Coal mining and policy responses: are *externalities* appropriately addressed? [1] A meta-analysis

Ferrini Silvia[1,2*], Virna Talia[1], Di Matteo Massimo[1]

[1]University of Siena, Department of Political Science and International, via Mattioli, 53100 Siena,
[2]University of East Anglia, CSERGE, Norwich, UK
*Correspondent author, s.ferrini@uea.ac.uk

Abstract

The paper combines a systematic literature review and a cluster analysis to investigate the progress and challenges of policy instruments designed to mitigate coal mining externalities. Coal is a widely abundant fossil fuel and it is forecasted to remain in the energy mix for many years to come. However, coal mining is responsible for multiple social and environmental externalities that need to be fully internalized in the coal supply market. Around the world, multiple policy instruments have been adopted to mitigate externalities but our review reveals that several coal mining externalities remain largely neglected, including impacts to biodiversity. The cluster analysis provides a comprehensive reading of the literature findings and reveals that policy instruments can moderate the negative externalities of coal mining but the majority of current coal mining policies lack a formal assessment and quantitative performance measures. It is noteworthy, that market-based instruments as well as innovative instruments are more effective than command and control at internalising coal mining externalities especially coal mine methane. A second cluster analysis by country highlights the heterogeneity of policy instruments adopted and the mix of success and failure. We conclude that few successful policies exist, that there is a need for more policy evaluation and that growth in coal mining poses challenges for our sustainable future.

---

[1] The research has been conducted within Fessud, a research group funded by EU on financialization and sustainable development, FP7 Theme: SSH-2010-1.2-1, Project Number: 266800.

1. Introduction

Historically coal was the dominant primary energy resource for many countries but in recent decades, many high-income countries responding to environmental concerns switched from subsidising coal mining, to regulating and reducing coal consumption and associated carbon emissions. Assessments of this switch in policy instruments from incentivizing mechanisms to regulating and taxing systems are infrequent. This oversight is critical as emerging economies are intensifying their use of coal. In this paper we aim to verify if policies are successful at mitigating coal mining externalities and if they could be adopted by developing countries (Jakob et al., 2020). This is not an easy task and we offer a few considerations later in the paper to reflect on how lessons learnt from historic coal mining countries can support sustainable development of emerging economies.

In the 1990s, coal mining environmental pressures were first discussed globally. In 1995, the International Conference on "Social Costs and Sustainability", reported on growing concern over the environmental externalities of coal production and consumption in Europe. The "External Costs of Energy" (ExternE) project was the first comprehensive attempt to use a consistent "bottom-up" approach to evaluate the external costs of different fossil fuel production chains. At the policy level, European countries ended coal mining subsidises by 2000, and since then have imported coal from other continents (BP, 2018), as well as, investing in new emission abatement technologies (carbon capture and storage) and renewable energies. Australia, Russia, China, and the USA are still major coal producers and have implemented diverse strategies to mitigate coal production externalities.

In 2018, according to the International Energy Agency (IEA), coal made up 38.5% of the global energy mix. Energy transition is a long and complex process (Smil 2010, Sovacool 2016) and it is credible that coal mining will remain an important economic sector for decades. This is despite the growing attention to CO_2 emissions and renewable technologies (York and Bell, 2019). Emerging countries (e.g. Colombia, India, Ghana, Turkey) are investing in coal production to support their rapid development strategies and Gellert and Ciccantell (2020, p.9) argue that "coal is not in demise – at least not yet".

In light of the central role of coal, this paper aims to review the main coal mining externalities and assess which policy instrument(/s)is(/are) successful in mitigating coal mining externalities and potentially in restoring the natural ecosystems (e.g. Dallimer et al., 2020). The aim is to provide a set of successful policy instruments that could be adopted by emerging economies to promote sustainable energy pathways and minimize the coal mining externalities. In detail, the paper sets out to answer the following questions:

Q0. For each coal mining externality can we find a corresponding policy instruments?

Q1. Are policy instruments successful in terms of effectiveness and efficiency?

Q2. Which are the most effective instruments for internalizing coal mining externalities?

Q3. Are different countries treating coal mining externalities similarly, and can newly industrialising countries learn from experiences in high-income countries?

