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Zero Emission Building and Conversion Factors between Electricity Consumption and Emissions of Greenhouse Gases in a Long Term Perspective

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Abstract **– The CO_2 emissions from a building's power system will change over the life time of the building, and this need to be taken into account to verify whether a building is Zero Emission (ZEB) or not.**

This paper describes how conversion factors between electricity demand and emissions can be calculated for the European power system in a long term perspective through the application of a large scale electricity market model (EMPS). Examples of two types of factors are given: a conversion factor for average emissions per kWh for the whole European power system as well as a marginal factor for a specific region.

Keywords **– conversion factors, marginal emissions, specific emissions, Zero Emissions Building.**

I. Introduction

Buildings represent 32 % of the total final energy consumption in the world [1] and both Zero Emission and Zero Energy Buildings (ZEB) are important concepts in the development towards a more sustainable future with a limited emission of greenhouse gases (GHG).

So far no common agreement exists on a clear and sound definition of a zero energy or zero emission building [2]. Conceptually, a zero energy building is a building with greatly reduced energy demand, so that the remaining energy demand can be balanced by an equivalent generation of electricity (or other energy carriers) from renewable sources over a defined time period. In a zero emission building such balance is achieved not directly on the energy demand and generation but on the associated CO_2 equivalent emissions, sometimes including both direct emissions during the lifetime of the building as well as embedded emissions in materials and during the construction and demolition of the building. The energy imported from the grid(s) into the building is accountable for certain emissions. The export of renewable energy from the building to the grid(s) is accountable for avoiding similar emissions by other (non-renewable) energy producers connected to the same energy grid(s). In [2] a consistent framework for defining Net Zero Energy Buildings is given. This framework is partly described in Chapter 2, with focus on the weighting system with conversion factors. This paper describes how conversion factors between electricity demand and emissions can be calculated for the European power system in a long term perspective by a large scale electricity market model. Five different scenarios for possible development of the European power system towards 2050 are formulated. Examples of two types of factors are given: a conversion factor for average emissions per kWh for the whole European power system, as well as a marginal factor for a specific region or country. The marginal factor shall be understood as the marginal changes in emissions caused by changes in power production as a consequence of a marginal change in electricity consumption. The average factor is applicable for all countries in Europe, while the marginal factor in this case is specific to Norway. However, the methodology for calculating the marginal factor is generic and could be implemented for any country or region.

Chapter 2 presents a review of relevant literature. The methodology used in the analysis is described in Chapter 3 and the results are presented in Chapter 4. Finally, in Chapter 5 the results are discussed and recommendations for use of the conversion factors are given.

II. Selected literature review

The main part of the available literature focuses on Zero Energy Buildings. In this chapter ZEB could be either Zero Emission or Energy Building. In the following chapters, ZEB shall be understood as a Zero Emission Building.

A. The regulation, requirements and status related to ZEBs in Europe

European legislation has set out a cross-sectional framework with ambitious targets for achieving high energy performance in buildings. Key parts of the European regulatory framework are the European Performance of Buildings Directive 2002/91/EC (EPBD) [3] and its recast [4]. The recast of EPBD has established several new or strengthened requirements such as the obligation that all new buildings should be nearly zero-energy by the end of 2020. Reference [5] have analysed state-of-the art national regulations for nearly zero-energy buildings in Europe. According to [5] three dimensions and their integration are fundamental in the EPBD recast: 1) integration of energy efficiency and renewable technologies, 2) the translation of investment in energy savings into economic value and 3) commitment towards a "nearly zero-energy" target. Reference [5] found that almost all European countries have employed at least one of the regulatory or policy instruments analysed. However, all EU countries have to strengthen their national regulations in order to achieve EU's energy saving targets and improve their contribution to energy efficiency governance. In particular integration among renewable energy sources and energy efficiency measures through quantitative targets, the boost of energy efficient buildings in national real estate markets and the transition to nearly zero-energy buildings are in their early state of adoption.

[6] describes the status for different EU Member States more specifically. By 2016 all new homes in the UK are to be zero carbon [2]. The German government has set its energy target so that by 2050 the entire building stock should be "almost climate-neutral" and the primary energy demand is reduced by 80 % [7]. Throughout Europe, there is a great variety of concepts, models and examples of highly energy-efficient or low energy buildings. In Germany more than 13,000 passive houses have been built since the 1990s [8].

