Value for Money Department

Ministry of Finance of the Slovak Republic / www.finance.gov.sk/uhp

Decarbonization of the Slovak economy by 2030

Formulation of marginal abatement cost curves

March 2022

Abstract

The Slovak economy has significantly decreased its carbon intensity since the 1990s, but decarbonization had effectively ceased by 2015. Slovakia needs to decarbonize further to contribute to EU-wide targets. To identify the most effective decarbonization pathways, a marginal abatement cost curve (MACC) was constructed for the Slovak economy to 2030. The Slovak MACC shows that the EU-wide target, a 55% decrease of greenhouse gases in 2030 compared to 1990, can be reached with relatively low expenditures, as a significant part of the levers (policies or measures) have negative abatement costs. Decarbonization beyond this point will require significant investments, primarily in the steel sector. A 67% decrease in annual emissions (compared to 1990) can be achieved with levers whose costs do not significantly exceed €100 per tCO_2e. The full 2030 abatement potential represents 76% abatement compared to 1990 and includes relatively costly carbon capture and storage technology. Slovak decarbonization benefits from the low carbon intensity of its electricity production, but the transportation sector will remain a challenge and is difficult to decarbonize in the next decade. The total costs of decarbonization are between 2.6 and 13.5 billion EUR. However, the vast majority of the public funding needed for the 67% decrease goal may be covered by the existing or planned sources outside of the state budget.

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List of abbreviations

CAPEX	Capital expenditures
ETS	EU Emissions Trading System
EU	European Union
BCG	Boston Consulting Group
CAP	Common Agricultural Policy
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon capture and storage
DCR	Direct cast and roll
EAF	Electric arc furnace
EV	Electric vehicle
ESIF	European structural and investment funds
ICE	Internal combustion engine
IEP	Institute for Environmental Policy
IRR	Internal rate of return
JTF	Just Transition Fund
GHG	Greenhouse gases
LULUCF	Land use, land-use change, and forestry
MACC	Marginal abatement cost curve
MF SR	Ministry of Finace of the Slovak Republic
NPV	Net present value
OPEX	Operating expense
RRF	Recovery and Resilience Facility
tCO_2e	Tonnes of carbon dioxide equivalent
TPS	Tariff for system operation (*tarifa za prevádzkovanie systému)*
ÚHP	Value for Money Department, Ministry of Finance (*Útvar hodnoty za peniaze*)
WACC	Weighted average cost of capital

Executive summary

Although the Slovak economy has decarbonized significantly in the last thirty years, further decarbonization is needed. Slovakia went through a period of abrupt decarbonization in the 1990s and 2000s that was caused by the changing structure of the economy, and technology improvements. Regardless of the improvements achieved so far, further decarbonization is needed to contribute to the EU-wide decarbonization goals in 2030 – decrease greenhouse gases (GHGs) by 55% compared to 1990 levels. This equals to abating an additional 6.3 million tonnes of CO_2 equivalent annually by 2030 (approximately 15% of current gross emissions).

To model the most cost-effective path of decarbonization, the first Slovak marginal abatement cost curve (MACC) was constructed. MACC compares various decarbonization measures from all sectors of the economy by their price for a tCO_2e abated, and their abatement potential in 2030. Three emission-reduction goals were identified – 55%, 67%, and 76% based on the MACC. These goals together with needed levers are discussed below in turn.

Slovakia is close to achieving the EU-wide "Fit for 55" target to reduce emissions by 55% (6.3 $MtCO_2e$) in 2030 compared to the 1990 levels. While there is not yet an official target for Slovakia, a 55% reduction is achievable at a total cost of 2.7 billion EUR, via cost-effective levers below 30 EUR per tCO_2e (many of which have a negative price). Nevertheless, these levers are individually small and require complex implementation efforts across many stakeholders. Therefore, Slovakia should aim also beyond the 55% target and implement additional levers.

Electrification of the steel sector is the key in the push for decarbonization beyond the "Fit for 55" target. Currently the most polluting industry, it has many levers available that enable deep decarbonization even without implementing carbon capture and storage (CCS). Electrification and efficiency improvements of the steel sector can abate in total 6.2 $MtCO_2e$ per year. Additional levers across industries before the CCS could abate 1.7 $MtCO_2e$ by 2030 at a cost of almost 4 billion EUR. In total, this would lead to a 67% decrease compared to 1990.

Reaching the full 2030 decarbonization potential requires significant CCS investments. The key lever beyond 14.2 $MtCO_2e$ abatement is the carbon capture and storage technology implemented across key point emitters to capture their remaining emissions. However, investing in CCS is CAPEX-intensive and would require significant political and societal efforts, including implementing supporting regulations. Total abatement compared to 1990 after implementing all the available levers would be 76% at a cost of over 13.5 billion EUR.

Slovakia has a low-carbon electricity mix and expected electricity oversupply to support decarbonization. Slovak low emissions intensity electricity creates suitable conditions for decarbonization via electrification of the key sectors (e.g. transport and steel) as it will not result in significant secondary GHG emissions. With the decommissioning of Nováky and Vojany coal power plants, and the opening of nuclear power plants Mochovce 3 & 4, Slovakia will decarbonize its electricity generation even further (achieving ~90 tCO_2e/GWh) and will secure sufficient electricity supply to fulfill an increased demand from decarbonization levers (e.g. electric arc furnaces).

The costs of decarbonization are in billions of euros, but the needed public funding is significantly lower. Depending on the chosen target, the total costs are between 2.7 and 13.5 billion EUR by 2030. However, the required public funding for decarbonization is significantly lower (0.9 to 6.6 billion EUR, assuming current ETS price forecasts). Moreover, the case study of reaching the 67% target shows that the vast majority of the funding can be covered by the existing or planned sources outside of the state budget (Modernization Fund, Recovery and Resilience Facility, European Structural and Investment Fund, Just Transition Fund and others). The methodology for estimating the public funding is a rough estimate and should be considered with caution.

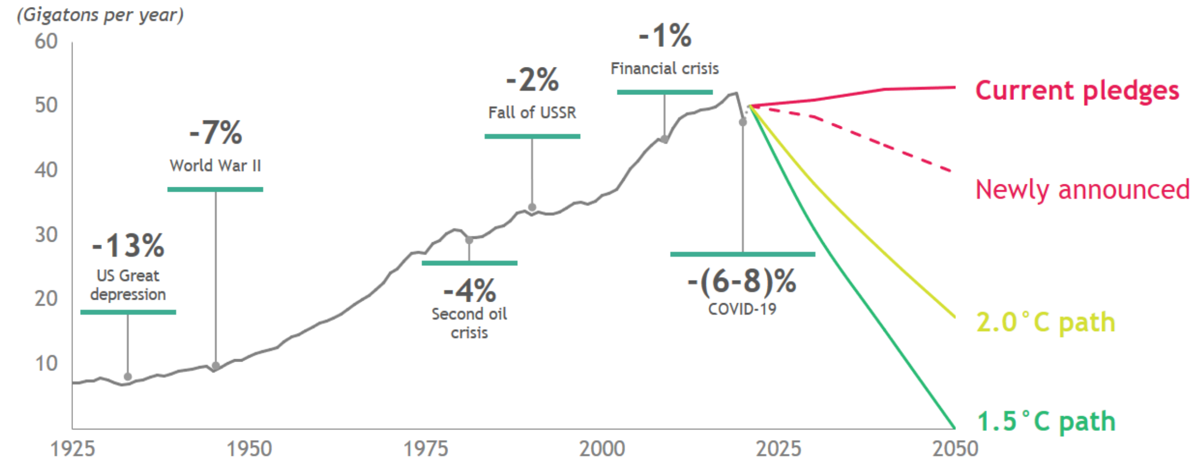
The study was prepared in a joint collaboration of ÚHP, IEP, and BCG during October and November 2021. The work was conducted via a joint project team composed of the authors of this study. During the MACC modeling, the authors used various internal and external benchmarks (including BCG proprietary databases and tools).

1 Necessity of decarbonization

Human activities are responsible for ~1˚C of global warming above the pre-industrial levels to date (IPCC, 2021). This is caused by the emission of GHGs, particularly carbon dioxide and increasingly methane. GHGs are emitted primarily by the energy, industry, and transport sectors. Both climate models and observational evidence suggest that climate change is already impacting weather patterns in the form of more intense rainfall and flash floods, and particularly in the form of extended droughts and more severe heatwaves.

As temperatures continue to rise, we will experience more extreme weather patterns, changes in biodiversity, and the large-scale extinction of species that can no longer survive in their habitats. The IPCC Special Report (2021) demonstrated that limiting warming to 1.5˚C is necessary to avoid more significant impacts on food and water security, human safety, economic growth, as well as biodiversity. As can be observed in Figure 1, significant additional effort is needed to reach the 1.5˚C pathway.

Figure 1: Global net CO_2e emissions, pledges, and gap to 2.0˚C and 1.5˚C climate paths (pre-COP26).



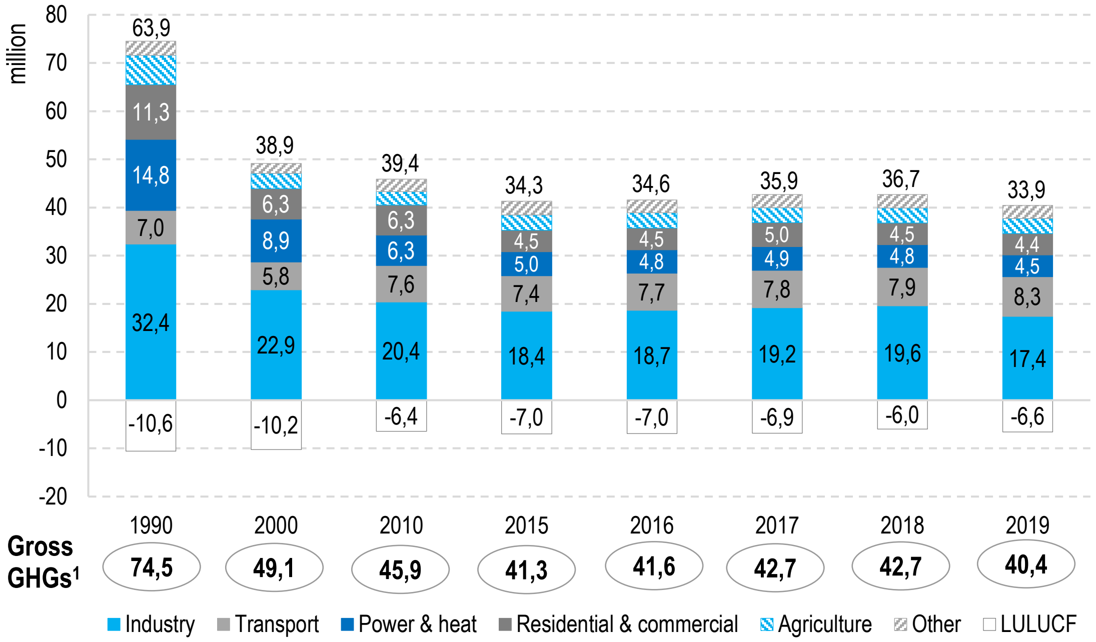
Note: Current pledges assume countries decarbonize further at the same annual rate that was required to achieve NDCs between 2020 and 2030; the 2°C path assumes a 25% reduction by 2030 and net-zero by 2070; 1.5°C path assumes 45% reduction by 2030 and net-zero by 2050.

