DIGITALES ARCHIV

ZBW – Leibniz-Informationszentrum Wirtschaft
ZBW – Leibniz Information Centre for Economics

Keiko, Alexander; Veselov, Fedor; Solyanik, Andrey

Article

Decarbonization options in the Russian energy sector : a comparative study on their economic efficiency

Provided in Cooperation with:
International Journal of Energy Economics and Policy (IJEEP)

Reference: Keiko, Alexander/Veselov, Fedor et. al. (2022). Decarbonization options in the Russian energy sector : a comparative study on their economic efficiency. In: International Journal of Energy Economics and Policy 12 (4), S. 368 - 378.
https://econjournals.com/index.php/ijeep/article/download/13100/6850/30775.
doi:10.32479/ijeep.13100.

This Version is available at:
http://hdl.handle.net/11159/12301

Kontakt/Contact
ZBW – Leibniz-Informationszentrum Wirtschaft/Leibniz Information Centre for Economics
Düsternbrooker Weg 120
24105 Kiel (Germany)
E-Mail: *rights[at]zbw.eu*
https://www.zbw.eu/econis-archiv/

Standard-Nutzungsbedingungen:
Dieses Dokument darf zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden. Sie dürfen dieses Dokument nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, aufführen, vertreiben oder anderweitig nutzen. Sofern für das Dokument eine Open-Content-Lizenz verwendet wurde, so gelten abweichend von diesen Nutzungsbedingungen die in der Lizenz gewährten Nutzungsrechte.

https://zbw.eu/econis-archiv/termsofuse

Terms of use:
This document may be saved and copied for your personal and scholarly purposes. You are not to copy it for public or commercial purposes, to exhibit the document in public, to perform, distribute or otherwise use the document in public. If the document is made available under a Creative Commons Licence you may exercise further usage rights as specified in the licence.

ZBW Leibniz-Informationszentrum Wirtschaft
Leibniz Information Centre for Economics

Mitglied der
Leibniz-Gemeinschaft

International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2022, 12(4), 368-378.

Decarbonization Options in the Russian Energy Sector: A Comparative Study on Their Economic Efficiency

Alexander Keiko, Fedor Veselov, Andrey Solyanik*

Energy Research Institute of the Russian Academy of Sciences, Moscow, Russia. *Email: andsolyanik@yandex.ru

Received: 24 March 2022 **Accepted:** 13 June 2022 **DOI:** https://doi.org/10.32479/ijeep.13100

ABSTRACT

The study is focused on the comparison of how costly different decarbonization options in Russia are, in terms of their total expenses per a unit of CO_2 avoided. We have constructed two marginal abatement cost curves reflecting different decarbonization policies in the Russian energy sector – basic and intensive scenarios. Doing that, we tried to adequately represent economic, regulation and climatic features of Russia (for instance, relatively low capital cost for most of the technologies, typical wind and solar conditions, regulation policy on natural gas cost, etc.). We found that non-carbon transport and energy savings in the demand side seem to be the most affordable decarbonization options in our country while solar heat, nuclear cogeneration and hydrogen as a carrier are uncompetitive in both scenarios observed.

Keywords: Decarbonization, Russian Energy Sector, Carbon Abatement Cost Curve, Non-carbon Technologies, Cost of Emission Avoided
JEL Classifications: Q42, Q47, Q48

1. INTRODUCTION

The global climate agenda has already led to a radical shift in the energy sector strategic planning all over the world. Just 15-20 years ago, the economic efficiency of the investments was the main criterion for policymakers; but nowadays the leading role in the strategic planning process is being played by environmental concerns of which decarbonization issues are generally assumed as most crucial. The need to reduce greenhouse gases (GHG) emission (especially CO_2 as the most prominent of them) in both the energy sector and the demand side (transport, energy-intensive manufacturing, residential sector) is broadly accepted now. To date, 48 countries that collectively account for 46% of global GHG emissions have proclaimed achieving the "carbon neutrality" of their economies by 2050-2060 (Climate Watch Net-Zero Tracker, 2020). Russia as a participant of the Paris Climate Agreement is also making some efforts toward this goal.

This study is aimed at the comparison of different decarbonization options in the Russian energy sector by their specific cost per a CO_2 unit avoided. We have calculated these costs with explicit consideration of national-specific conditions of Russia – both economic and climatic. Therefore, it should be noticed that the results of our study cannot be directly applied to any other country without taking into account its own national-specific features.

2. BACKGROUND

The majority of cost comparison studies on decarbonization technologies is conducted via so-called marginal abatement cost curves (MACC). MACC is a two-axis graph where the horizontal axis represents potential GHG emission reduction achievable via each decarbonization option while the vertical axis represents the specific cost incurred with this reduction.

According to our literature review, there are two principally different approaches to MACC formation – expert-based and model-based. In the first one, the costs are estimated individually for each of the analyzed technologies given the authors' assumptions about their technical and economic characteristics and for what extent they substitute the existing energy mix. It results in a "stepwise" MACC in which each "cost – emission" step corresponds with a certain technology. All the technologies are sorted by their specific cost per a unit of emission avoided. Some of them may even have negative cost if the energy savings overweight the overall cost associated with the deployment of a technology.

There are a lot of examples of the expert-based MACCs with the first of them taken place back in the early 1990s. Jackson (1991) presented the CO_2 abatement cost curve for the United Kingdom in 2005 which included 17 low-carbon technologies both in supply and in demand side. Mills et al. (1991) constructed MACC for 20 decarbonization technologies in Sweden. Blok et al. (1993) built a very detailed CO_2 abatement curve for the Netherlands with consideration of the payout time of mitigation measures. However, the early MACC studies were concentrated mostly on the power and heat supply and residential sector but did not include decarbonization options in the industry or transport. Also, the technological representation was limited from today's standpoint. For instances, renewable generation was usually treated as a "uniform" technology, without dividing it into wind, solar, biomass and other categories. In (Mills et al., 1991), only wind generation cost was calculated explicitly.

The first global MACC was developed by (McKinsey & Co, 2006) and represented the global CO_2 abatement cost curve engaging more than 40 decarbonization technologies across different sectors (energy sector, manufacturing, agriculture, transport, residential sector, etc.). The authors built the cost curve based on their own assumptions about technical, economic and environmental features of the technologies. They conducted the study "from a societal perspective" (McKinsey & Co, 2006, p. 9) and thus used a social discount rate, assumed full lifetime for capital-intensive technologies and excluded all taxes and subsidies from account. According to McKinsey's findings, roughly 1/3 of decarbonization options have negative values of CO_2 abatement cost which means they can pay their cost back themselves, without strong government support. The report found that transportation and housing services (water heating, air conditioning, lighting) are the most affordable decarbonization options. Later, the McKinsey's global MACC was updated in (Nauclér and Enkvist, 2009). Besides, some national-oriented MACCs were built on this methodological basis, each of them covers wide set of possible decarbonization options for the UK (HM Government, 2009), Ireland Republic (Kennedy, 2010), Mexico (Johnson et al., 2009), China (Du et al., 2015).

