Alternative scenarios investigation of 1990..2016 CO₂ emission from Public Electricity and Heat Production sectors in Europe

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Abstract. Proposed alternatives scenarios methodology allows retrospective analysing of decarbonisation processes in 26 national Public Electricity and Heat Production (PEHP) sectors in EU, based on 1990..2016 national CO₂ emission inventories. The CO₂ emission driving forces for PEHP sectors were defined and investigated in 26 years emission pathways approach. Graphical overview of 108 prepared (real and alternatives) emission pathways allow assessing CO₂ emission factors impact, pathways grouping and indicating the dominant pathway of 1990..2016 decarbonisation in EU national PEHP sectors. The alternatives scenarios methodology based on historical data enables to draw lessons from past to move the European PEHP into a low-carbon future.

1 Introduction and scope

The European Union (EU) Member States, bound by the Climate Package policy, meet the national targets to reduce CO₂ emissions compared to 1990 as a base level [1]. Published 1990..2016 inventories data [2] display the distribution of total EU CO₂ emission from fuels combustion by economic sectors, pointing permanently the Public Electricity and Heat Production (PEHP) as a most emissive sector with over one third of European CO₂ emission. In 26 years period, the reduction of CO₂ emission from fuel combustion was achieved in EU by 21.6% with simultaneously decrease in PEHP sector by 29.3%. PEHP is one of the well-controllably sectors of EU economy with a highly-centralized structure based on large-scale energy sources. It permits to realize the large-scale and long-life time [3] improvements in path with top-down management way with significant impact for region and EU scale. With so considerable share in CO₂ emission and large decarbonisation potential the PEHP sector plays an important role on national economies, legislation and technology level [3–8] for moving Europe to the low-carbon future.

The investigation of PEHP decarbonisation based on simple comparison of 1990 and 2016 emissions gives only a basic overview of long-term processes and activities in PEHP. European PEHP emission in 1990..2016 period was shaped by EU MS national emissions changes with different trends and rates. Proposed methodology of PEHP

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decarbonisation investigation includes a year-by-year emission pathways and driving forces for European and national fuel combustion PEHP sectors in 1990..2016 period.

Fig. 1. Distribution of total European CO₂ emission from fuels combustion in 1990 and 2016 by economic sectors (based on [2] data).

2 Methodology

The aim of the paper was to investigate the 1990..2016 PEHP decarbonisation pathways base on defined technological indicators in form of CO₂ emission driving forces. From all data published in annual reports the set of indicators describing the annual PEHP emission and technology was pre-defined. Based on specific ranking two indicators were finally selected (fig. 2): annual primary energy consumption (PEC) for electricity and heat production from fuels’ combustion, and annual CO₂ emission factor (EF). The EF was defined as an amount of CO₂ emission per energy consumption unit of combustion fuels. Variability of EF determines decomposition in fuel mix and development in combustion technologies in PEHP.

Fig. 2. Indicators considered in PEHP emission assessment.

PEC and EF indicators were implemented into proposed methodology of alternative scenarios' investigation of 1990..2016 CO₂ emission from PEHP sectors in Europe. The comparison of real and calculated alternative emission pathways show the 1990..2016 effects and ways of decarbonisation in national PEHP sectors. Based on 108 prepared real and alternatives emission pathways, for EU and 26 EU countries: the 1990..2016 decarbonisation effects and ways were assessed; the characteristic decarbonisation patterns were observed, defined and grouped; the impact of indicators PEC and EF were assessed; and finally the “good and bad guys” of EU PEHP decarbonisation were indicated.

