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External costs of electricity generation options in Lithuania

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ABSTRACT

This article deals with external cost of electricity generation in Lithuania. The external costs of electricity generation are the most important environmental criteria shaping decisions within the electricity system. External costs of electricity generation were calculated based on ExternE methodology for Lithuania during EU (European Union) Framework 6 project Cost Assessment for Sustainable Energy Systems (CASES). The article presents the methodology and results of external costs of electricity generation in Lithuania. The assessment of external costs provided that future energy policy should be oriented towards the renewable energy generation technologies having the lowest external costs. External costs for electricity generation technologies were analysed in terms of external costs categories, electricity generation technologies life cycle stages and time frame 2010–2030.

1. Introduction

The sustainable energy development is the key issue of national and international policies [1–3]. Efforts towards a sustainable energy system are progressively becoming an issue of paramount importance for decision makers. Environmental sustainability constitutes the main energy policy objectives for a sustainable energy system. Implementation of new energy technologies is a key mean towards a sustainable energy system. The environmental sustainability of electricity generation technologies can be addressed by integrating external costs of electricity generation in decision making. The electricity generation technologies should be selected by taking into account life time external costs.

External costs for electricity are those that are not reflected in the price of electricity, but which society as a whole must bear. For example, the biggest damage to human health is caused by emissions of particulate matter, SO_2, NO_x and NMVOC [4]. There are also costs associated with non-health impacts. SO_2 is the main pollutant of concern for building-related damage, though ozone also does affect certain materials. The secondary pollutants formed from SO_2, NO_x and NMVOC also impact on crops and terrestrial and aquatic ecosystems.

The external costs arising from the environmental impact of electricity production are significant in most EU countries and reflect the dominance of fossil fuels in the generation mix. In 2005–2010 the average external costs of electricity production in the EU were about 6 Eurocent/kWh [5]. The externalities also vary between the EU Member States, as a result both of the fuel mix and location. Higher damages typically occur from emissions in countries in Western Europe because of the large population affected. Countries with lower mean externalities are Austria, Finland and Sweden, reflecting their low population density (in the two latter) and greater use of nuclear and renewable energy and, in particular, hydropower. Despite progress, these external costs are still not adequately reflected in energy prices. Consumers, producers and decision makers do not therefore get the accurate price signals that are necessary to reach decisions about how best to use resources [5]. Table 1 presents external costs of classical pollutants for EU member states [6]. The costs were recalculated in 2010 prices to adjust inflation.

Damages from climate change, associated with the high emissions of greenhouse gases from fossil fuel based power production, also have considerable costs. However, given the long-time scales involved, and the lack of consensus on future impacts of climate change itself, there is considerable uncertainty attached to the damage costs. The external costs of CO_2emissions must thus be interpreted with care [7]. There is no single value and that the range of uncertainty around any value depends on ethical as well as economic assumptions [7]. The damage factors for CO_2 used in this factsheet range from 22.5 EUR/t CO_2 (low estimate, based on ExternE-Pol) and 95 EUR/t CO_2 (high estimate, based on [7] recalculated in 2010 prices. These two values are common to all countries.

At present, more than one hundred estimates of the marginal external costs of the emissions of greenhouse gases (particularly CO_2) have been made. The estimates range from slightly negative

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Table 1
External costs of pollutants in EU-15, EUR 2010/t.

	External costs (EUR 2010/t)		
	SO_2	NOx	Particulates
Denmark	4841–6826	5310–7655	5488–10,792
Sweden	3816–4549	3168–3789	4423–6217
Finland	1663–2409	1379–2247	2169–4227
Germany	2914–22,161	17,720–24,447	15,381–37,909
United Kingdom	9758–16231	9287–15562	12952–37103
Ireland	4533–8581	4452–4857	4533–8767
Belgium	18,438–19,656	18,661–19,907	39,742–39,725
Netherlands	10,046–12,274	8872–9852	24,295–27,248
Austria	14571	27199	27199
Portugal	8030–8487	9674–10,624	9010–11,260
Spain	6897–15,515	7530–19,519	7153–32,785
France	12,143–24,771	17,453–29,142	9875–92,283
Greece	3202–12,680	2008–12,625	3261–13,402
Italy	9228–19,428	7447–21,965	9228–33,513
EU average	7859–13,438	10014–14,956	13634–27,316

(<0) to over 400 USD per ton CO_2 currently emitted [7]. R. S. Tol constructed a probability density function of published estimates [8]. The function is highly skewed to the left, with a long right tail of sparse but high estimates. The mean value of the published estimates is 25 USD per ton of CO_2, but 50% of the studies report costs of less than 4 USD/ton (this is the median value). On the other extreme, 5% of the studies report costs of over 95 USD/ton. If only peer-reviewed studies are taken into account, the mean estimate drops to 12 USD/ton with a standard deviation of 23 USD/ton.

Most researchers agree that the marginal impacts of greenhouse gas emissions increase with the concentration of greenhouse gases in the atmosphere. The literature reports annual increases in the marginal costs of CO2 emissions range between 1 and 2 percent [9,10]. Annual increases of marginal costs for other greenhouse gases may differ in relation to their expected lifetime in the atmosphere. Recently, there has been a flurry of research projects on the 'social cost of carbon' (SCC) in the United Kingdom [11,12]. The social cost of carbon is the social cost of the emission of one tonne of CO2 at a particular date; hence it is another word for the marginal (social) cost of CO_2 emissions. It is measured as the present value of the impacts of one tonne of CO_2 over its lifetime in the atmosphere. The Stern Review [13] assessed the economics of moving to a low carbon economy, focussing on a medium to long term, plus the potential of different approaches to adaptation and lessons for the UK, in the context of climate change goals. Using the results from an integrated assessment model (the PAGE model), the review estimated that the total damage costs of climate change could be at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more. The review suggested a SCC of € 85 per ton of CO_2, which is considerably higher than the UK government's "illustrative value" of € 28 per ton, and also far out in the right tail of R. S. Tol's probability density function [10]. In contrast to these high costs of inaction, the costs of action–reducing greenhouse gas emissions to avoid the worst impacts of climate change–can, according to Stern, are limited to around 1% of global GDP each year.

