Postprint of: Jaskólski M., Modelling long-term technological transition of Polish power system using MARKAL: Emission trade impact, Energy Policy, Vol. 97 (2016), pp. 365-377, DOI: 10.1016/j.enpol.2016.07.017

Modeling long-term technological transition of Polish power system using MARKAL: Emission trade impact

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Abstract[b]

The need for technological transition of electricity production becomes a global problem. However, in coal-dominated Polish power system this need is even more crucial than anywhere, since technical lifetime of the most domestic power plants is ending. In this paper, the impact of the EU Emission Trading Scheme (EU ETS) for CO_2 combined with sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emission trading mechanism

[b] **Abbreviations:** BAU – Business As Usual case; CBM – Coal Bed Methane; CCGT – Combined Cycle Gas Turbine; CCS – Carbon Capture and Storage; CEN – baseline (central) EUA price case; CHP – Combined Heat and Power; CO_2-eq. – equivalent of CO_2 emission on emission allowance; EFF – efficient (case); ETS – Emission Trading Scheme; EUA – emission allowance (CO_2); FBC – Fluidized Bed Combustion; FGD – Flue Gas Desulfurization; HIGH – high EUA price case; IED – Industrial Emission Directive; IGCC – Integrated Gasification Combined Cycle; LCP – Large Combustion Plants; LOW – low EUA price case; LWR – Light Water Reactor; MARKAL – Market Allocation modelling framework; MSR – Market Stability Reserve; NPP – Nuclear Power Plant; PCC – Pulverized Coal Combustion; PLN – Polish zloty (currency); PSE SA – Polskie Sieci Elektroenergetyczne Spółka Akcyjna (Polish Power Transmission System Operator); PV – Photovoltaics; REF – reference (case); RES-E – electricity from renewable sources; SC – Supercritical.

on power technology choice was studied using Market Allocation (MARKAL) model of Polish power system. Poland can contribute to achieving ambitious EU CO_2 emission reduction goals to 2050 by switching to diversified electricity mix of low-carbon coal technologies with CCS, and carbon-free options e.g. nuclear, biomass IGCC, wind onshore and offshore. This 'low-carbon' mix can be achieved only at high emission allowance prices, stimulated by the introduction of Market Stability Reserve to EU ETS and successive decrease in EU CO_2 emission cap. At high emission allowance prices, Poland's CO_2 emissions from ETS-participating electricity generating plants are expected to decrease in 2010-2050 period by 96-99%, depending on the projected electricity consumption. Model results prove that SO_2/NO_x emission trading scheme, envisaged in Poland, is not effective, in view of Industrial Emission Directive implementation, and should be reconsidered.

Keywords:

emission trading scheme;

energy model;

power generation planning;

Poland;

Market Stability Reserve;

sulfur dioxide emission trading

1. Introduction

1.1 Background and motivation

Since the contribution of fossil fuels to worldwide electricity production is approximately 66% (2013) (Energy Information Administration, 2013), there is a global need for technological transition of power systems to mitigate their environmental impact. European Union (EU) emphasized the need in decarbonization strategy drawn in EU Energy Roadmap 2050 (European Commission, 2012). To achieve the

long-term goal of carbon-free power production, two instruments for emission reduction have been implemented before the publication of Energy Roadmap, i.e. Carbon Dioxide Emission Trading Scheme (EU ETS) (European Commission, 2009) and the mechanism of the integrated pollution prevention, implemented in Industrial Emission Directive (IED) (European Commission, 2010). Investment decisions in power sector have to be in line with the EU and national energy policy goals which are: sustainability, security of energy supply, and competitiveness (European Commission, 2007; Ministry of Economy of the Republic of Poland, 2009). Simultaneous consideration of all long-term energy policy objectives in search of optimal electricity mix is a complex problem, so using decision making support tools is desired. These tools are usually simulation or optimization models of energy system, very often built with the use of energy modeling framework e.g. MARKAL (Market Allocation), EFOM (Energy Flow Optimization Model), MESSAGE (Model for Energy Supply System Alternatives and their General Environmental Impacts) or TIMES (The Integrated MARKAL-EFOM System). In such case, the research problem comes down to developing the approach to modeling energy policy instruments such as emission trading scheme and promotion mechanisms for both renewable electricity (RES-E) and high-efficiency cogeneration (Bućko, 2007). If maintained, these mechanisms are expected to have the biggest impact on the choice of electricity generating technologies within next decades.

Poland, where electricity production is dominated by coal, has rejected to adopt ERM 2050 (Reuters, 2012), expecting high costs of decarbonization, i.e. $18\text{-}22 \cdot 10^9$ EUR'05/yr after 2050 (Jankowski, 2010). However, as an EU Members State, the country implemented EU ETS in their legal framework (Ministry of the Environment of the Republic of Poland, 2011a) and proposed draft act on the trading scheme of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions (Ministry of the Environment of the Republic of Poland, 2011b). As of 2013, almost 40% of Polish power units were over 40 years old and more than 15% were over 50 years old, and should be considered for decommissioning (Polish Information and Foreign Investment Agency, 2013). Therefore, investments in power sector are necessary in a short- and medium-term perspective to avoid power imbalance (The Energy Market Agency, 2011). This creates a chance for switching to clean

electricity production. However, vast majority of large power plant projects, being in progress in Poland, are coal and natural gas power plants and combined heat and power (CHP) plants (PSE SA Polish Transmission System Operator, 2010; The Energy Market Agency, 2016), with small contribution of biomass. Failure to accomplish them by the end of this decade, increases the risk of power deficit. In search for carbon-free options in long-term perspective, Polish government has approved the nuclear power program in 2013, expecting to commission the first nuclear power plant in 2024 (Ministry of Economy of the Republic of Poland and Polish Government Commissioner for Nuclear Power, 2014). However, neither the location of the plant, nor the technology vendor is known, to date. Scientists, environmentalists and decision makers debate on whether Poland should build nuclear power plant or invest more in distributed generation based on renewable energies (Ministry of Economy of the Republic of Poland, 2012). Because of the lack of consensus on the future electricity mix, there is a need to build the methods and tools to support energy system planning, based on transparent and objective rules and incorporating emission reduction mechanisms. Recently, the draft version of Energy policy of Poland until 2050 (Ministry of Economy of the Republic of Poland, 2015a) was presented for public discussion. This paper reflects author's vision of power system development and is a counter-analysis for projections appended to the document (Ministry of Economy of the Republic of Poland, 2015b).

Bearing in mind the problems described in previous paragraphs, the modelling approach was proposed to include emission trading schemes in energy system optimization model that support investor decisions in view of EU ETS continuation and planned implementation, in Polish legal framework, of country-specific trading schemes for NO_x and SO_2 emissions. Using Market Allocation (MARKAL) modelling framework, the model was developed to find the mix of technologies that are least-cost and in line with EU energy policy concerning renewable electricity standards and emission reduction goals. These policies were expressed in terms of indicative goals (e.g. obligatory share of renewable electricity in total electricity sales to final consumers) or emission allowance trading. As a result of the implementation of the proposed modelling approach, optimal structure of power technologies for Poland by 2050 was calculated.

1.2 Review of related work

Energy systems modelling and the impact of emission trade on power generation were the subjects of previous works. Agent-based modelling, in which actors (i.e. companies acting in power sector, usually power generation systems) are represented by agents living in a simulated world, was applied in (Chappin and Dijkema, 2009; Cong and Wei, 2010; Ermoliev et al., 2015; Matsumoto, 2008; Richstein et al., 2014). There was also a number of applications of energy-technology-oriented models to study the impact of emission trading on technology choice and its long-term consequences. MARKAL bottom-up partial-equilibrium model was used to analyze emission trade in (Anandarajah and Strachan, 2010; Barreto and Kypreos, 2004; McDowall et al., 2012; Victor et al., 2014). Similar model i.e. The Integrated MARKAL EFOM System (TIMES) was employed to study the cases of Finland (Kara et al., 2008), Czech Republic (Rečka and Ščasný, 2016) and Portugal (Amorim et al., 2014). A computable general equilibrium model was applied to analyze the impact of climate policy on the supply of renewable energy (Boeters and Koornneef, 2011), and to assess emission trade both in global scale (Springmann, 2012) and at national level i.e. for Romania (Loisel, 2009). A model developed using General Algebraic Modelling System (GAMS), defined as a Linear Complementarity Problem, was employed for power generation expansion planning under emission trading schemes (Linares et al., 2008). The studies concerning Polish energy system modelling include PolMark game theoretic model, applied to study the impact of different factors, among others CO_2 emission tax, on the market potential of coal for power generation (Kamiński, 2011, 2009). TIMES model, including the projections of CO_2 emission allowance prices, was used to study the long-term development of Polish power system (Pluta et al., 2012; Wyrwa et al., 2014). Previous concepts of Polish MARKAL model were presented in (Jaskólski and Bućko, 2015, 2013; Jaskólski, 2014, 2012a, 2012b).

1.3 Contribution of the paper

The main contribution of this paper is the modelling approach to EU ETS for CO_2, combined with NO_x and SO_2 emission trading schemes (SO_2/NO_x ETS) and its implementation for the case of Polish power system. MARKAL – technology-oriented optimization tool offering linear programming (LP) in its standard version

(Loulou et al., 2004) – was applied to build energy system model for Poland. Reference Energy System, technology database, energy carrier price projections and electricity demand projections were improved in relation to previous Polish MARKAL studies (Jaskólski and Bućko, 2015, 2013; Jaskólski, 2014, 2012a, 2012b).

2. European Union emission trading scheme

EU ETS was implemented in 2005 to promote reduction of anthropogenic greenhouse gases (GHG) emissions. As the scheme was developing, EU set the goals for GHG emission reduction i.e. by 20% by 2020 in relation to the levels from 1990 (30% if other developed countries declare their will to reduce emissions by a comparable percentage) (European Commission, 2009). According to recent EU legislative proposal (European Council, 2014), by 2030 GHG emissions must be reduced by 40% in relation to 1990, which means that within ETS sector GHG emission reduction must be 43% to 2030, as compared to the levels of 2005. EU emission reduction goal for 2050 is 80-95%, as compared to 1990 levels (European Commission, 2011a). EU ETS covers the following emissions: a) carbon dioxide (CO_2) from power and heat production, civil aviation and energy-intensive industry sectors; b) nitrous oxide (N_2O) from nitric, adipic, glyoxal and glyoxic acids; c) perfluorocarbons (PFCs) from aluminum production. Participation in ETS is compulsory for the above sectors in all 28 EU member states as well as Iceland, Liechtenstein and Norway (European Commission, 2013a). The scheme is based on "cap and trade" approach. From 2013 onwards, emission cap, i.e. the sum of allowances to be allocated and auctioned, is set at the EU level, whereas to that date national limits were imposed. Each ETS participant receives free of charge or buys emission allowances (EUA). Companies participating in ETS are obliged to surrender one EUA for each ton of CO_2 emitted by them in the preceding year. EUA are subject to trade between ETS participants. Each company that surrender insufficient number of EUA has to buy them on auction to cover the shortfall and pays the fine of 100 EUR/t CO_2 (for 2013 and increasing over years in accordance with inflation rate in Eurozone). During the first two trading periods (2005-2007 and 2008-2012), EUA were predominantly allocated free of charge, whereas from the beginning of the third trading period, i.e. from 2013 onwards, auctioning is the main method for

EUA allocation. Free allocations will be possible only by 2027. Starting from 2013, EU-wide-issued annual quantity of EUA for power plants and other industrial installations decreases each year by 1.74%. Also from 2013, all electricity generators must purchase their allowances on auctions, with the exception of power plant operators in eight countries that accessed EU in 2004, including Poland. Governments of these countries can continue to grant limited number of free allowances by 2019. Five percent of total EUA will be allocated over the period 2013-2020 for new entrants i.e. installations that, after 30 June 2011, either entered ETS or had significant extension. Sectors being at risk of carbon leakage received 80% of allowances for free in 2013 on condition of reaching benchmark performance level. This allocation will be reduced to 30% in 2020 (European Commission, 2013a, 2009).

In 2014, EU proposed the framework for climate and energy policy in the period 2020-2030 (European Council, 2014), stating *inter alia* that ETS is not a sufficient driving force for low-carbon technology investments. Therefore, EU proposed the reform of ETS. The factor, by which the amount of allocated EUA within ETS is decreased annually, should increase from 1.74% in third trading period to 2.2% from the beginning of fourth trading period i.e. the year 2021 (European Council, 2014). In addition, due to economic crisis, since 2008, reduction of GHG emissions within ETS was greater than expected, which resulted in a surplus of EUA that weakened the functioning of carbon market (European Commission, 2013a). Therefore, postponement auctioning of 900 million allowances to 2019-2020 period was proposed (European Commission, 2013b). Recent EU legislative proposal on ETS (European Commission, 2014) concerns market stability reserve (MSR) mechanism to be applied from the start of 2021. According to this proposal, adjustments of auctioned allowances will be made, if total number of allowances on the market is outside certain range. If total surplus exceeds 833 million EUA, 12% of EUA, being traded on the market two years before the action is taken (or a minimum of 100 million EUA), will be added to MSR and deducted from future auction volumes. Conversely, 100 million EUA per year will be released from MSR and added to future auction volumes, if total surplus does not surpass 400 million EUA (European Commission, 2014).

