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Target for national carbon intensity of energy by 2050: A case study of Poland's energy system

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ABSTRACT

The article analyses CO_2 emissions from fossil fuel combustion and provides tools for estimating the target for national carbon intensity of energy by 2050. A case study of the energy system of Poland is presented. It is revealed that if carbon emissions are to be reduced by 80% from 1990 to 2050, the energy mix of Poland will require significant structural changes. This will be however challenging, because Poland has a huge coal sector and limited potential for harvesting renewable energy sources, excluding only biomass. The carbon intensity of primary energy would have to be reduced in Poland from 20 g C MJ^{-1} in 2009 to about 4.1 g C MJ^{-1} in 2050 (including LULUCF). Further, the study suggests the national energy mix suitable for achieving this energy decarbonisation target. It is found that a significant share of coal/peat can be retained only when CCS is applied to all fossil fuel-fired power plants and to large-scale industries. Besides, the share of biomass, other renewables and optionally nuclear energy must be significantly increased which will be both costly and technologically challenging. Further, deployment of carbon negative bioenergy as well as CO_2 recycling are suggested as promising energy decarbonisation options.

1. Introduction

Stabilisation of greenhouse gases (GHGs) in the atmosphere means considerable re-organisation of the way in which society works (work, transport, leisure, city planning, housing, electricity production) [1]. GHGs are emitted to the atmosphere from various sources but the main present-day anthropogenic contribution is associated with the combustion of fossil fuels. European Climate Foundation has recently proposed a new target for anthropogenic GHGs emissions reduction, i.e. the cut by 2050 to the level of 80% of the GHGs emissions in 1990 base year [2]. Similar deep GHGs reduction targets are considered by various regions and OECD countries [3]. These relatively challenging reductions will affect national energy systems all over the world but in particular in developed countries still having GHG-intensive economies. The main burden of GHGs emissions reductions will have to be incurred by energy-related sectors, e.g. projected CO_2 reductions in the EU-27 power sector are estimated at 95% [2]. Consequently, countries having highly GHG-intensive power sectors might need deep structural and technological changes of their energy systems. It is expected that main directions until 2050 will be associated with fossil fuel substitution by renewable energy sources (RES), energy saving and energy efficiency measures as well as with deep decarbonisation of power sectors.

Among three main GHGs, CO_2 is most strongly involved in a highly reversible natural global cycle, i.e. in the global carbon cycle. The global carbon cycle includes CO_2 fluxes through e.g. photosynthesis, oceanic solubility, carbonate mineralisation in soils which all enable making anthropogenic CO_2 emissions less irreversible, thereby counteracting the accumulation of CO_2 in the atmosphere. In contrast, the emissions of CH_4 and particularly N_2O are more irreversible because these two gases accumulate in the atmosphere with less natural mechanisms which could recycle them back to Earth. CH_4 is however oxidised to CO_2 in the atmosphere with half-life period of 12 years, thereby CH_4 is partly involved in the global carbon cycle. CH_4 is today mainly emitted by agriculture and fuel industries while the majority of N_2O emissions source from agriculture. Therefore, any strategies for the reduction of emissions of these three GHGs should be analysed separately

Abbreviations: C, carbon; CCS, carbon capture and sequestration; CCR, carbon capture and recycling; CH_4, methane; CIFE, carbon intensity of final energy (g C MJ^{-1}); CIPE, carbon intensity of primary energy (g C MJ^{-1}); CO_2, carbon dioxide; CO_2-EAE, ecologically allowable CO_2 emissions (g C yr^{-1}); EU, European Union; ECF, European Climate Foundation; GHG, greenhouse gas; IEA, International Energy Agency; LULUCF, land use, land use change and forestry; ME, Ministry of Economy of Poland, Ministerstwo Gospodarki (Poland); N_2O, nitrous oxide; OECD, Organisation for Economic Cooperation and Development; RES, renewable energy source; TPES, total primary energy supply (J).

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using different methodologies. Therefore, this article focuses only on CO_2 emissions from fossil fuel combustion.

Given the expected rise in energy demand until 2050 (at least in developing regions), the ability to achieve the CO_2 emissions reduction target can largely be attributed to major declines in life cycle CO_2 intensities of energy across various energy commodities. Therefore, assessments of targets for CO_2 intensity of energy are central for developing any national energy strategies. CO_2 intensity of energy, further called here carbon intensity of energy, is one of useful indicators for estimating which part of a national energy system is environmentally inefficient and generates significant unwanted CO_2 emissions. Sectors characterised by significant carbon intensity of energy should be considered by policy makers as most suitable for structural and technological changes. Therefore, the current study discusses the problem of CO_2 emissions reduction through the assessment of carbon intensity of energy throughout sectors of the economy and throughout energy sources. It is attempted to calculate targets for carbon intensity of various energies which could enable to achieve GHGs emissions reduction targets set for 2050. The energy system of Poland which is heavily dependent on coal is taken as a case study.

The paper is structured as follows. Section 2 is aimed at the definition and characterisation of carbon intensity of energy in relation to primary energy supply and in relation to final energy consumption. Section 3 provides a detailed analysis of carbon intensity of energy in the energy system of Poland. Section 4 formulates main national energy system level recommendations and summarises main conclusions from the study.