The numerical results of studies into the external costs of greenhouse gas emissions remain speculative, but they can provide insights on signs, orders of magnitude, and patterns of vulnerability. Results are difficult to compare because different studies assume different climate scenarios, make different assumptions about adaptation, use different regional disaggregation and include different impacts.

Lithuania has started challenging project – construction of new nuclear power plant however there are debates between policy makers and the strong opposition from various non-governmental organizations considering nuclear as environmentally dangerous generation option. The comparison of external costs of various electricity generation options in Lithuania would allow assessing and ranking possible future electricity generation options based on their environmental impacts.

The aim of the paper is to compare external costs of the main electricity generation technologies for Lithuania and to define the technologies having the lowest external costs. The main tasks of the paper are to present methodology for assessment of external costs of electricity generation; to select future electricity generation technologies relevant to Lithuania; to define external costs of electricity generation options and to rank electricity generation technologies based on external costs.

2. Methodology for assessment of external costs in electricity sector

During EU Framework 6 project CASES external costs of electricity generation were assessed for all EU member states for 2010–2030. External cost of electricity generation (in EuroCents/kWh) are calculated by multiplying the average height of release values of unit of emission for classical air pollutants (2005 Eurocent/kg) times the quantity of emission for unit of electricity generated (kg/kWh).

Marginal external costs for classical air pollutants are calculated for CASES project by applying updated *EcoSenseWebV1.2* tool [14].

To estimate external costs by transforming impacts that are expressed in different units into a common monetary unit, the *ExternE* methodology was adopted [15–17]. The methodology for assessment of external costs was developed and updated during EU projects: ExternE, NewExt, ExternE-Pol, DIEM, ECOSIT, INDES, MAXIMA, NEEDS and CASES.

The principal stages of the ExternE methodology are the following [16]:

- Definition of the activity to be assessed and the background scenario where the activity is embedded. Definition of the important impact categories and externalities.
- Estimation of the impacts or effects of the activity (in physical units). In general, the impacts allocated to the activity are the difference between the impacts of the scenario with and the scenario without the activity.
- Monetisation of the impacts, leading to external costs.
- Assessment of uncertainties, sensitivity analysis.

The impact categories which are addressed using the ExternE methodology and that are analysed in the full costs assessment are the environmental impacts (on human health, crops and loss of biodiversity) the damage to materials and the global warming impact. The approach used to quantify environmental impacts is the *Impact Pathway Approach* (IPA). The principal steps can be grouped as follows [17,18]:

- Emission: specification of the relevant technologies and pollutants emitted by a power plant at a specific site, for the whole life cycle, which is from construction to dismantling, including fuel extraction and transportation;
- Dispersion: calculation of increased pollutant concentrations in all affected regions, using models of atmospheric dispersion;
- Impact: calculation of the cumulated exposure from the increased concentration, and calculation of impacts (damage in physical units) from this exposure using an exposure-response function;
- Cost: valuation of these impacts in monetary terms.

The costs of emission were calculated with respect to the impact of pollutants on human health, crops, damage to materials, and loss of biodiversity caused by acidification and eutrophication. For all these categories of impact the following air pollutants are considered [19]:

- Ammonia (NH_3),
- Non-methane volatile organic compounds unspecified (NMVOC),
- Nitrogen oxides (NOx),
- Particulates (PPMco – between 2.5 and 10 um, and PPM_{25} – less than 2.5 um),
- Sulphur dioxide (SO_2).

In addition the cost of sulphur dioxide and nitrogen oxides emissions in the atmosphere is calculated with respect to the damage to materials.

Results for damage costs related to impacts on human health, environment, crops and materials are regionally detailed and are available for each EU-27 country and for the EU27 as an average. For these costs different values, corresponding to conditions in 2010 and values corresponding to possible conditions in 2020, are proposed. It is assumed that in most cases the emissions in 2020 are lower than in 2010. Since no further reduction of emissions costs are foreseen after 2020, all marginal external costs estimated for 2020 are used also to calculate values for 2030. Then estimated values are not affected by the assumption of an arbitrary year, but they reflect more typical and average conditions [19].

External costs related to human health were also assessed per unit of emission for formaldehyde and the following heavy metals:

- Cadmium (Cd),
- Arsenic (As),
- Nickel (Ni),
- Lead (Pb),
- Mercury (Hg),
- Chromium, (Cr)
- Chromium IV (Cr-IV).

This set of marginal external costs is not country specific, hence the same value for each EU-27 country is considered. In addition since variation of these values with time is not foreseen, the same result is used to estimate full costs for present (2005–2010), 2020 and 2030.

An additional set of pollutants for which a generic marginal external cost is estimated for all Europe and for the whole period 2005–2030 consists of the following radionuclides [20]:

- Aerosols, radioactive, unspecified into air,
- Carbon-14 into air and water,
- Hydrogen-3, Tritium into air and water,
- Iodine-129 into air,
- Iodine-131 into air,
- Krypton-85 into air,
- Noble gases, radioactive, unspecified into air,
- Radon-222 into air,
- Thorium-230 into air and water,
- Uranium-234 into air and water.

An important component of the total external cost of electricity production is the cost of greenhouse gases. In the framework of the CASES project two approaches are followed to assess global warming. With the first methodology the quantifiable damage is estimated, while with the second one the avoidance cost in estimated. To calculate the full cost of electricity generation the results obtained with the first approach were used in EU projects New Energy Externalities Developments for Sustainability (NEEEDS) and CASES. The damage cost for unit of emission is calculated for CO_2, CH_4 and N_2O. The values which are used to calculate the full costs are calculated by the NEEDS project. Since data are not site specific, the same value for all EU-27 countries are used. Data are time specific, hence different values are used for the periods 2000–2009, 2020–2029 and 2010–2039 [21].

