power Plants Hard Coal - CLASS 3	HARD_COAL	ELC_HV	0.45	1	31.54	0.85	40
EX_PP_BC_CLASS_A	Power Plants Brown Coal - CLASS 1	BROWN_COAL	ELC_HV	0.32	1	31.54	0.85	40
EX_PP_BC_CLASS_B	Power Plants Brown Coal - CLASS 2	BROWN_COAL	ELC_HV	0.44	1	31.54	0.85	40
EX_PP_BC_CLASS_C	Power Plants Brown Coal - CLASS 3	BROWN_COAL	ELC_HV	0.44	1	31.54	0.85	40
EX_GT	Gas Turbine	NAT_GAS	ELC_HV	0.38	1	31.54	1.00	25

TechName	Stock~2011	Stock~2015	Stock~2020	Stock~2025	Stock~2030	Stock~2035	Stock~2040	Stock~2045	Stock~2050	FIX OM	VAR OM
	GW	GW	GW	GW	GW	GW	GW	GW	GW	zl/kW	zl/GJ
EX_PP_HC_CLASS_A	13.91	12.76	10.71	10.71	10.29	6.36	3.71	2.30	2.30	243.00	1.81
EX_PP_HC_CLASS_B	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	243.00	1.81
EX_PP_HC_CLASS_C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	243.00	1.81
EX_PP_BC_CLASS_A	7.65	7.44	6.20	6.20	6.20	5.83	3.67	1.89	1.53	261.00	2.31
EX_PP_BC_CLASS_B	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	1.24	261.00	2.31
EX_PP_BC_CLASS_C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	261.00	2.31
EX_GT	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	60.00	1.39

Table 24: electric PP characterization

- RES - that describes the existing renewable sources technologies (Table 25);

TechName	*TechDesc	Comm-IN	Comm-OUT	EFF	CAP2ACT	Peak	FIXOM	AFA	LIFE
			\I:	%	PJ/GW		zl/kW	%	years
EX_PP_HYDRO	Power Plants Hydro	HYDRO	ELC_HV	1	31.536	1	80.00	0.18	60
EX_PP_WIND_ON	Power Plants Wind Onshore	WIND_ON	ELC_HV	1	31.536	1	160.00		25

TechName	Stock~2011	Stock~2015	Stock~2020	Stock~2025	Stock~2030	Stock~2035	Stock~2040	Stock~2045	Stock~2050
	GW	GW	GW	GW	GW	GW	GW	GW	GW
EX_PP_HYDRO	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32
EX_PP_WIND_ON	1.62	1.62	1.62	1.62	1.62	0.50	0.00	0.00	0.00

Table 25: Renewable sources technologies characterization

- STORAGE - that describes the electricity storage process previously declared (Table 26);

TechName	***TechDesc**	**Comm-IN**	**Comm-OUT**	**STG_EFF**	**Peak**	**FIXOM**	**CAP2ACT**	**AFA**
						zl/kW		
CAES_STG	Compressed Air Energy Storage technology	ELC_HV	ELC_HV	0.70	1.00	0.03	31.536	1

TechName	**Stock~2011**	**Stock~2020**	**Stock~2030**	**Stock~2040**	**Stock~2050**
	GW	GW	GW	GW	GW
CAES_STG	0.50	1.00	1.00	1.00	1.00

Table 26: energy storage process characterization

- TRANSF_HV_LV - that describes the conversion from high voltage to low voltage - final electricity (Table 27).

TechName	TechDesc	Comm-IN	Comm-OUT	AFA
			\I: UNITS	%
ELC_TRANSF_HV_LV	Electricity transmission and distribution network and transformers	ELC_HV	ELC_LV	1

Table 27: conversion technology characterization

The column headers used in these sheets are:

- TechName - defines the technology name.
- TechDesc - description of the technology.
- Comm-in - identifies the name of the input commodity of a process.
- Comm-out - identifies the name of the output commodity from a process.
- EFF/STG_EFF - specifies the technology efficiency.
- STOCK - identifies the existing capacity in GW.
- AFA - defines the annual availability factor of the technology.
- FIXOM - identifies the fixed operational and maintenance cost.
- VAROM - identifies the variable operational and maintenance.
- LIFE - specifies the lifetime of the process in years.
- Peak - specifies the fraction of a technology capacity that is considered to be secure and thus will most likely be available to contribute to the peak load in the time-slice where the demand level will be the highest.
- CAP2ACT - the capacity to activity conversion factor.

The 'ELC_DEMAND' sheet is used to define the service demand levels for the base year and for the following periods within the simulation horizon (Table 28).
In this model this sheet reports the electricity demand over the entire horizon.

Com	DEMAND~2011	DEMAND~2015	DEMAND~2020	DEMAND~2025	DEMAND~2030	DEMAND~2035	DEMAND~2040	DEMAND~2045	DEMAND~2050
*	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ	PJ
ELC_LV	500.184	504.060	542.356	579.234	617.438	661.813	706.85	743.52	771.274

Table 28: Electricity demand declaration

The last sheet is the 'EMI' sheet: it contains the emissions factors (Table 29). The workbook used in this sheet is ~PRCCOMEMI (to link the emissions to the electricity production by a process). The emissions factor is provided for each process via this workbook and it is associated with each of the commodities listed as column headers.

TechName	CommName	HARD_COAL	BROWN_COAL	NAT_GAS
EX_PP_HC_CLASS_A	CO2	94.19		
EX_PP_HC_CLASS_B	CO2	94.19		
EX_PP_HC_CLASS_C	CO2	94.19		
EX_PP_BC_CLASS_A	CO2		109.08	
EX_PP_BC_CLASS_B	CO2		109.08	
EX_PP_BC_CLASS_C	CO2		109.08	
EX_GT	CO2			55.82
EX_PP_HC_CLASS_A	SO2	0.0555		
EX_PP_HC_CLASS_B	SO2	0.0555		
EX_PP_HC_CLASS_C	SO2	0.0555		
EX_PP_BC_CLASS_A	SO2		0.0645	
EX_PP_BC_CLASS_B	SO2		0.0645	
EX_PP_BC_CLASS_C	SO2		0.0645	
EX_GT	SO2			0.0000
EX_PP_HC_CLASS_A	NOX	0.0555		
EX_PP_HC_CLASS_B	NOX	0.0555		
EX_PP_HC_CLASS_C	NOX	0.0555		
EX_PP_BC_CLASS_A	NOX		0.0645	
EX_PP_BC_CLASS_B	NOX		0.0645	
EX_PP_BC_CLASS_C	NOX		0.0645	
EX_GT	NOX			0.0135
EX_PP_HC_CLASS_A	TPM	0.0037		
EX_PP_HC_CLASS_B	TPM	0.0037		
EX_PP_HC_CLASS_C	TPM	0.0037		
EX_PP_BC_CLASS_A	TPM		0.0043	
EX_PP_BC_CLASS_B	TPM		0.0043	
EX_PP_BC_CLASS_C	TPM		0.0043	
EX_GT	TPM			0.0000

Table 29: Emissions factors for each power plant defined

7.3.3.4 New technologies specification

The SubRES-B-NEWTECHS template contains the new technologies definition and data specification. For this project this template consists in one sheet in which are declared and defined commodities and processes (Tables 30-36).

The workbooks used in this sheet are equal to those used in the ELC or SUP sheets.

All the tables in this sheet are shown below:

Csets	**CommName**	**CommDesc**	**Unit**	**CTSLvl**	**Ctype**
NRG	ELC_HV	Electricity - High Voltage WITHOUT Grid Costs	PJ	DAYNITE	ELC
	HARD_COAL	Hard Coal	PJ		
	BROWN_COAL	Brown Coal	PJ		
	NAT_GAS	Natural Gas	PJ		
	HYDRO	Water	PJ		
	URAN	Uranium	PJ		
	WIND_ON	Wind Onshore	PJ		

ENV	CO2	Carbon Dioxide - Combustion (ELC)	kt		
	SO2	Sulphur Dioxide - Combustion (ELC)	kt		
	NOX	Nitrogen Oxides - Combustion (ELC)	kt		
	TPM	Total Particulate Matter - Combustion (ELC)	kt		
DEM	ELC_LV	Total LV electricity	PJ	DAYNITE	ELC

Table 30: Commodities definition for the Newtechs template

Sets	**TechName**	**TechDesc**	**Tact**	**Tcap**	**Tslvl**	**Vintage**
ELE	NEW_PP_HC	Steam Turbine HC	PJ	GW	ANNUAL	NO
ELE	NEW_PP_HC_CCS	Steam Turbine HC + CCS	PJ	GW	ANNUAL	NO
ELE	NEW_PP_BC	Steam Turbine BC	PJ	GW	ANNUAL	NO
ELE	NEW_PP_BC_CCS	Steam Turbine BC + CCS	PJ	GW	ANNUAL	NO
ELE	NEW_GT	Gas Turbine	PJ	GW	DAYNITE	NO
ELE	NEW_CCGT	Combined Cycle	PJ	GW	DAYNITE	NO
ELE	NEW_CCGT_CCS	Combined Cycle + CCS	PJ	GW	DAYNITE	NO
ELE	NEW_PP_NUC	Nuclear plant	PJ	GW	ANNUAL	NO
ELE	NEW_WND_ON	New Wind Onshore Power Plant	PJ	GW	DAYNITE	NO
ELE	NEW_HYDRO_SMALL	New Hydro Small Power Plant	PJ	GW	DAYNITE	NO
ELE.STGTSS	NEW_HYDRO_PUMP	New Hydro Pump Power Plant	PJ	GW	DAYNITE	NO
ELE.STGTSS	NEW_CAES	NEW_CAES	PJ	GW	DAYNITE	NO

