The role of biomass to replace fossil fuels in a regional energy system - the case of West Sweden

THE ROLE OF BIOMASS TO REPLACE FOSSIL FUELS IN A REGIONAL ENERGY SYSTEM – THE CASE OF WEST SWEDEN

by

Jan KJARSTAD* and Filip JOHNSSON

Department of Energy and Environment, Chalmers University of Technology, Gothenburg, Sweden

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This paper analyses the potential role of biomass to meet regional CO_2 emission reduction targets up to year 2050 in two counties in the west of Sweden. It is concluded that the region could double its production capacity of solid biomass to 2030, from 6 to 12 TWh. Modelling of the electricity sector in the region indicates that bio-based electricity generation in combined heat and power plants could almost triple by 2050 while at the same time replace fossil based generation in district heating. Biomass can also contribute to fuel shift in the transport sector. Yet, the transport sector requires a series of actions to significantly reduce demand in combination with use of electricity and biofuels and its transformation is obviously strongly linked to an overall transformation of the European transport sector. The total need for biomass could potentially increase from 14 TWh in 2010 to 48 TWh already from 2040, considering the electricity and transport sectors and under the assumption that large energy savings can be achieved in the building sector and that all fossil based heat generation can be replaced by biomass heating. Assuming that biomass also replace the fossil based raw materials used by the industry, including three refineries, requires 170 TWh biomass to be compared to the 130 TWh currently used for the entire Sweden.

Key words: *west Sweden, fossil fuels, system perspective, biomass, CO_2-emission reduction targets*

Introduction

EU's climate policy is aiming to limit the global mean temperature increase to 2 °C. Reaching this target will be a significant challenge since policies and efforts must not only be carried out on an international, EU and national level but also on a local level. The local level is of importance since many decisions are taken on this level and the results of these decisions have direct implications on aggregated national results. The local level is also where the policies will have direct impact on the general public. Clearly, there is a strong regional and local interest to develop society towards a more sustainable one and many cities and regions have taken substantial steps to reduce energy demand through conservation and efficiency measures while at the same time increasing the contribution of renewable energy, see for instance [1, 2]. The site-specific nature of renewable sources, the need to involve citizens in the energy-planning process and the perspective of local governments also emphasize the strategic role played by municipalities in the energy planning process as shown in [2-6]. At the same time however, it is important to recognize that local authorities are likely to have limited capacity to act in sectors like transport and industry. Although the works presented in

* Corresponding author; e-mail: kjan@chalmers.se

[2-6] give valuable information on the importance of local and regional energy planning there is a lack of investigations which assess future regional use of biomass, considering both an estimate of future biomass supply and demand for biomass from all relevant sectors. The present work is an attempt to make such study using west Sweden as a case study. The work is based on a comprehensive assessment on how west Sweden can contribute to reach the Swedish target of zero net CO_2 emissions in 2050* [7]. Figure 1 shows the location of west-Sweden in light green (marked SE23).

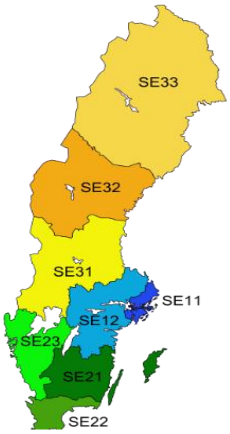

Figure 1. The location of the west Sweden region is marked with SE23

West Sweden is divided into two counties; Vastra Gotaland county (VG) and Halland county with 49 and 6 municipalities, respectively. The political power (the capacity to act) is mainly with the municipalities, *i. e.* the municipalities have so-called local self-government. The municipalities are often large property owners and also usually own the main energy utility company in the municipality. The region is characterized by substantial industrial activities, including energy intensive industries (*e. g.* refineries, chemical clusters and pulp and paper industry). The development of these are obviously dependent on development of global markets.

In Sweden, use of biomass for energy purposes has increased significantly over the last two decades, from a total supply of 68 TWh in 1993 to almost 130 TWh (468 PJ) in 2013. Most of the biomass is used for heat and electricity generation in the industry or in combined heat and power (CHP) plants and for production of fuel for the transport sector [8]. The major part of the Swedish biomass used for energy purposes is residues from the forest industry, *i. e.* linked to the wood and pulp-and-paper industry. There has been a net growth of the Swedish forest for many decades, *i. e.* the Swedish forest represent a carbon sink for which additional outtake is possible and still yielding a net GHG reduction. Thus, the use of Swedish biomass can give a positive and cost-efficient contribution to reaching long term renewable and GHG emission targets. Yet, expansion of the use of biomass yield will also increase requirements for logistical systems supplying the biomass [9, 10].

The EU renewable energy directive requires that 10% of all transport fuels should be supplied from renewable sources in all member states by 2020. According to [11], referring to the national renewable energy action plans (NREAP), more than 85% of this is expected to come from biofuels. However, in order to reach near zero GHG emissions by 2050, the transport sector will have to be completely transformed (change in fuel mix, electrification, change in modes and reduced transportation work) and biofuels are expected to play a substantial part in this transformation replacing fossil fuels along with various electrical options such as batteries, hydrogen fuel cells and various hybrids. However, biomass is also seen as an important fuel to replace fossil fuels in both industry and in the heat and power sectors in all parts of the world.