3. MARKAL model of Polish power system

3.1. Model description

Overview

MARKAL model is the combination of an in-built mathematical structure, developed within the framework of Energy Technology Systems Analysis Program (ETSAP), and the sets of data prepared by model user. Minimization of total energy system cost, calculated as a sum of annual costs discounted back to the first year of the analysis, is the optimization criterion applied in MARKAL model. Complete mathematical formulation of MARKAL was presented in (Loulou et al., 2004).

Emission trading scheme modelling approach

Fig. 1 illustrates the basic concept of EU ETS and SO_2/NO_X ETS implementation in MARKAL. For this purpose, different subsets of environmental emission set (ENV in MARKAL) were used for emissions of CO_2 from EU ETS and non-ETS participants. Subsets of emissions form EU ETS were further differentiated to reflect groups of installations receiving different numbers of allowances for free in the first, the second (Ministry of the Environment of the Republic of Poland, 2006, 2004) and the third trading period (Council of Ministers of the Republic of Poland, 2014). Assignment of technologies to ETS and non-ETS groups was based on the type and the typical size of the plant being represented by technology option in question. EU ETS participants were technologies representing the plants combusting non-renewable fuels of input thermal capacity exceeding 20 MW_t (European Commission, 2009). Similar rules were applied to emissions of SO_2 and NO_X from Large Combustion Plants (LCP) and non-LCP. Technologies of typical input thermal capacity above 50 MW_t (European Commission, 2010) were assigned to LCP group, but without further specification of the installation type, as it was in EU ETS modelling approach. MARKAL calculated the amount of emissions on the basis of environmental factors and technology activity i.e. annual production of electricity (power plants and CHP plants) or heat (district heating plants). Emissions were subject to two types of upper constraints, namely the allocation of free allowances to each of the ETS-participant groups and the emission cap imposed on ETS participants at national (2010 model period) and EU level (from 2015 to 2050 period).

If emission of the group of plants exceeds the number of allocated allowances, this group must purchase EUA on auctions or from other actors on ETS market. Exceeding national or EU ETS cap (the limit imposed on allowances in circulation) is associated with the payment of penalty by a group of installations.

Fig. 1. The concept of EU ETS implementation in Polish MARKAL model

The costs of and revenues from emission allowance trading were included in objective function value by means of its standard formulation i.e. using the costs of imports and revenues from exports of commodity. Objective function was modified to take into account allowance allocation and to calculate the penalty for exceeding emission cap by a certain group of plants:

$$Z' = Z + \sum_{t=1}^{T}\left[(1+d)^{M(1-t)} \sum_{i=1}^{i=M} \sum_{env \in tem} ETSCOST_{env,t}\,(1+d)^{1-i}\right] = min \qquad (1)$$

where: *Z'* was the value of modified MARKAL objective function, including discounted costs of and revenues from ETS (from the point of view of the ETS participants); *Z* was the value of standard objective function in MARKAL (Loulou et al., 2004); *t* was the set of five-year time periods of the model (e.g. $t = 1$ for 2010, $t = 2$ for 2015, …, $t = 9$ for 2050); *i* was the subset of *t*, representing the numbers of years in each five-year time period of the model (e.g. for $t = 1$ i.e. time period 2010: $i = 1$ for 2010, $i = 2$ for 2011, …, $i = 5$ for 2014; for $t = 2$ i.e. time period 2015: $i = 1$ for 2015, $i = 2$ for 2016, …, $i = 3$ for 2019, etc.), *env* was the set of environmental emissions; *tem* was the subset of *env,* representing emissions from ETS-participant group of plants (see Fig. 1); *T* was the number of five-year time periods of the model ($T = 9$); *M* was the number of years per each time period of the model ($M = 5$ yrs); *d* was general discount rate for the entire energy system ($d = 10\%$); $ETSCOST_{env,t}$ was the annual cost of ETS for environmental emission *env* in time period *t*.

Annual cost of ETS was the sum of the costs of EUA purchased on ETS market and fines for exceeding emission cap subtracted by the revenues from EUA sales on the market:

$$ETSCOST_{env,t} = \sum_l \left(PRI_{env,t,l}\, EUAPUR_{env,t,l} - PRI_{env,t,l}\, EUASAL_{env,t,l}\right) +$$

$$+PEN_{env,t}\left(EMI_{env,t} - \sum_l EUAPUR_{env,t,l} + \sum_l EUASAL_{env,t,l} + ALLOC_{env,t}\right) \quad (2)$$

where: $PRI_{env,t,l}$ was the price (at price level l) of one allowance for 1 ton of emission *env* in time period t; $EUAPUR_{env,t,l}$ was the number of emission allowances *env*, purchased annually at price level l, in time period t; $EUASAL_{env,t,l}$ was the number of emission allowances *env*, sold annually at price level l, in time period t; $PEN_{env,t}$ was the penalty for the shortfall of one emission allowance for emission *env* in time period t; $ALLOC_{env,t}$ was the number of emission allowances allocated annually for free to the plants belonging to group *env*, in time period t.

Reference Energy System

Fig. 2 depicts the idea of Reference Energy System for Polish MARKAL. Power system was divided into four representations: 1) transmission system for electricity 400 kV, 220 kV, 2) distribution system for electricity – grouping the following power grids: high voltage 110 kV, medium voltage 10-30 kV, and low voltage 0.4 kV, 3) microgrids for electricity and 4) power systems of industrial autoproducing CHP plants, i.e. typically producing electricity in cogeneration with process steam for the needs of industrial plants e.g. sugar factories, oil refineries, etc. MARKAL grid link (LNK) technology was used as a representation of all 400/110 kV/kV and 220/110 kV/kV power transformer stations connecting transmission and distribution systems and to model connections between power system and the electrical systems of industrial autoproducing CHP plants. Imports and exports of electricity represented the connections of Polish power system within the European Network of Transmission System Operators for Electricity (ENTSO-E).

New technology options included 29 power plant and cogeneration technologies. To properly model cogeneration, aggregated representation of heating systems and heating plants was proposed in the model. This concept was presented in (Jaskólski, 2012b). Heat from microgeneration CHP systems was modelled as a separate energy carrier to reflect lower heat losses from this type of sources, as compared to centralized heating plants and cogeneration systems.

Fig. 2. Simplified scheme of electrical power system in Polish MARKAL. Note: CBM – Coal Bed Methane, CCGT – Combined Cycle Gas Turbine, CCS – Carbon Capture and Storage, CHP – Combined Heat and Power, FBC – Fluidized Bed Combustion, IGCC – Integrated Gasification Combined Cycle, PCC – Pulverized Coal Combustion

3.2. Data

The analysis covered time perspective between 2010 and 2050, divided into five-year time periods. Variables and parameters of the model are identical for each year in a given time period with one exception i.e. the variable representing new capacity additions. Investments occur only in the beginning of each time period, but the resulting installed capacity is available throughout that period (Loulou et al., 2004) and the following periods i.e. by the end of the model horizon or technical lifetime of technology, whichever comes first. In MARKAL, each year of the model is divided into six time subdivisions, i.e. Season – Day/Night combinations, to reflect load variation in power system. Installed capacity was calculated using reserve margin, which was 38% of the highest average power load over MARKAL year subdivisions i.e. in Winter-Day. It accounted for both peak load and 20% of installed capacity reserve. To calculate peak power system load and electricity demand distribution over year, the data from (PSE SA Polish Transmission System Operator, 2014) were used.

All costs in the model were expressed in euro of the year 2010 (EUR'10). Discount rate for the entire energy system was 10% in real terms, but electricity generating technologies were given individual discount rates (see Table 1.).

Fees for the use of environment are imposed in Poland on plant operators for emitting selected pollutants. These fees were obtained from Polish legislation, e.g. (Ministry of the Environment of the Republic of Poland, 2014). Projections of these fees, as illustrated in Fig. 3, were developed on the basis of the trends from 2004-2015 period and recalculated to the currency of 2010 using inflation rate projection i.e. 1.5%

(from 2015 onwards), which is National Bank of Poland low percent target rate (World Bank Group, 2015). Currency rate was 1 EUR = 4 PLN (polish zloty).

Fig. 3. Fees for the use of environment

Source: Author's projections on the basis of (Ministry of the Environment of the Republic of Poland, 2014)

Representations of existing power plants and new power technologies were modelled separately. Fig. 4 demonstrates projections of total installed capacity available in technologies representing existing power stations. They were based on the operators declarations of phasing out large power units connected to transmission power system by 2025, which was included in (PSE SA Polish Transmission System Operator, 2010). For time perspective 2030-2050, power unit qualification for retirement depended on the extent of maintenance and modernization made prior to the year 2010. Retirement of new power plants was modelled endogenously by including technical lifetime parameter for each technology.

Fig. 4. Projections of capacity installed before 2010 and available in 2010-2050

Source: Author's illustration on the basis of (PSE SA Polish Transmission System Operator, 2010)

Table 1 demonstrates data on electricity generation technologies. Technical and economic data for MARKAL database were from (International Energy Agency and Nuclear Energy Agency, 2010; International Energy Agency, 2014; Kannan, R., Strachan, N., Pye, S., Anandarajah, G., Balta-Ozkan, 2007; The Energy Market Agency, 2016). Energy technology investment costs development was projected using the trends from (Capros et al., 2014). Technology-specific discounts rates were assumed on the basis of (García-Gusano et al., 2016; Oxera, 2011)

Table 1. Electricity generation technology data used in Polish MARKAL model.

Note: START – first year technology is available; LIFE – Technological lifetime; AF – Availability factor; EEF – Electrical efficiency; INVCOS – specific investment cost; FIXOM – specific fixed operation and maintenance cost; PEAK – contribution to peak demand; PTHR – Power to heat ratio; DISC – Technology specific discount rate; SC – Supercritical; PCC – Pulverized Coal Combustion; IGCC – Integrated Gasification Combined Cycle; CCS – Carbon Capture and Storage; FBC – Fluidized Bed Combustion; CCGT – Combined Cycle Gas Turbine, LWR – Light Water Reactor; PV – Photovoltaic; CHP – Combined Heat and Power, NA – Not applicable.

Sources: [a] (Kannan, R., Strachan, N., Pye, S., Anandarajah, G., Balta-Ozkan, 2007), [b] (International Energy Agency and Nuclear Energy Agency, 2010), [c] (International Energy Agency, 2014), [d] (Capros et al., 2014), [e] (The Energy Market Agency, 2016), [f] (Oxera, 2011), [g] (García-Gusano et al., 2016)

Fig. 5 illustrates fuel prices including delivery costs, calculated on the basis of (International Energy Agency and Nuclear Energy Agency, 2010) and (Capros et al., 2014; European Commission, 2011b).

Fig. 5. Fuel price projections to 2050

Source: Author's illustration on the basis of (Capros et al., 2014; European Commission, 2011b; International Energy Agency and Nuclear Energy Agency, 2010)

Modelling RES-E support mechanisms in Polish MARKAL was demonstrated in (Jaskólski and Bućko, 2015; Jaskólski, 2012b). Indicative target for Poland to 2020 is 19% of renewable electricity in total final electricity consumption. Planned objectives for the years: 2030, 2040, and 2050 are: 27%, 40%, and 50%, respectively.

3.3. Model cases

Electricity demand projections

Electricity demand projections were calculated on the basis of the dynamics of: gross domestic product (GDP), electricity intensity of GDP, *per capita* electricity consumption, and population. Annual growth of GDP and population growth projections were from (Capros et al., 2014). Two cases were proposed i.e. Efficient (EFF) and Reference (REF). Table 2 presents the projections of final electricity demand and macroeconomic data used for calculations.

Electricity demand dynamics for industry and commercial sector was calculated as follows:

$$\frac{E_t}{E_b} = \frac{EI\_GDP_t}{EI\_GDP_b}\frac{GDP_t}{GDP_b} \quad (3)$$

Where: E_t, E_b were electricity demand in time period *t* and in base year (2010), respectively; EI_GDP_t, EI_GDP_b were electricity intensity of GDP in year *t* and base year, respectively; GDP_t, GDP_b were GDP in year *t* and base year, respectively. For residential, agricultural and transport sector, electricity demand was calculated as follows:

$$\frac{E_t}{E_b} = \frac{EC\_CAP_t}{EC\_CAP_b}\frac{POP_t}{POP_b} \quad (4)$$

where: EC_CAP_t, EC_CAP_b were electricity consumption *per capita* in year *t* and base year, respectively; POP_t, POP_b were population in year *t* and base year, respectively.