Table 31: New processes definition

TechName	*TechDesc	Comm-IN	Comm-OUT	START	PEAK	CAP2ACT	AFA	LIFE	D COST
			\I:		%	PJ/GW	%		zl/kW
NEW_PP_HC	Steam Turbine HC	HARD_COAL	ELC_HV	2015	1	31.536	0.85	40	336
NEW_PP_HC_CCS	Steam Turbine HC + CCS	HARD_COAL	ELC_HV	2030	1	31.536	0.85	40	575
NEW_PP_BC	Steam Turbine BC	BROWN_COAL	ELC_HV	2015	1	31.536	0.85	40	404
NEW_PP_BC_CCS	Steam Turbine BC + CCS	BROWN_COAL	ELC_HV	2030	1	31.536	0.85	40	699
NEW_GT	Gas Turbine	NAT_GAS	ELC_HV	2015	1	31.536	0.55	25	87
NEW_CCGT	Combined Cycle	NAT_GAS	ELC_HV	2015	1	31.536	0.85	25	163
NEW_CCGT_CCS	Combined Cycle + CCS	NAT_GAS	ELC_HV	2030	1	31.536	0.85	25	349
NEW_PP_NUC	Nuclear plant	URAN	ELC_HV	2025	1	31.536	0.90	50	3373
NEW_WND_ON	New Wind Onshore Power Plant	WIND_ON	ELC_HV	2015	1	31.536		25	313
NEW_HYDRO_SMALL	New Hydro Small Power Plant	HYDRO	ELC_HV	2015	1	31.536		60	640
NEW_HYDRO_PUMP	New Hydro Pump Power Plant	ELC_HV	ELC_HV	2015	1	31.536	1	60	245
NEW_CAES	New CAES plant	ELC_HV	ELC_HV	2015	1	31.536	1	60	

Table 32: New Processes characterization

TechName	EFF~2011	EFF~2015	EFF~2020	EFF~2025	EFF~2030	EFF~2035	EFF~2040	EFF~2045	EFF~2050
	%	%	%	%	%	%	%	%	%
NEW_PP_HC	0.45	0.453	0.457	0.461	0.465	0.466	0.468	0.469	0.47
NEW_PP_HC_CCS					0.365	0.369	0.373	0.376	0.38
NEW_PP_BC	0.44	0.442	0.445	0.447	0.45	0.454	0.458	0.462	0.466
NEW_PP_BC_CCS					0.33	0.338	0.345	0.353	0.36
NEW_GT	0.38	0.3830	0.3870	0.391	0.395	0.398	0.40	0.403	0.405
NEW_CCGT	0.60	0.6040	0.6090	0.615	0.62	0.62	0.62	0.62	0.62
NEW_CCGT_CCS					0.53	0.533	0.535	0.538	0.54
NEW_PP_NUC				0.367	0.37	0.37	0.37	0.37	0.37
NEW_WND_ON	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NEW_HYDRO_SMALL	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

TechName	STG_EFF~2011	STG_EFF~2015	STG_EFF~2020	STG_EFF~2025	STG_EFF~2030	STG_EFF~2035	STG_EFF~2040	STG_EFF~2045	STG_EFF~2050
	%	%	%	%	%	%	%	%	%
NEW_HYDRO_PUMP	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
NEW_CAES	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Tables 33,34: New processes efficiency

TechName	INVCOST~2012	INVCOST~2015	INVCOST~2020	INVCOST~2025	INVCOST~2030	INVCOST~2035	INVCOST~2040	INVCOST~2045	INVCOST~2050
	zl/kW	zl/kW	zl/kW	zl/kW	zl/kW	zl/kW	zl/kW	zl/kW	zl/kW
NEW_PP_HC	6715	6571	6390	6209	6028	5847	5666	5486	5305
NEW_PP_HC_CCS					10041	9658	9275	8892	8509
NEW_PP_BC	8081	7907	7689	7472	7254	7037	6819	6601	6384
NEW_PP_BC_CCS					12208	11742	11277	10811	10346
NEW_GT	1744	1714	1678	1642	1605	1569	1532	1496	1459
NEW_CCGT	3269	3215	3146	3078	3009	2941	2873	2804	2736
NEW_CCGT_CCS					6175	5963	5751	5539	5327
NEW_PP_NUC				21700	21418	21137	20855	20573	20291
NEW_WND_ON	6262	6154	6018	5883	5747	5612	5476	5340	5205
NEW_HYDRO_SMALL	12798	12798	12798	12798	12798	12798	12798	12798	12798
NEW_HYDRO_PUMP	4904	4904	4904	4904	4904	4904	4904	4904	4904
NEW_CAES	3049	3049	3049	3049	3049	3049	3049	3049	3049

Table 35: New processes investment costs

TechName	FIXOM ~2011	FIXOM ~2015	FIXOM ~2020	FIXOM ~2025	FIXOM ~2030	FIXOM ~2035	FIXOM ~2040	FIXOM ~2045	FIXOM ~2050
	zl/kW	zl/kW	zl/kW	zl/kW	zl/kW	zl/kW	zl/kW	zl/kW	zl/kW
NEW_PP_HC	120	117	114	110	106	103	99	96	92
NEW_PP_HC_CCS					178	171	165	158	151
NEW_PP_BC	135	132	128	124	120	116	112	108	103
NEW_PP_BC_CCS					201	193	186	178	170
NEW_GT	60	59	58	57	56	55	54	52	51
NEW_CCGT	80	79	77	76	74	73	71	70	68
NEW_CCGT_CCS					141	136	131	126	121
NEW_PP_NUC				304	300	296	292	288	284
NEW_WND_ON	160	156	151	147	142	137	133	128	123
NEW_HYDRO_SMALL	80	80	80	80	80	80	80	80	80
NEW_HYDRO_PUMP	60	60	60	60	60	60	60	60	60
NEW_CAES	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03

Table 36: New processes fixed O&M costs

TechName	VAROM ~2011	VAROM ~2015	VAROM ~2020	VAROM ~2025	VAROM ~2030	VAROM ~2035	VAROM ~2040	VAROM ~2045	VAROM ~2050
	zl/GJ	zl/GJ	zl/GJ	zl/GJ	zl/GJ	zl/GJ	zl/GJ	zl/GJ	zl/GJ
NEW_PP_HC	2.50	2.44	2.37	2.29	2.22	2.14	2.07	1.99	1.92
NEW_PP_HC_CCS					9.73	9.36	8.99	8.62	8.24
NEW_PP_BC	2.78	2.71	2.63	2.54	2.46	2.38	2.30	2.21	2.13
NEW_PP_BC_CCS					11.14	10.71	10.29	9.86	9.44
NEW_GT	1.39	1.37	1.34	1.32	1.29	1.26	1.24	1.21	1.19
NEW_CCGT	1.67	1.64	1.61	1.58	1.55	1.52	1.49	1.46	1.43
NEW_CCGT_CCS					6.82	6.58	6.34	6.09	5.85
NEW_PP_NUC				2.55	2.51	2.48	2.45	2.41	2.38
NEW_WND_ON	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NEW_HYDRO_SMALL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NEW_HYDRO_PUMP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table37: New processes variable O&M costs

TechName	Comm Name	HARD_COAL	BROWN_COAL	URAN	NAT_GAS	WIND_ON	HYDRO
NEW_PP_HC	CO2	94.19					
NEW_PP_HC_CCS	CO2	11.30					
NEW_PP_BC	CO2		109.08				

NEW_PP_BC_CCS	CO2		13.09				
NEW_GT	CO2				55.82		
NEW_CCGT	CO2				55.82		
NEW_CCGT_CCS	CO2				6.70		
NEW_PP_NUC	CO2			0.00			
NEW_WND_ON	CO2					0.00	
NEW_HYDRO_SMALL	CO2						0.00
NEW_PP_HC	SO2	0.0555					
NEW_PP_HC_CCS	SO2	0.0555					
NEW_PP_BC	SO2		0.0645				
NEW_PP_BC_CCS	SO2		0.0645				
NEW_GT	SO2				0.0000		
NEW_CCGT	SO2				0.0000		
NEW_CCGT_CCS	SO2				0.0000		
NEW_PP_NUC	SO2			0.0000			
NEW_WND_ON	SO2					0.0000	
NEW_HYDRO_SMALL	SO2						0.0000
NEW_PP_HC	NOX	0.0555					
NEW_PP_HC_CCS	NOX	0.0555					
NEW_PP_BC	NOX		0.0645				
NEW_PP_BC_CCS	NOX		0.0645				
NEW_GT	NOX				0.0135		
NEW_CCGT	NOX				0.0135		
NEW_CCGT_CCS	NOX				0.0135		
NEW_PP_NUC	NOX			0.0000			
NEW_WND_ON	NOX					0.0000	
NEW_HYDRO_SMALL	NOX						0.0000
NEW_PP_HC	TPM	0.0037					
NEW_PP_HC_CCS	TPM	0.0037					
NEW_PP_BC	TPM		0.0043				
NEW_PP_BC_CCS	TPM		0.0043				
NEW_GT	TPM				0.0000		
NEW_CCGT	TPM				0.0000		
NEW_CCGT_CCS	TPM				0.0000		
NEW_PP_NUC	TPM			0.0000			
NEW_WND_ON	TPM					0.0000	
NEW_HYDRO_SMALL	TPM						0.0000

Table 38: Emissions factors for the new power plants

7.3.3.5 Scenario files

All the Scen_<name>.xls files contain additional information and parameters for the entire reference energy system, commodities and technologies. These files can only manipulate information associated with previously declared reference energy system components, new commodities and processes may not be added via scenario files.