The damage costs of greenhouse gases due to climate change impacts are estimated with EcoSenseWeb by using the FUND2.916 applied model. The model estimates a selection of the potential impacts of climate change on agriculture, forestry, unmanaged ecosystems, sea level rise, human mortality, energy consumption, and water resources.

To calculate the external cost of each kWh of electricity produced, the marginal value for unit of emission is multiplied by the quantity of pollutants emitted at each production stage per unit of electricity. For the CASES project the emission database for electricity and heat generation in 2007, 2020 and 2030 was developed [22]. The life cycle inventory data for basic processes are taken from the Life Cycle Assessment (LCA) database Ecoinvent in the version 1.2 [23].

3. External costs categories

The main environmental dimension indicators for energy technologies assessment are: external costs of climate change, environmental external costs, the external health costs and radionuclides external health costs [24,25].

External costs of climate change. These costs were assessed in EURcnt/kWh based on life cycle emissions of GHG emissions in kg (CO_2-eq.)/kWh and damage costs of GHG emissions (Table 1). Climate change is the dominating environmental concern of the international environmental political discussion of today. Global warming is not only an issue for the environment, but rather for human society as a whole, since rising global temperatures might have serious consequences not only on the environment, but on our economy and social life as well. Among the potential consequences are more frequent extreme weather events like heat waves, storms, flooding and droughts, stress due to higher temperatures for plants and humans, rising sea level, and altering occurrence of pathogenic organisms. The indicator reflects the potential negative impacts of the global climate change caused by emissions of greenhouse gases for the production of 1 kWh of electricity. Table 2 presents the results of costs in Euro 2010 per ton of emissions. The costs developed by NEEDS [26] and CASES [21] projects were recalculated in EUR 2010 to adjust to inflation.

The external health costs in EURcnt/kWh provide the estimates for damages to health due to emissions to air, soil and water of particles, gases, the formation of ozone, and emissions of metals. Marginal external costs for classical air pollutants were calculated for CASES project by IER with the updated EcoSenseWebV1.2 tool. To estimate external costs by transforming impacts that are expressed in different units into a common monetary unit, the ExternE methodology is used. The costs of emission were calculated with respect to the impact of pollutants on human health for all

Table 2
Average external costs of climate change, EUR(2010)/t.

GHG emissions	2010	2015	2020	2025	2030	2040	2050
CO_2	25	25	25	27	36	54	72
CH_4	522	522	522	572	746	1144	1517
N_2O	7710	7710	7710	8444	11014	16888	22395

these categories of impact the following air pollutants are considered: Ammonia (NH_3), Non-methane volatile organic compounds unspecified (NMVOC), Nitrogen oxides (NOx), Particulates (PPMco—between 2.5 and 10 um, and PPM_{25} less than 2.5 um), Sulphur dioxide (SO_2) [20,27]. Table 3 presents the external health costs related to classical pollutants emissions for Lithuania and EU average in 2010 and 2020.

As one can see from Table 3 external human health costs are significantly lower in 2020 comparing with 2010 values. The external health costs in Lithuania are almost twice lower comparing with EU-27 average values. This is related with quite high population density and the location of power plants in the biggest cities or very close to then and low GDP/capita adjusted to Power Purchasing Parity (PPP) in Lithuania then external costs are monetised.

The set of marginal external health costs of heavy metal releases is not country specific, hence the same value for each EU-27 country is considered. In addition since variation of these values with time is not foreseen, the same result is used to estimate full costs for present (2005–2010), 2020 and 2030. Table 4 provides average external health costs related to releases of heavy metals for EU-27.

Radionuclides external costs in EURcnt/kWh are external costs estimates for damages to health due to emissions of life cycle radionuclides including indirect use of nuclear electricity in the production of other technologies. The release of these radionuclides and the corresponding radioactivity into the environment causes impacts to human health. The impacts considered are fatal cancers, non-fatal cancers and hereditary defects. The cost in Euro/kBq is obtained by multiplying the collective dose estimation unit (manSv) per kBq, which is specific for each pollutants, times the cases of fatal cancer, non fatal cancer and hereditary defects per manSv and the corresponding Willingness To Pay (WTP) values in Euro per endpoint. The factors relating collective dose to impact, so called risk factors, are determined by a linear dose–effect relationship. The values used in calculation are: 0.05 cases per manSv for fatal cancers, 0.12 cases per manSv for non-fatal cancers and 0.01 cases per manSv for hereditary defects. To calculate the cost in Euro/kBq for radionuclide unit of emission the respective number of cases of endpoint per kBq is multiplied by the following values for WTP per endpoint: 1.120.000 Euro for fatal cancers, 481.000 for non-fatal cancers and 1.500.000 for hereditary defects10. These WTP values are derived from estimates for different types of cancer, e.g. leukaemia, lung cancer, etc. Types of cancer differ in latency and estimated YOLL and YLD (year lost due to disability). For fatal cancers, 15.95 YOLL + 0.26 YLD are assumed. The monetary value for fatal cancer includes also an additional estimation of WTP to avoid the illness based on the costs of illness (COI) (ca. 481,050 E) The YOLL are multiplied with 40,000 Euro/year of life lost. Heredity effects have been valued at the same value as a statistical life, since there are no WTP estimates of such impacts available, and given the relevance usually attributed to such effects. Generic marginal external radionuclides cost were estimated for the following radionuclides: Aerosols, radioactive, unspecified into air; Carbon-14 into air and water; Hydrogen-3, Tritium into air and water; Iodine-129 into air; Iodine-131 into air; Krypton-85 into air; Noble gases, radioactive; unspecified into air; Radon-222 into air; Thorium-230 into air and water; Uranium-234 into air and water [20,27]. The radionuclides external costs estimates are based on ExternE, NEEDS and Cases project results. The average European values for 2030 were applied for evaluation of electricity generation technologies in this paper. Table 5 presents the average external costs of radionuclides for EU-27.