Furthermore, [6] presents an overview of the current ZEB status. The countries included are those that are able to demonstrate some level of ZEB activity. The overview is an indication of activity, and does not claim to be definitive. The overview indicates that Germany is the EU Member State that demonstrates the greatest numbers of ZEB built examples. Other European countries with some activity related to ZEB are: Switzerland, UK, Denmark, France, Austria, Finland, Sweden and the Netherlands.

B. Definition of Zero Energy/Emission Buildings

There are several publications related to the definition of ZEBs, e.g. [2, 9–15]. In [13] a review of definitions and calculation methodologies is given.

In [2] a consistent framework for definition of Net Zero Energy Buildings is given. The word "Net" indicate that there should be a balance between energy supply including network losses and production to the energy grids over a given period of time. The Net ZEB definition framework is organized in several criteria: 1) building system boundary, 2) weighting system, 3) net ZEB balance, 4) temporal energy match characteristics and 5) measurement and verification.

The weighting system converts the physical units of different energy carriers into a uniform metric (e.g. CO_2 emissions) hence allowing for the evaluation of the entire energy chain, including the properties of natural energy sources, conversion process, transmission and distribution grids. To check that a building is in compliance with the Net ZEB definition applied, a proper measurement and verification process is required.

According to [2], quantification of proper conversion factors is not an easy task, especially for electricity and thermal networks as it depends on several considerations, e.g. the mix of energy sources within certain geographical boundaries (EU-27, USA, etc.), average or marginal production, present and expected future values, etc.

However, weighting factors will vary over time and space. Consequently the evaluation of weighting factors should be updated at regular intervals to reflect the development of the energy grids. It is also possible to evaluate weighting factors on an hourly basis leading to a dynamic accounting. For energy prices it is already quite common to have hourly prices, while for other metrics, such as carbon emissions. this is not standard practice today but it may become more common in the future.

C. Impacts on marginal emissions from demand reduction

In the literature review few publications related to marginal emissions from the reduction of energy consumption were found and nothing was found about marginal emissions in a time perspective beyond 10–15 years. In [17] two methods are discussed for estimation of the marginal emission factor (MEF – measures the CO_2 intensity of electricity not used as a result of interventions for demand reduction) for the present power system. [17] also makes an attempt to project the MEF over a time frame of 10–15 years to enable assessments in a longer time perspective.

III. METHODOLOGY

In this paper, both average and marginal CO_2 emissions relevant for grid-connected ZEBs are calculated for the European power production system in a time perspective to 2050. A scenario methodology is used for analyzing the future European power system.

A. EMPS – A Multi Area Power Market Simulator for Europe

The analysis is performed with the Multi-area Power Market Simulator (EMPS) for Europe [18]. The EMPS model is a stochastic optimization model for hydro-thermal electricity markets used for price forecasting, corporate and governmental energy system planning and production scheduling. The model is used by all main actors in the Nordic power market, among other all the transmission system operators. In the model, the electricity market is settled such that electricity prices balance demand and supply in each area for each time step, see Figure 1. Options for balancing the market in an area include non-dispatchable renewable production (sun, wind, ...), hydropower, thermal power (lignite, coal, gas, etc), import/export and reduced demand, etc. Non-dispatchable renewable production plants are described by their capacities, and are regarded to have no variable costs. Sun and wind resources are represented by data sets with many years of measured radiation or wind. Thermal power plants are mostly described by their capacity and marginal production costs including fuel costs and CO_2 emission permit costs. For hydropower the availability of water is a limited resource. Reservoirs can be used to store water from low price periods to periods with higher prices so there are considerable time-couplings in the operational strategy. The optimal operational strategy is formulated as a stochastic dynamic programming problem due to the stochastic nature of inflow, wind and solar resources.