Estimates of biomass supply potential vary significantly as indicated in [12-15]. For instance The European Environment Agency assessed the environmentally compatible bio-

* Both VG and Halland county as well as each of the 55 municipalities in the region have set individual emission reduction targets. Yet, they are all aiming towards the national goal of achieving zero net GHG emissions by 2050 which however currently is being re-evaluated by the Swedish Government

mass potential for the EU-25 at 9,800 PJ [13] while the Biomass Futures project indicated that the biomass potential for EU-27 in 2020 could reach 15,700 PJ [14]. In 2013 some 5,860 PJ of bioenergy was consumed within the EU and by 2040 IEA projects this to increase to 10,550 PJ in its so-called 450-scenario [16]. The expected increased use of biomass in several sectors in the future (transport and power and heat in the energy sector, bio-based materials) is likely to put considerable strain on the environment (land use patterns, biodiversity, water resources) while at the same time it may also create opportunities for an integrated use of biomass through cascading and bio-refineries as claimed by [15-19] or through combined production of electricity and heat (see above). As mentioned above, although there are many articles on biomass demand and supply in a regional context, an integrated approach assessing all relevant sectors taking into consideration also measures to conserve energy and other renewable energy sources is lacking.

This paper discusses and analyses the role of biomass as part of an overall mitigation portfolio to transform the energy system of the region so that it can meet the Swedish target of zero net CO_2 emissions by year 2050. The pathway includes renewable energy and energy efficiency measures in line with the renewable and efficiency targets defined by the VG and Halland counties. Both counties endorse the national target for renewables and energy efficiency. For renewables this means that half the energy consumption in 2020 should be from renewables and that there should be at least a 10% share of renewable fuels in the transport sector. The energy efficiency target states that energy consumption in 2020 should be 20% more efficient than in 2008 measured as energy intensity, *i. e.* gross energy consumption divided by gross regional product in constant 2008 prices [20, 21]. The main objective of this paper is twofold:

(1) to develop a methodology assessing future requirements for biomass in the energy sector, and
(2) to analyse what volumes of biomass that may be required in west Sweden anticipating strict CO_2-emission reduction targets while at the same time maintaining existing activity levels for the emission intensive industry in the region.

This work assumes sustainable biomass supply, *i. e.* that there is a corresponding growth in biomass so that the conversion of biomass can be seen as emitting net zero CO_2 emissions. It should also be emphasized that data on energy use given in this report has not been temperature corrected.

The present energy system

The VG region is characterized by a high degree of industrialization including Sweden's largest oil refinery. In fact, three refineries and a chemical plant in VG combined emit some 3.4 Mt CO_{2e} annually, corresponding to almost 24% of all GHG emissions in VG and Halland. The Halland region contains the site of a major nuclear power plant generating around 24 TWh electricity annually of which the bulk are exported out of Halland. Figure 2 shows the combined reference energy system (RES) for the two counties in year 2010. The RES shows the flow of energy (in GWh) within the region from primary energy going into the system through conversion and transport to final consumption by end-users.

As can be seen from fig. 2, primary energy into the region is dominated by uranium (nuclear power production) and crude oil. The oil is refined within the VG county but more than 50% of the refined oil is exported out of Sweden while most of the generated nuclear power is exported from Halland county to VG, *i. e.* the electricity is consumed within the region. There is also a considerable amount of fossil gases going into the system, in total

19.2 TWh, mostly natural gas used for power and heat generation in the industry as well as for generation of district heat (DH). Most of the CO_2-emissions in the region originate from
(1) Natural gas based heat generation.
(2) Natural gas based industrial heat generation.
(3) Fossil consumption in the transport sector.

Electricity is generated mainly by nuclear (24 TWh) and smaller amounts of hydro and biomass (2.8 and 1.6 TWh respectively), the latter mostly in combined heat and power plants. In total the region burnt 4.2 TWh fossil fuels to produce mainly heat (0.2 TWh for electricity generation) in 2010 (industry not included) of which 3.2 TWh natural gas. As evidenced by the large CO_2-emissions mentioned above, the industry is a large consumer of fossil energy; 19.2 TWh in 2010 of which almost 16 TWh in the form of gas (natural gas, city gas, kerosene, LPG).

