Impact of reduction of CO$_2$ emissions in the households and tertiary sector on PM2.5 concentration and human health

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Abstract. Significant efforts are being made in the world to reduce greenhouse gas emissions. In the households and tertiary sectors, where energy is mainly used for heating, one should also expect a shift away from fossil fuels (including natural gas) to renewables. In the REFLEX project the energy and emission scenarios were developed for various sectors with the use of Astra, Eltragas, TIMES-HEAT-EU and Forecast models for analysing the long-term situation up to 2050. The paper presents the results of the evaluation of air quality and health impacts associated with direct emissions of air pollutants from households and tertiary sector based on the Driver-Pressure-State-Impact-Response framework. Ambient concentration of air pollutants in Europe was calculated with the use of Polyphemus Air Quality System. Health impacts were estimated based on the concentration-response functions for PM2.5, which is responsible for the most significant impacts to human health. The study shows that according to analysed scenarios, particulate matter (PM2.5 and PM10) emissions from residential and tertiary sectors in Europe will decrease by 30 times until 2050 compared to 2015. These emission reductions lead to improvement of the air quality. The largest reduction in PM2.5 ambient concentrations is observed over Poland. Consequently, it is expected that in 2050 the negative impact of air pollution on human health as well as the associated external costs will be reduced in EU-28.

1. Introduction

The aim of the study was to evaluate the changes of the impact of direct emissions of air pollutants released from households and tertiary sector on air quality and health impacts in the EU-28. The changes of emission were associated with the different energy scenario elaborated within the REFLEX H2020 Project. The aim of the project was to analyse the possibilities for fostering the deployment of renewable energy sources in different Member States in order to achieve a reduction in greenhouse gases emission. The changes in the energy production structure (including that of households and tertiary sector) causes the changes in amounts of emissions of pollutant that directly affect air quality and human health.

In Europe the household and tertiary sectors were the largest contributor of particular matter (PM) and benz(a)pyrene (B(a)P) emissions in 2018. The share of emission from this sector to overall emission in EU-28 was 39% for PM10, 56% for PM2.5 and 66% for B(a)P [1]. This share varies significantly among Member States. For example, in Poland contribution of households sector in overall national emission is estimated at 45% of PM10, 48% of PM2.5 and 66% for B(a)P [2]. In France the contribution of household sector is estimated at 38% of PM10, 42% of PM2.5 and 63% of B(a)P [3]. In Romania these values are PM2.5 - 81%, PM10 - 65%, and 71% for B(a)P. Conversely only 8% of PM10 and 15% of PM2.5 are emitted from the household sector in the Netherlands. However, in the Netherlands most...
part of B(a)P i.e., 82% is emitted from the household sector. The households and tertiary sector have the significant impact on the ambient air quality, mainly in the local scale. The emissions from these sectors are typically released below 40 meters above ground level. The pollutants emitted below 40 meters above ground level, are relatively weakly transported in the atmosphere, which causes that they affect significantly the local air quality. The most significant impact of emissions from the households and tertiary sector occurs in Eastern and Central Europe, which is the most polluted region in entire EU and where many houses and flats use coal to heat living space. Often, solid fuels are burned in old, low-efficiency, highly-polluting furnaces and boilers [4]. In the Central and Eastern Europe 45% of PM10 and 32% of PM2.5 that occur in ambient air are emitted from households and tertiary sector. For comparison in western Europe these contributions are 15% for PM2.5 and only 7% for PM10 [5].

Estimations show that even 20%, 19% and 8% of urban population in the EU-28 is exposed to elevated concentrations of, respectively: benzo(a)pyrene (B(a)P), PM10 and PM2.5, that are above the EU reference values [1], [6]. As a consequence, the indicator of years of lost life due to the concentration of PM2.5 in EU-28 was equal to 3 848 000 in 2016. It gives 800 of years of lost life per 100,000 inhabitants. The impact of NOX and O3 were much lower i.e., 100 and 30 years of lost life per 100,000 inhabitants, respectively [1].