In this project there are five scenario files:

- Scen_AF, containing the Availability Factor (AF) of the wind based power plants in each time-slice within a year:

Time Slice	Attribute	Year	PL	Pset_PN
1R1MO1	AF	2011, 2015, 2020, 2025, 2030, 2032, 2035, 2040, 2045, 2050	0.82733472	EX_PP_WIND_ON, NEW_WND_ON
1R1MO2	AF	2011, 2015, 2020, 2025, 2030, 2032, 2035, 2040, 2045, 2050	0.86678305	EX_PP_WIND_ON, NEW_WND_ON
1R1MO3	AF	2011, 2015, 2020, 2025, 2030, 2032, 2035, 2040, 2045, 2050	0.9019219	EX_PP_WIND_ON, NEW_WND_ON
1R1MO4	AF	2011, 2015, 2020, 2025, 2030, 2032, 2035, 2040, 2045, 2050	0.95689862	EX_PP_WIND_ON, NEW_WND_ON
1R1MO5	AF	2011, 2015, 2020, 2025, 2030, 2032, 2035, 2040, 2045, 2050	0.90481043	EX_PP_WIND_ON, NEW_WND_ON
..	..	..	..	..

Table 39: 'Scen_AF' table

- Scen_CO2TAX, containing the carbon tax related to each ton of CO_2 emitted:

Attribute	Year	PL	Cset_Set	Cset_CN
COM_TAXNET	2011	0	ENV	CO2
COM_TAXNET	2012	0	ENV	CO2
COM_TAXNET	2013	0.041	ENV	CO2
COM_TAXNET	2015	0.041	ENV	CO2
COM_TAXNET	2020	0.062	ENV	CO2
COM_TAXNET	2025	0.062	ENV	CO2
COM_TAXNET	2030	0.07	ENV	CO2
COM_TAXNET	2035	0.074	ENV	CO2
COM_TAXNET	2040	0.078	ENV	CO2
COM_TAXNET	2045	0.082	ENV	CO2
COM_TAXNET	2050	0.087	ENV	CO2

Table 40: 'Scen_CO2TAX' table

- Scen_COM_FR, containing the demand distribution within a year, thus the % of the total demand that has to be satisfied in each time-slice:

TimeSlice	Cset_SET	Cset_CN	Attribute	Year	PL
1R1MO1	DEM	ELC_LV	COM_FR	2011-0	0.003241481
1R1MO2	DEM	ELC_LV	COM_FR	2011-0	0.003233878
1R1MO3	DEM	ELC_LV	COM_FR	2011-0	0.004210803
1R1MO4	DEM	ELC_LV	COM_FR	2011-0	0.004628117

1R1MO5	DEM	ELC_LV	COM_FR	2011-0	0.004629694
1R1MO6	DEM	ELC_LV	COM_FR	2011-0	0.004443216
1R1MO7	DEM	ELC_LV	COM_FR	2011-0	0.004550308
1R1MO8	DEM	ELC_LV	COM_FR	2011-0	0.004344974
1R2TU1	DEM	ELC_LV	COM_FR	2011-0	0.003645646
1R2TU2	DEM	ELC_LV	COM_FR	2011-0	0.003570804
1R2TU3	DEM	ELC_LV	COM_FR	2011-0	0.004378503
..	..	..	..	..	..

Table 41: 'Scen_COM_FR' table

The annual demand for electricity in each modeling year is spread over the time slices based on the historical data provided by the transmission system operator - PSE (http://www.pse-operator.pl).

Although the 'Year' column contains only the year 2011 this demand distribution is maintained for all the years within the model horizon.

- Scen_NCAP, containing the fixed amount of new capacity that has to be built during the time horizon regarding wind power plants - with the intention to follow the path showed in figure 46 - while for hydro power plant it contains the maximum new capacity that can be build during the time horizon, due to the very low Polish hydro potential.

TimeSlice	LimType	Attribute	Year	PL	Pset_PN
ANNUAL	FX	NCAP_BND	2015	3	NEW_WND_ON
ANNUAL	FX	NCAP_BND	2020	3	NEW_WND_ON
ANNUAL	FX	NCAP_BND	2025	3	NEW_WND_ON
ANNUAL	FX	NCAP_BND	2030	3	NEW_WND_ON
ANNUAL	FX	NCAP_BND	2035	5	NEW_WND_ON
ANNUAL	FX	NCAP_BND	2040	5	NEW_WND_ON
ANNUAL	FX	NCAP_BND	2045	7	NEW_WND_ON
ANNUAL	FX	NCAP_BND	2050	10	NEW_WND_ON
ANNUAL	UP	NCAP_BND	2015	1	NEW_HYDRO_SMALL
ANNUAL	UP	NCAP_BND	2020	1	NEW_HYDRO_SMALL
ANNUAL	UP	NCAP_BND	2025	1	NEW_HYDRO_SMALL
ANNUAL	UP	NCAP_BND	2030	1	NEW_HYDRO_SMALL
ANNUAL	UP	NCAP_BND	2035	0.6	NEW_HYDRO_SMALL
ANNUAL	UP	NCAP_BND	2040	0	NEW_HYDRO_SMALL
ANNUAL	UP	NCAP_BND	2045	0	NEW_HYDRO_SMALL
ANNUAL	UP	NCAP_BND	2050	0	NEW_HYDRO_SMALL

Table 42: 'Scen_NCAP' table

- Scen_STG_PARAM, containing all the parameters related to storage: the flow-in and flow-out costs - the cost related to the charge (FLO_COST) and discharge (FLO_DELIV) processes of one PJ -, and the flow-in and flow-out bound - maximum amount of PJ flow (in and out) in each time slice.

Time Slice	Attribute	Year	PL	Pset_PN	Cset_CN
1*	FLO_COST	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	CAES_STG, NEW_CAES	ELC_HV
2*	FLO_COST	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	CAES_STG, NEW_CAES	ELC_HV
3*	FLO_COST	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	CAES_STG, NEW_CAES	ELC_HV
4*	FLO_COST	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	CAES_STG, NEW_CAES	ELC_HV
1*	FLO_DELIV	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	CAES_STG, NEW_CAES	ELC_HV
2*	FLO_DELIV	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	CAES_STG, NEW_CAES	ELC_HV
3*	FLO_DELIV	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	CAES_STG, NEW_CAES	ELC_HV
4*	FLO_DELIV	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	CAES_STG, NEW_CAES	ELC_HV
1*	FLO_COST	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	NEW_HYDRO_PUMP	ELC_HV
2*	FLO_COST	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	NEW_HYDRO_PUMP	ELC_HV
3*	FLO_COST	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	NEW_HYDRO_PUMP	ELC_HV
4*	FLO_COST	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	NEW_HYDRO_PUMP	ELC_HV
1*	FLO_DELIV	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	NEW_HYDRO_PUMP	ELC_HV
2*	FLO_DELIV	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	NEW_HYDRO_PUMP	ELC_HV
3*	FLO_DELIV	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	NEW_HYDRO_PUMP	ELC_HV
4*	FLO_DELIV	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	0.0001	NEW_HYDRO_PUMP	ELC_HV
1*	STGIN_BND	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	2	CAES_STG, NEW_CAES	ELC_HV
2*	STGIN_BND	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	2	CAES_STG, NEW_CAES	ELC_HV
3*	STGIN_BND	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	2	CAES_STG, NEW_CAES	ELC_HV
4*	STGIN_BND	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	2	CAES_STG, NEW_CAES	ELC_HV
1*	STGOUT_BND	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	2	CAES_STG, NEW_CAES	ELC_HV
2*	STGOUT_BND	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	2	CAES_STG, NEW_CAES	ELC_HV
3*	STGOUT_BND	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	2	CAES_STG, NEW_CAES	ELC_HV
4*	STGOUT_BND	2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045, 2050	2	CAES_STG, NEW_CAES	ELC_HV

Table 43: 'Scen_STG_PARAM' table

7.3.4 Managing the templates via VEDA-FE

In order to generate a TIMES model, the information declared in the templates is gathered into a single database.