The environmental external costs in EURcnt/kWh is the estimates for damage to ecosystems due to emissions to air, soil and water of particles, gases, the formation of ozone and the emissions of metals. These costs were obtained during ExternE, NEEDS and CASES projects and were used in these projects for electricity generation technologies assessment. Environmental external costs are calculated with respect to the impact of pollutants on crops, damage to materials, and loss of biodiversity caused by acidification and eutrophication. For all these categories of impact the life cycle emissions of air pollutants are considered: Ammonia (NH_3), Non-methane volatile organic compounds unspecified (NMVOC), Nitrogen oxides (NOx), Particulates (PPMco—between 2.5 and 10 um, and PPM_{25}—less than 2.5 um), Sulphur dioxide (SO_2). In addition the cost of sulphur dioxide and nitrogen oxides emissions in the

Table 3
External health costs of classical pollutants in Lithuania and EU average, EUR (2010)/t.

Pollutants	2010		2020	
	EU-27	Lithuania	EU-27	Lithuania
NH_3	11,230	5149	6913	2808
NMVOC	692	386	282	66
NO_x	6621	4697	7840	5511
Particulates (PPMco)	1569	462	1636	470
Very small particulates (PPM_{25})	28,909	12,991	28,649	13,227
SO_2	7189	5225	7903	5942

Table 4
Average external health costs of heavy metals releases for EU-27 during 2020–2030, EUR(2010)/t.

Heavy metals	External costs, EUR/t
Cd	46,200
As	94,700
Ni	4700
Pb	710,600
Hg	10,421,800
Cr	37,300
Cr-IV	284,200
Formaldehyde	236,900
Dioxine	4,40E+13

Table 5
Average external costs of radionuclides for EU-27 in 2010–2030, EUR(2010)/Bq.

Radionuclides	External costs, EUR/Bq
Aerosols, radioactive, unspecified into air	3.05E + 00
Carbon-14 (into air)	1.41E + 02
Carbon-14 (into water)	1.52E + 00
Cesium-137 (into air)	1.13E + 01
Cesium-137 (into air)	1.49E − 01
Hydrogen-3, Tritium (into air)	6.25E − 03
Hydrogen-3, Tritium (into water)	1.30E − 03
Iodine-129 (into air)	9.76E + 01
Iodine-131 (into air)	3.09E + 01
Krypton-85 (into air)	3.26E − 04
Noble gases (into air)	6.56E − 04
Radon-222 (into air)	3.81E − 03
Thorium-230 (into air)	4.57E + 01
Thorium-230 (into water)	4.57E + 01
Uranium-234 (into air)	1.22E + 01
Uranium-234 (into water)	1.22E + 01
Uranium-238 (into air)	1.07E + 01
Uranium-238 (into water)	1.07E + 01
Sr-90	7.16E − 03
Ru-106	5.03E − 03
Pb-210	1.52E + 00
Po-210	1.52E + 00
Ra-226	9.15E − 01

atmosphere is calculated with respect to the damage to materials [20,27]. Table 6 presents external environmental costs for Lithuania and EU average for 2010 and 2020 based on updated EcoSense-WebV1.2 model run for CASES project.

As one can see from Table 6 some external environmental costs are negative, i.e., the emissions of NMVOC have positive impact on biodiversity and emissions of NH_3 and SO_2 have positive impacts on crops. External environmental costs are decreasing in 2020 comparing with environmental external costs in 2010 for all pollutants. External environmental costs for Lithuania for biodiversity losses in Lithuania are little bit higher than average environmental costs for EU-27. External costs related to crops and material damage in Lithuania are very similar with average values for EU-27.

4. External costs of the main electricity generation technologies in Lithuania

Based on results of CASES and NEEDS projects total eternal costs of electricity generation technologies were assessed for Lithuania for 2010, 2020 and 2030. To calculate the external cost of each kWh of electricity produced, the marginal value for unit of emission is multiplied by the quantity of pollutants emitted at each production stage per unit of electricity. For the CASES project the emission database for electricity and heat generation in 2007, 2020 and 2030 was developed [23,28]. The life cycle inventory data for basic processes are taken from the LCA-database Ecoinvent in the version 1.2. The methodology adopted to estimate the emissions of pollutants for energy generation subdivides the process of electricity generation into four sub-processes representing the life cycle stages: power plant construction, fuel supply, power plant operation, power plant dismantling. Starting from a detailed process chain analysis, which for most technologies was specified down to the individual power plant components and their performance, the material and energy demand as well as the waste and the release of emissions were identified and quantified. These results for the individual processes refer to the functional unit of one kilowatt hour (1 kWh) of generated net electricity (i.e. electricity, which is supplied to the grid) and summed up along the process chain [29]. The LCI data analysis performed within CASES covers transport and construction services and the supply of materials. All direct and indirect emissions of the manufacturing and transportation of materials for the power plant construction are relevant. In addition, since during construction phase there is heat demand for several construction processes and before commissioning of fossil power plants, there are test runs of turbines, which go without generation of electricity, the also the heat and the energy demand for construction are taken in to account. Along the life cycle all wastes of the power plant operation as well as the material specific final end-of-life treatment at the power plant dismantling are balanced. Emissions caused by disposal of operational wastes are included in the process of power plant operation. While disposal of wastes at the end of the technical life time of the power plant are assigned to the process of power plant dismantling.

The 33 possible electricity production technologies [30,31] were selected as feasible for Lithuania for the assessment of external costs and presented in Table 7.

The total external costs consists from external costs of GHG emissions, external human health costs related to classical pollutants, external health costs related to emissions of heavy metals and radionuclides and external environmental costs due to biodiversity losses, damage to crops and materials. The following formula is applied to assess total external costs of specific electricity generation technology:

Table 6
External environmental costs in Lithuania and EU average in 2010 and 2020, EUR (2010)/t.

