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Bioenergy pathways for cars: Effects on primary energy use, climate change and energy system integration

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A R T I C L E I N F O

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A B S T R A C T

Different pathways and technologies can be used to convert woody biomass to transport services, but the biomass use and climate implications vary strongly between the alternatives. This study focuses on primary energy use and climate change effects of using bioenergy for transportation in the context of a renewable-based energy system. Integrated pathways to improve the energy efficiency of power and transportation sectors and integrated intermittent renewable energy are considered. The results show that the bioenergy pathway that produces biomotor fuels to replace fossil fuels leads to high primary energy use and instantaneous biogenic CO_2 emission per km of driving distance, thus increasing global warming during the first 40–50 years, compared to fossil alternatives. The electric vehicle pathway using bioelectricity from combined heat and power plants leads to immediate global cooling and much greater climate benefits in the long run compared to biomotor fuels. Climate change effects of light-duty vehicles could be strongly reduced by changes in technology together with system integration that links the transport sector to the electricity and heating sectors. The use of biomass should be considered in the context of the overall integrated energy system, and in relation to the development of energy conversion technologies between different sectors.

1. Introduction

Efficient energy chains and renewable energy resources are important for a sustainable development. Currently, the global energy system is heavily dependent on fossil fuels with 81% provided by coal, oil and gas, and fossil fuels are still expected to play a major role in the future energy system [1]. Electricity, heat, and fuels are the major energy carriers that supply different final energy services [2]. The future energy system is expected to be more dependent on renewable resources that need to be integrated due to the intermittent characteristic of them such as solar and wind. The integration of such renewable resources in energy systems will depend on how the overall energy system is designed including the interaction between energy supply and use.

Renewable energy resources are limited and must be combined with energy efficient energy chains. In the EU, the power and transportation sectors have large potentials for energy efficiency improvements (Fig. 1). The energy carriers in Fig. 1 illustrate the energy amount after the conversion losses of central conversion plants. The final energy use shows the energy amount after energy conversion facilities of end users. Nearly 50% of final energy use in the EU is heat for residential, service or industrial purposes. Heat for the residential and service sectors has higher conversion efficiency from primary to final energy compared to electricity, and much higher compared to transportation fuel. Hence, strategic changes are needed for power and transportation to improve the system efficiency of the sectors.

Modern CHP (combined heat and power) plants using solid biomass have a conversion efficiency of about 85–90%, compared to power production in standalone plants with an efficiency of about 35–40%. The expansion of district heating systems will allow for a large expansion of CHP plants in EU and improving the system efficiency of the power sector. About 6000 district heating systems exist in the EU and they accounted for approximately 13% of total heat supply in the residential and service sector in 2010. The expansion potential is from this 13% up to 30% and 50% in 2030 and 2050, respectively [3].

Biomass is currently the most important renewable energy resource globally [1] and is considered as a key resource to mitigate climate change. Biomass can be used directly or indirectly in the

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Nomenclature

BIGCC	biomass integrated gasification with combined cycle
BST	biomass-based steam turbine
CHP	combined heat and power
CRF	cumulative radiative forcing
DHS	district heat production system
DME	dimethyl-ether
EV	electric vehicle
FV	fuel-based vehicle
GHG	greenhouse gas
MeOH	methanol
PHV	plug-in hybrid vehicle

electricity, heat and transport sectors to substitute for fossil fuels. The increasing global potentials of biomass for modern applications make them more important in the global energy system. However, biomass is a limited resource and different biomass pathways may influence the overall energy system in different ways.

In Sweden, forest residues are increasingly used for energy purposes and currently 20% of all harvestable residues in Sweden are used for bioenergy [4,5]. Still, there is a large potential for increasing the extraction of forest residues. The Swedish Forest Agency [6] estimates the potential harvest of tree branches and tops in Sweden to be in the range of 16–25 TWh/year. Potential stump harvest in Sweden is estimated in the range of 21–34 TWh/year. In the long run, Swedish forest biomass has the potential to provide half of the Swedish final energy use [7,8]. Intensive forest management and increased harvest levels may further increase the potential to harvest branches, tops and stumps [9].