Source: BCG

To combat global climate change, the European Union, which produces 8% of global GHG emissions (European Environmental Agency, 2020), has set itself a binding target of achieving carbon neutrality by 2050 (European Commission, 2021). Carbon neutrality means reducing greenhouse gas emissions to zero by balancing released emissions with the amount stored by carbon sinks. As a step toward this goal, the European Union has also raised its 2030 climate ambition considerably, by committing to cutting emissions by at least 55% by 2030 relative to 1990 levels (compared to a previous target of 40%). To help reach this ambition, the EU proposed a revision of climate, energy, and transport legislation under the 'Fit for 55 package' in July 2021. This included extending the EU emissions trading system to cover road transport and buildings, a change in emissions standards for cars and vans, following the principles of circular economy, and a ban on new fossil fuel vehicles from 2035, among others.

Slovak GHG emissions decreased by almost 40% between 1990 and 2000, as can be observed in Figure 2. This was due to the closure of numerous highly polluting industrial companies and increasing the energy efficiency throughout the economy. The commissioning of the two Mochovce nuclear units in 1998 and 1999 also improved the energy mix significantly. Between 2000 and 2010, the decarbonization trend slowed down and net emissions rose by 1% due to the reduction in land use, land-use change, and forestry (LULUCF) sinks. The decrease in emissions continued until 2015 as net emissions fell by 13% between 2010 and 2015.

Figure 2: The development of Slovak GHG emissions



1. Excluding LULUCF sinks *Source: EEA*

Since 2015, emissions have stagnated, driven by developments in sectors, such as transportation, due to a growing vehicle fleet. The industrial sector still accounts for the largest share of the nation's overall emissions despite improvements in energy efficiency.

Although Slovakia has already abated a significant share of its emissions compared to the 1990s, it started from a high baseline typical for a socialist economy relying on high-polluting heavy industry. The relative economic prosperity of the Slovak economy today is a result of decades of high carbon footprint growth in the past. A part of the volume of GHGs emitted in these decades is still in the atmosphere and is, therefore, still contributing to climate change.

The 2016-2019 average[1] (see Figure 3) shows that the current largest sector emitting GHGs is the iron, steel & ferroalloys industry. The largest player, the U. S. Steel plant in Košice, accounts for most emissions in the sector. Transport is the second-largest emitter and increasing emissions are driven by the growing vehicle fleet. Although Slovakia has low carbon-intensity electricity, the power & heat sector is still a significant GHG producer, but its prominence will decrease after the planned closure of the Nováky (modeled for 2023) and Vojany (modeled for 2025) coal power plants. Three other industrial sectors combined (minerals & building materials, petroleum, and chemicals) emit less than the steel or transport sectors but are, nonetheless, significant emitters.

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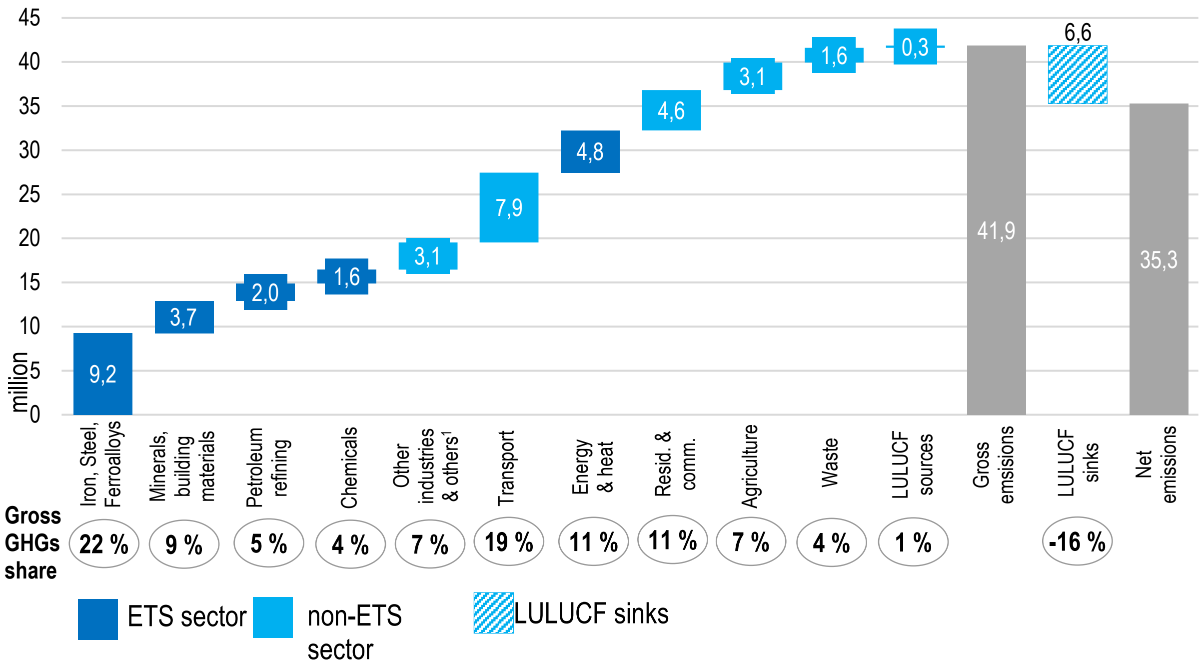
[1] In section 2.2, we explain the reasons for our decision to use 2016-19 average values as the baseline for our abatement analysis.

Figure 3: Slovak emission and sectorial split (2016-2019 average)



1. Including product uses as substitutes for ozone-depleting substances and fugitive emissions from mining, etc. *Source: EEA*

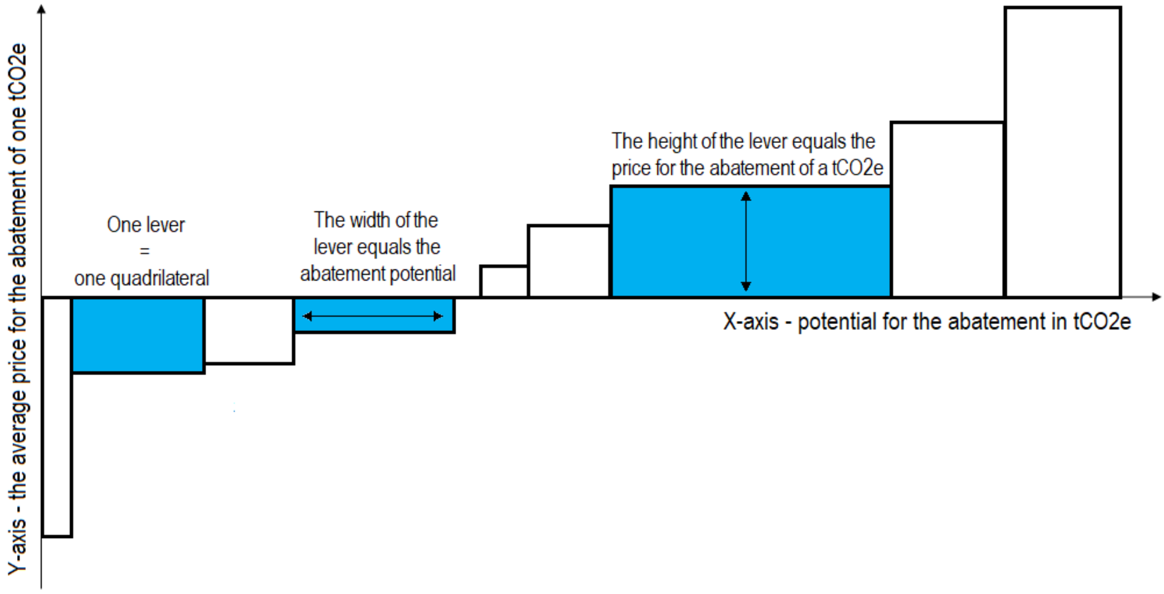
Resid. & comm. = residential and commercial sector (primarily includes heating, but not the heating plants).

In our modeling, we primarily worked with the above-mentioned six sectors. As the biggest emitters, they have the biggest abatement potential. We also modeled all other sectors, including carbon sinks (LULUCF), but these brought lower abatement potential than the priority sectors.

2 Introduction to the marginal abatement cost curve

Given the need to reduce GHG emissions, the question is how to reduce emissions in the most efficient, least-cost manner. The MAC curve helps answer this question. It shows abatement levers organized by the cost of abatement (measured in cost per ton of CO_2e abated – see Y-axis in Figure 4), from the cheapest to the most expensive lever. The curve is marginal in the sense that it estimates the cost of abatement for the next (cheapest) unit of GHGs. For simplicity, the marginal abatement costs are referred to only as abatement costs or costs thorough the paper. Unit abatement costs may be negative if the given lever can simultaneously save costs and abate GHG emissions. A typical example of this is ceasing support for domestic lignite production and use. Closing the Nováky power plant and the associated mining operations will decrease societal costs as coal mining and its energy use require public subsidies.

Figure 4: Illustrative MAC curve



Source: BCG

Apart from the cost of abatement, we must think about the abatement potential that a lever can achieve. Closing the Nováky mine will have negative costs, but there is a clear limit to the amount of CO_2e that can be abated. This is also crucial for policymakers to see how many of the levers need to be adopted to reach a pre-determined threshold.

