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# Breaking the biomass bottleneck of the fossil free society

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# Summary

The focus on global warming and security of resource supply has led many sectors in society to look for alternatives to oil and other fossil resources. Biological resources – biomass in brief – is at present a preferred alternative in many sectors of society. Biomass is, thus, in growing demand for heat and power services as well as for transportation fuels and as feedstock for chemicals and materials – i.e. in practice all sectors today being dependant on fossil fuels.

At the same time, unfortunately, the food sector is also in growing demand for agricultural crops. World population is still growing and even more importantly, the composition of food is changing towards more meat on the menu, especially in the many countries in economic transition towards higher welfare; i.e. China, India, Malaysia, Indonesia, South Africa, Mexico, Brazil and more. Even without the new customers for biomass, this alone puts pressure on agricultural land and leads to new land cultivation. A look at proportions of biomass resources compared to the new customers, thus, shows that there is very far from enough for all.

The world has already had an early warning in terms of potential influences from excessive biomass demand on food prices, namely the food crisis in 2007 – 2008. During this period, market prices on food and feed crops increased by almost a factor of 2, and the part of the world population suffering from hunger and starvation increased from 800 million to 900 million people.

The amount of biomass that the world can sustainably use is, therefore, concluded to be small compared to the potential demand for it. The problem is that a fossil free society implies a set of conditions that make biomass in high demand:

- biomass can be stored and thus provide flexibility in electricity production,
- it can be converted to high-density fuels for mobility purposes, and
- it is a key source of carbon feedstock

All in all, everything points to the fact, that biomass (and agricultural land) may be a severe bottleneck in the fossil free society and that excessive use can have severe consequences for the world's forest resources, the food sector and the poorest part of the world population.

We can, however, break this bottleneck. First of all, we must seek further energy savings. Secondly, we need to look for ways to de-carbonize society. There is a growing consensus among energy scientists and energy planners that society is heading towards increased electrification. The transport sector shall to the widest possible extent run on electricity and domestic and district heating shall be converted to heat pumps to the extent possible. This will help pulling more wind and solar power into our systems, and it will help balancing electricity supply and demand from fluctuating sources, because electricity is then stored in the batteries of the car fleet and in reservoirs for heating. Further electricity buffering can be provided by water reservoirs for hydro power or by various means of pressure based reservoirs, and smart grids and international trade will further assist in the balancing.

But these measures are not enough. We still need high density fuels especially for aviation, but to some extent also for long distance, heavy transport on road and for sea transport. We also need carbon feedstock for our chemicals and materials. Finally, some amount of storable fuel for providing flexibility on the supply side of our electricity systems will be a big advantage. Looking at proportions in how much biomass is available without influencing the food sector shows that we have far from enough even for these priority customers alone. We need to do something to reduce our demand for biomass further.

Using hydrogen as an agent to capture the electricity from wind and solar power through electrolysis is an obvious route to follow. This is judged to be a significant part of the solution. But storing and transporting hydrogen is not easy, and due to this it may be attractive to use hydrogen as an intermediate energy carrier for the final production of carbon based fuels and feedstock.

In this way, using hydrogen to upgrade and recover carbon from biomass may well be the final keystone for the successful fossil free society. Through a process called hydrogenation it is possible to use biomass as a source of carbon and react hydrogen with it to produce hydrocarbons of much higher energy content and energy density than the original biomass. Moreover, using the biomass and the biogenic carbon from hydrogenation in central applications like heat and power, it is possible to collect the $CO_2$ from the biomass and further recover and recycle it in a process here called Carbon Capture and Recycling, CCR. This will further multiply the use of the biogenic carbon from the biomass.

Overall, upgrading and recycling biogenic carbon by hydrogenation and CCR, can approximately **five-double** our biomass potential for providing storable and high-density fuels and carbon feedstock compared to the presently applied technologies for converting biomass to fuels and feedstock. This can fully and effectively break the biomass bottleneck of the fossil free society.

In this way, wind and solar power can save nature and land for food production. Assuming the next generation 6 MW wind mill, it is found that

> *one off-shore wind mill can save 5 km$^2$ of nature or agricultural land*
> *equivalent to 2500 tons of food crop kernels per year equal to the*
> *average calorific intake of food for 10000 people*

In a Danish fossil free society we seem to lack 160 PJ of biomass residue. We could import this or produce energy crops ourselves, and for the purpose we would need 8000 km$^2$ of arable land equal to 30 % of Danish agricultural land. Or we could follow a wind-for-biomass strategy and put up 1600 off-shore 6 MW wind mills and create the 160 PJ extra biogenic fuel and feedstock by hydrogenation and CCR. By doing this, we would then save these 8000 km$^2$ of nature or agricultural area and food production equivalent to the calorific food intake of 16 million average world citizens.

The cost of CCR is greater than the fossil fuels of today, but the extra cost of it still only amounts to around 2-3 % of Danish GDP. In this cost estimate, the benefits of ultimately ensuring supply security of energy and chemical feedstock, ultimately reducing greenhouse gas emissions, avoiding food crises due to excessive use of land for energy crops, and avoiding cutting down virgin forest are not included.

A road map to the sustainable use of biomass and land for energy and material feedstock purposes should be developed. In doing this, we should aim at using biomass residues only, i.e. co-products and wastes deriving from food production, forestry, industry, households, etc. We should distinguish between residues types and respect the special compositions and contents of these in terms of carbohydrates, nutrients (especially phosphorus), and proteins.

It is tempting to conclude that manure and other wet residues should be reserved for biogas, and that the biogas should subsequently be hydrogenated and stored in the natural gas grid. Wooden, mainly carbohydrate containing residues should be hydrogenated to upgrade their energy content and quality up front. And care should in general be taken to use biogenic carbon at central applications as a first case allowing for a subsequent capture and recovery of the biogenic carbon. When finally converted to transport fuels, the carbon is lost with photosynthesis as the only subsequent way of recovery, and photosynthesis is unfortunately very slow in comparison.

# Dansk resumé (summary in Danish)

Samfundets fokus på drivhuseffekt og energiforsyningssikkerhed har fået mange sektorer til at se sig om efter alternativer til olie og andre fossile brændsler. Biologiske ressourcer – eller biomasse, som det kort kaldes – er de aktuelt foretrukne alternativer i mange af samfundets sektorer. Der er således stigende efterspørgsel efter biomasse til el og varme formål såvel som transportbrændsler og råvarer til kemikalier og materialer – dvs. i praksis alle sektorer, der i dag er afhængige af fossile brændsler.

Desværre stiger fødevaresektorens efterspørgsel efter afgrøder på samme tid som de nye kunder melder sig. Verdens befolkning vokser fortsat og, hvilket måske er endnu mere væsentligt, en stadigt større del af befolkningen vil forventeligt få mere kød på menuen, herunder især blandt befolkningerne i vækstøkonomierne i Kina, Indien, Malaysia, Indonesien, Sydafrika, Mexico, Brasilien m.fl. Selv uden de nye kunder til biomasse, sætter denne udvikling i fødevaresektoren klodens landbrugsarealer under pres for nye landindvindinger. Et overblik over proportionerne af jordens biomasse ressourcer sammenlignet med de nye kunder til biomassen viser klart, at der langt fra er nok til alle.

Verden har for nyligt fået en 'early warning' i forhold til den potentielle indflydelse, som en storskala brug af biomasse til energiformål kan få på fødevarepriserne, nemlig under fødevarekrisen i 2007 – 2008. Gennem denne periode steg prisen på fødevare- og foderafgrøder næsten med en faktor 2, og antallet af sultende mennesker i verden steg fra 800 til 900 millioner.

Det kan således konkluderes, at mængden af biomasse, som verden kan anvende bæredygtigt, er lille sammenlignet med den potentielle fremtidige efterspørgsel. Problemet er, at et fossil frit samfund indebærer nogle betingelser, som gør biomasse meget attraktivt:

- biomasse kan lagres og dermed medvirke til at øge fleksibiliteten af el-produktionen, så den bedre kan følge svingninger i efterspørgslen,
- biomasse kan omdannes til brændsler med stor energitæthed
- biomasse er den væsentligste kilde til kulstof og dermed råvarer til kemikalier og materialer

Alt peger derfor på, at biomasse (og landbrugsareal) kan blive en alvorlig flaskehals i det fossil-frie samfund og at overdrevet brug kan få alvorlige konsekvenser for klodens skovarealer, fødevaresektoren og den fattigste del af verdens befolkning.

Vi kan imidlertid knække – eller rettere udvide – biomasse flaskehalsen. For det første skal vi øge vore bestræbelser for at spare energi generelt. For det andet, skal vi finde kulstof frie løsninger. Der er herunder stigende konsensus blandt energiforskere og energiplanlæggere om, at samfundet skal elektrificeres. Transportsektoren skal i videst mulig omfang drives på elektricitet og el-drevne varmepumper skal ind i opvarmning af husstande, herunder også i fjernvarmen. Det vil hjælpe med at trække mere sol- og vindkraft ind i systemet, og det vil hjælpe med at balancere produktion og forbrug af elektricitet fra de fluktuerende kilder, som sol og vind er, fordi elektriciteten kan lagres i bilparkens batterier og i lagertanke for varme. Yderligere lagring af el kan etableres i form af vandkraft lagre eller forskellige former for trykbaserede lagre, og 'smart grids' og international handel med el kan tilsvarende hjælpe med balanceringen af el-systemet.