The paper reviews policy options for coal mining externalities in several countries and through a cluster analysis provides a systematic review of empirical findings on policy instruments performance. The paper is organized as follows. In Section 2, we describe social and environmental externalities that derive from coal mining and identify those that we investigate. The main policy instruments available for addressing externalities coupled are reviewed with a description of assessment criteria. Section 3 describes the research method, including literature review and cluster analysis. Results from the cluster analysis are presented in Section 4 and Section 5 discusses our findings on a country basis. Finally, Section 6 discusses the quality and limits of our analysis.

2. Coal *mining* externalities and policy options

Galetovic-Munoz (2013) and Goulder and Parry (2008) have categorized coal mining externalities into social and environmental effects noting that the characteristics of the impacts change with different coal extraction systems. The coal extraction process either takes place underground or via surface mining (Tiwary, 2001). In past decades, underground mining was predominant and came with substantial environmental and social consequences. More recently, advanced economies have moved towards surface mining buttressed by technological improvements. While this shift has improved economic efficiency[2], externalities costs remain sizeable (Zhang et al., 2017).

Epstein et al. (2011) present the most comprehensive life cycle analysis of the USA's coal production system and the main externalities are attributed to extraction and combustion (in Appendix Figure A.1.1). Although consumption impacts are predominant (more than 70%), coal mining effects are not negligible and further investigation on coal mining externalities might reveal wider impacts (Giam et al., 2018).

Table 1 summarises the environmental and social externalities that are rarely internalized in any functioning coal market. Notably the main impacts of coal mining are health consequences for workers. This leading issue has been widely discussed (Boden, 1977; Lewis-Beck and Alford, 1980; Darmstadter and Kropp, 1997; Lofaso, 2011) and this paper focuses instead on the impact of health issues on coal mining communities as they are not compensated by any adjustment in market prices. Coal mining activities have also produced significant economic consequences and Matheis' (2016) review of 100 years of coal mining in the US concludes that the long-term economic and social consequences are not negligible and deserves further study. Local economies (e.g. tourism) are primarily impacted by coal mining but relative prices of local goods and services will capture the negative effects of coal mining and lead to a new economic equilibrium. Therefore, when a market exists, efficiency is promoted by the market functioning. Contrary for environmental and social effects, that are not related to markets, the efficiency rule is not met unless policy instruments mitigate these effects. Our interest is to investigate this research gap: do policy instruments manage coal mining externalities fairly, efficiently and effectively when market forces are not operating?

Table 1. Classification of key coal mining externalities and related impacts.

Mining	***Social externalities***	***Environmental externalities***
Underground	Mortality and morbidity in coal communities	Methane emissions
	Health risks due to abandoned mines	Abandoned mines
Surface Mining	Mortality and morbidity in coal communities	Biodiversity loss

---

[2] Surface mining offers a higher rate of extraction efficiency, for example, mountaintop removal uses explosives to break up rocks and to access buried coal; it requires fewer workers, but it is the main driver of land-use changes in several regions. This technique is now the major form of mining in the USA.

	Coal miners/workers health risks[3]	Rivers, stream, ponds water contamination
		Air contamination
		Methane Emissions
	Health risks due to abandoned mines	Acid Rain
		Landscape effects due to abandoned mines

Source: Adapted from Epstein et al. (2011)

A suite of policy instruments is available to decision makers to correct for negative externalities (Fig. 1). Command-and-control policies set uniform standards to internalize externalities irrespective of different firm's production costs. The standard can be technology or performance based. The former dictates the method or the equipment that firms must use to reduce the externalities. The latter defines a target that firms have to achieve using different technologies.