Table 2. Projections of final electricity demand and macroeconomic data used for demand calculation

Sources: [a] (Capros et al., 2014); [b] Author's projections on the basis of (Capros et al., 2014; Ministry of Economy of the Republic of Poland, 2015a, 2015b, 2009)

Emission trading schemes

Eight model runs were prepared to analyze the impact of emission reduction mechanisms on power generation technology choice. Each demand projection (Cases: EFF and REF presented in Table 2) was

combined with four cases of emission allowance prices projections (Table 3). Business as usual (BAU) cases are theoretical and assume withdrawal from ETS after 2020. Cases LOW, CEN and HIGH reflect low, baseline (central) and high EUA price, respectively. Aa a result, model cases were named EFF_BAU, REF_BAU, EFF_LOW, etc. In EFF/REF_LOW cases Market Stability Reserve (MSR) was not included (Ministry of Economy of the Republic of Poland, 2015b), whereas in EFF/REF_CEN cases MSR was assumed to be fully operational from 2025 onwards, and in EFF/REF_HIGH – from 2015 planning period, based on the suggestion in (DECC, 2015). EU ETS cap decreases annually by 2.2% in time periods 2020-2030, by 4% in 2030-2040, and by 5% in 2040-2050. In 2050, it is 77% lower, compared to ETS cap in 2005, which was equal to 2.4 Gt CO_2-eq./yr (European Environmental Agency, 2015).

Table 3. Emission trading schemes - projections of allowance prices and emission limits to 2050

Sources: [a](Ministry of Economy of the Republic of Poland, 2015b), [b] Author's calculation on the basis of (DECC, 2015), [c] Author's assumptions on the basis of (Ministry of the Environment of the Republic of Poland, 2011b), [d] Author's calculation on the basis of (European Environmental Agency, 2015), [e] Author's calculation on the basis of (Council of Ministers of the Republic of Poland, 2014; Ministry of the Environment of the Republic of Poland, 2006, 2004), [f] Author's assumption

4. Results and discussion

4.1. Electricity production

Fig. 6 illustrates the structure of electricity production for Poland by 2050. The share of power plants commissioned before 2010 in total electricity production decreases by 2050 to 1-2%, depending on the case, leaving a room for investments in new power units and creating circumstances for long-term transition towards clean electricity mix. Non-CCS base-load coal plants can still play significant role in electricity production in Poland, especially at a low EUA price or in case of ETS discontinuation after 2020. Their

market share in 2050 is 45-47% in EFF/REF_BAU and EFF/REF_LOW cases. High EUA price (EFF/REF_HIGH) results in reduced market penetration of non-CCS brown coal and hard coal technologies, down to 0% from 2045 onwards. They can be perceived as a temporary solution (to 2040) at high EUA price. As the technical lifetime of coal plants is 40-50 years, to construct them in the years 2015-2020 and to cease production in 2045 can lead to their unprofitability. Their construction is necessary in short-term horizon (until 2025) to avoid power deficit, because other technologies either have limited technical potentials (e.g. biomass, wind) or are not available (e.g. nuclear, coal with CCS) in this time period. They should be constructed so as to be ready for retrofit by CCS.

High EUA price combined with the introduction of SO_2/NO_x emission trade and maintaining renewable promotion mechanisms will require to search alternative base-load technologies. New Coal with CCS plants can be competitive, if EUA price is at the highest of considered levels. In cases: REF_HIGH their share is 17% of total electricity production in 2050 and in EFF_HIGH - 10%. Biomass Integrated Gasification Combined Cycle (IGCC) with combined cycle gas turbine (CCGT) is a technology option that can contribute to meeting both emission reduction goals and renewable share targets. The highest level of installed capacity in biomass power plants is 7.9 GW (REF_HIGH case in 2050) and highest biomass fuel consumption is 359 PJ/yr, which is 23% of estimated biomass potential, amounting to 1596 PJ/yr (IRENA, 2015). In 2050, the share of Biomass IGCC in total electricity production is 22-24% in all REF cases and 12-13% in all EFF cases and slightly depends on EUA price pathway. Ambitious renewable electricity indicative target i.e. 50% in 2050 is the driving force of biomass plants construction. This technology contributes also to emission reduction goals, because biomass combustion or gasification is considered to be carbon neutral.

Nuclear power plants (NPP) with Light Water Reactors (LWR), considered to be built in Poland, are justified only at baseline and high EUA prices, projected in this analysis. NPP share in electricity production in 2050 is from 25% in REF_CEN to 44% in EFF_HIGH, but the highest production level is in REF_HIGH, i.e. 99 TWh/yr (2045-50). To achieve this level, total capacity additions of 13.6 GW and investment expenditures of approximately $58 \cdot 10^9$ EUR'10, between 2030 and 2050, are required.

Due to projected high price of fuel, natural-gas-based technologies do not have significant share in long-term electricity generation plan and their role as base-load plants is limited. Contribution of natural gas CCGT technologies (including those with CCS) to total electricity production is maximum 6% (REF_HIGH case in 2025). Market penetration of natural gas cogeneration is maximum 1%. Investments in these types of power plants and CHP plants are in progress (The Energy Market Agency, 2016). Natural-gas-based microgeneration can be a solution of the problem of power imbalance, if power rationing levels are introduced again in Poland, as in the Summer of 2015 (Bućko et al., 2016). MARKAL proposed to install natural gas microturbines already in 2015 planning period, indicating that commissioning of large power units, postponed for 2020 and subsequent years (The Energy Market Agency, 2016), will require microgeneration contribution to avoid supply-demand gap. Large gas turbine units can play the role of back-up plants in Polish power system in view of expected increasing share of wind power. Installation of the total installed capacity of 2.5 GW in natural gas peak plants was suggested in REF_HIGH case in considered planning horizon (2010-2050).

Wind power contribution to electricity production in 2050 in EFF cases is 31-33% (of which wind offshore is 5-7%) and in REF cases - 21-22% (of which wind offshore is 8-9%). Annual electricity production in this technology is comparable for all EUA price pathways. Similarly to biomass technologies, investment in wind turbines is due to renewable electricity indicative targets. Total installed capacity in 2050 in onshore wind farms was limited to 16.2 GW, and in offshore wind farms - to 8.0 GW. These constraints result from grid connection capabilities, taking into account network expansion planned by Transmission System Operator PSE SA (PSE SA Polish Transmission System Operator, 2010).

Fig. 6. Annual electricity production for Poland to 2050 by technology type. Note: HC – Hard Coal; BC – Brown Coal; NG –Natural Gas; FC – Fuel Cell; BIOM – Biomass; REN – Renewable; DG – Distributed generation; MT – microturbine, other abbreviations as in Table 1

Source: Author's illustration on the basis of MARKAL model calculations

4.2. Emissions from power generation technologies

Fig. 7 presents emissions of CO_2 from technologies generating electricity (including both ETS and non-ETS participants). Withdrawal from EU ETS after 2020 results in the increase of CO_2 emissions from electricity generating plants in REF_BAU by 5% in 2010-2050 horizon, while in EFF_BAU they are reduced by 41% in the same time frames. Within ETS participants from electricity sector, CO_2 emission reduction is 17% in REF_BAU and 47% in EFF_BAU. Stabilization of electricity demand in long-term perspective, as in EFF cases, contributes significantly to reduction of CO_2 emissions. Low EUA market price results in the reduction of CO_2 emissions form ETS-participating electricity generating plants by 29% in REF_LOW and by 55% in EFF_LOW between 2010 and 2050. Similar emission reduction levels are in BAU cases, which indicates that at low EUA price the system is insufficiently effective to meet ambitious emission reduction targets adopted by EU. Baseline and high EUA prices (CEN and HIGH cases), supported by fully operational Market Stability Reserve, lead to the reduction, in 2010-2050 period, of CO_2 emissions from ETS-participating electricity generating plants, amounting to 79% in REF_CEN, 81% in EFF_CEN, and up to 96% in REF_HIGH and 99% in EFF_HIGH. In these cases, electricity sector sufficiently contributes to meeting EU-adopted emission reduction targets for 2050.

One of the consequences of decarbonization of electricity production is the capture and the storage of CO_2. In REF_HIGH case the amount of captured CO_2 is 38 Mt/yr in 2050. Cumulative CO_2 storage potential is estimated at 9620 Mt (Wójcicki, 2009) and is sufficient for 250 years of plants operation, if annual emissions are stabilized at the abovementioned level.

Fig. 7. Emissions of CO_2 from electricity generating plants. Note: CHP plants (ETS) category includes emissions from industrial autoproducing CHP plants participating in EU ETS

Source: Author's illustration on the basis of MARKAL model calculations

Fig. 8. SO_2 emissions from electricity generating plants

Source: Author's illustration on the basis of MARKAL model calculations

Fig. 9. NO_X emissions from electricity generating plants

Source: Author's illustration on the basis of MARKAL model calculations

Fig. 8 and Fig. 9 illustrate emissions of SO_2 and NO_x, respectively, from electricity generators, both LCP and non-LCP. The reduction of SO_2 emissions between 2010 and 2050 from LCP electricity producers in baseline cases is 89% in EFF_BAU and 83% in REF_BAU, while in cases with SO_2/NOx emission trade in place and at low EUA price it is 89% in EFF_LOW and 85% in REF_LOW. Reduction of SO_2 emissions from LCP generating electricity is 98% in EFF_HIGH and 94% in REF_HIGH. These results reveal low effectiveness of SO_2 trading scheme. Reduction of NO_X emissions from LCP generating electricity between 2010 and 2050, in baseline cases (SO_2/NO_X ETS not implemented) is 77% (EFF_BAU) and 63% (REF_BAU), while at low EUA price and SO_2/NO_X in place it is 80% (EFF_LOW) and 69% (REF_LOW). At high EUA price this reduction is 95% (EFF_HIGH) and 87% (REF_HIGH). Similarly to SO_2 trade, these outcomes prove low effectiveness of NO_X allowance trade, specifically at efficient electricity use cases (EFF). EU ETS can also contribute to SO_2 and NO_x reduction, especially if EUA prices are at the highest projected level. Even if Poland decides to continue to build new coal power stations (as e.g. in REF_BAU and EFF_BAU), they will be equipped with wet Flue Gas Desulfurization (FGD) and denitrification systems, which results from IED requirements and can be sufficient to achieve SO_2 and NO_x emission reduction goals.

4.3. Economic factors

To assess the long-term costs of both emission trading schemes, and technology choices resulting from their implementation, objective function values, i.e. total system costs discounted to the year 2010, were compared. For each case with ETS in place (e.g. EFF_HIGH), the cost of emission reduction mechanisms, discounted over the entire model horizon (2010-2050), was calculated as a difference between the objective function value in this case and in corresponding BAU case (e.g. EFF_BAU). The discounted cost of emission trading schemes is $13.9 \cdot 10^9$ EUR'10 in EFF_LOW and $16.2 \cdot 10^9$ EUR'10 in REF_LOW. In EFF_CEN and REF_CEN the cost is 36% and 43% greater than in EFF_LOW and REF_LOW, respectively, while in EFF_HIGH and REF_HIGH it is 2.7 and 2.6 times greater than in EFF_CEN and REF_CEN, respectively.

MARKAL model calculates shadow price i.e. the change in objective function value – total cost of the energy system – when the production of electricity increases by one unit (marginal cost of electricity). The prices are equal to 55.6 EUR'10/MWh in 2010 for all time subdivisions. As presented in Fig. 10, the cost of daytime electricity production increases to 2050 in all cases, but its level is dependent on the prices of emission allowances. Even in BAU cases, daytime electricity production cost increases between 2010 and 2050 from two to five times, depending on the season. High EUA price path (REF_HIGH/EFF_HIGH) leads to a four- to sevenfold increase in daytime electricity generation cost.