Men disse tiltag er ikke nok. Vi har fortsat behov for energitætte brændsler især til luftfart, men i nogen udstrækning også til langturstransport og tung transport på vej og søtransport. Ydermere har vi behov for kulstofholdige stoffer som råvarer for vore kemikalier og materialer. Endelig vil en vis mængde lagringsegnet brændsel til at give fleksibilitet på forsyningssiden af el-produktionen fortsat være en stor fordel. Men et blik på proportionerne for, hvor meget biomasse der kan blive tilgængeligt uden at påvirke fødevareproduktionen, viser, at vi langt fra har nok, selv hvis vi afgrænser brugen til de her prioriterede formål. Vi er nødt til at reducere vores efterspørgsel efter biomasse yderligere.

En oplagt vej at forfølge er at anvende brint som energibærer til at fange og lagre elektriciteten fra sol og vindkraft. Dette vurderes at være en væsentlig del af løsningen. Men det er vanskeligt at lagre og transportere brint, og på grund af dette kan det blive attraktivt at anvende brint som en midlertidig energibærer i produktionen af kulstofholdige brændsler og råvarer.

På denne måde at bruge brint til at opgradere og genvinde kulstof fra biomassen kan vise sig at være den endelige slutsten i bygningen af det fossil fire samfund. Gennem en proces kaldet hydrogenering kan biomasse som kulstofkilde reageres med brint under fremstilling af kulbrinter med meget højere energiindhold og energitæthed end den oprindelige biomasse. Ved desuden at anvende biomasse og de biogene kulstofholdige brændsler fra hydrogeneringen på centrale anlæg som kraft/varme værker, er det muligt at opsamle $CO_2$'en fra biomassen og igen reagere kulstoffet i den med brint for herigennem at opgradere og genvinde den gennem en proces kaldet Carbon Capture and Recycling, CCR. Dette vil yderligere multiplicere brugen af det biogene kulstof fra biomassen.

Samlet set vil opgradering og genvinding af biomassens kulstof gennem hydrogenering og CCR kunne **femdoble** biomassens potentiale for at levere lagringsegnede og energitætte brændsler og kulstofholdige råvarer sammenlignet med de i dag anvendte teknologier til at omdanne biomasse til biobrændsler og bio-kemikalier. Dette kan effektivt udvide biomasse flaskehalsen og muliggøre et fossil-frit samfund.

På denne måde kan sol- og vindkaft via elektrolyse til brint spare naturarealer og landbrugsarealer til fødevareproduktion. Antager vi næste generation vindmøller på 6 MW, vil det betyde, at:

> *En off-shore vindmølle kan spare 5 km$^2$ naturareal eller landbrugsareal med en fødevareproduktion på 2.500 tons kerner om året, svarende til et gennemsnitligt kalorieindtag for 10.000 mennesker*

I et dansk fossilfrit samfund ser det ud til, at vi kommer til at mangle omkring 160 PJ biomasse, når de nationale biomasse residualer sammenstilles med et prioriteret behov for biomasse til el, industri, transport og materialer. Vi kunne vælge at importere denne biomasse, eller vi kunne producere den selv i form af energiafgrøder. Dette ville kræve 8000 km$^2$ svarende til 30 % af det danske landbrugsareal. Vi kunne også følge en vind-for-biomasse strategi og opstille 1600 off-shore 6 MW vindmøller og producere de 160 PJ ekstra biogene brændsler og råvarer via hydrogenering og CCR ud fra vores eksisterende biomasse residualer. Herved ville vi spare de 8000 km2 naturareal eller landbrugsareal med en fødevare produktion svarende til kalorieindtaget for 16 millioner gennemsnits verdensborgere.

Omkostningen ved CCR er større end de fossile brændsler af i dag, men den ekstra omkostning er stadig kun 2-3 % af vores nationale BNP. I dette omkostningsestimat er gevinsten ved den ultimative sikring af energi- og råvareforsyning, den ultimative klimaløsning, bevarelsen af skovarealer og undgåelsen af fødevarekriser fra overdrevet brug af areal til energiafgrøder ikke inkluderet.

En ‘road map’ mod bæredygtig brug af biomasse og areal til energi og transport formål bør etableres. I denne ’road map’ bør vi kun sigte mod at anvende biomasse residualer, dvs. sideprodukter og affald fra fødevareproduktion, skovbrug, industri, husholdning, mm. Vi skal skelne mellem de forskellige typer af biomasse residualer og respektere deres individuelle sammensætning og indhold af kulhydrat, næringssalte (især fosfor) og proteiner.

Det er nærliggende allerede på nuværende tidspunkt at konkludere, at husdyrgødning/gylle og andre våde restfraktioner skal reserveres til biogas, og at biogassen efterfølgende skal hydrogeneres og lagres i naturgasnettet. Træ-agtige og overvejende kulhydratholdige restfraktioner bør på det lange sigt hydrogeneres for at opgradere deres energiindhold og energitæthed inden brug. Det bør efterfølgende overvejes at anvende denne biogene kulstof på centrale værker først for at det efterfølgende vil være muligt at samle kulstoffet (i $CO_2$’en) op med henblik på at kunne genvinde det ved yderligere hydrogenering. Efter endeligt at være omdannet og anvendt til transportbrændsler, vil kulstoffet være tabt med fotosyntese som den eneste tilbageværende mulighed for at samle det op igen, og fotosyntesen er desværre meget langsom i sammenligning med vore andre muligheder for at genvinde kulstoffet.

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# Preface

This report was prepared for the Danish Climate think tank CONCITO in August-September 2010 as part of a larger project on the sustainable use of biomass. Findings of the study was presented at a conference on biomass, September 13th 2010, organized by CONCITO, the Danish Agriculture & Food Council (representing the farming and food industries of Denmark) and the Danish Energy Association ( a branch organisation for large energy suppliers in Denmark).

The report and the findings is the responsibility of the author alone. The version in hand is Version 1 and it has not been reviewed by any other party. It will be sent for external review and a version 2 including review comments will be made available at a later stage soon.

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# Introduction

Till now, the part of our economy being based on biological resources has largely been confined to the food sector. But due to a wish to reduce global warming and dependency on fossil resources, many new customers to biological resources enter the scene: electricity, heat, transportation (on road, sea and air), polymers, and organic bulk chemicals. With this increasing interest in our biomass resource, the issues of competition for the biomass and the need for prioritising it have become evident.

## Constraints on biomass and land

A look at the proportions and the magnitude of these new-coming biomass customers compared to our agricultural sector as we know it, illustrates how big they are. With the average daily diet of around 2700 kcal per person, the total calorific food intake is around 25 EJ per year by the world's population. This is the energy equivalent of the total end-product of world agriculture. The global fossil fuel consumption today is around 400 EJ per year, i.e. 16 times larger. So the new customers are big compared to agriculture of today. The energy content of the crops underlying our food consumption is, however, bigger than the 25 EJ/year, due to the losses in the supply chain for food, and based on data from FAO, the gross energy production in agricultural crops today, thus, amounts to an estimated 150 EJ/year (FAO Statistics Division, 2007). On the other hand, if fossil fuels were to be substituted fully by biomass, increased energy conversion losses would be entailed in the energy and transport sectors as well, and the needed biomass input for full fossil substitution would be around 500 – 600 EJ/year.

The proportion is, thus, that using biomass for all energy demands, today satisfied by fossil fuels, would require an agricultural area 4-5 times the present with similar crop yields. Moreover, with population still growing and with the rapid growth in welfare of large countries in economic transition like China, India, Malaysia, Indonesia, South Africa, Brazil, Mexico and others, there is a growing demand for food in general as well as a strong trend of increasing demand for meat on the menu. This is in itself a strong driver for increased crop demand, especially due to the high metabolic losses from feed crop to meat, and even without the new customers for biomass, there is a pressure for more agricultural land. Looking, further, at historic and projected growth in energy consumption as well as economic growth in general, it is evident that the near-term future developments in agricultural yields on the one side and consumption on the other side are not likely to improve the relation between demand and potential supply of biomass, on the contrary.

