Master's Thesis project

# Alternatives for using biomass in large Combined Heat and Power Plants


Gregers Nis Søborg Larsen
Sustainable Energy Planning & Management
Urban, Energy & Environmental Planning
Aalborg University

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**Alternatives for using biomass in large Combined Heat and Power plants**

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**Student report by:**

Gregers Nis Søborg Larsen
Sustainable Energy Planning & Management
School of Architecture, Design and Planning
Aalborg University

**Supervisor:**
Brian Vad Mathiesen

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*Gregers Nis Søborg Larsen*



Department of Development and Planning
Vestre Havnepromenade 5,1., 9000 Aalborg

Semester secretary: Dorte Holmegaard Jensen Tel. 9940 8448 - Dorteh@plan.aau.dk

**Abstract**

This study builds itself upon the discussion among professionals and academics in the Danish energy sector about the transition from mainly coal to biomass resources as fuel for large CHP plants in the Danish energy system. The report present five scenarios and a reference scenario that uses different technologies for the large CHP plants in a larger systems resembling the Danish energy system, with a series of variable renewable energy sources (VRE) capacities. The scenarios models the systems in relation to their electricity production and whether excessive power production is allowed or regulated for.

The report compares the different scenarios under the VRE capacity conditions and finds that the best suited scenario depends highly on the installed VRE capacity in the system. For all scenarios, the utility of the installed wind power declines when more than 5,000 MW installed. For scenarios presenting technologies producing both electricity and heat, flexible scenarios fair significantly better than inflexible ones. The cheapest CHP scenario combusts wood pellets, fitting the current transition trend. However, the system with grid-based syngas shows the largest reduction in fossil fuels, can use domestic fuels and have possibilities that go beyond the scope of the report

# Preface

This study has been conducted by Aalborg University master's student Gregers Nis Søborg Larsen as the main work for his master's thesis.

This student wish to thank his supervisor, Brian Vad Mathiesen, for patience and guidance throughout the project.

Throughout the report, several references are made to data files of types fitting to the softwares EnergyPLAN or Microsoft Excel.

Microsoft is a widely used licensed software in the Microsoft Office suite. Only versions newer than 2007 can open and edit the files descripted in the study.

EnergyPLAN is a "freeware" licensed software developed by Aalborg University, Department of Planning, specially designed for performing system analyses on energy systems. A license is obtained by download from http://www.energyplan.eu/.

All analysis files are available from an online file depository. The link for this depository as well as the contents of this is showed in Appendix A

# Report contents

# Fuel dependency and the right fuel choice

## 1 Historical overview of fuel crises and fuel discussions in the Danish energy sector

Since the first commercial power plant started delivering power to its customers in Køge in 1891, the Danish energy system has undergone several minor and major changes, many of these driven by fuel dependency issues. This subchapter presents these changes and their causes in a historical timeline up to the fuel discussion in Denmark today. Historical annecdotes are based on (Wistoft, Thorndahl og Petersen 1992) and (Skov og Petersen 2007)

The development of using electricity for lighting, heat and mechanical purposes started with the use of natural resources such as wind power and hydropower, but gained popularity and widespread deployment with the utilisation of using fossil fuels in the early 20th century. The production and consumption functioned as another commodity in the society, governed mainly by market powers. For the United States of America, one company even owned 90% of the oil (the far most important fuel at the time) production capacity, effectively creating a monopoly (The Linux Information Project 2004).

In Denmark the first introduction to electricity on industrial scale happened shortly before the introduction to oil a fuel, in 1857 and 1861, respectively (Gyldendal 2009) (Gyldendal 2009). The first industrialised electric production facility produced for neighbouring factory consumers in Copenhagen. The first application of electricity to power lights and heat in residential areas and for public use was in Køge, and only a few months later in Odense, in 1891.

In the first long period of the history of electricity in Denmark, the production was decentralised with many small power plants and few local CHP plants. With no national grid and no regulations on the area, there was no standard on the power, voltage or even if AC or DC was used.

The first fuel crisis in Denmark happened as an unavoidable bi-product of the First World War, even though Denmark did not actively participate. The majority of the fuel used in Denmark was imported oil, which to war related sea barriers did not reach the harbours of Denmark. The inadvertently refocused to worse solid fuels, such as brown coal and peat, mining these from the Danish heathland and undergrounds.

In the period between the two World Wars, the country again shifted its energy production towards the use of imported coal, along with oil for the growing machine transportation sector. The fossil fuels were abundant energy sources, leading to significant economic growth like in most of the West. The local electricity grids expanded into regional ones, mostly significantly with the almost total coverage of Zealand already before World War II.

### 1.1 Denmark is occupied, the energy sector is needing

Where the energy crisis in Denmark during the First World War was limited, as few people had access to electricity and power, the sudden oil crisis during the Second World War hit the country with much more force. The power in Denmark was majorly produced using British coal as fuel. The beginning of the war lead to shorter and shorter supplies, the German navy restricted shipping from England to the east. The invasion of Denmark in 1940 cut off all supplies from England. To make matters worse, Sweden abruptly shut off import through the recently laid cable underneath Øresund. The cable reopened a few weeks later, supplying much needed power to Copenhagen.

For the first time, energy production was a key sector in Danish industry and society and had to go through the war in any way it could. During the years Denmark was occupied by Germany, the Danish energy sector survived on using a variety of domestic fossil resources. In Jutland, a massive undertaking of mining brown coal started near the city of Herning. The brown coal mining mainly used cheap labour force armed with hand shovels. The only machines on the building site were mechanic belts to transport the wet coal from the mining holes to the surface, from where workers transported it to be dried.

For the transport sector, Zealand relied on German imported oil. This resource was unreliable as the German forces prioritized the distribution of fuels to the different battlefield fronts first. The German forces in Denmark had little consideration of the public, overusing reserves. Examples of clever electricity producers using blackouts and brownouts to teach German forces the value of conservatism are found throughout local history. In Jutland, the transport sector began relying heavily on the newly found resource of natural gas. Converting vehicles was possible and natural gas was used for heavy transport and freight. The public in general had no access to machine transport. Bornholm, isolated from the rest of the country, began producing power using local coal sources, the only black coal in Denmark. During the years of German occupation, the Danes started showing the first ingenuity for producing power. Students of the Askov Folk School programme for wind turbines started producing small scale wind turbines to use domestically in addition to the small power plants.

The largest source of fuel in Denmark during the occupied years was black and brown coal from Germany. Early in the occupation, the Danish government signed a treaty with the occupying forces of trading coal from Germany for cheap Danish labour forces in Germany. During the occupied years, a constant labour force of 40.000 Danish men worked in German mines, machine factories and other labour intensive industry sectors.

## 1.2 Postmodern times and rising energy demand

The energy consumed by German forces, like other commodities, during the WWII occupation of Denmark was paid for, using money from the Danish national bank. After the war ended, negative payment balances and international debt plagued the Danish government. To rectify, the government enforced the continuation of rationing in Denmark years after the war ended.

Using loan from the Marshall treaty, the Danish energy sector started development of standardisation and expansion of the electricity grid to a national level. The goal was centralisation of power production using large CHP plants in Denmark's greater cities. After some debate, the alternate current and voltage standards were decided in the industry. The Danish government had still very little influence on the energy sector.

In the post-war years, crude oil declined heavily in price, making it the most affordable fuel to import. With closing of many smaller power producers in the name of centralisation, the new big combined heat and power plants consumed oil as their primary fuel, like the whole of the Danish transport sector shifted to refined oil products.

During the late 1950ies and 1960ies, changed family relations caused sharp economic upswings in the Western economy and at the same time a new, large consumer sector. Among new working mothers in Western society, there were focus on making the family chores easier and require less work. The commercial solution to this demand was electrified tools and products for the household and kitchen in particular. The consumer electronics industry educated the public on the possibilities of electric products under such slogans as "Not just for light" and "washing without tears" with great success. This, and the continued electrification of industrial sectors and the popularisation of the refined oil fuelled vehicle caused sharp increases in energy demand.

By the start of 1973, Denmark's energy demand was met 90% of imported oil, setting the country up the biggest shock to its society seen in modern times.

## 1.3 The shock of 1973

Following a brief war in 1967, where Syria and Egypt lost territories to Israel, the two countries in collaboration engaged in a surprise offence against the Jewish state the 6th of October 1973 to win back the land lost six years before. The support from the United States to Israel during the conflict and general unhappiness in OPEC about low crude oil prices caused Arab states and later all the members of OPEC to create an oil embargo against the USA and other western countries.

While the oil embargo mostly hit the United States and only lasted half a year, the production cuts, the quadrupling in crude oil and the sudden realisation of oil dependency and how this could be weaponized hit the West by surprise and immediately caused a state of shock through the West.

I Denmark, the high reliance of cheap imported oil caused the state to impose emergency responses in energy use. Most famous (or infamous) example remembered today is the policy of not allowing any car use on Sundays to not waste fuel.

Internationally as well as nationally, the permanent rise in oil price and the realisation the correlation of political and oil price instabilities, caused the energy producers to shift strategies from oil to other energy sources produced closer to home and from more politically friendly states. For Denmark, this meant again relying on imported coal products from Britain and Germany, along with further investments in natural gas and domestic oil exploration from the North Sea, started commercial production in 1972.

In the 1950ies, Denmark was involved in an international project exploring alternative energy sources to avoid foreign reliance during wars by exploring wind power, measuring data on a rebuilt WWII era turbine in Gedser. The experiment ran from 1957 to 1962 and proved wind power uncompetitive with cheap oil, but after the 1973 oil crisis interest was renewed in the alternative energy source.

Internationally, nuclear power for peaceful energy production gained momentum in the 1960ies. In Denmark however, public resistance and failed commercialisation of the Risøe experiment along with industry resistance toward state control caused the technology to never take hold and finally in 1985 after a national election on the subject nuclear power was rejected as a usable resource for Denmark. Denmark needed to find alternatives to nuclear power for modern energy.

The rejection of atomic energy came as a part of the first national policy on electricity production in Denmark in 1976 when the government decided to postpone the decision and finally rejecting the possibilities in 1979. The electricity production of 1976 and the first law on heat production in 1979 marks the start of national energy planning, where the Danish government takes an active role in planning the energy system.

## 1.4 Climate crisis and the rise of "Green"

The theory behind human caused climate change through greenhouse gasses originates from the work of Swedish scientist Svante Arrhenius, published in 1896. The theory gained political traction as a positive effect evading a near future ice age in the early 1970ies. The threat of another ice age in the 20th century turned out no existent, instead the theory showed a threat of the use of fossil fuels on industrial scale.

The idea of humans causing harmful global warming by utilising fossil fuels gained political traction in Europe when Margaret Thatcher, then prime minister in Britain, used it as an argument for nuclear power in Britain, fuelled by disputes between the government and coal miner unions.

Throughout the 1980ies and the 1990ies, the threat of climate change, or global warming, became increasingly mainstream and confirmed by intergovernmental studies by the United Nations climate change counsel, IPCC.

The focus internationally have since shifted from policies on pure economic and energy security, to policies involving avoiding climate change and shifting the energy production and consumption to more sustainable resources. Denmark is a pioneer in this discussion, having the largest share of variable renewable energy (VRE) of any nation in the world through the country's large bet in wind power, while at the same time being at the forefront of energy efficiency policies.

# 2 Discussion on fuel source for Danish CHP and power plants

Denmark in the forefront of using VRE in the electric system through the country's determent use of wind power. Of the total energy consumption in Denmark, renewable energy produces 25% as of 2013 (Danish Energy Agency 2014).

Variable renewable energy sources produces, as the name suggests, energy with variable capacities, uncontrollable for the user. Other energy sources in the system needs to balance the VRE capacity to constitute a complete and reliable energy system. In the Danish energy system, this electricity capacity consists of power plants and CHP plants of varying size, ranging from fast acting small systems of only few megawatts peak capacity to large CHP plants with capacities upwards to 800 MW electric capacity (DONG Energy n.d.).

The current generation of CHP and power-only plants uses fossil fuels. Smaller plants largely uses natural gas as the primary fuel, while the dominant fuel type of larger CHP plants and power plants is coal. Some smaller plants uses biogas, derived from local farming bi-products. Many plants have production capacity that produces energy from oil, largely left over from the days of cheap abundant crude oil in the 1960ies, mostly in backup boilers for district heat production. Across the sizes and types of plants, the greener alternative, biomass, replaces solid fossil fuels. Biomass for combustion exists in many form and qualities. The most popular replacement form is premade wood pellets, which in combustion quality emulates coal the most.

## 2.1 The argument for biomass combustion

The climate related argument for firing with biomass is essentially the argument for the "greenness" of biomass. Biomass, meaning combustible plant material is deemed sustainable because the plants in their lifecycle absorbs carbon dioxide. Plants thereby is the most obvious negative production part of the carbon cycle. The carbon dioxide emitted during energy production from biomass is carbon dioxide the plant stored through its lifetime and thereby does not emit new carbon dioxide, unlike fossil fuels.

In the question of energy security, biomass have several advantages over fossil fuels and coal in particular. The amount of coal in the Danish underground is little and the quality poor. All coal is therefore imported, mostly from our neighbouring countries, Britain and Germany. Denmark have long tradition with farming and is a modern producer of crops and its derived products. Compared to other countries, agriculture uses a large share of the Danish land surface and the soil is nutrient-rich compared to many other countries. Denmark's ability to produce agriculture-derived biomass is rich. Combustion separates and excludes many of the nutrients in biomass in the form of ashes, usable to fertilise the earth. The biomass derived from agriculture bi-products are low-grade, eroding the energy facility due to acids, producing many unwanted bi-products and have low energy content per mass. The preferred biomass for combustion is heavy sorts of tree, dried to as little water content as possible. Much of the forests in Denmark was lost due to preparation for agriculture, giving low possibilities for self-sufficiency. Instead, the majority of biomass used in the Danish energy sector is imported wood pellets.

## 2.2 Are wood pellets in reality sustainable?

The argument for using biomass is the emitted carbon binds to replacement plants during their lifetime. Using that argument, biomass is $CO_2$ neutral as long as the sown replacement plants are similar to the biomass harvested.

There are challenges to this statement for different reasons. The sustainability requires the harvested biomass to be renewed. This replacement living biomass has to achieve the same age as the biomass used and grow to the same energy content as the combusted biomass, assuming no process loss. Wood pellets per energy unit emits more $CO_2$ than coal. This means the replanted trees must grow older than 38 years for the wood pellets to be less $CO_2$ emitting than coal and far longer to be sustainable. The "sustainable" biomass used in year 2014 is then only less $CO_2$ emitting than coal in 2052. (Bredsdorff 2011)

The process losses for biomass are high, especially for the heavily processes wood pellets. The process of making sustainable wood pellets includes harvesting, milling, drying, transporting, grounding the pellets before firing and replanting, the latter happening either by plantation or naturally. During this process, upwards of 20% of the energy is lost (using 20% of the energy content in the process) before combustion. A third of that is transport. The process of producing wood pellets relies on fossil fuels, where a third of the process $CO_2$ emissions are from transport, mostly shipping. In most wood pellet producing countries, the drying process relies on either coal or natural gas. (Wittrup 2014)

The harvesting of the biomass for wood pellets leaves the roots in the ground. These roots contains a large share of the tree's $CO_2$ content, which emits when the tree roots rots. Replanting the tree to live the same age as the harvested one does not account for the tree root $CO_2$ emissions. This criticism of existing analyses predicts that sustainability for wood pellet biomass occurs only after 500 year. (Djursing 2014). On the other hand, removing the roots from the ground during harvest removes important nutrients to be recycled in the system, causing soil depletion. In the use of straw for biomass, this tendency shows when removing all biomass instead of letting it rot on the fields (Bredsdorff 2011).

The age of the trees at the time of harvest and the importance of that too is under discussion for the sustainability of wood pellets. There is doubt whether trees continue to absorb $CO_2$ during the full life span from acorn to natural death or whether the vast majority of this $CO_2$ absorption occurs during the growing phase of the trees' lifecycle. If the trees absorb during their full lifecycle, harvesting happens prematurely and absorption capabilities are lost. If the trees stop absorbing $CO_2$ after their growing phase, the harvesting of the tree is neutral as the replacement tree can absorb again, ignoring process losses.

In the case of any biomass, harvesting and replacing one-to-one in terms of weight, type and age does not make the fuel sustainable, simply due to process losses. Other particulars of the carbon cycle of trees, and how this matters to biomass sustainability, is under debate. The carbon lifecycle for other, lower grades of biomass are shorter due to the shorter life span of the plantation and the lower process losses. If replacing plant technology with types that are able to utilise wet, low-grade biomass better, the fuel would be, if not fully, then more sustainable than wood pellet use.

# Research design

The framework for this report builds upon the discussion taking place among professionals and academics about the transition from coal to wood pellets, briefly explored in Section 2.2. The bases of the discussion and the technological transition is the dependency and climate related issues with fossil fuels used in the energy sector, such as coal. Coal is in the core of this discussion, being the primary fuel for large power plants and CHP plants in Denmark. From the political standpoint on climate change in Denmark and the country's image as a leader in renewable energy and energy conversion, fossil fuels needs expulsion from the Danish energy system within a foreseeable time frame.

From a holistic perspective on the Danish energy system, some solutions make makes traditional plant production of energy redundant, changing the energy system entirely. Under the existing institutional structure, the fossil fuels needs replacement in similar production facilities rather than total system change in the shorter term.

The discussion of renewing these production facilities mainly focuses on the fuel change from coal to wood pellets, which is technically similar in in the handling process and combustion for the domestic energy producers in Denmark. This discussion, most evident on the dedicated forum for the issue on the online portal for Danish engineers, primarily focuses on the climate effects of wood pellets and the scientific justification of replacing coal with wood pellets as fuel for large power producing units (Ingeniøren A/S 2014).

The focus on replacing coal, and to a minor extent natural gas, with wood pellets without any other alternatives explored creates somewhat of a Hobson's choice for a large part of the Danish energy sector. The decision is to either accept the transformation towards using wood pellets or staying with the current fuel variety, choosing nothing at all. As there are multiple options, both for the system and the large power producers as an entity, this report seeks to rectify such unilateral discussion.

## 2.3 Theoretical approach and scope of report

This report seeks to create Choice Awareness for its readers in the discussion of exchanging coal with other, arguably more sustainable, fuel sources. Choice Awareness, in the context of this study, represents providing theoretical evidence for the existence of more than one equally realisable choices to infuse to the collective perception of the discourse. This fits the general definition provides by (Lund, Renewable Energy Systems - The Choice and Modelling of 100% Renewable Solutions 2010).

To further the discourse of replacing fuels in large power plants and CHP plants, this report takes on the scope, which centres the discussion. The scope of the report, like the discourse presented in Section 2, is the transformation of using biomass fuels in the large energy plants in the Danish energy system. The report seeks to find alternatives to both the non-choice of utilising business-as-usual fossil systems and the utilisation of wood pellets in existing technologies. This report does not utilise theories of Radical Technological Change, also presented in (Lund, Renewable Energy Systems - The Choice and Modelling of 100% Renewable Solutions 2010). Radical Technological Change examines the broader change of elements constituting technology as a societal term, where this reports uses a much narrower definition of technology. The technology changes proposed in this report seeks to create minimal organisational and institutional change outside the implied subsector. Changing of technique for such a large sector as the large producer plants of Denmark always generates some institutional change, if only limited. This however, is outside the scope of this report.

The report use the Reference year of 2020 to compare the different technology alternatives. This yearly scope covers the timely area of when many of the large CHP plants in the Danish system are due for replacement or upgrading. Also the year is in the foreseeable future and forecasts are there deemed more reliable and accurate than for forecasts for the further future.

The report uses analyses that builds and compares scenarios. The scenarios are built in such a way so the scenarios are evaluable compared to the business-as-usual reference. These different technology scenarios are comparable with each other and the report does so in a dedicated chapter. The different scenarios and the scenario comparison performs feasibility studies of the different technologies in similar systems. The feasibility studies tests the mutual viability of the different scenario systems. By comparing the feasibilities of the different scenarios under equivalent conditions, judgements of the scenarios are made, individual and comparative.

This report takes an atomistic framework to the technological change in the energy sector's large producer plants. The report seeks to present alternatives under equivalent conditions throughout the analyses. The large energy plants in Denmark are part in a large holistic energy system, where any changes in one part of the systems ripples through the other parts. In order to test under equal conditions, the analyses in this reports tests technological alternatives in a larger system-wide context. All other parts of the system remain unchanged, apart from influences by subsector changes.

## 2.4 Research question

**What are the alternative technologies usable in the large CHP plant sector in Denmark, how will they act in the system and which is best suited for Denmark's future?**

### 2.4.1 Technology specific questions

- Which technologies are usable for to replace the current large CHP technologies?
- What are the choices in biomass fuels for technologies?
- How will the technologies act in the energy system?

### 2.4.2 Energy system questions

- How will the energy systems of alternative scenarios act compared to the reference?
- Do any technologies perform better than the reference?

### 2.4.3 Scenario specific questions

- Which of the scenarios will save the most fossil fuels?
- Are any of the alternative scenarios less costly than the reference?
- Which reference utilise VRE sources the best?

## 2.5 Research methodology

### 2.5.1 Literature review and company specific information

The information about the different markets and technologies will predominately come from relevant governmental institutions, energy companies and academic institutions. The data received from these sources is reviewed and compared before use, as are the sources judged for relevance and professional reputation. If possible, the report will use data from the Danish Energy Agency.

### 2.5.2 Yearly production system methodologies

The future production of irregular electricity supply acts like the current level, adjusted to scale. The report uses two distinct system methodologies to judge technology alternatives in the Danish energy system. These system analysis methodologies are dubbed Open system and Closed system and differentiates in how the systems react to excess electricity production.

### 2.5.3 Analysing alternative technologies

The report uses the methodology of building different system scenarios to analyse, compare and judge different technologies. The scenarios are built for full energy systems from a reference and the technologies are modelled on equal terms in the scenarios.

### 2.5.4 Modelling of scenarios

The report uses a primary and a secondary model tool. The primary model tool is the software EnergyPLAN, developed at Aalborg University and meant for modelling full energy systems of varying size. The study uses the EnergyPLAN model software to model the different energy system scenarios. EnergyPLAN models on an hourly basis.

The second modelling software used in the study is the data handling software Microsoft Excel. EnergyPLAN provides an output for each scenario and system in numeric, mostly yearly values for this study. The study uses Microsoft Excel for further analyses, such as creating graphical representations of the EnergyPLAN output data, comparison and analyses comparing single entities between the scenarios.

### 2.5.5 Hourly distributions

The study heavily relies on the EnergyPLAN library for hourly distributions of consumptions and productions of different entities and subsectors in the scenario energy systems. The atomistic scenario relations means most sector productions and demands are shared between the scenarios.

### 2.5.6 Technology properties

The available technologies for the system acts very differently and must be treated as such. The technologies are analysed on equal parameters that they all have in common. These parameters show the usage of the individual technologies and is not based on comparison with other technologies. The results from the properties are used for fitting the different technologies into the systems of future scenarios. The technologies compares with no considerations to the market specific powers in the current Danish energy system. The technologies are analysed and judged mainly on their technical performance.

While the subject of this report analyses are highly theoretical, the technologies used in analyses are commercially available. The report uses datasets from impartial authorities in Denmark to characterise technologies used.

# Reference scenario for the Danish energy system

As described through Chapter 1, the Danish energy system has gone through evolutionary and revolutionary iterations. The current energy system, while still dominated by fossil fuel technology, heavily prefers renewable energy, both in the Nordpool marketplace for selling electricity and investments in installing new capacity.

The reference energy system is modelled on the current energy system in Denmark, based on the different consumption and production patterns for technologies. The reference system is analysed hourly.

The Reference use updated components and system wide features from the CEESA analysis headed by Aalborg University. Demands, productions and distributions for the different sectors uses the Reference from this system-wide analysis for Denmark (Aalborg University Department of Planning 2011).

## 2.6 Reference energy system components

The reference electricity system is based upon the Danish electricity system anno 2012 with hourly data for consumption and production. The Reference system uses data from the CEESA project, which is based on the real energy system in Denmark, but is corrected for a climatic normal year and does not include import or export. The exclusion of import/export is due to the system analysis methods, which scope is limited to the national energy system as an isolated system.

The electricity demand is in the reference system is at a stable level of 35.62 TWh/year, corresponding with the national electricity demand in Denmark in the early 2010s. The energy consumption in the system is irregular, but follows day-by-day patterns. Figure 1shows the hourly distribution of the electricity consumption in the system.

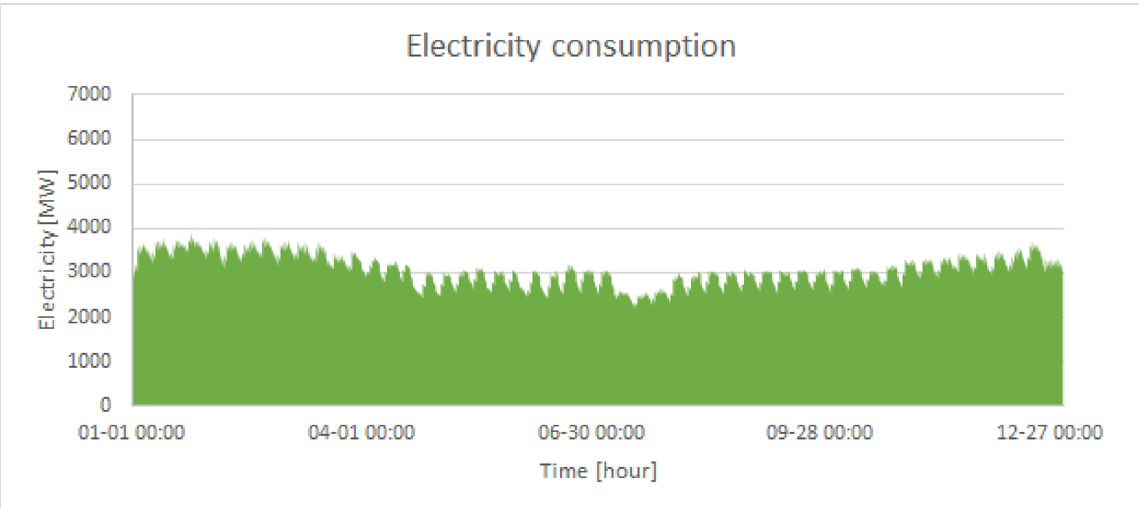


*Figure 1 - Hourly electricity consumption in the Reference scenario*

The reference system has different technology producers of electricity, some VRE, some through combustion. Most of the plants for producing power is CHP plants that produces heat as well. In Figure 2, the stacked area graph shows the hourly electricity production from the different sources.

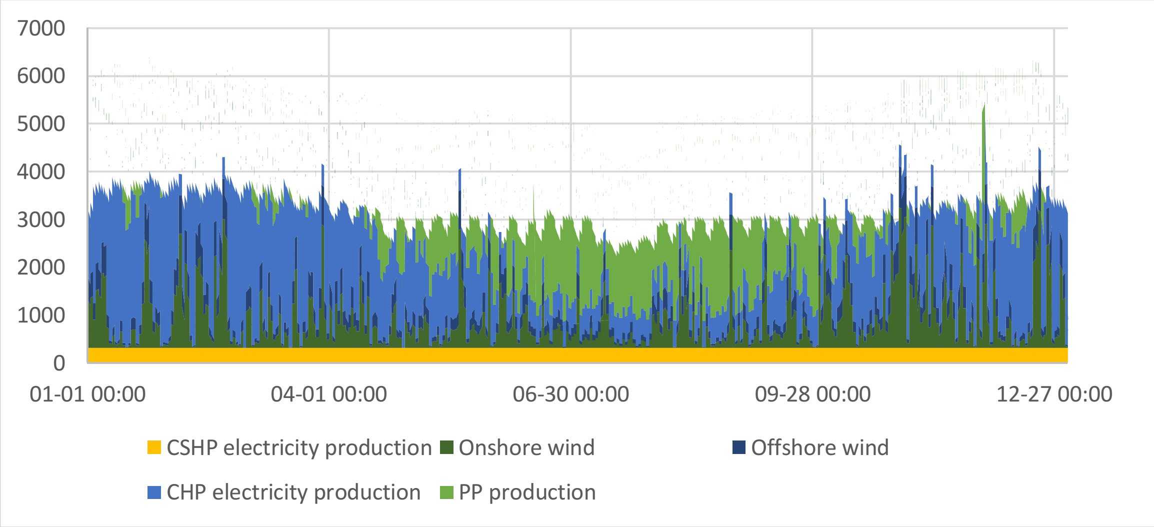


*Figure 2 - Electricity production in the Reference system from different sources*

The Reference scenario assumes no use of Photovoltaic cells, even if these exists in the Danish energy system on a small scale. Figure 2 shows the irregular variability of the VRE sources, with the production from wind (offshore and onshore combined) producing anywhere between 0 MW and well beyond the electricity demand of the scenario. On midnight 31-10 for instance, the combined production from wind resources reach more than 3800 MW while the demand is less than 3,000 MW.