As illustrated in Figure 4, the x-axis on the MAC curve represents the abatement potential of the given measure. All levers are represented in the form of discrete rectangles, the height of which represents their cost per ton of CO_2e abated, the width - their abatement potential, and the area - their total cost to society.[2]

MACCs have some limitations. Arguably, the key one is that the effects of levers are estimated only in regards to the OPEX and CAPEX. Changes in the GDP or employment are by definition omitted, regardless of the fact whether they are positive or negatives. MACCs represent the abatement cost for a single point in time and hence cannot capture differences in the emission pathways of the different levers. Other limitations, together with the assumptions used are in box 1.

The first step in our modeling was to identify a baseline from which emission reduction was calculated. We used the average of multiple years (2016-2019) to decrease the influence of a singular event (in any given year) on the

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[2] The scope of this paper does not allow for a literature review of the use of MACCs and different types of MACCs. Such an overview is available, for example, in Kesicki, 2011.

emissions baseline. For example, in 2019 emissions decreased in the steel sector due to the temporary closure of one of the blast furnaces in the Košice steel plant. The year 2020 was not used due to the significant influence of the COVID-19 pandemic and consequent lockdowns. Therefore, all abatement discussed below takes as a reference fixed average numbers from years 2016-2019.

After choosing a baseline, key abatement levers across sectors were identified using academic sources, information from company-specific projects from industrial players, think-tank materials, expert consultations, and external benchmarks. Levers that are still in the research phase were excluded due to the difficulty and subjectivity inherent in estimating the expected impact and cost of such early-stage technologies. For the identified levers, we estimated and verified the abatement potential, the capital expenditure (i.e. capital investment or CAPEX), and the operating costs (running costs or OPEX) relative to the baseline.

For calculation of the y-axis, we divided the net present value (NPV) of total cost in the period 2022-2030 by the NPV of abatement in 2022-2030 (using a discount rate of 4%, following the methodology of Slovak state institutions for evaluating the financial investments). Discounting the abatement is important as it stresses the fact that earlier abatement is more valuable than later abatement due to the caused greenhouse effect. The NPV of the total cost was calculated as a year-by-year change in expenditure (sum of OPEX and annualized CAPEX), compared to a no technology change scenario. The CAPEX was annualized based on the lifetime of the device or the technology (assumed 25 years for most industry levers). The x-axis represents the total abatement in one calendar year (in this case, 2030).

Importantly, we did not include the change in ETS expenditures in the OPEX. This is because it distorts the comparison of ETS sectors (steel and iron, chemicals, power generation, etc.) and non-ETS sectors (commercial, transport). This is a common practice followed by other MAC curves, e.g. for New Zealand (Ministry for the Environment, 2020) or Germany (Gerbert et al., 2018).

While some MAC curves are estimated with longer horizons (usually 2050), we modeled the curve to 2030 for two reasons. First, the 55% abatement compared to 1990 should be reached across the EU by 2030 and thus a 2030 MAC curve is more useful in informing public discussion and policy choices in Slovakia. Second, using the 2030 horizon decreases the likelihood that the curve will change significantly due to technological changes. The Slovak MAC curve mainly consists of levers that are readily technologically available today and do not require technological breakthroughs, therefore, they fit well the 2030 modeling horizon. Partial exceptions are transportation levers which are modeled based on future changes in prices of different technologies, and the CCS levers that are currently on varying levels of technological readiness. However, it is expected that by 2030 these technologies will be commercially available (CCUS Set-Plan, 2021: 15-16, IEA, 2020: 49).

Nevertheless, using the 2030 horizon also has some limitations. Firstly, it leads to the inability to model the cost of reaching carbon neutrality. Secondly, abatement of some levers is not immediate. This is especially true for the transportation sector, where electrification of the vehicle fleet is a gradual process. Even if from now on all cars being sold were electric vehicles (EVs), it would take decades to replace the current fleet, which currently consists of mostly internal combustion engine (ICE) cars. This is partly why the abatement potential in the transportation sector in 2030 is relatively low compared to other sectors. The full list of general assumptions is in box 1.

BOX 1: List of assumptions and limitations

In this analysis, we have made the following assumptions:

- The average of 2016-2019 emissions is taken as a baseline. This means that we do not model any expected change in GHG emissions across sectors. Instead, the average of 2016-2019 emissions was considered as a static starting point. This is particularly problematic in growing sectors like transport, in which emission levels have been rising for the last years and a further increase is expected in the future. It is assumed that continuing energy efficiency improvements in other sectors will balance out these increases.

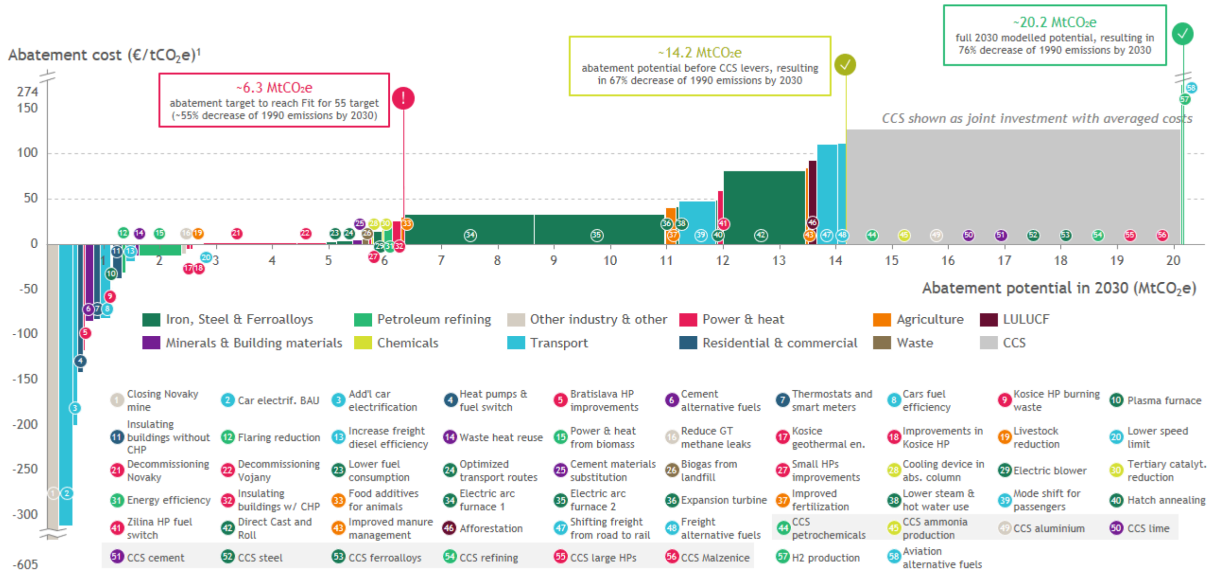
- Modeling horizon until 2030.
- Expected economic expansion due to the RRP investment in the 2020s was not taken into account.
- 25-year lifetime for most technologies (unless sector insights say otherwise) used to annualize CAPEX investments.
- We did not include the change in ETS expenditures in the OPEX. We have chosen this approach as it is common practice to avoid uncertainties connected to the ETS price, and it enables comparison across sectors included in ETS and excluded from ETS.
- ETS extension to transport and residential & commercial sectors is not included. Currently, there is not enough information about the implementation of this extension to reliably model its effects.
- We take a mixed approach for commodity and electricity prices until 2030. Futures prices of commodities are used in the short term and results of BCG energy modeling via Plexos are taken in the longer horizon.
- The investments are implemented as soon as possible (based on available project proposals) and are not optimized expecting lower prices of technologies later in time.
- The model assumes the availability of additional commodities without the need for additional CAPEX to obtain them, i.e. electricity (2.2 TWh p.a.), scrap metal (0.4 Mt p.a.), natural gas (2.5 PJ p.a.), hot bricketed iron (1.2 Mt p.a.), biomass (1.5 Mt p.a.), waste fuel (0.2 Mt p.a.) and others.
- Our model also does not capture the effect of all indirect costs and gains. For example, some of the levers may lead to a decreased need for labor, others will increase employment as labor will be needed to install new technologies that may be more labor-intensive compared to no technology change.
- Political factors are not taken into account. Some of the levers could also be rejected by the public despite their economic feasibility (Kesicki and Ekins, 2012: 223-224).
- Where possible, primarily for levers with large abatement potential, we verified the estimates with other sources. Most often, we cross-checked data from businesses and data from other available public sources and external benchmarks. Estimating the changes in OPEX was more difficult as this required more detailed data. If this was not available, OPEX changes were assumed to be zero, although this was the case only for levers will low abatements.

MACCs have their limitations and caution is advised when interpreting them. MACCs are always as good as the data input. Even with a great amount of time spent on validation, some of the levers were too specific to be meaningfully validated, which applies also to OPEX estimations for smaller levers. The most significant risks of the practical use of MACCs stem from possibly low-quality project proposals that may overstate the abatement or understate the costs. Also, external political events, such as the Russian invasion of Ukraine in early 2022 were not taken into account, even if these may significantly affect the prices of commodities, the availability of natural gas, and wider EU energy security goals. Additionally, in general, MACCs enable only a limited treatment of uncertainties, and they omit by default ancillary benefits and costs (Kesicki and Ekins, 2012: 230-231). Therefore, as Kesicki and Ekins (2012: 233) argue, "MAC curve is not, and should not be used as, a one-stop shop for ranking abatement policies." MACC should be just one of the aids of the decision-making for sound decarbonization policies.

3 Slovak MACC and sectorial deep-dives

While there is no official Slovak 2030 decarbonization target yet, we have outlined three potential target options within the constructed MAC curve (see Figure 5). The first one is an abatement target of 6.3 $MtCO_2e$ (relative to our 2016-19 baseline), which implies a ~55 % reduction compared to 1990, the target adopted by the EU for 2030. The second target is 14.2 $MtCO_2e$, which includes all the levers that are right now fully technologically available. This target includes all levers with better cost efficiency than the carbon capture and storage (CCS) levers and would achieve a 67 % reduction in emissions compared to 1990. Finally, the last target represents the full 2030 potential of 20.2 $MtCO_2e$ that includes all available levers. It results in a 76 % emissions decrease compared to 1990 levels. A table with a full list of levers, their abatement, CAPEX and OPEX is available in appendix 1.

Figure 5: 2030 MAC curve for Slovakia[3]



Note: HP = Heating Plant, CHP = Central Heating Plant (District Heating Plant)
1. NPV of abatement costs until 2030 / NPV of abatement until 2030. CAPEX only includes annualized costs until 2030.

