One million ton of hydrogen is the key piece in the Danish renewable energy puzzle

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1. Abstract

Designing a 100 % renewable energy system (RES) for Denmark, the availability of a sustainable biomass resource potential is found to be a limiting factor. The biomass demand derives from specific needs in the system, i.e. 1) storable fuel for energy for balancing fluctuating power production, 2) carbon feedstock for materials and chemicals and 3) energy dense fuels for the more demanding branches of the transportation sector such as aviation, ship freight and long distance road transportation.

The challenge of balancing electricity over different timeslots comprise a short term balancing of supply and demand in every second, but also a long term balancing between days and even seasons. Two alternative technologies are available on a significant scale, which are able to deliver balancing services for Denmark. The first is storage in Norwegian hydropower, while the second is electrochemical storage, i.e. storing wind power through electrolysis and further reaction of hydrogen to hydrocarbons with carbon feedstock from biomass. This involves biomass gasification and hydrogenation of the syngas or hydrogenation of recycled CO_2. The advantage of hydro storage is a superior energy efficiency and storage capacity, while the advantage of electrochemical storage is flexibility and, most importantly, the option of producing hydrogenated fuels for use in the transport sector, thereby displacing biomass with wind power in even the most challenging branches of the transport sector.

Therefore, the needed scale of wind power production will largely be determined by the availability of residual biomass. Two different situations are of interest. The first is characterized by having a (hypothetical) biomass potential of 320 PJ/year. In this situation, the ratio between deficit and surplus electricity production is 1:1. If so, the main task is direct balancing between the surplus and the deficit, making hydro storage a potential alternative. However, the biomass demand in this situation is much above the sustainable biomass potential. To reduce the biomass dependency from this level down to a level of 200 PJ/year, the production of wind power has to be increased to a level of surplus electricity of almost 150 PJ/year in order to ensure sufficient quantities of hydrogen for the hydrocarbon demand. At this high electricity surplus, the ratio between deficit and surplus becomes 1:20. In such a situation the use of hydro storage is limited. The electricity surplus is peak-shaved by

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electrolytic conversion, and the electricity deficit and, thus, the need for regulating power, becomes very limited.

Keywords: Renewable energy system, biomass consumption, hydrogenated fuels, surplus electricity, deficit electricity, hydro power

2. Introduction

With the long term political goal of the Danish government to become completely independent of fossil fuels in 2050, the Danish energy sector is presented with a series of obstacles. Amongst the most challenging are the limited availability of residual biomass resources and the integration of unregulated electricity production from wind, photo voltaic and wave power [1]. When constructing a 100 % RES, the design of the infrastructure supply of energy is defined by the available renewable energy resources. In the case of Denmark, this is predominantly wind power and to a lesser extends solar energy and biomass [2]. This constellation presents the designers of the RES with the challenges of efficiently integrating a large share of intermittent energy resources into the energy system, especially electricity supply [3,4], while at the same time producing sufficient quantities of energy dense and storable fuels for the transportation sector [5].

Since the extensive consumption of biomass and land use changes associated with large-scale biofuel production, is resulting in significant environmental and climate issues [6], it is essential to remain focused on how to design a 100 % RES, without overexploiting biomass resources. Hence it is evident that reducing the demand for biomass based energy, will reduce the stress placed on arable land and significantly reduce the environmental issues related to the 100 % RES.

Considering the option of integrating fluctuating renewable energy in place of biomass, the objective of this study is to analyse the ability of alternative balancing technologies to effectively integrate wind, wave and solar power. By taking into consideration the optimal allocation of constrained biomass resources, the relevant roles of the different balancing technologies is identified in the context of a 100 % RES. Based on this analysis alternative scenarios are suggested utilizing the different technologies, with the purpose of reducing the extensive biomass consumption displayed in the CEESA 2050 recommendable scenario [7] without increasing the reliance on yet undeveloped technologies. The economic feasibility of the 100 % RES will be tested against a reference scenario which allows the use of fossil fuels.

3. Methodology

3.1 Energy system analysis model

A detailed energy system analysis is carried out using the freeware modelling tool EnergyPLAN[1] [8]. The model allows for different regulation strategies to reduce critical excess electricity production, prioritising combined heat and power (CHP) and how much the system is able to trade with neighbouring energy systems.

As part of this study it will be analysed how relevant elements can be utilized to increase flexibility and thereby ensuring the best integration of the fluctuating renewable energy supply.

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[1] Version 10 released on the 14. Oct. 2012.

3.2 Energy system analysis methodology

One of the greatest challenges of this study is the construction of the alternative scenarios needed to compare the different technologies. It is considered to be central for the legitimacy of the study, that each of the alternative balancing technologies are placed in a plausible context of a 100 % RES, from where they can be both analysed and compared on an objective and equal basis, despite having different characteristics. It is considered essential that each technology is given the same starting point and context from where the technology can interact with the surrounding energy system.

Therefore, it is decided to use the CEESA 2050 recommendable scenario [7] as a platform for each of the alternative scenarios. This scenario is based on a very elaborate and interdisciplinary research project focused on the integration of a 100 % RES in Denmark. As the CEESA recommendable scenario forms the basis of all the alternative scenarios, many of the same assumptions and prerequisites used in the modelling of the CEESA scenarios are also used in this study.