3 Alternative scenarios

The research is based on proposed alternative scenarios' methodology to investigate and illustrate the 1990..2016 effects, pathways and driving forces of PEHP decarbonisation. Using published emission inventories reports [2] and prepared calculations, the 1990..2016 pathways of CO₂ emission from EU national PEHP sectors were determined according to four alternative scenarios:

- Scenario S0 represents the 1990 base level of CO₂ emission (green line on fig. 3),

- Scenario S1 presents the real 1990..2016 inventoried pathway of CO₂ emission changes with historical PEC and EF data variability (blue line on fig. 3). Compared to 1990 base level S1 pathway illustrates historical PEHP decarbonisation effects at national and EU levels,
- In scenario S2 the EF factor was fixed on 1990 level. The alternative scenario pathway of 1990..2016 PEHP emission was calculated with real PEC and constant EF changes (red line on fig. 3). Fixed EF reflects lack of development in PEHP technology and fuel mix. Calculated CO₂ emission pathways follow the real 1990..2016 fuel consumption for public electricity and heat production,
- In scenario S3 the PEC factor was fixed on 1990 value. The alternative emission pathway was calculated with fixed PEC and real EF changes (yellow line on fig. 3). The CO₂ emission pathways follow the real 1990..2016 changes of EF factor, reflecting technology development and fuel mix decomposition in PEHP sectors.

The investigated PEHP emission 1990..2016 pathways, real and calculated, were plotted for European PEHP (fig. 3) and for EU 26 national PEHP sectors (fig. 4).

4 Results

Fig. 3 shows in detail the investigated emission information for European PEHP sector. The chart presents four 1990..2016 year-by-year emission pathways according to the developed alternative scenarios methodology. All pathways begin at common point representing the 1990 emission, as an EU climate package [1] base level. The endpoints represent the 2016 emission achieved in each scenario.

Fig. 3. Alternative scenarios of CO₂ emission in EU PEHP sector 1990..2016.

On fig. 3 the green line, representing the S0 scenario, determines the base level from 1990 with 1,441,720 Gg CO₂/a. Scenario S1 pathway, drawn as blue line, illustrates real emission changes to 1,012,150 Gg CO₂/a in 2016, which corresponds to 29.3% decrease. Despite the periodic increases and stagnation, the blue line remains positively below green 1990 level, as a positive effect of long-term decarbonisation actions in European PEHP in accordance with the EU climate package targets. In scenario S2 red line represents theoretical emission pathway with fixed EF. The emission changes followed the real 1990..2016 PEC fluctuations in EU. Between 2002 and 2011, calculated emission achieved higher than the 1990 level and maximizing in 2007, due to the increase in European energy consumption from PEHP. In following years reduction of power and heat production from fuel combustion decreases the CO₂ emission below base level, to 1,235,380 Gg CO₂/a in 2016. It illustrates the energy supply move into the low-carbon sources, beyond fuels combustion PEHP sector with simultaneous reduction in overall electricity and heat consumption [9–11]. Yellow pathway in scenario S3, with constant PEC, shows consistent

decrease in computational 1990..2016 emissions, as a result of consistent fall of EF in European PEHP sector by technical development and low-emission fuel mix decomposition. The comparison of four 1990..2016 CO₂ emission pathways indicates a stronger impact of EF changes than PEC in European PEHP sector decarbonisation in past 26 years.

Fig. 4. Year by year alternative scenarios of national CO₂ emission changes in EU countries PEHP sector 1990..2016.

The same information for 26 national PEHP sectors are shown in figure 4, with 108 investigated emission pathways. National emission charts are maximally simplified for quick graphic interpretation and comparison. A clear and well-formatted image successfully replaces the text description. The interpretation is analogical as for EU PEHP chart in fig. 3.

5 Grouping

Based on overview of 108 national PEHP emission pathways (fig. 4) three specific patterns of relation between base and particular alternative scenarios' pathways, named A, B and C, were observed and defined. In favourable pattern "A" (marked in green) the scenario emission pathway is always below the 1990 base level. In dynamic pattern "B" (marked in yellow) scenario emission is periodically lower or higher than 1990 level. In negative pattern "C" (marked in red) scenario emission is always higher than the base level (fig. 5).

Fig. 5. Three defined pattern of 1990..2016 CO₂ emission pathways used in national PEHP grouping.