Fig. 10. Shadow prices of electricity in 2050 for MARKAL year subdivisions (I – Intermediate, S – Summer, W – Winter, D –Day, N - Night)

Source: Author's illustration on the basis of MARKAL model calculations

5. Conclusions and policy implications

ETS will be the driving force of technological transition in electricity production within European Union. In Poland, aged base-load coal plants, commissioned before 2010 - merely in 1970s and 1980s, will have to be replaced by 2050 by base-load options that are: carbon free e.g. nuclear power, carbon neutral e.g. biomass

gasification, or low-carbon e.g. CCS-equipped coal technologies. New non-CCS coal plants, planned in Poland in short-term and medium-term perspective, will not be competitive on the electricity market in long-term horizon (2045-50), if decarbonization policy is continued and EUA prices are at the highest projected level. In such case, CCS retrofit should be considered individually for each of these plants. From the point of view of limited market penetration of coal power, and in the light of expected increase in electricity demand, the decision to continue governmental program to build nuclear power plants is justified. Nuclear power will have the most significant contribution to the reduction of CO_2, NO_X and SO_2 emissions, if EUA prices are at baseline and high levels and specific investment cost of NPP is as projected in this study (i.e. 4212 EUR'10/kW in 2030 – the first year this technology is available - and decreasing over time to 3949 EUR'10/kW in 2050). Biomass IGCC (BIGCC) technologies, including BIGCC CCS associated with negative CO_2 emissions, can be another key base-load technology options to replace coal units. To meet this objective, sufficient fuel supplies should be available for planned power plants. Negative CO_2 emissions from biomass CCS technologies are not rewarded within EU ETS (Zakkour et al., 2014). BIGCC CCS technology can be competitive on electricity market, against BIGCC without CCS, if this policy changes and revenues from trading EUA granted to these plants at least cover additional costs of capital, operation and maintenance, and fuel. Intermittent renewable sources of energy, e.g. wind and solar photovoltaic, will have limited share in power production structure, if current power system configuration persists. In these circumstances, base-load plants will continue to play significant role in meeting electricity demand. Construction of back-up power plants based on natural gas will be necessary to assure production-demand balance, especially in view of the increased share of wind power in electricity production. Electrical energy storage technologies should be of the highest priority in Research and Development programs in both Poland and Europe, since renewable energy sources contribute to achieve both renewable energy indicative targets and emission reduction goals. Decarbonization of electricity production to 2050 in Poland is possible, when emission allowance prices are kept at the highest level projected in this study. Introduction of Market Stability Reserve to EU ETS combined

with further decreasing of EU ETS cap will play key role in stimulating EUA price and in achieving European Union CO_2 emission reduction objectives to 2050.

Model calculations revealed that country-specific SO_2/NO_X ETS has low effect on SO_2 and NO_x emissions from LCP generating electricity, especially if EU ETS is in place. Therefore it is recommended to reconsider implementation of this system. EU ETS (for CO_2) combined with the standards resulting from Industrial Emission Directive implementation are expected to be sufficient to reduce emissions of these pollutants. Implementation of SO_2/NO_X ETS will generate additional costs of electricity production, transferred to the price of electricity to final consumers.

Polish MARKAL will be developed towards microgeneration, hybrid systems and storage technologies as an alternative for large technology options proposed by the model in this study. In further perspective, inclusion in the model of more detailed representation of heat production and other industry sectors is envisaged. It is also desired to assess the feasibility of power plant investments proposed by MARKAL from the point of view of power grid limits and detailed power system technical-economic characteristics. Because the projections of: energy carrier prices, emission allowance prices and specific investment costs of key technologies are uncertain in considered time horizon, uncertainties will be included in the following model studies. Detailed studies of modern technologies will require to use endogenous technology learning curves in energy system model.

Acknowledgments

This paper is a result of my own project financed by the statutory research fund of the Faculty of Electrical and Control Engineering, Gdańsk University of Technology. I would like to greatly appreciate the time and effort of two anonymous reviewers. Special thanks to Włodek J. Kulesza from Blekinge Institute of Technology (BTH) and to Paweł Bućko from Gdańsk University of Technology for their expertise concerning paper preparation.

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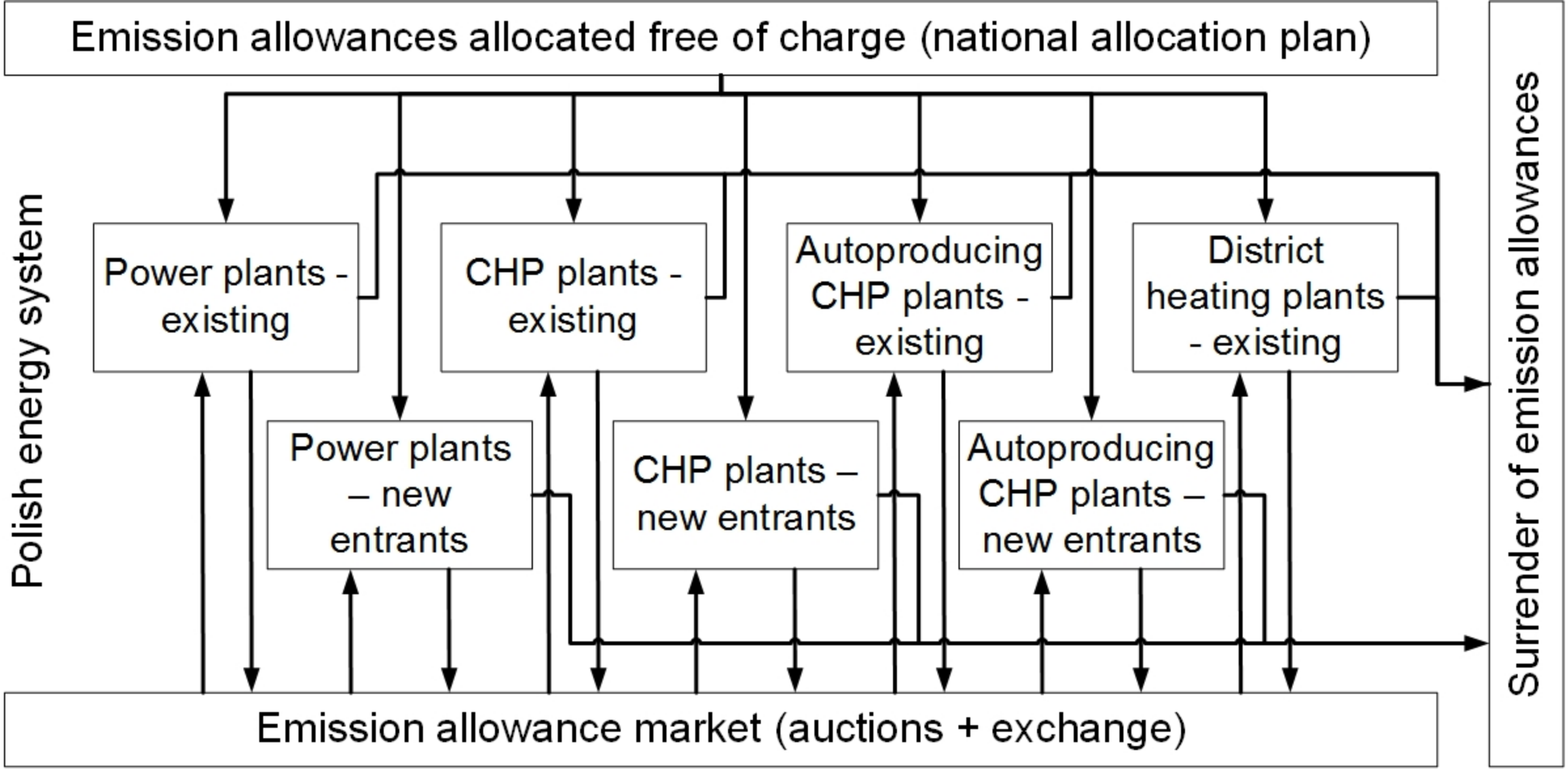
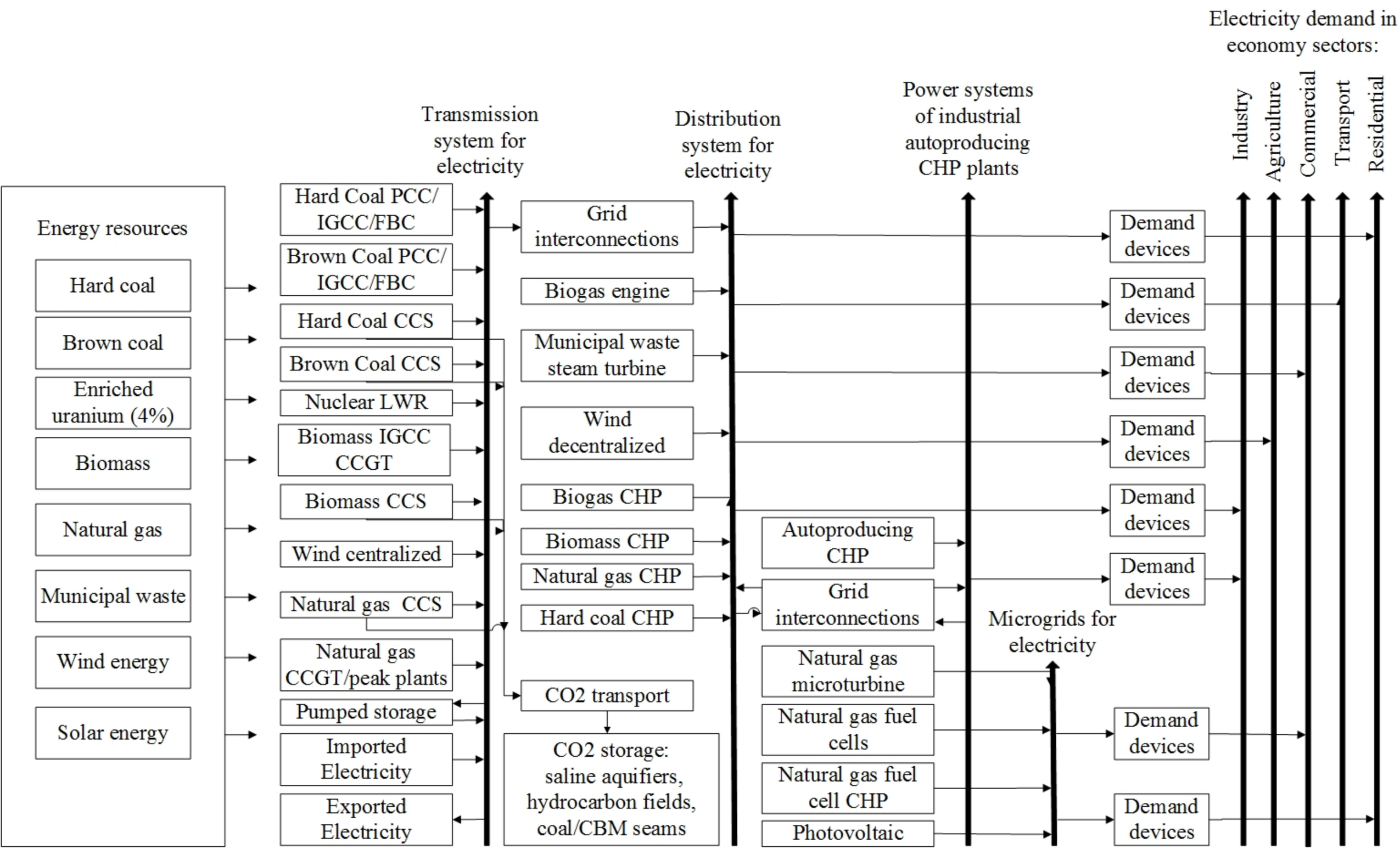

Emission allowances allocated free of charge (national allocation plan)
Polish energy system
Power plants - existing
CHP plants - existing
Autoproducing CHP plants - existing
District heating plants - existing
Power plants – new entrants
CHP plants – new entrants
Autoproducing CHP plants – new entrants
Emission allowance market (auctions + exchange)
Surrender of emission allowances