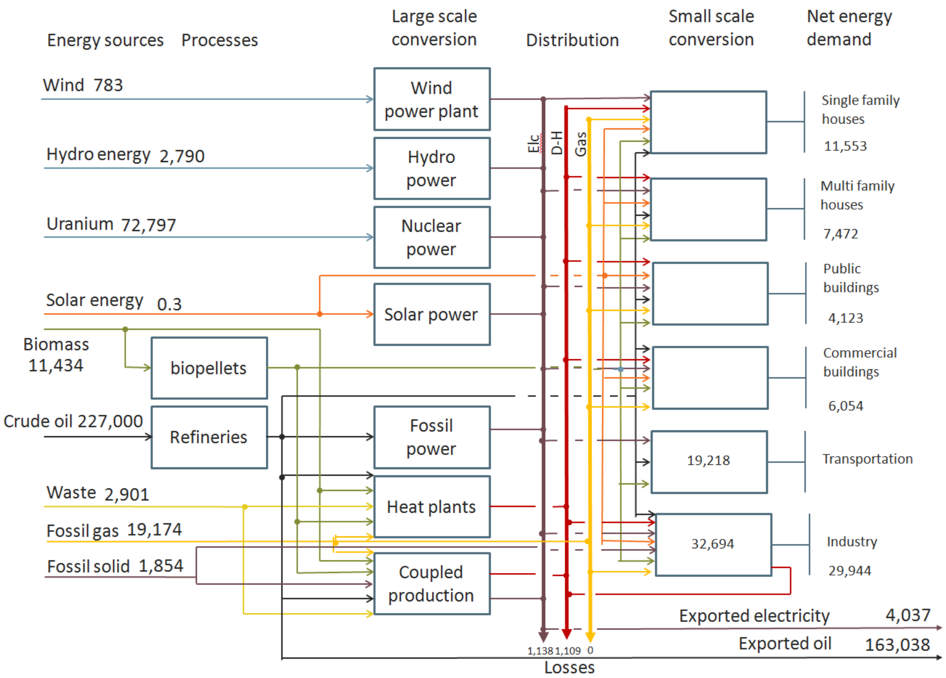

Figure 2. The reference energy system for VG and Halland combined in year 2010, figures are in [GWh] [7] (for color image see journal web site)

Out of the 11.4 TWh biomass entering the system in 2010, some 21% was burnt directly in single family houses for domestic heat generation while 22% was burnt in heat-only plants to generate district heat (DH). Another 16% (1.8 TWh) was burnt for generation of electricity and DH in CHP. The industry consumed 38%, or 4.4 TWh, of total biomass entering the system in 2010 of which 80% was burnt to generate heat while the rest, 840 GWh, was used in industrial processes. Finally, a minor share, 3% or 305 GWh, was used in the transport sector [7].

Since 1990 final energy consumption (FEC) has increased by 26%, from 61 to 77 TWh in 2012. However, most of this increase occured between 2000 and 2003 after which FEC has been relatively constant just below 80 TWh apart from a dip to 72 TWh in 2009 due to the economic recession. The increase was almost entirely caused by the industry in the region which increased its annual energy consumption from around 21 TWh in 2000 to 35 TWh in 2003 which remained until 2008 after which it has declined slightly to the current level of 32-33 TWh. The industry's share in total FEC increased from 33% in 2000 to the current share of almost 45% thus emphasizing the strong role of the energy intensive industry in the region. Transport and households account for much of the rest of FEC in the region, some 23-25% and 16-17%, respectively. However, while energy consumption in the households has gone down by almost 30% between 1990 and 2009 (there are no statistics for households after 2009), consumption in the transport sector has increased by almost 30% between 1990 and 2012 [22].

Figure 3 shows total GHG emissions (in CO_{2e} and including and excluding agriculture), GHG emissions in the agriculture sector, total CO_2 emissions and CO_2 emissions by sector for the region in 1990, in 2000 and between 2005 and 2012. The data has been taken from [23].

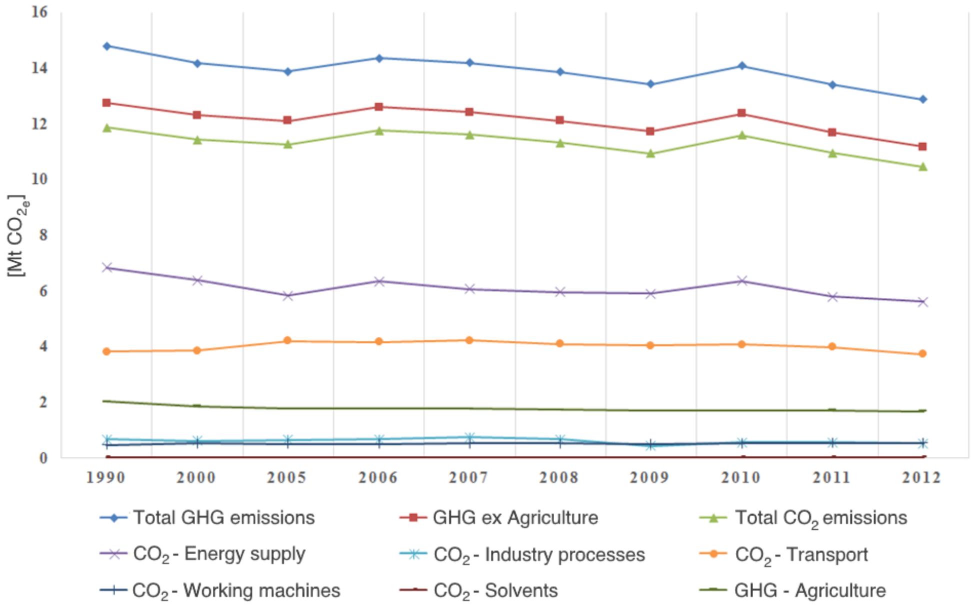

Figure 3. Total GHG emissions (in CO_{2e}), total GHG emissions ex agriculture, GHG emissions agriculture, total CO_2 emissions and CO_2 emissions by sector for VG and Halland in 1990, in 2000 and between 2005 and 2012 [23] (for color image see journal web site)