VEDA-FE interface opens displaying the VEDA-Navigator, which provides a comprehensive view of all the templates in the various folders managed by VEDA for the current model. It is the main vehicle for accessing, importing and coordinating the various templates.

The VEDA-Navigator also provides feedback as to status of the various templates and the actual assembled database managed by VEDA. The consistency of the templates and the integrated database managed by VEDA is immediately evident based upon whether the 'ALL OK' blue icon or the 'SYNC' red icon is showed. In addition, if there are some inconsistent templates they will be displayed in red. The way to synchronize the template in the application folder is to hit the SYNC button. The files that will be imported are the red ones.

Once the templates have been imported it is possible to review the resulting data and to check the reference energy system.

Search and view data

In order to view and directly edit the data the user need to: select 'Basic Function', 'Browse/Edit', and then 'TIMES view' or 'VEDA view'. The TIMES view option will display the TIMES parameter, instead the VEDA view shows the same information but with the parameters names used in the templates.

As a result the user can view the subset of assembled data in a dynamic matrix by selecting the scenario(s), region(s), process(es), commodity(ies), and attribute(s) of interest. Moreover the user can rearrange the layout of this dynamic matrix by adding or removing dimensions to the table by dragging and dropping components from/to the area above the current row designator columns.

A filter mechanism help the user to quickly select only the subset of the reference energy system and associated data of interest by selecting the component from the list-box and pressing F3.

To edit the data the user may click on 'Direct edit' and then double click on the data to be edited; VEDA-FE then opens a pop-up window in which is possible to modify directly the data.

Process, Commodity and Commodity Group Master

The process master option, selected from the 'Advanced Functions' menu, shows detailed process information like set memberships, units and input/output commodities.

The commodity master option shows detailed commodity information like set membership, units and producers/consumers.

The commodity group master shows the commodities associated with all user-defined and VEDA-created commodity groups.

<u>Reference energy system view</u>

In order to view the reference energy system of the model the user needs to select 'Basic Functions' and then 'RES'. The result depends on which information is currently selected in the Browse. In this window is possible to navigate around the model by clicking on the element which allows the user to see all producing and consuming processes in case of commodity and all input and output flows in case of process.

7.3.5 Running and solving the model

In order to generate and solve the model, the data managed by VEDA-FE must be extracted and prepared for the TIMES code. To do so the user has to select the 'Solve' facility from the 'Basic Functions' menu: it will open the Case Manager window where the user can select the scenario(s), the region(s) and the ending year. The appropriate solver could be selected via the pull-down list, the choice is between CPLEX, XPRESS or OTHER. Other options on the Case Manager form allow the user to update the 'RUN' file: the GAMS command file that launches the batch solution program.

Once the appropriate selections have been made, simply click the 'SOLVE' button in this form. After the data are extracted from the database a Command Prompt window is opened and displays the progress of the matrix generation, the solution and a report of the TIMES model run.

7.3.6 Analyze the model results with VEDA-BE

The second component of the VErsatile Data Analyst, called Back End is used for the analysis of the model results.

In order to analyze the results of a model run you need to import the scenario run solution files into VEDA-BE. To do this select 'Results', 'Import/Archive' and check the run just made.

When the results are correctly loaded, the main VEDA-BE selection form opens. The screen is divided into two parts: the table selection list on the left, and the table specification component selection on the right. The table selection list allows the user to select predefined tables from the pull down list or to define a new table.

The tabs on the specification area correspond to the various aspects of a table. The Attribute window shows the various model result such as costs or commodity production. Two tabs deserve special attention: the Commodity and the Process tabs, in which we have two sections: the upper part listing the sets and the lower part listing the individual items.

After requesting a table the user can rearrange it by adding or removing dimensions to the table by dragging and dropping components.

Generally, a new table is fully defined in two steps by:

- Selecting the content of the table, i.e. what results have to be presented in the table, assigning the units (if desired), and
- Arranging the layout for the table.

Creating a new table requires selecting which types of results to show (attributes) and perhaps which subset of processes, commodities, regions, scenarios, time-periods, etc, have to be included.

The obtained results for the TIMES_STG_PL model are analyzed in the following chapter.

Chapter 8:

TIMES_STG_PL results

8.1 Sensitivity analysis results

Generally speaking, sensitivity analysis concerns the mathematical model representation of a physical system, and attempts to assess the sensitivity of the model output to variations of the model inputs given by parameters and variations of model assumptions.

Sensitivity analysis can be useful for a range of purposes, including: testing the robustness of the results of a model in presence of uncertainty, increased understanding of the relationship between input and output data in a model, searching for errors in a model.

As explained in the previous chapter the scope of this project was to test the variations in the model output due to variations in the power provided by the wind onshore power plants. The output variable we were interested was the energy storage new capacity installed within the time horizon, thus the new energy storage capacity that the model needed to optimize the total system cost. To do this 42 different wind profile were tested.

The sensitivity analysis' results are displayed in figure 65 and reported in table 44.

To perform the sensitivity analysis the model was run considering the existence of a carbon tax.

2000_1	1.17	2001_1	4.04	2002_1	0.94	2003_1	2.42	2004_1	2.20	2005_1	1.85	2008_1	1.86
2000_2	2.28	2001_2	1.19	2002_2	2.39	2003_2	1.90	2004_2	2.02	2005_2	3.72	2008_2	3.13
2000_3	1.19	2001_3	1.48	2002_3	1.16	2003_3	2.65	2004_3	2.21	2005_3	2.53	2008_3	2.37
2000_4	2.73	2001_4	1.62	2002_4	3.71	2003_4	1.90	2004_4	2.13	2005_4	2.19	2008_4	2.37
2000_5	3.10	2001_5	1.87	2002_5	3.12	2003_5	2.29	2004_5	1.91	2005_5	2.16	2008_5	1.95
2000_6	3.33	2001_6	2.82	2002_6	1.93	2003_6	1.69	2004_6	2.41	2005_6	2.02	2008_6	2.28

Table 44: Required CAES system capacity in 2050 for all the investigated wind profiles - the red value is the highest one while the green value is the lowest one.

We can see how the required CAES capacity ranges between 0.94 and 4.04 GW, thus the required caves volume ranges between about 10 millions m^3 and 40 millions of m^3. Since the existing facilities for the storage of natural gas in Poland amount to about 1,821 million of m^3 and the UGS potential there is very high (many millions of cubic meters) these results could be achievable by 2050.