The heating system in the Reference scenario there are multiple heat sources, which is divided into district heating for communities and individual heating for single housings. The heating demand occurs mostly during the winter months, as the system assumes the temperature variations of the Nordic climate. There is no cooling need for the summer period. Figure 3 shows the heating demand delivered as district heating and individual heating on an hourly basis.

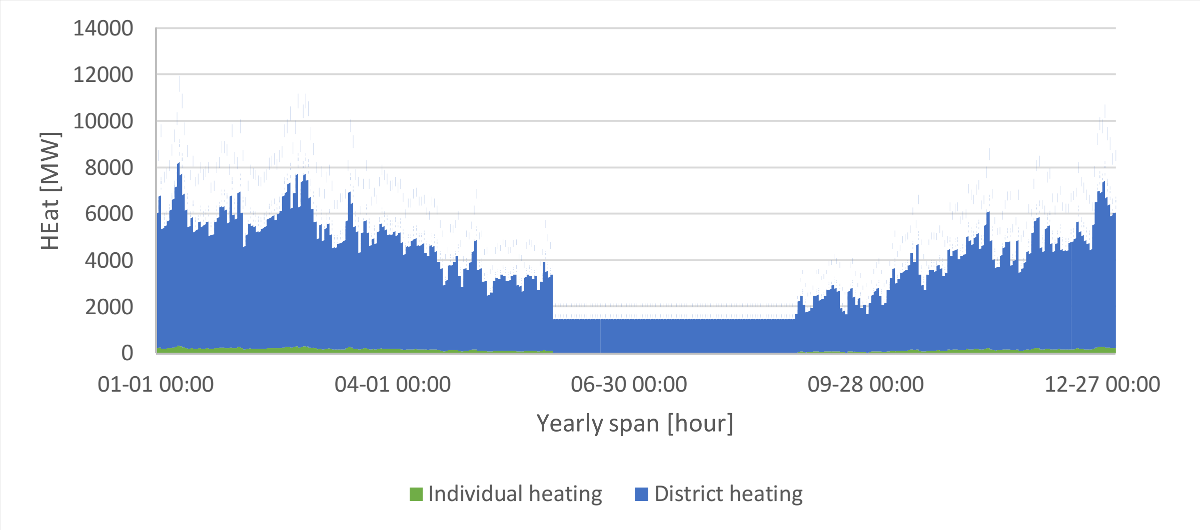


*Figure 3 - Hourly heating demand of reference system*

A number of sources in the reference scenario delivers the heat demand, both for district heating and individual heating. As shown in Figure 3, the majority of delivered heat is in the district heating networks, where the production capacity mostly is in the form of CHP plants, utilising waste heat from the electricity production to produce heat. Figure 4 shows the yearly heat production in the Reference scenario from different sources.

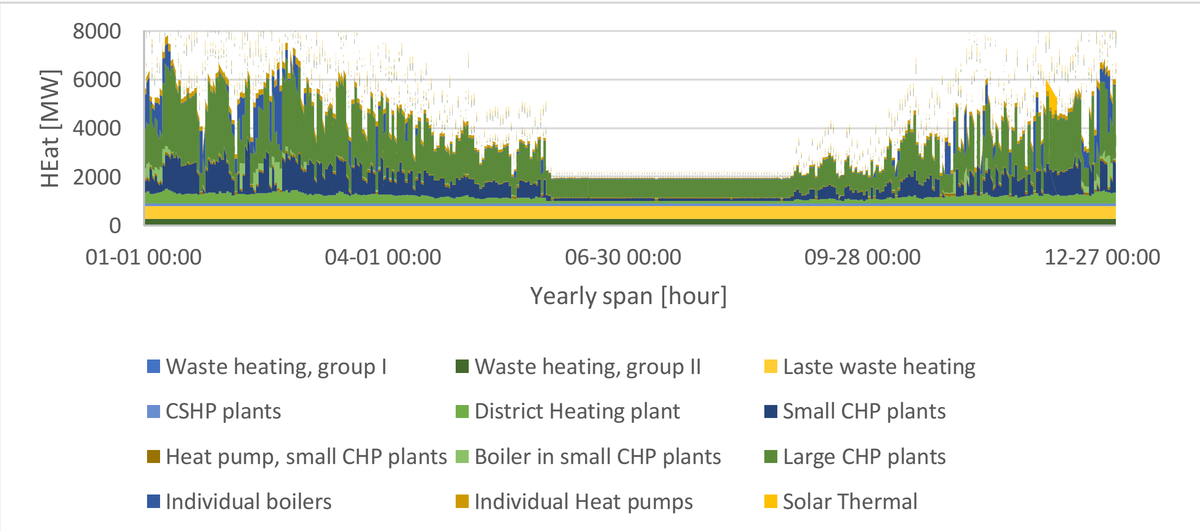


*Figure 4 - Heat production in the Reference scenario*

There are vast hourly differences between the heat demand in Figure 3 and the heat production in Figure 4. This is possible due to short-term heat storage in both individual and district heating systems.

## 2.7 Regulation strategies for the reference systems

The report presents technical optimisation strategies in the modelling with interaction between the heat and power sectors. The model aims to balance both electricity and heat demands on hourly basis, with the ability of reducing the production from CHP plants to stabilise the electricity grid. In all reference models, VRE have highest priority, even if its high production causes ramping losses for CHP plants.

At least 10% of the electricity production comes from stabilising power units, meaning units that can quickly ramp their production up or down to provide stabilisation. For systems with the technologies used in the Danish system, such large share is a conservative setting. The influence of this on the system is shown in Appendix B in Section 10.1

Large power plants based on turbine technology (instead of engine technology, often used in smaller CHP plants) need a minimum running capacity to maintain pressure. The large-scale power plants therefore always deliver a minimum capacity to the system, needed or not. The minimum capacity in the system is set as 450 MW. The sensitivity effect of this is shown in Section 10.2 in Appendix B.

The Reference system assumes no import/export to other systems. The systems regulates to avoid energy deficiency as well as excess production of electricity (for short terms, heat is stored). If electricity is either deficient or in excess, the model states this. In the Reference system, deficiency does not occur, but excess electricity is stated as "Excess Electricity Production (EEP)". Figure 5 shows the electricity production divided into consumption and EEP.

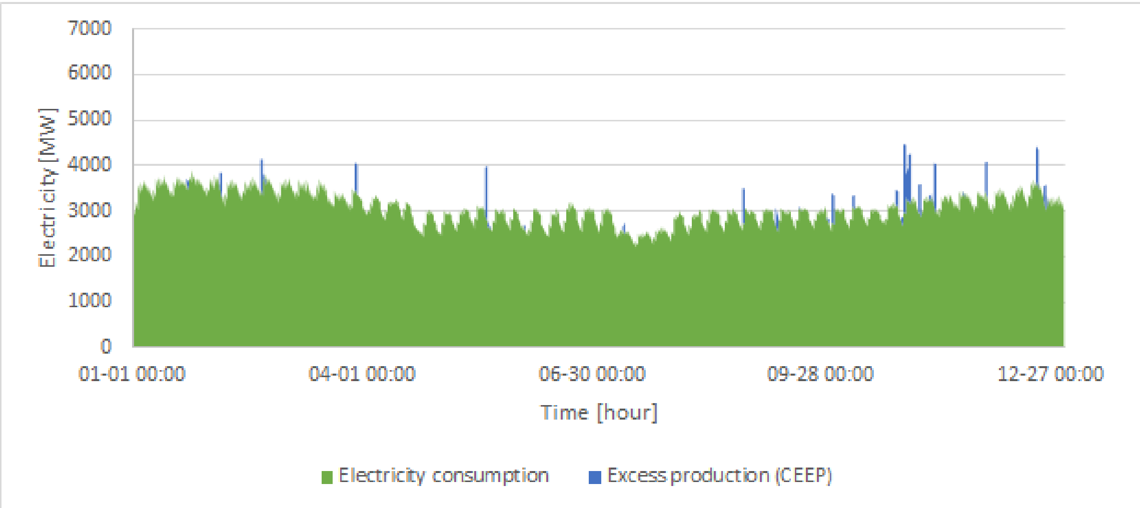


*Figure 5 - Electricity production divided into consumption and excess production*

EEP in the Reference system occurs in hourly "spikes" each only lasing few hours. A comparison between Figure 2 and Figure 5 shows that EEP occurs in hours where VRE production almost or entirely exceeds the electricity demand in the system. For the system in the current form, EEP is expected to increase with added VRE capacity.

## 2.8 Adding VRE capacity – Open system

For adding VRE capacity to the system, two different system operation strategies are analysed. The general methodology of the first, Open system, is described here along with its effect to the Reference scenario. The other, Closed system, is described in Section 2.9.

Open system analysis seeks to analyse the excess electricity production (EEP) of the system under different VRE capacity conditions. The system in the analysis method therefore does not regulate for EEP. In real systems, excess electricity capacity is a threat to the systems, causing instability and, in worst case scenarios, blackouts.

The Open Reference system assumes stepwise sub-scenarios with added VRE capacity in the system while other components remains unchanged. The added VRE capacity in the model is comprised only of offshore wind power. The capacities of onshore wind power as well as non-VRE sources stay. While testing the influence of adding VRE capacity to the system, the assumption of onshore wind capacity saturation the reference source of 2,934 MW holds true, so no new capacity is added while the current capacity is stable. The added VRE capacity is in the form of offshore wind power. The general method for doing this in EnergyPLAN is shown in Appendix C in Section 11.

The added VRE capacity in the Open Reference system model is stepwise between the current level from Reference scenario in Section 2.6 to cover the yearly electricity demand in its entirety. Figure 6 shows the excess electricity production by adding VRE in the Open Reference system.

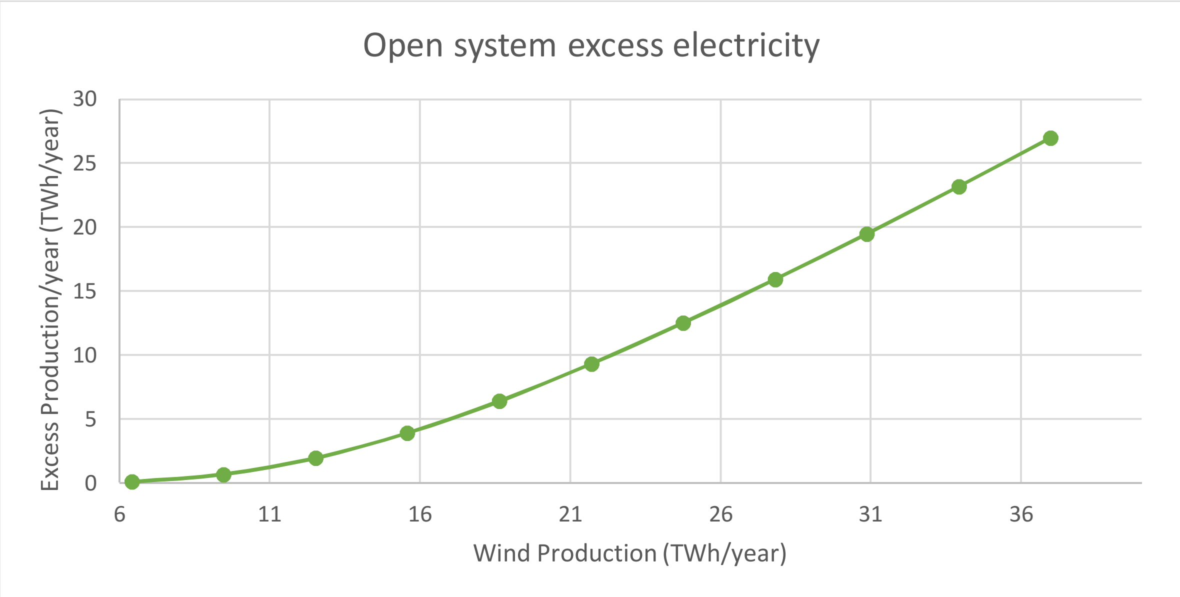


*Figure 6 - Excess electricity (EEP) in the Open Reference system with integration of VRE sources*

Figure 6 shows the effect of added VRE in terms of producing excess electricity on a yearly basis. With low further implementation of VRE, excess electricity develops slowly. VRE capacity beyond 18 TWh (~50%) causes linear development of EEP, showing the exhaustion of regulation capabilities within the Reference system. As an alternative measure, the yearly EEP is found when allowing the system to regulate for hourly EEP by replacing CHP production with boilers in the system, limiting the CHP produced power. The alternative shows very little improvement, with only maximum 7.2% less EEP or maximum 0.09 TWh less EEP per year. The report no further refers to the alternative base scenario and the non-regulated is referred to as the Open Reference system.

## 2.9 Adding VRE capacity – Closed system

The analysis of the Closed energy system is built upon the framework of the Open energy system. The stepwise addition of VRE are under the same conditions, with the added capacity being solely offshore wind power and the maximum added VRE capacity corresponds to the yearly demand in production. Where the systems separate is the relation to excess electricity production. In the Open system described in Section 2.8, excess electricity production is accepted as is, assuming the system can manage the load.

The Closed system avoids EEP where needed by direct regulation. The model regulates EEP by, in order, replacing small CHP capacity with boiler capacity, replacing large CHP capacity with boiler capacity and finally limit the capacity of the VRE in the system to avoid curtailment. The method used in EnergyPLAN to do this is shown in Section 12 in Appendix C.

Using curtailment regulation to limit excess electricity production, the system shows boundaries for VRE self-sufficiency. Adding more VRE capacity may not increase the share of yearly VRE energy consumed in the system. Due to regulation restrictions of existing power plant technologies, yearly share of curtailment for VRE rises per-capacity added. Figure 7 shows the use of non-VRE primary energy supply (PES) with further integration of VRE energy sources. The figure compares non-VRE PES to the capacity production potential of the integrated VRE sources. Non-VRE PES is generally fossil fuels.

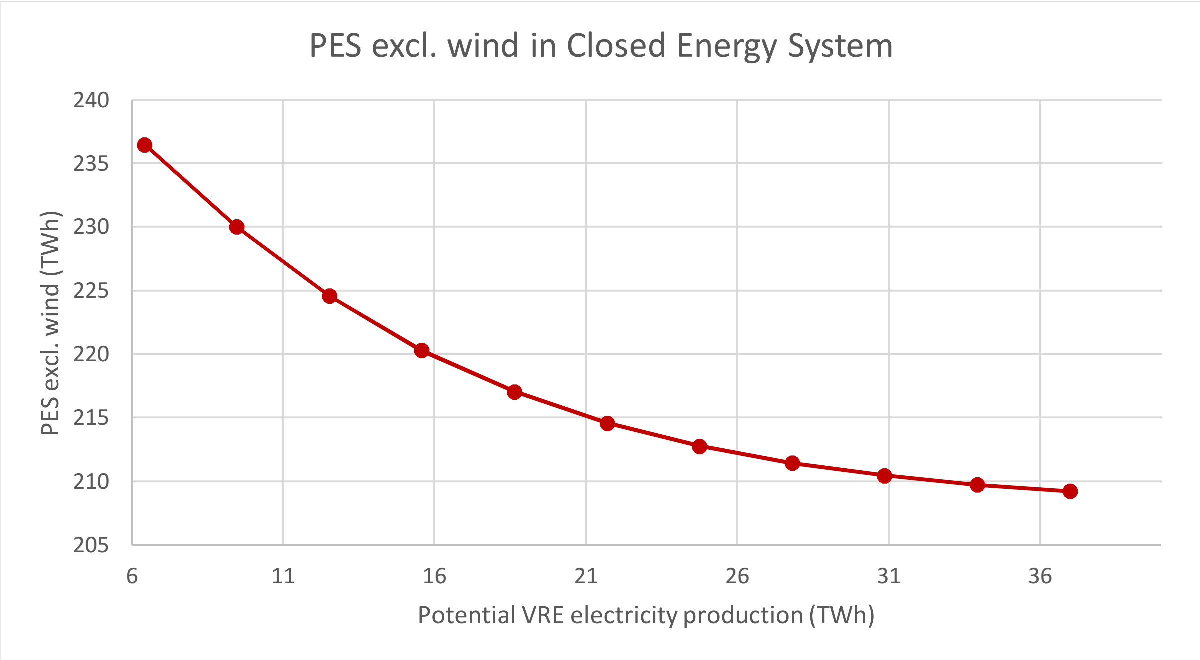


*Figure 7 - Use of non-VRE primary energy supply with further VRE integration in Closed Reference system*

Figure 7 shows the relation between VRE implementation and fuel savings in the Closed Reference system. For high implementation share of VRE, the use of non-VRE fuels are present in the system, decreased by ~12% from the current Reference system.

The Closed Reference system regulates VRE curtailment by shutting off wind turbines. Using this methodology, fuel-free energy production is lost. Figure 8 shows the regulated electricity production compared to the unregulated potential production.

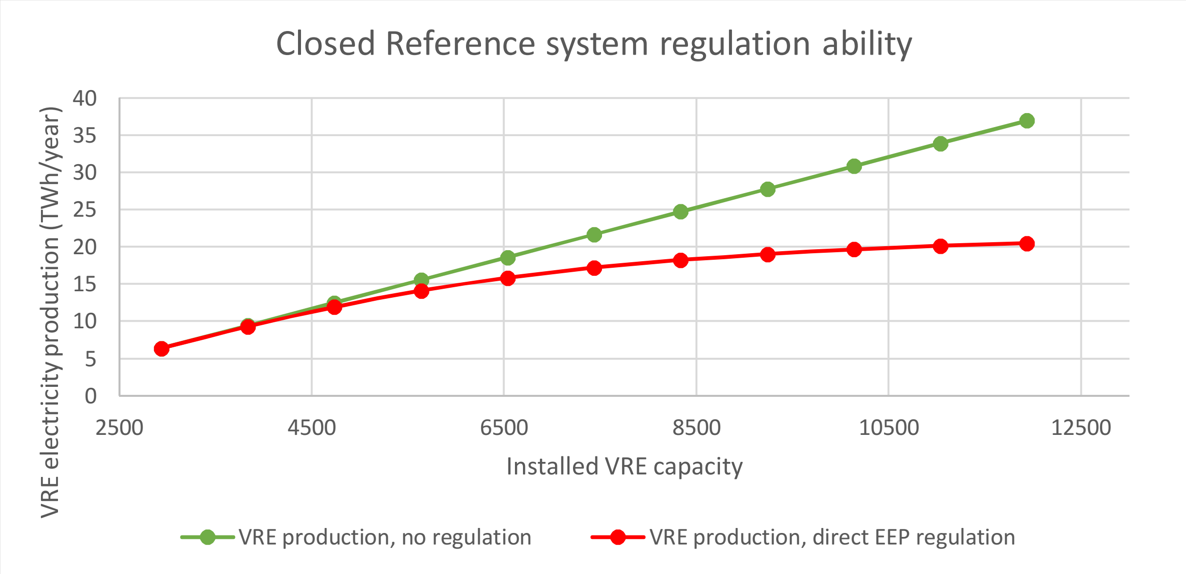


*Figure 8 - Closed Reference system VRE production compared to potential*

The analysis method of Closed system seeks to limit excess electricity production. With the conservative production share of 0.1, no excess electricity occurs during the course of a year with any tested implemented VRE capacity.

## 2.10 Framework for future technologies

The Open and Closed analyses of the Reference system shows the limited regulation ability of the existing system with more VRE implementation. The Open system analysis methodology shows the overproduction of the system with no excess electricity production, while the Closed system shows the lost fuel-free energy potential and the savings in fuels when the VRE production is EEP regulated.

The technologies analysed in this report seeks to improve VRE implementation in the system. The sought function for the analysed technologies is to regulate the system by limiting excess production of electricity in VRE peak hours. The method for doing so depends on the individual technologies. All technologies in this report are analysed with both Open and Closed analyses methods.

Using the Open analysis method, the aim for the technologies is to decrease excess electricity production. Where the Open Reference analysis shown in Figure 6 increases linearly with higher implementation of VRE, analysed technologies aims to decrease the slope of this development. The more successful the technology, the lower the EEP of the Open analysis.

In the Closed analysis method, the amount of PES from different energy sources is analysed when regulating specifically for EEP. The amount of non-VRE PES, shown in Figure 7, when implementing VRE sources approaches stability still above 200 TWh/year, with a lesser negative slope per capacity VRE added. When implementing new technologies, the natural boundary of VRE in an EEP regulated system seeks to be lower. A consequence of this is a further utility optimisation of the installed VRE capacity, approaching its non-regulated limit as shown in Figure 8 for the Reference system

# 3 The technology of Circulating Fluid Bed gasification

Circulating Fluidised Bed gasification (CFB) is a technology able of producing synthetic gas from low-grade biomass and biodegradable waste as well as coal products. The section relies on multiple technical sources for explaining the CFB technology. If no other source is specifically mentioned, the sources are (Babcock & Wilcox Power Generaon Group, Inc. 2006), (VTT 2014), (Chalmers University of Technology; Foster Wheeler energia oy; CeRTh/IsFTa; VTT TechnIcal Research 2006), (VTT Technical Research n.d.)

## 3.1 Overview of technology

CFB technology is a mainly experimental technology that focuses on producing synthetic gas from a variety of solid carbon materials, ranging from low quality fossil fuels to high grade biomass. The technology bases upon the principles of gasification.

Gasification is the process of superheating solid or fluid materials while controlling the input of oxygen to avoid combustion. The carbonaceous material then thermochemically converts into synthetic gas (also known as syngas or, if made from organic resources, producer gas). While there are several methods for gasifying carbonaceous materials, this section focuses on the process of fluidisation. Figure 9 - Schematic of Circulating Fluid Bed plant (BFB subtype) shows a schematic for a Circulating Fluid Bed plant.

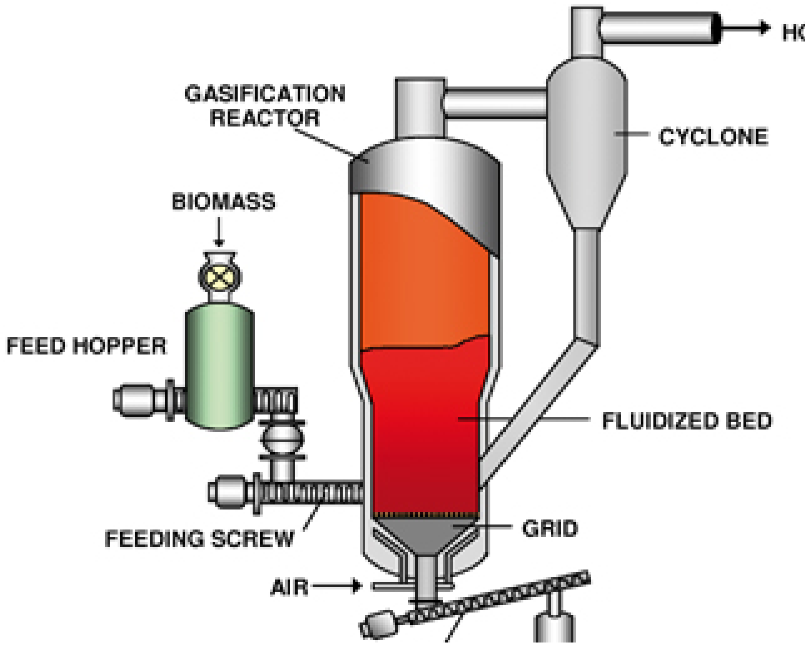


*Figure 9 - Schematic of Circulating Fluid Bed plant (BFB subtype) (Andritz AG 2014)*

Fluidised Bed gasification, using fluidisation as the name implies, uses a mixture of heated air and steam, heated by a separate combustion process, to fluidise the carbonaceous material. The fuel material is granulised and fed into a superheating chamber where it lies on the base through which the air/steam mix is flowing minimally through the material. The flow in superheated conditions causes the material to split into simpler carbon molecules which take on a fluid or steam like state and separates particles. Ashes fall through the bottom of the reactor. If the flow of air/steam flows slightly faster than the minimally possible, the reaction within the reaction chamber assumes a state resembling bubbling, making the plant a bubbling fluidized-bed (BFB) plant. The BFB reactor improves gasification of wet materials such as low-grade biomass and some waste.

The synthetic gas escapes the reactor through the top, with some particles mixed in. These particles are separated from the syngas in a (or a series of) cyclone, sending the particular matter back into the reaction chamber.

The now scrubbed synthetic gas is lead through the outlet to further application.

## 3.2 Advantages of CFB technology

Compared to combustion technologies CFB (and its variations, such as BFB) offers a much larger fuel flexibility. The circulating fluid bed technology can utilise a wide range of fuel with largely only two criteria: The feeding material is carbonaceous and is either fluid or liquid. This opens the technology for co-firing fossil and biomass materials as well as using feeding fuels of inferior quality for combustion. Notably is the ability to converting landfill waste and wet biomass.

Combusting wet biomass and low-grade waste materials causes efficiency loss due to unnecessary heating of water into unused steam. In CFB reactors, steam reacts to form hydrogen to the synthetic gas. Efficiency for CFB based CHP plants is shown in Table 1.

Using gasification in place of combustion of solid fuels has several other advantages; both related the gasification process and synthetic gas as a product. The CFB gasification separates particles much better than combustion methods, separating 99.7% of particles in the process, so only about 2.3% is emitted. The gasification process utilises most of the carbon monoxide and carbon dioxide for the synthetic gas. The CFB process, even if using low-grade fossil fuels makes for a very clean, efficient and flexible power production.

In this report CFB is used only for locally producing power and heat, utilising synthetic gas as fuel. Synthetic, like other gasses can be utilised for making liquid fuels such as methanol. Synthetic gas can also, long term, utilise the existing gas network to replace natural gas.

## 3.3 Disadvantages of CFB technology

Although the feeding fuel for CFB reactors are solid materials, the technology is not flexible in production output, due to process constraints within the reactor. Where combustion technologies of solid fuels have limited, but some possibilities for ramping its power production, the adjustment time for CFB are too long for any balancing purposes. The CHP production side of the plant, combusting syngas for power and heat, can in theory ramp. In reality, the constant production of synthetic gas prevents this. The technology is power adjusted rarely and only for constant output for long periods.

## 3.4 Key numbers for analysed CFB technology

The technology of Circulating Fluid Bed technology is analysed under different conditions using technology data from the Danish Energy Agency. Table 1 shows the technology data for CFB reactors when combined with either a combination of an industrial gas boiler and a combined cycle gas turbine or a gas boiler/Spark ignition gas engine.

*Table 1 - Technology overview for CFB energy production (Danish Energy Agency 2014)*

| Technology and fuel | | |
|---|---|---|
| Input | Output | Capacity |
| Biomass, coal, char etc. | Electricity (through syngas combustion) | 1 MW-800 MW (fully scalable) |
| **Efficiencies** | | |
| | Electricity | Heat |
| CHP production - Engine | 41% | 60% |
| CHP production - Gas turbine | 41% | 60% |
| Heat production - Boiler | 0% | 100% |
| **Economic data** | | |
| | Specific Investment cost (MDKK/MW) | O&M cost (DKK/MWh) |
| CHP production – Engine/boiler | 13.055 | 86.536 |
| CHP production - Gas turbine/boiler | 14.547 | 36.554 |

The two CHP production methods shown in Table 1 both are known systems for utilising natural gas based CHP production. While the CFB reactor has no method for regulation, the utilisation of the produced syngas can either be used to produce power and heat or just only, dependent on need. Likewise, the CHP plant technologies described in Table 1 regulates quickly. With the lack of demand-based regulation of the CFB reactor, these combinations offer flexibility for the energy production.