During the study a total of 20 alternative energy pathways where designed and modelled to explore different applications of biomass and balancing technologies. Common to all systems, including all pathways and the CEESA recommendable scenario, is that they deliver the same functional output in terms of electricity, heat and transport fuels. This is both in terms of quantity and distribution. The annual energy demand is found in Table 1 below:

Table 1: Energy consumption in the CEESA 2050 recommendable scenario [9] and the alternative pathways in 2050

Conventional electricity	District heating and process heat	Transport (fuel)	Transport (electricity)
88.9 PJ/year	247.7 PJ/year	115.7 PJ/year	29.6 PJ/year

Each pathway is evaluated on especially two specific parameters. The first is the gross biomass consumption while the second is the critical excess electricity production. Since the production of wind, wave and solar power production is kept constant in all pathways, the biomass consumption will largely constitute the marginal energy supply and is closely linked to the efficiency of the total energy system. The critical excess electricity production reveals how flexible the energy system is and how good the system is at integrating the intermittent electricity production. Flexibility is extremely important, partly because unused excess electricity can overload the electric grid [10], and partly because a flexible energy system is far better at utilizing fluctuating renewable energy and thereby reducing biomass consumption.

In all systems, including the CEESA 2050 recommendable scenario [9], critical excess electricity production reduction is regulated as follows:

- Reduce decentral CHP and replace it with boiler if appropriate
- Reduce central CHP and replace it with boiler if appropriate
- Replace boiler with electric heating in decentral district heating with maximum capacity of 600 MW
- Replace boiler with electric heating in central district heating with maximum capacity of 600 MW

Additionally most systems also increase hydrogenation of captured carbondioxide if additional capacity is available. It is only in the rare occasion that the production of fuels from this technology needed to be set at a fixed level that this regulation was left out.

All pathways are modelled as closed systems using a technical regulation criteria optimization. This implies that EnergyPLAN regulates the system to optimize energy consumption and energy efficiency and the system is unable to trade with any surrounding energy systems. This is not considered a realistic scenario. Nonetheless this is necessary for several reasons. It is not possible to document the full extent of a given effect brought about by any changes done to the pathways, if neighbouring systems interact with the test system. As the energy trading conditions, both with regards to prices and capacities, in 2050 are subject to major uncertainties it is important to demonstrate that the system is able to operate without being dependent on trade. Lastly it is not possible to document that the energy system is 100 % renewable, unless it can be documented that the foreign inwards marginal electricity production is 100 % renewable, something which is considered outside the scope of this study to do. Based on the modelled pathways, a selection of scenarios is created to demonstrate and quantify the difference between the different balancing technologies. In respect of this boundary storage in Norwegian hydropower is simulated as a pumped hydro system, but with an energy efficiency of 95 % on both the pump and turbine. By doing so it is ensured that the model imports the same amount of electricity as it exports and the initial assumptions regarding a closed system can still be maintained.

The CEESA 2050 recommendable scenario

The data template for the CEESA 2050 recommendable scenario [9] used in this study is kindly provided by the research team behind the CEESA project and as such it is essential to emphasize that the CEESA 2050 recommendable scenario is not part of the work behind this study. Being the platform of the alternative scenarios, the CEESA 2050 recommendable scenario operates as a reference for the purpose of the energy system analysis, in the sense that the performances of the pathways and alternative scenarios are compared to the CEESA 2050 recommendable scenario.

3.3 Flexibility analysis

A flexibility analysis is carried out to compare each alternative scenario’s ability to integrate intermittent renewables. This is done by simulating each scenario with increasing penetration of fluctuating renewable electricity. The alternative scenarios are all modelled with different annual intermittent electricity production ranging from 0 PJ/y to 272 PJ/y.

3.4 Reference energy system

The reference energy system is the “business as usual” scenario. This is how the energy system is expected to look if no active political actions are taken to integrate a RES. This reference system is based on the Danish Energy Agency’s forecasts from April 2009 [11] and is identical to the one used in the CEESA project [7]. The annual energy consumption in the reference system is found in Table 2 below.

Table 2: Energy consumption in the 2050 reference system

Conventional electricity	District heating and process heat	Transport (fuel)
168.8 PJ/year	364.7 PJ/year	285.1 PJ/year

Note that the consumption levels given in Table 2 are far higher than those given in Table 1. This is because the energy conservations suggested in the CEESA study [1,7] is not realized in the reference system.

4. Biomass, biomass conversion and balancing technology in the 100 % RES

Biomass is a renewable resource. Yet as with all renewable resources the supply of biomass is finite [3,12-15]. As biomass is effectively storable energy with relatively high energy density, it is very valuable in a 100 % RES, where it to some extent can substitute fossil fuels directly [2,13]. When limiting the energy production to renewable sources, biomass is indeed the only reserve capacity available in any substantial quantity when the production of intermittent renewable electricity is insufficient to meet the electricity demand.

Unlike residual biomasses such as straw, manure and the organic fraction of MSW which are all a co-product of other processes, energy crops can respond to an increase in demand. However, the use of energy crops is known to have a significant impact on the both the environment and the climate [6]. It is primarily the consequences of direct and indirect land use changes, which gives cause for concern. As a result, the constraint on biomass implies that it is important to utilize the biomass most effectively and only consider the use of biomass if no alternative is available.

Several studies have been carried out to determine the biomass potential in Denmark [2,3,7,16]. It is for the purpose of this study assumed that the technical realisable residual biomass potential in Denmark is 200 PJ/y, not including any fossil or none-organic waste fractions.

4.1 Balancing technologies

In broad two different types of technology is considered in this paper. The first is storage in Norwegian hydropower and the second is electrochemical storage.

Storage in Norwegian hydropower is assumed to let the Norwegian hydropower plants operate as reserve capacity on an international market, thereby enabling the Danish energy sector to export wind power when electricity is in excess and import renewable hydropower when electricity is in deficit. A similar system design is described by [17]. By doing so, pumped hydro is kept at a minimum, while conversion efficiencies are as high as possible.

Electrochemical storage operates by producing hydrogen from the electrolysis of water. All pathways assume an electricity-to-hydrogen efficiency of 73 % in the electrolyser [3]. The hydrogen is then reacted with carbon monoxide or carbon dioxide to produce a synthetic energy carrier. The carbon can come from various sources and several different variations of this technology are considered. The first is anaerobic digestion producing a mixture of methane and carbon dioxide, which can be hydrogenated to produce *synthetic natural gas* (SNG) [18,19]. This is done by allowing the following reaction to take place [18]:

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O \qquad (1)$$

The overall energy balances used to model the methanation of biogas is depictured in diagram 1 below.