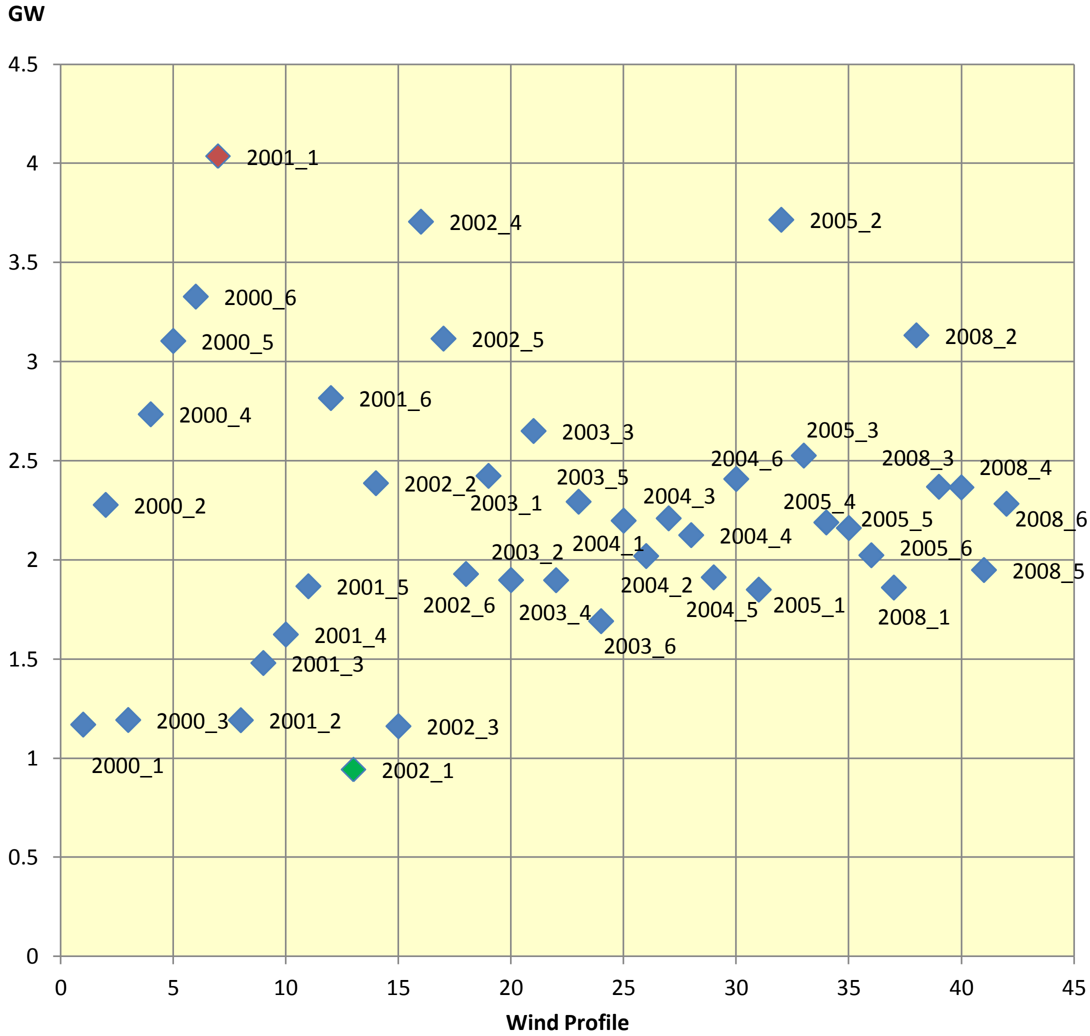


Figure 65: Sensitivity analysis result: overall CAES new capacity in 2050 for each wind profile

Figure 66 gives an example of how the demand is satisfied for the year 2050 considering the 2001_1 wind profile -spring (R) and summer (S) seasons -, figure 67 shows the flow-in and flow-out from the NEW_CAES system for the same wind profile portion.

From figure 66 we can see how the PP meet the demand: there are the base-load power plants - EX_PP_BC_CLASS_A, EX_PP_BC_CLASS_B, EX_PP_HC_CLASS_B, NEW_PP_BC - that produce a constant amount of electricity, then we have the peak power plants (wind and hydro PP), and finally we have the electricity that flows out from the storage processes. The diagram shows how the surplus of energy produced by the wind power plants is stored to be re-used when necessary. We can see also how the model always chooses to produce the maximum of electricity from the wind power plants and to not produce from natural gas plants.

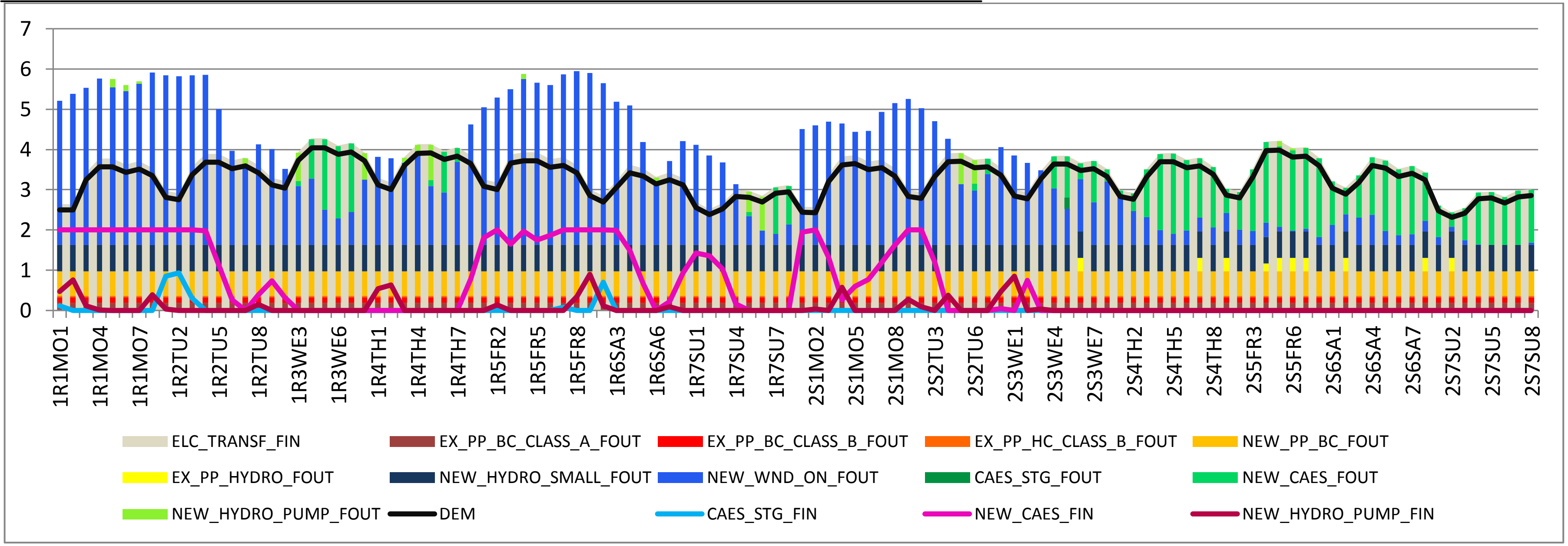


Figure 66: How the system satisfies the demand in 2050's spring (R) and summer (S), considering the 2001_1 wind profile

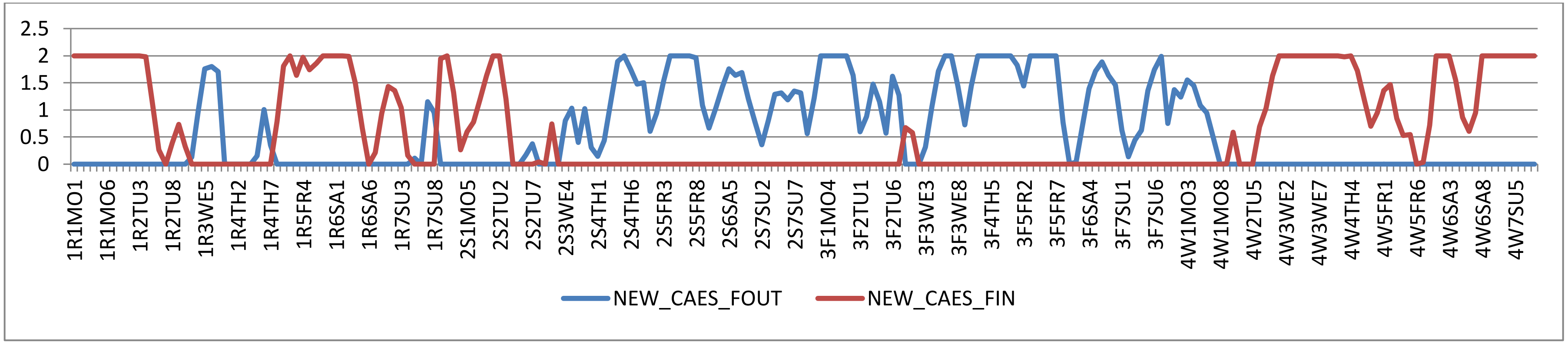


Figure 67: Flow-in and flow-out from CAES process

This happens because the variable costs of the wind plants are zero while the natural gas plants are the most expensive. Note finally that the flow-in of the transformation process differs from the demand because its efficiency is less than 1.

8.2 Total system's cost and renewable sources share

The total system cost components are:

- Fixed Operation and maintenance cost (note that since the existing PP must have been installed at least the year previous the base one also the fixed O&M costs for this year are taken into account) ;
- Variable Operation and Maintenance cost;
- Flow costs (commodities' supply costs, import costs and storage flows costs);
- Decommissioning costs;
- Investment costs;
- Salvage costs (associated with the new power plants);
- Taxes.

As an example the following table reports the total system cost for the two extreme cases in Polish złotys.

mln Zl	*NO STORAGE*		*STORAGE*	
	CARBON TAX	**NO TAX**	**CARBON TAX**	**NO TAX**
2001_1	449,066.52	374,029.5	385,296.8	310767.8
2002_1	457,629.86	375,219.1	402,107.8	321410.2

Table 45: Total system costs for the 2 extreme cases

The taxes policy influence the total system costs in a percentage that ranges from about 17% to 20%.

The storage allows a total system cost reduction that ranges from 12% to about 17%.

Finally the share of renewable sources in the total electricity generation is between 40% and 60% for all the wind profile investigated, thus the main assumption has been satisfied.

8.3 Emissions

The following tables show how the storage and the CO_2 taxes affect the emissions for the two extreme cases, 2001_1 and 2002_1. The emissions values are reported in kilo tons.