Thus, new land cultivation seems inevitable. The magnitude of new agricultural land that earth can potentially provide is, however, only around a doubling. Looking at climatic conditions, soil fertility, and other bio-physical factors essential for cultivating land, leading geographers found that earth can provide a maximum of 120% new cultivable land, most of which is found in tropical South America and Africa (Ramankutty et al., 2002). The figure is theoretical, and actually cultivating this land would imply deforestation including violation of nature preservation, and the realistic magnitude of new land cultivation is much lower. Moreover, primary forest and other un-touched nature types have in many cases sequestered much more carbon than the agricultural land following the cultivation, and the release of carbon due to cultivation may be very high compared to the subsequent carbon offsetting by the crops substituting fossil fuels, around 2-9 times higher over a 30 year period according to a recent publication in the leading scientific journal Science (Righelato and Spracklen, 2007), and many other publications report on the same proportions. The conclusion of this rough look at proportions is that while we need 4-5 times more crops in order to fully replace fossil fuels by biomass, we can at maximum double our cropland, and we can do far from that without carbon releases exceeding carbon savings. In 2008, the Danish Ministry of Food and Agriculture published a report concluding that only a 30-40 % increase in land cultivation would be sustainable (Ministry of Food and Agriculture, 2008).

A review of scientific studies reporting on biomass potentials shows an interval from 75 to 1500 EJ/year from the most pessimistic to the most optimistic estimates of the maximum *biophysically available* potential of biomass for energy purposes in 2030 – 2050 (Dornburg et al., 2010). These estimates, however, concern the biophysical maximum independent of any barriers for harvesting the potential. The studies including economic and *market oriented considerations* find the potential to be lower, i.e. in the interval of 75–150 EJ/year or equivalent to 10–20% fossil substitution. Further, studies looking at the biomass *residue part* only, i.e. the biomass potential not in competition with food production, the reported interval lies from 15 to 100 EJ/year, or around 2–15% fossil substitution in 2030. A review of high quality studies were done by Hedegaard et al. (2008), and an overview of this is listed in table 1 together with one very recent study from 2010 (Dornburg et al., 2010).

*Table 1. Biomass potentials compared to biomass required for full fossil substitution (based on: Hedegaard et al., 2008)*

| Study | Geogr. scope | Temporal scope | Resource focused | Demand driven | Sce-nario | Biomass potential (EJ/y) | | | Biomass req. for full fossil fuel subst.[a] | Fossil fuel subst. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Re-sidues | Energy crops | Total | EJ/y | % |
| i) | EU25 | 2030 | X | | | 6.7 | 5.2 | 11.9 | 79-90 | 16-18% |
| ii) | EU27 | 2015-2025 | X | | | 2.8 | 1.8 | 4.6 | 89-102 | 4-5% |
| | EU27 | 2025-2045 | X | | Low | 2.9 | 5.6 | 8.5 | 89-102 | 8-9% |
| | EU27 | 2025-2045 | X | | High | 3.5 | 7.2 | 10.7 | 89-102 | 10-12% |
| | EU27 | >2040 | X | | Low | 2.5 | 15.4 | 17.9 | 89-102 | 17-19% |
| | EU27 | >2040 | X | | High | 3.1 | 19.9 | 23 | 89-102 | 21-25% |
| iii) | Global | 2030 | X | | Low | 96 | 219 | 315 | 631-716 | 42-48% |
| | Global | | X | | High | 96 | 315 | 411 | 631-716 | 55-62% |
| iv) | Global | 2030 | X | | | 87 | 151 | 238 | 631-716 | 32-36% |
| v) | Global | 2025-2050 | X | | | 31 | 267 | 298 | 631-716 | 40-45% |
| vi) | Global | 2020 | X | | | 15 | 112 | 127 | 631-716 | 17-19% |
| vii) | Global | 2025 | | X | | | | 74 | 631-716 | 10-11% |
| viii) | Global | 2025 | n.d. | n.d. | | | | 85 | 631-716 | 11-13% |
| ix) | Global | 2025 | X | X | BI | 56 | 17 | 74 | 631-716 | 10-11% |
| x) | Global | 2030 | | X | FFES | | | 91 | 631-716 | 12-14% |
| xi) | Global | 2025 | X | X | RIGES | 65 | 80 | 145 | 631-716 | 19-22% |
| xii) | Global | 2050 | X | | | 100 | 400 | 500 | 631-716 | 69-79% |

[a] Based on energy demand scenarios in IEA (2005) and IEA (2004), assumed fossil fuel substitution efficiencies, and supplementary energy statistics in IEA (2007). i) European Environment Agency, 2006; ii) Ericsson and Nilsson, 2006; iii) Fischer and Schrattenholzer, 2001; iv) Swischer and Wilson, 1993; v) Hall et al., 1993; vi) Dessus et al., 1992; vii) Leemans et al., 1996; viii) Shell International, 1995; ix) Williams, 1995; x) Lazarus et al., 1993; xi) Johansson et al., 1993; xii) Dornburg et al. 2010
n.d.: not documented. BI: Biomass Intensive variant, FFES: Fossil Free Energy Scenario. RIGES: Renewables-Intensive Global Energy Scenario.

One thing is, however, the biomass potential itself, looking at the proportions: do we have enough? Another thing is that any huge scale demand of biomass for energy purposes implies a high risk of seriously influencing the food market and food prices, simply because it is there next door to the food market and next door to the millions of farmers who may choose to sell to either market. So even though we politically aim at using only biomass residues, can we really control this?

## The risk of influencing food production and food prices

Most long term bio-fuel policies and strategies around the world converge towards the so-called 2. generation fuels demanding only biomass residues. Due to the energy markets being so big compared to the food market, politicians see the risk of bio-energy policies influencing food prices and, thereby, hunger and starvation among the poorest part of the world population. The risk is judged to be real; during the financial and food crises 2007 – 2008, the number of starving people increased from 800 to 900 million people. For this reason, the residue biomass potential has the biggest political interest, i.e. up to the 100 EJ/year or 15% fossil substitution.

On top of this, there is the option of sustainably cultivating more land, e.g. by biennial crops on marginal land not being cultivated today. However, going into a very large scale bio-energy strategy, say e.g. around 200 EJ/year, will under all circumstances create a huge market for biomass, much larger than today's food market measured in energy equivalents. To control the sustainability of this and enforce future sustainability criteria for biomass is an issue in itself. If biomass in terms of e.g. chips or pellets for an international energy market, or bio-fuels from local/national biomass resources, can be traded in any harbor and any larger town at internationally defined price levels, it will be a difficult task to trace, control and ensure its sustainable origin. What prevents the small farmers from growing Miscanthus, willow or energy-maize on their farmland at the expense of food crops, when the market is there just outside the door, and the profit margin per hectare is bigger than for food crops? How do we control that chips, pellets or biofuels come from residue biomass or non-cultivated land only? It is difficult, as it is today, just to control the timber market and the origin and sustainability of timber for the construction and furniture markets.

Besides the energy market being bigger than the food market, the energy market customers will most probably also be willing to pay more. With a reference $CO_2$ quota price of 32 €/ton (Danish Energy Agency, 2009), a reference price on $CO_2$ removed by CCS at 40-50 €/ton (Korshøj, 2010) and a yield of 12 tons of dry matter/ha for an energy crop, the $CO_2$ off-set value of the energy crop alone will be around 640 – 1000 €/ha. On top of this comes the fuel value of the energy crop, equal to 3.4 €/GJ when substituting coal or 675 €/ha ton (Danish Energy Agency, 2009). A typical cereal food crop today with a kernel yield of around 5 t dry matter/ha (in Denmark) is sold at around 13-16 €/100 kg of kernels (in Denmark) making also around 650 – 800 €/ha. On top of this comes the energy value of the straw, but there will be a smaller quantity from the food crop than from the energy crop. The total market value of an energy crop as a $CO_2$ neutral fuel is, thus, most probably significantly higher than the value of an equivalent food crop from the same hectare of land. Moreover, growing e.g. willow, Miscanthus or another bi- or perennial crop needs only a low input of fertilizers and low farming expenses in general, so the net difference in profit margin becomes even bigger. This is good for the farmer and the reason that agriculture around the world is enthusiastic about bio-energy. But it does point to the fact that a new and large scale demand for energy crops, even exceeding today's food crop production measured in energy equivalents, more than likely leads to very significant food price increases. The US bio-ethanol production was given part of the blame for the world food crisis in 2007-2008, during which market prices on food and feed crops almost doubled. US ethanol was found to be from 2% to 70 % of the reason for this by the many studies reported, with an average around 40%. There is probably no simple answer to how much was caused by bio-fuel production. But the answer to this question is not that interesting either. The interesting question is how market prices will react, when/if we really mean business. At the time, USA's bio-ethanol was only equivalent to around 0.15 % of world energy consumption. What happens to food prices when we want to replace 20 or 30 % of our fossil fuel consumption by biomass? As mentioned the number of people suffering hunger and starvation increased from 800 to 900 million people during the food crisis in 2007 – 2008. The implications can, thus, be tremendous.

# Sustainability criteria for bio-energy

The biomass conversion strategy will depend on the framework conditions of society, and which criteria for sustainability – or survival – of the conversion technology that dominate. At the end, economic criteria will rule, but these may in turn be influenced by policy. So a key question is what the most important criteria will be for biomass conversion. Will it be cost and energy efficiency alone? Or will protein recovery or phosphorus recovery be a decisive issue as well? Or – like it is claimed in this report – may the efficiency of *carbon* recovery turn out to be of key importance in a fossil free society?