	2010		2020	
	EU-27	Lithuania	EU-27	Lithuania
Biodiversity losses				
NH_3	3868	2640	3902	2698
NMVOC	−79	−33	−57	−30
NOx	1069	699	1028	660
SO_2	210	165	227	
External costs related to crops damage				
NH_3	−217	−13	−217	−12
NMVOC	224	41	122	19
NOx	388	153	515	123
SO_2	−32	−17	−49	−19
External costs related to materials damage				
NOx	84	88	84	88
SO_2	307	221	307	221

Table 7
Selected electricity and heat generation technologies for long-term sustainability assessment.

Technologies and type of power plant for electricity production		
Nuclear		European Pressurized Reactor (EPR)
		Pebble Bed Modular Reactor (PBMR)
Fossil fired power plants	Oil	Heavy oil condensing power plant (PP)
		Light oil gas turbine
	Coal	Condensing PP
		Integrated Gasification Combined Cycle Power Plant (IGCC PP)
		IGCC PP with CO_2 capture and sequestration
	Lignite	Condensing PP
		IGCC
		IGCC PP with CO_2 capture and sequestration
	Natural gas	Combined Cycle PP
		Combined Cycle PP with CO_2 capture and sequestration
		Gas turbine (GT)
Hydropower	Run of river	Hydro Power Plant (HPP) with capacity <10 MW
		HPP with capacity <100 MW
		HPP with capacity >100 MW
	Dam	
	Hydro Power Pump Storage (HPPS)	
	Tidal power	
Wind	On shore	
	Off shore	
Solar PV	Roof	
	Open space	
Solar thermal		
Technologies and PP for electricity and heating production (CHP)		
Combined heat and power (CHP) plat with an extraction condensing turbine	Natural gas	Combined Cycle Power Plant (CC PP)
		CC PP with CO_2 capture and sequestration (CCS)
	Coal	PP
		IGCC PP with CO_2 capture and sequestration
CHP back pressure turbine	Natural gas	
	Coal	
Biomass CHP with an extraction condensing turbine	Straw	
	Wood chips	
Fuel cells	Natural gas	Molten Carbonate Fuel Cell (MCFC)
		Solid Oxide Fuel cell (SOFC)
	Bio gas	MCFC

$$E_{\text{technology}} = E_{\text{GHG}} + E_{\text{health class pol}} + E_{\text{Heavy metals}} + E_{\text{Radionuclides}} + E_{\text{environmental}} \quad (1)$$

here $E_{\text{technology}}$—total external costs of electricity generation technologies, EUR/kWh; E_{GHG}—external costs of GHG emissions, EUR/kWh; $E_{\text{health class pol}}$—the external human health costs related to classical pollutants, EUR/kWh; $E_{\text{Heavy metals}}$—external health costs related to emissions of heavy metals, EUR/kWh; $E_{\text{Radionuclides}}$—external health costs related to emissions of radionuclides, EUR/kWh; $E_{\text{environmental}}$—external environmental costs due to biodiversity losses, damage to crops and materials.

The external costs per specific category of external costs for current and future electricity generation technologies were evaluated by multiplying external costs of atmospheric pollutants, heavy metals and radionuclides emissions presented in Tables 2–6 by life cycle emissions of relevant pollutants per each electricity generation technology.

The external costs of GHG emissions for specific electricity generation technology are evaluated by applying the following formula:

$$E_{\text{GHG}\,j} = \sum_{i=1}^{3} e_{i\text{GHG}} \times k_{ij} \quad (2)$$

here $E_{\text{GHG}j}$—the external costs of GHG emissions for j technology, EUR/kWh; $e_{i\text{GHG}}$—external costs of i—pollutant (CO_2; CH_4; N_2O) emissions (Table 2), EUR/t; k_{ij}—lifecycle emissions of i-pollutant for j-technology, t.

The external human health costs related to classical pollutants for specific electricity generation technology are evaluated by applying the following formula:

$$E_{\text{health class pol}\,j} = \sum_{i=1}^{6} e_{i\text{ class}} \times k_{ij} \quad (3)$$

here $E_{\text{health class pol}}$—the external human health costs related to classical pollutants for j technology, EUR/kWh; $e_{i\text{ class}}$—external health costs of i- pollutant (NH3; NMVOC, NOx, PPMco, PPM_{25}, SO_2) emissions (Table 3), EUR/t; k_{ij}—life cycle emissions of i-pollutant for j- technology, t.

The external health costs related to emissions of heavy metals for specific electricity generation technology are evaluated by applying the following formula:

$$E_{\text{Heavy metals}\,j} = \sum_{i=1}^{9} e_{i\text{ heavy metals}} \times k_{ij} \quad (4)$$

here $E_{\text{Heavy metals }j}$—external health costs related to emissions of heavy metals for j technology; EUR/kWh; $e_{i\text{ heavy metals}}$—external health costs of i—heavy metal (Cd, As, Ni, Pb, Hg, Cr, Cr-IV, Formaldehyde, Dioxine) emissions (Table 4), EUR/t; k_{ij}—lifecycle emissions of i-heavy metal for j-technology, t.

The external health costs related to emissions of radionuclides for specific electricity generation technology are evaluated by applying the following formula:

$$E_{\text{Radionuclides}\,j} = \sum_{i=1}^{23} e_{i\text{ Radonuclides}} \times k_{ij} \quad (5)$$

$E_{\text{Radionuclides }j}$—external health costs related to emissions of radionuclides for j-technology, EUR/kWh; $e_{i\text{ Radionuclides}}$—external health costs of i-radionuclide emissions (Table 5), EUR/Bq; k_{ij}—life cycle emissions of i-radionuclide for j-technology, Bq.

Table 8
External costs of electricity generation technologies in Lithuania in 2010–2030, EURcnt (2010)/kWh.