2. Definition and characterisation of carbon intensity of energy

Carbon intensity of energy is defined as CO_2 emissions from fossil fuel combustion to the atmosphere per amount of energy. The carbon intensity of energy is frequently given either in relation to primary energy supply or in relation to final energy consumption.

2.1. Carbon intensity of primary energy (CIPE)

For fossil fuel combustion carbon intensity of primary energy (CIPE) depends mainly on the content of carbon and energy in the fuel. Table 1 provides CIPE for three fossil fuels calculated as the ratio of global CO_2 emissions (in g C) from fossil fuel combustion per global total primary energy supply (TPES) of the relevant fossil fuel, i.e. the CIPE is averaged over the world for all analysed fossil fuels. From Table 1 it is seen that the CIPE ranges from 24.5 g C MJ^{-1} for coal/peat to 14.7 g C MJ^{-1} for natural gas. According to International Energy Agency the global CIPE in 2009 averaged overall energies was 15.4 g C MJ^{-1} [4] which reflects the mix of carbon intensive fossil fuel energies and nearly carbon neutral nuclear and renewable energies in the global TPES.

2.2. Carbon intensity of final energy (CIFE)

Carbon intensity of final energy (CIFE) depends again on the content of carbon and energy in the fossil fuel and, additionally, on the efficiency of conversion of primary energy into final energy. Hence, the CIFE better reflects the environmental efficiency of converting primary energy e.g. in power cycles. When final energy in the form of electricity is generated in a fossil fuel-fired power plant with electricity-to-fuel efficiency of 40%, the attained CIFE is 2.5 times greater than CIPE.

Table 1
Carbon intensity of primary energy (CIPE) for main fossil fuels. CIPE is calculated as the global average for the specific fossil fuel-based on ref. [4].

Fossil fuel	CIPE (g C MJ^{-1})
Coal/peat	24.5
Oil	17.5
Natural gas	14.7

CIFE for renewables is usually calculated by counting all life cycle CO_2 emissions. Interestingly, renewable energies such as wind or hydro often have CIFE well below 4 g C MJ_e^{-1}, i.e. the majority of renewable energies are nearly carbon neutral. Therefore, for simplicity the current study neglects life cycle-related carbon emissions from RES, and also from nuclear and fossil fuel-based technologies.

When energy mix in a given national energy system has a significant share of RES, the resulting overall CIFE can be particularly low. For instance McCollum et al. [3] have estimated that the carbon intensity of electricity in California is 25 g C MJ_e^{-1}. This is less than CIFE of natural gas-derived electricity at 40% electricity-to-fuel efficiency and CIPE = 14.7 g C MJ^{-1} which gives CIFE = 36.8 g C MJ_e^{-1}. The reason is the electricity mix of California which is based on natural gas combustion and on renewable hydro power. In Europe very low CIFE have Norway and Sweden due to the expanded use of RES and nuclear power (0.4 and 1.3 g C MJ_e^{-1}, respectively). In contrast, Poland has CIFE of its electricity as high as about 75 g C MJ_e^{-1} [5] which makes deploying any decarbonisation strategies particularly challenging. The CIFE of heat in Poland by 2009 is assumed at 57 g C MJ_{th}^{-1}.

It is worth noting that the proposed CIPE and CIFE indicators are suited to account for energy saving and energy efficiency measures. Energy saving (understood as demand reduction by e.g. adoption of more efficient technologies in energy use) and energy efficiency (understood as production technology improvement by e.g. combination of CHP and raising generation efficiency in electric power plants) [6] have great potential in Poland. When energy is saved energy demands are reduced. At lower energy demand CIPE and CIFE decrease because RES can achieve a greater share in the national energy mix. Similarly, when efficient generation technologies are adopted allowing for more energy efficient production, energy demands can be met with less fossil fuels which decreases CIPE and particularly CIFE because the latter depends on the energy conversion efficiency. In calculations of the current study for Poland from one unit of primary energy 0.667 units of final energy is obtained by 2009 and 0.688 by 2050, i.e. relatively conservative assumptions regarding energy conservation measures are made.

3. Case study of Poland

Among the top electricity producers worldwide, Poland has one of the highest CO_2 emissions per unit of electricity generated (i.e. CIFE). Electricity generation in Poland is very dependent on hard coal and lignite and still has a significant share of relatively old and thus rather low-efficient power plants. Therefore, achieving ambitious CO_2 reduction targets might be particularly challenging for this country.

According to ref. [2] all EU-27 countries are projected to reduce their GHGs emissions by 80% from 1990 to 2050. Among all economic sectors power, transport and buildings sectors are expected to incur the main decarbonisation burden. The power sector of Poland is expecting to replace around 7 GW_e of total generating capacity between 2010 and 2020 [7] but the current presumption that much of this replacement capacity will be coal-fired power plant is rather at odds with the imperative to dramatically reduce carbon emissions [2]. Poland has however no simple alternatives for providing energy to its society because Poland has limited renewable energy capacity potential. Poland is a lowland country