Moreover, there are numerous expert-based MACCs aimed at a specific sector of decarbonization policy. For instance, Thunder Said Energy Ltd, a consulting firm, UK, has built MACCs for carbon capture-and-storage technologies in different businesses (Thunder Said Energy Ltd, 2020). Similar curves but related to the energy saving options were built in (Jakob, 2006) for residential sector in Switzerland and in (Fleiter et al., 2009) for European manufacturing. Timilsina et al. (2017) evaluated carbon abatement cost for the building sector in Georgia and Armenia. Sotiriou et al. (2019) presented the cost curve for the activities that are not subject to European emission trading system.

The other way of MACC construction is the model-based approach. It utilizes a system-wide optimization model which simulates the outputs of different decarbonization policies. The most common method is to simulate different carbon payment rates (rarely – the impact of direct restrictions on several carbon-intensive technologies). In this case, MACC reflects the scenario-based cost of emission avoided rather than technology-based one (i.e., each "cost – emission" point on the graph corresponds to a certain decarbonization scenario). Consequently, MACC constructed via model-based approach is "smooth," not "stepwise," while there are some works aimed at transforming "smooth" model-based MACC into "stepwise" form using some assumptions (Kesicki, 2013).

There are two types of models that can be used for MACC construction. Energy system models (MARKAL, TIMES, OSeMOSYS, etc.) are aimed at proper simulation of the energy sector development with limited detalization of the other sectors of the economy (van Vuuren et al., 2004; Chen, 2005; Yu et al., 2020; Prina et al., 2021). In turn, general-equilibrium models (GEMs) are focused on the macroeconomic relations; they are quite helpful in measuring the outcomes of decarbonization policy on the economy-wide level (though highly aggregated), but their forecasting power is rather limited when investigating the outcomes for any individual industry. One of the first MACCs based on GEM were presented in several studies of MIT (Ellerman and Decaux, 1998; Paltsev et al., 2005). The authors used their original EPPA model under different constraints on carbon emissions, such as 10%, 20%, or 30% below reference emissions. For each set of constraints, the corresponding shadow prices of carbon are an output of the model. Other prominent works using computable general equilibrium framework were published later (Klepper and Peterson, 2006; Morris et al., 2012; Landis and Rausch, 2017).

Both expert-based and model-based approaches have their own pros and contras. Expert-based MACCs are more explicit, convenient for understanding, but they are unable to capture interrelations between different decarbonization options which can cause some positive or negative synergetic effect. Besides, expert-based MACCs are generally built as static (for present or certain forecast year) and therefore are limited in tracking how the investment decisions would really impact the energy mix in dynamics.

However, expert-based MACCs are helpful in screening out some options that are clearly uncompetitive under most of the scenarios overseen (these options are positioned close to the right edge of the MACC). Thus, stepwise MACC helps to establish the set of reasonable limitations and assumptions for each of decarbonization scenarios. These scenario assumptions would be subsequently included into the energy system models used as an analytical tool for the national energy policy development (EIA, 2014; PRIMES, 2017; ERIRAS, 2011). As a result, we have conducted our present study on an expert basis, while in our following studies we are going to implement an explicit system-wide modeling of the energy sector`s decarbonization scenarios.

The novelty of our study is the construction of the national-specific MACCs reflecting the economic, regulation and climatic conditions of Russia (we have not found any relevant works on MACCs for Russia or former USSR area). In particular, we considered relatively low-cost deployment of nuclear power plants which is specific for Russia due to almost 100% domestic production of technological equipment and low installation cost. We also evaluated the actual capacity factors for wind and solar generation, which correspond with the weather and climatic conditions of our country. For each conventional technology being replaced, the relevant mix of carbon-intensive fuels was estimated based on the actual national statistics. Finally, we also considered the current regulatory practice of limiting the natural gas prices which has a strong impact on the competition between energy carriers in the Russian energy market.

3. METHODOLOGICAL FRAMEWORK

The article observes a broad range of non-carbon technologies both in supply and demand side of the energy sector:

1. Energy-saving technologies in the demand side
2. Non-carbon electricity and heat generation technologies (nuclear, hydro and renewable power plants, carbon capture, utilization and storage (CCUS) on thermal plants, heat pumps, solar thermal plants, nuclear and biomass cogeneration)
3. hydrogen technologies for power sector (fuel cells and combined cycle gas turbines (CCGT) on hydrogen);
4. Non-carbon transport technologies (electric, biodiesel and fuel cell vehicles)
5. Electrification in the industry and residential sector (assuming that “green” electricity would substitute carbon-intensive processes, incl. process heat and steam generation in industry and residential heating).

In this paper, we present the MACC constructed from “social” rather than commercial standpoint. It means that we consider the full stuff of cost related to the technology integration (both capital and operational ones) excluding taxes and fees (being so-called transfer payments), but including all the cost related with the infrastructure necessary for decarbonization technologies considered (e.g., charging stations for electric cars and hydrogen refueling stations for fuel cell vehicles). Also, we consider the energy saving cost associated with the displaced fossil fuels.

MACC indicates specific cost associated with each 1 t of CO_2 avoided (*emission avoided cost, EAC*) which is calculated for each non-carbon technology as follows:

$$EAC_i = \frac{ADC_i - ES_i}{CE_i} \quad (1),$$

where i – index of the technology (nuclear plant, heat pump, electric vehicle and so on);

ADC – annualized discounted cost associated with deployment and operation of each technology from the list; *ADC* comprises three main parts – capital cost, fixed and variable operational cost (Equations 2-4);

ES – cash-denominated energy savings (annual avoided consumption of the carbon-intensive fuels that are assumed to be substituted by non-carbon energy) – see Equation 9;

CE – annual physical amount of the carbon emissions saved due to technology *i* deployment (see Equation 10).

In our study, the *ADC* is calculated as follows:

1. For the technologies producing electricity or heat:

$$ADC_i = \left[\frac{capex_i \cdot A + opex\_f_i}{CF_i \cdot 8760} + ER_i \cdot P_i\right] \cdot W_i \quad (2),$$

where $capex_i$ – capital expenses per a unit of the installed power/heat capacity of the technology *i*;

A – annuity rate;

$opex\_f_i$ – fixed operational cost per a unit of installed power/heat capacity produced of the technology *i*;

CF_i – capacity factor of the technology *i* which characterizes its capacity utilization rate on an annual basis;

8760 – full number of hours in a year;

ER_i – the efficiency rate at which technology *i* converts its input energy into the output energy;

P_i – price per a unit of the energy carrier consumed by technology *i*;

Wi – annual amount of electricity (heat) produced by the technology *i* (Equation 6).