## Distinguish between short and long term strategy

The scientific and political debate on the use of biomass would, further, be more qualified, if it would distinguish between short and long term strategies and priorities. The short term is here defined as the period of time, in which we still use oil and/or natural gas in large amounts in our heat and power sectors. The long term is defined as a time, in which we do not any longer use oil and/or natural gas for heat or power to any significant extent.

The reason to distinguish between the two time perspectives is that they constitute very different conditions for optimizing biomass use. On the short term, we can still *exchange* biomass for fossil fuels, and use the substituted fuels for other needs. The key question in this perspective is where to achieve the best exchange rate for the biomass and money that we have. On the long term, we have to *convert* biomass to whatever purpose we need it for, and the key question becomes how to best use the biomass in the puzzle of all energy technologies and chemical/material production technologies.

Moreover, following a strategy for the short term optimization should preferably support the strategy for the longer term optimization. The short term should ideally be a transition towards a sustainable society, and the path followed should lead in the right direction and support building the right infrastructure platform for the longer term optimization.

## The short term strategy

For several decades ahead, we still depend heavily on fossil fuels, and we can only replace them to the extent and with the speed that alternatives become available. Around 40% of the oil consumption in the EU is used outside the transport sector (Edwards et al. 2008), to a wide extent still for heat purposes, and natural gas is widely used for heat and power and will by all probability continue to be so for many years.

On the short term, therefore, we have the option of prioritizing our biomass for heat and power saving oil or natural gas in this sector, and subsequently run our transport sector on what we have saved in heat and power. This increases the possibilities for optimization compared to a situation, where we have to convert biomass to transport fuels. Instead of *converting* biomass to transport fuels, we can *exchange* biomass to transport fuels at a much better exchange rate. Both in terms of cost, greenhouse gas emissions and oil savings, it is in general much better to use the biomass for heat and power than trying to convert it directly to transport fuels. By exchanging it instead, we save the conversion loss and the conversion cost of making liquid fuels from it.

It may sound contra intuitive that oil or natural gas is better for transportation than bio-fuels, knowing that bio-fuels are of a biogenic nature and therefore inherently $CO_2$ neutral. But it *is* so, and the reason is simply that biomass is limited and *using it* for transport fuels means *losing it* for heat and power. As the use for heat and power is more efficient, both environmentally efficient and cost/efficient, this becomes the overall conclusion. The only case, where this general truth may be altered is if the biomass in question contains significant amounts of valuable constituents like e.g. protein that is lost in conversion to heat and power, but may be saved in the conversion to liquid fuels. To reveal this requires a detailed investigation in the specific case.

## The long term strategy

On the long term, the development still may take different directions. Let us assume that climate change is a priority issue and that a long term target is to reduce greenhouse gas emissions at a level corresponding to the IPCC 2 $^{o}$C scenario. This may, however, still be achieved in different ways. At the one extreme, we may discover new fossil fuel reserves and/or chose a coal-to-liquid strategy, and stay fully fossil. This would require Carbon Capture and Storage (CCS) on flue gas emissions as well as CCS from the atmosphere in order to compensate for mobile emissions. The latter part will be more expensive, but probably still doable. At the other extreme, we may become fully fossil free and apply only renewable energy. As fossil fuels do seem to become scarce, this may not be that extreme after all, and it is the expressed strategy by the Danish Government and Parliament.

Depending on the direction development takes, different boundary conditions will prevail for optimizing future systems for energy, transport, material production, waste management etc. The following performance criteria, or sustainability criteria, may play a smaller or greater role:

- Technical performance, stability
- Economy, cost
- Climate change
- Energy supply
- Resource supply: Area (arable land), Biomass, Water, Phosphorus, Protein, Carbon
- Food supply
- Nature preservation
- Social and ethical concerns
- Other

In a fully fossil society, the most important sustainability criteria, and success criteria for technical solutions, are technical performance, cost, energy supply (and energy efficiency), and climate change. Climate change will be a target criterion, and cost efficiency and security of energy supply will be the governing performance criteria in the effort to achieve the target.

In a fully fossil free society, the picture will be very different. Being fossil free, the climate change issue will still be there, but related mainly to our use of land. Cost will still be the ruling constraint, but it may be influenced politically by other concerns of priority. It is foreseen that the constraints on biomass and arable land will be strong, and that area efficiency will be a governing concern for technical solutions. Phosphorus may become a scarce resource and the efficiency of phosphorus recovery thereby a strong issue. Last, but not least, the availability of carbon as a resource is judged to be a strong concern in a fossil free world.

It may seem ironic, but this is how it is: In a fossil society as today, carbon is a problem, because there is too much of it. In a fossil free society, carbon will be a problem, because there is too little of it.

## Carbon constraints in the fossil free society

The reason biomass becomes attractive in a fossil free society, relates to its character and the role it can play. Some key aspects and problems to deal with in a fully renewable energy system are:

- Balancing fluctuating electricity production with consumption
- Storing electricity, storable fuels
- Energy density (energy/mass; energy/volume) of energy/fuels for mobility purposes
- Carbon supply

Balancing wind and solar power, including storing electricity and having access to storable fuels, is a well acknowledged issue and much research and development goes into it. It involves carbon free solutions like smart grids, international electricity trade, physical electricity storages (hydro, pressure, etc.). In the fossil free system, however, biomass is the obvious storable fuel and it can help balancing electricity systems. Moreover, it can be converted into energy dense fuels suitable for providing mobility. Finally, it is a source of carbon for the material/chemical universe in which carbon is a key building block. If we become fossil free, the only other major carbon sources are carbonates and $CO_2$.

These characteristics of biomass are, thus, what makes it attractive in the fossil free society. We can to a wide extent reduce our needs for carbon, and energy dense and storable fuels, but there is a threshold beyond which it becomes difficult. Materials and chemicals simply need carbon, and jet fuels for aviation benefit very much from being carbon based, and it seems less realistic to aim for other solutions like batteries or hydrogen for aviation. For long distance transport on road and for sea transport, carbon based fuels are also highly advantageous. Finally, to have some extent of storable fuels in the electricity system is also highly advantageous. Priority customers for biomass and carbon based fuels are, thus: chemicals/materials, jet fuels, long distance and heavy road transport, sea transport and electricity buffering. In table 2 below is given an overview of projected global energy demands divided on these customers.

*Table 2. Projected fuel, feedstock and biomass demands for 2030 divided on priority customers for biomass. The asterisk * indicates biomass demand with present conversion efficiency to liquid fuels and chemicals*

| Demand type | Fuel or feedstock demand (EJ/year) | Biomass demand (EJ/year) |
|---|---:|---:|
| Chemicals and materials | 30 | 60* |
| Jet fuels | 25 | 50* |
| Long distance road (20% of road) | 20 | 40 |
| Heat & electricity fuel buffer (20%) | 90 | 90 |
| Short distance road (80% of road) | 80 | 160 |
| Heat & electricity bulk (80%) + other | 350 | 350 |
| | ≈ 600 | ≈ 750 |

The highest priority customers for biomass are chemicals and aviation, and these two customers alone can take all the residue biomass that is judged to be biophysically available, not to mention what cost/effectively can be harvested, cf. table 1 and the previous section on biomass constraints.

The shortage on biomass residue can be seen on the national level for Denmark, too, see the overview in table 3.

*Table 3. Overview of projected energy content of the most essential biomass residues in Denmark and the prioritized use of biomass in a 100% Renewable Energy system, year 2050 (source on energy supply: Bentsen and Astrup (2009), and on biomass energy demand: the CEESA research program, preliminary data, www.ceesa.dk)*

| **Biomass type** | **Energy supply** | **Biomass use** | **Energy demand** |
|---|---:|---|---:|
| Straw | 65 PJ | Electricity and heat | 120 PJ |
| Manure | 27 PJ | Industry | 70 PJ |
| Wood chips and pellets | 10 PJ | Transport | 75 PJ |
| Firewood and forest residuals | 32 PJ | | |
| Unexploited forest growth | 17 PJ | | |
| Waste | 47 PJ | Chemicals & materials | 100 PJ |
| | | | |
| In total | 198 PJ | In total | 365 PJ |

Denmark is a nation with a very high agricultural production compared to our consumption, and we produce 3-5 times more food than we consume ourselves. This implies that the straw and manure residues are high in Denmark compared to world average. On the other hand, forest residues are comparably smaller than for some other countries. In Denmark, our biomass residues have an energy equivalent of just over 20% of our energy consumption, whereas the same relation for the world average is estimated to be around 15%.

# Breaking the biomass bottleneck

This report does not look at energy savings. Many opportunities for energy savings still exist, however, and they will often prove to have a much better cost/efficiency ratio than any other ways of reducing $CO_2$ emissions. Also in the context of this report, energy savings will help reduce the demand for biomass.