Electricity demand in economy sectors:
Industry
Agriculture
Commercial
Transport
Residential
Transmission system for electricity
Distribution system for electricity
Power systems of industrial autoproducing CHP plants
Energy resources
Hard coal
Brown coal
Enriched uranium (4%)
Biomass
Natural gas
Municipal waste
Wind energy
Solar energy
Hard Coal PCC/ IGCC/FBC
Brown Coal PCC/ IGCC/FBC
Hard Coal CCS
Brown Coal CCS
Nuclear LWR
Biomass IGCC CCGT
Biomass CCS
Wind centralized
Natural gas CCS
Natural gas CCGT/peak plants
Pumped storage
Imported Electricity
Exported Electricity
Grid interconnections
Biogas engine
Municipal waste steam turbine
Wind decentralized
Biogas CHP
Biomass CHP
Natural gas CHP
Hard coal CHP
CO2 transport
CO2 storage: saline aquifiers, hydrocarbon fields, coal/CBM seams
Autoproducing CHP
Grid interconnections
Natural gas microturbine
Natural gas fuel cells
Natural gas fuel cell CHP
Photovoltaic
Microgrids for electricity
Demand devices
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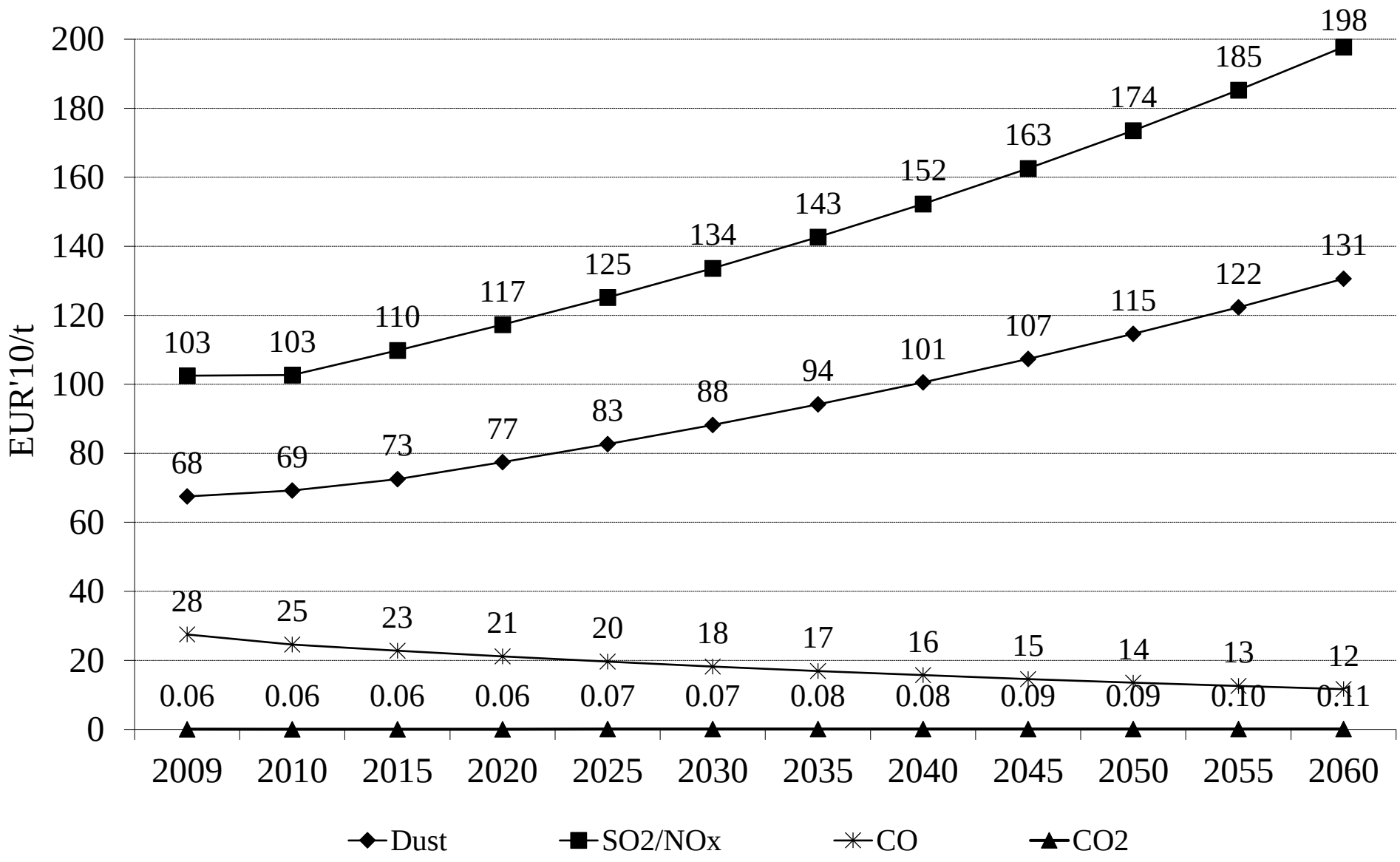