The climate benefits of using forest residues depend on it applications and what would have happened to the forest residues if they were left in the forest. Currently, direct combustion to produce heat and steam is the most common application of woody biomass [10]. The produced steam is normally used for electricity generation via steam turbines and for industrial applications. Different studies suggest different ways and benefits of using biomass to replace fossil fuels [10–12]. Using biomass to replace coal in electricity production is currently a cost and energy efficient way to reduce fossil carbon dioxide emission [13]. Electricity generation from biomass is expected to be a substantial source of renewables-based power in the coming decades [1]. However, in the context where other resources can be effectively mobilized for power production, the use of biomass for other purposes may be of interest and should be considered [11,14,15].

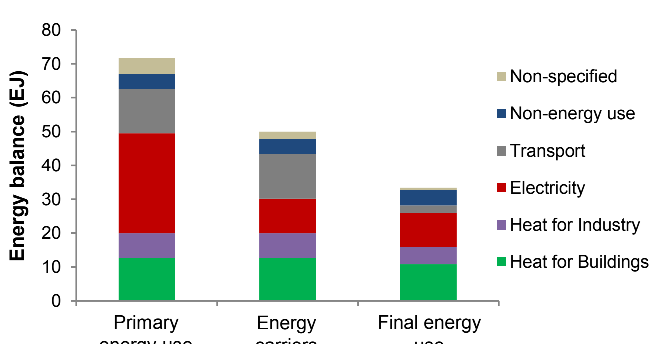

Fig. 1. Primary to final energy use in the EU27 in 2010 [3].

The transport sector is very dependent on fossil oil. Globally, the transport sector used about 53% of total oil use during 2012 while light-duty vehicles used about 50% of the oil use in road transport [16] and gasoline accounted for more than 50% of the fuel use for road transport [1]. In the EU, road transport is the second largest source of GHG (greenhouse gas) emission [17]. The liquid fossil fuel use in the transport sector is around 95% [1].

The development of bioenergy technologies, including biomass gasification with improved conversion efficiency [18], offers more effective ways to use different biomass feed stocks both for liquid biomotor fuels production, such as DME (dimethyl-ether) and MeOH (methanol), as well as for electricity production. Low-carbon fuels in the transport sector are expected to be of importance for ambitious carbon abatement, and the demand for biofuels in the transport sector is expected to increase in the future [1]. Along with efficiency improvements in combustion engines, the introduction of different light-duty vehicle types including battery EV (electric vehicle) and PHV (plug-in hybrid vehicle) could help to reduce the fossil fuel dependence and improve the energy efficiency of the sector.

Recent developments in technologies offer opportunities for improved systems of road transport. The effects of technological changes in the transport sector on primary energy use and climate change can be complex to analyse, and depend on the energy conversion systems involved. A system analysis of different vehicle types and energy pathways with a focus on integration potentials with current and future renewable energy technologies could show how different vehicle types may perform within an overall energy system. Furthermore, the biomass use may vary in different pathways for a given driving distance. Biomass is a limited resource and should be used as efficiently as possible. Therefore, biomass use for a specific driving distance and its climate change effects is of interest to analyse.

In a biomass-based energy system, the climate change effects of the biogenic CO_2 emission depends on the biomass resource. Of the total biomass of a mature spruce tree, about 50% is contained in the branches, foliage, stump and roots of the tree [19], which has typically remained in the forest after harvest. In principle, if forest residues are used for energy to replace fossil fuel, the biogenic carbon is emitted immediately to the atmosphere. If residues are left in the forest and not used as fuel, a corresponding amount of fossil fuel will be used instead resulting in immediate fossil carbon emissions, followed by gradual emission of biogenic carbon from the naturally decaying residues.

Changed carbon flows over time can be significant to the climate change effects of forest residues used for energy [13] as within any finite time period, the climate change effects depend on how much GHG is emitted and when it is emitted. Under this context, CRF (cumulative radiative forcing) is a metric that more accurately estimates the time-dependent climate impacts of dynamic systems than GHG emissions. However, CRF is a more complex analytical procedure than GHG emission calculation and requires information on time profiles of emissions and removals of GHG [20]. Radiative forcing measures the imbalance between incoming and outgoing energy radiation of the earth system.

This study focuses on bioenergy for transportation in the context of a renewable-based energy system. Integrated pathways to improve the energy efficiency of the power and transportation sectors and integrated intermittent renewable energy are considered. We contrast three different biomass-to-transportation pathways: (i) biomotor fuel production in standalone plants, (ii) bioelectricity production in standalone plants and (iii) bioelectricity production in CHP plants with district heating systems and heat storage capacity. Three different versions of transportation means of the same size are considered, (i) battery EVs, (ii)