# 4 Using CFB for direct infusion in CHP model

Heat and power production using Circulating Fluid Bed technology acts significantly different from common CHP plant technologies to require tailored modelling methods. The modelling methodology for Circulating Fluid Bed and gas turbine produced heat and power is detailed throughout this section.

Due to limitations in the utilised EnergyPLAN modelling software, the modelling method for CFB produced heat and power comprises of different production scenarios and production distribution, detailed in Sections 4.2 and 4.3.

## 4.1 Basic energy system for CFB integration

To integrate CFB-based heat and power production the Reference scenario in Section 2.6, the scenario runs a minimally changed model from the Reference scenario. The scenario is reminiscent of the Reference scenario on most inputs, including all demands and most producers.

From the Reference scenario in Section 0, three areas changes in the CFB scenario. In the basic CFB energy system scenario, there are no offshore VRE capacity. The scenario keeps the basic onshore VRE capacity of 2,934 MW from the Reference scenario and remains unchanged through all analyses. This is to compare the direct impact of exchanging conventional CHP plants with CFB-based plants. The basic CFB energy system has no industry based heating or power, explained in the next paragraph.

The analyses of the Reference scenario in Section 0 accounts for industrial produced heat of 115 MW and 109.3 MJ/s heating with constant capacity, producing 1.01 TWh electricity and 0.96 TWh heat per year. The model regards The CFB-based CHP plants as industrial plants due to model constraints in EnergyPLAN. To accommodate the use of only biomass in the CFB-based CHP plants, other industrial sources are removed in the CFB scenarios.

The different CFB scenarios removes the capacity of conventional large CHP plants and replaces it, dependent on scenario, with CFB-based capacity. In the different CFB scenarios there are no large CHP plants producing with conventional means. The scenarios keeps capacity from larger condensing power plants. The capacity of these plants depends on scenario. Likewise, the CFB scenarios keeps the large capacity of 7978 MJ/s of conventional large boilers in the system.

## 4.2 Production distributions for CFB syngas production

CFB reactors have no method of regulating for demand, explained in Section 3.3. The system are able to perform capacity adjustments for lower or higher fixed production. This adjustment takes too long for any regulation purposes, but not too long for seasonal optimisation. Less heat is required during the Danish summer, as well as less electricity. In this report, different seasonal capacity distribution profiles are analysed. Figure 10 shows the different production distribution profiles. Changing between profiles in EnergyPLAN is shown in Section 14 in Appendix C.

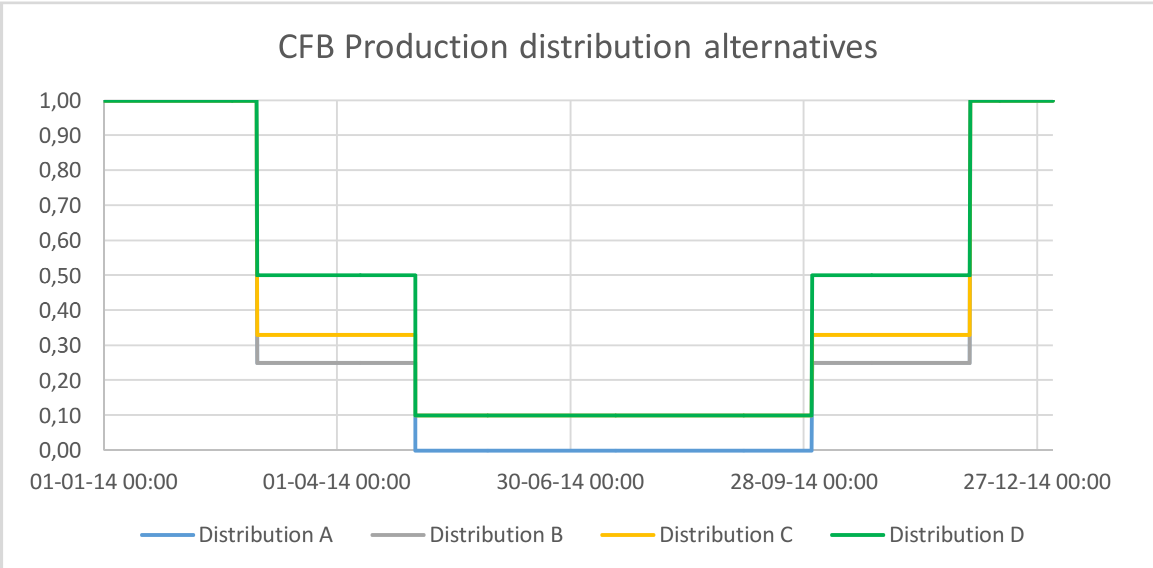


*Figure 10 - Seasonal CFB capacity profiles*

Figure 10 shows the five different capacity profiles for CFB syngas production. Distributions assume adjustment four times during the year, with capacity share levels for each season.

The model assumes unchanged efficiencies for heat and power production for all production capacities.

## 4.3 Production scenarios

Due to model software constraints, the energy production from CFB plants are modelled in three capacity scenarios. The scenarios centres around three utility scenarios. In scenario α uses the Reference electric capacity for large CHP plants to determine the heat and power production from CFB plants. In scenario β, the Reference large CHP heat capacity determines the CFB production, while in scenario γ; the CFB plants produce heat only, determined by the Reference heat capacity.

- Scenario α installs CFB-based capacity based on the conventional large CHP electric capacity it replaces.
- Scenario β uses large CHP heat capacity as a base point for the installed CFB-based capacity to replace it.
- Scenario γ uses the CFB-based plants to produce heat only, losing the electric capacity from the large CHP plants it replaces.

The different approaches makes for very different production capacities for heat and power in the different scenarios. Table 2 shows the different capacities of scenarios. In the Reference scenario, conventional large CHP plants fulfil the capacities, while the capacities are fulfilled by large CFB-based plants, either CHP or heat only, in the Greek letter scenarios.

*Table 2 - Large CHP plants capacities in different scenarios*

| Large CHP capacities in scenarios | | | | |
|---|---|---|---|---|
| | **Reference** | **Scenario α** | **Scenario β** | **Scenario γ** |
| **PES capacity [MW]** | 7,942 | 6,098 | 6,980 | 4,188 |
| **Electric capacity [MW]** | 2,500 | 2,500 | 2,861.8 | 0 |
| **Heat capacity [MW]** | 4,188 | 3,659 | 4,188 | 4,188 |

### 4.3.1 Scenario α – electric capacity optimised CHP production

Scenario α assumes that all large CHP plants in the Danish energy system has been replaced with CFB gasification plants connected to combined cycle gas turbines. Due to model constraints, there is no override of the gas turbine to produce heat only, different to the Reference scenario.

The sum capacity of electric capacity in the Reference scenario for large CHP plants is 2,500 MW. This exact capacity is replaced in Scenario α by CFB-based plants. Different capacity ratios for technologies heat capacity to differ between scenario α and the Reference scenario. The heat capacity in scenario α is 3,659 MJ/s. The larger total efficiency also reduces the total installed PES plant capacity to 6,098 MW.

Where the large CHP plants in the Reference scenario can regulate and produce extra heat using boilers, the heat and power production of the CFB-based plants are only adjusted quarter annually. The heat production from the CFB plants are more dependent on heat storage to fulfil the district heating requirements. Figure 11 shows the different capacity distribution productions from the large CFB-based CHP plants and the corresponding heat demand. The heat demand comes from the fulfilment share of the large CHP plant and the demand distribution.

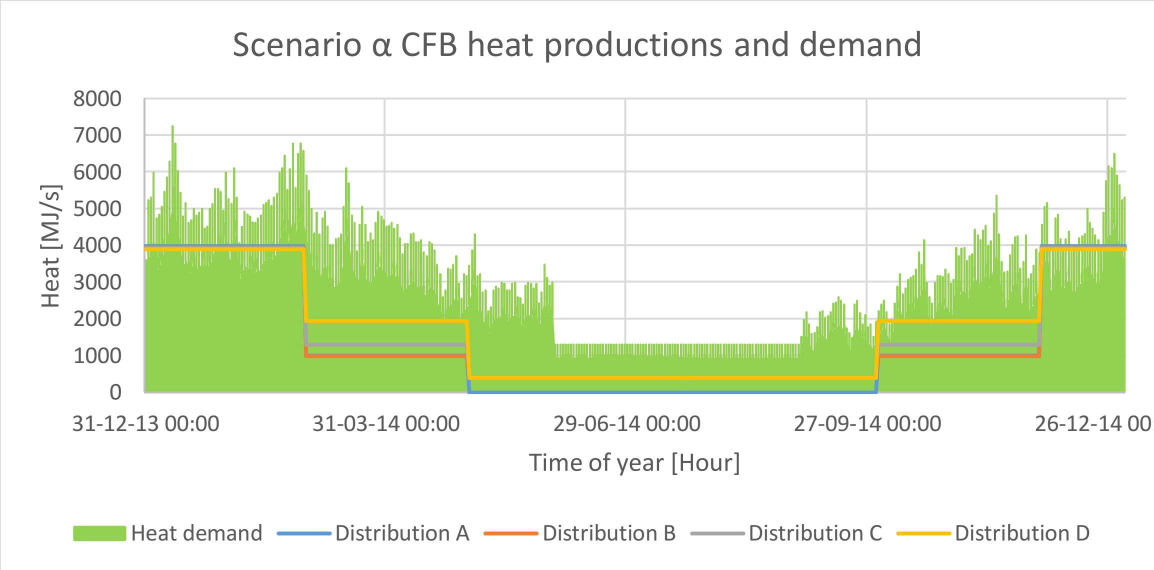


*Figure 11 - Distribution wise heat production and heat demand for large CHP plants in scenario α*

Shown in Figure 11, the heat production of heat in the different capacity distributions offsets from the heat demand. Installed boilers covers underproduction. For hours with overproduction, the heat is wasted. Figure 12 shows the yearly overproduction for the capacity distributions in scenario α.

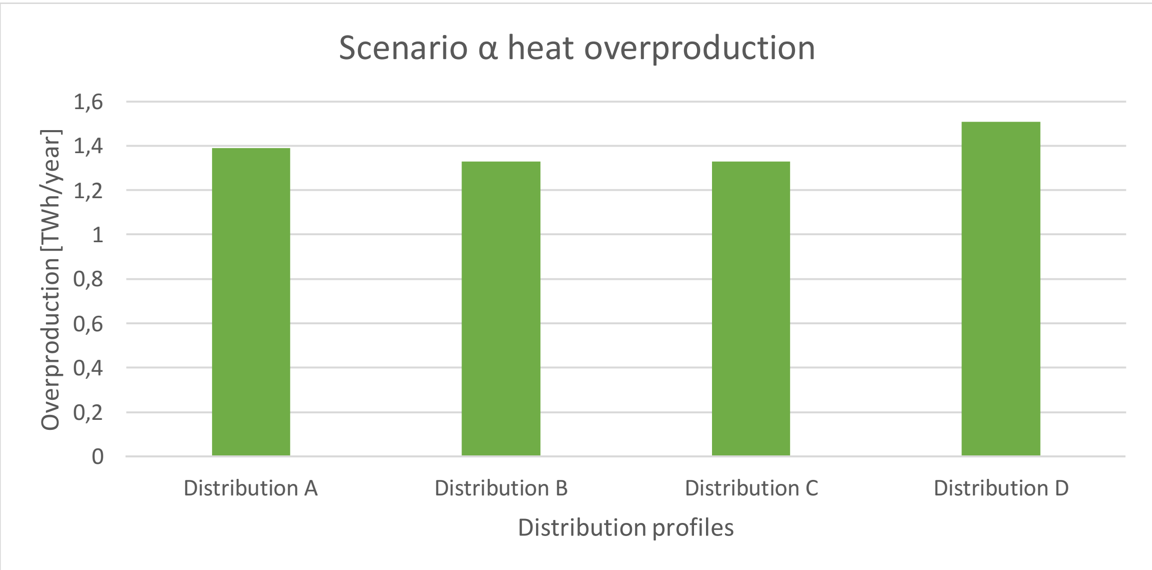


*Figure 12 - Yearly heat overproduction for capacity distributions in scenario α*

Figure 12 shows that all capacity distributions in scenario α overproduces heat from the large CFB-based CHP plants on a yearly basis. The overproduction, ranging from 5.9%-6.7% of the demand is considerable, as this energy is wasted. The differences in distribution profiles have no larger impact on the overproduction of heat, while small trends between the distributions are visible in Figure 12.

Where the conventional large CHP plants are able to regulate their production capacity for both heat and power, the CFB-based units have no such ability. In scenario α, the decided capacity comes from the Reference scenario large CHP electricity capacity. Lacking the regulation ability, the electricity production does not adjust to the hourly demand, creating larger possibility for electricity excess and shortage. In the system, other power plants and smaller CHP plants regulates for lacking electricity during hours where the CFB-based plants are running at too low capacity, avoiding electricity deficiency. The lacking ability for the large CFB-based plants to regulate capacity downwards during high VRE capacity hours causes unavoidable excess electricity production when other producers reach regulation limits. Figure 13 shows the yearly excess electricity production in the basic scenario α system with the different capacity distributions. In the basic scenario analyses keeps VRE capacity to a minimum by not having any offshore VRE capacity. The analyses have 2934 MW of onshore VRE capacity able to cause peak production of power with potential of excess electricity production.

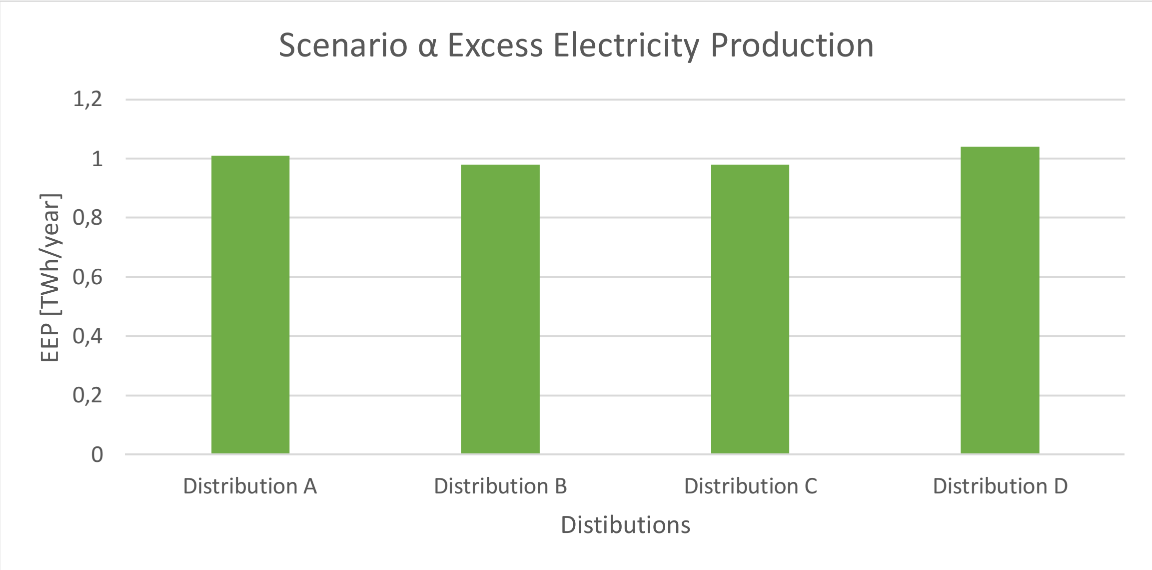


*Figure 13 - Yearly excess electricity production in basic scenario α*

As shown in Figure 13, all capacity distributions have excess electricity production. As with heat overproduction, shown in Figure 12, the EEP for the distributions show similar ratios between the different distributions. This hints that the capacity of the CFB-based CHP plants is higher than optimal and that overproduction of heat and power are likely to occur in the same hours. The demand for large CHP produced electricity and large CHP produced heat varies from each other on hourly basis and have no correlation, other than in a negligible share of heat pumps.

### 4.3.2 Scenario β – heat capacity optimised CHP production

Where scenario α replaces conventional large CHP plants with CFB-based CHP plants by replacing the electric capacity and letting it produce heat as it would, scenario β takes the opposite approach. In scenario β, heat capacity of the conventional large CHP plants functions as the base for the replacement installed CFB-based CHP plants. Because of the closer ratio between power and heat production of CFB-based plants, the electricity capacity is higher in scenario β than in the Reference scenario.

Scenario β uses the same capacity distributions as the other Greek letter scenarios. The larger power and heat capacities of scenario β produces both more heat and power for the same demand. Figure 14 shows the hourly heat production and heat demand in scenario β.

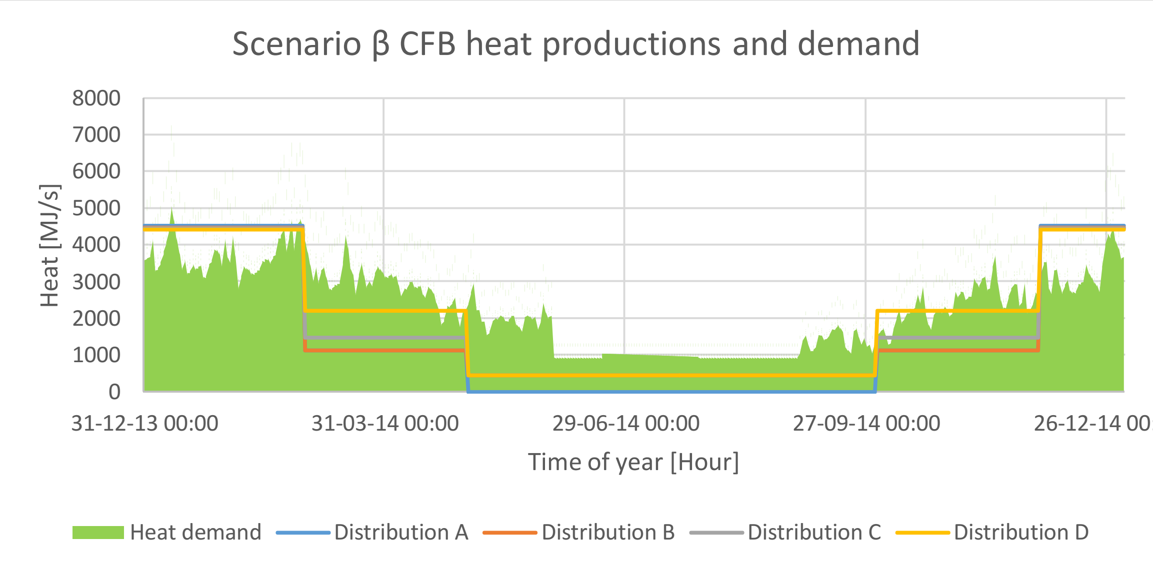


*Figure 14 - Distribution wise heat production and heat demand for large CHP plants in scenario β*

Figure 14 shows much higher production capacities for scenario β than for previous scenarios. During the winter months, the CFB-based CHP plants produce more heat than needed in most hours, while the production/demand ratio is more moderate in most hours of the other seasons. Figure 15 shows the yearly overproduction of heat in scenario β.

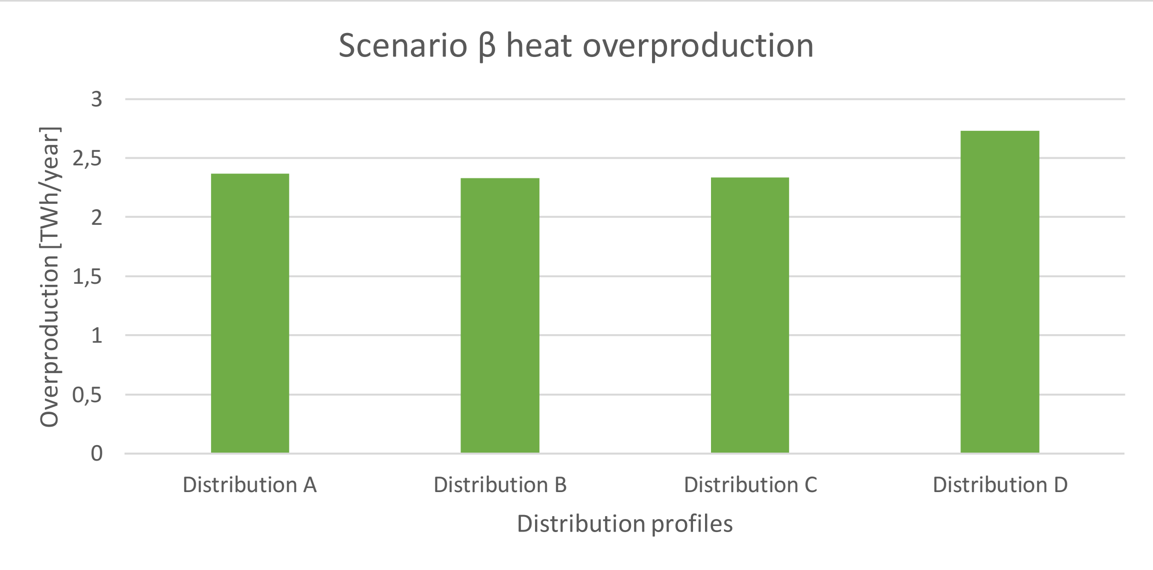


*Figure 15 - Yearly heat overproduction for capacity distributions in scenario β*

Figure 15 shows that the capacity of the CFB-based CHP plants in scenario β overproduces heat in an amount higher than scenario α with a smaller capacity. The ratio of heat overproduction between the capacity distribution profiles closely resembles that of scenario α. In scenario β, distributions A, B and C have the closely resembling overproduction of heat over the course of a year, despite the different capacity distributions producing widely more distinct yearly heat productions. This supports the notion showed in Figure 14 that most overproduction occur during the winter season and that the installed heat capacity, when producing constantly, is too high.

CFB-based CHP plants have a closer ratio between the production of power and heat than the large CHP plants of the Reference system. The power capacity, like the heat capacity is higher in scenario β than in scenario α. This higher electricity capacity produces more electricity in the system, both during hours when the system needs it and in hours where the production, in summation with other sources, VRE and otherwise, deliver too much. Figure 16 shows the yearly excess electricity production for the different distribution profiles in scenario β.

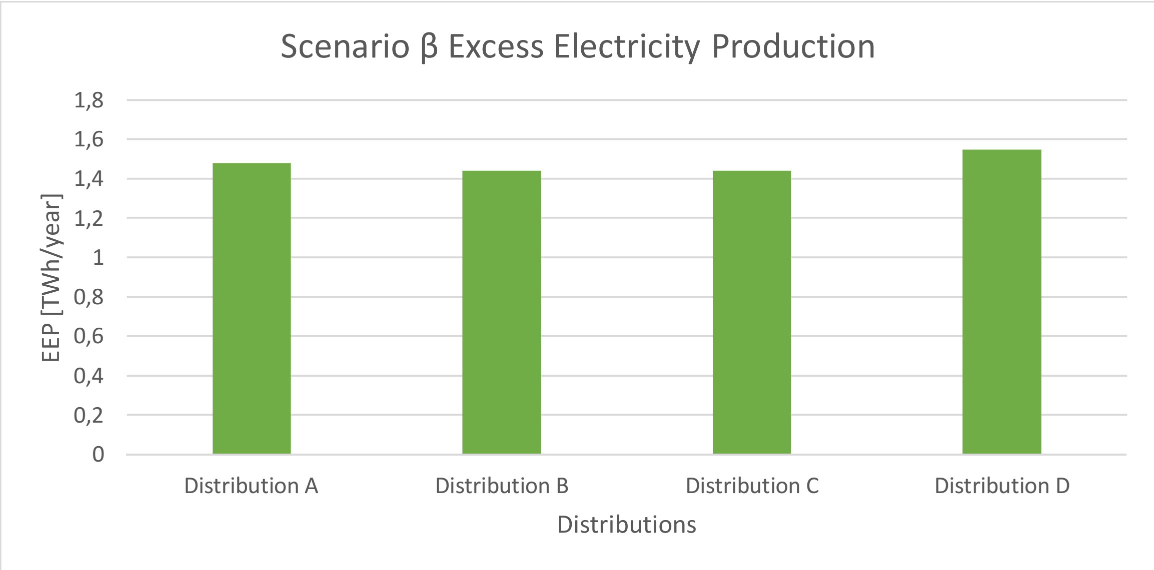


*Figure 16 - Yearly excess electricity production in basic scenario β*

Compared to EEP in scenario α shown in Figure 13, excess electricity production for scenario β is expectably higher. Like with heat overproduction, the ratio between the distributions is low. The close resemblance between the EEP of different distribution profiles confirm the situation of EEP occurring during uncontrolled VRE capacity spikes, shown for the Reference scenario in Figure 5. The small difference of EEP between the distribution profiles while all having large amounts of EEP hints that EEP largely occurs during hours where the CFB-based CHP plants are in production on all the distribution profiles.

### 4.3.3 Scenario γ – heat production only

The core technology of Circulating Fluid Bed plants is, as explored and stated in Section 3.1 and 3.2, the gasification of solid fuels. The energy production is a derivative of the gas production and requires additional equipment. The combined heat and power production from CFB plants is therefore not a given. In the future, further development in areas such as fuel cells could create the basis for using CFB technology for power-only plants. With the technology available today, using CFB plants for producing just power is unattractive in comparison to CHP. Using CFB produced synthetic gas to produce exclusively heat utilising a gas boiler is an attractive solution for district heating. Scenario γ explores this option by replacing all large CHP from the Reference scenario with heat-only production. The capacity in scenario γ is, like in scenario β, decided to match the Reference scenario heat capacity.

Like in scenarios α and β, the production from the CFB plants are constant, adjusted four times yearly using the capacity distribution profiles from Figure 10. The heat capacity and distribution profiles for scenario γ is the same as in scenario β. The distribution wise heat production and demand for scenario γ is therefore similar as for scenario β. Figure 17 shows the heat production and heat demand for different profiles in scenario γ.

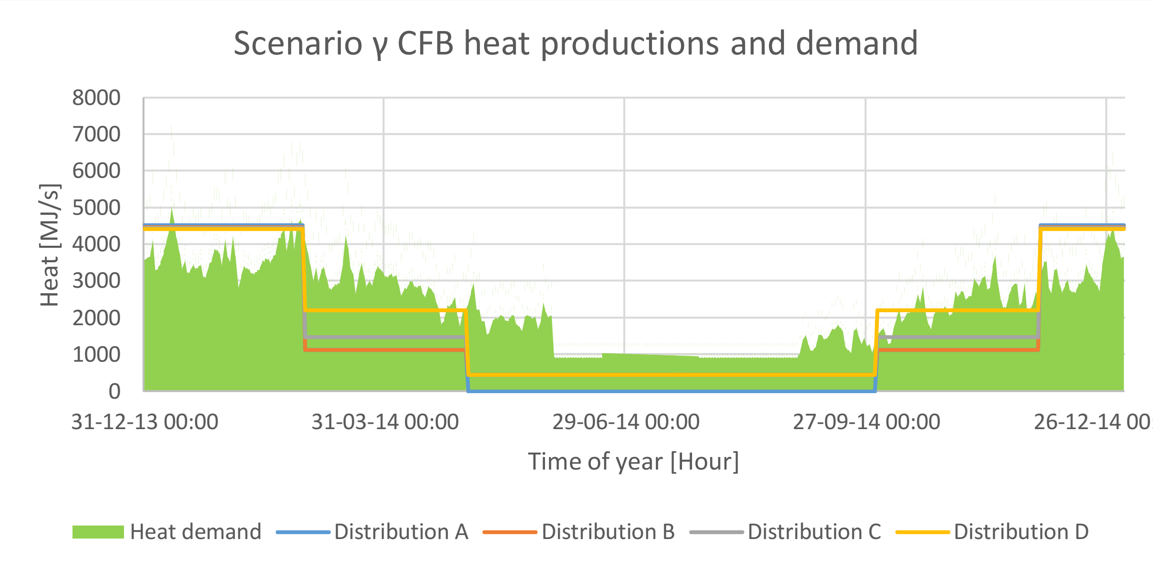


*Figure 17 - Distribution wise heat production and heat demand for large CHP plants in scenario γ*

Figure 17 shows that in scenario γ, like in scenario β, the distributions overproduce heat for large periods of time during the year. Especially in the winter season, the CFB-based boilers produce excessive heat in all capacity distributions. As the heat production in capacity and distributions is the same in scenario γ as in scenario β, Figure 18 shows similar overproduction of heat as Figure 15.