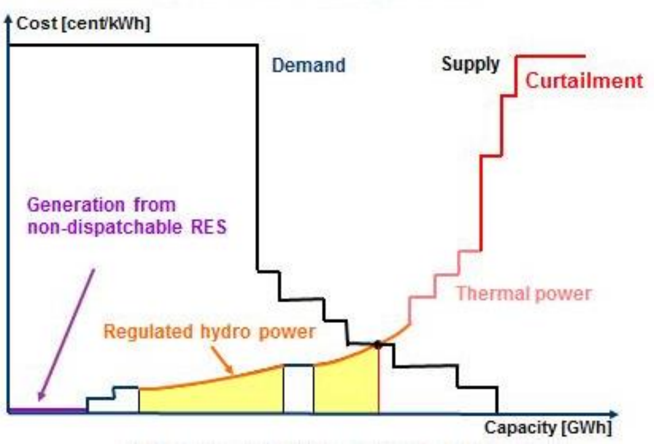

Fig. 1. Calculation of market balance (per area and time step).

The power system under consideration is divided into a number of interconnected areas. The area boundaries are set on the basis of production possibilities, bottlenecks in the transmission system and country borders. In this paper, the European power system is modelled with 54 areas (countries/regions), representing "EU-28" plus Norway, Switzerland, Albania, Bosnia, Moldova, Macedonia and Serbia. 95 interconnections between the areas are modelled as well as 15 offshore wind areas. 75 years with statistical data are used for each area to simulate the inflow to hydro power plants and reservoirs, wind resources available at wind production parks and radiated solar energy available for photovoltaic (PV) or Concentrated Solar Power (CSP) plants. Start/stop costs for thermal production units are included in the analysis. For each area the demand is modelled with a weekly and yearly profile, but is not price-sensitive in this analysis. The model includes an aggregated hydro storage subsystem per node. Pumping, curtailment of load and surplus production are included in the energy balance. Surplus is calculated as energy produced but not possible to sell, because there is not enough demand at the time. Electricity production per technology, total demand, CO_2 emissions (metric tons of CO_2 equivalents) and the marginal power price (Euro/MWh) are reported for each area and time period from EMPS.

B. European scenarios to 2050

The analyses in this paper are mainly based on scenarios from the EU funded project SUSPLAN (Development of regional and Pan-European guidelines for more efficient integration of renewable energy into future infrastructures). A full description of the scenario methodology and the scenarios are given in [18]. A basic assumption for the scenarios is a strong political drive in Europe to promote sustainable development and security of supply. This strong political drive results in the use of necessary incentives and regulations for increased deployment of Renewable Energy Sources (RES). A further assumption is that the share of RES in the future European energy system will be large. It is assumed that the EU “20-20-20” targets are met, and that the development of RES in Europe will continue towards 2050, although with different momentum in different storylines. Two main uncertainties are identified as primary driving forces according to relevance for the objective of the analyses. One “hard” driver (Technology development) and one “soft” driver (Public attitude) are chosen. The rest of the unknown factors are combined into 4 storylines defined by these main drivers to establish the background for the scenario analyses, as shown in Figure 2. The four different storylines created by the two main drivers have the following main characteristics (Technology development, Public attitude):

• Green: (High-tech, Positive public attitude) many advanced and mainly distributed technologies for RES energy and reduced energy demand.

• Yellow: (Low-tech, Positive public attitude) reduced energy demand, mainly achieved through changed behaviour of consumers as there are fewer advanced technologies to “help” energy efficiency improvements.

• Blue: (High-tech, Indifferent public attitude) many advanced technologies but low interest from public and commercial interests - mainly large-scale developments driven by governmental regulations and instruments.

• Red: (Low-tech, Indifferent public attitude) mainly centralized development with traditional technologies.

In addition to the four scenarios from the SUPLAN project, a fifth scenario is developed. The scenario is designed to have very low CO_2 emission and is called UltraGreen. The situation in 2050 is modelled with an even higher deployment of energy-efficiency technologies than in Green and also with increase of nuclear capacity compared to 2010. In addition a large increase in trans-national transmission capacities is assumed.

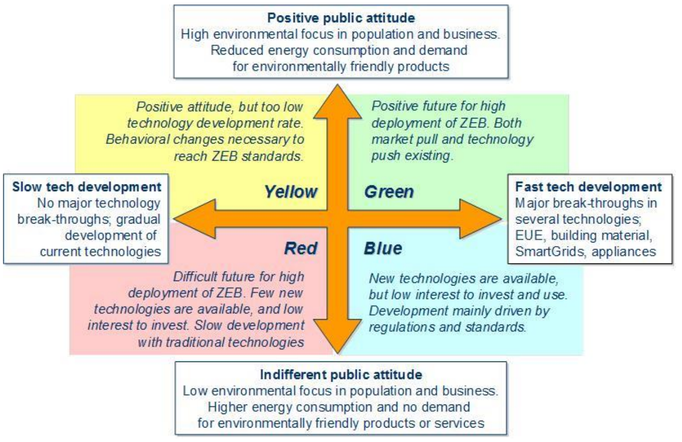

Fig. 2.Overview of the four scenarios.