PM2.5 fractions are the most harmful to health and are associated not only with respiratory diseases but also with cardiovascular diseases and others negative impacts on the organs of the human body [7]. The fine fractions of particulate matter can easily pass the barrier of upper respiratory tract (nose, sinuses, pharynx or larynx) and are deposited in the pulmonary alveolus. Subsequently, they enter to the circulatory system and various organs of the human body. It was reported that each 10 µg.m⁻³ elevation in long-term exposure to fine particulate air pollution was associated with approximately 6% increased mortality [8].

The Driver-Pressure-State-Impact-Response (DPSIR) methodological framework is commonly used for the evaluation of the impact of the energy scenarios on the future inhabitants’ health and external costs [9], [10], [11]. In the framework of the REFLEX project, the energy scenarios have accounted for information on the activities of technologies (e.g. electricity production by CCGT - combined cycle gas turbine) as well as on the fuel consumption. Secondly, the emission scenarios were elaborated by applying technology- or fuel-specific emission factors. Next, the air quality modelling system Polyphemus was used to analyse the changes in future ambient pollutants concentration over Europe [12], [13]. The obtained concentration fields, population data concentration-response functions derived from the epidemiological studies were used to estimated health impacts of air pollution. Finally, the external costs associated with different energy scenarios were calculated.

2. Methodology

The Driver-Pressure-State-Impact-Response (DPSIR) framework approach was used for calculating the external costs of direct pollutant emissions (Figure 1), [11].

![Concept of Driver-Pressure-State-Impact-Response (DPSIR) framework.](image-url)
"Drivers" links to the REFLEX energy scenarios developed with the use of ASTRA, ELTRAMOD, TIMES-HEAT-EU and FORECAST models. The ASTRA model was used for transport, ELTRAMOD for electricity sector, TIMES-HEAT-EU for heating plans and combined heat and power plants and FORECAST for future energy demand [14]. The scenarios were prepared for EU-28 and other European countries (Norway, Albania, Switzerland) with the 2050 time horizon. In addition to the household sector the REFLEX modelling system also covered the industry and transport. The base year was 2015. Three scenarios were elaborated i.e. Mod-RES, High-RES decentralized and High-RES centralized. As regards to the fuel mix they differ mainly in the use of biomass in power, households and tertiary sector. "Pressures" were represented by the emission scenarios. Emission were calculated based on future sector activities, technologies and fuel consumption. The emission factors for the households and tertiary sector were extracted from the GAINS model and for small combustion installations the current Ecodesign limits were applied [15], [16]. The emission of PM2.5 in 2015 and relative reduction in 2050 is presented in Table 1.

Table 1. Total PM2.5 emissions from households and tertiary sector in 2015 and relative reduction in 2050 compared to 2015 according to REFLEX scenarios: Mod-RES, High-RES decentralized and High-RES centralized.