Fig. 6 presents detailed results of national PEHP grouping in S1..S3 alternative scenarios, according to observed A, B or C emission pathways' pattern. The matrix-picture shows: 1) the groups of national PEHP sectors meeting the 1990..2016 emission pathways patterns, 2) the mapping of national PEHP sectors based on CO₂ emission pathways patterns, and 3) the grouped aggregated area charts of national 1990..2016 CO₂ emission in all investigated national PEHP sectors.

Among the real emission pathways from scenario **S1** the favourable pattern "A", marked **S1.A** and green, occurred in national PEHP sectors of 9 countries: BGR, EST, FRK, GBE, LTU, LVA, POL, ROU and SVK (fig. 4 and 6). In entire 1990..2016 period these countries have maintained PEHP emission lower than the 1990 base level. Only in 2016 these 9 countries have saved 302 822 Gg CO₂. It is as much emission as if 1990's POL and ROU PEHP sectors disappeared from European 2016 emission map. The green fields on area chart illustrates a large share and favourable changes in S1.A PEHP sectors decarbonisation. The dynamic S1.B pattern (yellow) occurred in 13 countries: AUT, BEL, CZE, DEU, DNK, ESP, GRC, HUN, ITA, MLT, PRT, SVN and SWE (fig. 4 and 6). In spite of the unstable path, these countries have achieved the final drop in emissions between 1990 and 2016 (except for PRT, where the 2016 issue is higher than 1990 base). The large yellow field on area chart determines the largest and stable share of **S1.B** in EU PEHP emission, with several of increase and decrease episodes. The additional CO₂ reduction in S1.B is comparable with ITA and ESP 2016's PEHP emission. The unfavourable **S1.C** pattern occurred in four national PEHP sectors, which increased emissions in relation to 1990: CYP, FIN, IRL and NLD (fig. 4 and 6). Fortunately, the negative group is small, with marginal participation in EU emissions confirmed by the narrow red ribbon on the 1990..2016 emission area chart.

Fig. 6. Grouping, mapping and area charts of national PEHP emission patterns in investigated alternative scenarios S1, S2 and S3.

An alternative scenario **S2** presents PEHP emission pathways assuming a fixed EF on 1990 level, illustrating the emission changes forced by real PEC fluctuations. The favourable change described in the **S2.A** pattern was achieved in seven national PEHP sectors: BGR, EST, LTU (despite the episode at the beginning), LVA, POL, ROU and SVK. In all countries (with the exception of ROU) an initial decrease in emissions and a consequent reduction were noted. By fixed EF the national PEHP emission in pattern **S2.A** illustrates moderate but steady decrease of PEC from fuel combustion PEHP in EU (green area on area chart). Calculated emission changes in 13 national PEHP sectors corresponds to the dynamic pattern **S2.B**: AUT, BEL, CZE, DEU, DNM, FRK, GBE, GRC, HUN, ITA, MLT, PRT and SVN. The emissions changes are influenced by the fluctuations of PEC in national PEHP sectors, as a compromise between the economy needs and climate commitments. On emission area chart the **S2.B** group is the largest yellow field, shaping the EU emission from PEHP. The negative **S2.C** pattern takes place in 6 national PEHP sectors: CYP, ESP (despite the episode at the beginning), FIN, IRL, NLD and SWE. The increase in **S2.C** calculated emissions is a consequence of PEC increase. This change is unfavourable from PEHP and EU decarbonisation point of view. The red strips on emission area chart are a small but growing part of the CO₂ emission from fuel combustion PEHP in EU.