Assuming realistically, however, that a large energy demand still resides after energy savings, we still need to find a way to break the carbon constraints in a fossil free society. Two approaches to this exist:

- De-carbonize society, develop non-carbon solutions
- Upgrade and recover biogenic carbon

This report elaborates mainly on the second of these options, the first will only be briefly introduced.

## De-carbonize society

There is a growing consensus in energy research and energy planning that development towards more electrification is almost a precondition for success in our effort to achieve a fossil free society. Firstly, because wind and sun are the obvious and only abundant renewable energy resources: we have space enough for windmills and solar power, they are *highly* area efficient, and they are among the most cost/efficient renewable energy technologies. Secondly, because electric motors for transportation are much more energy-efficient than combustion engines, and because heat pumps constitute an energy-efficient route to heat supply besides being an attractive way to capture and store wind and solar power, thus helping to balance the electricity system.

Electrification of society, however, induces the challenge of balancing supply and demand of electricity over time. Three approaches to this exist:

- Flexible supply
- Flexible demand
- Electricity storage

### Flexible supply

Flexible supply means to adjust electricity production to match the demand curve. This is the key approach in today's system. Fossil fuels are stored and power plants can be turned on and off according to demand. Being also storable, biomass fits into this strategy, and this is, therefore, an obvious role for biomass in the fossil free system. It is less attractive to turn wind and solar power off, because they entail no or very small operation costs but high investment costs. To a small extent, wind turbines are regulated (by turning the wings) to lower production at extreme peak production, but this is not an attractive economic solution on a larger scale.

## Flexible demand

Flexible demand means designing products and systems to give priority to using electricity in periods of high electricity production in the system. Examples are cooling/freezing appliances and washing machines which have a high degree of flexibility in when they need electricity. But flexible consumption is mainly for balancing the 24 hour variations and lowering the morning and evening peaks of consumption. Seasonal variations and several days of wind-still cannot be counteracted by flexible consumption, and this is the major part of the balancing need.

## Electricity storage

Electricity storage means converting the electricity to some energy storage from which it can be converted back to electricity or other energy services when needed. Heat pumps for domestic heating and district heating with heat reservoirs has been found to be one of the most cost/effective ways of storing electricity (Lund, 2010). A large car fleet of electric battery cars is another very effective storage with a major impact, but again best for the 24 hour variations. Another promising option is the 'pump' storage, i.e. pumping water to a water reservoir during peak wind or solar production. The most promising way is to use existing hydropower reservoirs and simply pump water back into these at peak wind/solar production. This will require extension of high voltage electricity transmission from regions with high wind production (like e.g. Denmark) to regions with high hydropower production (like e.g. Norway) and it may, further, require an extra low altitude reservoir as a buffer for fresh water before pumping it back up to the present high altitude reservoir. This option is by many perceived to be the most cost/effective of all, but it is, of course, limited to the available water reservoir capacity, which on the global scale is relatively small, hydropower being only 2,2 % of global primary energy supply (IEA, 2008). Further options are then to build artificial hydro storage, compressed air storage or other means of pressurized storage.

Finally, electricity can be chemically stored by using it to convert chemical substances to higher energy levels. The best known example is the electrolysis of water to hydrogen and oxygen, where the electrical energy is captured and stored in the hydrogen.

## Hydrogen

Hydrogen as an energy storage and energy carrier has long been, and still is, a candidate to play a role in the fossil free society, both as a way to store electricity and as an energy carrier/fuel for transportation. Hydrogen has an extremely high energy density per unit of weight with a lower heat value of 121 MJ/kg – being e.g. three times higher than the lower heat value of oil (42 MJ/kg). Unfortunately, however, the volumetric energy density of hydrogen is extremely low, and the space requirement of the storage is a key problem. Hydrogen stores take up very large space, which make them disadvantageous for transportation purposes compared to carbon based fuels. A lot of research goes into reducing the space requirements, but we are still far from having reached an acceptable level.

Due to the storage problem of hydrogen, it may be attractive to use carbon based energy storage and convert the energy of hydrogen into a carbon based fuel. Moreover, as we need carbon in our chemicals and materials, it may be attractive to also build these assisted by hydrogen, as elaborated on in the next section.

## Upgrade and recover biogenic carbon

Two reasons, thus, exist that the ‘hydrogen society’ is not the final answer to the fossil free society: the problem of storing, and thereby of transporting, hydrogen, and the need for carbon feedstock as such. But hydrogen can play an important role in solving these problems as well, being an intermediate agent to capture the wind and the sun through electrolysis. Having captured the electricity from wind and solar power in the hydrogen, we can use this to create and upgrade a store of carbon based fuels and feedstock for chemicals/materials based on the initial content of carbon in biomass. This can solve the problem related to the hydrogen and it can effectively break the biomass bottleneck by enhancing the use and potential of biomass many times.

First, hydrogen can be used to upgrade the energy content and energy density of biomass. This is well known as the process of hydrogenation. Secondly, it can be used to convert $CO_2$ to any form of hydrocarbon, and from there on to any known chemical substance. We call this Carbon Capture and Recycling, CCR. By hydrogenation of biomass, we can thus enhance the potential and usefulness of the biomass energy, and by CCR we can recover and recycle the carbon of the biomass into fuels and feedstock again. In this way we can almost five-double the carbon based fuel and feedstock, we can get out of the available biomass, see the following sections for further elaboration.

### Hydrogenation

Hydrogenation of biomass involves gasifying the biomass into a syngas consisting of carbon oxide, hydrogen and water gases from the biomass and then reacting hydrogen with this gas. A variety of end products can be achieved including e.g. methane and diesel.

The stoichiometric equations for the hydrogenation of biomass into methane and diesel are given below. Under the equation is given the energy content of the inputs to and outputs from the reaction in terms of the lower heat value of the substances. The values given are per mole of substance.

Hydrogenation to methane:

$$\begin{array}{ccccccc} C_6(H_2O)_5 & + & 12\ H_2 & \longrightarrow & 6\ CH_4 & + & 5\ H_2O \\ \text{biomass} & & \text{hydrogen} & & \text{methane} & & \text{water} \\ \text{2,8 MJ} & & \text{2,9 MJ} & & \text{4,8 MJ} & & \end{array}$$

Hydrogenation to diesel:

$$\begin{array}{ccccccc} C_6(H_2O)_5 & + & 5{,}75\ H_2 & \longrightarrow & \tfrac{1}{2}\ C_{12}H_{23} & + & 5\ H_2O \\ \text{biomass} & & \text{hydrogen} & & \text{diesel} & & \text{water} \\ \text{2,8 MJ} & & \text{1,4 MJ} & & \text{3,8 MJ} & & \end{array}$$

As can be seen from the equations, the reactions are exothermic, meaning that chemical energy from the biomass and hydrogen is released as heat during the reaction. This is why some energy is 'lost' from the input side to the output side. This is emitted as heat and is helping to run the reaction. But as is also evident from the equations, the energy content of the methane as well as the diesel is much higher than of the biomass. Moreover, the quality and usefulness of the energy is higher, as both methane and diesel are better energy carriers than biomass with higher energy density and higher applicability for several purposes. This, further, implies that the energy conversion process when subsequently using these fuels can have better energy efficiencies.

## Carbon Capture and Recycling, CCR

'Carbon fixation' is another term used to designate the concept of CCR. It is a well known chemical process, and it has often been exemplified by the synthesis of methanol from $CO_2$ and hydrogen, see the stoichiometric equation below:

Methanol synthesis by CCR:

$$CO_2 + 3\,H_2 \longrightarrow CH_3OH + H_2O$$

In relation to the issue of global warming and energy supply, the concept of capturing and fixing $CO_2$ into fuels and feedstock using hydrogen has been named the 'methanol society', and an often cited publication on this issue is the one by Olah (2005).

In a fossil free society, the hydrogen for reacting the CO2 derives from electrolysis. A potential further synergy of the concept is that the oxygen co-generated along with the hydrogen in the electrolysis can be used for an effective combustion of the biomass in a so-called oxy-fuel combustion process using pure oxygen. The concept is illustrated in Figure 1 below.