No.	Electricity generation technologies	2010	2020	2030
1	Nuclear power plant (European Pressurized Reactor)	0.591	0.587	0.572
2	Heavy fuel condensing power plant	4.865	5.180	4.947
3	Light oil gas turbine	3.206	3.035	2.531
4	Had coal condensing power plant	5.250	4.404	3.425
5	Hard coal IGCC without CO_2 capture and sequestration (CCS)	4.960	3.696	2.891
6	Hard coal IGCC with CO_2 capture and sequestration	4.960	1.463	1.317
7	Lignite condensing power plant	5.381	4.367	3.828
8	Lignite IGCC without CO_2 capture and sequestration	5.312	4.078	3.123
9	Lignite IGCC with CO_2 capture and sequestration	5.312	1.252	1.122
10	Natural gas combine cycle without CO_2 capture and sequestration	2.549	2.126	1.652
11	Natural gas combine cycle with CO_2 capture and sequestration	2.549	0.949	0.827
12	Natural gas turbine	3.786	3.320	2.552
13	Hydropower run of river (10 MW)	0.160	0.159	0.143
14	Hydropower run of river (<100 MW)	0.114	0.113	0.103
15	Hydropower run of river (>100 MW)	0.103	0.102	0.092
16	Hydro power dam	0.199	0.197	0.179
17	Hydro power pump storage (HPPS)	0.193	0.192	0.175
18	Wind on-shore	0.137	0.135	0.124
19	Wind of-shore	0.152	0.150	0.141
20	Solar PV roof	0.548	0.529	0.465
21	Solar PV open space	1.142	1.105	0.981
22	Solar thermal parabolic trough	0.128	0.098	0.071
23	Natural gas CHP with extraction condensing turbine without CO_2 capture and sequestration	2.330	1.975	1.543
24	Natural gas CHP with extraction condensing turbine with CO_2 capture and sequestration	2.330	0.875	0.766
25	Hard coal CHP with extraction condensing turbine without CO_2 capture and sequestration	2.330	1.975	1.543
26	Hard coal CHP with extraction condensing turbine with CO_2 capture and sequestration	4.625	1.131	1.026
27	Natural gas combined cycle CHP with backpressure turbine	2.575	2.288	1.795
28	Hard coal CHP with backpressure turbine	5.005	4.358	3.478
29	Biomass (straw) CHP with an extraction condensing turbine	6.980	6.184	4.818
30	Biomass (woodchips) CHP with an extraction condensing turbine	6.038	5.368	4.004
31	MCFC (natural gas)	2.146	2.049	1.676
32	SOFC (natural gas)	1.273	1.021	0.906
33	MCFC (biogas)	3.400	3.329	2.622

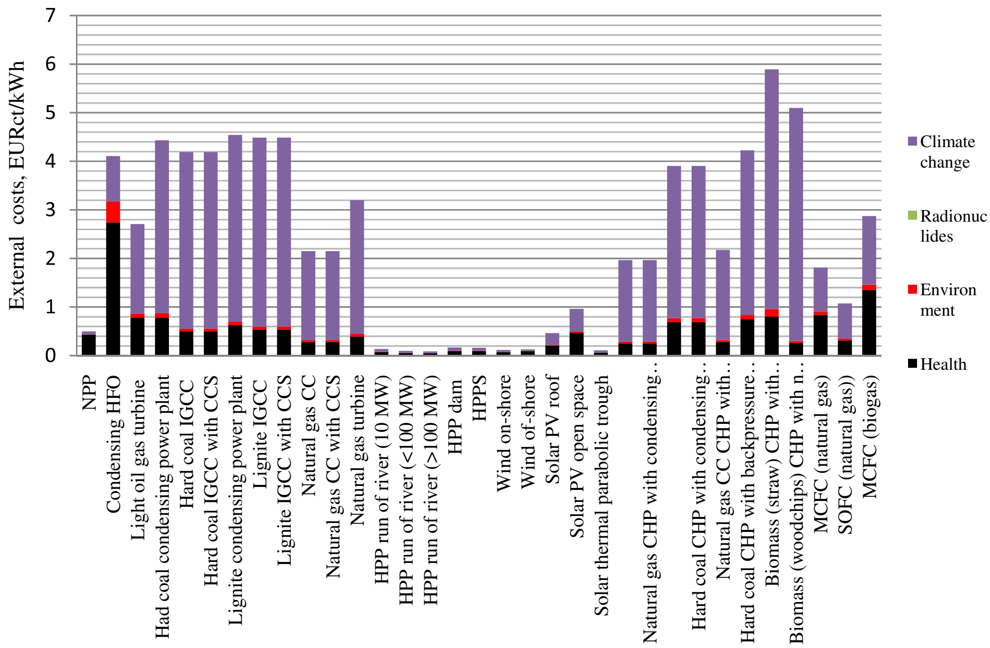

Fig. 1. External costs of 4 main categories for electricity generation technologies in Lithuania in 2010.

The environmental costs related to classical pollutants for specific electricity generation technology are evaluated by applying the following formula:

$$E_{\text{environmental}\ j} = \sum_{i=1}^{4} e_{i\ \text{biodiversity}} \times k_{ij} + \sum_{i=1}^{4} e_{i\ \text{crops}} \times k_{ij} + \sum_{i=1}^{2} e_{i\ \text{materials}} \times k_{ij} \quad (6)$$

here $E_{\text{environmental}\ j}$—external environmental costs due to biodiversity losses, damage to crops and materials for j-technology, EUR/kWh; $e_{i\ \text{biodiversity}}$—external environmental costs due to biodiversity losses of i-pollutant ($NH3$; NMVOC, NOx, SO_2) emissions (Table 6), EUR/t; k_{ij}—life cycle emissions of i-pollutant for j-technology, $e_{i\ \text{crops}}$—external environmental costs due to crops damage of i-pollutant (($NH3$; NMVOC, NOx, SO_2) emissions (Table 6), EUR/t; $e_{i\ \text{materials}}$—external environmental costs due to materials damage of i-pollutant (NOx, SO_2) emissions (Table 6), EUR/t.