The variable cost ($ER_i \cdot P_i$) of hydro, geothermal, wind and solar power plants equals zero as they do not consume fuel.

2. For the demand-side technologies consuming electricity (i.e., electrification options in manufacturing or residential sector)

$$ADC_i = \left[\frac{capex_i \cdot A + opex\_f_i}{CF_i \cdot 8760} + P_i\right] \cdot E_i \quad (3),$$

where E_i – annual amount of electricity consumed by the technology *i* (Equation 7).

The main difference of the Equation 3 contrast to the Equation 2 is that the former operates the variables (*capex*, *opex_f*, *CF*) specified per a unit of consumed rather than produced power – an approach that is largely common in the technical literature when it comes to economic comparison between technologies consuming electricity in the demand side.

3. For the transport technologies:

$$ADC_i=(capex_i \cdot A+opex\_f_i) \cdot n_i+P_i \cdot E_i \quad (4)$$

$ADC_i = (capex_i \cdot A + opex\_f_i) \cdot n_i + P_i \cdot E_i$ where n_i – the number of the automotive units of type *i* which can be obtained as:

$$n_i = \frac{E_i}{\bar{m}_i} \qquad (5),$$

where $\bar{m}_i$ – the average annual mileage covered by an automotive unit of type *i*.

The distinguishing feature of the Equation 4 is that it operates the variables (*capex, opex_f, CF*) expressed per a unit of automotive fleet. The full number of units deployed can be found by dividing the cumulative annual energy consumption of the fleet (E_i) on the average annual mileage covered by an automotive unit of this type. For the average Russian light duty vehicle, this figure is 17500 km (Autostat, 2019).

All major inputs for *ADC* calculations are summarized in Table 1. These data corresponds to the cost and performance parameters of technologies being commissioned to 2025. It is obvious that due to the technological learning parameters of the carbon abatement technologies listed below will change considerably even by 2035-2040 and it will affect the profile of MACC for the future. That's why we considered the evolution of MACC from 2020-2025 to 2035-2040 using the lower capex estimations for almost all technologies.

For each of the technologies considered, its energy produced (W_i) or consumed (E_i) is derived from the corresponding value of the carbon-intensive energy *j* (E_j) which is subject to be substituted. Here E_j values are our expert-based estimations developed for each of the decarbonization scenarios simulated.

$$W_i = E_j \cdot k_{ij} \cdot \eta_j \qquad (6)$$

$$E_i = \frac{E_j \cdot k_{ji} \cdot \eta_j}{\eta_i} \qquad (7),$$

where E_j – annual amount of primary energy associated with the carbon-intensive fuel *j* that is assumed to be substituted by non-carbon energy carrier *i* (relationships between substituting and substituted energy carriers are summarized in Table 2);

k_{ij} – coefficient converting primary energy to the natural energy units of the non-carbon energy carrier *i*;

η_j и η_i – net efficiency rates of the substituted (*j*) and substituting (*i*) technology.

For non-carbon technologies related with combined production of electricity and heat (nuclear or biomass cogeneration) we have

Table 1: List of non-carbon technologies analyzed and their technical parameters

	CAPEX (2020-25)	CAPEX (2030-35)	Const-ruction time, years	OPEX, % of CAPEX	CF, %	η, %	Ref.
Power supply							
Nuclear PPs	2270 USD/kW	2050 USD/kW	6	3	90		OECD, IEA 2020
Hydro PPs	1650 USD/kW	1650 USD/kW	8	2	50		IRENA, 2021
Wind PPs	900 USD/kW	700 USD/kW	2	2	15		Power purchase agreements
Solar PPs	1100 USD/kW	975 USD/kW	2	3	27		
Geothermal PPs	3335 USD/kW	3335 USD/kW	3	2	74		IEA 2020; IRENA 2021
CCGTs with CCS	2650 USD/kW	2550 USD/kW	4	4	70	50	IEA, 2020
Heat supply							
Biofuel district heat	300 EUR/kW_{th}	300 EUR/kW_{th}	2	2	40	85	European Commision, 2018
Nuclear CHPs	350 000 RUB/kW	300 000 RUB/kW	3	2	65		Data collected from national nuclear engineering companies
Solar heat (CSP)	4800USD/kW[1]	3850 USD/kW	2	2	65	90	IRENA, 2021
Heat pumps	950 EUR/kW	860 EUR/kW	1	1	40	300	(DEA 2020), 3 MW system
Transport							
Electric vehicles	28400 USD/unit	21800 USD/unit	-	5	-	18,7 kWh/100 km	Nissan Leaf (caranddriver.com; fueleconomy.gov)
Hydrogen-fueled heavy duty vehicles (HDV)	258000 USD/unit	198000 USD/unit	-	5	-	0,8 kg H_2/100 km	(NREL 2020), 750-miles HDV
Biodiesel vehicles	23500 USD/unit	21500 USD/unit	-	5	-	7 l/100 km	
Electrification in the demand-side							
Manufacturing	30 USD/kW	30 USD/kW	1	11	90	95	Domestic manufacturer data
Residential services	40 USD/kW	40 USD/kW	1	11	50	95	
Hydrogen technologies							
CCGT on hydrogen	1150 USD/kW	1000 USD/kW	3	2	60	60	(IEA, 2019), ERI RAS estimations
Fuel cells on hydrogen	1300 + 350 USD/kW (electrolyzer + compressor and storage)	800 + 250 USD/kW (electrolyzer + compressor and storage)	3	2	90	65	

---

[1] Excluding cost of the steam turbine (approximately 20% of the total CSP cost)