C. Data model

Different sources are used for quantification of the input parameters to the EMPS analysis:

• Development of fossil fuel-, CO_2- and biomass prices up to 2050 [19]

• The distribution of resources like hydro inflow, wind and solar radiation [20] [21]

• RES-electricity deployment. Based on run of model described in [22]

- Development of conventional production capacities [23]
- Electricity demand development (shown in Figure 3) [24]
- Transmission capacities [25]

Several of the sources only cover the time period to 2030. Extrapolation of input data to 2050 has been done. More details of the data model are given in [26].

The CO_2 emissions factors from thermal generation are assumed to be unchanged over the analysis period to 2050. The factors used in the analysis are given in Table 1 [27].

Generation costs including quota price, fuel prices and efficiency are given in Table 2. A quantification of the different elements in the costs and the sources for the data used is given in [26]. Note that with the current assumptions, lignite is the most expensive of the solid fossil fuels. UltraGreen is assumed to have the same generation costs as the Green scenario.

Development of demand is shown in Figure 3.

TABLE I
CO_2 EMISSION FACTORS FROM GENERATION PLANTS [CO_2/KWH][27]

Emission gram CO_2 per kWh at defined efficiency from generation plants	2007
Lignite	1 220
Coal	929
Oil	857
Gas	357
Nuclear	0
Renewables	0

TABLE II
GENERATION COSTS FOR DIFFERENT SCENARIOS [€/MWH] [26]

Yellow/Green	2030	2040	2050
Lignite	118	140	162
Coal	56	59	62
Gas	70	79	80
Oil	138	141	143
Biomass	62	63	64
Red/Blue			
Lignite	118	140	162
Coal	99	116	132
Gas	108	122	135
Oil	195	221	245
Biomass (Red/Blue)	53/49	51/45	48/41

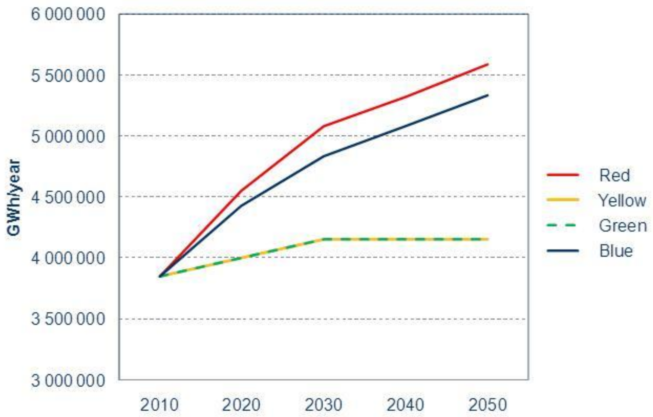

Fig. 3. Development of gross electricity demand in all scenarios.

D. The marginal emissions

The marginal emissions in the different scenarios are the marginal changes in emissions in Europe as a consequence of changes in the demand of 1 TWh in Norway. The following methodology is used to calculate the emissions:

1) The demand in Norway is increased with 1 TWh/year distributed proportionately over all load periods in a year;

2) EMPS is run with and without this increase in demand;

3) Differences in energy production show how the increased demand is covered in each time period, and the corresponding changes in emissions are calculated.

Since Norway is connected to other countries through transmission lines, increase in demand in Norway will in most cases increase production also in other countries.

E. Explanations of variation of the marginal emissions

EMPS schedules generation units according to marginal cost in each node/area (merit order), cf. Figure 1. Since investment costs are not included, the non-dispatchable renewable technologies (wind, solar, run-of-river hydro etc) have the lowest price. Nuclear production will also have low operational costs according to our assumptions. The order of the fossil technologies will be dependent of the resulting marginal costs for both fuel and emissions of CO_2. Marginal cost (i.e. value) of large-scale hydro power with storage is calculated depending on size and level of its reservoirs, expected inflow and future market prices.