As shown in fig. 3, there is a slight decrease in emissions since 1990 (13% decrease in total GHG emissions and 12% decrease in CO_2-emissions), although variation in economic activities and average temperature are possible reasons for the variations. CO_2-emissions from energy supply (including the industry) has declined by 18% while emissions from industrial processes have declined by 21%. GHG emissions from the agriculture sector have also declined substantially over the period, by 17%. The only sector that has increased emissions over the period is working machines noting a 13% increase although from a relatively low level, from 0.49 Mt to 0.55 Mt. Emissions from the transport sector has remained relatively constant throughout the period. In 2012, CO_2-emissions account for 81% of total GHG emissions of which energy supply including the industry sector and transport together account for nearly 90% [23].

Analysis by sector

The potential for large-scale integration of biomass and other renewables in the power sector was analysed in two ways; firstly the potential for biomass/waste, hydro, wind, and solar was analysed from a "bottom-up" perspective and in a local context [7]. For biomass/waste this involved a literature study on the biomass resource potential in the region and an assessment of announced plans for development of new biomass/waste CHP's by the municipalities and the industry in the region. The potential for onshore wind power in the region was estimated using Arc-Info software to identify so-called conflict areas, *i. e.* areas where wind power installations are considered as not being possible or feasible for different reasons. In total, more than 30 different conflict areas were analysed including lakes and seas, densely populated areas, roads, environmental and cultural protection areas, airports and recreational areas and including buffer zones where appropriate. Having identified the conflict areas, the remaining area was combined with geographical distribution of wind availability originating from the wind-speed database managed by European Centre for Medium-Range Weather Forecasts which revealed possible and profitable wind power investments in the region. Identifying solar PV potential in the region was restricted to consumer installations since virtually all solar PV installations in Sweden have occurred on the demand side due to the tax system which favours decentralized PV installations. Using estimates of available roof area for single family dwellings, multi-family dwellings and non-residential buildings and assuming an installation size of 150 Wp/m^2 and a generation of 900 Wh/Wp to account for that not all roofs are south facing then gave a range in production potential. Finally, it was decided to maintain hydro based generation at current levels based on a literature review.

Secondly, the electricity investment (ELIN) model was applied to analyse the prospects and possibilities for renewables in the power generation sector in west Sweden from a "top-down" perspective and in a European context. ELIN models the entire EU27 (+Norway and Switzerland). Such geographical scope is necessary since the electricity system of the region is connected to the Swedish system which, in turn, is linked to the European system through interconnectors allowing electricity trading between regions. Based on an exogenously given CO_2 emission cap the ELIN model yields the economic optimum fuel mix based on minimizing the net present value of the sum of annual costs of generating electricity in the EU (excluding taxes and subsidies) during the time period studied. The model uses the Chalmers power plant database [24] as input for description of the existing power plant infrastructure. For more information on ELIN see [25]. In this work, the ELIN model was applied to analyse the prospects and possibilities for renewables, including biomass, in the power generation sector in west Sweden from a "top-down" perspective.

The top-down analysis involved two scenarios for Europe's power generation; the Green policy and the Regional policy scenario. The two scenarios were chosen since we believe that they best reflect the CO_2 emission reduction targets of the region and have a substantial inclusion of renewables also in line with the target of the region. In both scenarios CO_2-emissions from electricity generation were set to decline by 95% by 2050 relative to 1990 emissions. Additionally, the Green policy scenario implies that 90% of total electricity generation in Europe is renewable in 2050 which of course will require strong policy intervention. In the Regional policy scenario around 65% of total electricity generation is renewable in 2050. Furthermore, in the Green policy scenario, new investments in nuclear power and the commercialization of carbon capture and storage (CCS) are ruled out. In the Regional policy scenario new nuclear power plants and CCS are optional if considered profitable by the modelling. Finally, existing nuclear power plants have an expected lifetime of 45 years in the Green policy scenario and 60 years in the Regional policy scenario [7].

Since the ELIN model yields the economic optimum fuel mix, the results are compared with the bottom-up analysis with respect to regional limitations to allocate wind power and biomass supply.

The analysis of the transport sector is based on an assessment of a key report on the national transport system in order to derive a reasonable scenario to achieve CO_2 emission targets for the transport sector in VG and Halland counties. Both counties as well as Sweden have targeted a transport sector independent of fossil fuels by 2030. Additionally, as mentioned above, Sweden has a target of net zero GHG emissions by 2050 (see however footnote 1) which, by most analysts, have been interpreted as reducing GHG emissions by 80% up to 2030 and a completely phase-out of fossil fuels in the transport sector by 2050.

The total demand for biomass in the region up to 2050 has been estimated in two cases, case A and B assuming a gradual increase of biomass used in the power and heating sector, in the transport sector and in the industry both to produce steam and to be used as raw material in the refineries and in the chemical industry. In case A biomass is only in part used to replace fuel for generating energy carriers in industries whereas in case B biomass is gradually also replacing fossil fuels as raw material to the Borealis chemical plant in Stenungsund and to the three refineries in the region.