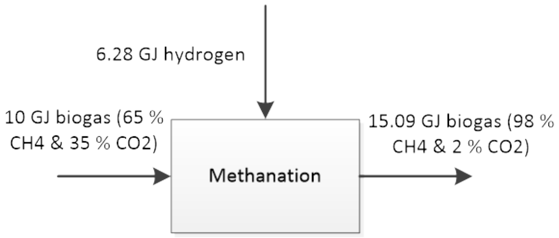


Diagram 1: Energy balances of the methanation of biogas [18]

Alternatively it is possible to produce syngas through thermal gasification of solid biomass, containing a mixture of primarily carbon monoxide, carbon dioxide, various organic compounds and water [19-22]. The syngas is then subsequently hydrogenated into methanol using the following reactions [21]:

$$CO + 2\,H_2 \rightarrow CH_3OH \tag{2}$$

$$CO_2 + 3\,H_2 \rightarrow CH_3OH + H_2O \tag{3}$$

Finally it is also possible to capture carbon dioxide either from biomass conversion plants [23,24] or ambient air [25,26]. The captured carbon dioxide can then be converted into methanol using (3). The overall energy balances used to model hydrogenation of syngas and captured carbon are depictured in diagram 2 below.

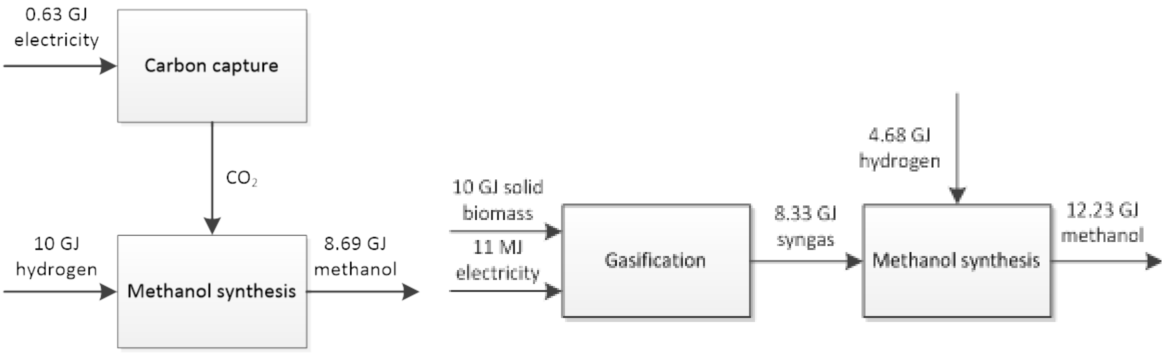


Diagram 2: Energy balances of hydrogenation of syngas and captured carbon dioxide [9]

4.2 Biogas allocation

The unique characteristics and flexible nature of biogas make it worth investigating where in the 100 % RES, that biogas utilized most efficiently. The CEESA 2050 recommendable scenario suggests utilizing the biogas for heat and power production [7]. Alternatively the biogas can be used to produce high quality heat in the industry or displace methanol in the transport sector. Both alternatives are investigated as part of this study. Based on [27] it is assumed that methane is able to displace methanol 1:1 in the transport sector on a calorific basis.

5. Modelling input data

Key input data used in the modelling of the pathways is presented Table 3 to Table 7 below. Any electricity production, including CHP production, is assumed to utilize full cell technology [7]. Therefore, CHP plants and peak load power plants are all fuelled by syngas from biomass gasification, while biomass boilers are fuelled by solid biomass. By constructing the gasification as *integrated gasification combined cycle* it is possible to create a very load flexible decentral combined fuel and power plant [28].

Table 3: Modelling input data for district heating grids and power plants including cost of these plants [9]. This dataset is common to all pathways. *The capacity of the power plants depends on the pathway, please see chapter 5.2 for details.

Dimension	Demand	Plant capacity		Efficiencies			Investment	Life time	Variable O&M	Fixed O&M
				Elec.	therm.	COP				
Unit	PJ/y	MW-e	MW-th	%	%	%	MDKK/MW	years	DKK/MWh	% of inv.
District heat gr 3	10.7	-	-	-	-	-	-	-	-	-
Boiler	-	-	-	-	94.6	-	-	-	-	-
District heat gr 3	39.9	-	-	-	-	-	-	-	-	-
Boiler	-	-	3484	-	94.6	-	1	20	1	3
CHP	-	1945	1682	46.3	40	-	6.6	20	20	5.75
Heat pump	-	300	-	-	-	350	21.6	25	2	2
Electric boiler	-	-	600	-	-	-	-	-	10	-
District heat gr 3	87.6	-	-	-	-	-	-	-	-	-
Boiler	-	-	7574	-	94.6	-	1	20	1	3
CHP	-	2500	1269	59.7	30.3	-	9.5	30	20	4
Heat pump	-	500	-	-	-	350	21.6	25	2	2
Electric boiler	-	-	600	-	-	-	-	-	10	-
Power plant	-	*	-	62.8	-	-	8.3	30	15	4

Table 4: Modelling input data for thermal solar and energy storage including cost of these technologies [9]. This dataset is common to all pathways. *The capacity of the hydrogen storage tanks depends on the pathway, please see chapter 5.3 for details.