| Country | Emission Base year 2015 [Mg] | Reduction in 2050, Mod-RES scenario [%] | Reduction in 2050, High-RES decentralized scenario [%] | Reduction in 2050, High-RES centralized scenario [%] |
|---------|-------------------------------|-----------------------------------------|---------------------------------------------------|---------------------------------------------------|
| AT      | 8012                          | 93.5                                    | 86.2                                              | 92.5                                              |
| BE      | 12971                         | 96.2                                    | 90.3                                              | 93.9                                              |
| BG      | 24416                         | 99.5                                    | 99.0                                              | 99.5                                              |
| CH      | 2410                          | 72.1                                    | 62.2                                              | 64.7                                              |
| CY *    | 80                            | 65.0                                    | -2.5                                              | -5.0                                              |
| CZ      | 29734                         | 97.9                                    | 97.3                                              | 98.4                                              |
| DE      | 20915                         | 72.5                                    | 65.6                                              | 75.3                                              |
| DK      | 14642                         | 98.1                                    | 97.5                                              | 98.5                                              |
| EE      | 2592                          | 97.1                                    | 94.9                                              | 97.0                                              |
| ES      | 53488                         | 97.7                                    | 94.4                                              | 94.9                                              |
| FI      | 10215                         | 96.6                                    | 93.4                                              | 97.6                                              |
| FR      | 71163                         | 96.5                                    | 93.4                                              | 95.1                                              |
| GR      | 10680                         | 97.3                                    | 95.6                                              | 97.0                                              |
| HR      | 15664                         | 98.8                                    | 96.3                                              | 98.1                                              |
| HU      | 46252                         | 98.2                                    | 97.2                                              | 98.0                                              |
| IE      | 7539                          | 97.2                                    | 96.2                                              | 96.8                                              |
| IT      | 110505                        | 98.2                                    | 95.5                                              | 97.1                                              |
| LT      | 3157                          | 93.9                                    | 92.1                                              | 94.6                                              |
| LU      | 513                           | 94.5                                    | 85.6                                              | 87.9                                              |
| LV      | 9453                          | 98.7                                    | 97.9                                              | 98.9                                              |
| NL      | 2051                          | 61.5                                    | 54.1                                              | 77.8                                              |
| NO      | 16224                         | 98.6                                    | 98.0                                              | 98.6                                              |
| PL      | 65995                         | 96.2                                    | 94.6                                              | 96.6                                              |
| PT      | 16137                         | 97.7                                    | 97.2                                              | 97.3                                              |
According to the REFLEX scenarios the PM2.5 emissions in the households and tertiary sector are reduced by 30%, 17% and 25% in Mod-RES, High-RES decentralized and High-RES centralized scenarios, respectively. In this sector the coal consumption will be reduced almost to zero. The natural gas and oil consumption will be reduced by 2 times in Mod-RES, 7 times in High-RES decentralized and 8 times in High-RES centralized scenario. The biomass consumption in the households and tertiary sector in 2015 was 540 TWh and according Mod-RES will decrease to 510 TWh, but in two other scenarios the higher amounts of biomass consumption are expected i.e. in High-RES decentralized scenario 541TWh and High-RES centralized scenario 792 TWh.

“States” links to the concentration and deposition of air pollutants which were calculated with the use of Polyphemus air quality modelling system [12], [13]. The analysis were performed for a domain with the geographical extend of 35.0°N – 69°N of latitude and 12.0°W – 27°E of longitude, with a horizontal resolution of 1.0° x 1.0°. Five vertical levels were used with the following limits [in meters above surface]: 0; 50; 600; 1200; 2000; 3000. The simulations were run with the time step of 10 minutes and results as the average value from 6 time steps were saved each 1 hour. Four simulations of the pollutants dispersion over Europe were run. First with the use of the historical data reported to EMEP for 2015 [3]. Next three simulations were based on the emission data for households and tertiary sector in 2050 for Mod-RES, High-RES decentralized and High-RES centralized scenarios. The emissions from these sectors for each country were horizontally desegregated based on EMEP data [3]. The emissions from other sectors and natural emissions remained at the level of 2015. The meteorological fields were calculated based on the European Centre for Medium-Range Weather Forecasts (ECMWF) meteorological data for 2008. The results of concentration of various pollutants obtained from Polyphemus were evaluated against measurements over Europe and over Poland in many articles e.g. [11], [13], [17]. In Polyphemus the following PM2.5 components are considered: mineral dust, black carbon, SO$_2$, NO$_x$ and NH$_3$ aerosols, hydrochloric acid aerosols, aromatics, primary and secondary organic aerosol.

“Impact” links to the calculated health impacts and external cost. To quantify the health effect, the value of the three commonly used indicators were estimated i.e. years of life lost (YOLL), restricted activity days (RAD) and chronic bronchitis (CB) with the use of Equation 1 [18], [19], [20].

$$HI = CRF \cdot CON \cdot POP \cdot FR$$  \hspace{1cm} (1)

where:

- HI is the health impact of a given type (i.e. YOLL, CD or RAS) [cases],
- CRF is the concentration-response function for a given impact type [cases.µg$^{-1}$.m$^3$],
- CON is average annual concentration of PM2.5 at ground level [µg$^{-1}$.m$^3$],
- POP is population exposed [number],
- FT denotes the fraction of population affected [%].
The population data were taken from GEOSTAT 2011 dataset which included population distribution with 1 km x 1 km spatial resolution [21]. In this study the CRF has the values for: YOLL – 3.42 \times 10^{-4}, 3.90 \times 10^{-5} for CB and 4.20 \times 10^{-4} for RAD [22], [23], [24]. FR values of 100% for YOLL and 80 % for CD and RAD were assumed. The external costs associated with the PM2.5 ambient concentration over Europe were calculated using the unit value of 57 510 [EUR.case^{-1}] for YOLL, 38 578 [EUR.case^{-1}] for CB and 98 [EUR.case^{-1}] for RAD.