The role of biomass in the heat and power sector

The bottom-up analysis indicates that production of solid biomass within the region could be raised from the current 6 TWh to 12 TWh per year, *i. e.* slightly above current consumption of biomass for energy purposes (see fig. 2). The region may of course also continue to import biomass, either from other regions in Sweden or from abroad provided it is produced in a sustainable manner. The bottom-up analysis of the electricity sector indicates a significant potential for cost efficient installation of onshore wind capacity in the region, up to 10 GW could be installed assuming income levels for new wind-power investments between 60-70 €/MWh (including the above mentioned green certificate). The bottom-up studies indicate that solar PV could, at the very best, contribute 2.5 TWh per year under the current subsidy regime while hydro was not believed to have any additional potential of significance.

Figure 4 shows the resulting electricity generation system by source/technology for the two scenarios up to 2050 as given by the modelling exercise. As can be seen, in both scenarios, there is an increased use of biomass for electricity generation. Yet, in both scenarios, the contribution from biomass is less than wind power. In the Green policy scenario (fig. 4 right), where the target is a system with 90% renewable generation, most renewable is from wind. This is due to that there is a large cost-efficient wind potential in the region as was also indicated in the bottom-up studies mentioned above. In the Regional policy scenario, where nuclear has a prolonged lifetime relative to the Green policy scenario there is less renewables in the region towards the end of the period and also significantly more import of electricity to the region. As a consequence there is less biomass used for electricity generation. Yet, both scenarios yield large amount of intermittent wind power which give opportunities (but also requirements) of variation management such as from energy storage, demand side management (DSM) and enhanced distribution networks (the results include the possibility to enhance transmission capacities between the modelled regions).

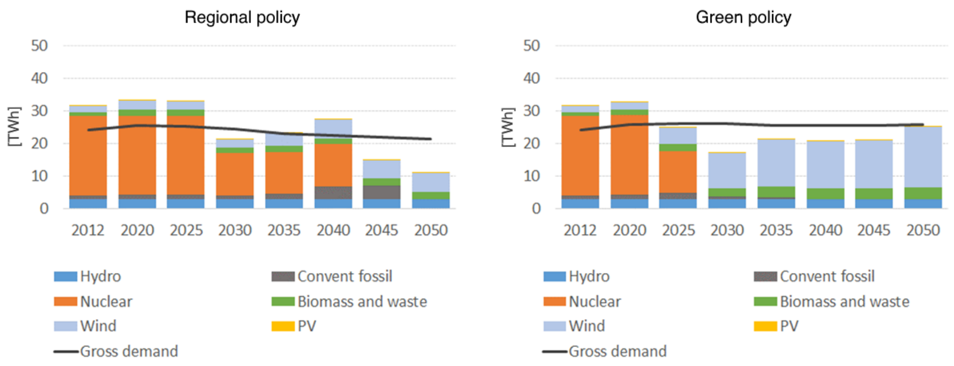

Figure 4. Electricity generation [TWh] up to 2050 in VG and Halland by source/technology in the two scenarios as obtained by the modelling exercise. For a detailed description, see [7]
(for color image see journal web site)

As can be seen from fig. 4, bio-based electricity generation is relatively modest in both scenarios increasing from 1.2 TWh in 2012 to between 2.2 and 3.7 TWh in 2050, depending on scenario. At the same time bio-based generation in CHP in the DH systems increases from around 4 TWh in 2012 (fossil plus bio/waste) to 4.5 (Regional policy) and 7.5 TWh (Green policy) in 2050 (bio/waste only). Assuming a conversion efficiency of 0.35 for bio-based electricity generation the two scenarios imply a biomass consumption in 2050 ranging from 6.3 to 10.6 TWh depending on scenario which, in both cases, is well below the production potential for biomass within the region. Also, since the bio-based electricity generation illustrated in fig. 4 includes generation from bio-based waste this means that the use of biomass is actually lower than indicated above.

The contribution from wind power is significant, particularly in the Green policy scenario (fig. 4 right). The model selects large additions of wind capacity over biomass for purely economic reasons. Yet, the costs for the upgrade of grids and transmission lines and thermal back-up capacity for the large amounts of intermittent capacity may be underestimated in the modelling. Thus, increasing this additional costs for variation management would lead to that the model selects more biomass CHP capacity at the expense of wind power. This has not been investigated in this work. Also, assuming full decarbonisation of the transport sector, electricity is likely to play a significant role in the transportation sector implying

(1) Demand for electricity will be higher than illustrated in fig. 4.
(2) Biomass will be utilised more efficiently in the transport sector if it is burnt to generate electricity (and heat) instead of being converted to a fuel.

It should be recognised that the ELIN model lacks somewhat in level of detail when it comes to solar PV installations. The major market for PV installations in Sweden is likely to be small-scale investments made by electricity end-users such as households, which is not reflected in the modelling (although this feature is included in current version of the ELIN model). Hence, incentives for PV may be somewhat underestimated in the model calculations of this study.