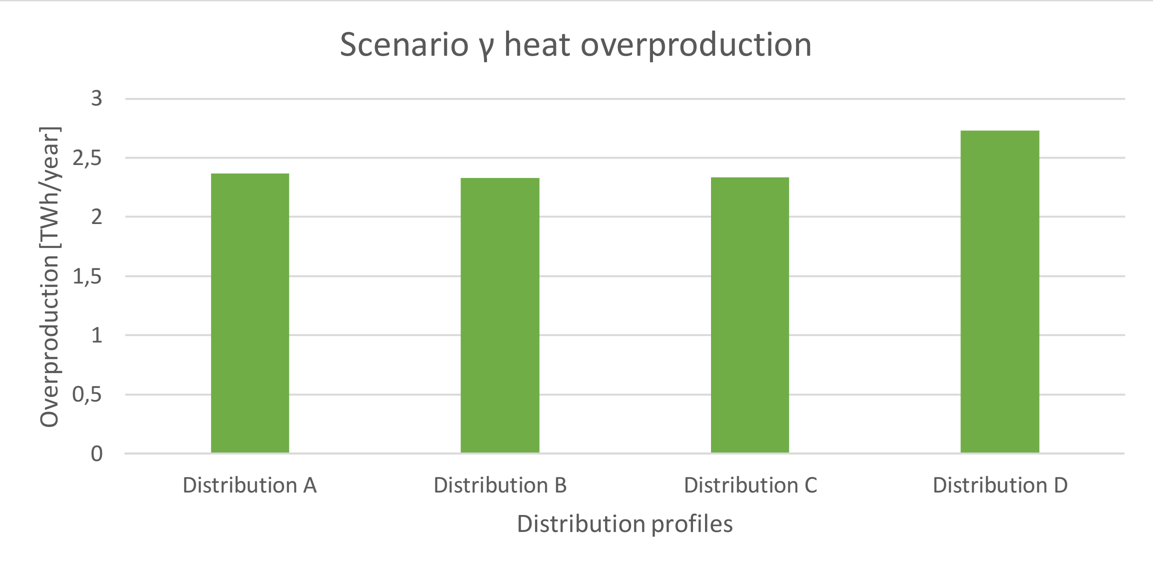


*Figure 18 - Yearly heat overproduction for capacity distributions in scenario γ*

Like scenario β, scenario γ have large quantities of heat overproduction in the different capacity distribution profiles. Optimal heat capacity for large production plants delivering base load, CHP or heat-only, lies beneath the installed capacity in the Reference scenario and all scenarios α, β and γ.

The CFB-based boilers in scenario γ does not produce electricity. Compared to the Reference scenario, scenario γ lacks maximum 2,500 MW power capacity. Other power sources in the system covers this lack of capacity completely. These other power sources produces electricity at higher capacity levels than in the Reference scenario and can scale back if needed, providing larger flexibility to the system. The system, shown in Figure 19, have no excess electricity production for any of the capacity distribution profiles.

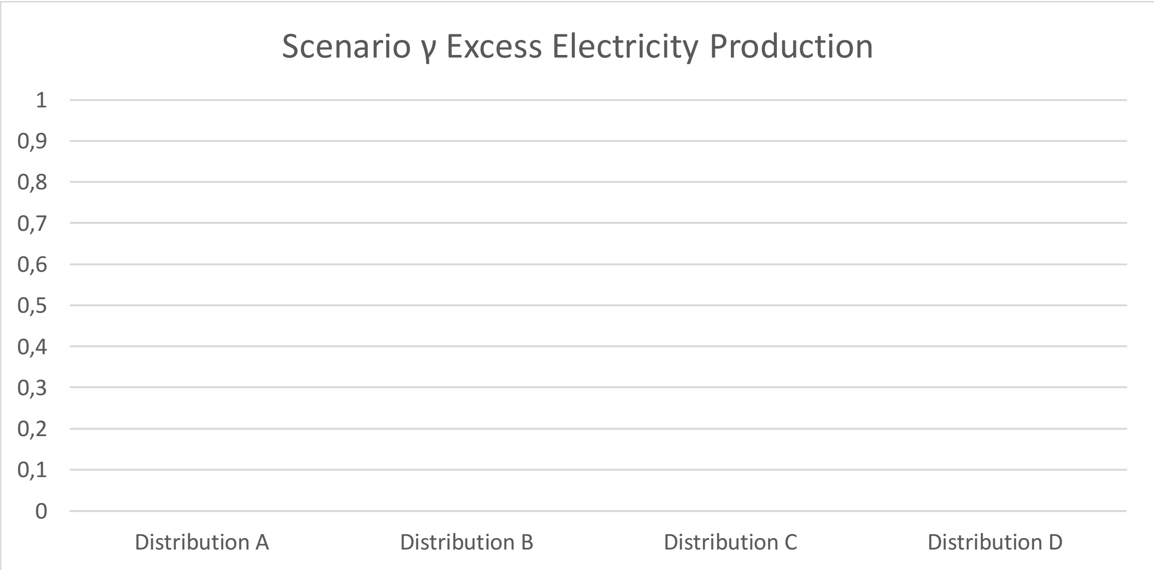


*Figure 19 - Yearly excess electricity production in basic scenario γ*

Figure 19 shows no excess electricity production in the system of scenario γ independent of capacity distribution profiles. Other energy sources fulfils the lacking large CHP capacity without overproducing heat compared to scenario β in Figure 15. This hints larger production by power plants in the system, as well as regulated power plants or CHP plants.

### 4.3.4 Comparison of Greek letter basic scenarios

Both capacity distribution profiles and scenarios have influence on the excessive productions of heat and power. As well, some mentioned analysis in the singular Greek scenario sections covers the different systems in between. This section explores these and compares the Greek letter scenarios.

Figure 12, Figure 15 and Figure 18 shows the overproduction of heat in the individual Greek letter scenarios. For better overview, Figure 20 shows these in comparison.

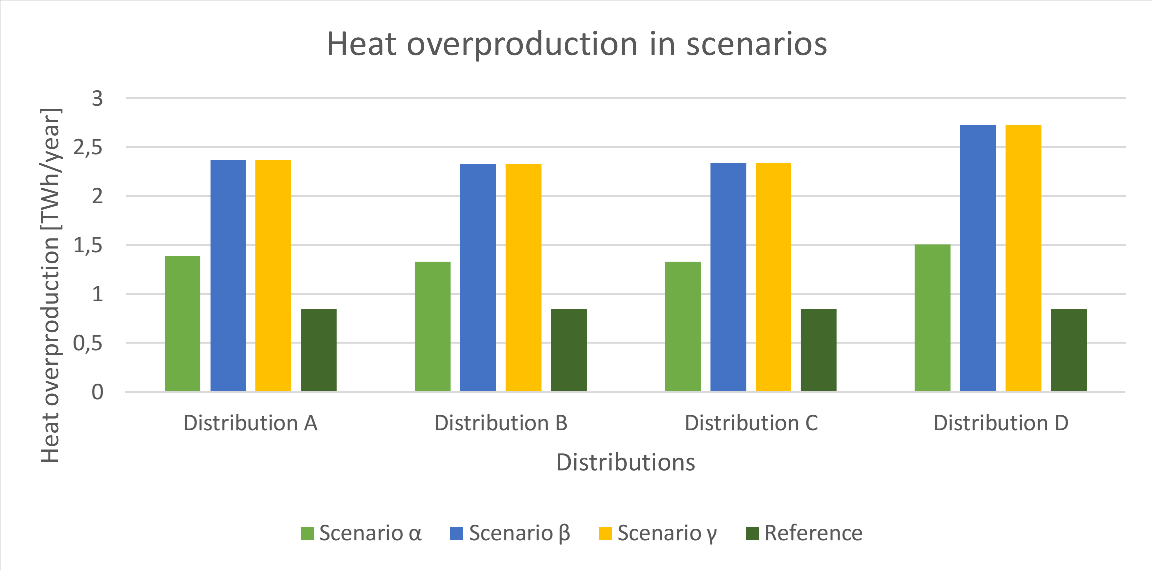


*Figure 20 - Comparison heat overproduction between scenarios*

Figure 20 shows little difference between the Reference scenario and the capacity distributions in scenario α. Despite efficiency differences and difference in regulation ability, the heat productions are very similar between the two scenarios.

Most of the scenarios have excess electricity production, due to the combination of large base load production from the CFB-based CHP plants, power plants and CHP plants with lower capacity limits and almost 3,000 MW of VRE capacity. The difference between conventional large CHP plants, that are able to regulate some, and CFB-based plants that are not able to regulate at all is visible in the excess electricity production. Figure 21 shows an overview of the EEP between scenarios.

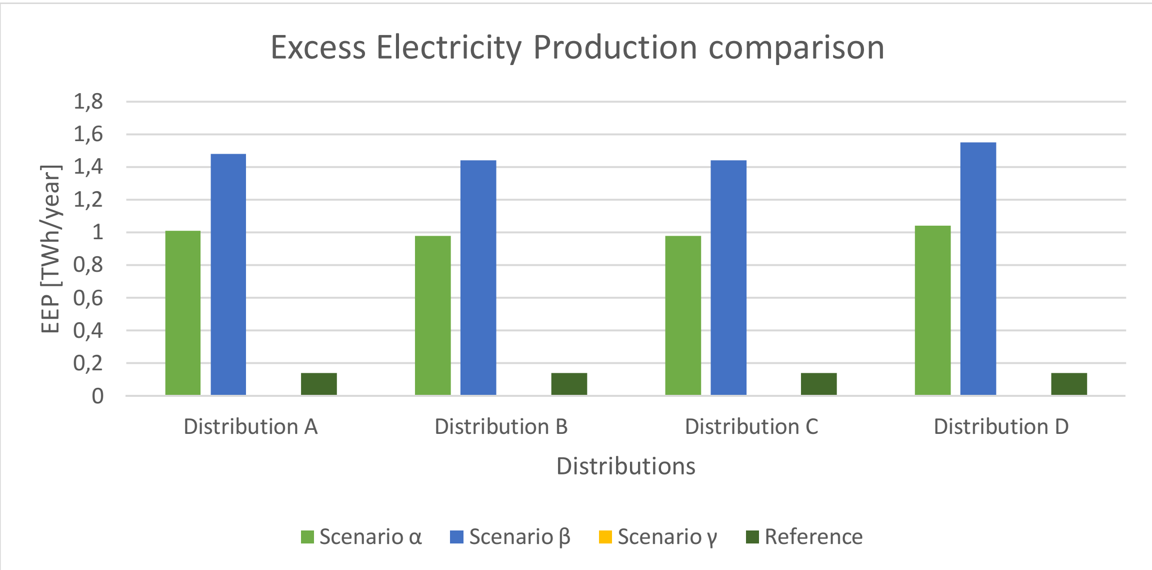


*Figure 21 – Yearly excess electricity production between scenarios*

Figure 21 shows that the unregulated production of electricity from CFB-based CHP plants creates more excess electricity production than the Reference scenario in any scenario and with any distribution analysed that produces electricity. In scenario γ, where the CFB technology is used for boilers, the system lacks a large electricity capacity compared to the Reference scenario. The deficiency is fulfilled by larger production from other non-VRE sources in the energy system.

The cause of excess electricity production is high production and small demand of electricity in the energy system. In the CFB scenarios, two sources for electricity production are not flexible. These are the VRE sources (onshore wind turbines) and the CFB-based CHP plants. In the Reference system, the large CHP plants can regulate for low demand and high VRE source production. The large excess electricity production in scenarios α and β is a product of the lacking downward regulation of the system. Figure 22 shows the hourly excess electricity production for the different CFB scenarios. As Figure 21 shows the similarity in capacity distribution profiles in the single scenarios, Figure 22 uses distribution A only. Figure 22 also shows the hourly capacity share for comparison.

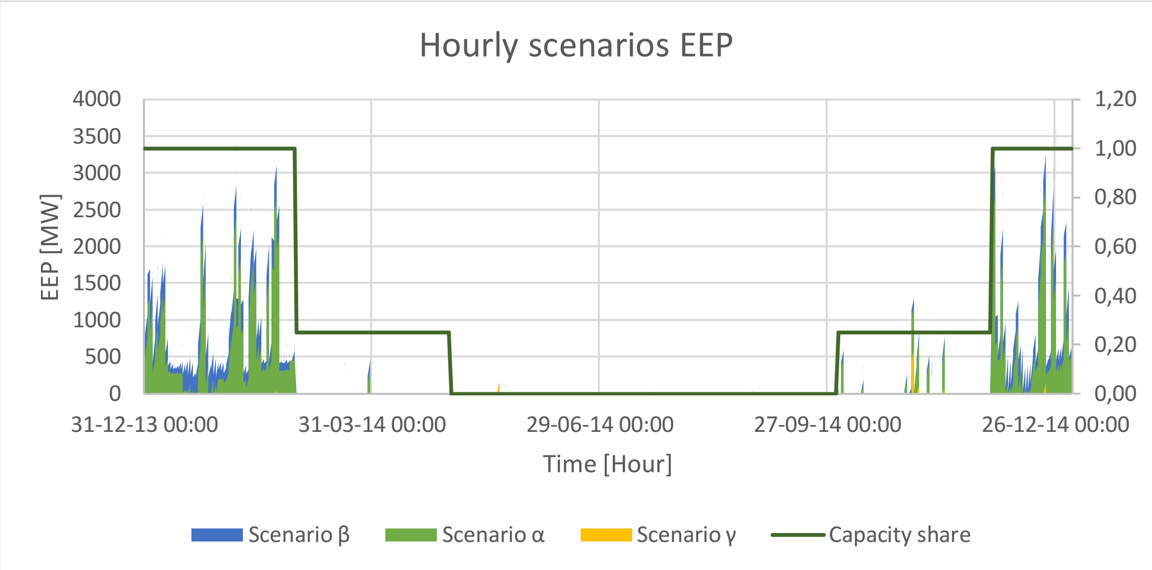


*Figure 22 - Hourly EEP and capacity share for distribution A. Capacity share is on second Y-axis*

Figure 22 shows how the EEP in the system predominantly occurs in periods where the CFB-based CHP plants produces electricity on high capacity. During other periods with capacity share, the excess electricity production severely diminishes. For scenarios α and β, hours with EEP occurs in the majority of hours in the winter season. This suggests capacity excess of CFB-based plants.

For the scenario with most EEP, scenario β, the winter period sees EEP between 0 MW and 3604 MW. The average hourly EEP during the winter season 642 MW for scenario β, with much higher values occurring in spikes only few hours long for both scenarios α and β. These EEP spikes occurs simultaneously with high production capacity of VRE sources.

## 4.4 Open Analysis for direct infusion CFB-based systems

The core methodology is the analysis of technologies during mass implementation of VRE sources. The methodology regards the energy system in question as an isolated system, with no regards for import and export. Explored in Section 2.8 and Section 2.9, the implementation of VRE sources happens under two different analysis conditions, Open system and Closed system.

The Open system allows the system to produce excess electricity and does not regulate for this. During implementation of VRE source capacity, the EEP in Open system analysis increases as the regulation opportunities in the system are exhausted in more hours and the total capacity in the system increases. Figure 23 shows the excess electricity production during VRE implementation for the different scenarios. All scenarios use distribution profile C. While distribution C is not the least consuming distribution, it has the least excess electricity production and least heat overproduction, shown in Figure 21 and Figure 20.

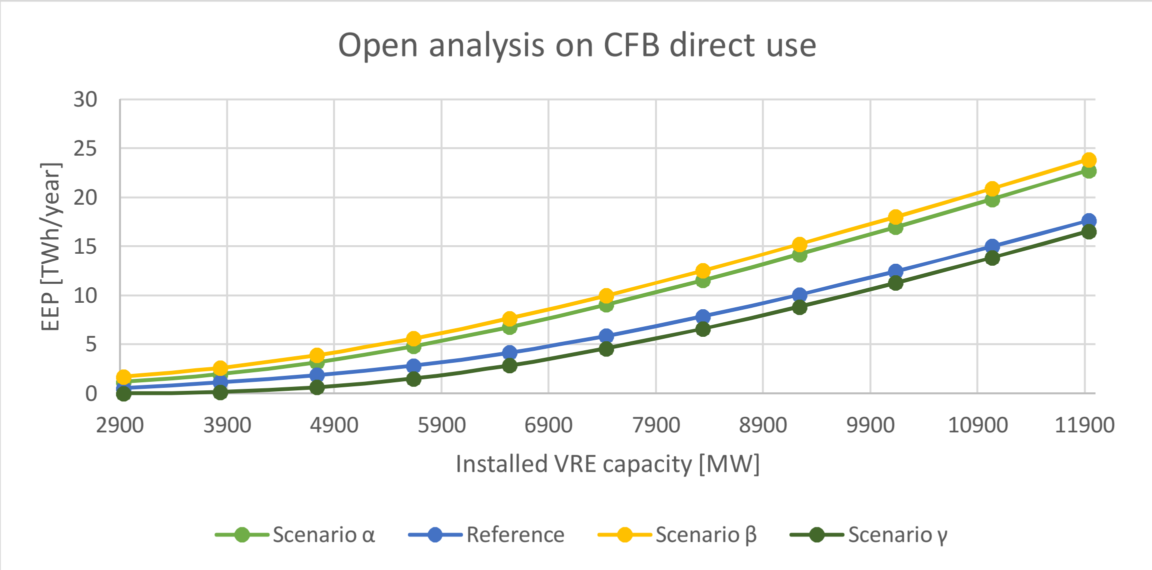


*Figure 23 - Open analysis results of the direct CFB scenarios*

Figure 23 reinforces the conclusions from Figure 21. Scenario γ, where all the CFB-based capacity produces heat, have the least excess electricity production. The inability to regulate the CFB-based CHP plants show a predictable increase in yearly EEP from the Reference scenario, where large CHP plants can regulate freely. The situation from Figure 21 where scenario β produces more EEP than scenario α holds with the mass implementation of further VRE sources.

As the regulation options exhausts for both scenarios with lower VRE instalments for most hours during the year, much of the added capacity mainly produces EEP. In the case where the installed capacity is enough to covers the yearly demand, 62% of the total VRE production is EEP for scenario α, 65% for scenario β and 45% for scenario γ. In comparison, of the total produced VRE in the Reference scenario, 48% is EEP.

## 4.5 Closed CFB analysis

Closed system analysis allows no excess electricity production as its differentiating condition from the Open analysis methodology. To do this, the method regulates EEP directly by first replacing small CHP plants with boilers, secondly trying to replace large CHP capacity with boilers, which is not possible in the scenarios and lastly stopping curtailed wind turbines. Figure 24 shows the amount of fuel (excluding VRE electricity) the system uses under these conditions for the different scenarios. As in the Open system analysis in Section 4.4, Closed analysis uses only distribution C for all scenarios.

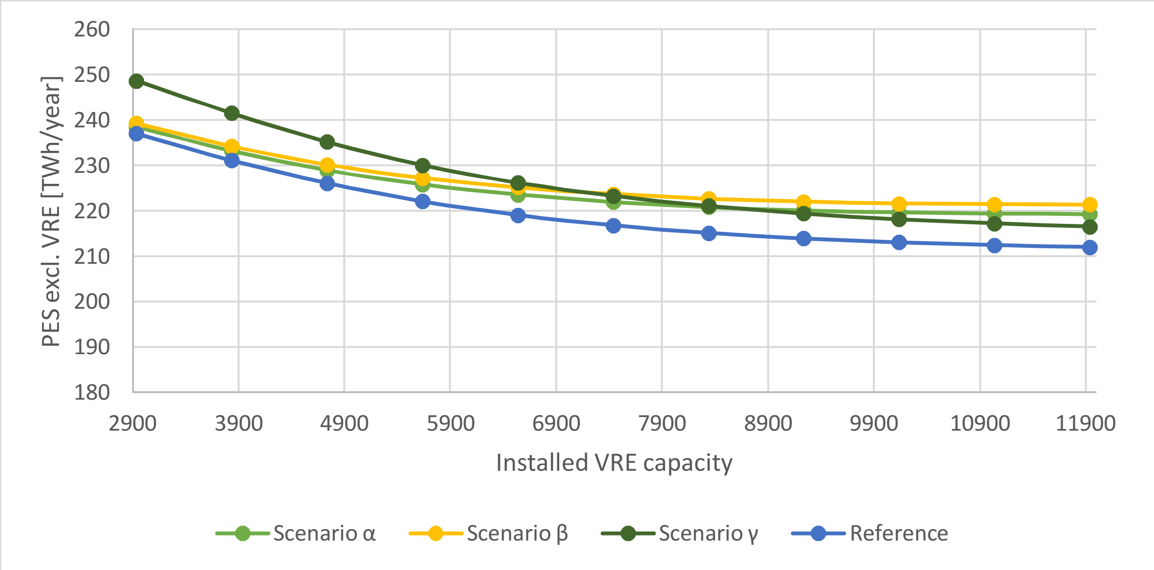


*Figure 24 - Closed analysis results of the direct CFB scenarios*

Predictably, Figure 24 shows scenario β to develop slowest, having large electricity capacity that lacks the ability to regulate. Scenario α, having the same conditions but smaller capacities follow the same pattern with less impact per capacity installed VRE. The Reference scenario, in comparison, with its ability to regulate most of its fossil-based electricity capacity (and switching to high efficiency boilers if heat is needed) shows less fuel use with higher VRE electricity capacity.

The development in scenario γ shows the scenario's ability to better adapt to high-VRE systems. By only using CFB technology to produce heat in boilers and separately producing power from conventional power plants, the fuel use is significantly higher in systems with low VRE. In the other scenarios, including Reference, the waste heat from power production is utilised for district heating, saving the production fuel for this purpose. In scenario γ, the power plants wastes the by-product heat.

As more heat is added to scenario γ, the utilisation of the power plants decline through regulation, while the heat production remains constant for the scenario. No additional boilers needs to be utilised for district heating, saving fuel in the systems. In instances with high capacity of VRE, scenario γ allows for more of the installed plant electricity capacity to regulate, increasing the utilisation of the VRE capacity and saving fuel.

# Model - Using CFB technology to produce grid gas

The technology of Circulating Fluid Bed and its sub-technologies described in Section 3 are pure gasification technologies. The main product from the technology is synthetic gas, which is used in other technologies to produce heat and power. Some gasification plants produce a by-product of district heating. Sections 4.3 to 4.5 explores the option of producing synthetic gas directly to use in a large CHP plant locally, treating the gasification of the biomass and the combustion of the product gas as one process. Another option is using the gas network in a system, in this report Denmark, to transport and store the gas.

The gas network in Denmark consists of tubes transporting gas, similar to water or sewage networks, with dimensions ranging from main tubes, district tubes down to tubes feeding the individual household with gas. The gas network in Denmark uses natural gas, a cleaner fossil fuel compared to oil and coal products. Modelled in this section, the possibility of using syngas in the gas grid for powering large CHP plants. The analysis uses the EnergyPLAN software to model the scenarios.

## 4.6 Conditions of model

To further explore the option of using CFB technology in the energy system, and to be able to compare to the CFB direct use model results, CFB technology entirely produces the synthetic gas for the CHP plants. Also like the model throughout Section 4, the large CHP plants and their demand are the scope of this model.

To produce the synthetic gas, the analysis assumes Circulating Fluid Bed gasification plants. In this analysis, model separates the gasification plants from the large CHP plants, acting as standalone plants. In the utility of the gas network, the gas is stored in tanks if beneficial. With the intermediate of storage, the CHP plants can freely regulate while the CFB plants run with fixed production. The model assumes no storage losses and always-abundant storage capacity. The production of synthetic gas has to cover the yearly consumption, assuming stored syngas capacity for the hour-to-hour demands.

In the CFB direct use model in Section 4.3, the analysis treats the CFB-based CHP plants as combined technologies, using a single set of characteristics for the functioning of the plants. This model separates the technologies and treats them after their own set of characteristics. The characteristics comes from the Danish Energy Agency's technology datasheets. The CFB gasification plants produces the required amount of synthetic gas the large CP plants need on a yearly basis during the year. On the yearly basis, there is perfect alignment of syngas production and consumption.

The CFB gasification plants are highly efficient, having a biomass-to-gas efficiency of 95% (Danish Energy Agency 2014). The gasification technology relies not only on the input of biomass, but uses electricity, steam and sand material among its inputs. For electricity about 15 kWh is consumed for every one MWh of biomass material (calculated from (Danish Energy Agency 2014)). For steam, the share is 20 kWh per MWh biomass.

While the model assumes a perfect, no losses transport and storage system, the CHP plants has characteristics from Combined Cycle Gas Turbine CHP plants, as defined by the Danish Energy Agency. In this analysis, this technology can regulate freely on an hourly basis. The system then differentiates itself severely from the analysis in Section 4, where the production capacity from large CHP plants adjusts only for the main seasons. In hours of heat overproduction, the system utilises hot water tanks. In hours of excess electricity production, the system regulates the CHP plants and run boilers if needed. The boilers uses conventional fossil fuels. The large CHP plants based on Combined Cycle Gas Turbines have an overall efficiency of 91% distributed on 52% electric efficiency and 39% heat efficiency (Danish Energy Agency 2014).

## 4.7 Methodology of analyses

Since the large CHP plants freely regulates in this model, there is no need for custom distributions. The large CHP plants in this model is treated as in the Reference scenario, but running entirely on gas. EnergyPLAN does not distinct between synthetic gas and natural gas on the consumer side. With no custom distributions to compare under basic, minimal VRE conditions, the Grid syngas model does not need different scenarios analyses using a methodology more reminiscent of the Reference scenario.

There is distinct differences between the modelling methodology of this analysis and the Reference. The fuel is always abundant in the Reference scenario and comes from sources outside the scope of the energy system. For the Grid syngas scenario, the combusted syngas originates from the CFB plants. The CFB that produces the syngas from biomass uses electricity for the syngas production, thereby interacting in the system.

Due to this interaction, the analysis bases itself on numeric math to estimate the syngas needs of the large CHP plants. The syngas production from the CFB plants aligns with the demand from the CFB plants, requiring numeric math with several iterations. The modelling software EnergyPLAN is an analytic model, why user interaction processes the iterative result search. EnergyPLAN has constraints on the decimal points showed for results, making an accuracy of more than 0.1 TWh impossible. The method for doing this in EnergyPLAn is shown in Section 13 in Appendix C.

To estimate the gas consumption of the large Combined Cycle gas CHP plants, the model runs a first time under certain conditions. Other than the conditions described in Section 4.6, analysis method (Open or Closed analysis) and installed VRE capacity are the main conditions. This finds the preliminary large CHP syngas consumption. By use of the preliminary gas and the conditions of syngas production described in Section 4.6, the user estimates the preliminary CFB biomass consumption and preliminary CFB syngas production. Keeping the conditions of VRE capacity and methodology fixed, the model runs to find the second iteration of the CHP syngas consumption, influenced by the CFB electricity consumption. From this, the user search for the second iteration of the CFB biomass consumption and syngas production. The process repeats until the results align within 0.1 TWh. For the results in this model, the number of iterations range between two and five. The iterative process start over with each condition change, i.e. changing the VRE capacity or changing between Open and Closed system analysis.

## 4.8 Open system analysis for Grid syngas

The Open system analysis measures the deregulated excess electricity production per year under increasing VRE capacity installed in the system.

For the Grid syngas model, the increasing VRE capacity means reduction in large CHP usage, as these regulates. The reduction in yearly energy production from the large gas fired CHP plants means reduction in the production of synthetic gas from the CFB gasification plants. Figure 25 shows the consumption of synthetic gas, the consumption of biomass for CFB plants.