2001_1	NOSTG	NOTAX							
Comm	2011	2015	2020	2025	2030	2035	2040	2045	2050
CO2	173380.06	139626.88	131728.51	124594.02	117275.31	114848.50	89440.27	78945.42	75418.86
NOX	102.28	81.72	76.82	72.35	67.72	65.98	48.77	41.91	39.86
SO2	102.25	81.22	76.18	71.51	66.67	64.72	45.97	38.64	36.61
TPM	6.82	5.41	5.08	4.77	4.44	4.31	3.06	2.58	2.44
2001_1	NOSTG	TAX							
Comm	2011	2015	2020	2025	2030	2035	2040	2045	2050
CO2	173380.06	127925.68	114917.22	99867.52	80947.42	76855.71	62978.55	49923.75	33992.99
NOX	102.28	73.97	65.71	55.89	43.36	40.71	30.53	21.75	11.93
SO2	102.25	72.88	64.22	53.74	40.25	37.43	25.89	16.38	6.28
TPM	6.82	4.86	4.28	3.58	2.68	2.50	1.73	1.09	0.42
2001_1	STG	NOTAX							
Comm	2011	2015	2020	2025	2030	2035	2040	2045	2050
CO2	152073.94	129696.95	118105.19	107687.39	97374.17	88596.05	88384.53	76418.07	55329.39
NOX	89.77	76.58	69.72	63.59	57.51	52.33	52.20	45.15	32.71
SO2	89.77	76.58	69.72	63.59	57.51	52.33	52.20	45.15	32.71
TPM	5.98	5.11	4.65	4.24	3.83	3.49	3.48	3.01	2.18
2001_1	STG	TAX							
Comm	2011	2015	2020	2025	2030	2035	2040	2045	2050
CO2	152073.94	129696.95	118105.19	107687.39	97374.17	88596.05	88381.25	76418.07	54515.48
NOX	89.77	76.58	69.72	63.59	57.51	52.33	52.20	45.15	32.23
SO2	89.77	76.58	69.72	63.59	57.51	52.33	52.20	45.15	32.23
TPM	5.98	5.11	4.65	4.24	3.83	3.49	3.48	3.01	2.15
2002_1	NOSTG	NOTAX							
Comm	2011	2015	2020	2025	2030	2035	2040	2045	2050
CO2	174350.16	143593.99	136897.72	129672.57	121939.64	114850.93	106331.75	96042.78	92160.74
NOX	102.86	84.18	80.07	75.57	70.72	65.98	60.16	53.50	51.30
SO2	102.84	83.77	79.57	74.90	69.83	64.72	58.33	51.25	49.11
TPM	6.86	5.58	5.30	4.99	4.66	4.31	3.89	3.42	3.27
2002_1	NOSTG	TAX							
Comm	2011	2015	2020	2025	2030	2035	2040	2045	2050
CO2	174350.16	133982.02	123378.20	111914.12	99541.01	88793.55	85576.90	66075.01	48511.85
NOX	102.86	77.82	71.12	63.71	55.65	48.29	45.38	31.86	20.65
SO2	102.84	76.92	69.93	62.07	53.46	45.40	41.81	26.89	15.10
TPM	6.86	5.13	4.66	4.14	3.56	3.03	2.79	1.79	1.01
2002_1	STG	NOTAX							

Comm	2011	2015	2020	2025	2030	2035	2040	2045	2050
CO2	153408.21	133398.36	124212.20	116200.00	108292.37	102631.10	101739.70	92488.32	76539.40
NOX	90.55	78.76	73.32	68.60	63.94	60.60	60.10	54.65	45.24
SO2	90.55	78.76	73.32	68.60	63.94	60.60	60.10	54.65	45.24
TPM	6.04	5.25	4.89	4.57	4.26	4.04	4.01	3.64	3.02
2002_1	STG	TAX							
Comm	2011	2015	2020	2025	2030	2035	2040	2045	2050
CO2	153408.21	133398.36	124212.20	116200.00	108292.37	102631.10	101739.70	92448.83	75743.35
NOX	90.55	78.76	73.32	68.60	63.94	60.60	60.10	54.63	44.78
SO2	90.55	78.76	73.32	68.60	63.94	60.60	60.10	54.63	44.78
TPM	6.04	5.25	4.89	4.57	4.26	4.04	4.01	3.64	2.99

Table 46: Comparison between the emissions values in the 2 extreme cases

First, we can see that the CO_2 taxes greatly affect the model decisions. In fact with the taxes policy the model chooses to build many more natural gas plants even if they are more expensive.

Second, it can be notice how the storage's existence reduces the emissions without tax policy.

Applying the tax policy with the storage facilities does not influence the emissions very much. Probably it happens because the model attempts to optimize the integration of the storage process with the other processes, and the optimal use of the storage process requires a large base-load capacity, thus the capacity of these plants -based on fossil fuels- cannot be reduced so much.

8.4 Conclusions and future works

Since the Polish coal-based power sector is very vulnerable to the European climate policies, if stringent decarbonization targets will be imposed by the EU Poland will have to shift towards less carbon intensive electricity generation.

The attainment of the model storyline proposed in this project will depend first on the efforts that will be done by local authorities to bypass the legal, technical and financial obstacles - acquiring permission for investments in those regions under the Nature 2000 network, development of grid interconnections-, and second on the development and commercial availability of energy storage technologies.

Future works will be dedicated to further development of the structure of the reference energy system used in the model and more deep studies will be conducted on UGS potential in Poland.

Appendix A:

Complete code of the GAMS model

<u>*Note*</u>:

GAMS instruction are given in **bold**, elements description is given in *italics*.

________MULTIPERIOD PLANNING OF ELECTRIC POWER CAPACITY_____________

******************** V. Rosa **********************

option limrow = 1000;

** as a result all the equation will be reported in the .lst file in the directory of the model in the GAMS folder*

set

t *time* /1*38/

tech *existing technologies* /hydro, natgas, hardcoal, browncoal, nuclear, wind, solar/ ;

alias (t,s) ;

**alias function creates a duplicate of the parameter with the same features*

************Discount Rate ********************

scalar r /0.03/ ;

*____________General parameters ________________

************Demand ************************

Parameter

Dem(t) *demand forecast of electricity in MWh*

/1 146630000.00

2 149389042.4

3 152200000

4 154414607.5

5 156661438.9

6 158940963.2

7 161253656
8 163600000
9 165609999.5
10 167644694
11 169704386.8
12 171789385.2
13 173900000
14 175951044.4
15 178026279.6
16 180125990.9
17 182250467
18 184400000
19 186891743.5
20 189417157.2
21 191976696
22 194570821.2
23 197200000
24 199600825.9
25 202030880.8
26 204490520.6
27 206980105.5
28 209500000
29 211405037.5
30 213327398.1
31 215267239.1
32 217224719.6
33 219200000
34 220679882.4
35 222169755.9
36 223669688
37 225179746.6
38 226700000/ ;

****** Upper limit in electricity production for each technology per yr ********

the CALL function is used to import data from Excel file (.xls)

$CALL GDXXRW.EXE

```
C:\Users\Administrator\Documents\gamsdir\projdir\CostsEnrgCapPlan.xls
par=Max_Elc_Production rng=MaxElc_Prod!A1:G39
Parameter Max_Elc_Production(t,tech)   maximum electricity production potential
for each technology [MWh]
$GDXIN CostsEnrgCapPlan.gdx
$LOAD Max_Elc_Production
$GDXIN

* For the nuclear technology we consider an upper limit in capacity installation of
1500 MW every 5 years from 2025
scalar Max_Nucl_Cap /1500/       ;

*-------------------Parameter of energy technologies ----------------------
**************Installed Capacity ****************************
* we take in count 5% annual decomissioning for all existing technologies

$CALL GDXXRW.EXE
C:\Users\Administrator\Documents\gamsdir\projdir\CostsEnrgCapPlan.xls
par=Installed_CAP rng=ExistingCap!A1:H39
Parameter Installed_CAP(t,tech)  installed capacity in MW with 5% decomissioning
$GDXIN CostsEnrgCapPlan.gdx
$LOAD Installed_CAP
$GDXIN

parameter Op_hrs(tech)       operative hours of each technology [hrs per year];
        Op_hrs('hydro')= 3000 ;
        Op_hrs('hardcoal')= 6000;
        Op_hrs('browncoal')= 6000;
        Op_hrs('natgas')= 5000;
        Op_hrs('nuclear')= 6500;
        Op_hrs('wind')= 2000;
        Op_hrs('solar')= 1400;

parameter CF(tech)       capacity factor of each technology ;
        CF(tech)= Op_hrs(tech)/8760 ;
```

parameter Eff(tech) *efficiency of the process in fuel use***;**

Eff('hydro')= 1 ;

Eff('hardcoal')= 0.4;

Eff('browncoal')= 0.4;

Eff('natgas')= 0.5;

Eff('nuclear')= 0.34;

Eff('wind')= 1;

Eff('solar')=1;

parameter Lifetime(tech) *lifetime of technology in years* **;**

Lifetime('hydro')= 80 ;

Lifetime('hardcoal')= 40;

Lifetime('browncoal')= 40;

Lifetime('natgas')= 30;

Lifetime('nuclear')= 50;

Lifetime('wind')= 20;

Lifetime('solar')= 20;

parameter crf(tech) *capital recovery factor of technology tech* **;**

crf(tech)= (r*Power((1+r),Lifetime(tech)))/(Power((1+r),Lifetime(tech))-1);

************* Natural gas storage parameters *************

parameter NGas_supply_limit(t) *natural gas international supply limit in m^3*;