S3 scenario includes the alternative emission with fixed PEC indicator, with real EF changes as an emission driving force. In positive **S3.A** group two subgroups were defined: first with significant reduction in calculated emission (yellow line below, far from green base on fig. 4) including 10 national PEHP sectors: AUT, BEL, CZE, DEU, DNM, ESP,

FIN, FRK, GBE and SWE, and second subgroup with moderate decrease (yellow line below, close to green base) including 8 national PEHP sectors: GRC, IRL, ITA, MLT, NLD, POL, SVK and SVN. With fixed 1990 PEC, a favourable decrease in calculated CO₂ emissions indicates a reduction of EF in national PEHP sectors through the fuel mix decomposition and development in technology of energy production from fuel combustion. For all S3.A countries the yellow pathways on fig. 4 are none dynamically variable due to the large scale and structure of the PEHP sector. On area chart (fig. 6) the green colour of the S3.A pattern, containing group of 18 national PEHP sectors, covers practically entire CO₂ emission from European PEHP. This means, that S3.A pattern with consistent EF reduction was a dominant pathway of 1990..2016 decarbonisation in EU national PEHP sectors. The dynamic S3.B pattern groups 6 national PEHP sectors: CYP, EST, HUN, LTU, LVA and PRT. With a fixed PEC, the variable yellow pathway on fig. 4 reflects the periodic increase and decrease of EF in national sectors. Finally, national PEHP sectors started a favourable trend of EF reduction, but in different years. In the emission area chart (fig. 6), the yellow S3.B pattern forms narrow line, with a small share in the decarbonisation of EU PEHP. The S3.C pattern with an unfavourable increase in calculated 1990..2016 PEHP emission covers only two national PEHP sectors: BGR and ROU. The S3 pathway reflects the 1990..2016 EF factor decreases (fig. 4). This is a phenomenon of adverse changes in fuels mix and energy generation technologies in the PEHP sector or of improvements implementation whose first stages are not beneficial. Luckily S3.C red surface on are chart is small and very limited.

The proposed alternative scenarios' methodology allows also determining the factors of greater influence on 1990..2016 emission. The relevant criterion is the location of the alternative pathways S2 (red, fixed EF) and S3 (yellow, fixed PEC) in relation to the S0 base level (green). In national PEHP sectors where red and yellow pathways are on the same side in relation to green, the 1990..2016 CO₂ emission was shaping coherently by EF and PEC changes. This correlation was fulfilled by 5 countries (sometimes with episode at the beginning): EST, LTU, LVA, POL and SVK (fig. 4). The closer alternative pathway (S2 or S3) to the historical blue S1 line, the greater the EF or PEC impact on CO₂ emission. In all 5 mentioned countries the S2 (fixed EF) scenario improvements had greater influence. Skipping ending episodes, in 7 countries (BGR, FIN, IRL, MLT, NLD, ROU and SWE) S2 and S3 pathways are located on opposite sides of S1 line. This reflects the simultaneous improvement of one and aggravation of the second indicators (EF or PEC) in national PEHP sector in 1990..2016 period. In spite of this, three countries achieved emission reductions (BGR, ROU, SWE). The positive change in one indicator outweighed the impact of the second's deterioration. In the largest group of EU countries S2 and S3 pathways periodically changed their position in relation to S1 real and S0 base emission lines. This reflects the dynamic situation in national PEHP sectors over 26 years. Periodically, according to decarbonisation actions in national PEHP, the EF or PEC indicators have shaped CO₂ emission more strongly.

6 Conclusions

Proposed alternatives scenarios' methodology allows understanding the driving forces of 1990..2016 emission, identifying the ways and the trends both: in European PEHP decarbonisation and in limiting negative impact to the environment. It permits to investigate the 1990..2016 emission driving forces (PEC and EF), national decarbonisation pathways and its impact on EU emission. The defined PEC and EF indicators reflect the consumption, technologies and fuel mix developments in national PEHP sectors, in whole

investigated 1990..2016 period. Graphical illustration and grouping of emissions and patterns allow quick data comparing, trending and interpreting.

Different EU Members States show different 1990..2016 pathways and trends in PEHP decarbonisation, also negative and inconsistent with EU intentions. Grouping proved that the dominant pattern of PEHP decarbonization in EU was the consistent decreasing of EF with the falling PEC. It should be noted that is difficult to identify the best practice in 1990..2016 PEHP decarbonisation process, universal for all EU countries.

Proposed alternatives scenarios' methodology based on historical data allows to learn from past to move the European and national PEHP sectors into a low-carbon future.

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