Dimension	Output	Storage capacity	Investment			Life time	Variable O&M	Fixed O&M
Unit	PJ/y	GWh	MDKK/GWh	MDKK/MW-e	MDKK/(PJ/y)	years	DKK/MWh	% of inv.
Electrolyser	-	-	-	4.25	-	20	0	2.46
Hydrogen	-	*	124	-	-	20	-	0.5
Gas grid	-	3500	-	-	-	-	-	-
District heat gr 2	-	40	10	-	-	20	-	1
District heat gr 3	-	10	10	-	-	20	-	1
Thermal solar gr 1	4.79	80	-	-	890	25	-	0.05
Thermal solar gr 2	7.49	10	-	-	890	25	-	0.05
Thermal solar gr 3	3.6	0	-	-	890	25	-	0.05

Table 5: Modelling input data for offshore wind power, onshore wind power, photovoltaic power and wave power including cost of these plants [9]. This dataset is common to all pathways.

Dimension	Capacity	Correction factor	Investment	Life time	Fixed O&M
Unit	MW-e	*Dimension less*	MDKK/MW-e	years	% of inv.
Onshore wind power	4454	0.512	8.64	20	2.7
Offshore wind power	10490	0.8	14.9	30	2.9
Photovoltaic	5000	0.636	6.7	25	0.25
Wave power	300	0.93	19	30	0.72

Table 6: Cost of biomass gasification and synthetic fuel production [9]. This dataset is common to all pathways.

Dimension	Invest-ment	Life time	Fixed O&M
Unit	MDKK/ MW	years	% of inv.
Gasification plant	3.63	20	6.2
CO_2 hydrogenation	3.51	20	2.46
Methanol synthesis	3.63	20	3.96

In Table 6 above, the cost of biomass gasification and synthetic fuel production is displayed. The capacities of these plants depend on the specific pathway.

In Table 7 below is the input data for the anaerobic digestion shown. The biomass input and biogas production depends on the specific pathway. The conversion of wet biomass to biogas is defined to be 100 %, because the energy content of this fraction is calculated as the actual gas yield rather than the calorific value of the diluted organic particles.

Table 7: Modelling input data for anaerobic digestion including costs of these plants. This dataset is common to all pathways. *The conversion efficiency from dry biomass to biogas is based on extruded straw.

Dimension	Biomass feed to biogas conversion efficiency			Energy consumption		Invest-ment	Life time	Fixed O&M
	Wet biomass	Separated bio waste	Other dry fractions	Electricity	Heat			
Unit	%	%	%	% of gas prod.	% of gas prod.	MDKK/ (PJ/y)	years	% of inv.
Anaerobic digestion	100	64	51	2.5	14	780	20	11.25
Reference	Defined	[29]	[6]*	[30]	[30]	[9]	[9]	[9]

5.1 Cost of Norwegian hydropower reserve capacity

The price for storing intermittent electricity in Norwegian hydropower is believed to be determined by the electricity market in Northern Europe. [17] have investigated the expected value and market price of reserve capacity in Northern Europe. The cost of Norwegian hydropower reserve is calculated based on [17] and shown in Table 9 below:

Table 8: Market price and availability compensation for Norwegian hydropower reserve capacity [17].

Market price of reserve capacity (DKK/MWh)		Availability compensation (million DKK/MW)	
Upward regulation	Downward regulation	Upward regulation	Downward regulation
2306	317	0.3	0.5

It is for the purpose of this study assumed that the value of the exported wind power is negligible.

5.2 Peak load power plant capacity

In the CEESA 2050 recommendable scenario there is an installed peak load power plant capacity of 10,333 MW-e, which is approximately twice the needed capacity. In all of the alternative pathways the power plant capacity is corrected so the ratio between installed and demanded capacity is the same as in the CEESA 2050 recommendable scenario.

5.3 Hydrogen storage

To level out the hydrogen flows to the methanation and methanol synthesis displayed in diagram 1 and diagram 2, hydrogen is stored prior to each process. In the case of hydrogenation of the capture carbon, storage capacity is equivalent to the hydrogen production from 20 hours of full load production. This is kept constant in all pathways.

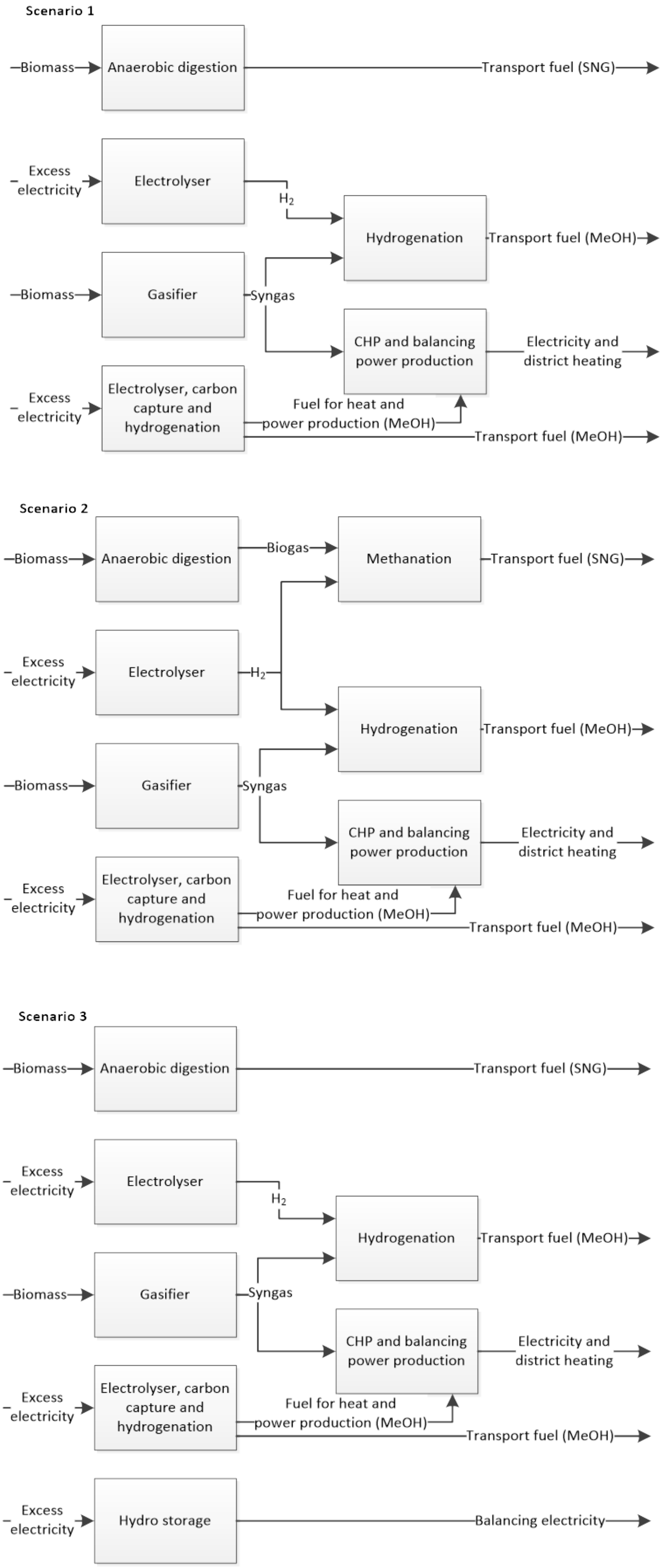
In the case of hydrogenation of syngas and methanation of biogas the hydrogen storage capacity in each of the pathways is optimized through an iterative process, starting at a storage capacity equivalent to the hydrogen production from 250 hours of full load production.