Source: BCG and ÚHP

To reach a 55% GHG reduction in Slovakia from 1990 levels by 2030, 33 levers would need to be implemented. The cheapest lever is the closing of the Nováky lignite mine (2023), which brings a benefit of 605 EUR for each ton of CO_2e abated. As a result of this lever, end-consumers would pay lower electricity bills (due to the termination of a subsidy for domestic coal within the TPS tariff that we included within this lever). The next two levers are connected to the electrification of the car fleet, where the lower OPEX of EVs compared to internal combustion engine (ICE) cars would, in the long term, outweigh the higher CAPEX of EVs. Apart from the cost of EVs, the costs of charging points and secondary emissions (GHGs from the electricity consumed) were also included in the calculation. In total, these three cheapest levers would abate 0.5 $MtCO_2e$.

Levers 4 to 20 are all levers with negative costs across numerous sectors that have individually low abatement potential. Together they abate 2.2 $MtCO_2e$. Levers 21 and 22 are the closures of the Nováky and Vojany coal power plants. These two levers come with positive costs as a result of the costs associated with the need to decommission the plants and the need to build a new central heating system for the municipalities surrounding Nováky. Closing the two remaining coal power plants in Slovakia would abate 2.2 $MtCO_2e$. Levers 23 to 33 would abate the remaining 1.4 $MtCO_2e$ of emissions to reach the 55% GHG reduction target by 2030. This target includes many small levers that may be challenging to implement. Therefore, Slovakia should aim for a somewhat more ambitious 2030 target.

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[3] The graph in high resolution is available in appendix 2.

Electrification of the steel sector is crucial to reducing emissions in Slovakia beyond the 55% target. As mentioned, the steel sector, namely U.S.Steel Košice, represents the largest point emitter in Slovakia and, therefore, is the key in reducing GHG emissions. Levers 34 and 35 are two identical levers - the replacement of two blast furnaces (out of three) with electric arc furnaces in the U. S. Steel Košice plant. These two levers, with modeled costs of 32.5 EUR per tCO_2e each, would abate in total 4.6 $MtCO_2e$. Lever 42 is connected with electric arc furnaces and represents the implementation of direct cast and roll in the U.S.Steel Košice plant with abatement costs of 81.7 EUR per tCO_2 and a potential of 1.5 $MtCO_2e$. Implementing these three key levers at U.S. Steel Košice has a similar abatement potential to levers 1 through 33 altogether, but has higher costs.

There are several additional levers that can be implemented before the CCS levers. Three transport levers have the highest abatement potential out of the remaining non-CCS levers: mode shift for passengers (lever 39), shifting freight from road to rail (lever 47), and alternative fuels for freight transport (lever 48). As can be observed, these levers come at various costs from 48 to 112 EUR per tCO_2e. Additional levers include several optimization levers for the remaining blast furnace (levers 36, 38, and 40) in Košice, improved fertilization and manure management in agriculture (levers 37 and 43), fuel switch in the district heating plant in Žilina (lever 41), and afforestation (lever 46). Implementing all the levers before the CCS levers would decrease emissions by 14.2 $MtCO_2e$, which would represent a 67 % decrease in GHGs by 2030 compared to 1990 levels.

To reach the full abatement potential of 20.2 $MtCO_2e$, which represents a 76% reduction in emissions compared to the 1990 levels, CCS technology would need to be implemented. This technology allows the reduction of industrial emissions which is not abatable with current technology. CCS involves capturing the carbon dioxide that is produced (e.g., as part of industrial processes) before it enters the atmosphere and transporting and storing this carbon in an underground geological formation. CCS is suitable as an abatement lever for large point emitters, such as iron & steel plants, petrochemicals, petroleum refining, cement and lime production, ammonia production, heat plants, and gas power plants (Malženice).

CCS has a significant abatement potential in Slovakia of 6.0 $MtCO_2e$ by 2030 (levers 44 through 56) but is costly to implement. Further analysis of the cost and potential risks of the CCS technology is given in box 2.

BOX 2: Carbon capture and storage costs

Carbon capture costs are an important component of CCS costs and vary widely across industries: capture costs are relatively low for the chemicals and petrochemicals sectors (16 EUR/tCO_2 for ammonia production) but high for industries such as cement, iron & steel, or power (84 EUR/tCO_2 for power generation).

The other component of CCS costs is the cost of carbon transport and storage. Given that no large carbon storage options exist within Slovakia, we have assumed that any carbon captured will need to be transported to saline aquifers in Poland. The need to develop a carbon transport storage infrastructure (i.e. pipelines) over a distance of over 300 km requires an investment of close to 5 billion EUR, driving up the costs of carbon transport and storage for CCS in Slovakia. No individual CCS investment in itself merits an infrastructure investment of this scale, and therefore significant state (or EU) support will be required for this “enabling investment”. We estimate a carbon transport and storage cost of 71 EUR/tCO_2, assuming that all CCS levers are applied and that 5.9 $MtCO_2$ is transported and stored in Poland annually. This cost greatly exceeds carbon transport and storage costs in countries with closer access to storage facilities. Developing this infrastructure will require significant time, hence we assumed that CCS could start operating in Slovakia in 2027. The prices of all the components of the CCS were estimated using external benchmarks.

The average cost of CCS for all sectors is 127 €/tCO2. Although the capture costs differ between the sectors, the MACC contains only one cost for the CCS technology as a whole. This is because it was modeled that there will be one common transportation and storage infrastructure for all CCS projects. Because of the economy of scale, this lowers overall costs. To follow one of the key principles of the MACC modeling that it must be possible to implement the levers independently of each other, it was decided that there will be only one CCS lever. An alternative would be to assume that each CCS installation would construct its own carbon transportation infrastructure, which would enable to apply the CCS only on some installations. However, this would decrease its cost-efficiency even more due to significantly increased transportation costs.

The total modeled abatement from the CCS levers is 5.9 MtCO2e per year. By 2030, the total costs would exceed 8.5 billion EUR. There is a range of risks around the feasibility of CCS in Slovakia. First, the investment is not reasonable without a long-term guarantee of storage opportunity (in Poland or elsewhere). One solution to this may be an intergovernmental agreement between Slovakia and the destination country. Second, there is no legal framework clarifying the liability for CO_2 stored over a multi-decade timescale (e.g. who bears the legal responsibility for any possible leaks from the storage facility). Third, the possibility of leakage of CO_2 from transport infrastructure and storage basins may limit the public acceptance of CCS. Fourth, since the costs of CCS are expected to decline over time, companies may want to postpone CCS investments, preventing short-term deployment. Last, the lack of commercial maturity of CCS in some industries implies that it carries a high risk from a project perspective. These risks may require additional government action; however, given the EU-wide need for CCS, if ambitious decarbonization targets are to be met, the Slovak government will likely not be facing these challenges alone.

The following subsections outline the methodology, data sources, and assumptions for modeling levers for each of the sectors. Due to a high number of levers, only the ones with the largest abatement are explained in detail, but the methods described largely apply also to the smaller levers.

3.1 Iron, steel, and ferroalloys

The iron, steel, and ferroalloys sector will require significant decarbonization investments, but using its abatement potential is crucial to reach more ambitious targets. As the most significant producer of GHGs, this sector is responsible for almost a quarter of all emissions (Figure 3). To model the levers, a number of different sources were used – Slovak Modernization Fund projects, external benchmarks, the expert literature, think-tank materials, and consultations with the topic experts.

Table 1: Decarbonization levers in the iron, steel, and ferroalloys sector

#	Lever name	Y-axis - abatement cost (EUR/tCO_2e)	X-axis - abatement ($ktCO_2e$)	CAPEX total (not annualized, mil. EUR)	OPEX change in 2030 (mil. EUR)
10	Plasma Furnace	-48	10	6,5	-0,9
23	Lower fuel consumption	3	194	8,3	0,0
24	Optimized transport routes	4	285	15,0	0,0
29	Electric blower	14	147	30,0	0,0
34	Electric arc furnace 1	33	2309	362,5	43,9
35	Electric arc furnace 2	33	2309	362,5	43,9
36	Expansion turbine	39	18	10,0	0,0
38	Lower steam & hot water consumption	41	51	27,0	0,0
40	Hatch annealing	49	39	25,0	0,0
42	Direct Cast and Roll	82	1464	580,0	70,2
52	CCS steel	139	1092	0,0	152,1
53	CCS ferroalloys	139	159	0,0	22,2
	Total		8077	1427	331

A significant effort was given to benchmark and verify three key levers – installation of two electric arc furnaces (EAF) using scrap metal, and direct cast and roll (DCR).[4] To model these, external benchmarks were used that were cross-checked with the Modernization Fund data and experts in the steel industry. The potential abatement was decreased by secondary emissions (from increased electricity demand), using Slovak carbon intensity of electricity production. Regarding the alternatives, we also considered direct reduction of iron combined with the EAF lever. Nevertheless, this option was proven not to be viable due to a weak business case for such technology in Slovakia and its very high electricity demand. For both levers, CAPEX for the needed electricity grid improvements was not included.

Apart from the three aforementioned key levers, there are several smaller levers that represent marginal technological updates, which provide low abatement for mostly low abatement costs. It was modeled that these can be implemented together with the EAFs and DCR technologies as the sources suggested such a possibility. Due to the lack of data, these levers were assumed not to bring changes in OPEX.

Except for lever 10, all of the levers from the sector apply to the Košice steel plant. The methodological decision to model primarily levers for this installation stems from the fact that it is the most significant producer of GHGs. Additionally, the Podbrezová steel plant has already installed EAF technology, which means that potential abatement is lower. After applying all the levers, an additional 1.2 $MtCO_2e$ is expected to be captured with CCS.

3.2 Building materials, petroleum, and chemical industry

A significant majority of emissions of these three sectors cannot be abated without CCS, which is a result of a significant amount of process emissions (coming from chemical transformation of raw materials) that are difficult to abate (Material Economics, n.d.: 146). For example, in the production of clinker (the main ingredient of cement), more than 60 % of emissions are process emissions (Material Economics, n.d.: 146, 173).