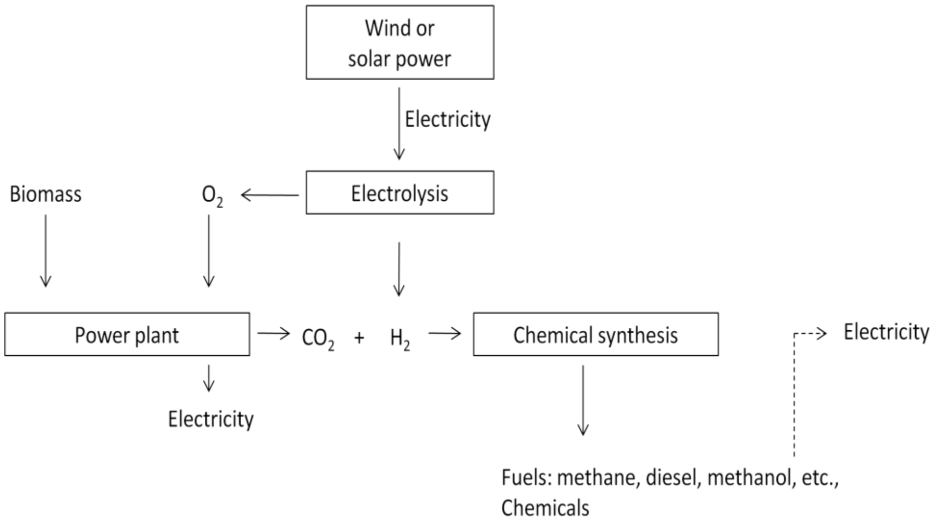

*Figure 1. Carbon Capture and Recycling, CCR using the oxygen from electrolysis in an oxy-fuel combustion of the biomass, and capturing the biogenic $CO_2$ from the biomass combustion by the hydrogen from electrolysis*

The idea of the CCR is twofold. First to supply carbon based fuels and feedstock be recycling $CO_2$, which means that these carbon compounds are provided with no use of biomass and no global warming as the $CO_2$ was biogenic in the first place. Secondly, to store wind electricity in a better way than the hydrogen itself could do it.

In this report, we have chosen to illustrate CCR into methane and diesel, partly because these are good fuels partly to be consistent with the hydrogenation. Making methane and diesel directly from $CO_2$ and hydrogen is well known technology.

The stoichiometric equations are shown below.

CCR to methane:

$$\underset{\substack{\text{carbon dioxide}\\ \text{0 MJ}}}{6\ CO_2} + \underset{\substack{\text{hydrogen}\\ \text{5,8 MJ}}}{24\ H_2} \longrightarrow \underset{\substack{\text{methane}\\ \text{4,8 MJ}}}{6\ CH_4} + \underset{\text{water}}{12\ H_2O}$$

CCR to diesel:

$$\underset{\substack{\text{carbon dioxide}\\ \text{0 MJ}}}{6\ CO_2} + \underset{\substack{\text{hydrogen}\\ \text{4,3 MJ}}}{17{,}75\ H_2} \longrightarrow \underset{\substack{\text{diesel}\\ \text{3,8 MJ}}}{\tfrac{1}{2}\ C_{12}H_{23}} + \underset{\text{water}}{5\ H_2O}$$

As can be seen from the equations also these processes are exothermic.

### Electro-fuels

A biotechnological variant of CCR has been named ‘electro-fuel’ production. Instead of using electrolysis for hydrogen production followed by a chemical synthesis, this concept makes use of microorganisms that can use electrons directly and transfer them to $CO_2$ and build further chemical substances from this. An example is methanogenic bacteria growing directly on an electrode and producing methane from the electrons and $CO_2$. But many other variants exist, and this approach is a growing research field in e.g. the USA.

It is, in principle, the same process as the chemical synthesis from methane and $CO_2$, and time will show which of the two approaches are most advantageous.

Figure 2 next page illustrates the electro-fuel production.

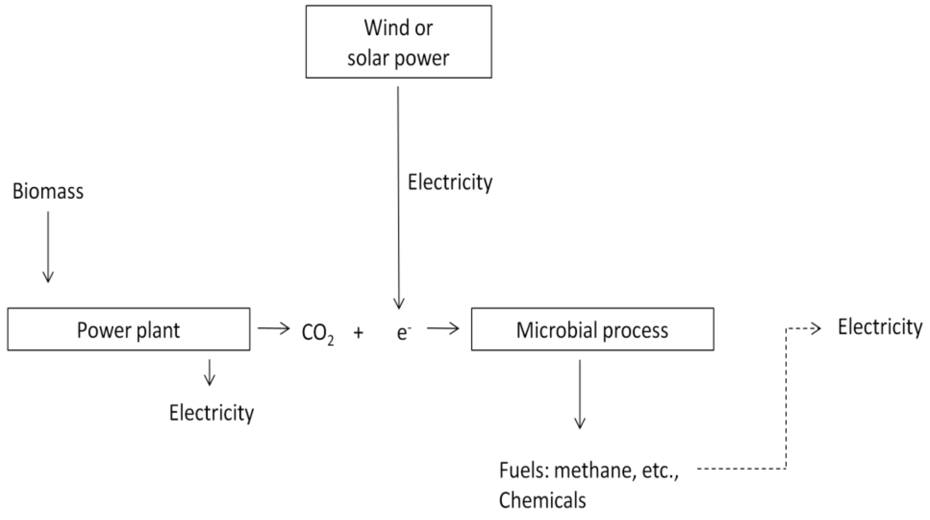

*Figure 2. Carbon Capture and Recycling, CCR using a microbiological process to combine electrons directly with $CO_2$ and have microorganisms produce fuel and feedstock substances from this*

## A potential five-doubling of high-density fuel and carbon based feedstock

These ways of using hydrogen to upgrade biomass and capture $CO_2$ and recycle the carbon into fuels and feedstock again can be combined in various ways.

By the hydrogenation alone, the energy content of the biomass can be increased by 70 % in the case methane and 30 % in the case of diesel, but at the same time, the quality of the fuels and feedstock is highly improved and easier to use for many applications.

By the CCR, the biomass can first be reserved for heat and power making and subsequently the $CO_2$ can be captured and recovered into fuels for e.g. transportation. This implies using the carbon twice and leads to a higher overall benefit and functionality in terms of storable fuels, high density fuels and carbon feedstock.

Finally, and even more efficient in terms of providing these functionalities, hydrogenation and CCR can be combined in various ways.

Figure 3 next page shows some of these variants and combinations in comparison with the conventional fermentation based conversion of biomass directly to liquid fuels.

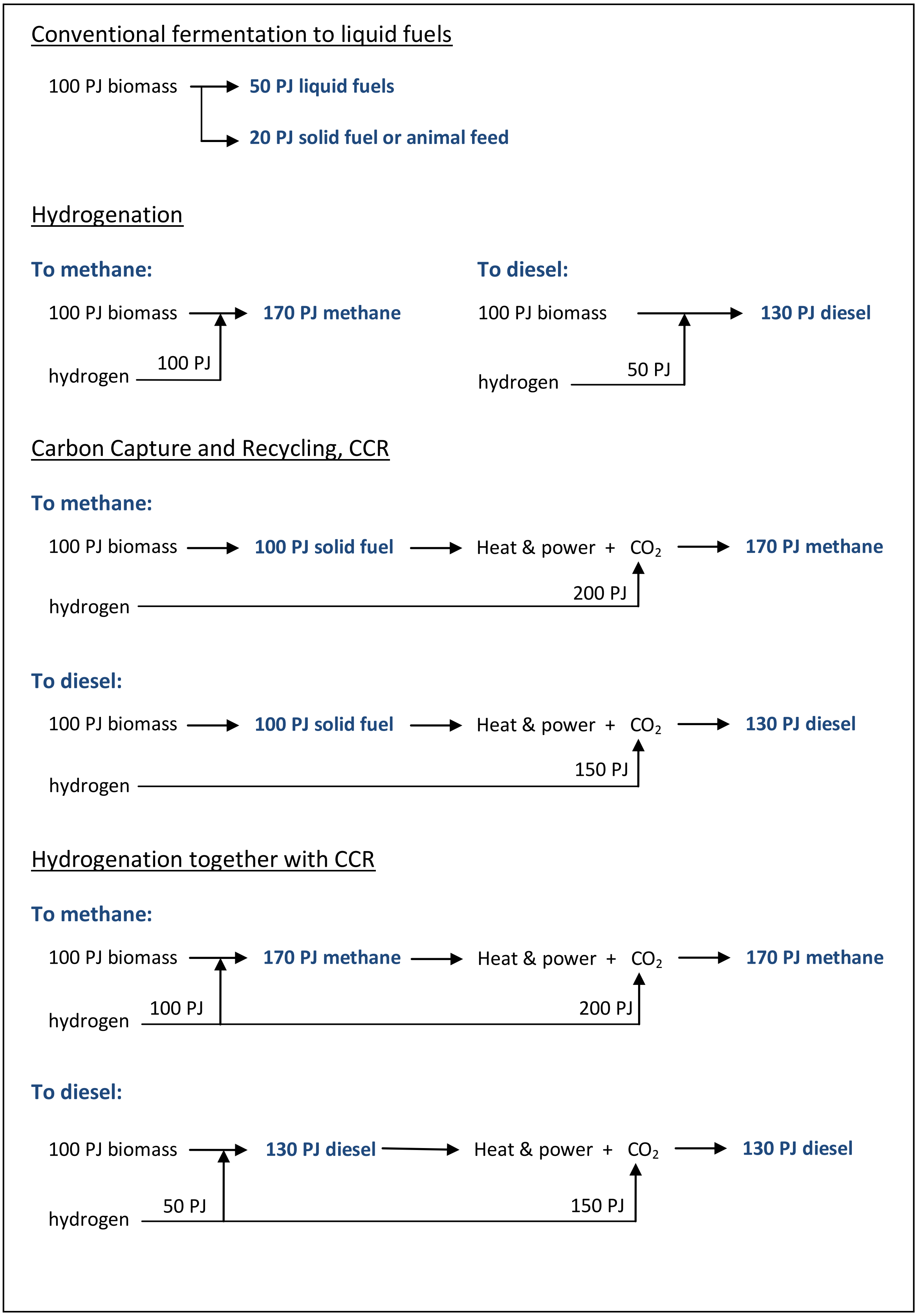

*Figure 3. Conventional fermentation based conversion of biomass to liquid fuels and feedstock against hydrogenation, Carbon Capture and Recycling and combinations hereof. All process flows and energy figures are based on an initial use of 100 PJ biomass*

As Figure 3 shows, there is a large difference in the quantity and quality of carbon based fuels and feedstock available for society in the different approaches. Table 4 below summarized this.