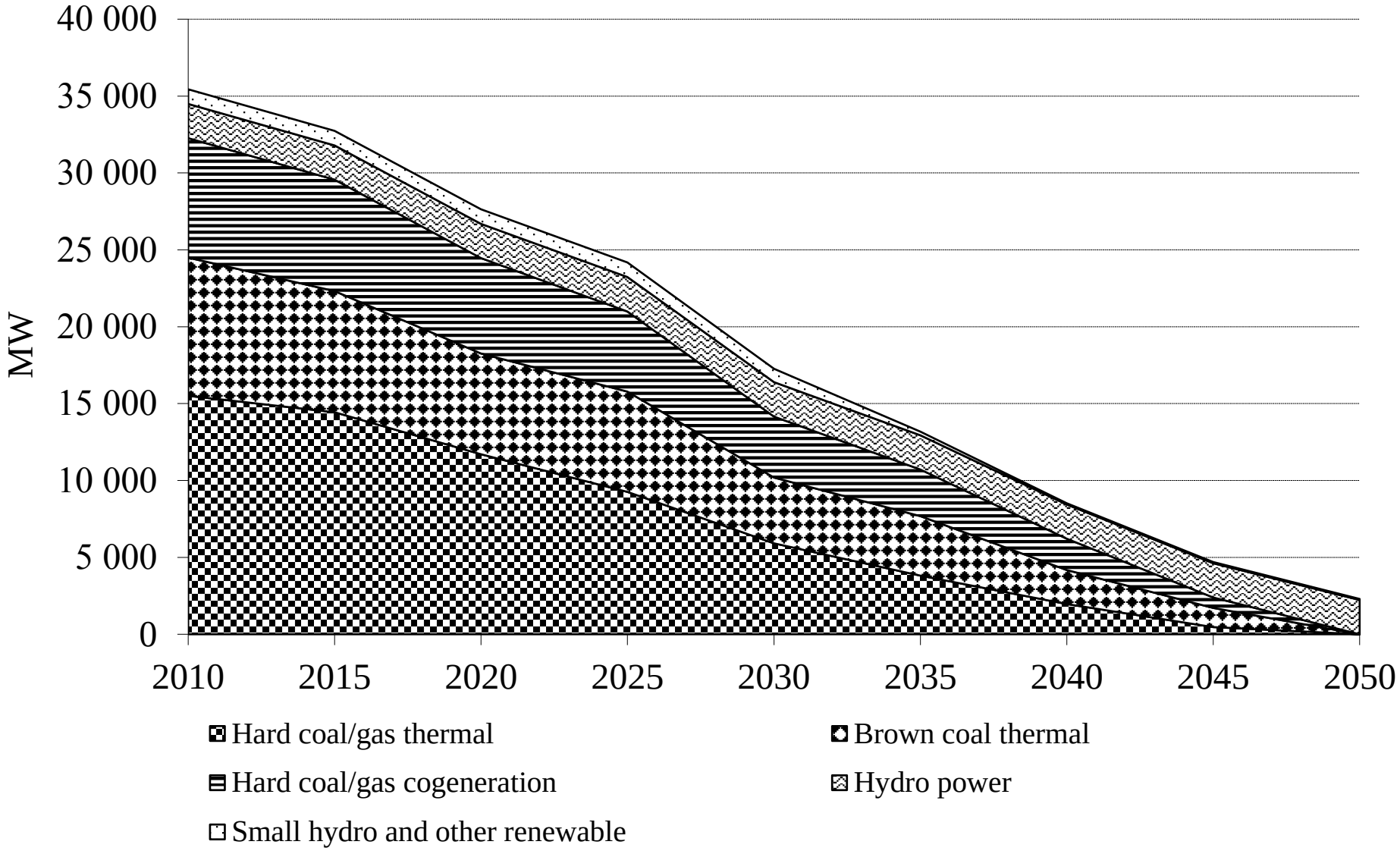

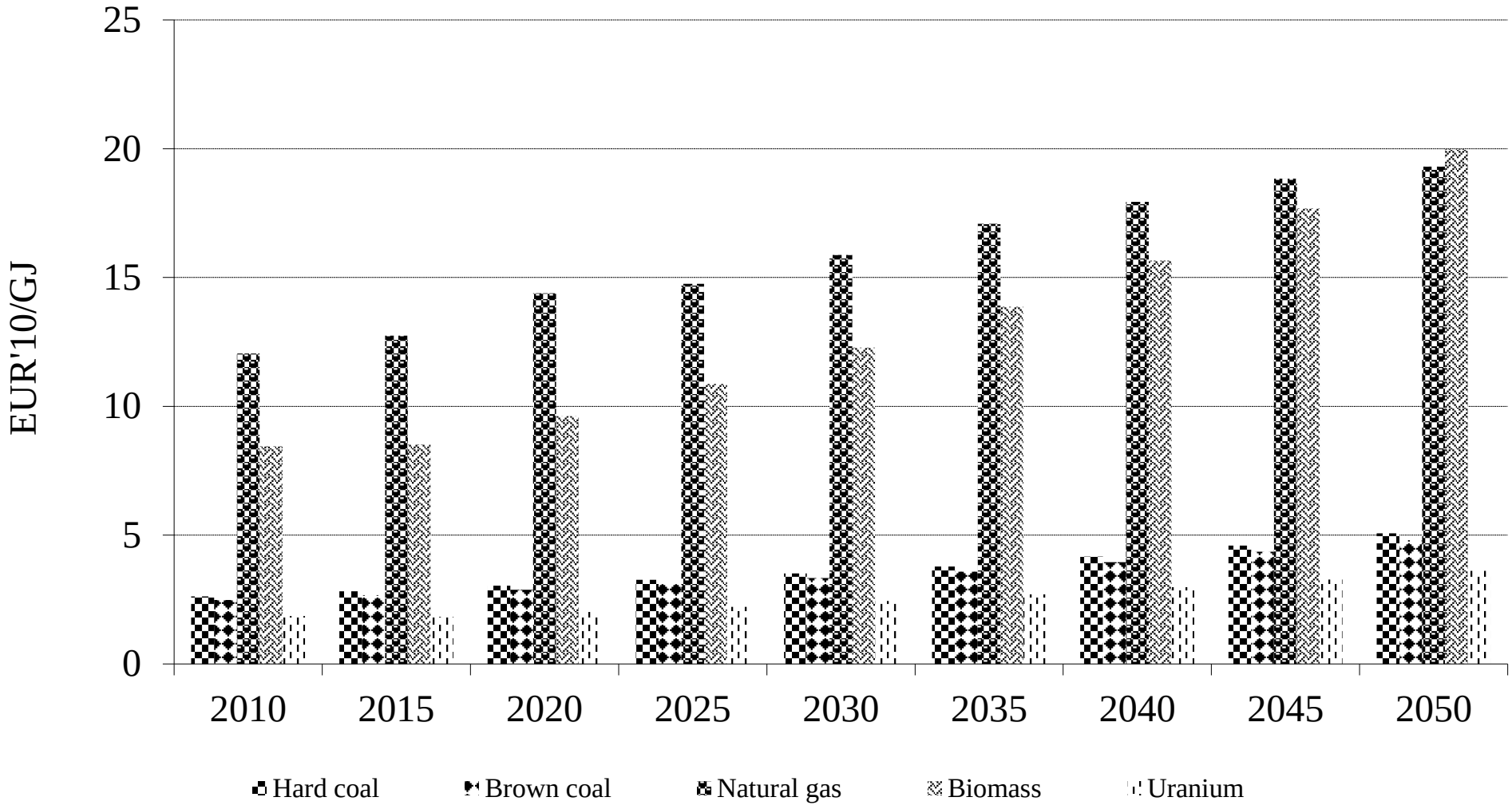

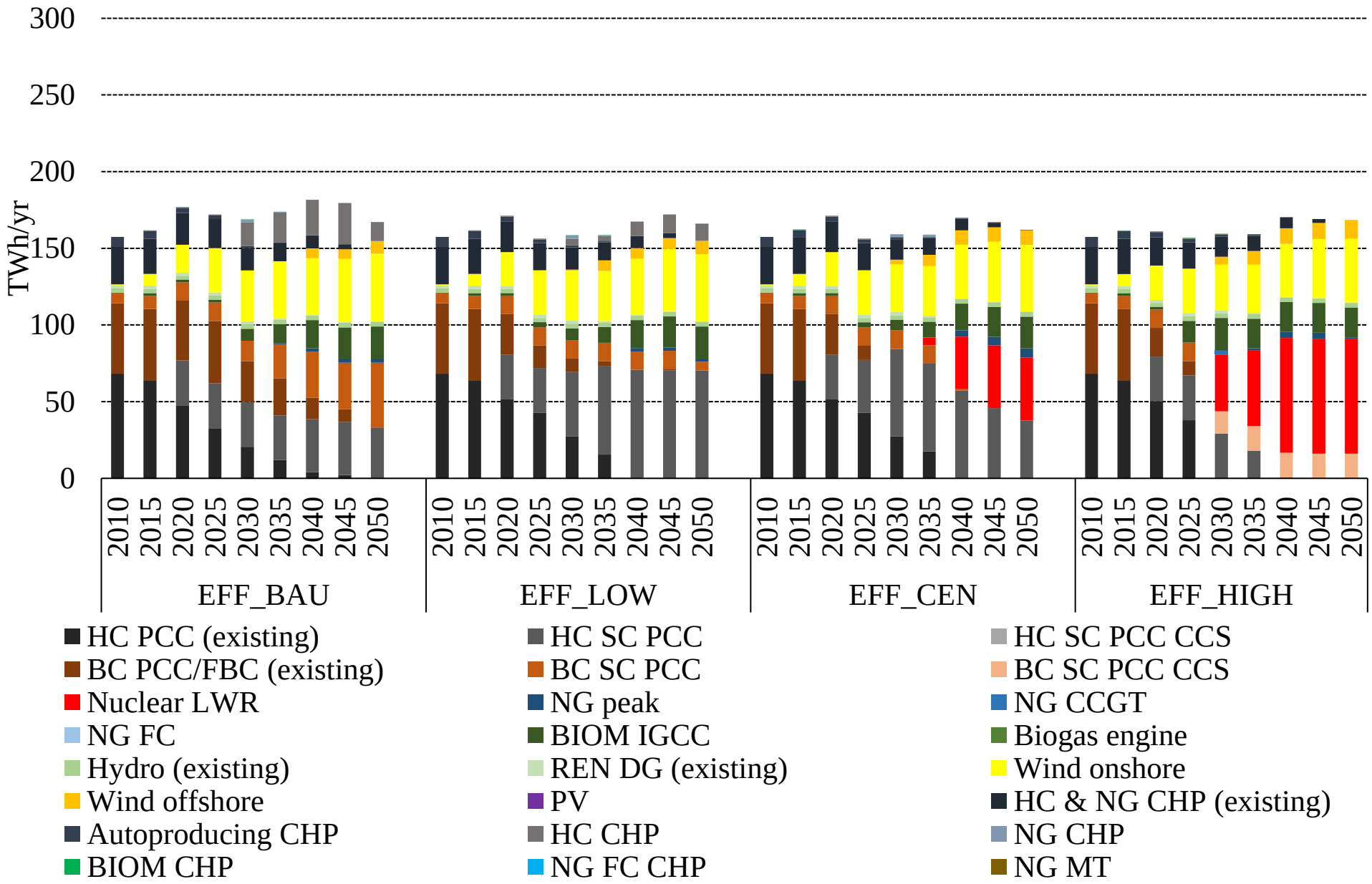

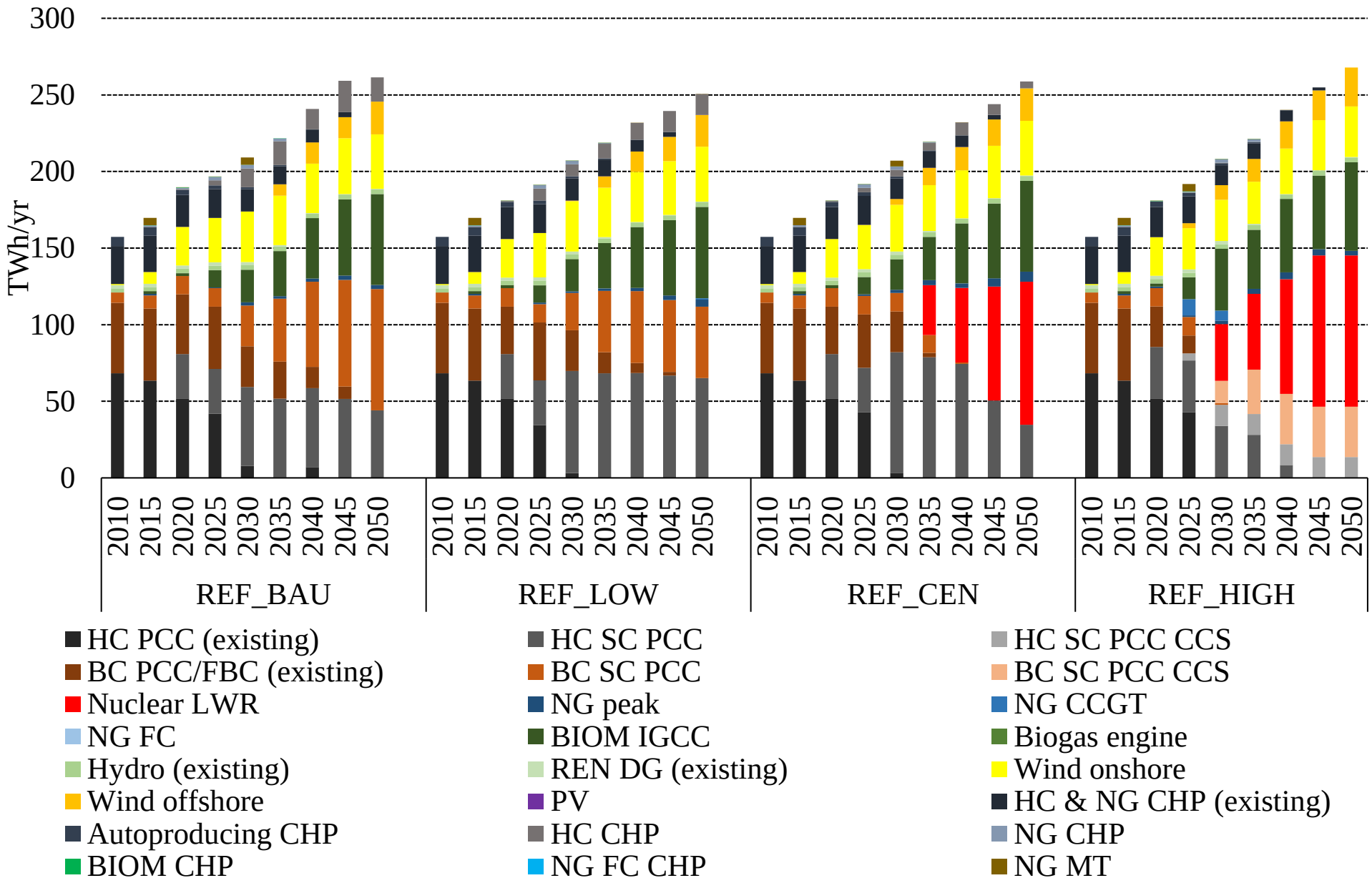

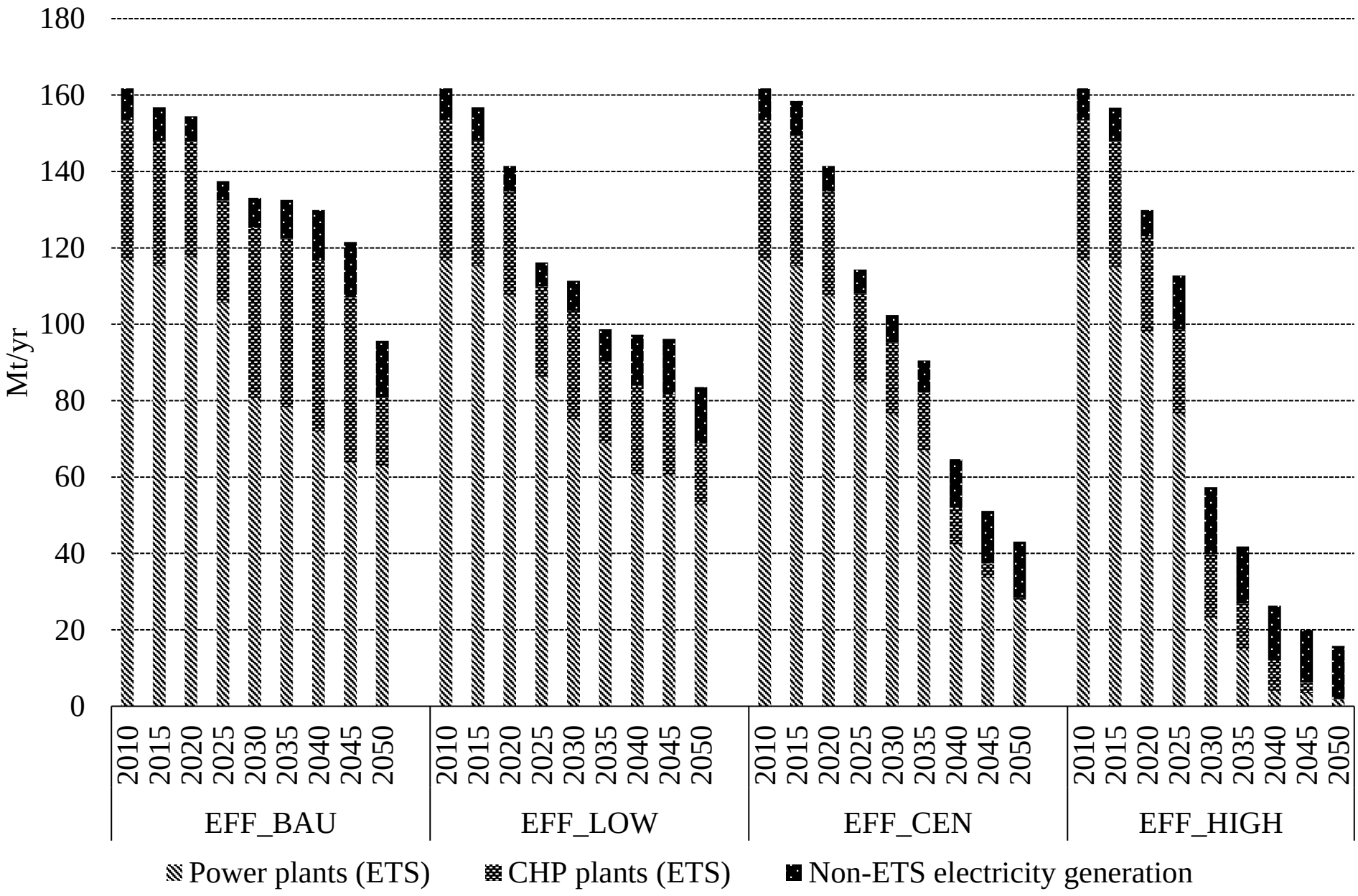

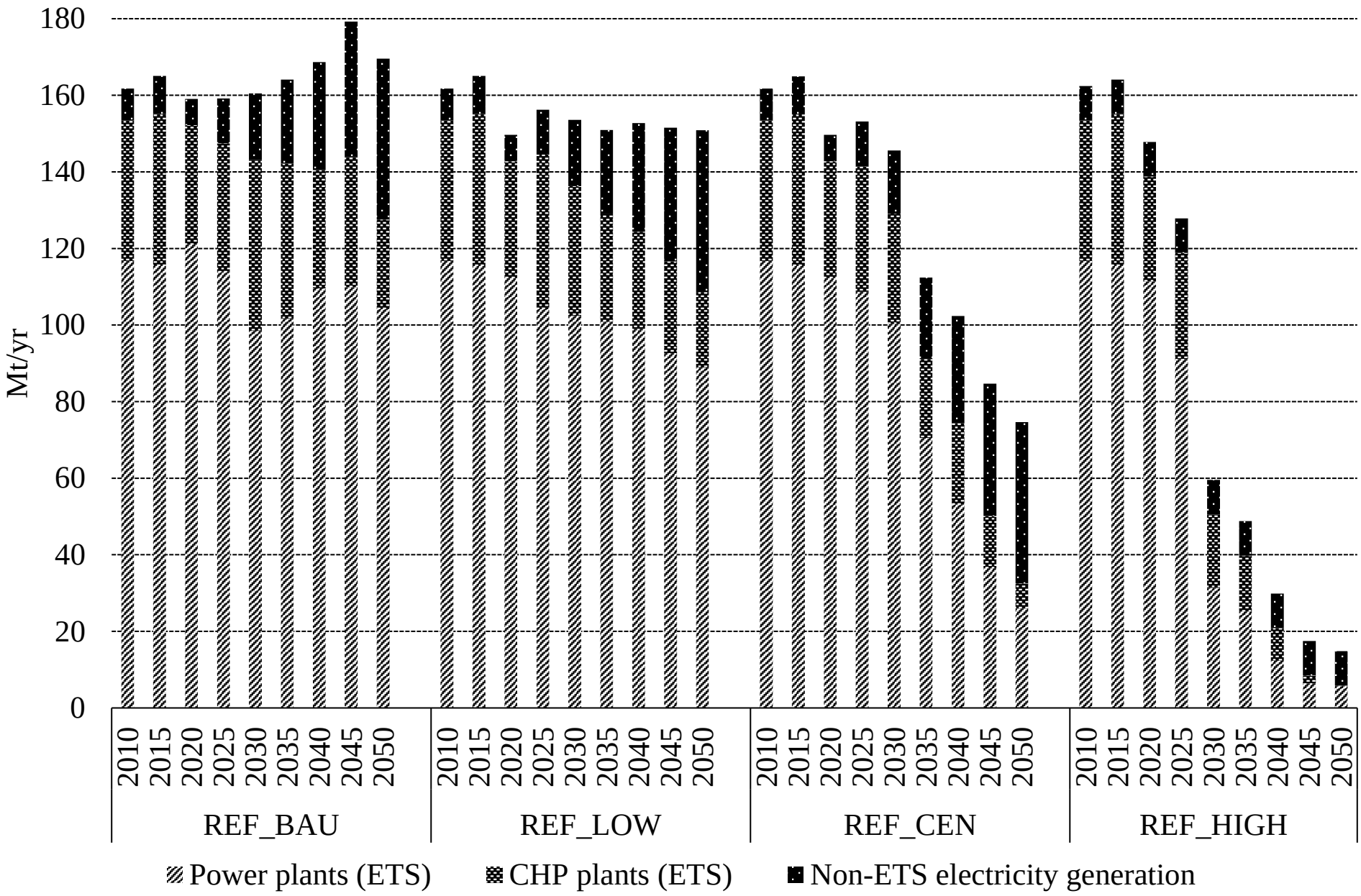

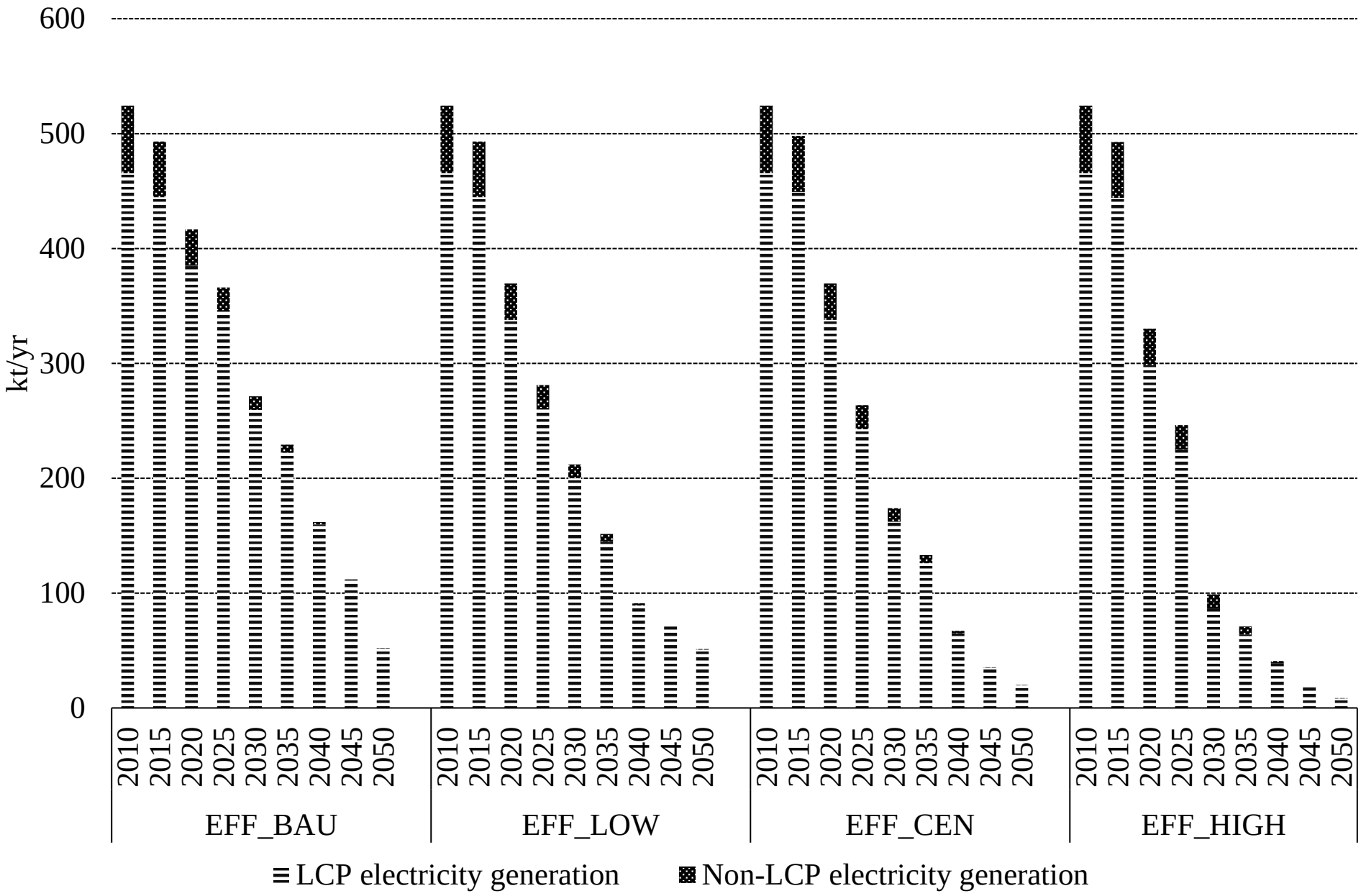

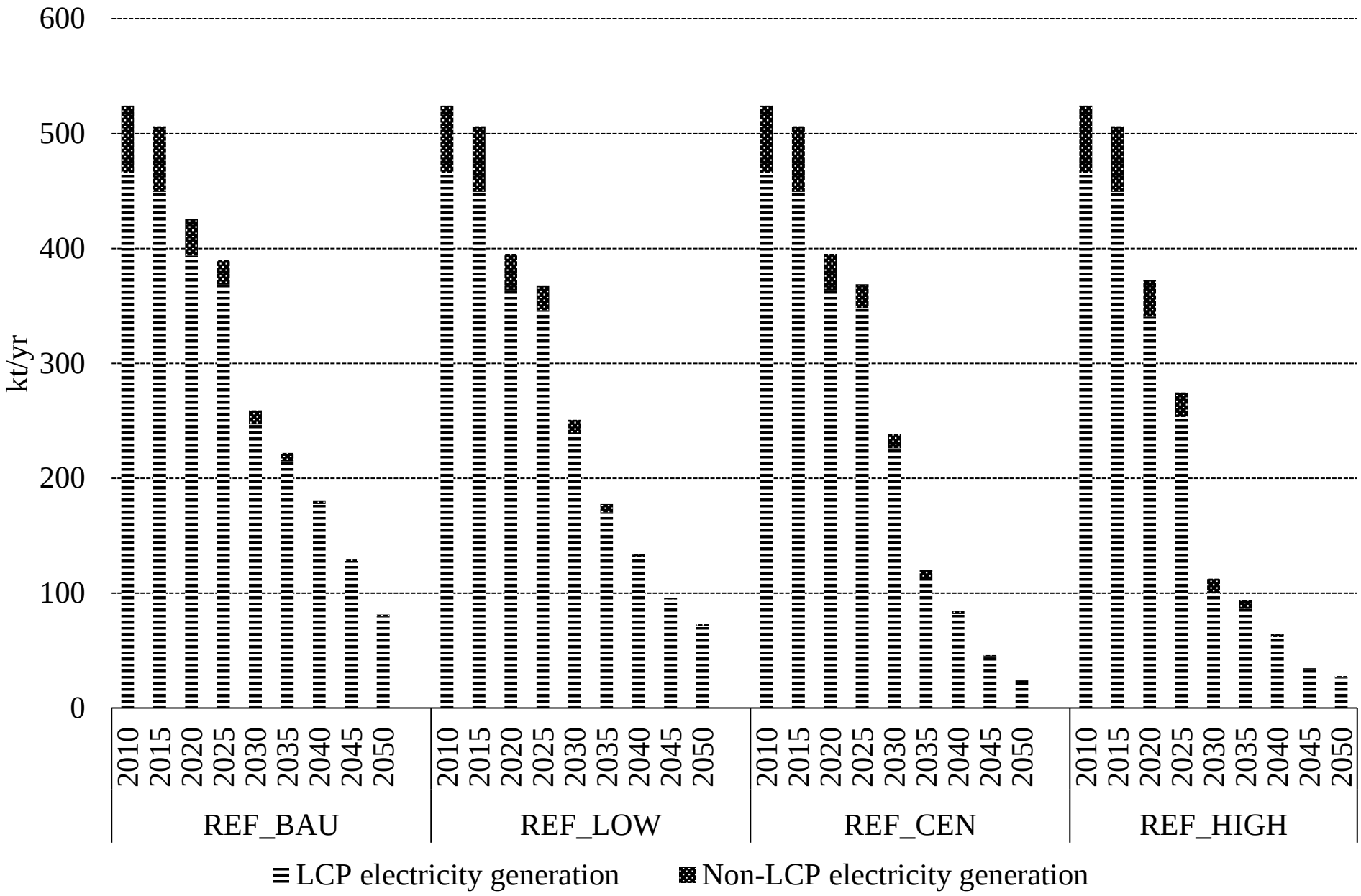

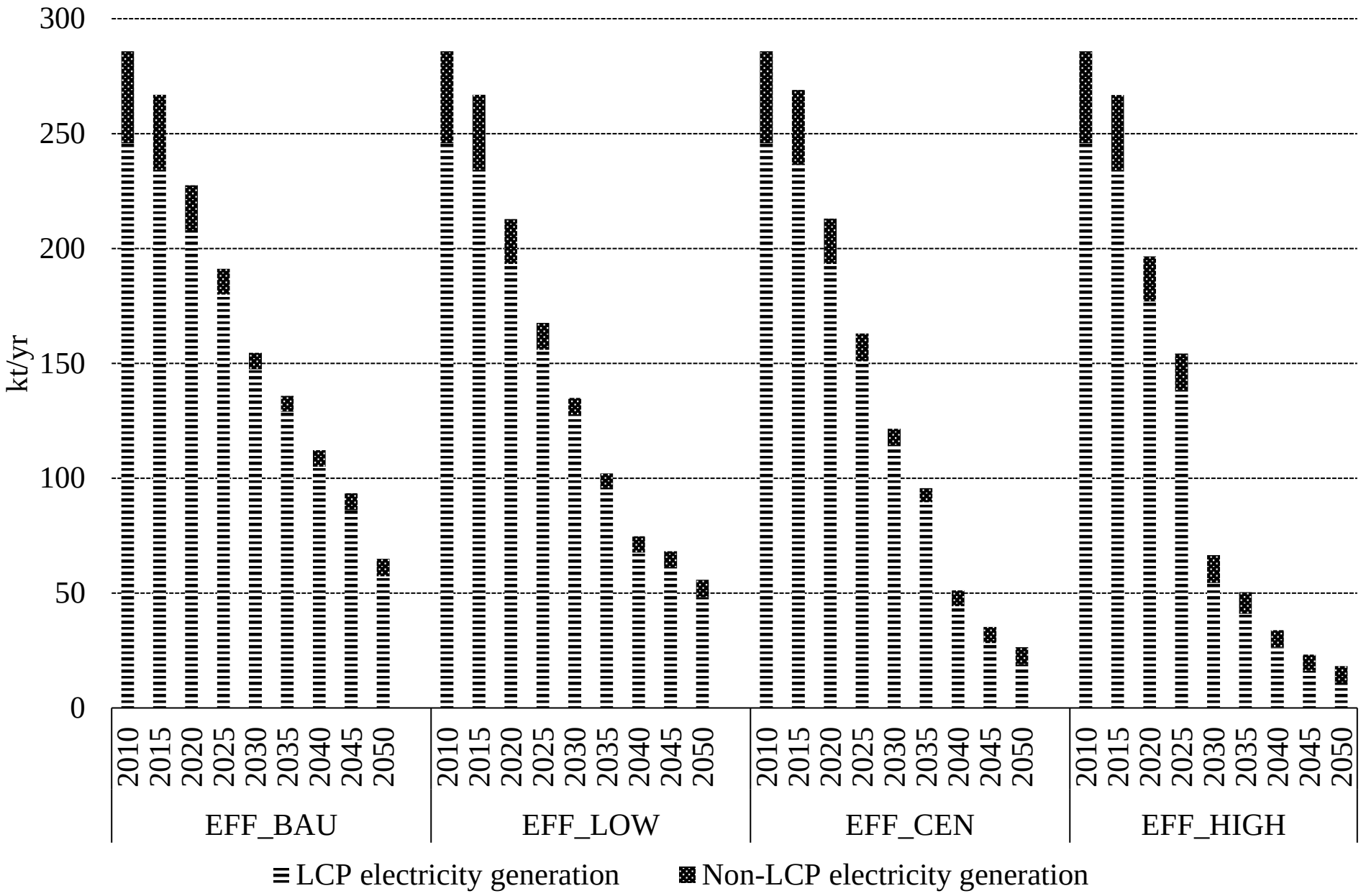

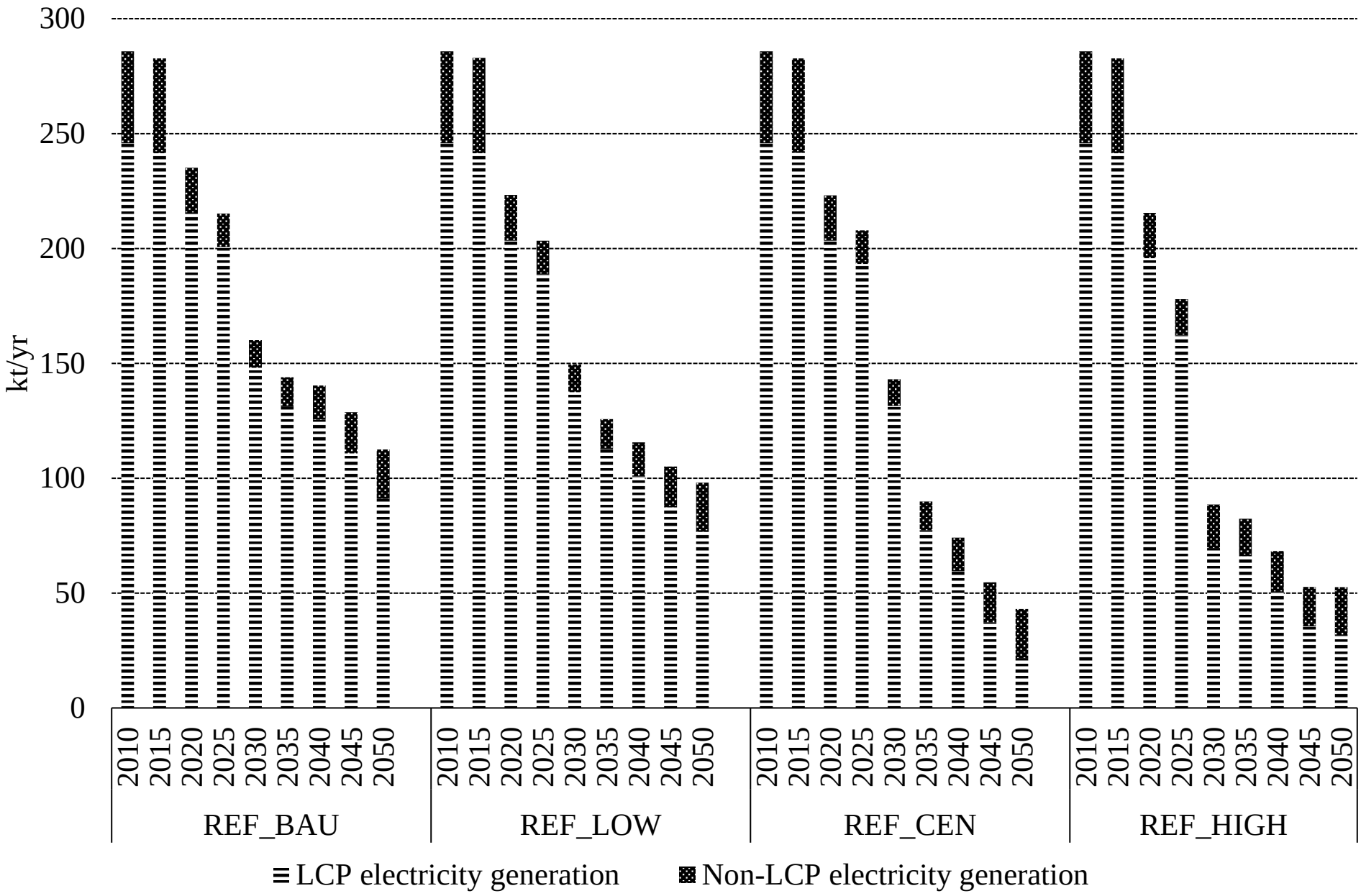

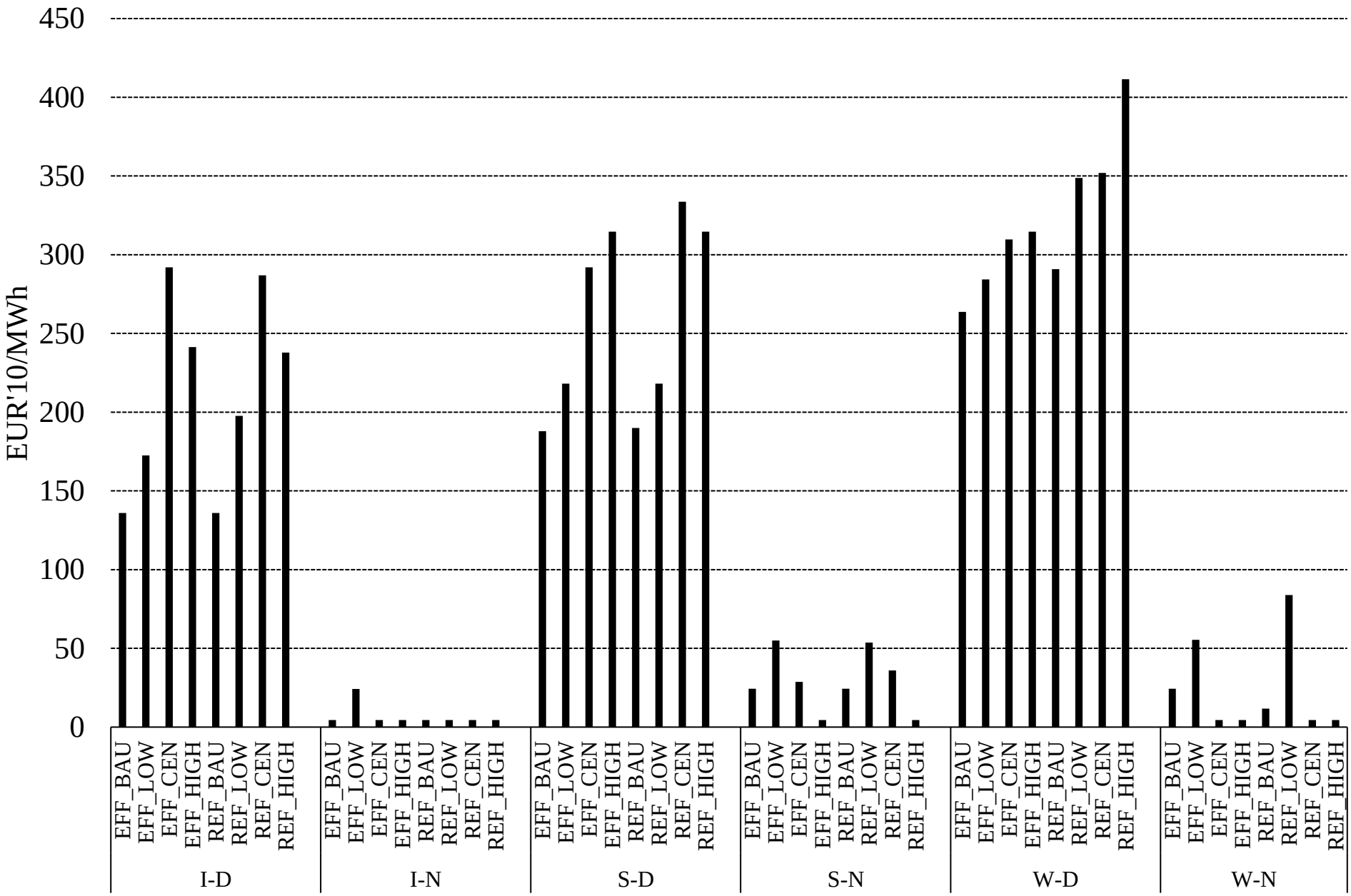

Technology name	START[a]	LIFE[a]	AF[a]	HR[a,b]	EEF[a,b]	INVCOS[a,c,d]		FIXOM[a,b,c]	PEAK[a]	PTHR[a]	DISC[f,g]
				kJ/		EUR'10/kW		EUR'10/			
	-	yrs	%	kWh	%	2010	2050	/kW/yr	-	-	-
Hard coal SC PCC	2015	50	90%	8 372	43%	1589[e]	1589	46.8	0.90	NA	0.10
Brown coal SC PCC	2010	50	90%	8 372	43%	2221[e]	2221	46.8	0.90	NA	0.10
Hard coal IGCC CCS	2025	35	90%	9 474	38%	3780	2681	99.1	0.90	NA	0.17
Hard coal SC PCC CCS	2025	50	90%	10 286	35%	3600	2553	84.2	0.90	NA	0.17
Brown coal SC PCC CCS	2025	50	90%	9 474	38%	3291	2857	84.2	0.90	NA	0.17
Brown coal SC FBC CCS	2025	50	90%	9 730	37%	5687	4937	84.2	0.90	NA	0.17
Brown coal IGCC CCS	2025	35	90%	8 372	43%	5867	5093	99.1	0.90	NA	0.17
Nuclear LWR	2030	60	83%	10 909	33%	4500	3949	117.0	0.90	NA	0.13
Wind onshore	2010	25	20-25%	3 600	100%	1300	1150	33.5	0.23	NA	0.10
Wind offshore	2020	25	25-45%	3 600	100%	4500	2829	90.5	0.43	NA	0.14
Solar PV	2015	30	0-15%	3 600	100%	2000	788	17.9	0.00	NA	0.09
Biomass IGCC	2015	20	83%	8 182	44%	3240	2598	62.4	0.90	NA	0.13