Table 2: Relationships between substituting and substituted energy sources

Non-carbon technology introduced	Substituted energy mix	Comments
Power supply		
Nuclear PPs	95% natural gas+5% coal	NPPs are planned to be installed in the European part of Russia only
Hydro PPs	30% natural gas+70% coal	Most of the hydropower potential is accumulated in the Asian part of Russia
Wind PPs	70% natural gas+30% coal	Average fuel mix in the Russian power supply sector
Solar PPs		
Geothermal PPs		
Thermal PPs with CO_2 capture and storage	100% natural gas	Assuming coal power plants to be entirely substituted by other non-carbon sources
Heat supply		
Biofuel CHPs pellets	30% natural gas+70% coal	Most of the biomass resources are situated in Siberia. Taking this, we assumed Siberian-based coal CHPs and boiler plants to be substituted in the larger part
Nuclear CHPs	95% natural gas+5% coal	Nuclear CHPs are planned to be installed in the European part of Russia only
Solar heat	70% natural gas+30% coal	Average fuel mix in the Russian heat supply sector
Heat pumps		
Transport		
Electric vehicles	100% gasoline	Light duty vehicles
Hydrogen fuel cell vehicles	100% diesel	Heavy duty vehicles, buses[2]
Biodiesel vehicles	100% diesel	Heavy duty vehicles, buses
Demand-side electrification		
Manufacturing	70% coal+30% oil fuel	Industrial heat plants (actual fuel mix in Russia)
Residential services	100% coal	Assuming the prior substitution of carbon-intense coal heat supply sources

implemented a more sophisticated procedure. First, we calculated specific cost of 1 Joule of output energy (hereinafter – levelized cost of Joule, LCOJ) the same way as in the equation 2, but with substitution of the latter multiplier by cumulative amount of output energy (i.e. electricity plus heat) produced by the technology within a year. Second, we reduced this value by subtraction of the specific cost of electricity (per kWh) calculated for the same technology assuming its operation in “electricity-only” mode without cogeneration. So that, the resulting formulae looks like:

$$LCOH_{chp} = LCOJ_{chp} - LCOE_{eop} \cdot W_{chp} / Q_{chp} \qquad (8),$$

where $LCOH_{chp}$ – levelized cost per a unit of heat generated by the considered cogeneration technology;

$LCOE_{eop}$ – levelized cost per a unit of electricity generated by the benchmarking “electricity-only” plant;

W_{chp} – annual electricity production by the cogeneration technology considered;

Q_{chp} – annual heat production by the cogeneration technology considered.

The cash-denominated amount of energy savings (*ES* in the Equation 2) can be found as:

$$ES_i = \sum_j F_j \cdot P_j, j \in i \qquad (9),$$

where F_j – annually consumed amount of the carbon-intensive fuel *j*; it is assumed each of the considered non-carbon technologies (*i*) would substitute corresponding sorts of carbon fuels (this relationship is summarized in Table 2);

P_j – price per a unit of the carbon-intensive fuel *j* (Table 3).

Table 3: Characteristics of carbon-intensive fuels

Energy carrier	Efficiency rate (η_j)	Price (P_j)	
		RUB/t c.e.[3]	USD/t c.e.
Coal (power supply)	370 g c.e./kWh	3300	45
Coal (heat supply)	0,167 kg c.e./Gcal		
Natural gas (power supply)	300 g c.e./kWh	4650	64
Natural gas (heat supply)	0,155 kg c.e./Gcal		
Gasoline	8 l/100 km	38000	520
Diesel	6,5 l/100 km	36800	504
Fuel oil	0,159 kg c.e./Gcal	15800	216

Appropriately, the physical amount of carbon emissions avoided (*CE* in the Equation 2) can be found as:

$$CE_i = \sum_j F_j \cdot \bar{c}_j, j \in i \qquad (10),$$

where $\bar{c}_j$ – CO_2 content per a weight unit of fuel *j* (Table 4).

4. RESULTS AND DISCUSSION

We have built MACCs for two scenarios each of them reflects different pace toward low-carbon economy in Russia. Each scenario was built under our expert judgements about energy mix shift spurred by different rates of carbon tax in our country.

The basic scenario assumes zero carbon tax. The need to comply with the environmental requirements introduced in the main export markets is assumed to be dominant driver of decarbonization in this scenario. We estimate the total volume of avoided carbon fuel consumption at 270 mln t of coal equivalent and the avoided volume of GHG emissions at 625 mln t of CO_2.

The intensive scenario assumes a sustainable increase in the carbon tax rate – up to 100 USD/t CO_2 by 2050. This would

---

[2] International studies indicate very low efficiency of hydrogen as a fuel for light duty transport

[3] National statistical data as of January 2021 г., converted in tonnes of coal equivalent (t c.e.) – ideal energy density measure (7000 kcal/kg)

inspire much more solid reduction of the carbon-intensive fuels utilization. Our estimates show the potential of this reduction can reach 630 mln t of coal equivalent with the reduction of GHG at 1480 mln t of CO_2.

Figures 1 and 2 presents our estimations of initial (capital) cost necessary for non-carbon technologies deployment. These figures, therefore, do not account for any operational costs related with analyzed technologies. Such MACCs are important when quantifying what amount of financial support is required for decarbonization projects to break-through into the market.

As the figures show, the strongest reduction in GHG emissions in both the basic and the intensive scenarios could be obtained through energy savings measures in the demand side (233 and 272 mln t of CO_2-equivalent, respectively). They are succeeded by nuclear PPs (reductions of 136 and 290 mln t of CO_2-equivalent, respectively). Hydroelectric power plants and (in the intensive scenario) wind power plants also provide significant savings in GHG emissions. The smallest contribution to GHG savings is made by hydrogen technologies, carbon capture and storage (CCS) and geothermal energy.

With investment costs standpoint, energy efficiency measures are the most efficient in both scenarios (less than 18 USD/t CO_2) succeeded by electrification technologies in industry and district heating (53 and 58 USD/t CO_2, respectively). The use of biomass (pellets for district heat, biodiesel for transport, biofuel boiler facilities) is also non-capital-intensive decarburization option. The level of investment costs required by them is approximately 108-138 USD/t CO_2.

Table 4: CO_2 content of carbon-intensive fuels (IPCC 2006)

Energy carrier	CO_2 content	
	t/TJ	t/t of fuel (t/th.m^3 of natural gas)
Coal	94.6	2.77
Natural gas	56.1	1.64
Gasoline	69.3	2.03
Diesel	74.1	2.17
Oil fuel	77.4	2.27

The majority of carbon-free power generation technologies are in the middle of the investment cost curve: Their capital cost varies from 280 to 560 USD/t CO_2. The lower end of the range corresponds to the indicators of nuclear power plants (NPPs) - the least-cost from all carbon-free generation technologies in the Russian conditions. Hydropower plants (HPPs) are in the middle of the range presented above. Renewable generation (wind and solar PP) is characterized by higher level of costs - 470 and 560 USD/t CO_2, respectively.

For the rest of the carbon-free technologies, implementation costs begin to skyrocket. Thus, the electrification of transport will require costs at the level of 800 USD/t CO_2. Heating plants based on solar concentrators require initial cost up to 2000 USD/t CO_2. The most capital intensive technologies are fuel cell vehicles and nuclear combined heat and power (CHP) plants (both of them require about 2500 USD/t CO_2 of investments).