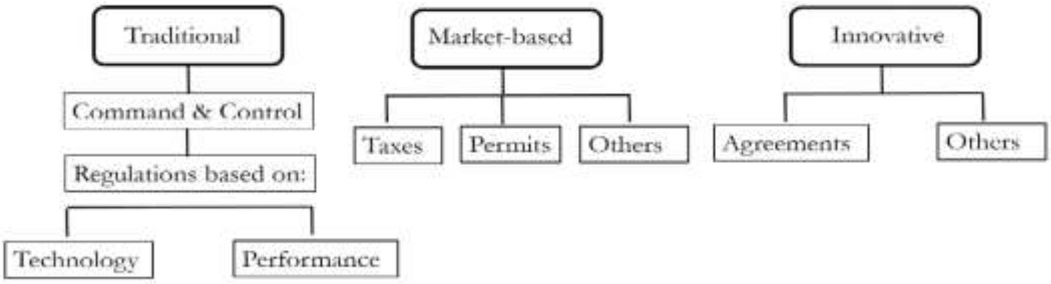


Figure 1. Policy options classification

Market-based instruments were initially proposed by Pigou (1920) but formally introduced in the 1980s to tackle environmental externalities. It is claimed that market-based instruments encourage environmentally-friendly behaviour through market signals, using for example, tradable permits or pollution charges (OECD, 2010). If these instruments are well designed and effectively implemented (e.g. tradable permits are well distributed), they encourage firms (and/or individuals) to undertake efforts which satisfy their own interests along with collective interests set by the government.

---

[3] The choice to overlook the external effects on coal miners is dictated by the salary system for risky jobs. In the case of health risks, the workers receive a wage premium which should equalize the marginal health risk of the job. Although the efficacy of the job market in fully internalizing coal miners' health risks is incomplete, as evidenced by several policy instruments that are constantly designed or updated to minimize workers' risks (Di Matteo et al., 2015). We assume in the following that coal miners' risks are internalized in functioning markets.

In the early 1990s several countries implemented a "green tax reform". In this context, innovative policy options, such as voluntary agreements or environmental bonds, were introduced. Since then, a variety of instruments, belonging either to the market-based or more innovative group, has been proposed (OECD, 2001). The objective was to encourage specific sectors to tackle externalities, or to capture complex environmental issues (OECD, 2012).

Economic literature and practical experience suggest that no single instrument is clearly superior across all the relevant decision criteria for policy choice; even a ranking with a single criterion often depends on the circumstances involved (Goulder and Parry, 2008). Therefore, policy decision makers frequently face the challenge of defining the appropriate mix of policy instruments. Accepted measures to assess the performance of policy instruments are effectiveness, efficiency, and distributional effects (Pearce and Turner, 1990; Perman et al., 2003).

Effectiveness measures the degree to which the achieved outcome corresponds to the intended goal of a policy instrument. The efficiency criterion has two key dimensions: (i) balancing marginal benefits and marginal costs in achieving environmental objectives; and (ii) whenever an environmental goal is pre-set, that goal should be achieved at the least possible economic cost, i.e., cost-effectiveness should be pursued (OECD & IEA, 2008). Efficiency can be conceptualised in static and dynamic terms. Static efficiency refers to the current costs of implementing the environmentally-friendly behaviour. Dynamic efficiency refers to the future cost of achieving the environmentally-friendly behaviour.

The distributional dimension of a policy instrument concerns the regressive/progressive impacts on society across multiple dimensions such as income classes, regions, ethnic groups, and generations. Chichilnisky and Heal (1994; 2000), among others, show that implementing a policy that aims to restore efficiency due to an externality inevitably involves considerations about income distribution.

3. Materials and methods

A systematic literature review and a cluster analysis were utilised in this study. A visual representation of the methodological steps is reported in Figure 2. The approach consists of a systematic web search where policy options and coal mining externalities were jointly queried (see Appendix A.1). This revealed useful information (externality addressed, policy applied, year, country, policy score, etc.) about the policy applied to internalize the externalities which were collected in a dataset. This data was then objectively summarized by the cluster analysis.