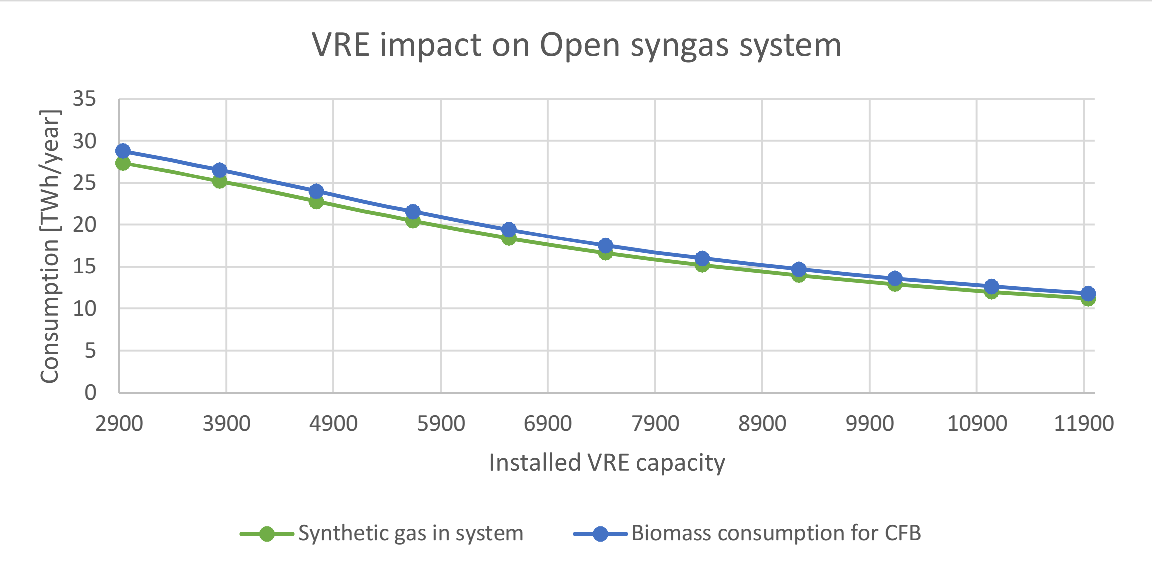


*Figure 25 - VRE capacity impact on biomass consumption and syngas production in Grid syngas Open system analysis*

Figure 25 shows a small difference in the biomass energy consumption and the syngas energy production, caused by the efficiency of the CFB gasification plant. The two energy amounts are bound together by this. Figure 25 shows a slow decline for the consumption of the fuels. The large CHP plants constitute the backbone of the energy system and the system regulates them less heavily than smaller CHP units, having a quicker regulation ability. These smaller units runs on a variety of fuels, see Appendix A.

Open system analysis does not regulate for excess electricity production. The different power units regulates in the system between them, but the system presents unavoidable excess electricity production as is. The introduction of deregulated VRE sources into the system causes the system produce more electricity in excess. Figure 26 shows the EEP for the CHP grid gas Open system analysis.

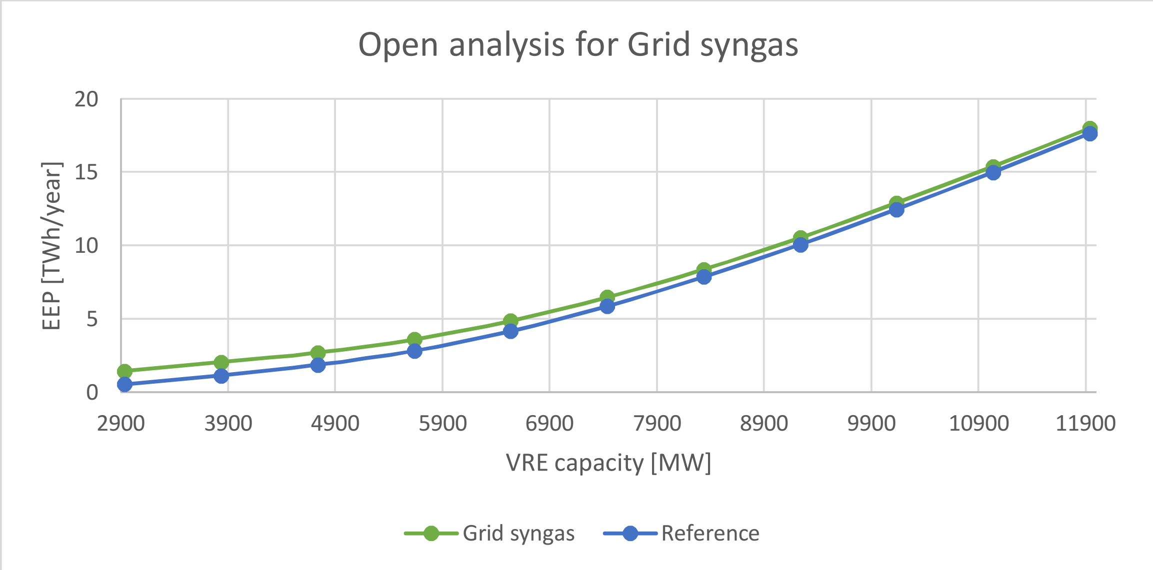


*Figure 26 - Open system analysis for Grid syngas model*

The process of using Circulating Fluid Bed gasification plants to produce fuel for Combined Cycle Gas Turbine plants have slightly higher efficiency than in the Reference system, but also have an inversed relationship of power and heat share of the production. In the Reference scenario, the large CHP plants produces 1.7 MWh heat for every MWh electricity. The gas turbine based large CHP plants in the Grid syngas scenario only produces 0.75 MWh. The capacity of the gas turbine CHP plants is based on the electric capacity of the Reference. The heat capacity is thereby much lowered heat capacity, 1,875 MJ/s compared to the Reference scenario's 4,188 MJ/s. To avoid heat deficiency in the large CHP district heating network, the system upward regulates the capacity of the large CHP plants, running more hours at larger electric capacity. As the second priority option, boilers are utilised. A larger excess electricity production is the result of this heat capacity difference. This is apparent in the low-VRE capacity analysis results in Figure 26.

In analysis results for high-VRE capacity, the difference largely disappears. The larger electricity-to-heat ratio of the syngas based large CHP plants causes a reduction in the CHP production, as well as a reduction of the produced electricity coming from power plants.

## 4.9 Closed system analysis for Grid syngas

The Closed system regulates all excess electricity production. In the Grid syngas scenario, the regulation strategy of only regulating VRE sources after regulating CHP plants by replacing it with boilers. The regulation of the large CHP plants causes a decrease in gas consumption. Figure 27 shows the syngas production and biomass consumption for the Closed system analysis under the different VRE capacity conditions.

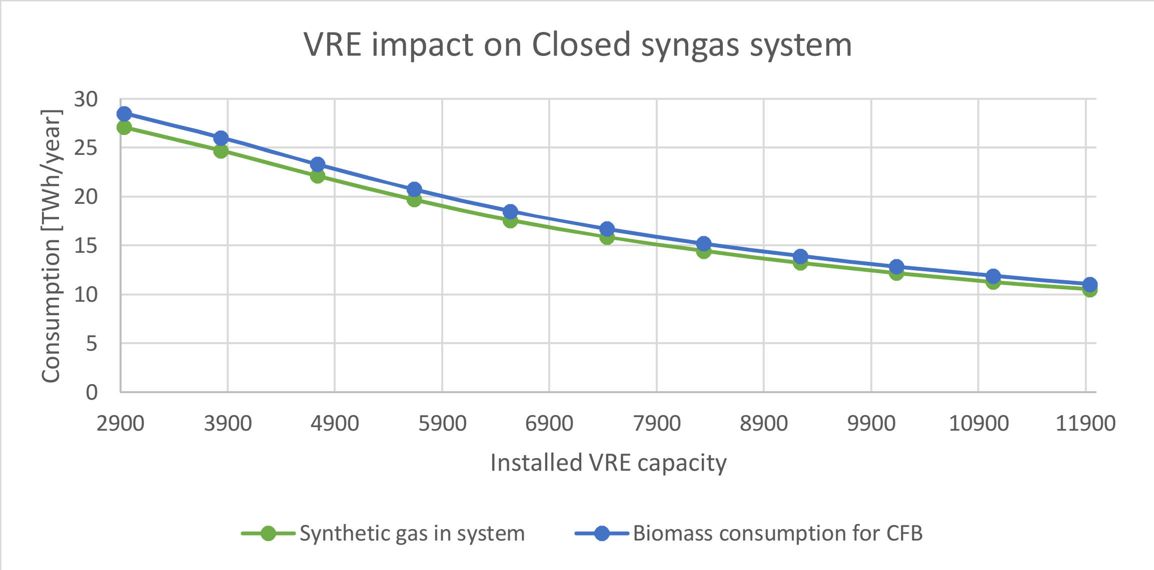


*Figure 27 - VRE capacity impact on biomass consumption and syngas production in Grid syngas Closed system analysis*

As in Figure 25, the value difference of biomass consumption and syngas production in Figure 27 constitutes the CFB gasification plant efficiency. In similar fashion to in the Open system analysis, showed in Figure 25, the large CHP consumption declines during implementation of VRE sources. In systems with almost 12,000 MW VRE capacity installed, the fuel use for large CHP plants in the model is almost a third of if the system had only the minimum of almost 3,000 MW VRE capacity installed. Comparing Figure 25 and Figure 27 shows very similar large CHP fuel uses, and thereby very similar annual productions, between the two system analysis methodologies. In the Closed system, the absolute regulation of excess electricity production constricts other actors in the system. The regulation in Open and Closed systems of the large CHP plants are very similar.

Where the Open system accepts excess electricity production as is, the Closed energy system enforces absolute regulation, allowing no EEP. The Closed energy system EEP regulation favours heat capacity transfer from CHP plants to boilers in hours of electric overcapacity before shutting down curtailed VRE capacity. Figure 28 shows the Closed energy system analysis results for the Grid syngas model.

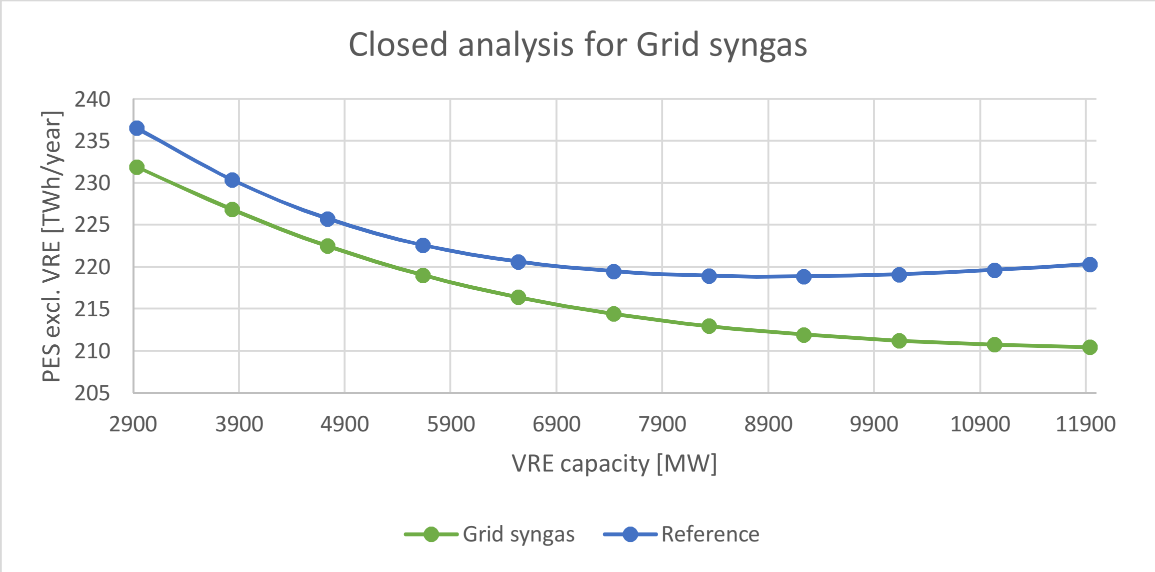


*Figure 28 - Closed system analysis results for Grid syngas model*

Under conditions with low VRE capacity, the Grid syngas scenario in Figure 28 performs with lower fuel use than the Reference scenario. This is due to the higher efficiency of the CFB gasification and Combined Cycle Gas Turbine combination. When the conditions of VRE capacity increases, the Grid syngas scenario separates itself by increasing better performance, lower fuel use. The ratio between electric and heat production in the gas turbines of the Grid syngas scenario, explored in Section 4.8, is with electricity in its majority, which allows the more energy efficient boilers to produce a larger share of the heat demand coverage. This saves fuel in the overall system, as witnessed by Figure 28.

# Wood Pellet Combustion CHP plants

The Reference scenario consists of mixed energy sources from the year 2010. The large CHP plants in the Reference system, which is the focus of this report, consists of plants fuelled by mainly coal. As read in model files in Appendix A, 73.5% of the Reference large CHP plant fuel is coal, while oil, natural gas and biomass constitutes 3.3%, 11.9% and 11.3% of the fuel use, respectively.

The large CHP plants in the Reference system are of different age and technologies. The average electricity efficiency of the large CHP plants is 31% and the heat efficiency is 53%. The CFB technology used in multiple scenarios and models uses technology data for year 2020.

As an alternative scenario to using synthetic gas made from biomass is combusting biomass directly, which is already widely adopted in the energy system at present time. Combusting biomass directly compared to gasification has both advantages and disadvantages over using gasification technologies. The process is simpler and very similar to burning solid fossil fuels such as coal and uses similar infrastructure. Issues with biomass quality occur in combustion technologies, where especially water content causes efficiency decline. Some unwanted bi-products of biomass utilisation occurs in higher quantities with direct combustion. The higher grade of biomass has added monetary costs, discussed in the scenario comparison in Section 7.

Biomass combustion is similar in conventional solid fossil fuel (coal products) combustion. The technology in the Wood Pellet Combustion model is the technology of Advanced Pulverised Fuel Power Plant (APF). This technology is both usable as for CHP plants and power-only plants. APF CHP regulates as freely as conventional large CHP plants, but produces with higher total efficiencies and a closer ratio between power and heat production. The electricity efficiency for APF CHP plants are 48.5% and the heat efficiency is 43.5%. This report dwells no further into the technical aspects of APF large CHP technology.

## 4.10 Open system analysis on Wood Pellet Combustion model

The system of the APF-based large CHP plants are very similar to the Reference system. Between the two scenarios, the discernable differences are the fuel type and the efficiency of the large CHP plants. The ratio between power and heat production is so that for every one TWh of electricity produced, the APF large CHP plants produces 0.89 TWh of heat. This ratio is majority-minority inverse to the technologies used for large CHP plants in the Reference scenario. Figure 29 shows the excess electricity production for the Wood Pellet Combustion model Open system analysis.

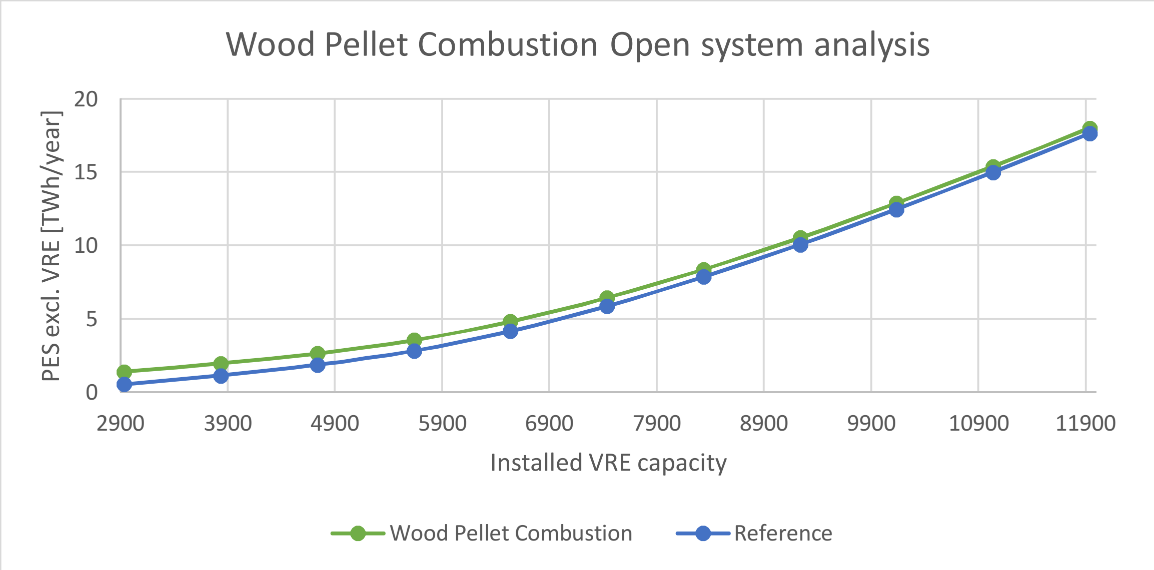


*Figure 29 - Open system analysis for the Wood Pellet Combustion model*

The inverse production ratio between electricity and heat causes more excess electricity production to occur in low-VRE conditions in the Wood Pellet Combustion scenario than in the Reference scenario under the same conditions. During hours where CHP produce to fulfil the heat demand, it produces more electricity, in excess if not demanded in the system. As the VRE capacity increases, the collected CHP plants of the system produces more electricity during the year than in the Reference system, reducing the power plant electricity production. The compared lesser power plant production causes the comparative EEP difference to decrease.

## 4.11 Closed system analysis on Wood Pellet Combustion model

With no direct regulation, the Wood Pellet Combustion model produces more EEP than the Reference. APF large CHP plants in the Wood Pellet Combustion model has higher efficiencies of electricity than the Reference, meaning a larger electricity production when utilising the CHP to cover heat demand. In EEP regulated hours with EEP risk and unfulfilled heat demand, boilers produces a larger share of heat. The boilers utilise a higher total efficiency than CHP plants. The higher total efficiency of the APF-based large CHP plants decreases the fuel use for the system under any VRE capacity, shown in Figure 30.

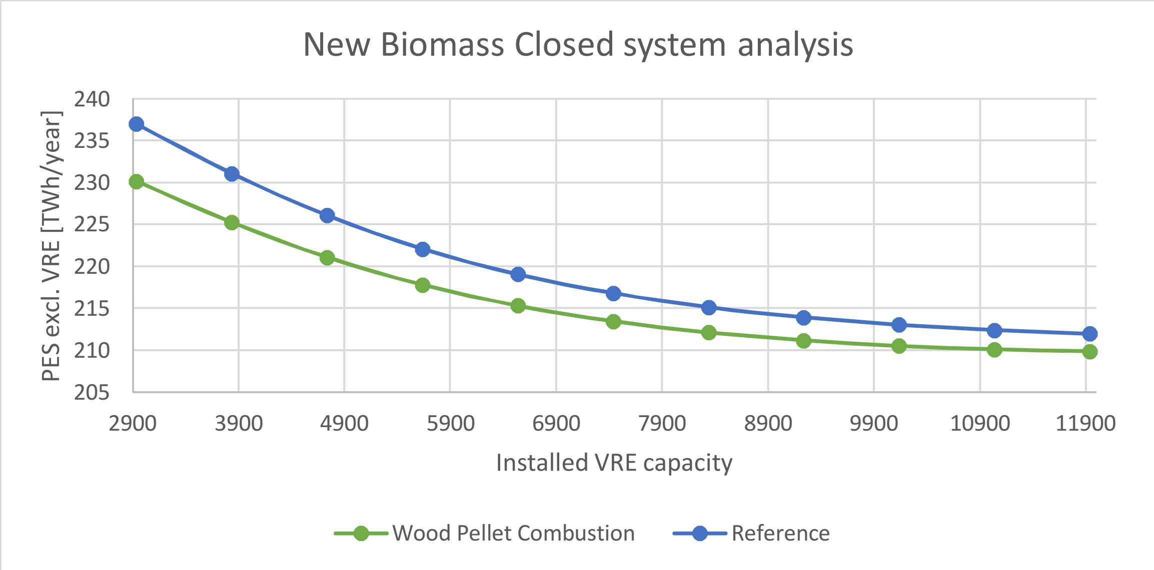


*Figure 30 -Closed system analysis for the Wood Pellet Combustion model*

Figure 30 shows the impact of the higher total efficiency of the large CHP plants between the Wood Pellet Combustion and the Reference models. As the production of the large CHP plants decreases under higher VRE capacity conditions, so does the efficiency difference influences between the two models.

# Model scenario comparison

This report presents four model scenarios exploring the role and impact of large combined heat and power plant in the Danish energy system by utilising different technologies and testing them in models under different conditions of VRE capacity. The models judge the different technologies and systems by their ability to adjust to changing capacity of wind power, in both analyses with abundant export abilities and analyses with all excess electricity production avoided by direct regulation. The scope of the report is limited to atomistic focus just on the large CHP sector and the impact changing this has on the energy system under different conditions.

Through Chapters 4-0 the different models are present in their ability toward handling excess electricity production. In the different sections, the models results are compared to those of the Reference systems. The results presented in Chapters 4-0 are technical in nature and not a comparison between different options, only to the business as usual case scenario.

Throughout this chapter, the different technology models and the Reference scenario are all directly compared to one another to clarify and discuss options of best strategy. The comparisons in this Chapter are both technical, as in the technology scenario sections, but also economic and environmental, touching upon the different aspects of policy discussion.

# 5 Technical comparisons between models

In the different sections throughout Chapters 0-0 shows technical aspects of the different models. This section compares these aspects directly for overview.

## 5.1 Open analysis comparison

The Open analysis describes the energy system where excess electricity production is acceptable. The analysis method shows the total annual electricity produced in the system if no boundaries are set for overproduction. The system does technical optimisation of both heat and power production, avoids deficiency of both and allows no import.

The models Reference, Grid syngas and Wood Pellets combustion are able to regulate their large CHP heat and power production, unlike the CFB direct use model. Three scenarios represents the CFB direct use model. Figure 31 shows the Open analysis comparison for the different models and scenarios. For the CFB direct use all scenarios uses distribution C. This distribution shows the best performance in the CFB direct use scenarios comparison in Figure 23 and Figure 24.

Figure 31 shows the comparison of EEP in the different models and scenarios using the Open system model methodology. All the scenarios and models perform under the same conditions of installed VRE capacity, use of boilers and other, smaller heat and power producers in the system.

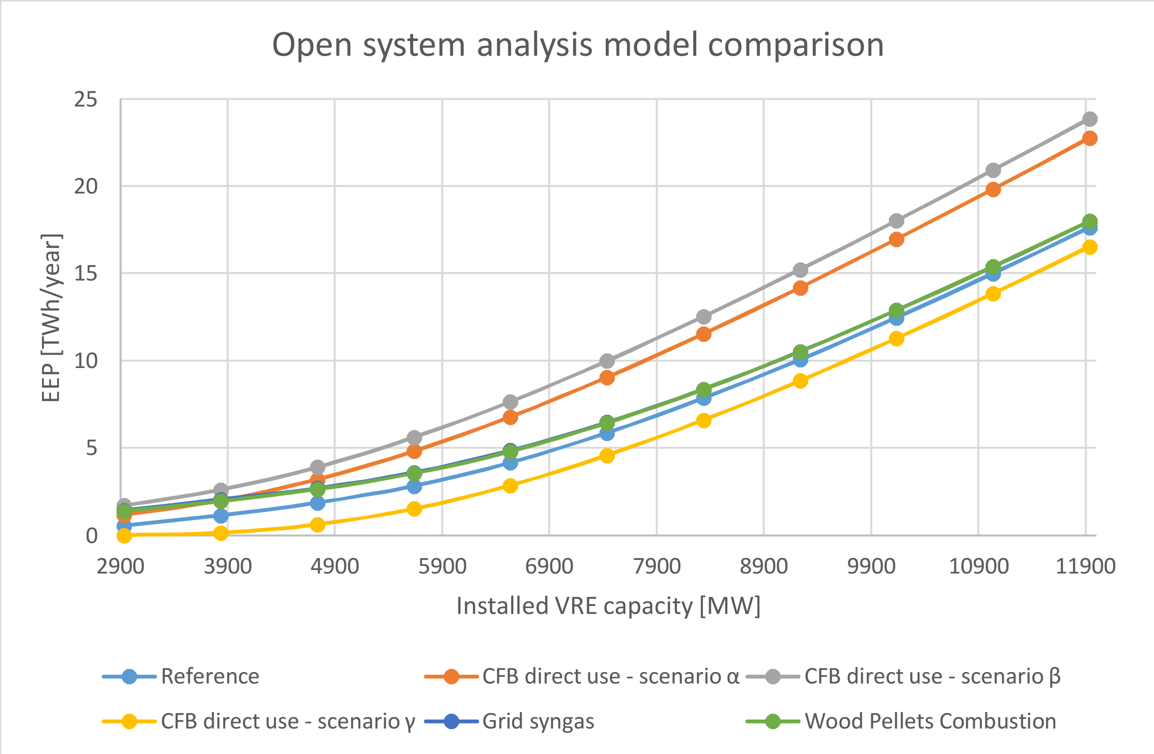


*Figure 31 - Open system analysis comparison for models and scenarios*

Through the iterations of installed VRE capacity, scenario α and scenario β consistently produces more excess electricity than other scenarios and models. The inflexibility of the heat and power production causing the large CHP plants in the scenarios to always produce at full capacity causes many hours where the large CHP plants alone can fulfil the electricity demand. Scenario γ, using the CFB-based syngas to produce only heat, produces less excess electricity than any other scenario. The system is then more dependent on other electricity sources in the system, VRE or otherwise. Scenarios β and γ overproduces heat by 2.33 TWh to 2.73 TWh on a yearly basis, as shown in Figure 20.

The systems with flexible technologies produces very similar amounts of excess electricity. The similar EEP comes from the shared electricity capacity for large CHP plants of the models. Differences in heat capacity causes small EEP differences, from hours where heat is in demand, produced by large CHP plants with electricity as a bi-product. To closer observe the difference Figure 32 shows the EEP flexible models under chosen VRE capacity conditions.

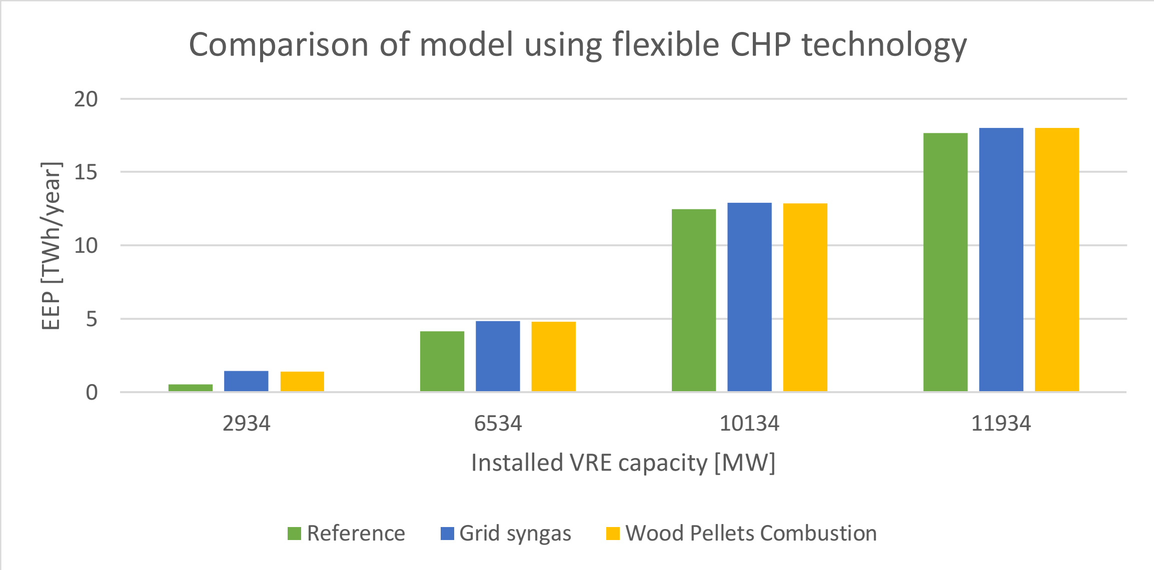


*Figure 32 - EEP comparison of models with flexible CHP technology*

Figure 32 shows how close the excess electricity production is of the different flexible large CHP scenarios. Between the two biomass fuelled models, Grid syngas and Wood Pellets combustion, the difference declines by raising the system's VRE capacity. Compared to the Reference scenario, the flexible large CHP systems shows a trend as the system adds more VRE capacity. The marginal difference for excess electricity production decreases with the increase of VRE capacity. The opposite trend shows in the scenarios where the electricity production is fixed. Figure 33 shows this visually for all scenarios and models, showing marginal excess electricity production to the Reference scenario.