5.4 SNG fuel infrastructure cost

[28] finds that the infrastructure costs related to SNG in a Danish context is around a quarter of that for methanol. This is because it is assumed that SNG is distributed via the national gas grid rather than by trucks.

Based on [28] it is under some uncertainty estimated that the transportation infrastructure costs are reduced from 16721 million DKK in the CEESA 2050 recommendable scenario to 15,000 million DKK in scenario 1 and scenario 3, while the cost of infrastructure in scenario 2 is reduced to 13,200 million DKK.

6. The alternative scenarios



Based on the modelling of the 20 alternative pathways, there is created three scenarios in total. A very simplified model of the central energy flows in each of the alternative scenarios is depictured in the figures to the left. In the CEESA 2050 recommendable scenario, half of the transport demand is covered by hydrogenated syngas and the other half is covered by hydrogenated captured carbon [9]. In scenario 1 biogas is upgraded and used as a fuel in the transport sector rather than to produce heat and power. Here it displaces hydrogenated captured carbon. Scenario 2 increases the displacement of hydrogenated captured carbon in the transport sector by methanating the carbon dioxide in the biogas. Scenario 3 introduces hydro storage to reduce the methanol used for heat and power production. With the exception of hydrogenation of captured carbon, none of the other balancing technologies have a large enough potential, to balance the entire electricity supply on its own. Therefore, all three scenarios use a combination of the different technologies.

Of all of the pathways modelled in this study, only the scenarios depictured on the left performed significantly better than the CEESA 2050 recommendable scenario.

Utilizing biogas in the industry was found to consume more biomass then in the CEESA scenario, while utilizing methanated biogas for heat and power created an energy storage, as opposed to a fuel for the transport sector, which proved less energy efficient than scenario 2.

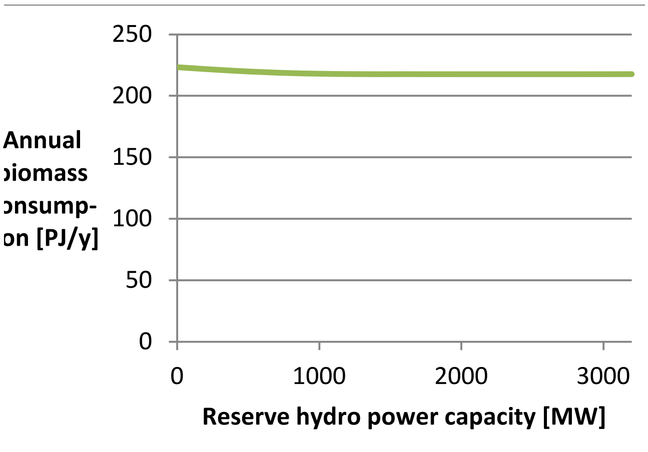
7. Results and discussion

The biomass consumption and electrolyser capacity in each of the alternative scenarios and the CEESA 2050 recommendable scenario is found in Table 9 below. The electrolyser capacity and, when applicable, hydro storage capacity is adjusted so that the critical excess electricity production in all systems is 0.9 PJ annually.

Table 9: Biomass consumption and electrolyser and hydro storage capacity in each of the energy systems.

Energy system	System characteristics	Biomass consumption	Total capacity of electrolyser, hydrogen storage and reserve hydropower
CEESA scenario	The original CEESA 2050 recommendable energy system [9]	239.6 PJ/y	ELT: 9,809 MW-e H_2 storage: 477 GWh Hydro: 0 MW-e
Scenario 1	Utilizing syngas hydrogenation and carbon capture hydrogenation to offset imbalances in the electricity supply	223.1 PJ/y	ELT: 10,125 MW-e H_2 storage: 483 GWh Hydro: 0 MW-e
Scenario 2	Utilizing hydro-methanation, syngas hydrogenation and carbon capture hydrogenation to offset imbalances in the electricity supply	222.9 PJ/y	ELT: 10,803 MW-e H_2 storage: 650 GWh Hydro: 0 MW-e
Scenario 3	Utilizing Norwegian hydropower, syngas hydrogenation and carbon capture hydrogenation to offset imbalances in the electricity supply	217.7 PJ/y	ELT: 9,928 MW-e H_2 storage: 478 GWh Hydro: 1,600 MW-e