For all the scenarios, coal is the cheapest fossil fuel, gas is the second cheapest and lignite is the most expensive in 2050 (see Table 2). Since the cheapest available technology always will be selected by the EMPS model, the merit order steps in each area from left to the right will be coal, gas and then lignite. However, transmission bottlenecks and losses between areas also impacts which technology is chosen. Figure 4 shows a simplified illustration of how a typical load profile is combined with the merit order supply curve for the area. The cheaper units (RES, nuclear, etc) are below minimum load and will always be in operation, while gas and lignite are used part of the day. Thus, these are the marginal units of the system.

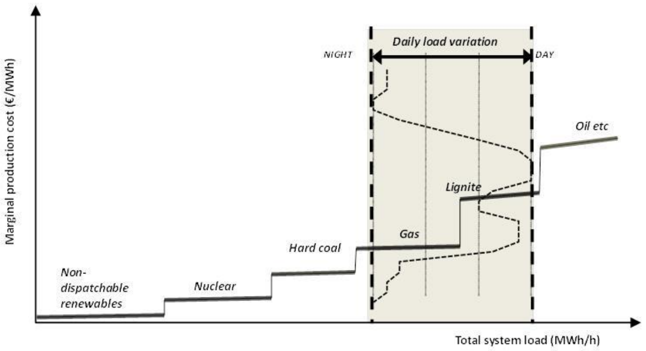

Fig. 4. Combination of marginal cost curve and curve with system load for a country/region.

During the night a marginal increase in demand will be covered by an increase in gas production. During the day it will be covered by an increase in lignite production. If the amount of renewable production in the system is increased, the merit order step representing the renewables will be wider and the whole supply curve will be pushed to the right. The marginal cost of the thermal units will not change, but their capacity will be activated at a higher system load. The marginal kWh will thus be produced by a more hard coal and less lignite and the emissions from the marginal production will decrease compared to the situation with a lower volume of renewables in the production portfolio.

The effect will be the same if we assume a general decrease in the demand. In this case, the daily load profile will move to the left on the supply curve, and the marginal production will mostly be hard coal fired units. Again the emissions from the production of the marginal kWh will decrease compared to a situation with higher demand. Thus, for this fictive example it can be observed that both an increase in RES capacity and a decrease in the system load will decrease marginal emissions. The introduction of a CO_2 tax will change the cost level of the technologies, but will not influence the total CO_2 emissions unless the tax is large enough to change the order of the technologies in the supply curve. This is the situation in our case where the CO_2 tax is assumed high enough to push lignite beyond the gas fired units on the merit order supply curve.

IV. RESULTS

A. Production portfolios

The resulting production portfolios for 2010, for Green in 2020 and for each of the scenarios in 2050 are shown in Figure 5.

Note that the input data in this study is based on references published before 2010, thus the 2010 figures are estimates and not measured values. Since the main differences between the low-carbon scenarios are after 2020, we have only shown results for 2020 for one of the scenarios (Green).

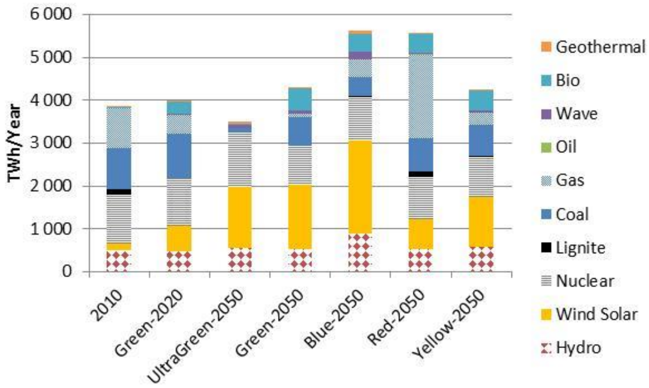

Fig. 5. Production portfolios for each scenario in 2050.

The development of shares of renewables in electricity production (RES-E) in the different scenarios is shown in Figure 6. EU's target of 20 % RES in the final demand of energy in 2020 implies about 35 % RES-E [28]. If we assume similar RES-E targets for 2020, the EU targets are achieved for all the scenarios except Red. The share of RES-E in Green 2020 is 35 %. The shares of RES-E in 2050 are similar in the Blue (69.3 %) and the Green (63.7 %) scenarios in spite of very different production portfolios. The volume of RES-E production is much higher in Blue (2 844 TWh/y) in 2050 than in the Green scenario (2 108 TWh/y), but the demand is also much higher. The Yellow scenario ends up between the Red and the Green. Limitations in new technologies result in the curve flatting out in the Yellow scenario.