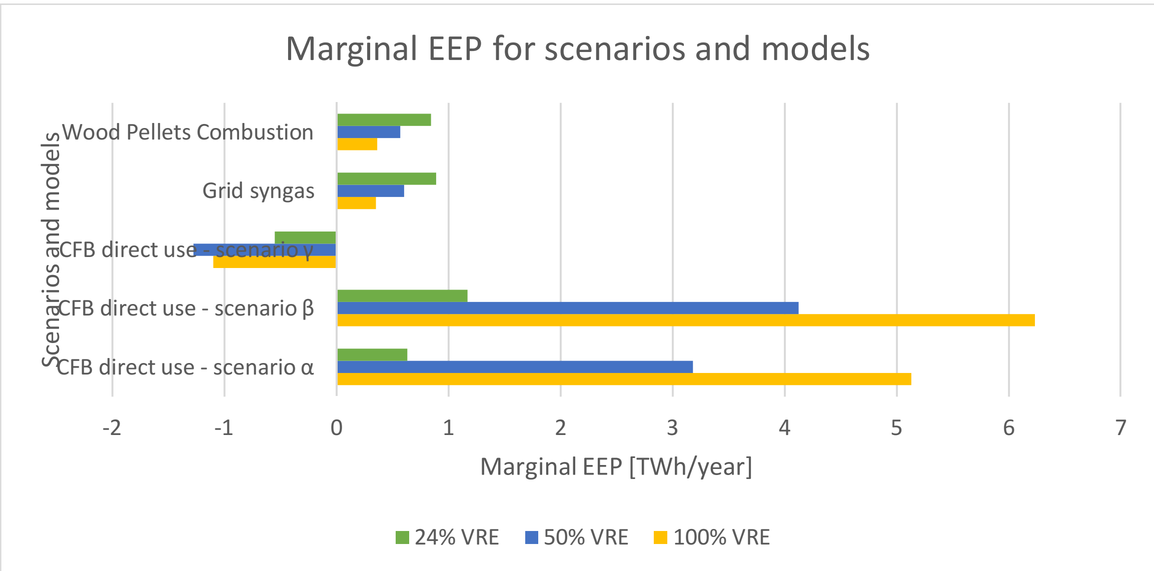


*Figure 33 - Marginal EEP from Reference in three different VRE capacity conditions for scenarios and models*

The missing flexibility of the large CHP plants in the CFB direct use scenarios α and β causes a constant production of electricity across seasons, even in hours and conditions where this is in excess. The flexible large CHP scenarios, Grid syngas and Wood Pellets combustion, follow the same pattern of production as the Reference scenario, but have different ratios between heat and power production. This ratio difference matters less the less produced yearly electricity, causing the marginal difference to decrease over VRE integration.

Scenario γ shows, as the only scenario, a negative marginal EEP. Scenario γ utilises much less electricity capacity in the system than other scenarios and the Reference. This marginally deficient electricity capacity means more of the VRE source electricity produces within the boundaries of excess. The VRE conditional production of excess electricity develops differently than in other scenarios, shown in Figure 31. Under some intermediate VRE capacity conditions, scenario γ produces marginally less excess electricity than under the minimum and maximum conditions.

There are considerable differences between the flexible and non-flexible methods of producing large CHP electricity in terms of excess electricity production. As shown in Figure 31, greater flexibility of large CHP plants causes greater flexibility of the overall system and avoids EEP. For comparable flexible energy sources, the type of plant and its fuel and efficiency characteristics matters little to the overall flexibility of the system. The electricity optimisation is little dependent on the heat production characteristics of the large CHP plants. The Open system analysis under rising VRE capacity strongly favours plants with the ability to either regulate electricity production or not produce electricity at all, as shown by scenario γ in Figure 31.

## 5.2 Closed analysis comparison of models

The Closed system analysis method seeks to avoid any excess electricity production. In hours with risk of EEP, the system uses three steps in priority to reduce electricity production forcefully. First priority is to replace small CHP heat production with boilers, avoiding the electricity bi-production. The second step is using the same method on large CHP plants. Final priority is shutting off wind capacity. The method uses these steps in priority until no EEP occurs or no more capacity is removable from the system. The more the system utilises VRE sources to cover demand, the less fuel other sources consumes. The Closed system analysis judges the technology on the yearly amount of fuel consumed in the system.

The better the system is to regulate its fuel consuming sources, the more variable renewable energy covers the system’s demand. Figure 34 shows a comparison of the different models and scenario analysed by the Closed system methodology under increasing VRE capacity. Scenarios that are capacity distribution dependent uses distribution profile C, as this proves the most efficient throughout Subsection 4.3.4.

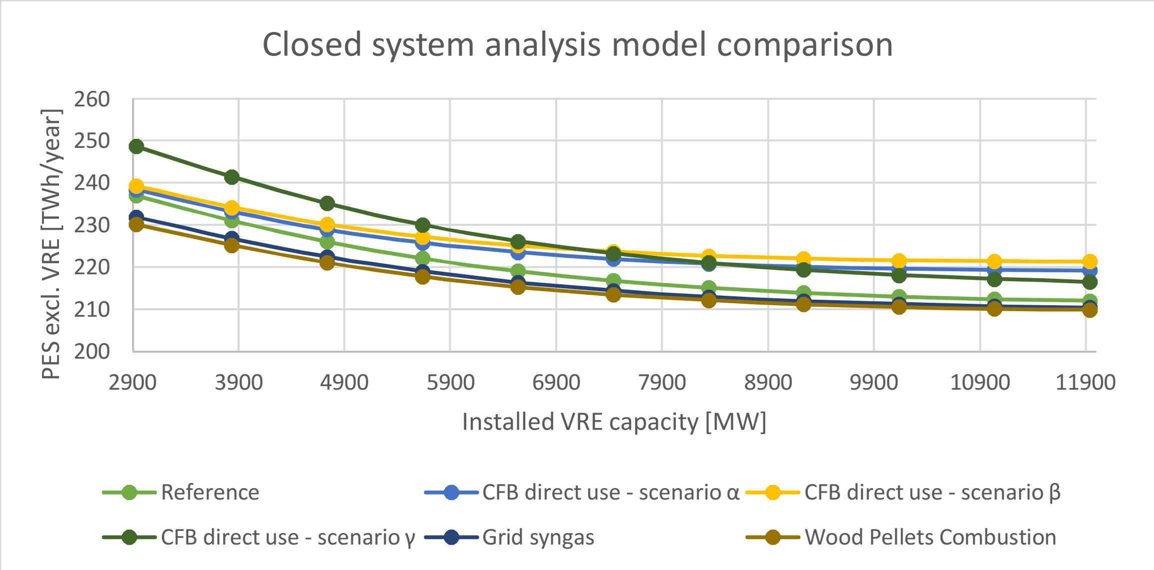


*Figure 34 - Closed system analysis comparison of the different models and scenarios*

For most of the models and scenarios showed in Figure 34, the fuel consumption decreases with a steady lesser decline as the system adds more VRE capacity. In CFB direct use scenario γ, large boiler capacity replaces the large CHP capacity, meaning a much lesser electricity capacity in the system. Under low-VRE capacity conditions, other sources produce the deficient electricity in the system, causing higher fuel use. Scenario γ also overproduces heat, wasting fuel. As the conditions shift towards 100% VRE capacity of demand, the VRE sources produces a larger share of the otherwise lacking electricity.

The first scenario presented in the report is the Reference scenario. All other scenarios and models build upon and compares to this. The purpose of this report is to analyse and show how system changes compare to the business as usual scenario that is the Reference. Figure 35 shows the marginal fuel use under three chosen VRE capacity conditions. Figure 35 uses the Reference scenario as its reference point, meaning zero in each of the conditions is the fuel use of the Reference scenario.

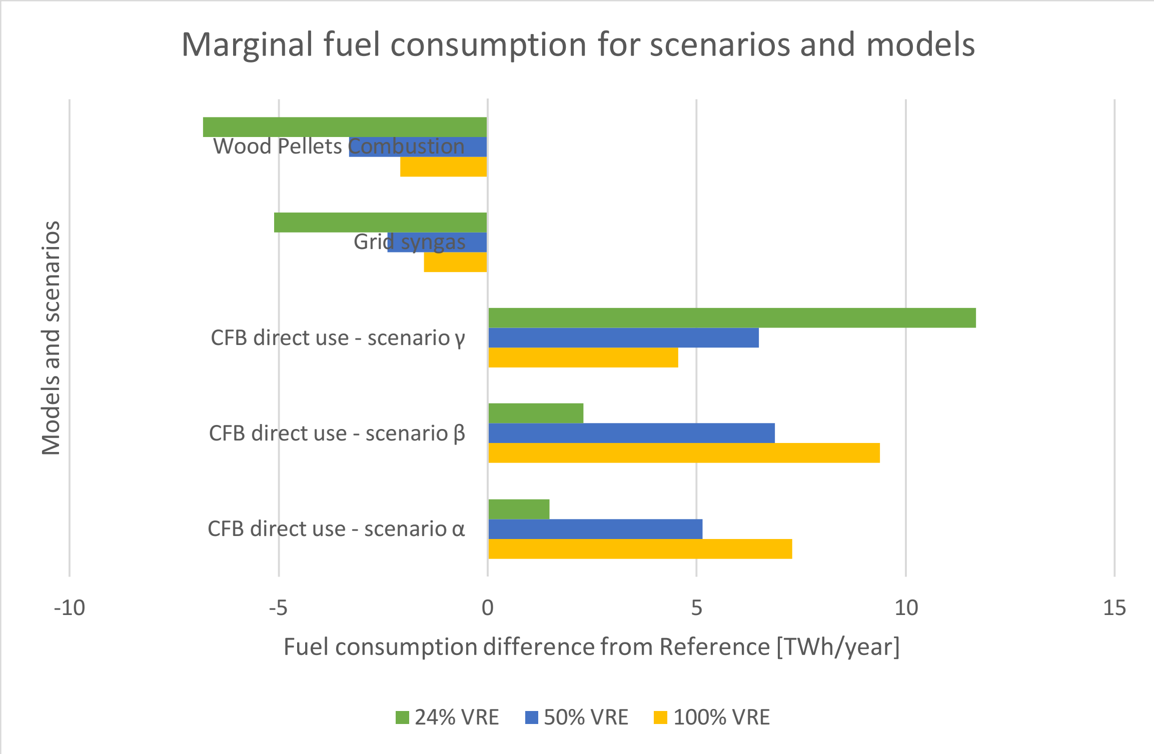


*Figure 35 - Marginal fuel use in different scenarios and models to the Reference scenario under three VRE capacity conditions*

Figure 35 shows that, for the scenarios and models where the electricity production is distribution wise bound; the marginal fuel consumption increases the larger the capacity of VRE sources. For models and scenarios where the large CHP electricity production capacity is either flexible or replaced by flexible sources, the marginal difference, whether more or less consumptive, decreases as more VRE capacity enters the system. The relevance of the large CHP plants for electricity production and the general fuel based electricity production decreases as the system gives priority to the ever more VRE.

After installation, the energy from VRE sources is marginally free, compared to fuel based sources. In this light, the EEP regulation VRE reduction is energy loss. The EEP regulation of Closed system analysis thereby wastes VRE electricity, compared to the Open system analysis method. Figure 36 shows the maximum potential (unregulated) yearly VRE production compared to the VRE utility of the scenarios and models.

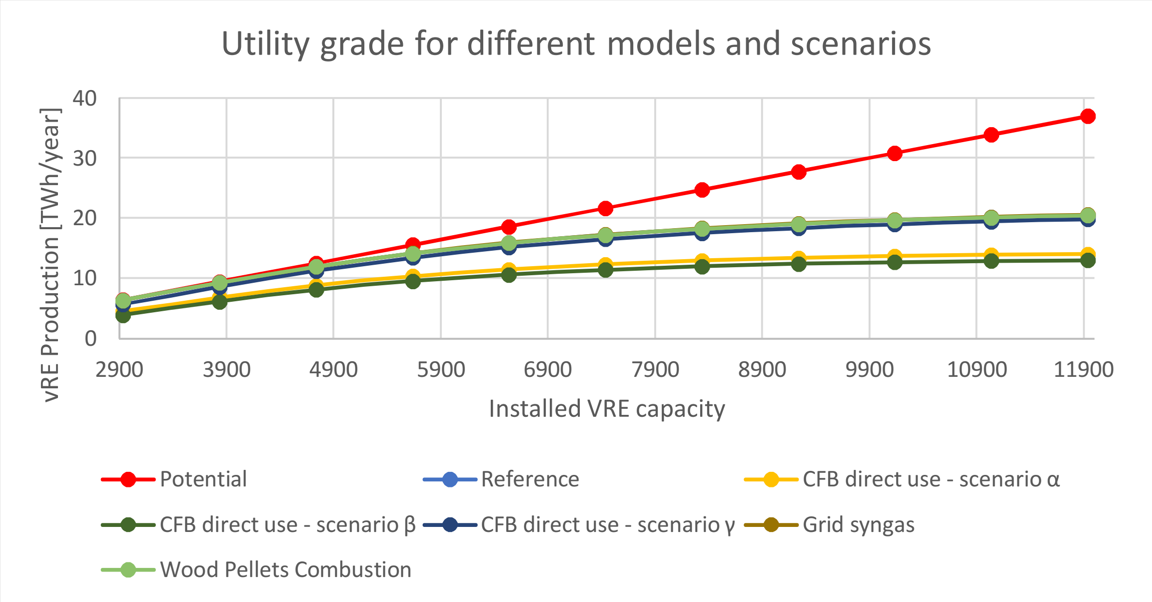


*Figure 36 - Unregulated potential and scenario utility of VRE source electricity*

The higher installed capacity of VRE sources, the more wasted VRE potential through EEP regulation. Systems with flexible large CHP plants utilises the VRE produced electricity more than systems with fixed electricity production from large CHP plants.

Figure 36 shows the marginal wasted potential under different conditions for the scenarios and models. With low VRE integration, the Closed system wastes little VRE potential, especially with regulated large CHP plants. An increase to twice the VRE capacity increases the wasted potential by a factor of between 4 and 450 (where the base have very little wasted VRE), or by 4.4 TWh/year and 7.8 TWh/year. The doubling of VRE capacity from 50% of yearly demand to 100% of yearly demand causes a waste increase of factors between 2.3 and 3 or between 12 TWh/year and 13.7 TWh/year.

# 6 Fossil fuels and foreign dependency

For some of the fossil and green fuels, Denmark is dependent on import from foreign sources. While Denmark produces some biomass and oil, the country vastly import these sources as well. Denmark has no domestic production of coal, making import a necessity. Denmark is self-sufficient in oil production, but it is socioeconomically beneficial to export these sources. Domestic sources produces the majority of the country's natural gas demand.

The historical overview of the Danish energy system in Chapter 1 shows the consequences of foreign dependency during times of international unrest. With large fuel producers' causing international diplomacy issues in current times as well, fuel self-sufficiency is not only a dated concern (Aljazeera 2014).

Other than foreign dependency, Denmark progresses towards a cleaner energy system, replacing fossil fuels with green energy sources. The different scenarios and models replaces fossil fuels in the large CHP plants with biomass and analysis its production and consumption under conditions with increasing VRE capacity. Figure 37 and Figure 38 shows the fossil fuel use of the scenarios and models marginal to the Reference scenario under three chosen VRE capacity conditions for Open and Closed systems, respectively.

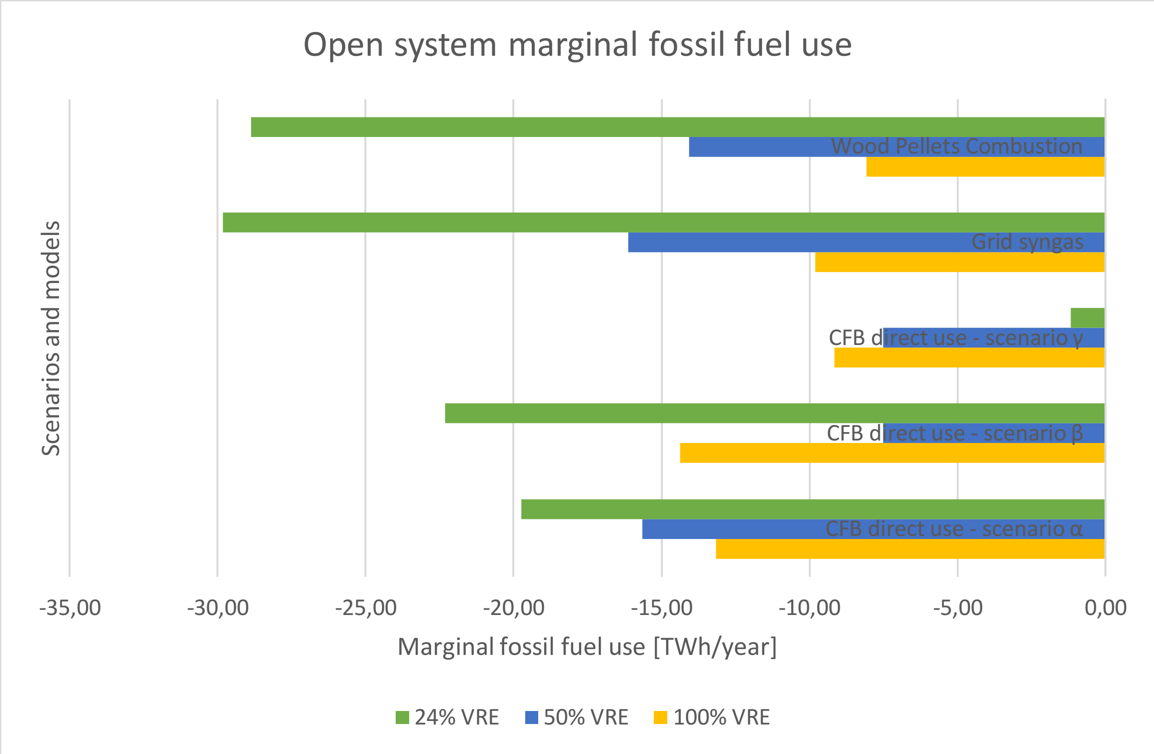


*Figure 37 - Marginal fossil fuel use of scenarios and models to the Reference in Open systems*

In Open system analysis, the non-VRE power producers regulate to fulfil the production demand not fulfilled by VRE sources. In order to fulfil heat demand, the technical analysis lets CHP plants produce electricity as a bi-product. Figure 37 shows that marginal fossil fuel savings for flexible models decreases as the conditions add more VRE capacity. The large CHP plants in both the models and in the Reference produces less energy while the other sectors (transport, individual, industry etc.) remains largely unchanged in their fossil fuel use. In inflexible scenarios, different adaptions to VRE conditions means the marginal fossil fuel use depends more on the exact capacities and distributions of the scenarios. Scenarios γ saves fossil produced heat and lets the VRE sources produce more without EEP.

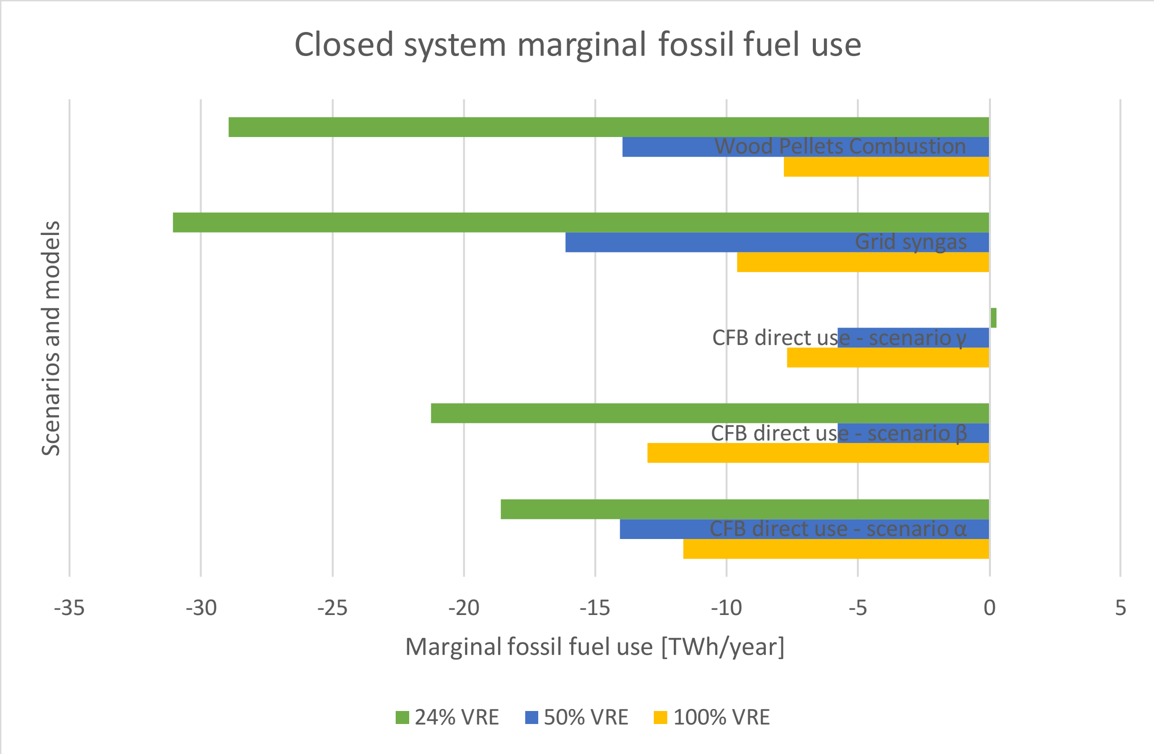


*Figure 38 - Marginal fossil fuel use of scenarios and models to the Reference in Closed systems*

Closed system analyses shows similar fossil fuel savings to the Reference as the Open system analyses in Figure 37. The models similarly replaces the capacity of fossil fuel based large CHP plants from the Reference scenario. The production from CHP and power plants are very similar for the models between the Open and Closed systems, showing similar results. The other sectors remain unchanged from between the analysis methodologies.

# 7 Economic comparison

The energy sector is associated with large costs, both in terms of investments, operation of producer, intermediate and consumer ide and fuel use in energy plants. The consumer costs associated with the Danish energy system lies within the area of 161 billion DKK (in 2012), including taxes and VAT (Danish Energy Agency 2013). For the energy sector as an industry, the running and investments in plants are associated with large costs and risks. Chapter 1 shows the radical change of the strategy in the Danish energy sector, which for most examples occurred due to changes in fuel prices and availability. The right fuels an technologies to use are highly determined by the forecasted costs and benefits in the system.

The economic analysis presented throughout this section is as the other analyses limited in scope to changing the large CHP plants in the system. Like most other analyses in the chapter, the economic assessment presents the marginal costs between the scenarios and models in this report. This economic marginal analysis divides into four parts; each presented in each their subsection. The subsections are, in order, economics for investment costs, marginal economics for operation and maintenance costs and marginal fuel costs ending with total marginal costs between the systems.

All prices are in 2014 DKK using inflation indexes from (Danmarks Statistik 2014). Where there is no 2020 prices, the prices are assumed the same as for 2012, adjusted for inflation.

## 7.1 Marginal investment costs

The analysis for the investment costs of the scenarios and models focuses on the marginal costs in the system by replacing large CHP plants. The analysis does not show the total investment costs of the system, like the analysis ignores the large investments in VRE sources between the conditions. The investments analysis assumes all other parts of the system are equally invested in and equally costly between the scenarios. This means that new investments in other plants, like small district heating plants or individual heating, is excluded from the analysis as they are marginally indifferent.

The investment costs depends largely on the scenario specific technologies and capacities. The marginal investment analysis presents the investment costs for the scenarios as yearly payment costs and follows certain financial assumptions:

*The value depletion of the plants occurs equally between years and the plants experience full value depletion over its lifetime.*

The different technologies have different investment costs and different life spans. The assumption states that the value of the plant declines gradually year-by-year over the life span of the plants and that the value at the end of the life span is zero.

*All investments takes place in year 2020 using loans with fixed yearly payments that spans the lifetime of the plant*

The value of the plants are full, as they are new in year 2020. This strategy does not occur in real systems, where investors timely diversify large investments and rollouts of technologies are desynchronised, but the analysis does it for simplification. Large investments obtains the money through loans. There are many different payment methods on loans, but for the ability to compare investments equally; all investments pays by fixed payments across all years. To show economic difference easily for plants of different life spans, the loan period of all investments is the lifetime of the plant.

*All loans have a fixed interest rate of 3%*

With large, secure investments with a long payment period, such as in large energy plants, the banks offer very low interest rates. Even if the life span of the technologies differ, causing different costs of interest rate, setting up equal loan methods for the plants helps comparison.

The different scenarios uses one or two technologies for the large CHP plants. The scenarios in Chapters 4-0 focuses on a single energy plant technology each and several have gasification technologies.

Table 3 presents the prices of the different technologies used in the scenarios.

*Table 3 - Investment prices for technologies in scenarios (Danish Energy Agency 2014), (Lund, Hvelplund, et al. 2011)*

| **Technology** | **Type** | **Investment price [MDKK/MW] or [MDKK/MJ/s]** | **Life span for technology [Years]** | **Scenarios** |
|---|---|---|---|---|
| Circulated Fluid Bed | Pregasification | 3.22 | 25 | CFB scenarios α, β, γ, Grid syngas |
| Combined Cycle Gas Turbine | Energy plant | 11.67 | 25 | CFB scenarios α, β, Grid syngas |
| Advanced Pulverized Fuel | Energy plant | 16.34 | 40 | Wood Pellets combustion |
| Gas boiler | Energy plant | 0.81 | 25 | CFB scenario γ |
| Reference technologies for large CHP | Energy plant | 17.08 | 40 | Reference |

By using gasification, the technologies needed to fire the synthetic gas needs less protection from corrosion, feeds the fuel easier and have lesser particle matter in the energy fuel. These factors all makes the technology of gas turbines cheaper than combustion technologies for solid fuels.

The investment costs of the scenarios and models marginally compares to the Reference scenario. For the investments in large CHP plants, different VRE capacity conditions have no influence. The capacity of the CHP plants differ between scenarios, why scenarios similar in technologies differ in investment costs. The marginal yearly payment calculates from the investment prices and the life spans of the technologies, presented in

Table 3, and the loan interest rate. For scenarios with two technologies, analysis calculates the yearly payment for each and sums them. Figure 39 shows the marginal investment costs for scenarios and models.

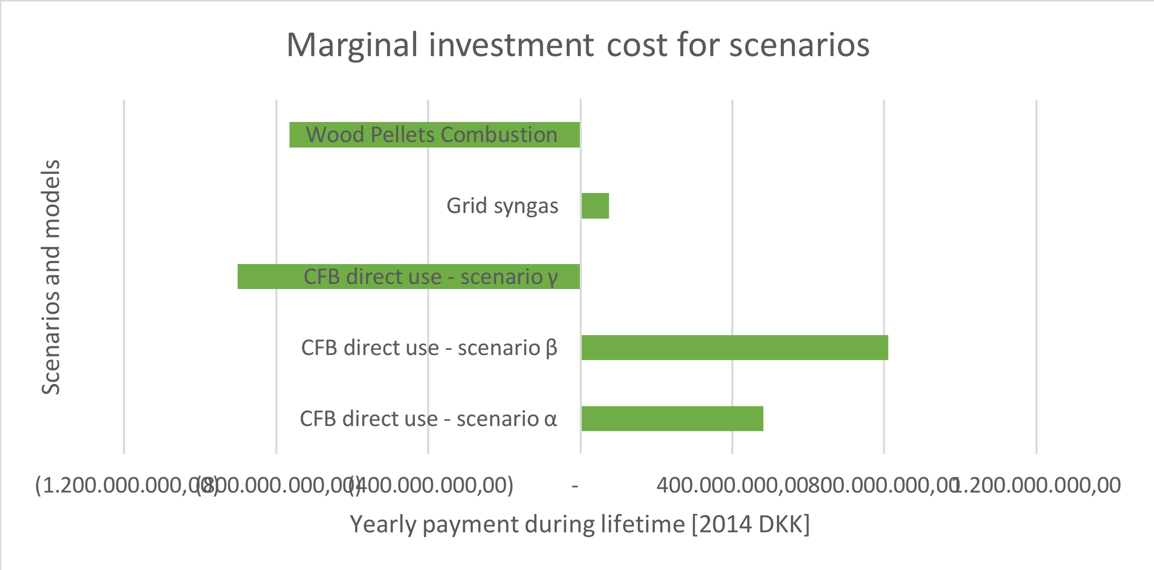


*Figure 39 - Marginal investment cost comparison for scenarios and model*

The investment costs of all of the scenarios are less than for the Reference, as indicated in Figure 39. The Reference cost per MW shown in

Table 3 is from 2011. This centralised number for all the large CHP technologies and their shares does not change towards year 2020 as for the technologies with data from (Danish Energy Agency 2014). For these technologies, future investment price reductions are in the area of 6%-20%. Expecting the same reductions for reference scenario technologies, the marginal investment costs for scenarios would be similarly larger.