The “Response” can be understood as the recommendation and conclusion prepared based on obtained results and presented at the end of the work.

3. Results
Polyphemus air quality system was run to obtain the results of PM2.5 concentration in 2015 and 2050 for Mod-RES, High-RES decentralized and High-RES centralized scenarios. Figure 2 shows the change in ambient PM2.5 concentrations between 2015 and 2050 at surface level for the Mod-RES scenario in which, as presented in Table 1, PM2.5 emissions in the households and tertiary sector are the lowest.

![PM2.5 Concentration Map](image)

The largest reduction in PM2.5 ambient concentrations is observed over in Eastern and Central Europe and (Figure 2). As mentioned before, in this region many houses and flats use the coal and biomass for heating. For example in Poland still approx. 4 million of boilers in households sector do not meet the emission limits required by the Ecodesign standard. Reducing the amount of coal burned in this sector and the use of modern boilers will lead to significant improvement of air quality over Eastern and Central Europe especially in Poland, which is one of the most polluted country in Europe. However, the reduction of pollution only from the households and tertiary sector is still inadequate and efforts should be made to reduce emissions from other sectors.
The results of the health impact assessment and external costs related to PM2.5 ambient concentration are presented in Table 2. The Table shows the baseline situation (year 2015) and the expected changes in 2050 according to the Mod-RES, High-RES decentralized and High-RES centralized scenarios in which emissions in households and tertiary sector changed in 2050 as presented in Table 1. The health effects in 2050 are almost the same for all scenarios due to similar PM2.5 emissions and ambient pollutants concentration levels in these scenarios. The estimated health related external costs attributed to PM2.5 exposure for the impact types considered in this study were estimated at about 170 billion EUR per year in 2015. The estimated reduction of external costs according to Mod-RES, High-RES decentralized and High-RES centralized scenarios in 2050 reaches 12.61, 12.17 and 12.55 billion EUR per year, respectively.

Table 2. Annual external attributed to PM2.5 exposure in 2015 and 2050 for the Mod-RES, High-RES decentralized (High-RES dec) and High-RES centralized (High-RES cen) scenarios.

| Type  | Health impacts [10^3 cases] | External costs [10^9 EUR] |
|-------|-----------------------------|---------------------------|
|       | 2015 | 2050 | 2050 | 2050 | 2015 | 2050 | 2050 | 2050 |
| YOLL  |     |     |     |     |     |     |     |     |
|       | 2401 | 2222 | 2228 | 2223 | 138.09 | 127.82 | 128.18 | 127.86 |
| RAD   |     | 235894 | 218357 | 218968 | 218432 | 23.12 | 21.40 | 21.46 | 21.41 |
| CB    | 219 | 2102 | 203 | 202 | 8.45 | 7.82 | 7.84 | 7.82 |
| Total |     |     |     |     |     | 169.65 | 157.04 | 157.48 | 157.10 |

The highest external cost in 2015 and 2050 were calculated for Italy (Table 3). The most significant reduction of external cost associated with PM2.5 emissions from households and tertiary sector is observed for Poland.