Biomass CCGT IGCC	2020	35	83%	6 207	58%	3240	3118	26.5	0.90	NA	0.13
Biomass CCGT IGCC CCS	2030	35	83%	10 588	34%	3888	2598	35.1	0.90	NA	0.13
Biomass IGCC CCS	2025	20	83%	11 250	32%	3240	2598	99.1	0.90	NA	0.13
Biogas engine	2015	20	57%	12 000	30%	2340	2340	85.0	0.90	NA	0.10
Municipal waste CCGT	2015	30	65%	7 200	50%	6630	4630	241.8	1.00	NA	0.10
Natural gas turbine peak plants	2015	35	peak	9 000	40%	390	390	15.6	1.00	NA	0.09
Natural gas CCGT	2015	35	83%	6 545	55%	898	778	19.5	0.90	NA	0.09
Natural gas CCGT CCS	2025	35	83%	6 792	53%	2200	1811	35.1	0.90	NA	0.17
Natural gas fuel cells	2020	25	50%	9 000	40%	4680	1950	87.4	0.90	NA	0.15
Hard coal CHP	2015	20	44%	15 750	23%	2317[e]	2317	33.5	0.50	0.40	0.10
Natural gas CHP	2015	20	67%	13 333	27%	1014[e]	1014	30.4	0.50	0.51	0.09
Biomass CHP	2015	20	55%	16 579	22%	3151	2894	118.6	0.50	0.40	0.13
Biogas CHP	2015	20	46%	10 286	35%	7742	6255	88.9	0.50	0.90	0.10
Natural gas fuel cell CHP	2020	20	90%	7 347	49%	4000	3728	87.4	0.90	2.46	0.15
Natural gas microturbine CHP	2015	20	70%	10 909	33%	4000	3118	19.5	0.50	0.70	0.09

Note: START – first year technology is available; LIFE – Technological lifetime; AF – Availability factor; EEF – Electrical efficiency; INVCOS – specific investment cost; FIXOM – specific fixed operation and maintenance cost; HR – heat rate; PEAK – contribution to peak demand; PTHR – Power to heat ratio; DISC – Technology specific discount rate; SC – Supercritical; PCC – Pulverized Coal Combustion; IGCC – Integrated