Figures 3-6 shows the values of full cost related with the deployment of carbon-free technologies in both scenarios. Since these estimations are accounted for operational costs along with capital expenditures, they are obviously different from those presented in the previous figures. In order to capture foreseeable progress in economics of the carbon-free technologies considered, we used 2 time slots – 2020-2025 and 2030-2035 – with the calculations made for each of them.

As of 2020-2025, large majority of carbon-free technologies has positive values of CO_2 avoided cost (Figure 3). Only two of them (biodiesel duty vehicles and energy conservation measures)

Figure 1: Initial cost (investments) per a unit of the CO_2 emission avoided (basic scenario)

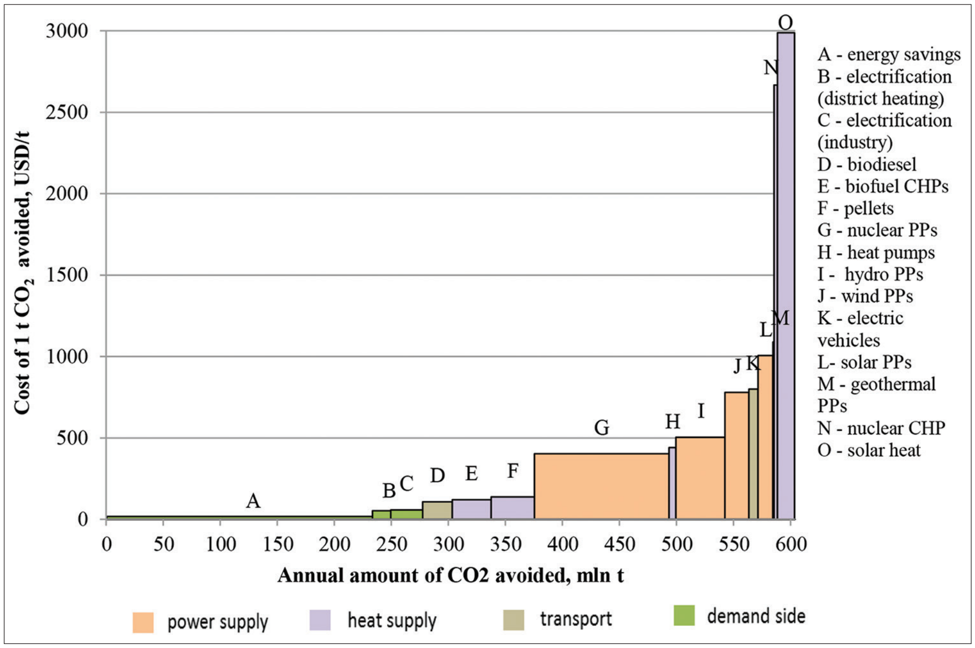


Figure 2: Initial cost (investments) per a unit of the CO2 emission avoided (intensive scenario)

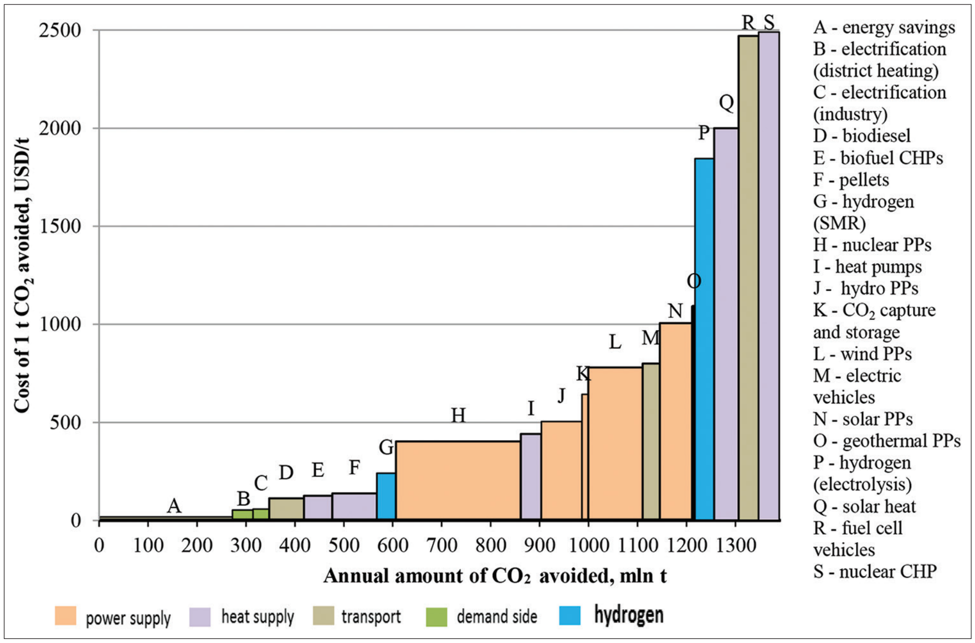
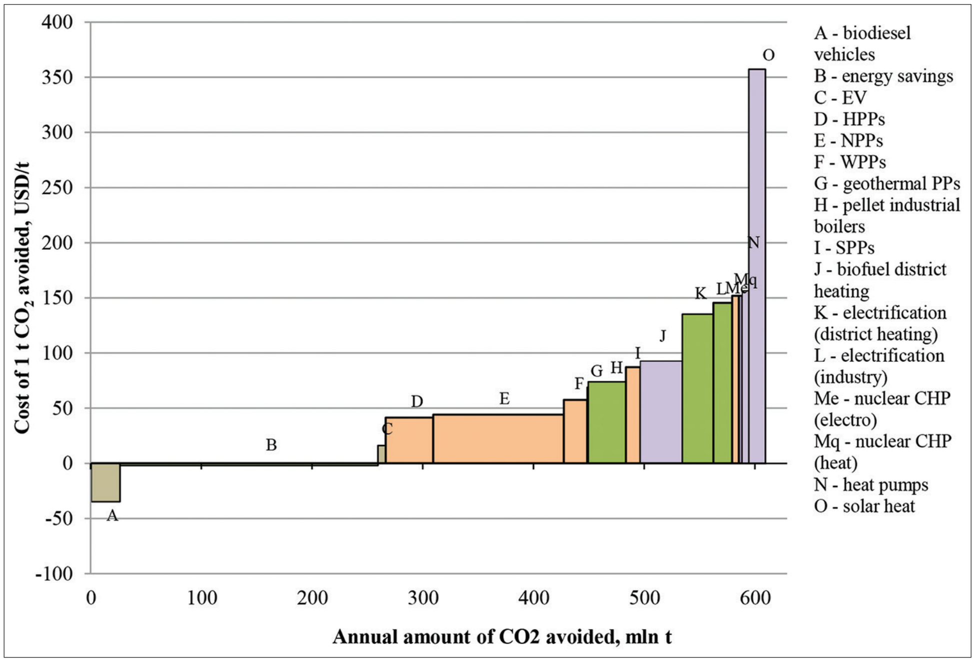