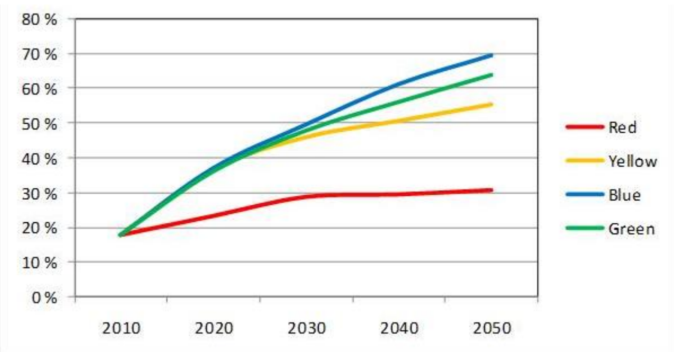

Fig. 6. Share of RES-Electricity on gross demand in all scenarios.

B. Development of CO_2 emissions

The average specific emissions for all the scenarios are shown in Figure 7, and the marginal emissions are shown in Figure 8. In 2010 the average specific emissions for EU-25 (Cyprus and Malta are not included) were 371 gCO_2/kWh based on the calculation from the EMPS model. In comparison, the European Environment Agency (EEA) has calculated the CO_2 emission factor for electricity production from all fuels in EU-27 in 2008 as 364 gCO_2/kWh [29].

The specific emissions from the UltraGreen scenario in 2050 are less than 10 % of the emissions in 2010, only 31 gCO_2/kWh.

The marginal production portfolio for 1 TWh increase in demand in Norway in 2050 is shown in Figure 9. As shown in the figure some production units may also have a reduction in output as a result of the demand increase, resulting in negative values.

The UltraGreen scenario has higher marginal emissions than Yellow, Blue and Green since the marginal production is covered by a larger share of coal than gas. Referring to Figure 4, the marginal will be on the coal (and nuclear) units.

The marginal emissions in the Blue scenario are among the lowest. The reason for this is that the Blue scenario has a very high wind and solar production that covers the marginal increase in consumption. The marginal increase in consumption will reduce the surplus of wind and solar production without generating any emissions. Furthermore, in the Blue scenario a considerable part of the marginal increase is covered by gas and biomass that have considerable less carbon contents compared to coal and lignite.

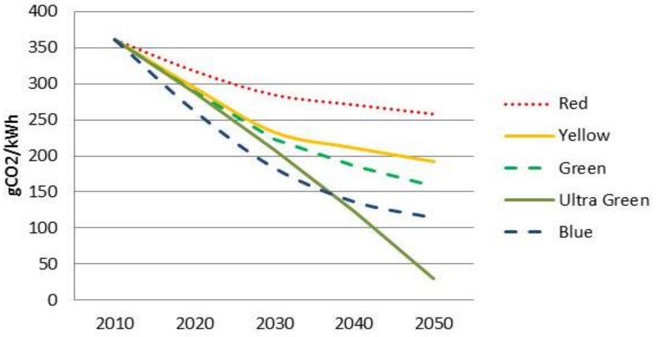

Fig. 7. Development of average specific emissions.

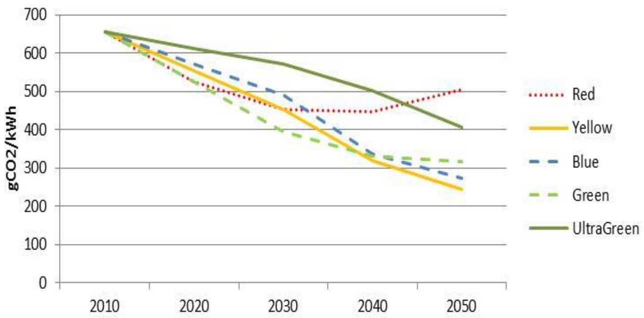

Fig. 8. Development of marginal emissions.