Table 2: Decarbonization levers in building materials, petroleum, and chemical industry

#	Sector	Lever name	Y-axis - abatement cost (EUR/tCO_2e)	X-axis - abatement ($ktCO_2e$)	CAPEX total (not annualized, mil. EUR)	OPEX change in 2030 (mil. EUR)
6	Cement	Cement alternative fuels	-85	154	41,4	-13,8
12	Petroleum r.	Flaring reduction	-32	73	14,2	-2,8
14	Cement	Waste heat reuse	-13	71	10,4	-1,3
15	Petroleum r.	Power & heat from biomass	-13	755	342,0	-25,7
25	Cement	Cement materials substitution	5	162	10,4	0,0
28	Chemicals	Cooling device	13	37	1,9	0,3
30	Chemicals	Tertiary catalytic reduction	21	33	5,0	0,3
31	Petroleum r.	Energy efficiency	22	158	37,4	0,7
44	Petroleum r.	CCS petrochemicals	84	477	0,0	40,1
45	Chemicals	CCS ammonia production	87	876	0,0	76,0
50	Cement	CCS lime	133	332	0,0	44,2
51	Cement	CCS cement	133	1559	0,0	207,9
54	Petroleum r.	CCS refining	148	366	0,0	54,2
57	Petroleum r.	H2 production	177	39	94,0	0,0
	Total			5093	557	380

Petroleum r. – petroleum refining

GHGs from the minerals and building materials (primarily cement and lime) sector come primarily from process emissions. These are complicated to abate as they are a result of the chemical transformation of raw materials. Therefore, the abatement potential is low. Less than 0.5 $MtCO_2e$ could be abated through the levers of alternative

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[4] The negotiations between the Slovak government and USSK to support decarbonization are ongoing (Kováč, 2021).

fuels, increased heat reuse, and increased use of alternative cement materials, all with very low costs. For the alternative fuels, 80% share of alternative fuels (waste) was assumed to be viable. Today the share is only 63%, but shares higher than 80% are already common abroad (Austria). The consultations with key Slovak producers proved that this is also viable in Slovak context. This leads to OPEX savings due to the decreased need for fossil fuels and supports the switch to a circular economy, which is one of the key parts of the European Green Deal (EC, 2020). Almost 2 MtCO2e can be then captured by CCS.In the petroleum sector, there are significant levers with negative costs, most importantly the switch to biomass for heat and electricity production that was modeled based on external benchmarks. Negative costs are due to forecasted increasing prices of gas that is replaced with biomass. Improving energy efficiency is also cost-effective, with an abatement cost lower than 30 EUR per tCO_2e. This lever was also modeled based on external benchmarks. Other levers include CCS and more costly hydrogen production (Modernization Fund).

The chemicals sector offers two relatively minor levers with low costs for ammonia production. These levers include estimated CAPEX as well as OPEX increase due to increased natural gas use in the new industrial installations (both levers from the Modernization Fund). CCS technology can be relatively cheap in this sector, especially in ammonia production. It was modeled that 900 $ktCO_2e$ of emissions can be captured for a relatively low price (16 EUR/tCO_2e), nevertheless, due to high transportation and storage costs, the total price is 87 EUR/tCO_2e, which is still somewhat lower than the CCS for other sectors.

3.3 Transportation

In transportation, only 1.9 $MtCO_2e$ can be abated by 2030. The transport sector is specific due to its decentralization. Therefore, abatement is possible only through a gradual change of consumer behavior, which needs to be incentivized. Due to this, the abatement takes a longer time to come about. By 2030, there will remain an unabated 6 $MtCO_2e$ in the sector.

Table 3: Decarbonization levers in building materials, petroleum, and chemical industry

#	Lever name	Y-axis - abatement cost (EUR/tCO_2e)	X-axis - abatement ($ktCO_2e$)	CAPEX total (not annualized, mil. EUR)	OPEX change in 2030 (mil. EUR)
2	Cars electrification	-312	248	840,4	-195,9
3	Cars electrif. ambitious scenario	-200	83	423,0	-75,0
8	Cars fuel efficiency	-83	176	3897,8	-652,4
13	Increase freight diesel efficiency	-19	160	616,6	-114,1
20	Lower speed limit	0	52	0,0	0,0
39	Mode shift for passengers	48	646	152,5	0,4
47	Shifting freight from road to rail	111	374	0,0	10,3
48	Freight alternative fuels	112	140	247,3	-118,8
58	Aviation shift to alternative fuel	274	9	0,0	3,2
	Total		1888	6178	-1142

The three key levers are car electrification, and passenger and freight mode shift. The car electrification scenario expects negative costs due to OPEX savings of EVs compared to internal combustion engine cars. According to the available data, the price parity of electric and ICE vehicles was already reached in 2021 (external benchmarks, see also Dow, 2021). Although in the Slovak market an EV is still on average 10% more expensive to buy than a combustion engine car, it saves 20% of operating costs each year, leading to total cost savings 4 years after purchase. The used model is conservative in the sense that it does not expect a further decrease in the prices of EVs between 2022 and 2030. CAPEX for the needed electricity grid improvements was not included.

It is expected that 40 % of cars sold in 2030 in the EU will be EVs (European Federation for Transport & Environment, 2020). On the other hand, it is expected that 7 % of the car stock in Slovakia (out of more than two million, the vast majority of which is currently ICE) will be EVs by 2030. This is based on Institute for Environmental

Policy internal estimates, and adjusted for the large second-hand car sales market in Slovakia (40 %, lagging 7 years behind new car sales), bringing them closer to the external benchmarks set for Visegrad 4 countries. By 2030, 26% of light vehicle sales will be electric (33% of new vehicles, 15% of second-hand sales). This lever does not include any subsidy.

Additional EV adoption could be achieved through the implementation of a subsidy on EV sales (lever 3). This lever assumes that there is an 8000 EUR subsidy on every fourth car that is bought. This helps overcome the higher initial cost of purchasing the vehicle. Such subsidies are common in, for instance, Germany and USA, but are somewhat inconsistent in Slovakia. Due to the subsidy, the costs of this lever are higher than the electrification scenario, but the abatement cost of the lever is still negative.

Mode shift for passengers was modeled with an expected increase of 100 million EUR CAPEX in infrastructure for cyclists and pedestrians (based on designated investments from the EU Recovery and Resilience Facility (Plán obnovy, 2021)) and OPEX and CAPEX in rail infrastructure (based on internal ÚHP investment estimates, as well as the EU RRF). By 2030, 16% of distance traveled by cars with combustion engines will be shifted to rail, public transport, or cycling. 10% of this shift will be to rail, for trips longer than 80 km which people do not take frequently, but are responsible for a large proportion of carbon emissions. The remaining 6% will switch to public transport and cycling, which is the equivalent of approximately 25% of inner-city car traffic. Freight mode shift works with an assumption of a 50% increase of rail freight transportation (from 20% to 30%), aided by subsidies recently proposed by the Ministry of Transport and Infrastructure SR (Ministerstvo dopravy a výstavby Slovenskej republiky, 2022).

3.4 Power and heat

A significant part of GHGs from the power and heat sector can be abated without CCS for low prices. For modeling levers for this sector, primarily the Modernization Fund, company press releases, and external expertise were used. Where suitable, Modernization Fund projects were cross-checked with other sources, primarily for the fuel switching in the power sector.

Table 4: Decarbonization levers in power and heat sectors

#	Sector	Lever name	Y-axis - abatement cost (EUR/tCO$_2$e)	X-axis - abatement (ktCO$_2$e)	CAPEX total (not annualized, mil. EUR)	OPEX change in 2030 (mil. EUR)
5	Heat	Bratislava HP improvements	-118	27	54,0	-7,3
9	Heat	Košice HP burning waste	-78	23	12,0	-2,8
17	Heat	Košice Geothermal energy	-6	71	60,0	-5,7
18	Heat	Improvements in Košice HP	-6	52	19,0	-1,8
21	Power	Decommissioning Nováky	1	1662	30,4	-0,3
22	Power	Decommissioning Vojany	1	524	8,4	0,0
27	Heat	Small HPs improv. & fuel switch	13	49	41,6	-2,5
32	Heat	Insulating buildings with CHS	26	150	309,6	-15,7
41	Heat	Žilina HP fuel switch	59	95	75,0	0,0
55	Heat	CCS large HPs	156	372	0,0	57,9
56	Power	CCS Malzenice	156	442	0,0	68,8
	Total			3467	610	91

CHS – central heating system. HP – heating plants.

The two most significant levers are the decommissioning of power plants Nováky (modeled for 2023) and Vojany (modeled for 2025)[5], which would abate over 2 MtCO$_2$e. The abatement prices of these levers are very close to 0 EUR as their costs include only one-off decommissioning costs (external benchmark) and a new central heating supply system for the surrounding municipalities (press-releases about the new heating plant in Nováky). Closing

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[5] As of 2022, the Vojany power plant uses secondary fuels from waste instead of coal.

the power plants will indirectly lead to decreased societal costs due to the decreased tariff (TPS) in the electricity prices (estimated as almost 140 mil. EUR per year[6]). These benefits are modeled into closing the Nováky coal mine lever as the tariff primarily serves to fund this part of the supply chain.

Other levers are within the heat sector. Most of them refer to key heating plants in Bratislava, Košice, and Žilina, based on the Modernization Fund projects. Levers can be divided into efficiency improvements and fuel switches.

In the case of increased energy efficiency levers, fuel OPEX was assumed to decrease due to lower consumption. This decrease was assumed to be proportional to the GHGs abatement. Fuel switch levers include divestment from coal to fuels such as waste, geothermal, and natural gas. For lever 27, the average abatement costs and percentage of abatement of the three key heating plants (apart from the geothermal energy project in Košice) were applied to other smaller heating plants, for the most of which the data from the Modernization Fund was not available. Finally, increased insulation rates in the residential and commercial sectors were assumed to lead to a decreased demand for public heating and decreased emissions. CCS was applied to the rest of the emissions in the sector, with an abatement of 800 ktCO2e.

3.5 Other sectors

A significant portion of emissions from other sectors will remain unabated. Apart from the priority sectors above that were analyzed and modeled in detail, the rest of the GHG emissions were analyzed on a higher level of abstraction. Twelve levers were identified from commercial and residential, agriculture and LULUCF, waste, and other industries sectors. For identifying these, Modernization fund projects, Slovak strategic policy documents, expert estimates, and the existing literature were all used.

Table 5: Decarbonization levers in other sectors

#	Sector	Lever name	Y-axis - abatement cost (EUR/tCO$_2$e)	X-axis - abatement (ktCO$_2$e)	CAPEX total (not annualized, mil. EUR)	OPEX Δ in 2030 (mil. EUR)
1	Other industry	Closing Nováky mine	-605	203	0,0	-126,7
4	Res. & com.	Heat pumps & fuel switch	-142	111	348,3	-29,3
7	Res. & com.	Thermostats and smart meters	-84	119	286,8	-37,9
11	Res. & com.	Insulating buildings without CHS	-39	167	784,2	-52,6
16	Other industry	Reduce methane leaks	-11	82	2,2	-0,9
19	Agriculture	Livestock reduction	0	126	0,0	0,0
26	Waste	Biogas from landfill	5	116	14,0	-0,4
33	Agriculture	Food additives for animals	30	59	0,0	1,8
37	Agriculture	Improved fertilization practices	40	189	0,0	7,5
43	Agriculture	Improved manure management	84	60	0,0	5,0
46	LULUCF	Afforestation	93	147	43,1	10,3
49	Other industry	CCS aluminium	126	271	0,0	34,3
	Total			1649	1479	-189

Res & com. – residential and commercial sector. CHS – central heating system.