Gasification Combined Cycle; CCS – Carbon Capture and Storage; FBC – Fluidized Bed Combustion; CCGT – Combined Cycle Gas Turbine, LWR – Light Water Reactor; PV – Photovoltaic; CHP – Combined Heat and Power, NA – Not applicable.

Sources: [a] (Kannan, R., Strachan, N., Pye, S., Anandarajah, G., Balta-Ozkan, 2007), [b] (International Energy Agency and Nuclear Energy Agency, 2010), [c] (International Energy Agency, 2014), [d] (Capros et al., 2014), [e] (The Energy Market Agency, 2016), [f] (Oxera, 2011), [g] (García-Gusano et al., 2016)

Parameter	Case	2010	2015	2020	2025	2030	2035	2040	2045	2050
Final electricity demand, TWh/yr	REF	144	158	174	184	199	209	222	229	238
	EFF	144	150	156	151	154	154	162	158	152
Annual GDP growth[a]	REF/EFF	0.0%	3.0%	3.0%	1.7%	1.7%	1.4%	1.4%	0.8%	0.8%
GDP dynamics in relation to 2010[a]	REF/EFF	1.00	1.16	1.34	1.46	1.59	1.71	1.83	1.90	1.98
Population dynamics in relation to 2010[a]	REF/EFF	1.00	1.01	1.01	1.00	0.98	0.97	0.95	0.93	0.91
Dynamics of electricity intensity of GDP in relation to 2010[b]	REF	1.00	0.95	0.90	0.85	0.83	0.80	0.78	0.76	0.75
	EFF	1.00	0.90	0.80	0.70	0.65	0.60	0.60	0.55	0.50
Dynamics of *per capita* electricity consumption in relation to 2010[b]	REF	1.00	1.10	1.20	1.40	1.60	1.80	2.00	2.20	2.40
	EFF	1.00	1.05	1.10	1.15	1.20	1.25	1.30	1.35	1.40

Sources: [a] (Capros et al., 2014); [b] Author's projections on the basis of (Capros et al., 2014; Ministry of Economy of the Republic of Poland, 2015a, 2015b, 2009)