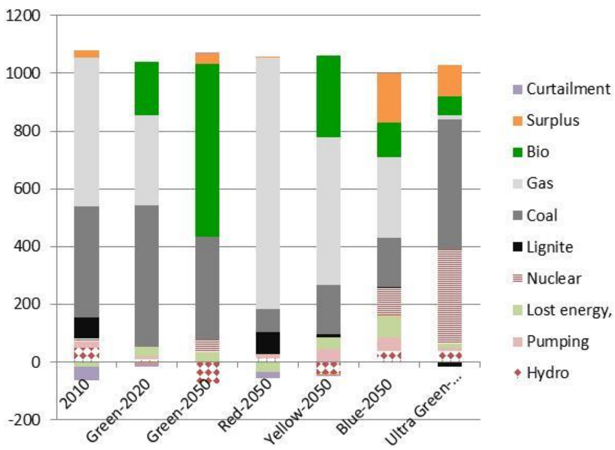

Fig. 9. Development of marginal production portfolio.

For the Red scenario the marginal emissions will increase towards 2050 because an increasing share of the marginal production is covered by lignite. Referring to Figure 4, more of the marginal production is lignite both since the demand is increasing (load curve moves to the right on the supply curve) and as the share of renewables is lower (the supply curve moves to the left).

The reason for the flattening out of the marginal emissions for Green between 2040 and 2050 is that the marginal to a larger degree is covered by coal and less by gas. The share of RES is increasing, and compared to Figure 4 gas is mainly pushed out of the marginal production.

C. Sensitivity analyses

The five scenarios used in this study are designed to be very different to capture a wide range of possible developments. The scenarios are based on 3 different levels of demand: Red/Blue (high), Green/Yellow (low) and UltraGreen (very low), different production portfolios: local/regional RES (Green/Yellow), large-scale RES (Blue), high share of nuclear (UltraGreen) and relatively high share of fossil production (Red). The scenarios also have different fuels and CO_2 prices resulting in different generation costs as shown in Table 2.

In addition two sensitivity analyses are performed for the input parameters to the Green 2050 scenario:

i) The price for CO_2 emissions is increased from 57 €/ton to 88 €/ton CO_2. The result is that coal, gas and biomass are changing places in the merit order list (see Figure 4). Biomass is now cheaper than gas and will be selected by the EMPS model before gas and coal whenever it is available. If there is no biomass available, gas will be selected before coal.

ii) Both the price for CO_2 emissions and the price for biomass are increased, so in the merit order list gas is the cheapest, biomass is second and coal is the most expensive.

The resulting production portfolios are shown in Figure 10. For alternative ii (to the right of the figure) the use of gas increased from 86 TWh/y in the "main" Green scenario to as much as 1084 TWh/y. Furthermore, since gas is so cheap, only a limited share of bio is left (157 TWh/y compared to 506 in "main" Green) and no coal.

The specific CO_2 emissions are 96 gCO_2/kWh compared to 157 in the "main" Green scenario. The reduction is a result of gas substituting coal, and since gas has much lower emissions than coal, the total emissions will be reduced.

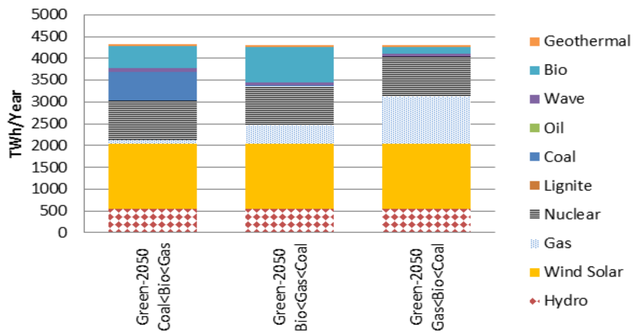

Fig. 10. Production portfolios for two sensitivity analyses of Green 2050 ("main" scenario to the left, alt i in the middle and alt ii to the right).

For alternative i (in the middle of Figure 10), theuse of biomass in electricity production is increased from 506 TWh/y in the "main" Green scenario to 805 TWh/y per year. Gas is increased from 86 TWh/y to 415 TWh/y and there is hardly any coal left in the system. The emissions are reduced from 157 gCO_2/kWh in the "main" Green scenario to 41 gCO_2/kWh in the alternative i. This the bio-gas-coal alternative results in very low emissions and may be considered as an alternative way to UltraGreen to develop a very low emission future. Figure 11 shows the production of the marginal unit for the sensitivity cases.