Figure 3: Total cost related to the CO_2 emission avoided, 2020-2025 (basic scenario)



are placed in the negative zone of the graph, i.e. they are net-beneficial. Electric vehicles (EV) require 16 USD for each t CO_2 abated. For most of the electricity generation technologies, this figure varies in the range of 40-90 USD/t CO_2. The lower end of this diapason is attributed to conventional types of carbon-free generation – nuclear and hydropower – while wind, geothermal and especially solar PV generation is more expensive (58, 69 and 87 USD/t CO_2, respectively). On the other hand, electricity generation technologies typically cause lower cost of CO2 abated than heat generation sources. Of the latters, biofuel district heating is the least-cost option (93 USD/t CO_2) while nuclear CHP, heat pumps and especially solar heat are much more expensive.

By 2030-2035, significant reduction in capital cost is expected for many of the carbon-free technologies observed (Figure 4). As a result, the cost curve would become more flat. The cost of CO_2 abatement would decrease for all electricity generation technologies, especially for wind and solar PP: with the cost of 41 and 55 USD/t CO_2 respectively, they would become fully competitive with conventional carbon-free generation in term of cost of emissions over the whole lifecycle. Heat supply options will also experience a cost decline (with the most visible drop attributed to solar heat, though it would remain the most costly decarbonization option in our country). But the most impressive progress throughout all the analyzed stuff of the technologies is expected for EV – their cost of CO_2 abatement would be as low

Figure 4: Total cost related to the CO_2 emission avoided, 2030-2035 (basic scenario)

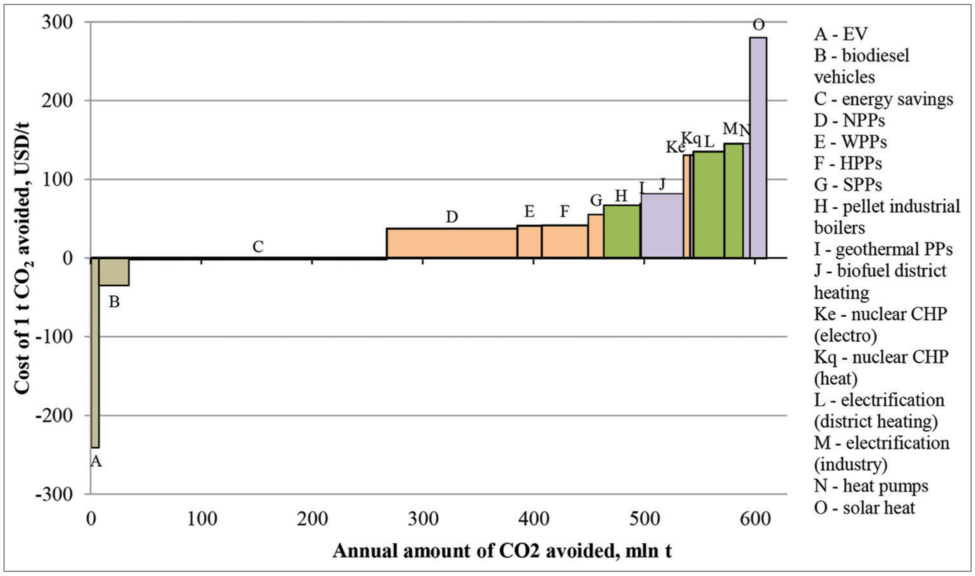
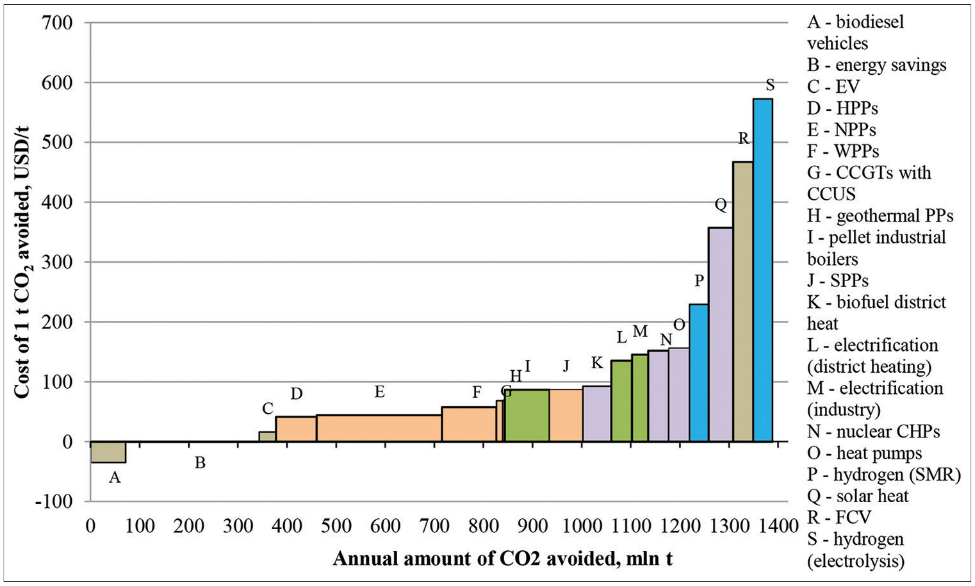


Figure 5: Total cost related to the CO2 emission avoided, 2020-25 (intensive scenario)



as −230 USD/t CO_2. This result is achievable thanks to expected drop in the cost of car batteries which are accounted for significant part of the car's initial cost as well as its total cost of ownership over the lifecycle.