The role of biomass in the transport sector

As mentioned above, a key national study was selected [7, 26] to derive at a relevant pathway to reach the targets for the transport sector in VG and Halland. The selected study comprised domestic transport including working machines. In order to derive results for the VG and Halland regions the results from the national study was simply scaled down to the

VG-Halland region based on population statistics which was considered as a feasible methodology for several reasons [7]. Figure 5 shows the results with regard to fuel consumption. The height of each bar indicates "apparent demand" while actual demand is given by the coloured part of each bar (fossil fuels – blue, renewables – green, electricity – purple). Thus the grey parts in each bar refer to actions to reduce "apparent" demand and CO_2 emissions, see also [7, 26].

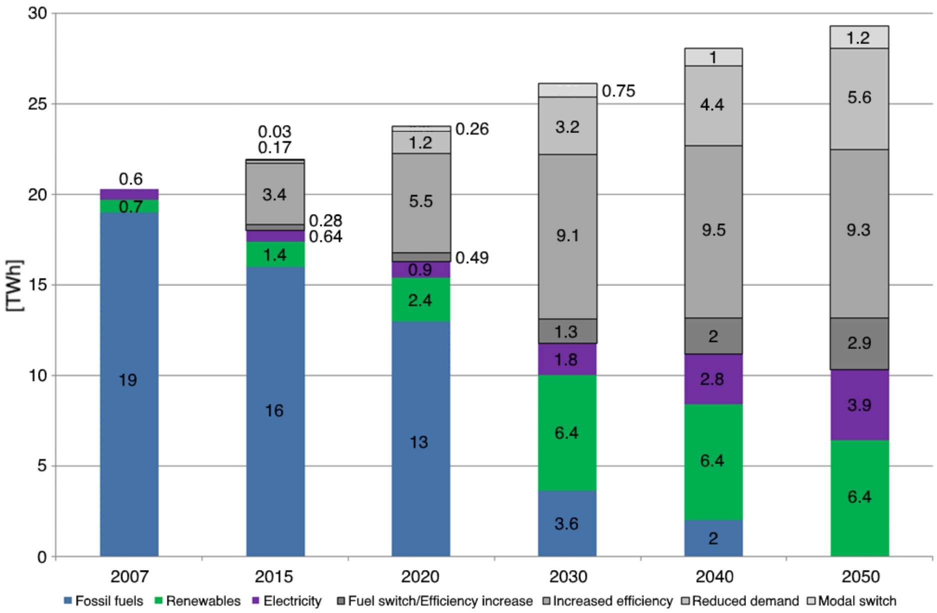

Figure 5. Fuel consumption for the transport sector in VG and Halland up to 2050 assuming 80% reduction in fossil fuel consumption to 2030 and zero GHG emissions in 2050. Sources [7, 26]
(for color image see journal web site)

As can be seen from fig. 5, consumption of bio-fuels reaches 6.4 TWh in 2030 and is thereafter kept constant. In 2050, biomass covers 62% of the transport sector's fuel demand with the remaining 38% being covered by electricity. Assuming a biomass to fuel conversion efficiency of 0.5, fig. 5 shows that consumption of biomass in the transport sector in the region increases from 1.4 TWh in 2007 to 4.8 TWh in 2020 and further to 12.8 TWh in 2030 after which it is assumed to remain constant. Again, this is slightly above the production potential for solid biomass in the region (see above) but, also as mentioned above, biomass (or biofuels) may be imported to the region. The reduction in CO_2 emissions corresponding to the results in fig. 5, are 82% to year 2030 and zero emissions by 2050, *i. e.* fulfilling the Swedish national target. Nearly three quarters of the emission reductions are derived from fuel shifting and increased vehicle efficiency.

In summary, it can be concluded that it is possible to reach zero emissions transport sector in the VG-Halland region and, thus, in Sweden in 2050 but only with strong and immediate policy intervention and economic incentives. For Sweden, such policy intervention will of course be on a national level, but in order for the transformation of the transport sector to be successful this will require a similar development on, at least, a European level since it is unlikely that vehicle technologies will be developed for a Swedish market alone.

The potential for biomass in the industry sector – energy only (case A) and biomass industry feedstock (case B)

In case A, demand in the industry assumes 25% of the current fossil based production of heat and process steam being replaced by biomass in 2020 increasing to 50% by 2030 and to 100% replacement in 2040. Also 0.8 TWh of bio-pellets currently (2010) being used in industrial processes has been included as raw material to the industry (termed "Industry feed"). In case A, demand in the power sector follows the Green policy scenario depicted in fig. 4 (right) assuming conversion efficiency for biomass CHPs increases from the current 30% to 35% from 2025 onwards. Demand in the transport sector follows demand given in fig. 5 assuming an overall biomass-to-fuel conversion efficiency of 60% over the entire period. Biomass use for generation of DH and for on-site generation of heat in the building stock (in single family dwellings) has been kept constant at 2010 consumption levels throughout the period, *i. e.* each at 2.5 TWh biomass. This has been done due to

(1) A techno-economic savings potential of between 5.5 and 7.4 TWh identified in the building sector in the region [7].
(2) The increased generation of DH in CHP's in the Green policy scenario as mentioned above.

For a closer description of cases A and B see [7].