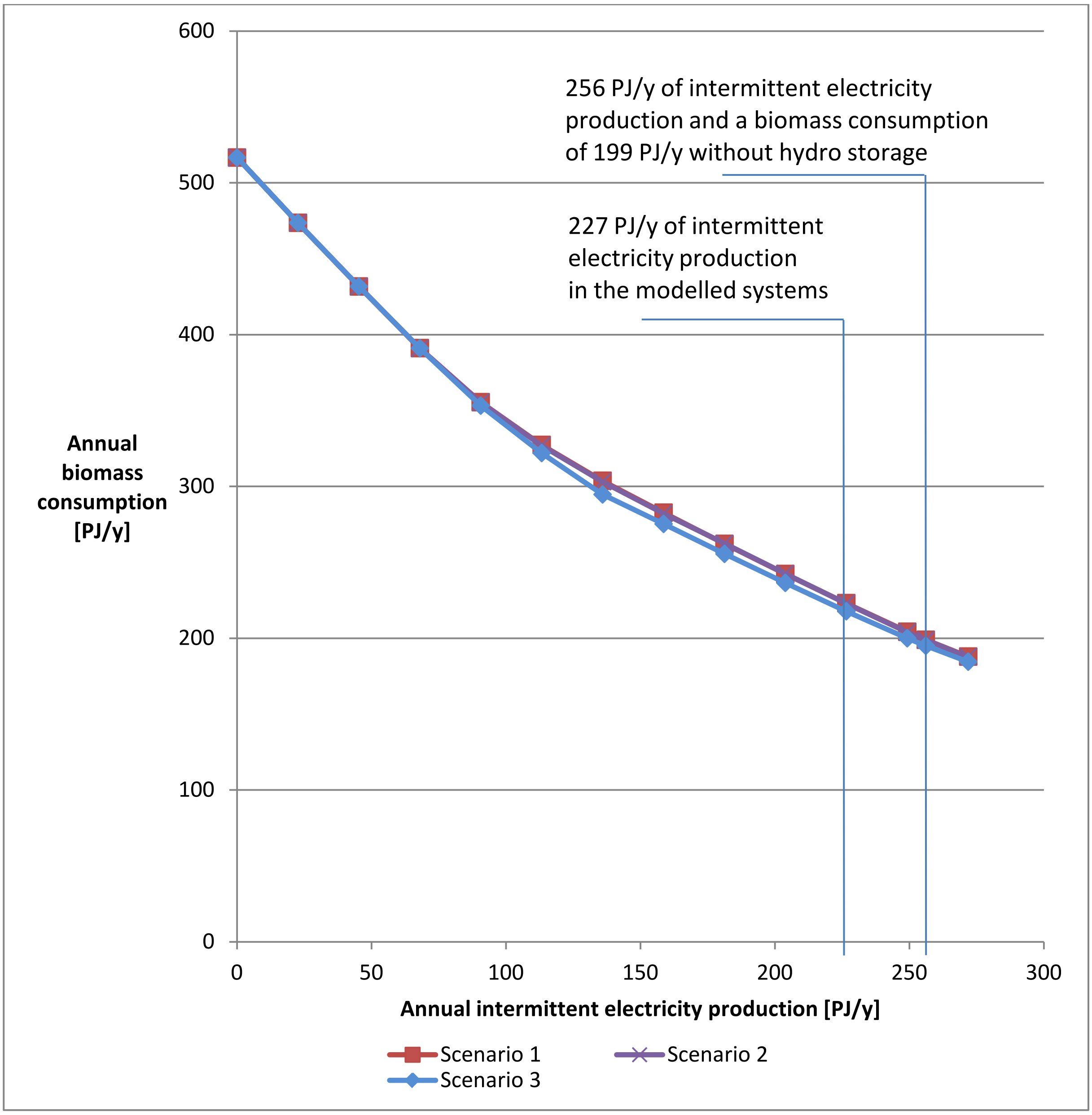
From Table 9 it can be seen that, compared to the CEESA 2050 recommendable scenario, scenario 1 and scenario 2 display biomass fuel savings in the range of 17 PJ/y, while scenario 3 displays savings in the range of 22 PJ/y. The savings in scenario 1 and scenario 2 are primarily linked to the application of SNG as a fuel in the transport sector. This prioritization greatly reduces the demand for hydrogen and ultimately electricity. The fact that scenario 1 and scenario 2 display such a significant reduction in biomass consumption, shows that marginal electricity supply for the electrolysers in the CEESA 2050 recommendable scenario does not come from intermittent electricity, but is instead produced by the CHP and power plants. In contrast, the electrolyser capacity in scenario 1 and scenario 2 is higher than in the CEESA 2050 recommendable scenario while the electrolyser capacity in scenario 3 is reduced due to the introduction of hydro power storage. Additionally there is a need of increased hydrogen storage capacity in scenario 2, due to an additional storage demand at the biogas plants. This shows that the savings in biomass consumption comes at the cost of increased investments.



Graph 1. Annual biomass consumption as a function of reserve hydro power capacity