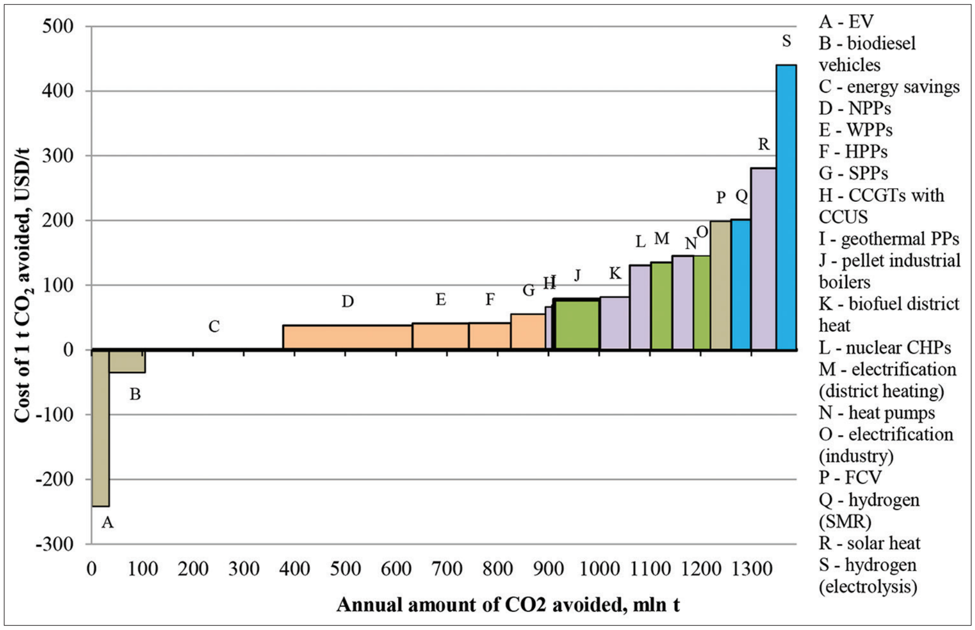
In the intensive scenario, some additional carbon-free technologies are added to the analysis – CCGT with CCUS, fuel cells vehicles and hydrogen production technologies. Besides, expanded ranges of annual amount of CO_2 abated are applied for most of the technologies. For instance, NPPs save 255 mln t CO_2 in the intensive scenario contrast to 118 mln t in the basic one. Similarly, wind PP's contribution in CO_2 reduction would rise from 21 mln t in the basic scenario by 110 mln t in the intensive scenario. Other carbon-free technologies also increase their participation in CO_2 reduction in 1.2-2 times regarding basic scenario.

The estimations of the carbon abatement cost related to the intensive scenario are shown in Figures 5 and 6.

According to our estimations, the most cost-efficient decarbonization options in Russia lie in transportation sector. The deployment of biodiesel-fueled vehicles could bring about 35 USD of net savings per each 1 t CO_2 avoided. Electric vehicles require only marginal expenses in 2020-2025 (16 USD/t CO_2) but could become net cost-benefit decarbonization option by 2030-35, with the annual effect of −230 USD/t CO_2. However, this figure does not include any infrastructural cost related with EV deployment. We assume that EV deployment will occur mostly in the biggest agglomerations of our country and therefore will be limited in scales of CO_2 abatement (only 35 mln t of savings per year).

Energy saving measures in the demand side are also net-positive from the total cost standpoint though they net effect is relatively modest (around 2 USD/t CO_2). Nonetheless, these measures play the leading role in the basic scenario accounting for around 30% of emissions cut in this scenario.

Figure 6: Total cost related to the CO2 emission avoided, 2030-35 (intensive scenario)



Within power generation sector, hydro and nuclear PPs are the least cost decarbonization options with 41 and 44 USD/t CO_2, respectively. They are succeeded by wind PPs which cost of emissions avoided is estimated at 55 USD/t CO_2. Solar power generation (87 USD/t CO_2) is expected to be the least effective decarbonization option in the power sector because of relatively poor insolation conditions in the most of the Russian Federation`s territory.

Within heat supply technologies, the most effective option is biofuel district heat which cost is around 93 USD/t CO_2 with amount of emission abated near 58 mln t annually. Solar heat utilization is the less efficient measure of decarbonization (345 USD/t CO_2) preceded by nuclear CHP (302 USD/t CO_2).

In the intensive scenario, some additional technologies occur, of which only carbon capture-and-storage (CCS) technology could be assumed as medium-effective (132 USD/t CO_2), but its niche is very limited because most of the carbon-intensive coal power plants in this scenario are substituted by other non-carbon technologies which are less cost.

Hydrogen is the least efficient energy carrier in the intensive scenario. When used via CCGT, its carbon avoided cost in 2030-35 will be 415 USD/t CO2. Hydrogen utilization via fuel cells will be more efficient (with carbon avoided cost at 375 USD/t CO2), but yet to make them economically rational option.

5. CONCLUSIONS AND POLICY IMPLICATIONS

In the study, we estimated specific cost of CO_2 emission abated for relatively wide range of low-carbon and carbon-free energy technologies taking into account some critical economic and climate conditions of Russia as well as its current energy mix. Doing this, we built the marginal abatement cost curve that exhibit the relative efficiency of these technologies in both economic and environmental terms.

It is shown that the most promising and least expensive methods of decarbonization in the Russian case study are automotive transport, primarily biodiesel and electric vehicles. This can be explained by foreseeable drop in the consumption of petroleum fuels and the possibility of maximizing the use of the infrastructure created for the production and operation of internal combustion engines. There is also a significant potential for energy saving in industry and construction.

These three areas of decarbonization can be treated as self-paid investment projects (excluding required charging/refueling infrastructure). Other areas discussed will require the introduction of certain CO_2 regulation mechanisms designed to reallocate investment resources in favor of low-carbon technologies. In this category, nuclear and hydropower plants seem to be the most competitive in terms of cost-to-climate efficiency, followed by wind and solar generation.

The conditions for the widespread use of CCUS technologies in Russia have not yet developed. The potential of this direction of decarbonization, which is in demand in areas with predominant coal generation, is currently relatively small.

The technologies of nuclear heat supply and hydrogen energy turned out to be closing. From this point of view, the programs of hydrogen energy development being adopted in Russia are still significantly separated from the real prospects for implementation.

At the same time, our assessments reflect the static state of the technology structure, and in the period up to 2050, which is chosen as the planning horizon, the situation may change due to the known effects of scientific and technological progress and the economic incentives for low-carbon energy being taken. The assessment of these effects and their impact on the structure of technologies in the Russian energy sector is the subject of our planned studies based on the model-based approach.

The results obtained are generally consistent with similar estimates for other countries and the world as a whole. The greatest differences are observed in estimates of the volume of application of CCUS technologies and the investments required for this, as well as in estimates of the prospects for hydrogen energy. The forecast for the development of these technologies for Russian conditions looks more pessimistic than in foreign studies. Refinement of these estimates is included in the development plans of this study.

6. ACKNOWLEDGMENT

This study was made under financial support of the Russian Science Foundation (RSF), № 21-79-30013.

REFERENCES

Autostat. (2019), Available from: https://www.autostat.ru/news/39841

Blok, K., Worrell, E., Cuelenaere, R., Turkenburg, W. (1993), The cost effectiveness of CO_2 emission reduction achieved by energy conservation Energy Policy, 21(6), 656-667.