## 7.2 Marginal operation and maintenance costs

Maintenance and operation (O&M) costs depends very much of technologies. The operation costs cover salary for plant workers, consultancy and system related costs. The maintenance costs cover reparations and changing equipment on the plant. The large cover of this cost segment also causes it to split in fixed costs, independent of use and marginal O&M costs that are production dependent. These differ in value and division from technology to technology. Because some O&M costs are production specific, the costs differ between Open system analyses and Closed system analyses.

The scope of the maintenance analysis covers the whole fuel based electric system. The different scenarios produce electricity from large CHP plants differently, which causes different reactions throughout the electricity system. Where there is no production from large CHP plant or VRE sources, the smaller CHP plants and large power plants produce the missing power. This causes extra O&M costs for these other plants, which is included in the analysis. Figure 40 shows the marginal operation and maintenance cost of the scenarios and models in Open systems.

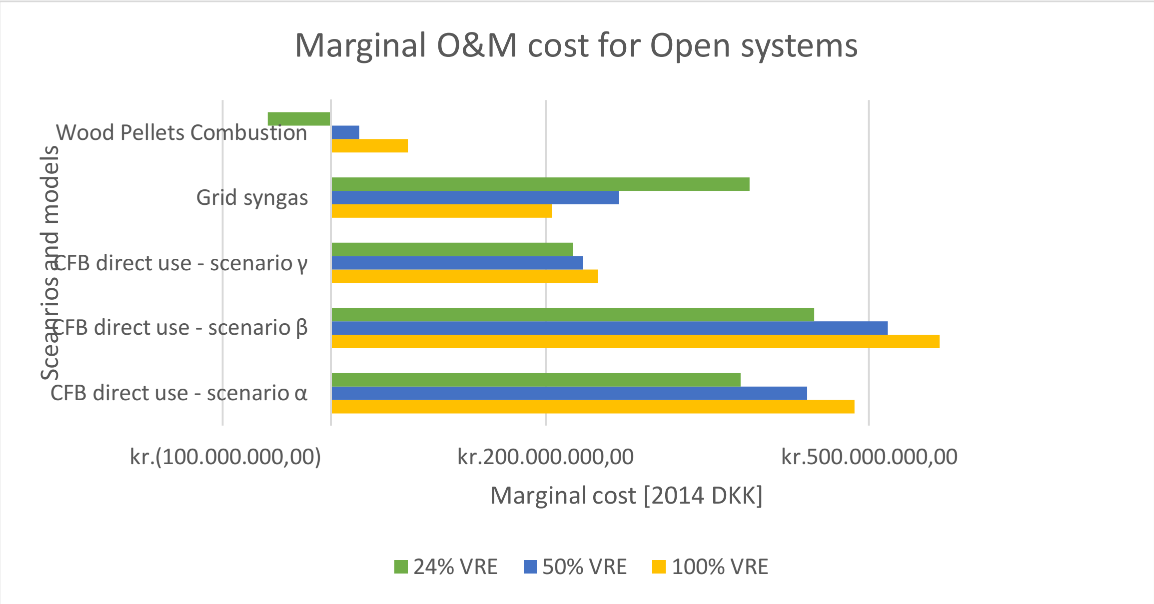


*Figure 40 - Marginal O&M cost to the Reference for scenarios and models in Open systems under three chosen VRE capacity conditions*

Figure 40 shows how the O&M costs in Open systems is larger for most scenarios and models under any VRE capacity condition. This too holds true for the O&M costs in Closed systems, shown in Figure 41.

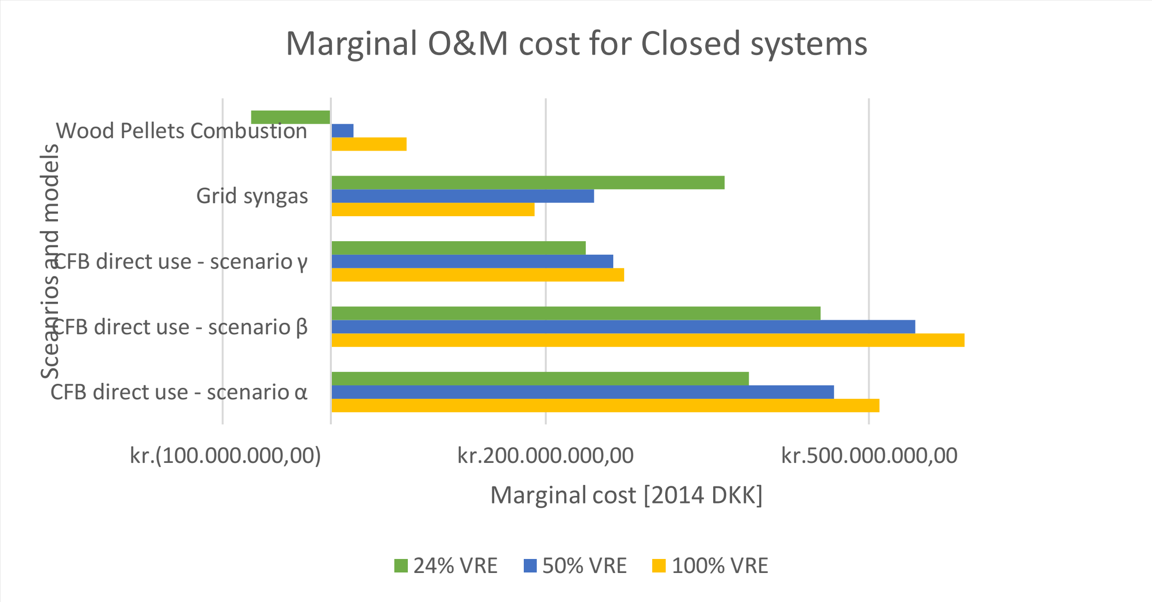


*Figure 41 - Marginal O&M cost to the Reference for scenarios and models in Closed systems under three chosen VRE capacity conditions*

Shown in Figure 40 and Figure 41, the marginal O&M costs between scenarios are very similar for Open and Closed systems. The majority of the O&M costs depends on the production of the plants. There is very little differences among the production in the electricity system plants in Open and Closed systems. The technology most similar to the Reference technologies in the Wood Pellets combustion scenario is the least costly in terms of O&M costs. The extra O&M costs associated with the gasification plants and different production capacities throughout the year contribute significantly to the O&M costs of the other scenarios.

## 7.3 Marginal fuel costs

The largest change from the Reference scenario to others analysed is their relation to fuel and fuel types, as shown in subchapters 5 and 6. Measured in price per energy unit, coal is the cheapest energy source; it will be too in year 2020. The cheapest biomass, straw, in year 2020 will per energy unit cost twice the price as coal while the most expensive will match the price of natural gas. Table 4 shows the 2020 fuel prices for producer plants, the price being in 2014 DKK.

*Table 4 - Year 2020 fuel prices for power producers, given in 2014 DKK*

| **Fuel prices 2020** | |
|---|---|
| | DKK 2014 [MDKK/TWh] |
| Coal | 89.67 |
| Natural gas | 277.68 |
| Oil | 353.44 |
| Biomass - straw | 163.25 |
| Biomass - Wood chips | 192.93 |
| Biomass - Wood pellets | 277.29 |

While no other fuel competes in price with coal, determining one biomass other another potentially saves the producer 41% of the fuel costs. The ability to utilise low-grade fuels depends largely upon technology, as wood pellets are far easier in their similar application to coal.

The different scenarios focuses on different types of fuel. The Reference scenario uses a variety of fuels, with coal as the majority in the large CHP plants. In the scenarios with gasification, the entire fuel for large CHP plants utilise low-grade biomass source straw and wood chips. These converts to synthetic gas through gasification and combusted in a fashion similar to natural gas.

The scope of the fuel analysis covers the entirety of the electricity-producing sector. VRE sources uses no fuel. The limited scope of this report assumes the same use of fuels in other sectors outside the scope, independent of scenario. Figure 42 shows the marginal fuel costs for the scenarios and model in Open systems.

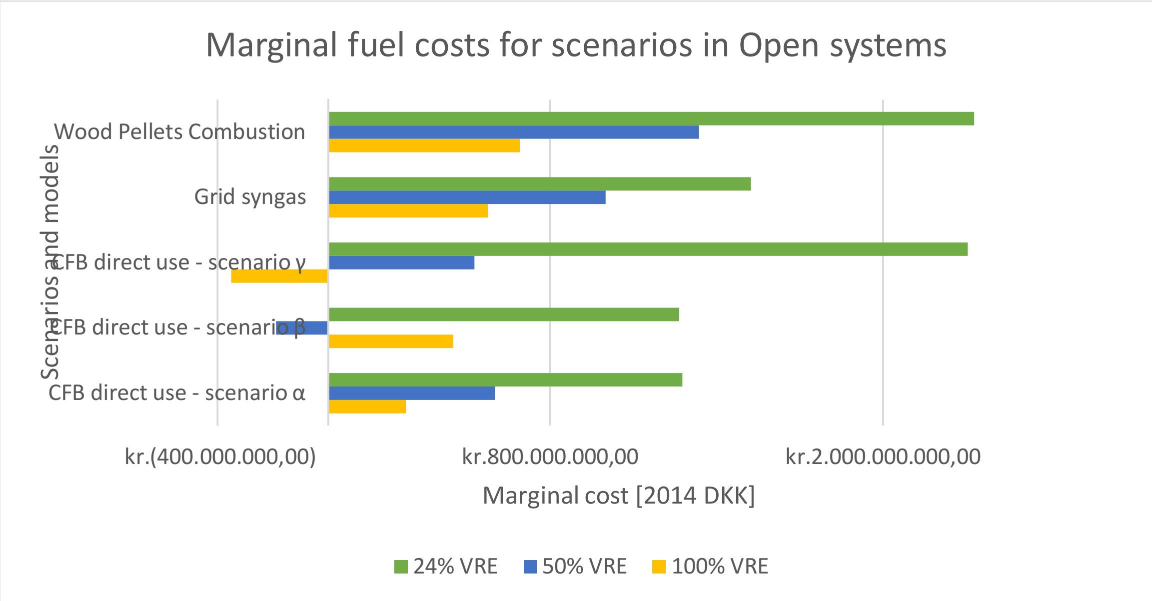


*Figure 42 - Marginal fuel costs under three chosen VRE capacity conditions for scenarios and models in Open system analysis*

Figure 42 shows the large impact of fuel prices on the systems. All of the alternative scenarios have significantly higher fuel costs in low-VRE conditions. In the higher VRE capacity conditions, as the large CHP plants produce less energy, the marginal fuel cost between the scenarios and the Reference decreases. The two most expensive cases in Figure 42 shows two different situations. For the Wood Pellets combustion scenario, the high fuel cost relates to the high price of wood pellets. The situation for CFB scenario γ is different, as the high fuel cost relates to the large use of low-grade biomass for heat only. Power plants and smaller CHP plants produce the lacking electricity, using more fuel in the process. In the Closed system analysis for marginal fuel costs, shown in Figure 43, the EEP regulation reduces the fuel cost significantly for flexible scenarios.

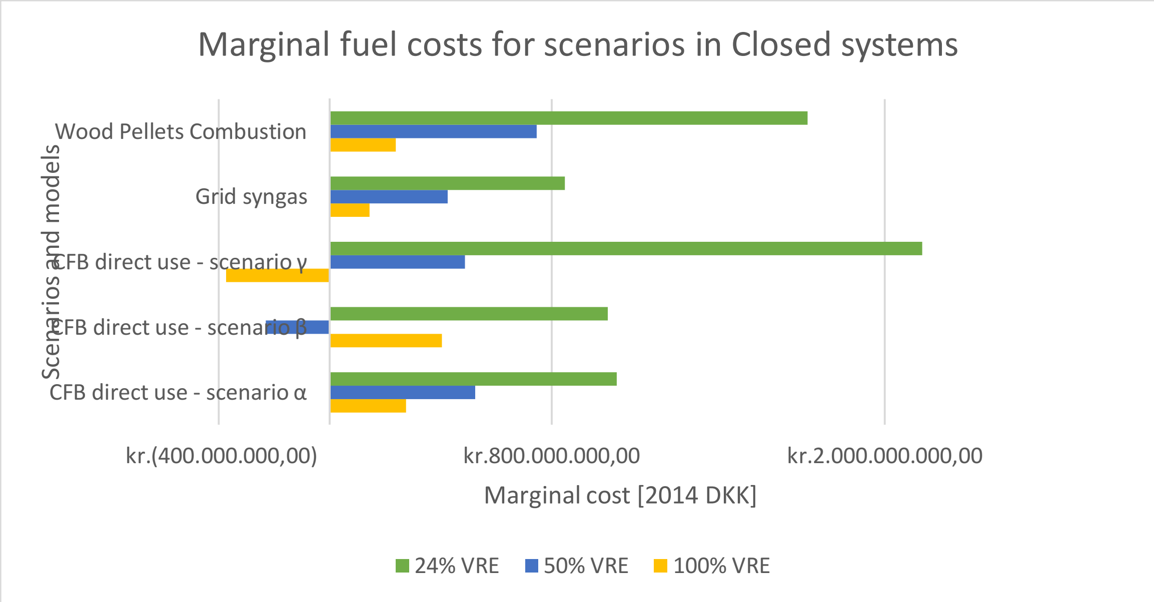


*Figure 43 - Marginal fuel costs under three chosen VRE capacity conditions for scenarios and models in Closed system analysis*

For both Open and Closed system analyses, only few cases show less fuel cost than the Reference scenario, primarily due to the fuel price difference.

## 7.4 Total marginal cost for scenarios

The different marginal cost differences presented throughout the section contribute to the total marginal costs for scenarios differently. Some technologies with low O&M costs are very high in fuel costs, and high fuel costs offsets the cheapest investment if the VRE capacity remains low.

The total marginal cost of scenarios and models combines the components of marginal costs presented through the section. The total marginal cost presents the yearly costs compared to the Reference scenario.

All the components contribute significantly to the total marginal costs for the different scenarios. The fuel costs for scenarios see most influence under conditions with low VRE source capacity. The large CHP plants produce less under higher VRE conditions, giving larger influence to other cost differences between the scenarios. Gasification direct use scenario γ shows this clearly in the total marginal cost comparison for Open system analyses shown in Figure 44.

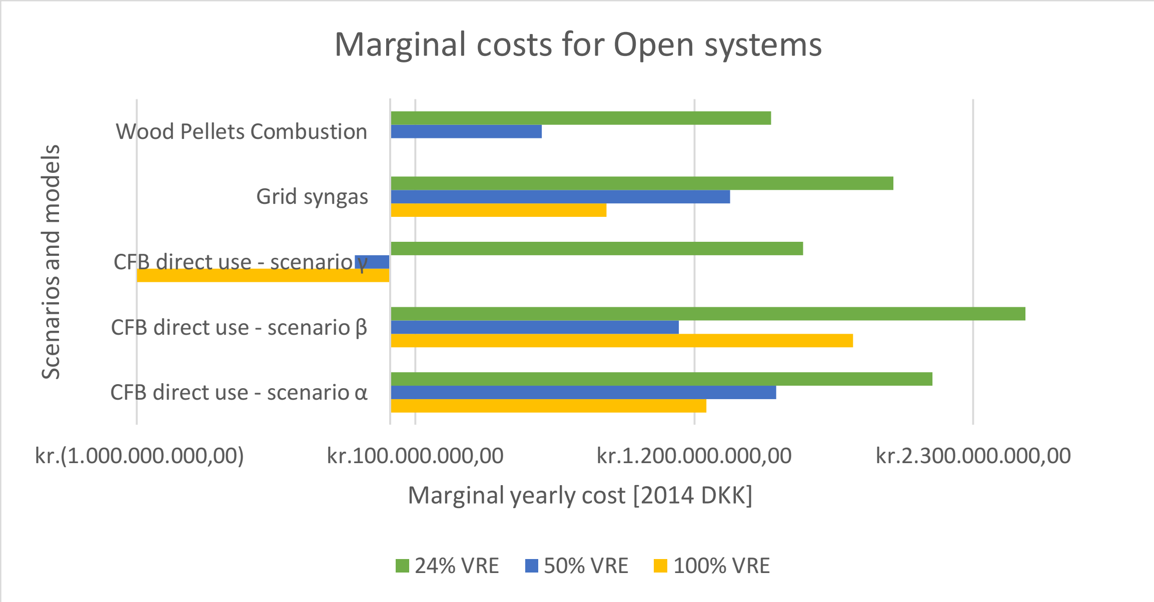


*Figure 44 - Total marginal costs for scenarios under three chosen VRE capacity conditions for scenarios and models in Open systems*

As VRE sources contributes a higher share of the yearly electricity production, the marginal cost between scenarios decreases and the yearly cost for different systems become more equal. Under high-VRE capacity conditions, the energy system needs less CHP and power plant capacity. The exaggerated investments in under these conditions contribute to a higher system price, both for the Reference and for the alternative scenarios. Planning in a way so these are reduced significantly lowers the system costs, as well as flexibility lowers the yearly fuel and O&M costs. Figure 45 shows the total marginal cost comparison, where this difference between flexible and inflexible large CHP scenarios figures prominently.

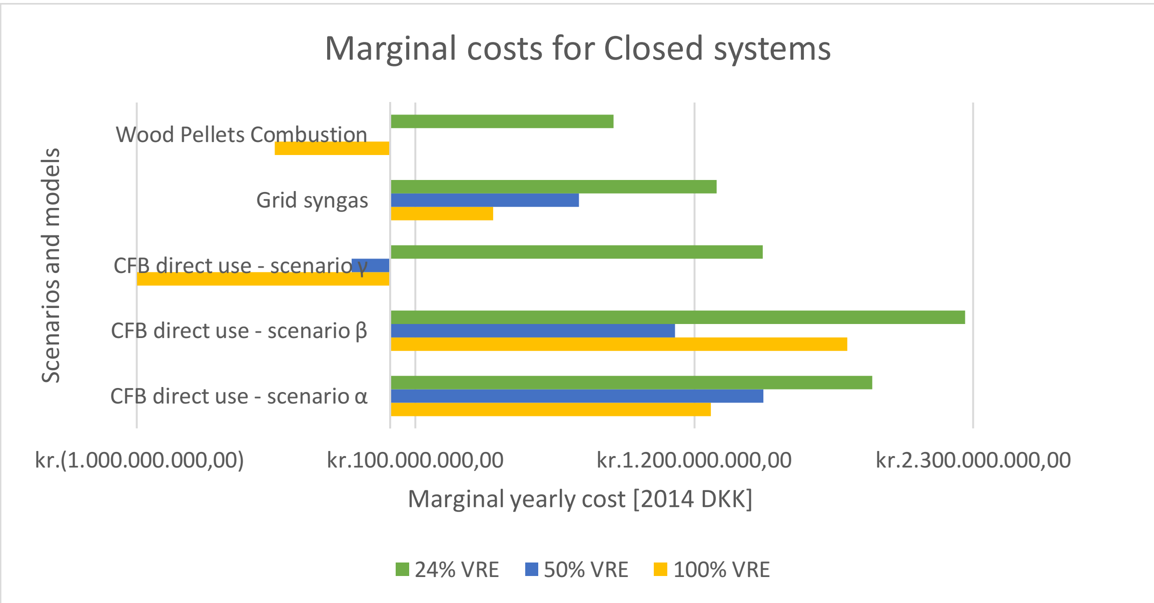


*Figure 45 - Total marginal costs for scenarios under three chosen VRE capacity conditions for scenarios and models in Closed systems*

In Closed systems, where the system actively regulates for EEP, the marginal costs are reduced significantly compared to the Open system comparison in Figure 44. In Closed systems with higher capacity of VRE sources, the flexible alternative scenarios enjoys a reduction of their marginal cost addition, while the inflexible systems stay stagnant or increase their marginal costs.

For both system analysis types the cheapest scenario under high-VRE conditions is the inflexible gasification scenario γ. However, this scenario, by removing all large CHP plants, shows the effect of reducing plants capacities in the electricity production when the system is saturated by VRE sources on a yearly basis. If all the scenarios reduced the installed plant capacity under such conditions, the system as a whole would benefit. In the high-VRE conditions, even low utilisation of the wind provides the majority of the base load needed from large CHP plants today.

# 8 Model comparison conclusion

All of the models analysed using the two system methodologies describe analytic system changes that are atomistic in nature. While a real system change of this scale happens with changes in the whole system, the models show which technologies can fulfil the place currently taken by large CHP plants that uses mainly coal as fuel.

Of the alternative scenarios, the cheapest under current, below 50% VRE capacity, is replacing the coal fired large CHP plants with similar technologies fuelled by wood pellet, as Figure 45 shows. However, as the current discussion is not just about the cheapest market price, but rather lowering the $CO_2$ emissions and reducing the dependency on foreign fossil fuels, grid distributed syngas shows a better alternative, having a larger reduction in the use of fossil fuels due to technology advantages. By utilising the technology described in this scenario as well, the regulation and size advantages can be utilised. Gas turbines have, marginally or significantly, dependent on source, better ramping abilities and can act in smaller units, opening up for further decentralisation.

If Denmark approaches wind capacities of up 100% of the yearly electricity demand, the large CHP plants is easily replaceable with large district heating plants instead. The scenario with using low-grade biomass through gasification to fuel large boilers instead of CHP show little potential with low VRE capacities. With higher capacities of VRE sources, this scenario has the lowest marginal fuel costs, using cheaper biomass and the lowest marginal investment cost, leading to the lowest overall marginal cost. This scenario has a lesser saving in fossil fuel, the smaller, often community owned, CHP plants can produce more of Denmark's electricity demand.

The comparison of the scenarios and models does not show an unambiguous best case for Denmark. The current discussion involves lowering the $CO_2$ emissions through use of biomass, whether wood pellets is the best or just the easiest choice and finding a solution that is economically, as well as ecologically sustainable. Dependent on the conditions and priorities, different scenarios fulfils these requirements the best, when looking at the issue isolated to large CHP plants. The transformation towards sustainability I the Danish energy system of course should not just focus on integrating wind power and alter existing capacity of large CHP plants, but a much wider system change. The different model results show that the part contributed by large CHP plants can transform towards different green resources, not just wood pellets, in ways that may not even add a significant price tag, looking at the system as a whole.

# Conclusion to report

This report analyses alternatives to the current fuel variety in Denmark's large CHP plants by replacing the plants with other technologies and biomass fuels in the year 2020. The report presents these alternatives in different system scenarios modelled to replace the large CHP technologies while remaining the other parts of the energy system at current level. The scenarios compares with each other and a Reference scenario, presented in Chapter 5.

Comparing the model results, there is no scenario standing out as the best performing. Compared economically, the cheapest solution depends on the general conditions in the systems. For systems having a large percentage capacity of VRE sources, the cheapest atomistic solution is to replace the current technologies with large boilers fuelled by low-grade biomass through gasification. Both in Open and Closed system analyses, this scenario only provides a lower marginal price than the Reference. If Denmark does not expand the VRE capacity further, the lowest-cost system among the tested in the report is the Reference system, using a mix of fossil and green fuels.

The discussion leading the theme of the report is how to interchange the fossil fuel use with more sustainable sources in the large CHP plants. The comparison in fuel use between the different scenarios show the least use of fossil fuels in the Grid syngas scenario, where all large CHP plants uses synthetic gas through the natural gas grid made from low-grade biomass. The marginal fossil fuel use between this scenario and the Reference is 29.8 TWh-31.1 TWh, dependent on system analysis model for conditions with low VRE capacity. For systems with higher capacities of VRE sources, the analyses for CFB scenario β roves lowest fossil fuel use. In this scenario, the gasification plant feeds the synthetic gas directly to the combustion chamber, making for inflexible production patterns focusing on large heat production. This scenario overproduces both heat and electricity on a yearly basis.

The report analyses the six scenarios mainly by focusing on the system reaction under two different system regulations. Open system analysis allows excess electricity production. The system measures the EEP under different VRE capacity conditions. General tendencies for systems under this analysis method is larger EEP as VRE capacity increases. Inflexible production patterns for large CHP plants in scenarios causes much larger excess electricity production than for the flexible scenarios with flexible electricity production from large CHP plants. The EEP under highest VRE capacity conditions are 26% higher for the inflexible scenario of least large CHP capacity than for the highest capacity flexible scenario. All scenarios, including the Reference, display EEP over 15 TWh/year for 100% saturation of VRE capacity for the electric system.

In Closed system, all electricity-producing units, including VRE sources, regulates to avoid EEP. The large CHP plants of the inflexible scenarios does not regulate, forcing the system to shut off more VRE capacity. This leads to higher fuel consumption for inflexible systems than for flexible ones. All the scenarios shows signs of VRE capacity saturation around 5,000 MW, where the percentage utility of the wind power in the systems decreases significantly. When approaching the analysis maximum VRE capacity of 12,000 MW, the added capacity almost no effect has on utility. For Closed systems, the curtailment of highest VRE capacity turbines is ~65% for inflexible scenarios and ~44% for flexible scenarios. Independent on VRE source capacity, alternative flexible systems uses less fuel resources than the Reference scenario does.

All the technologies of alternative scenarios, although presented for year 2020, are technologies commercially available in year 2014. The Circulated Fluid Bed gasification technology can utilise a variety of fuels, ranging from high-grade coals to low-grade biomass, at high efficiencies to produce synthetic gas for CHP plants, power plants and other uses. Application of this technology makes fuels of larger domestic share possible by gasifying resources such as straw from the agricultural sector.

While the total marginal costs are lowest for the Wood Pellets combustion scenario and the CFB direct use γ scenario, both these scenarios show significant issues. The marginal fuel consumption is much higher for the inflexible scenario γ, as well as the fossil fuel use. In reducing the dependency, both Wood Pellets combustion scenario and the Grid syngas scenario shows results far better than the other scenarios. The current demand for wood pellets relies heavily on import and is poised to do so in the future as well. Using gasification technologies, the flexible gas powered CHP plants could utilise domestic production of low-grade biomass fuels that regenerate on a yearly or bi-yearly basis.

The Grid syngas scenario, while not the cheapest or the one producing the least EEP or use the least fuels, fair well compared to the other scenarios overall. It is not the marginally worst scenario in any analysis category and fair in the better end of the scenarios in most. The flexibility of having two separate systems, gasification and combustion, also opens up for further, cross-sector flexibility. Redundant capacity of gasification plants could provide usable, green fuel to the transport sector or for individual use. This report, while somewhat inconclusive when looking at the analysis as is, deem the Grid syngas scenario the paramount among the tested, due to well performance in the analyses, the possibility for domestic low-grade fuels and the high flexibility, both in the heating sector and broader.

The Hobson's choice discourse currently happening among professionals and academics on the future of the large CHP plants (and power plants, not analysed) does not describe the only options for the sector. Without transforming the energy producing landscape significantly, the Danish energy sector can move towards using biomass as fuels on large CHP scales without using wood pellets of questionable sustainability. The only 113-year history of the Danish energy sector (counting from the first power plant) proves that sudden system changes because of fuel concerns has happened before without damaging the energy system in the long term.

# Report discussion

## 9 Scenarios

The report presents different scenarios, differentiated by different production capacities, different technologies and different approaches. This section discusses these scenarios as a whole and individual scenario approaches.

### Capacities of large CHP plants and VRE conditions

Projected demand determines the capacity of large electricity producing plants in a market based energy system, such as the Danish. Most of the scenarios use a capacity of 2,500 MW electricity, derived from the Reference scenario. The analyses use this electric capacity across all scenarios and conditions to study the analyses under equivalent conditions for comparison. Two scenarios (scenarios β and γ for direct CFB use) use purposely uses different electric capacities for large CHP plants, as they models other focuses for the plants.