Table 3. External cost attributable to air pollution of PM2.5 in 2015 and 2050 the Mod-RES, High-RES decentralized and High-RES centralized scenarios [10^9 EUR].

| Country | Base year 2015 | 2050 Mod-RES | 2050 High-RES decentralized | 2050 High-RES centralized |
|---------|----------------|---------------|-----------------------------|---------------------------|
| AT      | 2.49           | 2.33          | 2.33                        | 2.33                      |
| BE      | 3.87           | 3.43          | 3.46                        | 3.44                      |
| BG      | 3.32           | 3.17          | 3.17                        | 3.17                      |
| CH      | 2.38           | 2.25          | 2.26                        | 2.25                      |
| CZ      | 2.99           | 2.62          | 2.62                        | 2.62                      |
| DE      | 23.11          | 21.69         | 21.78                       | 21.66                     |
| DK      | 1.30           | 1.24          | 1.24                        | 1.24                      |
| EE      | 0.25           | 0.24          | 0.24                        | 0.24                      |
| EL      | 5.98           | 5.88          | 5.88                        | 5.88                      |
| ES      | 17.85          | 17.30         | 17.32                       | 17.32                     |
| FI      | 0.88           | 0.85          | 0.85                        | 0.85                      |
4. Conclusions and Recommendations

This study evaluates the air quality and health impacts of direct emissions of pollutants from households and tertiary sector associated with the energy scenarios elaborated within the REFLEX Project. According to the scenarios, the PM2.5 emissions from these sectors were reduced in 2050 compared to 2015 by 30 times in Mod-RES, 17 times High-RES decentralized and 25 times and High-RES centralized. The differences in emissions from households and tertiary sector are due to different structural use of solid biomass for heat consumption. In High-RES decentralized scenario, with higher emissions, more biomass is directly used by households. In High-RES centralized scenario, biomass is used in combined heat and power plants with better emission control. Consumption of coal in this sector is almost reduced to zero and the emissions from natural gas and oil are very low especially for PM2.5. Therefore, for local air quality, biomass consumption in households and tertiary sector will have the crucial importance. It is important to assure that biomass combustion in the sector will take place in boilers meeting the best emissions standards. Therefore, the implementation of emission limits more strict than those determined by the Ecodesign standards should be considered.

Results show the improvement in air quality and also the reduction in negative health effects by 2050 in all REFLEX scenarios as compared to the situation in 2015. The improvement in air quality was observed particularly in Eastern and Central Europe. In southern Poland, PM2.5 concentrations were reduced to 4.5 µg.m⁻³. The estimated reduction of external costs according to Mod-RES, High-RES decentralized and High-RES centralized scenarios due to changes in the structure of the households and tertiary sector in 2050 as compared to 2015 situation reaches approximately 12 billion EUR per year.

In Mod-RES, High-RES decentralized and High-RES centralized scenarios the GHG emissions from the household and tertiary sectors were also reduced in 2050 in relation to 2015 by 40%, 90% and 91%, respectively. While PM2.5 emissions from these sectors were significantly decreased in 2050, the external costs were only reduced by about 7%. The study shows that it is very important to take into account, in addition to greenhouse gases emissions, also the emission of pollutants which directly affecting human health when planning the development of future energy system.

|      |    |    |    |    |
|------|----|----|----|----|
| FR   | 19.09 | 17.66 | 17.72 | 17.68 |
| HR   | 1.62  | 1.49  | 1.50  | 1.49  |
| HU   | 3.47  | 3.01  | 3.02  | 3.01  |
| IE   | 1.51  | 1.47  | 1.47  | 1.47  |
| IT   | 26.59 | 24.68 | 24.74 | 24.70 |
| LT   | 0.71  | 0.65  | 0.65  | 0.65  |
| LV   | 0.44  | 0.40  | 0.40  | 0.40  |
| MT   | 0.34  | 0.34  | 0.34  | 0.34  |
| NL   | 5.26  | 5.01  | 5.03  | 5.01  |
| NO   | 0.91  | 0.87  | 0.87  | 0.87  |
| PL   | 11.68 | 9.19  | 9.22  | 9.16  |
| PT   | 4.19  | 4.01  | 4.01  | 4.01  |
| RO   | 7.18  | 6.49  | 6.49  | 6.49  |
| SE   | 1.71  | 1.66  | 1.66  | 1.66  |
| SI   | 0.71  | 0.64  | 0.64  | 0.64  |
| SK   | 1.78  | 1.51  | 1.51  | 1.50  |
| UK   | 18.04 | 16.98 | 17.06 | 17.02 |
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