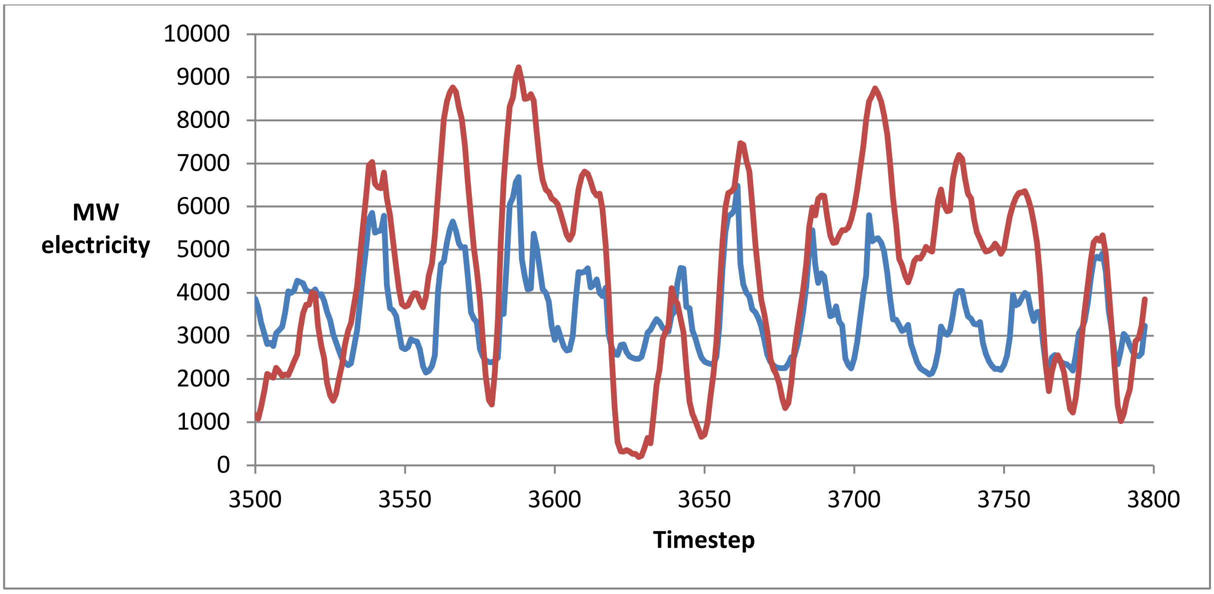
In scenario 3 further energy savings are achieved by reducing both the demand and the production of methanol for peak load power plants. The integration of hydropower storage is not able to influence on the CHP production. As a result, the demand for peak load power determines the potential for integrating hydropower storage. This is illustrated in graph 1 (above), where the annual consumption of biomass in scenario 3 is plotted as a function of reserve hydropower capacity. Ultimately the introduction of hydro storage has only a minor impact on the overall energy supply.

While reductions in biomass consumption are achieved, the consumption of biomass based energy in all alternative scenarios is still significantly higher than the Danish residual biomass potential. To compensate, it is possible to increase the production of intermittent electricity. The potential of increased intermittent electricity production is demonstrated by a flexibility analysis. The result is displayed in graph 2 below:

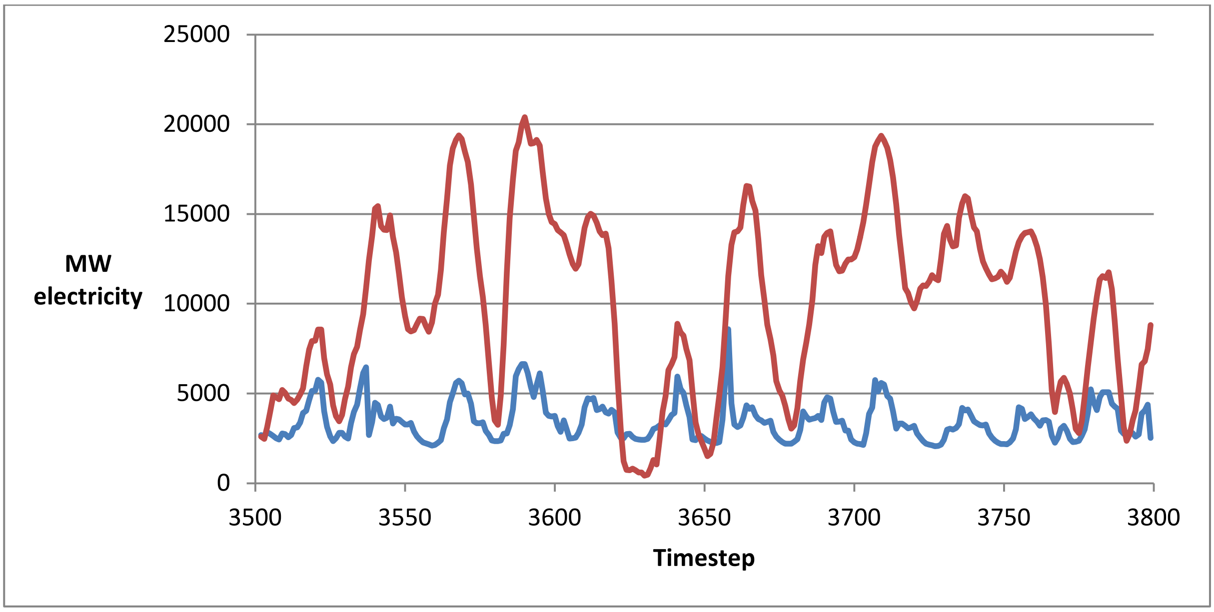


Graph 2. Flexibility analysis: Annual biomass consumption as a function of annual intermittent electricity production

From graph 2 it is seen that the difference between scenario 1 and scenario 2 is negligible throughout the entire analysis. The benefit of introducing hydropower storage is greatest in the range of 113 PJ/y to 227 PJ/y of intermittent electricity production. This phenomenon is explained partly by the inability of hydro storage to displace CHP production and partly by the fact, that with increasing annual intermittent electricity production the quantity of excess electricity increases, while the quantity of electricity deficit decreases. As a result the potential for direct balancing from periods with an excess in electricity production, to periods with a deficit in electricity production is dramatically reduced. This is illustrated in graph 3 and 4 below. In the first system (graph 3) the ratio between deficit and surplus electricity is 1:1, whereas the ratio between deficit and surplus in the second system (graph 4) is 1:20.