In designing elements for future energy systems, such as done in this report, investors optimise plant capacities to the forecasted system. In this report, which models systems under large range of VRE capacities, there is no optimisation of plant capacities.

In systems with very large capacities of VRE sources, the electric production from other systems needs to be limited and mainly for use in hours of little wind. Under condition as presented in the report, with capacities of VRE sources capable of producing the entire yearly demand, power plants are rarely operating at full capacity.

The flexible scenarios (including Reference) models large power plants with a minimum of 450 MW running capacity, to ensure functionality and ramping abilities. Large CHP plants can regulate off entirely. For inflexible scenarios, the large CHP plants (or large heating plants in scenario γ) does not regulate capacity, and thereby production, but are only adjusted four times yearly. In system design, these capacities would be adjusted appropriately to the system they are to engage in. Especially inflexible scenarios could avoid fuel use and EEP if the plant capacities are adjusted to the individual system for each VRE capacity condition.

### Optimisation of capacity profiles

The inflexible scenarios use capacity share profiles to determine the level of production for each season, and when these change. These profiles are similar built, but operate with different levels throughout the year. These profiles are not optimised, neither for electricity or heat production nor for accurate needed capacities. This leads to periods where the production is unmatched to the demand. Dependent on scenario, the heating demand in periods is either higher or lower than the capacity of the large CHP demand that covers the district heating area. This causes heat overproduction or the need for running boilers, wasting energy.

By optimising the dates for shifting season levels and the seasonal capacity levels, fuel and EEP would decrease while also avoiding heat overproduction.

### No heat storage in CFB direct use scenarios

Due to model constraints of the EnergyPLAN software, the large inflexible CHP plants in scenarios α, β and γ cannot store overproduced heat. The lacking ability means after several hours of overproduction, the system still needs boilers to fulfil the heat demand in peak hours. Figure 20 shows the otherwise unneeded production of heat.

# 10 Scope of the analyses

This report and its analyses take an atomistic perspective to the role of the large CHP plants in the system while measuring system-wide consequences. The section discusses this theoretical approach.

Since the national expansion of the electricity grid, the need for large central CHP plants is in the industry considered a truism, even during the deployment of smaller, decentral CHP and district heating plants. The reasoning for this shows fallible logic. Using the economics of scale to produce electricity with low per-MW investments while also providing the largest cities in Denmark with heat from the waste production heat. This saves fuels for the system, while providing extra income to the power producers. Having the production on large scale also means more strategic deployment of these large power plants, avoiding district heating plants in the inner cities and the infrastructure demand that follows.

With the vast integration of VRE sources in the system, the role for power plants of any size and use change. From being the backbone of the energy system, delivering base load electricity and heat, the large CHP plants now have to regulate hourly, balancing the production from VRE sources and the demand for electricity and their local heat demand. Where the role for large CHP plants was to produce electricity mainly and heat secondly, the role is now often reverse. The obligation to produce heat for the district heating systems while no electricity is needed forces large CHP plants sometimes to bit on the sport market for electricity, at prices below their production price. (EnergiWatch A/S 2013)

This change in utility and the difficulties thereof may mark a fundamental shift in the application of these large power producers. While the report analyses assumes the need for the same electric capacity in large plant in the future as today, the results for the Open system scenarios tell another story. The large excess electricity production under high-VRE capacity conditions do not only show strains in electricity system, but also possibilities.

If the main function in the future for large central CHP plants is to supply heat to Denmark's largest cities while the VRE capacity causes EEP, the next development for these large plants maybe is to, partially or fully, transform into large electricity based heat plants. By utilising large heating pumps and the large water supplies nearby all large CHP plants as heat sources, the system can reduce the EEP, while at the same time save fuel. In Closed system analysis, that would demand less regulation of the capacity from VRE sources. Using heat expanded heat sources, the VRE capacity could cover the majority of the electricity production and the heat production in large cities, while fast reacting small CHP plants in local communities could cover the main hourly balancing.

The balancing electric capacity of current decentral small CHP plants does provide enough power to alone provide the security needed in the Danish energy system. While very expensive storage systems such as Compressed Air Energy Storage, battery plants and pumped hydro are technically possible in Denmark, the far cheaper option is adding balancing capabilities to the large CHP plants. Letting the plants balance between two production methods in co-firing requires both technologies to have high abilities for ramping their energy production. The ramping capabilities of heat pumps are slower than for boilers, but manages by using parallel heat pumps. For large combustion plants, only fluid or gaseous fuel technologies have fast and high capacity ramping abilities. Taking into consideration the fuel costs, the only viable fuel choice is natural gas, biogas or synthetic gas. Natural gas is the only fuel available to the required scale, unless producers start mass gasification of biomass resources to produce syngas.

A such scenario would likely be reminiscent of the Grid syngas scenario in the report analyses with added heat pump capacity, without looking further into other power producers.

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# List of figures

# List of Tables

# Appendix A – Online file depository

All the files used in the analyses, tables and figures in this study is accessible through the online download link showed below. The files are digitally compressed in a single .zip file which can be downloaded and then opened by right-clicking and choosing “Extract All…”.

File location: http://1drv.ms/1hSEIuN

Alternate location: https://www.dropbox.com/s/4j2s9yhecrlj89x/Anaælyses%20files.zip

This Appendix shows the structure and digital content of the file titled “Analyses files.zip”. The different indent levels represent the file tree.

- EnergyPLAN analysis reports
  - CFB direct use - Scenario alpha
    - Closed Analysis
      - VRE0.oxps
      - VRE4500.oxps
      - VRE9000.oxps
    - Open Analysis
      - VRE0.oxps
      - VRE4500.oxps
      - VRE9000.oxps
  - CFB direct use - Scenario beta
    - Closed Analysis
      - VRE0.oxps
      - VRE4500.oxps
      - VRE9000.oxps
    - Open Analysis
      - VRE0.oxps
      - VRE4500.oxps
      - VRE9000.oxps
  - CFB direct use - Scenario gamma
    - Closed Analysis
      - VRE0.oxps
      - VRE4500.oxps
      - VRE9000.oxps
    - Open Analysis
      - VRE0.oxps
      - VRE4500.oxps
      - VRE9000.oxps
  - Grid syngas
    - Closed Analysis
      - VRE0.oxps
      - VRE900.oxps
      - VRE1800.oxps
      - VRE2700.oxps
      - VRE3600.oxps
      - VRE4500.oxps
      - VRE5400.oxps
      - VRE6300.oxps
      - VRE7200.oxps
      - VRE8100.oxps
      - VRE9000.oxps
    - Open Analysis
      - VRE0.oxps
      - VRE900.oxps
      - VRE1800.oxps
      - VRE2700.oxps
      - VRE3600.oxps
      - VRE4500.oxps
      - VRE5400.oxps
      - VRE6300.oxps
      - VRE7200.oxps
      - VRE8100.oxps
      - VRE9000.oxps
- Reference system
    - Closed Analysis
      - VRE0.oxps
      - VRE4500.oxps
      - VRE9000.oxps
    - Open Analysis
      - VRE0.oxps
      - VRE4500.oxps
      - VRE9000.oxps
  - Wood Pellets combustion
    - Closed Analysis
      - VRE0.oxps
      - VRE4500.oxps
      - VRE9000.oxps
    - Open Analysis
      - VRE0.oxps
      - VRE4500.oxps
      - VRE9000.oxps
- EnergyPLAN files
  - CFB direct use distribution files
    - Distribution_A.txt
    - Distribution_B.txt
    - Distribution_C.txt
    - Distribution_D.txt
  - Project files for scenarios and models
    - CFB direct use - Scenario alpha.txt
    - CFB direct use - Scenario beta.txt
    - CFB direct use - Scenario gamma.txt
    - Grid syngas.txt
    - Reference system.txt
    - Wood Pellets Combustion.txt
- Microsoft Excel pre- and postanalysis files
  - CFB direct use.xlsx
  - Grid syngas.xlsx
  - Model comparison.xlsx
  - Reference system.xlsx
  - Wood Pellets Combustion.xls
- Alternatives for using biomass in large Combined Heat and Power plants.pdf

# Appendix B – Sensitivity of system stability functions

The analyses of Open and Closed Reference system builds upon a standardised energy system representing Denmark in the early 2010s. This system have some specific measures for avoiding grid imbalance and instability. These measures are changed to fit the analyses of the report. These stability functions are explained here shortly and their impact on the Reference analysed.

## 10.1 Minimum grid stabilisation production share

The tool EnergyPLAN uses multiple stabilisation and regulation methods. The minimum grid stabilisation production share specifies the share of total non-VRE production capacity that is kept online for stabilisation purposes. This stabilisation method is especially applicable within systems with high risks of electricity deficiency. For the analysed systems, with abundant VRE combined different regulative technologies, this ability is not essential for the stability of the systems and causes excess production. Figure 46 shows the influence of different minimum grid stabilisation production share for the use of non-VRE PES in the Reference Closed system.

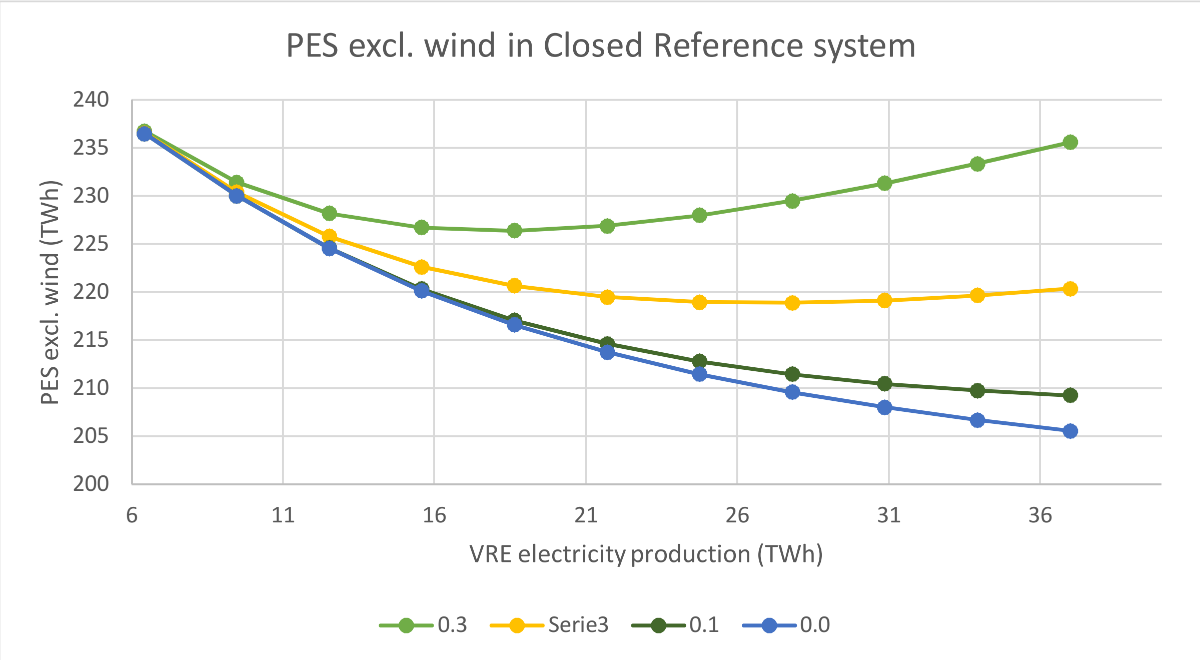


*Figure 46 - Different minimum grid stabilisation production share in Closed Reference analysis*

Figure 46 shows the effect of the minimum grid stabilisation production share for the Closed Reference analysis. For the Open Reference, the minimum grid stabilisation production share causes excess electricity production. In the technology analysis the conservative share of 0.1 is used.

## 10.2 Minimum base load of power plants

The large CHP plants in the Reference needs to run with a minimum capacity for mechanical and thermodynamic purposes. In the Reference analyses, this capacity is 450 MW. The minimal CHP capacity provides minimal base load in the system, which acts effectively in low VRE capacity hours. In hours with high capacity potential for VRE, the technical minimum for large CHP plants cause EEP (Open system) or curtailment of VRE sources (Closed system). Figure 47 shows the effect of large CHP minimal capacity in the Closed Reference system.

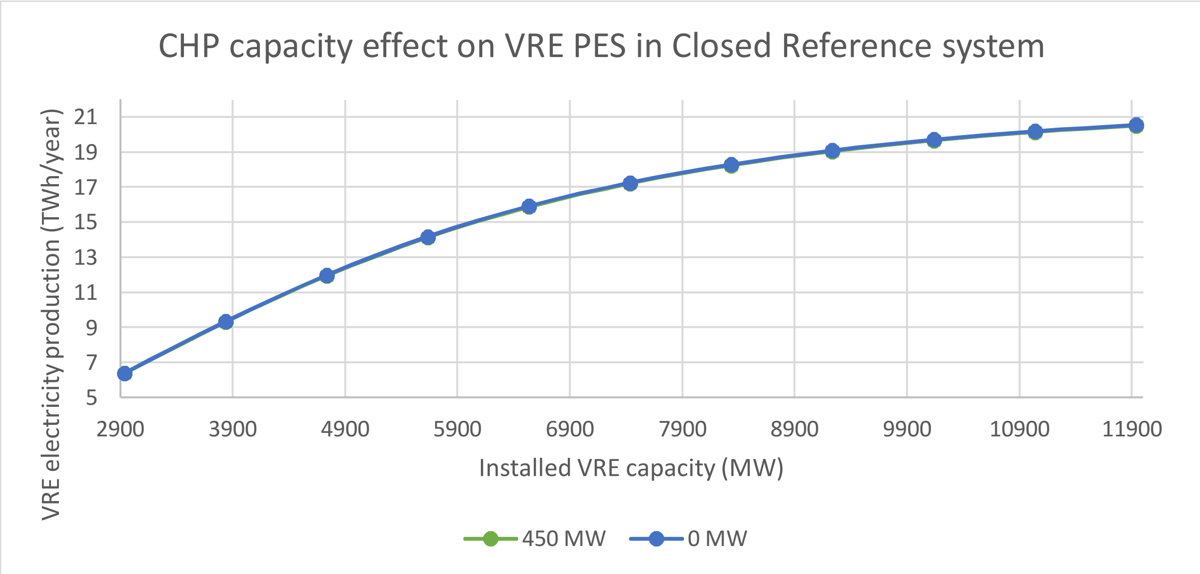


*Figure 47 - Large CHP minimum capacity effect on VRE PES utilisation*

Figure 47 shows almost no effect from the minimum large CHP capacity on the VRE source production. The curtailment regulation occurs in hours with large VRE excess production.

# Appendix C – Scenario modelling in EnergyPLAN

## 11General methodology of Open system analysis

All the scenarios in the report uses Open system analysis to analyse the excess electricity production of unregulated systems under 11 VRE capacity conditions. This section describes the general, not scenario specific, methodology for performing Open system analyses in EnergyPLAN. The methodology description is depicted as a step-by-step guide.

1) Open the EnergyPLAN software and choose the specific setting for the scenario you wish to work with.
2) Under the tabs Input -> RenewableEnergy, make sure the settings are as shown in **Fejl! Henvisningskilde ikke fundet.**Figure 48.

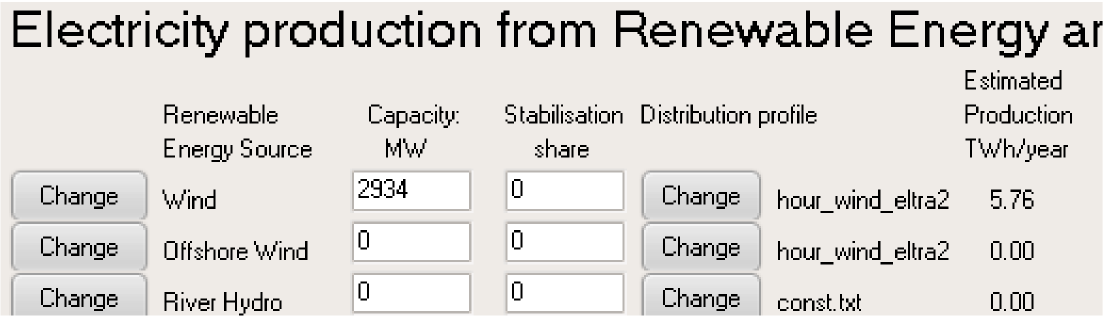


*Figure 48 - Open system start settings for Renewable Energy*

3) Under the tabs Regulation, make sure the CEEP regulation is 0 and the Transmission line capacity is 0, as shown in Figure 49.

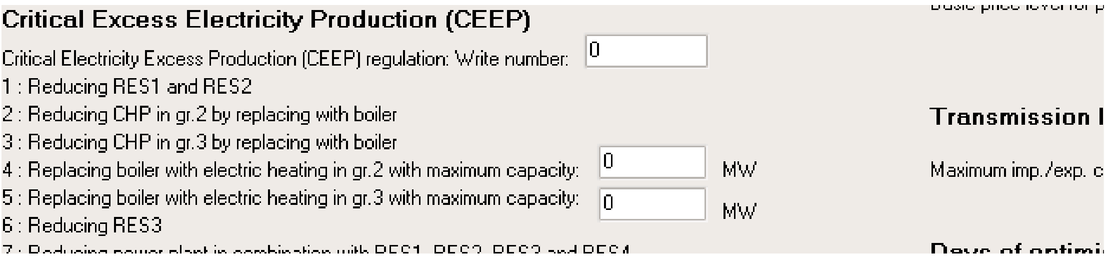


*Figure 49 - Open system settings for Regulation*

4) Run the model and note the yearly CEEP (EEP in the report)
5) Add 900 MW of Offshore Wind in Input -> RenewableEnergy, as shown in Figure 50.

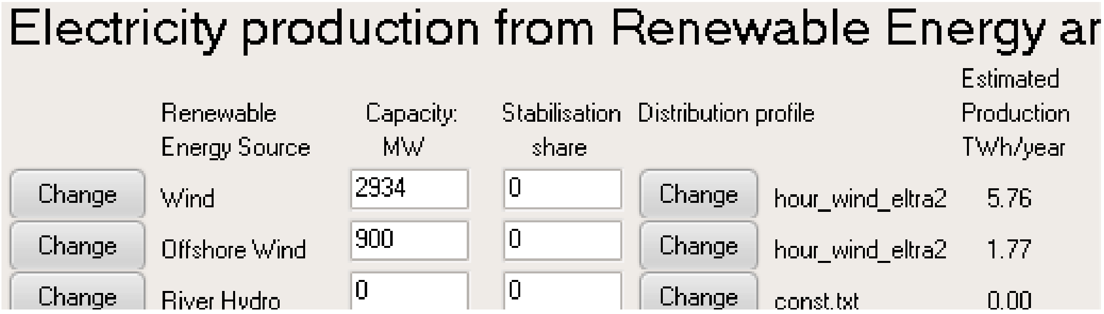


*Figure 50 - Added Offshore Wind capacity in Open systems*

6) Repeat steps 4-5 until you reach 9000 MW of Offshore Wind capacity and note down this.

# 12 General methodology of Closed system analysis

All the scenarios in the report uses Closed system analysis to analyse the excess electricity production of unregulated systems under 11 VRE capacity conditions. This section describes the general, not scenario specific, methodology for performing Closed system analyses in EnergyPLAN. The methodology description is depicted as a step-by-step guide.

1) Open the EnergyPLAN software and choose the specific setting for the scenario you wish to work with.
2) Under the tabs Input -> RenewableEnergy, make sure the settings are as shown in **Fejl! Henvisningskilde ikke fundet.**Figure 51.

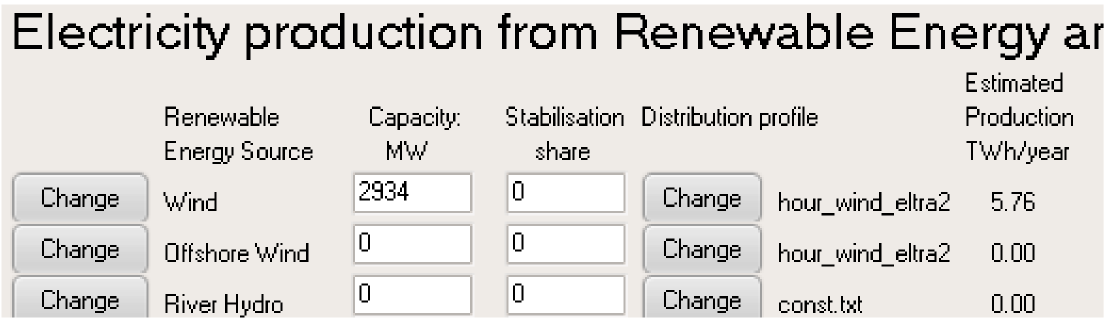


*Figure 51 - Closed system start settings for Renewable Energy*

3) Under the tabs Regulation, make sure the CEEP regulation is 231 and the Transmission line capacity is 0, as shown in Figure 52.

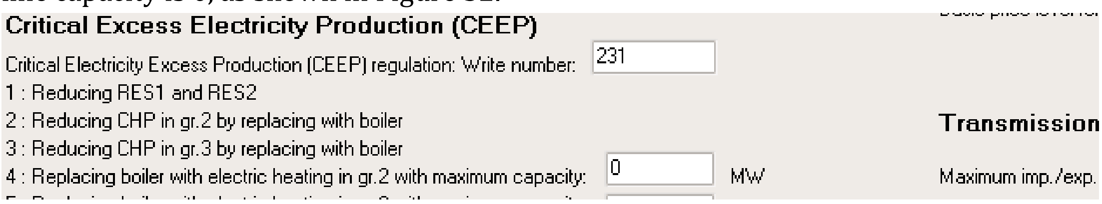


*Figure 52 - Closed system settings for Regulation*

4) Run the model and note the yearly CEEP (EEP in the report)
5) Add 900 MW of Offshore Wind in Input -> RenewableEnergy, as shown in Figure 53.

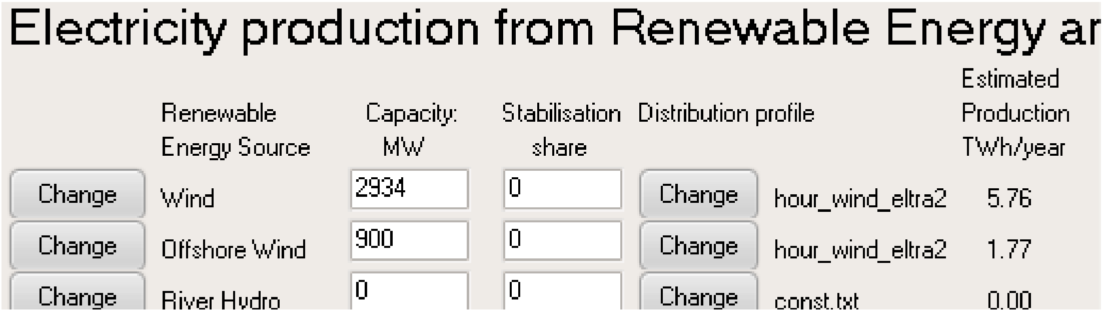


*Figure 53 - Added Offshore Wind capacity in Closed systems*

6) Repeat steps 4-5 until you reach 9000 MW of Offshore Wind capacity and note down this.

# 13 Method for Grid syngas scenario

The model for the Grid syngas scenario is iterative. To obtain results for fuel consumption and energy production, the model needs to run several for each VRE condition while the user change input to fit output. This section shows this process for the model under a single VRE capacity condition. For each change in the model, analysis methodology (Open/Closed) or VRE capacity, this iterative method is repeated. The methodology description is depicted as a step-by-step guide.

1) Open EnergyPLAN and open the file gridsyngas.txt from within the software.
2) After initial conditions are set, run the model so it produces an output file using "Run and print report"
3) In the printed report, observe the numbers for N.Gas (natural gas, also covers synthetic gas) for CHP3 in the Fuel Balance table on the bottom of page 1, as shown in Figure 54 marked in red.

FUEL BALANCE (TWh/year):

| | DHP | CHP2 | CHP3 | Boiler2 | Boiler3 | PP | Geo/Nu. | Hydro | Waste | CAES Elc.ly. | BioCon-version | Synthetic Fuel | Wind |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal | 0.00 | 0.28 | - | - | - | 16.43 | - | - | - | - | - | - | - |
| Oil | 0.71 | 0.03 | - | - | 2.55 | 0.66 | - | - | - | - | - | - | - |
| N.Gas | 0.90 | 13.88 | 27.38 | - | 3.24 | 2.19 | - | - | - | - | -27.38 | - | - |
| Biomass | 1.31 | 1.42 | - | 0.25 | 1.31 | 3.42 | - | - | 9.19 | - | 28.82 | - | - |
| Renewable | - | - | - | - | - | - | - | - | - | - | - | - | 6.28 |
| H2 etc. | - | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | - | - | - | - | - | - | - |
| Biofuel | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Nuclear/CCS | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Total | 2.93 | 15.61 | 27.38 | 0.25 | 7.10 | 22.70 | - | - | 9.19 | - | 1.44 | - | 6.28 |

*Figure 54 - Observance of synthetic gas consumption and production for Grid syngas*

4) Mentally note the observed amount and input this in "Biomass TWh/year" in Input -> Biomass Conversion, as shown in Figure 55. When writing the number, add approximately 5%.

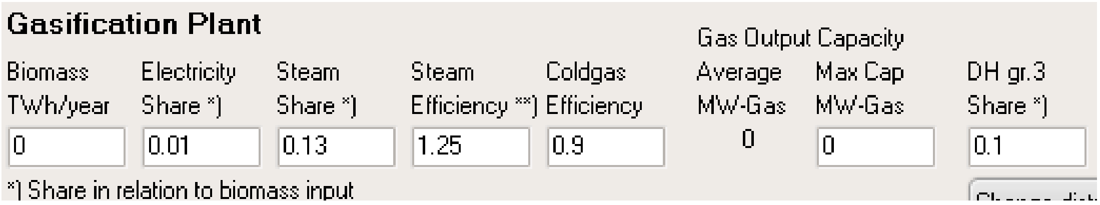


*Figure 55 - Input for syngas production in Grid syngas scenario*

5) Run the model it produces an output file using "Run and print report". Observe the number under Fuel Balances for BioConversion and natural gas, shown as the upper number marked in green in Figure 54. The number you wrote in step 4 is the lower number marked in green in Figure 54, showing the biomass consumption.
6) Adjust the biomass consumption number up or down to have the synthetic gas consumptions and productions fit each other. Synthetic gas production in BioConversion should be the exact negative of Natural gas consumption in CHP3.
7) Run the model using "Run and print report" and repeat steps 3-6 until the natural gas consumption and synthetic gas consumption fit together and note the numbers, save the file. Report files are in the online depository.
8) Change conditions, VRE capacity or system method and repeat all above steps.

# 14Choosing capacity share profile in CFB direct use scenarios

CFB direct use have three different scenarios, alpha, beta and gamma. Each of these scenarios are analysed in the report using four different capacity share profiles. This section briefly touches upon choosing these profiles. The methodology description is depicted as a step-by-step guide.

1) Open EnergyPLAN and open the chosen CFB direct use scenario
2) In File explorer, open the folder with the four capacity share profiles.
3) Mark these and move them to the folder EnergyPLAN\EnergyPLAN\energyPlan Data\Distributions to make them available in EnergyPLAN
4) In EnergyPLAN, click the button "Change distribution" under "Industrial CSP (CSHP) as showed in Figure 56. Choose the distribution file wished.

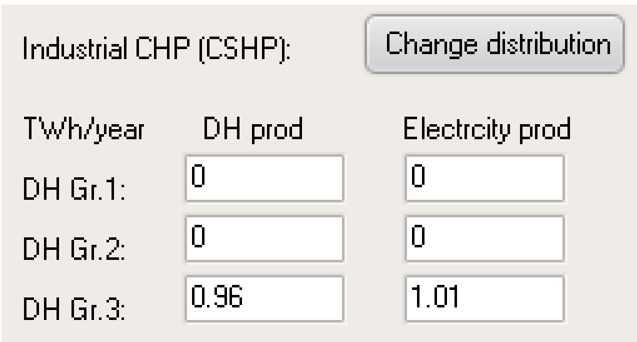


*Figure 56 - Change capacity share distribution in CFB direct use scenarios*

5) Run the scenario and change conditions as wished. For changing to another distribution, repeat step 4.