*Table 4. An overview of biomass and hydrogen inputs together with outputs of carbon based fuel and feedstock with the different degrees of upgrading and recovering biogenic carbon*

| Conversion process | Inputs (PJ) biomass | hydrogen | Outputs (PJ) solid fuel | liquid fuel road | liquid fuel road and air | methane |
|---|---|---|---|---|---|---|
| Fermentation | 100 | | 20 | 50 | | |
| Hydrogenation to methane | 100 | 100 | | | | 170 |
| Hydrogenation to diesel | 100 | 50 | | | 130 | |
| CCR to methane | 100 | 200 | 100 | | | 170 |
| CCR to diesel | 100 | 150 | 100 | | 130 | |
| Hydrogenation & CCR to methane | 100 | 300 | | | | 340 |
| Hydrogenation & CCR to diesel | 100 | 200 | | | 260 | |

As the table shows, a biomass potential of 100 PJ will by conventional fermentation based conversion provide a total of 50 PJ liquid fuels and 20 PJ solid fuels for heat and power or to be used as animal feed. Hydrogenation alone will upgrade the 100 PJ biomass to 130 PJ liquid, high energy density fuels or 170 PJ methane. CCR alone will first provide the 100 PJ biomass solid fuels and subsequently 130 PJ diesel or 170 PJ methane. i.e. up to 270 PJ solid and liquid fuels in total. Finally, combining hydrogenation and CCR will result in an output of 260 PJ diesel or 340 PJ methane from the 100 PJ biomass.

As also evident from table 4, however, this happens at the expense of hydrogen consumption, and energy is lost in conversion. The total energy content of the biomass and the hydrogen is, of course, greater than that of the fuels on the output side. If, therefore, hydrogen is sufficiently good for the demanded energy services in question, there is no sense in taking a detour of producing the carbon based fuels from the hydrogen. The conversion from hydrogen to carbon fuels as energy carrier is only justified by the inherent differences in the properties and qualities of the two.

### The wind versus biomass trade-off

What table 4 shows is that we can break the biomass bottleneck. What we can do by de-carbonization and by hydrogen directly, we should do before any hydrogenation and CCR. But whatever remains as non-doable or less attractive by these means, does not in turn imply the need to use excessive biomass: We do have the option of generating sufficient high-density and carbon based fuels and feedstock without an unsustainable use of biomass.

In a Danish fossil free system, the hydrogen would mainly come from electrolysis running on wind power. In other parts of the world, solar power could be the source of electricity. Wind turbines would in Denmark mainly be located at sea, and solar power would mainly be located on non-fertile land.

In this way, the use of hydrogen to replace biomass through either direct use of hydrogen, hydrogenation of biomass or CCR, becomes a way for wind power or solar power to save land for nature or food production. Let us take a look at this trade-off.

The next generation wind turbine is the 6 MW turbine. The present 2 MW off-shore wind turbines in Denmark produce a yearly average of 1 MW. Assuming the same ratio between effect capacity and average production for the 6 MW turbine, we can expect a production of 3 MW, i.e. an annual production of 3 MWh/h * 3,6 GJ/MWh * 24 h/d * 365 d/y ≈ 100.000 GJ/year. The yield of energy crops on an agricultural field (in Denmark) is equivalent to around 200 GJ/ha/year. One off-shore wind mill this size, thus, produces the same amount of energy in the form of electricity as 500 ha of land (equal to 5 $km^2$ of land) can produce in the form of biomass. Till now, the two forms of energy cannot substitute each other directly, due to the many reasons also touched upon in this report, but with using hydrogen directly and via hydrogenation and CCR of biogenic carbon, wind can be brought to replace biomass.

From table 4, the substitution ratio between hydrogen and biomass can be found. As illustrated, conventional fermentation based conversion of 100 PJ biomass results in 20 PJ solid fuel (suitable for heat and power making) and 50 PJ liquid fuel (suitable for transport) – or 70 PJ in all. Hydrogenation to methane results in 170 PJ methane suitable for heat and power as well as transport. Methane for heat and power would give better energy efficiency than the solid fuels residue from fermentation, but in this quick calculation, we look away from that. To provide 20 PJ for heat and power as well as 50 PJ for transport (70 PJ of methane in all), we would need to hydrogenate 40 PJ of biomass with 40 PJ of hydrogen. In other words, the 40 PJ of hydrogen would help us save 60 PJ of biomass. In the same way, we can calculate how much biomass hydrogen will save us when used in CCR or in combined hydrogenation and CCR. The figures are approximately:

| | |
|---|---|
| - Hydrogenation: | 40 PJ hydrogen saves 60 PJ biomass |
| - CCR: | 60 PJ hydrogen saves 70 PJ biomass |
| - Hydrog. + CCR: | 60 PJ hydrogen saves 80 PJ biomass |

Assuming a 75% conversion efficiency from electricity to hydrogen, it is evident that we can assume around a 1 : 1 substitution from wind power to biomass, i.e. 1 J wind power can save 1 J biomass. This is conservative with respect to the points made in this report, because there is also some heat released from the electrolysis as well as the hydrogenation and CCR that may be used for heat services, but let us look away from this also.

If we, thus, assume that the energy substitution ratio between wind power and biomass is 1:1, that the wind power comes from the next generation of 6 MW wind turbines, and that an average kernel yield of food crops in Danish agriculture is around 5 tons of kernels per hectare, the overall trade-off between wind power and nature or land for food production becomes:

> *one off-shore wind mill can save 5 km$^2$ of nature or agricultural land equivalent to 2500 tons of food crop kernels per year equal to the average calorific intake of food for 10000 people*

If we look at the overview of biomass supply and demand in a Danish fossil free system, we seem to lack around 160 PJ of biomass, cf. table 3. The data are preliminary, but they do give an impression of proportions. Assuming we would take this biomass from nature or agricultural land somewhere in Denmark, and assuming an energy crop yield of 200 GJ/ha/year, we would need around 0,8 Mha or 8000 km$^2$ of land equivalent to around 30% of Danish agricultural land. We could avoid this by putting up 1600 off-shore 6 MW wind mills. By doing this, we would then save these 8000 km$^2$ of nature or agricultural area and food production equivalent to the calorific food intake of 16 million average world citizens.

In comparison, the total number of wind mills in Denmark in 2009 was 5000, mainly being mills in the range 0,5 – 2,3 MW.

But what are the cost implications of such a wind-for-biomass strategy?

### A back-of-the-envelope look at cost

A quick and very rough look at cost implications of CCR shows that it is expensive compared to fossil fuels of today, but as an extra cost to society as a whole, it is still very small.

Based on the following assumptions:

- Off-shore wind power: 10 eurocents/kWh
- Energy efficiency of electrolysis: 75 %, i.e. 44 kWh/kg $H_2$
- Operation cost of hydrogen: 4.4 €/kg = 1.5 €/kg oil equivalent = 215 €/barrel oil equivalents
- Total cost of hydrogen including amortized investment: 250 – 300 €/ barrel oil equivalents
- Total cost of methane or diesel: max 350 €/barrel oil equivalents
- Petrol reference: 75 €/barrel oil equivalent

we find an extra cost of CCR fuel = 350 – 75 = 275 €/barrel oil equivalent.

At 100 PJ CCR fuel/year this would imply and extra cost of 4.2 billion €/year, being equal to 2 % of Danish GDP.

Hydrogenation is expected to be cheaper and a more cost/efficient way than CCR of providing high-density carbon based fuel and feedstock. But there is, of course, and upper limit of how much we can make by hydrogenation, and the potential can, then, be expanded by CCR.

But there are many benefits of hydrogenation and CCR that are lacking in this quick cost estimate. These include the benefits of a fossil free system with an ultimate security of supply and very little greenhouse gas emission – or they include the avoided cost of achieving the same targets in another way. They further include a system with no excessive use of biomass and agricultural land and, thereby, no negative influences on the food market. There is a wide political consensus on having a target for Danish foreign aid of around 1% of GDP. It would be interesting to know the influence on food prices from an energy crop production equivalent to the biomass saved by the hydrogenation and CCR, and to set this in proportion to achievements of foreign aid in general.