NGas_supply_limit(t) = 10000000000 ;

**Definition of base Gas that's the amount of natgas that is intended as permanent inventory in a storage reservoir to maintain adequate pressure, this % depend on the facility type: depleted reservoir 50%, aquifer reservoir 80%, salt formation 30%*

scalar Base_NGas /0.3/ ;

**Operational storage facilities in Poland. Source Gas Infrastructure Europe, GSE storage map 2011*

scalar Stg_Capacity stg *existing storage capacity in m^3* /1828000000/ ;

parameter Intial_Stored_NGas *we suppose that the initial amount of stored natgas* *is equal to the Base_Gas ;*

```
Intial_Stored_NGas = Stg_Capacity*Base_NGas;

********** CO2 EMISSIONS PARAMETERS ********************
********** Emissions ceiling for the start year (2013) in ton ******
scalar Emi_Ceiling_StartYr /270000000/    ;
parameter CO2_Emi(tech)  CO2 emissions for each technology in ton per MWh
produced ;
        CO2_Emi('hydro')=0.004 ;
        CO2_Emi('hardcoal')= 0.752;
        CO2_Emi('browncoal')= 0.900;
        CO2_Emi('natgas')= 0.341;
        CO2_Emi('nuclear')= 0.016;
        CO2_Emi('wind')=0.012;
        CO2_Emi('solar')= 0.046;

scalar CO2_tax euro per CO2 ton /58/ ;

*--------------------- Cost parameters-----------------------------------
*************** Capital costs ****************************

$CALL GDXXRW.EXE
C:\Users\Administrator\Documents\gamsdir\projdir\CostsEnrgCapPlan.xls
par=Inv_Costs rng=CapCost!A1:H39
Parameter Inv_Costs(t,tech)   capital costs of each technology in € per MW
$GDXIN CostsEnrgCapPlan.gdx
$LOAD Inv_Costs
$GDXIN

*************** Fixed Operation&Maintenance Costs **********
*Fixed Operation and maintenance costs consist in plant operating labor and
regular and irregular maintenance work but also tax, insurance

$CALL GDXXRW.EXE
C:\Users\Administrator\Documents\gamsdir\projdir\CostsEnrgCapPlan.xls
par=Fix_costs_Tech rng=FixCost!A1:H39
```

Parameter Fix_costs_Tech(t,tech) *fixed costs of each technology in € per MW*
$GDXIN CostsEnrgCapPlan.gdx
$LOAD Fix_costs_Tech
$GDXIN

************* Variable Operation&Maintenance Costs ***********
** this cost arise due to a constant maintenance contract and include periodic inspection, replacement, repair of sys components, auxiliary materials*

$CALL GDXXRW.EXE
C:\Users\Administrator\Documents\gamsdir\projdir\CostsEnrgCapPlan.xls
par=Var_costs_Tech **rng**=VarCost!A1:H39
Parameter Var_costs_Tech(t,tech) *variable costs of each technology in € per MWh produced*
$GDXIN CostsEnrgCapPlan.gdx
$LOAD Var_costs_Tech
$GDXIN

****************** Fuel Costs ***************************
$CALL GDXXRW.EXE
C:\Users\Administrator\Documents\gamsdir\projdir\CostsEnrgCapPlan.xls
par=Fuel_costs_Tech **rng**=FuelCost!A1:H39
Parameter Fuel_costs_Tech(t,tech) *fuel costs € per MWh produced*
$GDXIN CostsEnrgCapPlan.gdx
$LOAD Fuel_costs_Tech
$GDXIN

*-----------------Variables of the model----------------------------*****
Positive variable

NCAP(t,tech)	*Technology tech's new capacity brought on line at the beginning of t [MW per year]*
CAP(t,tech)	*Technology tech's total available capacity at t [MW per year]*
Tot_Inv_costs(t,tech)	*Investment in NCAP for technology tech [€ per year]*
Tot_Var_costs(t,tech)	*Total O&M variable costs_technology tech*

	[€ per year]	
Tot_Fixed_costs(t,tech)	*Total O&M fixed costs_technology tech [€ per year]*	
Tot_Fuel_costs(t,tech)	*Total fuel costs_technology tech [€ per year]*	
Total_Ann_costs(t)	*Total annual costs*	*[€ per year]*
Annual_Elc_Prod(t,tech)	*Total electricity produced from each technology each year*	*[MWh per year]*
Tot_Emi(t)	*Total CO2 emissions*	*[ton per year]*
Emi_Target(t)	*CO2 emissions ceiling for year t in ton*	
NGas_consumption(t)	*Consumed natural gas for elc production*	*[m3 per year]*
Stored_NGas(t)	*Stored natural gas*	*[m3 per year]*
Domestic_NGas_supply(t)	*Natural gas domestic production*	*[m3 per year]*
Stored_NGas_Consumption(t)	*Consumption of stored natural gas [m3 per year]*	
International_NGas_Supply(t)	*International supply of natural gas [m3 per year]*	
Carbon_Tax(t)	*Tax for CO2 emissions [€ per year]* ;	

Variable

Tot_Expansion_Costs *Total costs of capacity expansion* *[€]* ;

*------------------Equations of the model-------------------------**********

Equations

Total_Exp_costs_Eq	*Total expansion costs_objective function to minimize*
Tot_Ann_Costs_Eq(t)	*Expansion annual costs*
Tot_Inv_costs_Eq(t,tech)	*Investment cost in each technology in year t*
Tot_Var_costs_Eq(t,tech)	*Variable OM costs for each technology in year t*
Tot_Fix_costs_Eq(t,tech)	*Fixed OM costs for each technology in year t*
Tot_Fuel_costs_Eq(t,tech)	*Fuels variable costs for each technology except for the natural gas in year t*
Tot_CAP_Eq(t,tech)	*Total capacity within the Lifetime yrs of tech operation*

Balance_Dem_Eq(t)	*The available capacity must meet the forecasted demand*
Nuclear_Constraint_Eq(t)	*User constraint: no more than 20% of total capacity should ever be nuclear*
Max_Elc_Production_Eq(t,tech)	*The total electricity production cannot be greater than the maximum available electricity production potential*
Nuclear_Availability	*Nuclear capacity will be available for installation from 2025*
Max_Nuclear_Cap_Eq(t)	*For the nuclear technology we consider an upper limit in capacity installation of 1500 MW every 5 years*
Annual_Elc_Prod_Eq(t,tech)	*Technology tech generated electricity in year t*
Tot_Emi_Eq(t)	*Total CO_2 emissions in year t*
Decarbo_Path(t)	*Decarbonization path: calculation of CO2 emissions ceiling for years following the start_yr assumed that CO2 emissions have to be reduced by 50% in 2050*
Balance_Emi_Eq(t)	*The total CO2 emissions must be lower or equal than the emissions target*
NGas_consumption_Eq(t)	*Consumption of natural gas in m^3*
Initial_Stored_NGas_Eq(t)	*Initial m^3 of natural gas stored*
NGas_Storage_Eq(t)	*Storage process for international natural gas supply*
Balance_NGas_Eq(t)	*Domestic natural gas supply plus stored natural gas have to meet the natural gas request each year*
Domestic_supply_constraint(t)	*In year t no more than 50% of the natural gas consumed comes from domestic supply*
NGas_supply_limit_Eq(t)	*The international imported gas have to be lower than the supply potential*
NGas_Tot_fuel_cost(t,tech)	*Natgas technology fuel costs dependent on the volume of gas supplied*
Base_NGas_Constraint(t)	*The stored NGas in t have to be always greater or equal to the base NGas*
Stg_Cap_Limit(t)	*The stored NGas in t have to be always lower*