In case B the biomass for heating and electricity is as in case A while biomass is also used to gradually replace fossil fuels as raw material to the Borealis chemical plant in Stenungsund and to the three refineries in the region. Thus, we have assumed that biomass is used as feedstock instead of crude oil to the three refineries in the region and that the refineries in turn also provide bio-based feedstock to Borealis in Stenungsund (in the form of process residues). Chemical plants usually purchase their fossil feedstock as residues from refineries and this solution will enable the chemical cluster to keep the existing process units (the chemical plants could of course obtain bio-based feedstock from other refineries outside the region which would reduce biomass demand in VG and Halland correspondingly). Demand for biomass from the refineries is assumed to correspond to the evolvement of demand for biomass from the transport sector in VG and Halland as derived in fig. 5, *i. e.* that fuel to cover overall "real" demand for transport work is reduced by 20% in 2020 relative to 2010 (2007)* and that the share of biomass in total fuel consumption in 2020 is 15%. By 2050 overall fuel demand has declined to 51% of overall demand in 2010 while the share of biofuels is 62%. Hence, it has been assumed that the three refineries in the region are fully converted to bio-refineries supplying a global market evolving in the same way as depicted in fig. 5. To convert from demand of crude oil to demand of biomass a conversion factor of 0.6 has been applied yielding that 227 TWh crude oil supplied to the refineries in 2010 requires 378 TWh biomass. Feed to Borealis in Stenungsund is assumed to start in 2020 when a quarter of the feedstock is assumed to be replaced by biomass increasing to 50% in 2030 and further to 100% in 2040. It has been assumed that 33 TWh biomass is required to replace 16.5 TWh fossil based feedstock to Borealis in 2010 of which almost all was supplied by suppliers outside the region. However since the Borealis chemical plant in case B is assumed to receive feed directly from the refineries, efficiency gains have been estimated to reduce overall biomass demand to the industry by 13 TWh. Furthermore, no biomass is supplied to the transport sector in case B since biofuels are assumed to be supplied from any of the three

* Demand in the transport sector in the region has been practically constant since 2001

refineries in the region. Figure 6 summarizes the demand for biomass in the region for the sectors discussed above, for the two cases A and B.

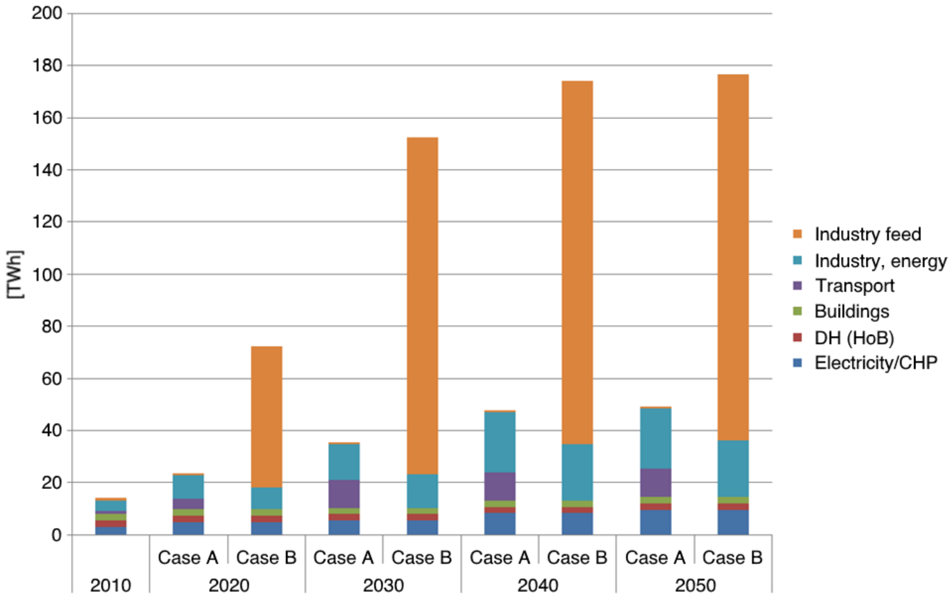

Figure 6. Projected biomass consumption up to 2050 in VG and Halland in case A and B. Industry feed refers to biomass gradually replacing fossil fuels as raw material to the Borealis chemical plant in Stenungsund and to the three refineries in the region (case B). In case B, demand for biomass in the transport sector has been set to zero since demand is assumed to be covered by the three refineries (for color image see journal web site)

In case A, total annual biomass demand (including bio-waste) increases from *ca* 14 TWh today to 24 TWh in 2020, to 36 TWh in 2030 before it reaches a plateau of around 48 TWh in 2040 onwards. In case B where biomass in addition to the demand in case A also gradually replaces natural gas as a feedstock to the refineries in the region which in turn supplies bio-based feedstock to the Borealis chemical plant in Stenungsund, biomass demand increases to *ca* 72 TWh in 2020 and further to 153 TWh in 2030 before reaching a plateau at around 174-177 TWh during the last decade. Thus, the obvious question is to what extent a future will manage to ramp up biomass use also as feedstock to the industry sectors which, as seen from fig. 6 would require up to almost an order of magnitude more biomass than if only considering biomass in the sectors where it is currently used.