Caranddriver. Available from: https://www.caranddriver.com/news/a37210246/2022-nissan-leaf-price

Chen, W. (2005), The cost of mitigation carbon emissions in China: Findings from China MARKAL-MACRO modeling. Energy Policy, 33(7), 885-896.

Climate Watch Net-Zero Tracker. (2020), Climate Watch Net-Zero Tracker. Washington, DC: World Resources Institute. Available from: https://www.climatewatchdata.org/net-zero-tracker

DEA. (2020), Technology Data for Generation of Electricity and District Heating. Danish Energy Agency. Available from: https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-generation-electricity-and

Du, L., Hanley, A., Wei, C. (2015), Estimating the marginal abatement cost curve of CO_2 emissions in China: Provincial panel date analysis. Energy Economics, 48(C), 217-229.

EIA. (2014), The Electricity Market Module of the National Energy Modeling System: Model Documentation. Washington, DC: EIA. Available from: http://www.eia.gov/outlooks/aeo/nems/documentation/electricity/pdf/m068(2014)pdf

Ellerman, D.A., Decaux, A (1998), Analysis of Post-Kyoto CO_2 Emissions Trading Using Marginal Abatement Curves. Cambridge, MA, Massachusetts Institute of Technology: Joint Program Report Series Report. p24.

ERIRAS. (2011), Modeling Complex SCANER, ERI RAS, Moscow. Available from: https://www.eriras.ru/data/92/eng

European Commission. (2018), Cost-efficient District Heating Development. Available from: https://ec.europa.eu/energy/studies_main/final_studiescost-efficiency-district-heating-development_en

Fleiter, T., Eichhammer, W., Hagemann, M., Wietschel, M., Hirzel, S. (2009), Costs and Potentials of Energy Savings in European Industry-a Critical Assessment of the Concept of Conservation Supply Curves. La Colle sur Loup, France: ECEEE 2009 Summer Study.

Fueleconomy. (2021), Available from: https://www.fueleconomy.gov/feg/Find.do?action=sbs&id=43664

HM Government. (2009), Analytical Annex-the UK Low Carbon Transition Plan. London: HM Government.

IEA. (2019), The Future of Hydrogen. IEA. Available from: https://www.iea.org/reports/the-future-of-hydrogen

IEA. (2020), World Energy Outlook 2020. Available from: https://www.iea.org/reports/world-energy-outlook-2020

IPCC. (2006) Inter Government Panel on Climate Change. IPCC. Available from: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf

IRENA. (2021), Renewable Power Generation Costs in 2020. International Renewable Energy Agency. Available from: https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020

Jackson, T. (1991), Least-cost greenhouse planning supply curves for global warming abatement. Energy Policy, 19(1), 35-46.

Jakob, M. (2006), Marginal costs and co-benefits of energy efficiency investments: The case of the Swiss residential sector. Energy Policy, 34(2), 172-187.

Johnson, T.M., Alatorre, C., Romo, Z., Liu, F. (2009), Low-Carbon Development for Mexico. Washington, DC: World Bank.

Kennedy, M. (2010), Ireland's Future: A Low Carbon Economy? The Impact of Green Stimulus Investment. Vilnius, Lithuania: IAEE European Conference.

Kesicki, F. (2013), Marginal abatement cost curves: Combining energy system modelling and decomposition analysis. Environmental Modeling and Assessment, 18, 27-37.

Klepper, G., Peterson, S. (2006), Marginal abatement cost curves in general equilibrium: The influence of world energy prices. Resource and Energy Economics, 28(1), 1-23.

Landis, F., Rausch, S. (2017), Deep transformations of the energy sector: A model of technology investment choice. Energy Economics, 68(S1), 136-147.

McKinsey Co. (2006), A Global Study of the Size and Cost of Measures to Reduce Greenhouse Gas Emissions Yields Important Insights for Businesses and Policy Makers. Available from: https://www.mckinsey.com/business-functions/sustainability/our-insights/a-cost-curve-for-greenhouse-gas-reduction

Mills, E., Wilson, D., Johansson, T.B. (1991), Getting started: No-regrets strategies for reducing greenhouse gas emissions. Energy Policy, 19(6), 526-542.

Morris, J., Paltsev, S., Reilly, J. (2012), Marginal abatement costs and marginal welfare costs for greenhouse gas emissions reductions: Results from the EPPA model. Journal of Environmental Modeling and Assessment, 17(4), 325-336.

Nauclér, T., Enkvist, T.P. (2009), Pathways to a Low-Carbon Economy-Version 2 of the Global Greenhouse Gas Abatement Cost Curve. McKinsey and Company. Available from: https://www.mckinsey.com/~/media/mckinsey/dotcom/client_service/sustainability/cost%20curve%20pdfs/pathways_lowcarbon_economy_version2.ashx

NREL. (2020), Future Automotive Systems Technology Simulator. National Renewable Energy Laboratory. Available from: https://www.nrel.gov/transportation/fastsim.html

OECD, IEA. (2020), Projected Cost of Generating Electricity. Paris, France: OECD, IEA.

Paltsev, S., Reilly, J.M., Jacoby, H.D., Eckaus, R.S., McFarland, J., Sarofim, M., Asadoorian, M., Babiker, M. (2005), The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. Cambridge, MA: MIT Joint Program on the Science and Policy of Global Change.

PRIMES. (2017), Model: An Overview. Available from: http://ec.europa.eu/clima/policies/strategies/analysis/models/docs/primes_model_2013-2014_en.pdf

Prina, M.G., Fornaroli, F.C., Moser, D., Manzolini, G., Sparber, W.

(2021), Optimisation method to obtain marginal abatement cost-curve through energy PLAN software. Smart Energy, 1, 100002.

Sotiriou, C., Michopoulos, S., Zachariadis, T. (2019), On the cost-effectiveness of national economy-wide greenhouse gas emissions abatement measures. Energy Policy, 128, 519-529.

Thunder Said Energy Ltd. (2020), CO_2 Capture: A Cost Curve? Available from: https://thundersaidenergy.com/downloads/co2-capture-a-cost-curve

Timilsina, G.R., Sikharulidze, A., Karapoghosyan, V., Shatvoryan, S. (2017), Development of marginal abatement cost curves for the building sector in Armenia and Georgia. Energy Policy, 108, 29-43.

van Vuuren, D.P., De Vries, B., Eickhout, B., Kram, T. (2004), Responses to technology and taxes in a simulated world. Energy Economics, 26(4), 579-601.

Yu, X., Deane, J.P., O'Gallachoir, B., Rogan, F. (2020), Identifying decarbonisation opportunities using marginal abatement cost curves and energy system scenario ensembles. Applied Energy, 276, 115456.