than the maximum stg capacity

```
Carbon_tax_Eq(t) ;

*________________Equation characterization_______________

Tot_CAP_Eq(t,tech)..
        CAP(t,tech) =E= Installed_CAP(t,tech) + sum( s$(ord(s) ge max(1,(ord(t)-
                (Lifetime(tech)-1))) and ord(s) le ord(t)), NCAP(s,tech) ) ;
Balance_Dem_Eq(t)..
        sum(tech, CAP(t,tech) * Op_hrs(tech)) =G= Dem(t) ;

Max_Elc_Production_Eq(t,tech)..
        CAP(t,tech)*Op_hrs(tech) =L= Max_Elc_Production(t,tech) ;

Annual_Elc_Prod_Eq(t,tech)..
        Annual_Elc_Prod(t,tech) =E= CAP(t,tech) * Op_hrs(tech) ;

**************** Decarbonization path ****************************
Tot_Emi_Eq(t)..
        Tot_Emi(t) =E= sum(tech,CO2_Emi(tech)*Annual_Elc_Prod(t,tech)) ;

Decarbo_Path(t)..
        Emi_Target(t) =E= Emi_Ceiling_StartYr -
(0.5*Emi_Ceiling_StartYr/(37))*(ord(t)-1) ;

Carbon_tax_Eq(t)..
        Carbon_Tax(t) =E= CO2_tax*Tot_Emi(t) ;

Balance_Emi_Eq(t)..
        Tot_Emi(t) =L= Emi_Target(t) ;

*************** Natural Gas Reserve *****************

NGas_consumption_Eq(t)..
        Gas_consumption(t) =E=
Annual_Elc_Prod(t,'natgas')/Eff('natgas')*(3.6/0.036) ;
```

```
Initial_Stored_NGas_Eq(t)$(ord(t) eq 1)..
        Stored_NGas(t) =E= Intial_Stored_NGas + International_NGas_Supply(t) -
                        Stored_NGas_Consumption(t) ;

NGas_Storage_Eq(t)$(ord(t) ge 2)..
        Stored_NGas(t) =E= Stored_NGas(t-1) + International_NGas_Supply(t) -
                                        Stored_NGas_Consumption(t) ;

Base_NGas_Constraint(t)..
        Stored_NGas(t) =G= Base_NGas * Stg_Capacity ;

Stg_Cap_Limit(t)..
        Stored_NGas(t) =L= Stg_Capacity ;

NGas_supply_limit_Eq(t)..
        International_NGas_Supply(t) =L= NGas_supply_limit(t) ;

Balance_NGas_Eq(t)..
        Domestic_NGas_supply(t) + Stored_NGas_Consumption(t) =E=
NGas_consumption(t) ;

Domestic_supply_constraint(t)..
        Domestic_NGas_supply(t) =L=  0.3000E+9 ;

NGas_Tot_fuel_cost(t,tech)$(ord(tech) eq 2)..
        Tot_Fuel_costs(t,tech) =E=
Fuel_costs_Tech(t,tech)*(0.036/3.6)*Domestic_NGas_Supply(t)+
Fuel_costs_Tech(t,tech)*(1+0.05)*(0.036/3.6)*International_NGas_Supply(t);

************ Nuclear Technology constraints **************

Nuclear_Constraint_Eq(t)..
        0.8 * (CAP(t,'nuclear')) =L= 0.2* ( CAP(t,'hydro') + CAP(t,'natgas') +
        CAP(t,'hardcoal') + CAP(t,'browncoal') + CAP(t,'wind') + CAP(t,'solar'));
```

```
Max_Nuclear_Cap_Eq(t)$(ord(t) eq 18 or ord(t) eq 23 or ord(t) eq 28 or ord(t) eq
33 or ord(t) eq 38)..
        sum(s$(ord(s) ge ord(t)-4 and ord(s) le ord(t)), NCAP(s,'nuclear')) =L=
                Max_Nucl_Cap   ;

Nuclear_Availability..
        sum(t$(ord(t) ge 1 and ord(t) le 13), NCAP(t,'nuclear')) =E= 0 ;

************** Costs' Equations ****************

*____Option 1: the investment costs are paid as single amount in the investment's
year
Tot_Inv_costs_Eq(t,tech)..
             Tot_Inv_costs(t,tech) =E= Inv_Costs(t,tech) * NCAP(t,tech) ;

*____Option 2: the investment costs are annualized and spread over all the year
within the lifetime of the technologies

Tot_Inv_costs_Eq(t,tech)..
        Tot_Inv_costs(t,tech) =E= CAP(t,tech)*Inv_Costs(t,tech)*CRF (tech) ;

Tot_Var_costs_Eq(t,tech)..
        Tot_Var_costs(t,tech) =E= CAP(t,tech) * Op_hrs(tech) *
                Var_costs_Tech(t,tech) ;

Tot_Fix_costs_Eq(t,tech)..
        Tot_Fixed_costs(t,tech) =E= CAP(t,tech) * Fix_costs_Tech(t,tech) ;

Tot_Fuel_costs_Eq(t,tech)$(ord(tech) eq 1 or ord(tech) ge 3)..
        Tot_Fuel_costs(t,tech) =E= (CAP(t,tech) * Op_hrs(tech)/ Eff(tech)) *
                Fuel_costs_Tech(t,tech) ;

Tot_Ann_Costs_Eq(t)..
        Total_Ann_costs(t) =E= sum ( tech, Tot_Inv_costs(t,tech) +
                Tot_Fuel_costs(t,tech) + Tot_Var_costs(t,tech) +
                        Tot_Fixed_costs(t,tech));
```

```
Total_Exp_costs_Eq..
            Tot_Expansion_Costs =E= sum (t, Total_Ann_costs(t) +
                      Carbon_Tax(t)) ;

model EnrgCapacityPlan /
Total_Exp_costs_Eq
Tot_Ann_Costs_Eq
Tot_Inv_costs_Eq
Tot_Var_costs_Eq
Tot_Fix_costs_Eq
Tot_Fuel_costs_Eq
Tot_CAP_Eq
Balance_Dem_Eq
Nuclear_Constraint_Eq
Max_Elc_Production_Eq
Nuclear_Availability
Max_Nuclear_Cap_Eq
Annual_Elc_Prod_Eq
Tot_Emi_Eq
Decarbo_Path
Balance_Emi_Eq
Carbon_tax_Eq
NGas_consumption_Eq
Initial_Stored_NGas_Eq
NGas_Storage_Eq
Balance_NGas_Eq
Domestic_supply_constraint
NGas_supply_limit_Eq
NGas_Tot_fuel_cost
Base_NGas_Constraint
Stg_Cap_Limit /;
*putting '*' in front of the equations we can exclude them from the run

solve EnrgCapacityPlan using lp minimizing Tot_Expansion_Costs;
```

```
****************** Results Output ******************
*The values of the variables are exported to .txt file named 'EnrgCapPlan_Results'

file EnrgCapPlan_Results
/C:\Users\Administrator\Documents\gamsdir\projdir\EnrgCapPlan_Results.txt/;
put EnrgCapPlan_Results;
      EnrgCapPlan_Results.pw = 300;
      EnrgCapPlan_Results.pc = 5;

put 'MULTIPERIOD PLANNING OF ELECTRIC POWER CAPACITY' /;
put/;
put '-----------------------------------------------' /;
put/;
put/;
put 'New capacity buit in each year in MW'/;
put/;
put/;
loop ((t,tech)$NCAP.l(t,tech),
        put t.tl'      'tech.tl'     'NCAP.l(t,tech)/;
        put/;
);
put/;
put/;
put 'Total annual costs (including capital, variable, fixed and fuel costs) in Eur'/;
put/;
loop (t$Total_Ann_costs.l(t),
        put t.tl'       'Total_Ann_costs.l(t)/;
        put/;
        );
putclose;
execute_unload 'Results' NCAP;
execute 'GDXXRW Results.gdx var=NCAP rng=New_Cap!A2 rdim=1 cdim=1';
execute_unload 'Results' CAP;
execute 'GDXXRW Results.gdx var=CAP rng=New_Cap!A35 rdim=1 cdim=1';
execute_unload 'Results' Annual_Elc_Prod;
```

execute 'GDXXRW Results.gdx var=Annual_Elc_Prod rng=Elc_Prod!A2 rdim=1 cdim=1';

execute_unload 'Results' Total_Ann_costs;

execute 'GDXXRW Results.gdx var=Total_Ann_costs rng=Tot_Ann_costs!A2 rdim=1';

execute_unload 'Results' Tot_Expansion_Costs;

execute 'GDXXRW Results.gdx var=Tot_Expansion_Costs rng=Tot_Ann_costs!A42';

execute_unload 'Results' Stored_NGas;

execute 'GDXXRW Results.gdx var=Stored_NGas rng=Storage_process!A2 rdim=1';

execute_unload 'Results' Stored_NGas_Consumption;

execute 'GDXXRW Results.gdx var=Stored_NGas_Consumption rng=Storage_process!C2 rdim=1';

execute_unload 'Results' International_NGas_Supply;

execute 'GDXXRW Results.gdx var=International_NGas_Supply rng=Storage_process!E2 rdim=1';

execute_unload 'Results' Tot_Emi;

execute 'GDXXRW Results.gdx var=Tot_Emi rng=Emissions!C2 rdim=1';

execute_unload 'Results' Emi_Target;

execute 'GDXXRW Results.gdx var=Emi_Target rng=Emissions!A2 rdim=1';

execute_unload 'Results' Tot_Inv_costs;

execute 'GDXXRW Results.gdx var=Tot_Inv_costs rng=Inv_cost!A2 rdim=1';

execute_unload 'Results' Tot_Fuel_costs;

execute 'GDXXRW Results.gdx var=Tot_Fuel_costs rng=Fuel_cost!A2 rdim=1';

execute_unload 'Results' Tot_Var_costs;

execute 'GDXXRW Results.gdx var=Tot_Var_costs rng=Var_cost!A2 rdim=1';

execute_unload 'Results' Tot_Fixed_costs;

execute 'GDXXRW Results.gdx var=Tot_Fixed_costs rng=Fix_cost!A2 rdim=1';

execute_unload 'Results' Carbon_Tax;

execute 'GDXXRW Results.gdx var=Carbon_Tax rng=carbo_tax!A2 rdim=1';

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