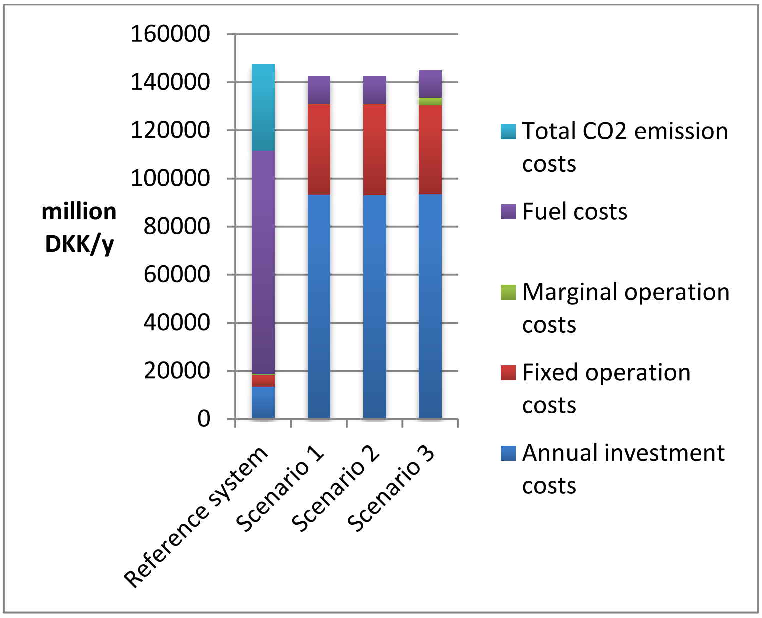


Graph 3. Electricty demand (blue) and intermittent electricty production (red) at 115 PJ/y of intermittent electricity production



Graph 4. Electricty demand (blue) and intermittent electricty production (red) at 256 PJ/y of intermittent electricity production

The modelling of the different alternative scenarios shows that there are some differences in the costs of the different systems. The cost of scenario 1 and scenario 2 are very similar, while the cost of scenario 3 is slightly greater, but still smaller than the cost of the reference. It is for the purpose of this study assumed that the cost of emitting fossil CO_2 is 650 DKK/tonne, which is based on [29].



Graph 5. Total annual costs of the modelled scenarios and the reference system

In graph 5 the costs and distribution of the costs are depictured. The only externality included in graph 5 is the costs associated with emitting CO2. While the economic values of eco-system services have been shown to be significant [32], the externalities caused by climate changes are by far the greatest [33]. While small differences in the cost of different systems are found, these are not statistically significant. Therefore it cannot be concluded that a RES is more or less cost-effective than fossil energy systems.

8. Sensitivity analysis

As part of the study a variety of previously assumed parameters was changes and the effect was observed. Parameters such as energy efficiency of the biogas vehicle, cost of fuel, cost of hydropower storage, cost of CO2 emissions, discount rate, marginal energy supply and annual wind power production. Overall the 100 % RES show less sensitivity towards the tested changes than the reference system. The choice of utilizing biogas in the transport sector is also beneficial even if the energy conversion efficiency of SNG is reduced to 70 % of the expected. Nonetheless is the eligibility of hydrogenation dependent on high energy efficiency of the SNG vehicles and vessels. The use of Norwegian hydro storage is at times found to have a countering effect on the changes introduced in the sensitivity analysis. Ultimately Norwegian hydro storage is found to be expensive and not a single analysis has shown that Norwegian hydro storage can be cost-effective.

In general the sensitivity analyses demonstrate that, unless radical changes to the conditions are introduced, all of the alternative energy systems are economically competitive with the reference. It is especially the uncertainties regarding the fuel costs and costs of CO_2 emissions which result in significant insecurities regarding the total cost of the reference system. The test of marginal energy production reveals that there is nothing suggesting that, producing marginal energy from unregulated renewable electricity rather than biomass will have a significant impact on marginal costs. Whether the production of marginal energy should come from biomass or unregulated renewable electricity should largely be decided by the significance of any externalities.

9. Conclusion

In this study three alternative energy systems have been described, quantified and modelled, all of which are 100 % renewable and take into consideration the optimal use of the constrained biomass resources. These three alternative energy systems are all based on the CEESA 2050 recommendable scenario and the performance of the alternative energy systems are compared against the CEESA scenario. The three systems utilize different combinations of balancing technologies to offset the difference in supply and demand of renewable intermittent electricity. This is done to test how the alternative balancing technologies are best applied and what difference the right choice of balancing technology makes. All three energy systems make use of a combination of electrochemical balancing technologies, while the third scenario also incorporates storage in Norwegian hydropower. It is found that in the case of a 100 % renewable Danish energy system the limitation on the potential for biomass based energy is a dimensioning factor, which necessitates a high penetration of intermittent renewable electricity production. Under such circumstances the applicability of hydro storage becomes negligible, while electrochemical conversion proves essential. Therefore, if the goal is to reduce biomass consumption in the 100 % RES to residual levels, biomass based fuels are more effectively displaced by offshore wind power production and hydrogenation of captured carbon to balance the electric grid. It is also found that if the penetration of intermittent electricity production is at more moderate levels, the use of hydropower reserves can reduce the fuel consumption. Therefore, it is not possible to exclude hydropower reserve as a viable technology used during the transition towards a 100 % RES.

Additionally it is found that the correct application of specific biomass resources, especially biogas, can make a significant difference regardless of balancing technology. The demand for hydrogenated fuels should be kept at a minimum because they are expensive and energy inefficient to produce. This implies that the synthetic biofuels should be reserved for where the demand is the greatest, namely the transport sector. Due to the high quality of SNG and the abovementioned constrains, the application of biogas in the transport sector is a viable and sensible choice. The sensitivity analysis reveals that the utilization of biogas in the transport sector is still favourable, even if the conversion efficiency of the biogas in the transport sector is reduced to 70 % of the expected. However, the use of hydromethanation is only eligible if the product gas is used as a transport fuel and if the expected conversion efficiency of SNG in the transport sector is realized.

It has not been possible to determine whether the 100 % RES are a cost-effective alternative to conventional energy systems using fossil fuels.

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