Key levers include building insulations, improved fertilization practices, closing Nováky mine (modeled for 2023), and CCS for aluminum production. For insulations, apartment block renovation was expected to continue at the 2011-2019 rate (3% p.a.) (Ministerstvo dopravy a výstavby Slovenskej republiky, 2020); by 2030, almost 30% of the 22 000 flat buildings in Slovakia will undergo deep renovation[7] (MH SR and SIEA, 2015). An extra 30 000 homes will be renovated by 2026, and 110 000 homes will switch away from solid fuel by 2030 as a result of RRF

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[6] Possibly, the TPS will be increased to fund the replacement of the capacity of the Nováky power plant. This has not yet been confirmed and, therefore, these costs are not included in the model.

[7] Deeply renovated buildings have an energy consumption below 50 kWh/m2.

funding. The abatement in the residential & commercial sector is rather low, taking into account the significant EU-wide efforts to decarbonize this sector, this is primarily due to the short modeling horizon of the MACC.

Improved fertilization practices include various measures, such as precision fertilization, use of advanced fertilizers, improved fertilization timing, use of nitrification inhibitors. The abatement cost is based on external benchmarks from abroad. Closing the Nováky mine is connected with closing the Nováky power plant. As explained above, the electricity tariff decrease was included in this lever, which leads to the lowest abatement cost out of all levers. Apart from this, the expected recultivation cost of 100 million EUR is also included as OPEX. Aluminium CCS applies to the Žiar nad Hronom plant, with a capture rate of 90% and a capture cost of 55 EUR/tCO_2 (external estimates).

3.6 Costs

To estimate the total costs of decarbonization, the sectors were divided on point and decentralized emitters. The former emit emissions at one or few sources and predominantly fall into the ETS sectors. The abatement cost in their case represents an immediate change of production technology, associated with one-off CAPEX. Therefore, the abatement of point emitters can be implemented relatively quickly.

On the other hand, emissions of decentralized emitters are spread across numerous sources (individual cars, houses, farms) in sectors such as transport, residential & commercial buildings, agriculture, and LULUCF. These sectors cannot be abated as quickly and need a gradual change of consumers' behavior and incentivization for such change. Therefore, the costs of decarbonization of decentralized emitters are not counted as CAPEX, but rather as a total net cost (cost-benefit). Table 6 provides information on the costs for each of the three targets, as discussed earlier (for example, in figure 5).

Table 6: Estimated total costs by individual goals

	Fit for 55 EU target	Target without CCS levers	Full 2030 potential
Reduction target	6.3 MtCO_2e (55% reduction since 1990)	14.2 MtCO_2e (67% reduction since 1990)	20.2 MtCO_2e (76% reduction since 1990)
Point emitters' one-off CAPEX	EUR 764 M	EUR 2.3 B	EUR 10.9 B
Decentralized emitters' net costs	EUR 1967 M	EUR 2.7 B	EUR 2.7 B
Levers implemented	Up to but excluding electric arc funaces (lever 33)	All levers cheaper than the CCS	All levers

Source: BCG, ÚHP

For the 55% reduction target, the costs exceed 2.7 billion EUR, the majority of which is for decentralized emitters. Comparing 55% and 67% targets, additional costs for 67% target are primarily invested into point emitters (additional 1.5 billion EUR), instead of decentralized emitters (additional 700 million EUR). The costs rise more than two fold in the last target (comparing 67% and 76% targets) due to the CCS infrastructure that is considered to be a part of the point emitters.

BOX 3: Comparison of costs with *A Low-Carbon Growth Study for Slovakia*

In January 2019 the World Bank published a paper *A Low-Carbon Growth Study for Slovakia*, which aimed to estimate Slovak costs of decarbonization. The study contained reference scenario (includes all national climate measures and obligations on climate action by 2020, but only ETS after 2020) and four decarbonization scenarios that were designed to contrast various combinations of share of renewables and energy efficiency targets and their trade-offs (The World Bank, 2019: vii). The results are described in table 7.

Table 7: Comparison of the results of Slovak MACC by 2030 with *A Low-Carbon Growth Study*

	Slovak MACC (Fit for 55 target)	Decarbonization scenarios 1-4
Baseline	Static average of 2016-2019	Dynamic referential scenario
Additional net costs by 2030	EUR 2.7 B	EUR 1.2 - 9 B
Total GHGs decrease 1990-2030	55%	47%
Environmental targets taken into account	Only total GHGs by 2030	Share of renewables, GHGs outside and within the ETS, primary energy savings, others
Scope	All sectors	All sectors except the LULUCF
Source	*Decarbonization of the Slovak economy by 2030*	*A Low-Carbon Growth Study for Slovakia*
Authors	ÚHP, BCG, IEP	World Bank, IEP
Year of publication	2022	2019

Source: World Bank, 2019; Haluš and Slučiaková, 2019

Out of the four scenarios, scenario 2 is the most balanced in its focus on both energy efficiency and renewables in roughly equal measure and reached a 47 % decrease of GHGs in 2030, compared to 1990. This reduction is, therefore, somewhat less ambitious than the targets outlined in this paper. This is primarily because the 55 % target was not adopted at the time of writing the World Bank paper.

Compared to the referential scenario, the costs of decarbonization scenario 2 were estimated to be 8 billion EUR by 2030. This is significantly higher than the estimates modeled in this paper, even if these have somewhat higher reduction targets. This can be explained by the different scopes of the two papers. Whereas this paper is preoccupied only by the total GHGs produced, the World Bank paper was preoccupied also with other environmental targets of Slovakia, such as the share of renewables in electricity generation or CO2 reduction in ETS sectors. Renewables in electricity generation was significantly less important in this paper due to the low emissions of the power & heat sector. Therefore it is understandable that the decarbonization scenario 2 was more costly as a result of its extensive investments into renewable energy, primarily biomass, and combined cycle power plants (The World Bank, 2019: ix).

Methodologically, the two papers differ as well. The World Bank paper used top-down economic modeling, whereas this paper used rather a bottom-up approach. In this sense, this paper offers greater precision in predicting the GHGs decreased by 2030, but is limited in its scope and does not analyze other environmental targets. These papers should, therefore, be understood not as complementary to each other.

4 Required public funding and available resources

Apart from the question of total costs, it is also important to identify the required funding for decarbonization. It will enable the policymakers to better understand the impact of decarbonization on the state budget and improve the decision-making by adding this perspective.

4.1 Methodology

To estimate the required public funding we used a top-down approach for both point and decentralized emitters. We estimated whether the levers will be realized without the funding and if not, how much of additional funding is required. For decentralized emitters, this was done by comparing the internal rate of return (IRR) of the investment and the weighted average cost of capital (WACC) in given industrial sector by 2050. The methodology and specificities of EAF and CCS levers are outlined in Box 3.

BOX 4: Methodology for estimating the public funding for point emitters

For decentralized emitters, the following steps were taken:

1. Construct investment „cash-flow“
    - OPEX is extended to 2050 (assuming fixed OPEX after 2030).
    - It is assumed that all CO_2 emissions reductions from the investment result in ETS allowances cost savings (not applicable to the EAF levers, see below).
    - The ETS allowances cost savings were added to OPEX (in the MACC itself they are excluded).
    - Three various ETS prices scenarios were used (€30, €67, and €51 to €108 per tCO_2[8]). The prices are assumed to remain constant after 2030.
2. Estimate IRR based on modeled cashflow
    - The industry-specific WACC (table 8) is taken from the Damodaran database that is also used by independent regulatory authorities in Slovakia (for example, ÚRSO, 2022).
    - If IRR > WACC, the investment is viable from a business point of view and no funding is required.
    - If IRR < WACC, the investment is not viable by itself. In that case, funding is provided to the level that reaches IRR = WACC, which is a point where the investor is indifferent between investing and not investing. It was assumed that after reaching this point, the investment will be realized.

Table 8: WACC estimates, real, pre-tax

Sector	WACC
Iron, Steel & Ferroalloys	5.9%
Minerals & Building materials	5.6%
Petroleum refining	5.3%
Chemicals	5.1%
Other industry & other	4.6%
CCS transport infrastructure	4.2%
Power & heat	4.1%
Waste	3.3%

Source: Damodaran, 2022

The two exceptions are EAF levers (34, 35), where the methodological steps to estimate the investment cash-flow work differently. This is due to the change in free allocation when using the EAFs, compared to the existing blast furnace. Because of the complex change of the technology and production process, the EU regulation stipulates that free allocation would decrease significantly. Due to numerous technical and legislative issues,

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[8] From € 51/tCO_2 in 2021 (year average up to October 2021) to € 108/tCO_2 in 2030.

this decrease is difficult to determine. A 90 % decrease of free allocation for both furnaces was modeled. For these two levers, it was also modeled that the Carbon Border Adjustment Mechanism (CBAM) will be implemented in 2026 with a 10% annual decrease in free allocation thereafter.

Regarding the CCS, due to the very high CAPEX of its transport infrastructure (4.9 billion EUR), it is expected that no individual actor would invest in it. Therefore, it was assumed that the investment must be fully funded by public sources. The initial investment can be later partially recovered from fees. Individual investors would fund carbon capture transport and storage OPEX if IRR > WACC. If IRR < WACC, public funding is provided using the same logic as described above.

The methodology for estimating the public funding is a rough estimate due to the various uncertainties. The results should be, therefore, considered with caution. We use a simplified model, which excludes several factors, namely the possibility of different WACCs, cash-flows from alternative investments, implementation problems, uncertainties, not fully rational decision-making, and so on. Our methodology uses sector-specific WACC estimates, but the WACC may differ significantly between individual firms even within one sector. Similarly, our analysis excludes consideration of alternative investments of the firms that may greatly impact their decision-making. Industries may also face implementation problems with their investments, especially if these require significant changes of technology and the firm does not have sufficient expertise. This may lead them to a decision to not decarbonize even if the investment seems economically viable. Firms may also face the problem of uncertainties, primarily about the ETS price, but also the prices of electricity and other commodities. Although many investments seem viable with the current ETS price, the firms may assume that the prices will decrease by 2030, which disincentivizes decarbonization. Finally, firms are not always rational and they may include other than financial considerations in their decision-making. Such considerations may both encourage decarbonization (positive public relations and reputation of a low-carbon company) and discourage it (less labor force needed with modern technologies). In this sense, the equipped model must be understood as a broad approximation.