# Conclusions and recommendations

The amount of biomass that the world can sustainably use is small compared to the potential demand for it. The problem is that a fossil free society implies a set of conditions that make biomass in high demand: it can be stored and serve as a fuel to buffer electricity production, at can be converted to high-density fuels for mobility purposes and it is a key source of carbon feedstock. Everything points, therefore, to the fact that biomass (and agricultural land) may be a severe bottleneck in the fossil free society and that excessive use can have severe consequences for the food sector and the poorest part of the world population.

We can, however, break this bottleneck. First of all, we must seek further energy savings. Secondly, we need to look for way to de-carbonize society. There is a growing consensus among energy scientists and energy planners that society is heading towards increased electrification. The transport sector shall to the widest possible extent run on electricity and domestic and district heating shall be converted to heat pumps to the extent possible. This will help pulling more wind and solar power into our systems and it will help balancing electricity supply and demand from fluctuation sources, because electricity is then stored in the batteries of the car fleet and in reservoirs for heating. Further electricity buffering can be provided by water reservoirs for hydro power or by various means of pressure based reservoirs, and smart grids and international trade will further assist in the balancing.

But these measures are not enough. We still need high density fuels especially for aviation, but to some extent also for long distance, heavy transport on road and for sea transport. We also need carbon feedstock for our chemicals and materials. Finally, some amount of storable fuel for providing flexibility on the supply side of our electricity systems will be a big advantage. Looking at proportions in how much biomass is available without influencing the food sector shows that we have far from enough even for these priority customers alone. We need to do something to reduce our demand for biomass further.

Using hydrogen as an agent to capture the electricity from wind and solar power through electrolysis is an obvious route to follow. This is judged to be a significant part of the solution. But storing hydrogen is not easy, and due to this it may be attractive to use hydrogen as an intermediate energy carrier for the production of carbon based fuels and feedstock.

Through hydrogenation it is possible to use biomass as a source of carbon and react hydrogen with it to produce hydrocarbons of much higher energy content and energy density than the original biomass. Moreover, using the biomass and the biogenic carbon from hydrogenation in central applications like heat and power, it is possible to collect the $CO_2$ from the biomass and further recover and recycle it by Carbon Capture and Recycling, CCR. This will further multiply the use of the biogenic carbon from the biomass.

Overall, the technologies of hydrogenation and CCR, can approximately five-double our biomass potential for providing high-density fuels and carbon feedstock compared to the presently applied technologies for converting biomass to fuels and feedstock, and this can effectively break the biomass bottleneck of the fossil free society.

In this way, wind and solar power can save nature and land for food production. Assuming the next generation 6 MW wind mill, it is found that

> *one off-shore wind mill can save 5 km$^2$ of nature or agricultural land equivalent to 2500 tons of food crop kernels per year equal to the average calorific intake of food for 10000 people*

In a Danish fossil free society we seem to lack 160 PJ of biomass residue. We could import this or produce energy crops ourselves, and for the purpose we would need 8000 km$^2$ of arable land equal to 30 % of Danish agricultural land. Or we could follow a wind-for-biomass strategy and put up 1600 off-shore 6 MW wind mills and create the 160 PJ extra biogenic fuel and feedstock by hydrogenation and CCR. By doing this, we would then save these 8000 km$^2$ of nature or agricultural area and food production equivalent to the calorific food intake of 16 million average world citizens.

The cost of CCR is more expensive than the fossil fuels of today, but the extra cost of it still only amounts to around 2-3 % of Danish GDP. In this cost estimate, the benefits of ultimately ensuring supply security of energy and chemical feedstock, ultimately reducing greenhouse gas emissions and avoiding food crises due to excessive use of land for energy crops are not included.

## Distinguish between biomass types

Before any general conclusions can be drawn on how to prioritize biomass, however, we need to take a more detailed look. Biomass comes in many different forms with different characteristics, and we need to distinguish between these, when we discuss how to prioritize it. The overall consideration till now are valid as a general principle and as an input to considerations of how to manage a future carbon constraint, but other concerns like e.g. phosphorus recovery may, as mentioned earlier, give rise to specific priorities.

First, the physical properties and composition of the biomass residue are decisive for how to prioritize it. We should especially distinguish between:

- wet and dry

biomass. Wet biomass like manure/slurry is inherently more suitable for conversion by fermentation and less suitable for incineration. Likewise, a dry biomass like straw and forest/wood residues is inherently more suitable for thermal conversion.

The composition of the biomass has further implications. Biomass residues can vary from containing:

- Mainly carbohydrates like starch, cellulose, hemi-cellulose including more or less lignin
- Nutrients – especially phosphorus is expected to become an issue
- Proteins

and the content may be important to a strategy of what to recover from the biomass besides carbon and energy.

In practice, residue biomass can be divided into four main categories covering the vast majority of biomass residues:

- Animal manure
- Straw, non-food residue of crops
- Forest residues
- Waste, from households, industry, gardens, etc.

### Illustrating biomass specific long term strategies

Based on our knowledge of existing fermentation processes, it is tempting already to conclude that wet residues like manure/slurry and maybe also the wet/green part of household waste are obvious to prioritize for biogas. Of all known fermentation based processes, biogas is the most efficient in recovering energy, carbon and nutrients for fertilization. The produced biogas may, then, be upgraded by hydrogenation prior to use or storage.

The dry, wooden and mainly carbohydrate containing residues, however, are obvious to use in thermal conversion or hydrogenation. With regard to this type of residues, the concerns for carbon management and breaking the carbon bottleneck are judged to be dominating, i.e. the previous consideration on these issues apply directly to these types of residues. It is tempting to conclude that such residues, on the long term, should be hydrogenated prior to their use in order to boost their potential up front.

Whether straw belongs to this category is a question of how much protein value it has. There is still some uncertainty on this issue, and it still remains to be demonstrated that the so-called molasses or black syrup from alcohol fermentation of straw has a protein value high enough to justify the extra costs and conversion losses of the fermentation based conversion compared to the thermal conversion. Moreover, the fermentation based conversion to transport fuels will divert the carbon directly to transport, where it is lost in first step, instead of using it for heat and power first, allowing for a potential subsequent recovery for transport fuels in a second step.

For very protein rich biomass types like some industrial wastes and other special fractions, care should be taken to try to recover the protein for feed or food prior to or in parallel with energy use. Fermentation based processes are superior for this.

Finally, bio-refineries on special crops may have the possibility to increase the overall efficiency and functional output from the crop in terms of food, feed, energy and special compounds. It should, however, be remembered that the reference is to use the non-feed or non-food part of the crop for energy and let the human or animal metabolism do the refining of the food/feed part. Further, it should be noted that a future reference will be that subsequent to the metabolic refining, whatever is excreted by the body is not lost but will probably go through biogas fermentation for further energy, carbon and nutrient recovery. This implies that there is only very little room for conversion losses in any up front bio-refinery operation, and that the functionality or nutrition value should be very much improved to justify conversion losses.

## Connecting the short and long term strategy

It should still be noted that on the short term, wind power still gets a better substitution efficiency and $CO_2$ reduction by other applications than through electrolysis to hydrogen, e.g. by substituting heat through heat pumps or even electric boilers. In the transition towards the fossil free society, therefore, we should respect the orders of priority and take the most efficient and cost/effective steps first.

But it should also be noted that the technologies that we promote in present time will to a wide extent anchor up in society due to the great inertia of technology development, and we should take care to build the right platform for the long term sustainability already now and not lock ourselves into any wrong tracks. This is why we need a road map to connect the present and short term with the longer term sustainable use of biomass.

Such a road map will not be developed here, a lot more work needs to be done in order to give recommendations. But a few examples illustrating the idea of elaborating a road map are given below.

Examples of elements of a road map for sustainable use of biomass for energy purposes:

- To have the long term target of not influencing the food sector and not create any food crisis due to competing demands for biomass between the food and the energy/transport sectors
- To have a long term target of hydrogenating dry wooden biomass in order to upgrade its potential up front. On the short term to prioritize a significant part of this for central applications for heat and power in order to ensure that carbon emissions are available and possible to recover.
- Build on the natural gas grid to connect the short and long term. On the short term the gas grid can facilitate the use of natural gas for transportation. This will increase supply robustness of the transport sector, and increase the potential of biomass to sustain heat and power as well as transport, because biomass can then indirectly release the pressure on the transport sector by cost/effectively saving natural gas in the heat and power sector. The gas grid can gradually be used for distribution and storage of biogas as well as any synthetic gas made from biomass. It can, thus, be an infrastructure component suited for the short as well as the long term.
- Do not invest in $CO_2$ removal from biogas. Use biogas directly for heat and power or upgrade biogas by hydrogenation. That will kick-start hydrogenation and lead to synergy with natural gas grid.
- ...etc.

It is recommended that such a road map is developed.

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