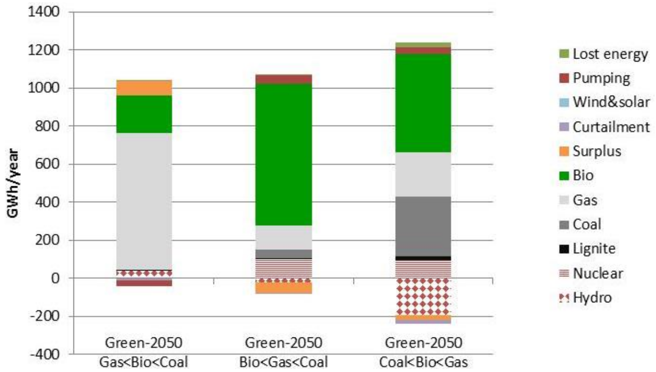

Fig. 11. Marginal production portfolio 2050 sensitivity analyses.

V. DISCUSSION AND RECOMMENDATIONS

This paper has presented a detailed analysis of CO_2 emissions from the power supply in Europe in a long term perspective. The analysis is based on scenarios that are in accordance with the European Commission's long term ambitions related to reduction of emissions of greenhouse gases. The scenarios represent possible alternative futures but without any preference or priority. The analyses have given both average emissions per kWh consumption as well as emissions from marginal change in consumption. The average emissions are calculated for the whole power production portfolio in Europe while the marginal emissions will be dependent of a few units producing the last kWh in the market.

The production portfolio will change over time, reflecting political targets and ambitions. The analyses described in this paper estimate that the average emissions per kWh from a low carbon power system in Europe in 2050 to 30–40 gCO_2/kWh (UltraGreen and one of the sensitivity analyses for Green), which are less than 10% of the present emissions. In a system with high shares of RES, nuclear and gas, the average emissions are nearly 100 gCO_2/kWh compared to approximately 360 gCO_2/kWh in the present system [29].

Average and marginal emissions can be used in several ways when defining conversion factors for Zero Emission Buildings:

1. An average conversion factor is useful for planning and designing future deployment of ZEBs. Buildings have a very long life time, and the power system will change considerably in the coming decades. Politicians and decision makers should have knowledge about how ZEBs can contribute to reduce GHG emissions in their life time, e.g. for comparing efforts related to ZEBs with other alternative efforts. The conversion factor needs to be calculated before the building is constructed and decades before it is demolished. For such purposes, it is convenient to apply a factor based on scenario analysis and average emissions per kWh since it is more robust and easier to understand than a factor based on marginal emissions. Furthermore, since the considerations will concern many buildings, a factor based on marginal calculations will not be correct for such purpose. The Norwegian Research Centre for ZEB has chosen to use a conversion factor based on average emission per kWh for their work in a long term perspective (132 g/kWh [2]).

2. A marginal conversion factor is useful for the optimal design of a single building that is built in accordance with local conditions like solar radiation, wind, etc. A single building should be related to the marginal emissions, but since the calculation has to be done before the building is constructed, it must be based on similar scenario analysis as shown in this paper.

3. A marginal conversion factor is necessary to operate an existing ZEB in an optimal way. When a ZEB is constructed it will in some periods produce electricity for the network and in other periods use electricity from it. To achieve zero emissions from the operation of the building, it is crucial to supply energy in periods when the marginal emissions from the power production are high and to consume energy in periods when the marginal emissions are low. Since this concerns a single or a few buildings in a short time perspective, the most correct approach would be to base the conversion factor on marginal emissions (each building will give a marginal contribution). In this case, the marginal calculations would be based on the current power system as described in [16] and not on future scenarios.

4. A marginal conversion factor is necessary for accounting and crediting each building for the reduction of emissions. In real time operation a marginal reduction of electricity consumption from a building will result in a marginal reduction of the production and a corresponding reduction of the emissions. Thus, the ZEB should be credited according to the marginal production and emissions. In a future power system with smart meters in all houses, such a crediting could be implemented through frequent (e.g. hour by hour) measurements of consumption in each building and by combing the information of consumption with knowledge about the real marginal power production and its emissions at the same time as described in [16].

VI. ACKNOWLEDGEMENTS

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