Life cycle emissions for the current and future electricity generation technologies for all EU member states including Lithuania were assessed during NEEDS and CASES projects and incorporate in data bases [28]. In Table 8 summarizes total life-cycle external costs of electricity generation technologies in Lithuania in 2010–2030.

As on can see from information provided in Table 8 the biomass (straw and woodchips) CHP with an extraction condensing turbine have the highest external costs. The next worst technologies in

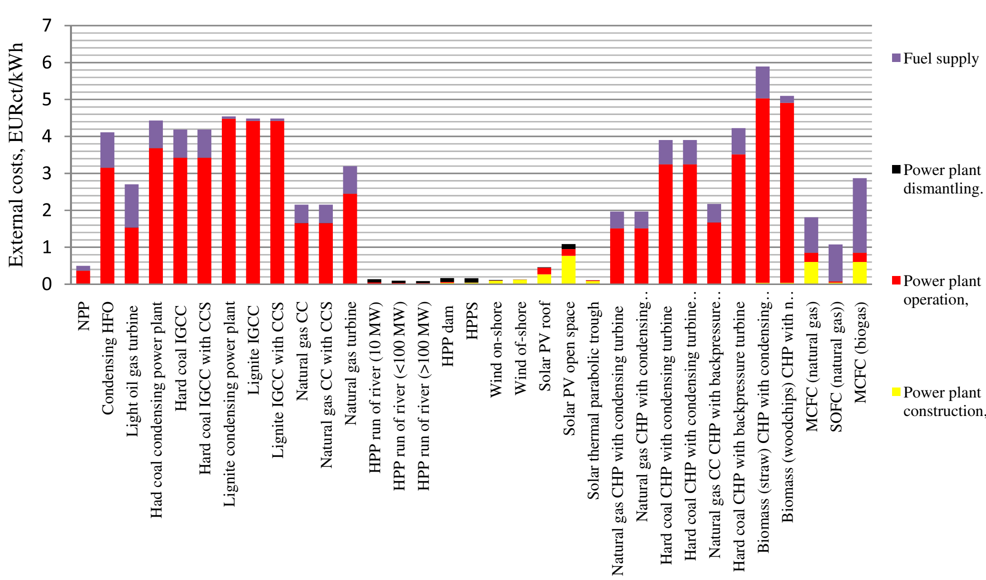

Fig. 2. External costs for sub-processes representing the life cycle stages of electricity generation technologies in Lithuania in 2010.

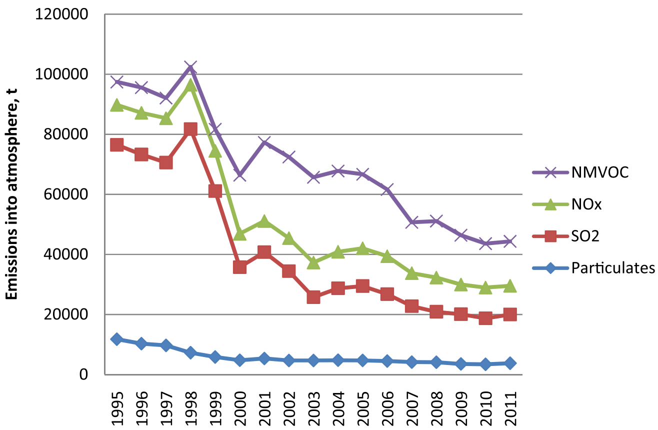

Fig. 3. The dynamics of NOx, SO_2, particulates and NMVOC and particulates in electricity sector of Lithuania.

terms of external costs are condensing power plants burning heavy fuel oil and anthracite. Nuclear power plants have the external costs lower than all other fossil fuel based technologies however their external costs are higher than for technologies based on renewable energy sources.

External costs of electricity generation technologies for 4 main categories of external costs: climate change external costs, external human health costs, external environmental costs and external costs of radionuclides in 2010 for Lithuania are presented in Fig. 1.

As one can see from Fig. 1 the highest external costs for all fossil fuel technologies and fuel cells technologies are related with climate change impacts. The second highest external costs for such technologies are related with human health. At the same time for renewable energy technologies external costs related to human health are high than external costs of climate change.

External costs for different stages of electricity generation technologies are presented in Fig. 2.

As one can see from Fig. 2 the highest external costs for traditional electricity generation technologies are related with power plant operation phase. At the same time for renewable energy technologies the highest external costs are related to power plant construction period. In addition nuclear power plants and power plants burning fossil fuel have quite high fuel supply costs.

Table 9 outlines estimates of external costs for technologies using specific fuels taken from other studies. The estimates are given in 2010 dollars, but have not otherwise been reconciled for heterogeneities in methodological approach.

The results obtained in the paper are compatible with other studies provided that fossil fuel based technologies have the highest external costs. Nuclear power plants have the external costs lower than all other fossil fuel based technologies however their external costs are higher than for technologies based on renewable energy sources. Other studies do not provide information on detailed structure of external costs. The estimated external costs of electricity generation technologies in Lithuania provides for policy recommendations discussed in the next chapter.

4.1. Policy implications

Before closure of Ignalina NPP in 2009 the nuclear electricity generation accounted for about 50% of all electricity generation capacities in Lithuania. Lithuania has ambitious plans to built new nuclear power plant. Currently Lithuania possesses the Lithuanian condensing power plant fired by oil, gas or orimulsion, several oil and gas fired combined heat and power plants and rather big hydro pumped storage power plant, several small hydro power plants and wind parks. The dynamics of electricity generation capacities in Lithuania is presented in Table 10.

As one can see from information provided in Table 10 the share of renewables in electricity generation in Lithuania has increased significantly since 1990. Especially significant increase can be noticed in wind energy. Currently thermal power generation having the highest external energy costs makes about 66% of total generation capacities. Renewables accounts to more than 34%. As regards to emissions to atmosphere they correspond to the positive changes of electricity generation structure. In Fig. 3 the dynamics of NOx, SO_2, particulates and NMVOC and particulates in electricity sector is presented.