Regarding required public funding for decentralized emitters, the estimation of the funding stemmed from the modeled levers themselves. For example, lever 3 (cars electrification, ambitious scenario) counted with the state subsidy of 2 000 EUR on every EV to accelerate their market penetration. Therefore, there was no need to do additional modeling for estimating the funding. This applies to all levers in the sectors of the residential and commercial buildings, transport, and others (analysis of costs by individual levers is provided below). In the case of agriculture and LULUCF, it was assumed that the full costs of levers will be financed from public sources. As they are outside of the ETS, these sectors have only a very limited motivation to decrease their GHG emissions.

4.2 Required public funding

The estimated public funding is in tables 8 and 9. For point emitters (table 8) it depends on two key factors – the ETS price (rows) and a chosen target (colums). With more ambitious targets, the required funding rises significantly across all three ETS price scenarios. Unsurprisingly, the CCS levers (modeled only in the last target) require the most funding. The ETS prices play a decisive role in the business decisions for point emitters as they significantly influence financial benefits from the decreased GHGs production. As the ETS prices are difficult to forecast, we worked with three ETS price scenarios – two fixed ones (€30 and €67 per tCO_2) and one using forecasts from October 2021[9].

In the case of the first target, the ETS price does not influence the required funding due to a low number of point emitters' levers and their high benefits, regardless of the ETS price. However, in the second and third targets, the

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[9] From € 51/tCO_2 in 2021 (year average up to October 2021) to € 108/tCO_2 in 2030

required funding varies significantly, based on the modeled ETS prices. A high fluctuation of the ETS price may be one of the key uncertainties that decrease the motivation of the businesses to decarbonize[10].

Table 9: Minimum public funding required for point emitters by target and ETS price

ETS price	Fit for 55 EU target	Target without CCS	Full 2030 potential
Current forecasts[6]	€ 9 M	€ 52 M	€ 4 948 M
Fixed €67 / tCO2	€ 9 M	€ 298 M	€ 6 243 M
Fixed €30 / tCO2	€ 9 M	€1 578 M	€ 9 812 M

Zdroj: BCG, ÚHP

Table 10: Minimum public funding required for decentralized emitters by target

	Fit for 55 EU target	Target without CCS	Full 2030 potential
Cumulative 2022-2030	€ 885 M	€ 1 676 M	€ 1 676 M
Annual average	€ 98 M	€ 186 M	€ 186 M

Zdroj: BCG, ÚHP

Decentralized emitters are not influenced by the ETS prices, therefore, three scenarios were estimated based on the target chosen (table 9). The required public funding for these emitters is already substantial in the first target, primarily due to the insulation expenses in the residential and commercial sector and the closure of the Nováky mine.

4.3 Available public resources

Apart from the state budget, there are several other possible sources of public funding, such as the European Structural and Investment Fund, Modernization Fund, Recovery and Resilience Facility (RRF), Just Transition Fund, and others.

To track the need for funding from the state budget, we linked the required public funding to a possible source based on the content of the levers. It was assumed that if no source of funding is available, only then the lever will be funded from the state budget. We modeled this using the target of 67% emission reduction (excluding CCS levers) and the current ETS price forecast. This scenario is underlined in tables 8 and 9. Using a more ambitious target than 55% allows for the possibility of imperfect implementation of levers without endangering the achievement of the EU-wide target. ETS forecast price was used as it represents the most likely scenario out of the three modeled.

Table 10 shows the required public funding broken down by sectors, with a possible source of funding. Funding required by point emitters can be covered by the Slovak Modernization Fund, Recovery and Resilience Facility (component 4), and from the future European Structural and Investment Funds (ESIF), the allocation of which is not yet determined. The funding required by the point emitters is significantly lower than the available funding for this sector.

As was pointed out before, the methodology used does not fully capture the decision-making of the industries and these may be reluctant to invest even if IRR > WACC. To give the state institutions sufficient leverage to motivate the industries to decarbonize and to help reach Slovak emission targets, the availability of higher funding than modeled is desirable.

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[10] Dutch SDE++ decarbonization scheme addresses this to decrease the business risk of the industries should the ETS price fall (Netherlands Enterprise Agency, 2021).

Table 11: Minimum public funding (67% target, ETS price forecast*) with linked sources

	Gross CAPEX	Public funding required by 2030	Available sources	
			Name	Budget by 2030
Point emitters	€ 2.3 B	€ 52 M	Modernization Fund, RRF (C4)**, ESIF	€ 4 B*, € 363 M, ?
Decentralized emitters	€ 7.9 B	€ 1.68 B		
Transport	€ 6.1 B	€ 778 M	RRF (C3), ESIF, State budget	€ 598 M, ?, ?
Residential & commercial	€ 1.7 B	€ 626 M	RRF (C2), ESIF	€ 528 M, ?
LULUCF & agriculture	€ 43 M	€ 166 M***	CAP, State budget	?
Nováky Mine	0	€ 105 M***	Just Transition Fund	€ 418 M
Total	**€ 9.4 B**	**€ 1.73 B**	**Modernization Fund, RRF, Just Transition Fund, ESIF, CAP, State budget**	**€ 4 B*, € 1.69 B, € 418 M, ?, ?, ?**

** Assuming current ETS price forecasts (from 51 to 108 €/tCO$_2$ in 2030). ** The number of the component. *** Includes OPEX.*

Similar to the point emitters, most of the public support required by the decentralized emitters can be funded by the existing or planned sources. However, unlike the point emitters where the support schemes usually support all types of decarbonization levers and technologies, the situation of decentralized emitters is different. This is because not all identified sources can be used for all of the levers in the given sector. For example, RRF supports insulation of houses, but not of flats. This is why further analysis is necessary to confirm whether all of the levers can be covered from available sources. All four decentralized sectors are discussed in turn.

Transport sector levers will be largely covered by existing sources (table 11). In the cars electrification lever, public funding is required only for the charging infrastructure, as it is expected that the EVs themselves will be financed by the public. The CAPEX of 44.3 million EUR will be funded by the RRF (component 3, investment 4). In the additional car electrification lever, the funding will be spent on direct subsidies to consumers, on average, 2000 EUR per EV. As far as we know, there are currently no planned schemes from the EU or elsewhere for direct subsidies. Therefore, it is modeled that this lever will be funded from the state budget.

Table 12: Breakdown of public funding in the transport sector

#	Lever	Public funding required for	Public funding required by 2030	Available sources	
				Name	**Budget by 2030**
2	Cars electrification	Charging points	€ 44.3 M	RRF (C3, I4)*	€ 45.9 M
3	Additional car electrification	Direct subsidies	€ 100 M	State Budget	?
39	Mode shift for passengers	Rail and cycling infrastructure	€ 152.5 M	RRF (C3, I1), ESIF	€ 536.1 M, ?
47	Shifting freight from road to rail	Rail infrastructure	€ 477 M	RRF (C3, I1), RRF (C3, I3), ESIF	€ 536.1 M, € 16.1 M, ?
48	Freight alternative fuels	Hydrogen fueling stations	€ 4.5 M	ESIF	?
	Total		**€ 778.3 M**	**RRF, ESIF, State Budget**	**€ 598.1 M, ?, ?**

** C = component, I = investment.*

Mode shift for passengers lever assumes investment into the rail (100 mil. EUR) and cycling infrastructure (52.5 mil. EUR). Rail CAPEX covers the most pressing investments in the sector. The calculation of cycling infrastructure used a conservative assumption of a kilometer of cycling route to cost 70,000 EUR, allowing for over 700 km of new routes. This lever can be funded by the RRF (component 3, investment 1). Additional rail infrastructure investment of 477 mil. EUR is expected in lever shifting freight from road to rail. The public funding required exceeds half of the total public funding in the transport sector. A part of its funding can be covered from the remaining resources in RRF component 3, investment 1 (as a part was used in the previous lever), and RRF component 3, investment 3. Although the ESIF allocation between individual areas has not been established yet, it can be expected that there will be more than enough resources for the rail infrastructure to fund the rest of this lever. Finally, the freight alternative fuels lever expects that the trucks on alternative fuels will be funded by businesses, but the state will have to provide subsidies for the hydrogen stations (4.5 mil. EUR). We expect that these will be available in ESIF. To sum up, except for the direct subsidies to consumers to purchase EVs (100 million EUR), the public funding in the transport sector can be fully covered by existing sources, namely RRF and ESIF.

In the residential and commercial sectors, the public funding required can be covered by the RRF and ESIF. Levers heat pumps & fuel switch that assumes 500 EUR subsidy per each installed heat pump or biomass boiler will be funded from ESIF. It is assumed that a significant share of these will be installed without a subsidy, therefore, an average subsidy will be somewhat higher. Lever insulating buildings not connected to the central heating system (assuming average subsidy of 40% of expenses) can be fully funded from the RRF component 2, investment 2. RRF cannot be used for the lever insulation of buildings with central heating that requires 155 mil. EUR subsidies (50% out of all expenses). This is because the RRF covers only the renovation of houses, not the houses of flats[11], the majority of which have central heating. Instead, this lever could be funded by ESIF. Although the allocation has not been decided, it can be reasonably expected that it will significantly exceed the required funding.

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[11] For simplicity, in this section, buildings not connected to central heating were assumed to be equal to houses.

Table 13: Breakdown of public funding in the residential and commercial sector

#	Lever	Public funding required for	Public funding required by 2030	Available sources	
				Name	Budget by 2030
4	Heat pumps & fuel switch	Direct subsidies	€ 31.6 M	ESIF	?
11	Insulating buildings without CHS**	Direct subsidies	€ 439.7 M	RRF (C2, I2)*	€ 528.2 M
32	Insulating buildings with CHS	Direct subsidies	€ 154.8 M	ESIF	?
	Total		**€ 626.1 M**	**RRF (C2, I2), ESIF**	**€ 528.2 M, ?**

** C = component, I = investment.** CHS = Central Heating System*

Public funding will be abundant also in two remaining sectors of decentralized emitters – agriculture and sector others (Nováky mine). Agriculture levers (see section 3.5) were modeled to be fully funded from public sources, needing 166 million EUR by 2030. This is expected to be funded from Common Agricultural Policy (CAP), which is yet to be adopted. Although exact allocations are not known, one of its key targets will be GHG reduction, therefore it can be expected that there will be enough resources for agricultural levers. Closing Nováky mine is expected to be fully funded from the Just Transition Fund.