This amount of biomass can be put in context by comparing with the current Swedish total supply of biomass and peat (for energy purposes) which amounted to 132 TWh in 2011, while the total additional technical supply potential for biomass produced in Sweden has been estimated to between 50 and 70 TWh by the Swedish Knowledge Centre for Renewable Transportation Fuels [27]. The results in case B implies that the refineries in the region probably will face severe difficulties in maintaining current activity levels and the results also strongly suggest that electricity probably should have a larger market share in the transport sector and this is further discussed below.

Case A obviously gives much less stress on biomass supply than case B, not at least due to the smaller amount of biomass that will be required. However, with regard to generation of electricity in the selected Green policy scenario the amount of intermittent power is substantial while at the same time base load power is decreasing rapidly. According to the modelling results discussed above, the contribution from base load power (hydro, conventional thermal, nuclear, bio and waste) in the Green policy scenario declines from 94% in 2012 to 36% in 2030 and further to 26% in 2050. A high penetration of intermittent renewables (wind, solar PV) along with nuclear decommissioning may lead to significant balancing problems and actually increase the need for renewable base load power, such as biomass. There are few possibilities to reduce biomass demand further in case A. It has been assumed same contribution as today in heating plants while on-site heating has actually been reduced as a consequence of the energy savings identified above in the buildings sector. The industry is very dependent on a secure and continuous supply of heat and there is already a substantial share of intermittent energy present in the energy system in the region. Also, the contribution from biomass in the transport sector was modest in case A while at the same time also assuming a significant reduction in demand for transport work (see fig. 5).

The supply and logistical challenges in case B will of course be tremendous. Already in 2030, case B consumes more than the entire Swedish supply of energy related biomass including peat. Also, demand for biomass is in such a scenario of course on the rise in most regions throughout Sweden, Europe as well as globally, both within the power and heat sector as well as in the industry and transport sectors. It seems likely that conditions required for case B to happen will be a strong European (or global) trend of greening both transportation fuels and materials (*e. g.* bio plastics). Indeed, Sweden and the Scandinavian countries have favourable conditions with respect to the supply and use of biomass with technologically advanced process industries and refineries, which would facilitate competitive conditions for a bio-based process industry.

Overall demand for biomass could be reduced through higher share of electric cars (and hydrogen), both locally as well as in Europe and globally. With the large amounts of biomass that otherwise will be required, this seems almost as a prerequisite for a well-functioning transport sector in the future. Also, there will be large amounts of heat available from the refineries and the chemical cluster and at least a small part of this heat could possibly be utilized for DH. Demand for biomass in case B could also be reduced through for instance recycling and energy recovery of plastics leading to overall lower demand for biomass in the chemical industry. However, as shown above, estimated biomass demand in the chemical cluster constitutes a relatively modest share of total biomass demand in case B (approximately 8%) and recycling and recovery of plastics has reached quite far in Europe and Sweden. However, in countries like Finland, Poland, UK and the Baltic States, recycling and recovery rates are considerably lower ranging from less than 30% in Latvia, Lithuania and UK to somewhat below 50% in Finland and stricter rules for disposal of plastics in landfills is expected to improve these ratios considerably [28].

Continued use of fossil fuels in the transport sector could still be possible also under a zero CO_2 emission regime by 2050 thereby significantly reduce the need for biomass. This can be achieved through a combination of CCS at the refineries and Bio-based CCS (BECCS) with the latter sufficiently large to neutralise direct emissions from vehicles still running on fossil fuels.

Conclusions

The VG-Halland region currently produces some 6 TWh solid biomass while consumption of biomass for energy purposes is about twice that level. The bottom-up study of the biomass production potential in the region gives that the region could in fact double its production capacity of solid biomass to 2030. The bulk of the biomass used in the region is currently used to generate heat in the industry and for generation of DH.

Modelling of the electricity sector in the region indicates that bio-based electricity generation in CHPs could, in a cost-efficient way, triple between 2012 and 2050. At the same time the modelling results show that generation of DH in CHPs could potentially double by 2050 while at the same time replacing fossil generation with biomass and waste. Assuming a conversion efficiency of 0.35 for bio-based electricity generation the two scenarios imply a biomass consumption in 2050 ranging from 6.3 to 10.6 TWh depending on scenario which, in both cases, is well below the production potential for biomass within the region.

For the transport sector it is shown that the region could reach zero CO_2 emissions by 2050 through a series of actions to significantly reduce demand in combination with use of electricity and biofuels. Applying a conversion efficiency of 0.5 from biomass to bio-fuels, it was estimated that the transport sector in the region would consume some 12.8 TWh biomass annually from 2030 onwards. It is also concluded that such a transformation is unlikely to occur only in the west of Sweden but rather it can be expected that such a development in west Sweden will be part of an overall European transformation of the transport sector.

Analysing each sector individually it is estimated that total need for biomass in the region could potentially more than triple from 14 TWh in 2010 to 48 TWh from 2040 onwards, following the results above for the electricity and transport sectors and under the assumption that all heat (DH and industrial heat) should be generated by biomass and that demand for DH would be reduced. Assuming that biomass also should replace the fossil based raw materials used by the industry in the region (including refineries) would raise demand to more than 170 TWh from 2040 onwards which would imply significant logistical challenges. Thus, this indicates that electricity, and possibly also hydrogen, should play a larger role in the transport sector than what has been suggested here. This in order to put less stress on establishing biomass based supply and conversion systems.

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