External costs are not fully internalized in Lithuania via pollution taxes. They are significantly lower for the classical pollutants comparing with external costs of these pollutants presented in this paper. In 2012 in Lithuania the indexed tariff for SO_2 emissions made 127 EUR/t; for NOx emissions – 240 EUR/t, Particulates emissions – 75 EUR/t and for NMVOC emissions – 30 EUR/t.

The core mechanisms used in Lithuania to support RES-E are feed in tariffs. In 2002, the National Control Commission for Prices and Energy approved the average purchase prices of green electricity. The tariffs are guaranteed for a fixed period of 10 years. For hydro power – 57.9 EUR/MWh wind – 63.7 EUR/MWh and for biomass – 57.9 EUR/MWh tariff are being applied. The implementation of a green certificate scheme was, however, postponed for 11 years. The biggest renewables potential in Lithuania can be found in the field of biomass.

As renewable energy technologies have the lowest external costs the attempt to internalize external costs are necessary by increasing pollution taxes and increasing feed-in tariffs for renewable electricity. The green certificate schemes would also be useful for internalizing high negative externalities of fossil fuel based technologies. Such policies would help to increase competitiveness of technologies having the lowest external costs.

5. Conclusions

1. The best suited electricity generation technologies in terms of external costs for Lithuania are electricity generation technologies using traditional renewable (hydro and wind) as they have the lowest external costs. Solar technologies have a little bit higher total external costs however the parabolic solar collectors have the lowest external costs from all electricity generation technologies analysed inn Lithuania.
2. The biomass (straw and woodchips) CHP with an extraction condensing turbine have the highest external costs. The next worst technologies in terms of external costs are condensing

Table 9
Summary of estimated of external costs from various studies, mills per kWh (2010 prices).

	Coal	Peat	Oil	Gas	Nuclear	Biomass	Hydro	PV	Wind
Lee et al., 1995 [32]	2.3	–	0.35–2.11	0.35	0.53	3	–	–	–
Rowe et al., 1995 [33]	1.3–4.1	–	2.2	0.33	0.18	4.8	–	–	0.02
ExternE, 1995 [16]	27–202	27–67	40.3–148	13.4–53.8	3.4–9.4	0–67	0–13	8.1	0–3.4
National Research Council, 2010 [34]	2–126	–	–	0.01–5.78	–	–	–	–	–

Table 10
Electricity capacity in Lithuania, (MW).

		1990	Share, %	2001	Share, %	2006	Share, %	2010	Share, %
Nuclear	Nuclear	3000	51.19	3000	45.70	1300	27.72	–	–
	Ignalina NPP	3000	51.19	3000	45.70	1300	27.72	–	–
Thermal	Thermal	2656	45.32	2649	40.36	2330	49.68	2380	65.56
	Lithuanian PP (n.gas HFO)	1800	30.72	1800	27.42	1500	31.98	1500	41.32
	Vilnius CHP (n.gas, HFO)	384	6.55	384	5.85	380	8.10	370	10.19
	Kaunas CHP (n.gas, HFO)	190	3.24	180	2.74	180	3.84	170	4.68
	Mazeikiai CHP (HFO)	210	3.58	200	3.05	160	3.41	160	4.41
	Other CHP (n. gas)	72	1.23	85	1.29	110	2.35	180	4.96
Hydro	Hydro	106.1	1.81	1105.8	16.85	1020	21.75	1030	28.38
	Kruonis HPPS	–	–	900	13.71	900	19.19	900	24.79
	Kaunas HPP	100	1.71	100	1.52	100	2.13	100	2.76
	Other small HP	6.1	0.1	15	0.2	20	0.43	30	0.83
Renewables	Other renewables	–	–	–	–	40	0.85	220	6.06
	Other renewable (biomass)	–	–	–	–	10	0.21	20	0.55
	Wind PP	–	–	–	–	30	0.64	200	5.51
Total		5861	100	6564	100	4690	100	3630	100

power plants burning heavy fuel oil and anthracite. Nuclear power plants have the external costs lower than all other fossil fuel based technologies however their external costs are higher than for technologies based on renewable energy sources except technologies using biomass.

3. External costs of electricity generation technologies were reducing from 2010 to 2030 for all technologies. For fossil fuel plants the installation of Carbon capture and Storage (CCS) technologies since 2020 have reduced external costs about 3 times.
4. New electricity generation technologies based on fuel cells have external costs similar to traditional fossil fuel technologies using natural gas. The MCFC based technologies have the highest external costs among these new electricity generation technologies.
5. Comparing external costs of electricity generation technologies in Lithuania according for 4 main categories: climate change, human health, environmental and radionuclides the highest external costs for all fossil fuel technologies and fuel cells technologies are related with climate change impacts. The second highest external costs for such technologies are related with human health impacts. At the same time for renewable energy technologies external costs related to human health are high than external costs of climate change.
6. Comparing external costs of electricity generation technologies in Lithuania according the stages of technologies life cycle the highest external costs for traditional electricity generation technologies are related with power plant operation phase. At the same time for renewable energy technologies the highest external costs are related to power plant construction period. In addition nuclear power plants and power plants burning fossil fuel have quite high fuel supply costs.
7. As renewable energy technologies have the lowest external costs the further attempts to internalize external costs are necessary in Lithuania by increasing pollution taxes and increasing feed-in tariffs for renewable electricity. Current pollution taxes for classical pollutants are significantly lower than external costs of these pollutants emissions.
8. The implementation of green certificate schemes in Lithuania would also be useful for internalizing high negative externalities of fossil fuel based technologies. Such policies would help to increase competitiveness of technologies having the lowest external costs. The wind energy has the highest electricity generation potential and lowest external costs of electricity generation in Lithuania.

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