Apart from the mentioned resources of public funding, there will be even more resources available in Innovation Fund and Social Climate Fund. Innovation Fund with a budget of at least 10 billion EUR (based on the ETS price) will support the demonstration of innovative low-carbon technologies (EC, 2022a). Although this budget is not Slovakia-specific (projects will be chosen from the whole EU), it is possible that it will support some innovative decarbonization projects of point emitters in Slovakia. Social Climate Fund (EC, 2022b) may provide additional funding, specific to the Slovak republic. The fund is aimed to finance direct income support for vulnerable households and support transport and building decarbonization. Nevertheless, the fund depends on the introduction of extended emissions trading to the building and road transport sectors. As we did not model this emissions trading extension in the MACC (box 1), we did not include it as one of the possible sources of funding in tables 9 to 11. Should this measure be adopted, deeper decarbonization can be expected than the one modeled above.

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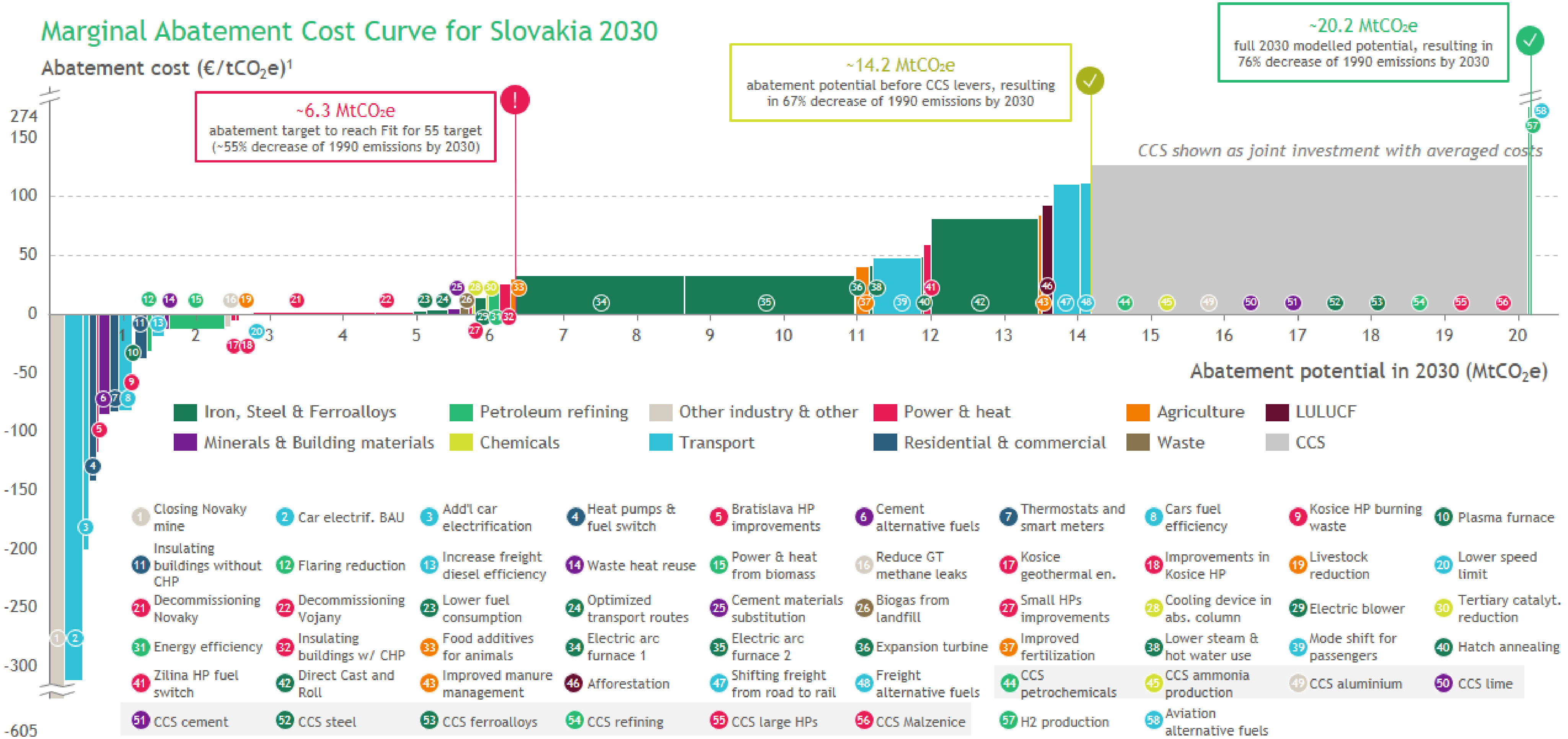
Appendix 1: A complete list of levers

#	Sector	Lever name	Y-axis - abatement cost (EUR/tCO_2e)	X-axis - abatement (ktCO_2e)	CAPEX total (not annualized, mil. EUR)	OPEX Δ in 2030 (mil. EUR)
1	Other industry	Closing Nováky mine	-605	203	0,0	-126,7
2	Transport	Cars electrification	-312	248	840,4	-195,9
3	Transport	Cars electrif. ambitious scenario	-200	83	423,0	-75,0
4	Res. & com.	Heat pumps & fuel switch	-142	111	348,3	-29,3
5	Heat	Bratislava HP improvements	-118	27	54,0	-7,3
6	Cement	Cement alternative fuels	-85	154	41,4	-13,8
7	Res. & com.	Thermostats and smart meters	-84	119	286,8	-37,9
8	Transport	Cars fuel efficiency	-83	176	3897,8	-652,4
9	Heat	Košice HP burning waste	-78	23	12,0	-2,8
10	Iron & steel	Plasma Furnace	-48	10	6,5	-0,9
11	Res. & com.	Insulating buildings without CHS	-39	167	784,2	-52,6
12	Petroleum r.	Flaring reduction	-32	73	14,2	-2,8
13	Transport	Increase freight diesel efficiency	-19	160	616,6	-114,1
14	Cement	Waste heat reuse	-13	71	10,4	-1,3
15	Petroleum r.	Power & heat from biomass	-13	755	342,0	-25,7
16	Other industry	Reduce methane leaks	-11	82	2,2	-0,9
17	Heat	Košice Geothermal energy	-6	71	60,0	-5,7
18	Heat	Improvements in Košice HP	-6	52	19,0	-1,8
19	Agriculture	Livestock reduction	0	126	0,0	0,0
20	Transport	Lower speed limit	0	52	0,0	0,0
21	Power	Decommissioning Nováky	1	1662	30,4	-0,3
22	Power	Decommissioning Vojany	1	524	8,4	0,0
23	Iron & steel	Lower fuel consumption	3	194	8,3	0,0
24	Iron & steel	Optimized transport routes	4	285	15,0	0,0
25	Cement	Cement materials substitution	5	162	10,4	0,0
26	Waste	Biogas from landfill	5	116	14,0	-0,4
27	Heat	Small HPs improvements & fuel switch	13	49	41,6	-2,5
28	Chemicals	Cooling device for absorption column	13	37	1,9	0,3
29	Iron & steel	Electric blower	14	147	30,0	0,0
30	Chemicals	Tertiary catalytic reduction	21	33	5,0	0,3
31	Petroleum r.	Energy efficiency	22	158	37,4	0,7
32	Heat	Insulating buildings with CHS	26	150	309,6	-15,7
33	Agriculture	Food additives for animals	30	59	0,0	1,8
34	Iron & steel	Electric arc furnace 1	33	2309	362,5	43,9
35	Iron & steel	Electric arc furnace 2	33	2309	362,5	43,9
36	Iron & steel	Expansion turbine	39	18	10,0	0,0
37	Agriculture	Improved fertilization practices	40	189	0,0	7,5
38	Iron & steel	Lower steam & hot water consumption	41	51	27,0	0,0
39	Transport	Mode shift for passengers	48	646	152,5	0,4
40	Iron & steel	Hatch annealing	49	39	25,0	0,0
41	Heat	Žilina HP fuel switch	59	95	75,0	0,0
42	Iron & steel	Direct Cast and Roll	82	1464	580,0	70,2
43	Agriculture	Improved manure management	84	60	0,0	5,0

44	Petroleum r.	CCS petrochemicals	84	477	0,0	40,1
45	Chemicals	CCS ammonia production	87	876	0,0	76,0
46	LULUCF	Afforestation	93	147	43,1	10,3
47	Transport	Shifting freight from road to rail	111	374	0,0	10,3
48	Transport	Freight alternative fuels	112	140	247,3	-118,8
49	Other industry	CCS aluminium	126	271	0,0	34,3
50	Cement	CCS lime	133	332	0,0	44,2
51	Cement	CCS cement	133	1559	0,0	207,9
52	Iron & steel	CCS steel	139	1092	0,0	152,1
53	Iron & steel	CCS ferroalloys	139	159	0,0	22,2
54	Petroleum r.	CCS refining	148	366	0,0	54,2
55	Heat	CCS large HPs	156	372	0,0	57,9
56	Power	CCS Malzenice	156	442	0,0	68,8
57	Petroleum r.	H2 production	177	39	94,0	0,0
58	Transport	Aviation shift to alternative fuel	274	9	0,0	3,2
	Total			20174	10249	-529

Res & com. – residential and commercial sector. Petroleum r. – petroleum refining. CHS – central heating system. HP – heating plants.

Appendix 2: 2030 MAC curve for Slovakia in high resolution



Marginal Abatement Cost Curve for Slovakia 2030

~6.3 $MtCO_2e$ abatement target to reach Fit for 55 target (~55% decrease of 1990 emissions by 2030)

~14.2 $MtCO_2e$ abatement potential before CCS levers, resulting in 67% decrease of 1990 emissions by 2030

~20.2 $MtCO_2e$ full 2030 modelled potential, resulting in 76% decrease of 1990 emissions by 2030

CCS shown as joint investment with averaged costs

Note: HP = Heating Plant, CHP = Central Heating Plant (District Heating Plant)

1. NPV of abatement costs until 2030/NPV of abatement until 2030. CAPEX only includes annualized costs until 2030.