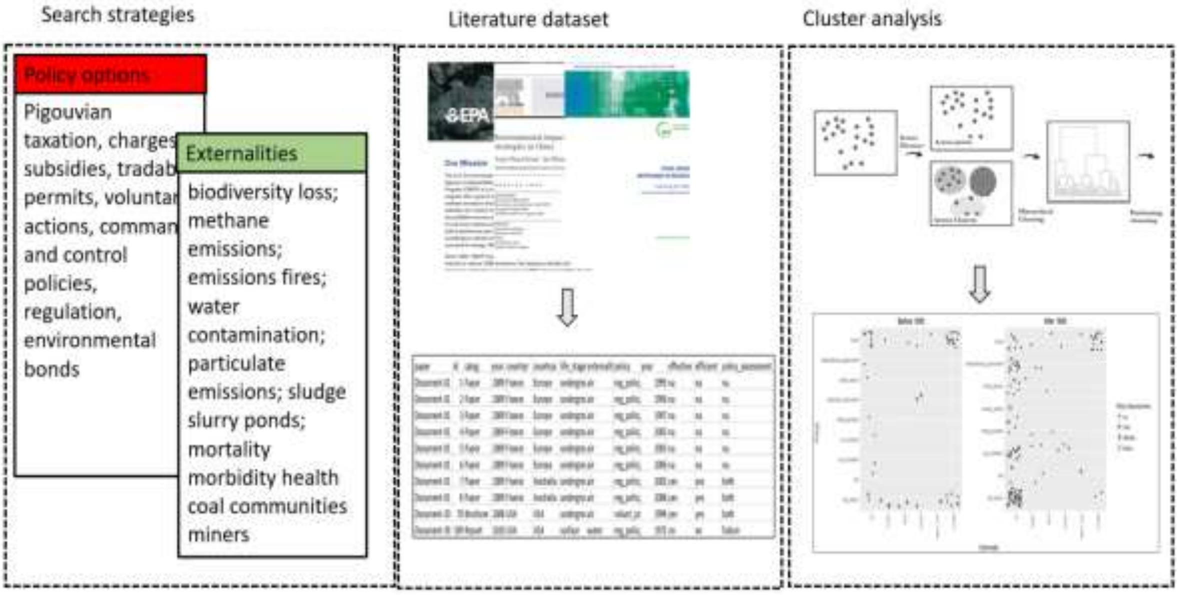


Figure 2. Framework of analysis and methodological steps

3.1 Systematic literature review

A systematic literature review (including grey literature whose value has been recognized inter alia by Dallimer et al., 2020) was conducted to match coal mining externalities and policy instruments in search strategies. A web interrogation routine was used, and details are reported in Appendix A.1. From the multiple studies found, we retrieved more than 120 pairs of externalities/policies that compile our dataset along with the performance measures (details on the classification strategy are in Appendix A1, A2). The performance measures are captured by dummy variables that take value one if the policy is effective, efficient and fair, and zero otherwise. The dataset also includes details about the country, authors, year etc. Policies analysed in the dataset were divided into pre- and post-1990 as this year landmarked growing environmental policy awareness (e.g. Kyoto Protocol).

3.2 Cluster Analysis

Cluster analysis is a classification method which, in a transparent and reproducible procedure, identifies groups of observations that are similar to each other considering their qualitative and/or quantitative characteristics. This method is particularly widespread in social science to classify observations and objectively identify patterns in the data and group them using the observable characteristics. A two-step process is followed in this paper, applying a hierarchical clustering and then a partitioning clustering. The appendix includes the details of the cluster analysis (section A3).

The hierarchical method includes two steps: the Gower distance and hierarchical clustering. Initially, every observational point is considered a unique cluster, then individual clusters start to be merged measuring the "dissimilarity"/"similarity" between data points. Similarity is based on all observable characteristics (e.g. year of study, type of externality, etc). So, two studies that present the same characteristics are classified as similar (closer), on the other hand, two studies presenting different characteristics are considered dissimilar (distant). All the pairwise distances are reported in the dissimilarity matrix. Once the dissimilarity matrix is computed the clusters are formed and the process continues measuring the distance between clusters.

Distance between clusters is calculated according to the method *average*: from the dissimilarity matrix and Gower measures we can plot a tree diagram (dendogram), where (hierarchical clusters) the number of potential groups is visible, and the partioning cluster can be applied. The partitioning analysis enables the identification of the key elements that describe the policy instruments and externalities along with the performance measures. For an overview of results, we run two cluster analyses (pre- and post-1990) and subsequently the analysis is deepened by countries. Results obtained from each cluster analysis are plotted in different graphs to visually discover which are the successful policies for each externality for any country. Whereas, the cluster analysis offers a comprehensive strategy to analyse the dataset, analysts can then provide a subjective interpretation of the literature findings.

4. Results

Studies retrieved in the literature review report that the main externalities analysed are methane and air contaminants (63%), communities' health impacts (18%), land and water contaminants (6% and 6%, respectively), and biodiversity and other externalities (5% and 2%). Figure 3 reports the predominant policy instruments retrieved by our literature review that have proposed to tackle externalities: command and control (regulatory policy) is the most widespread.

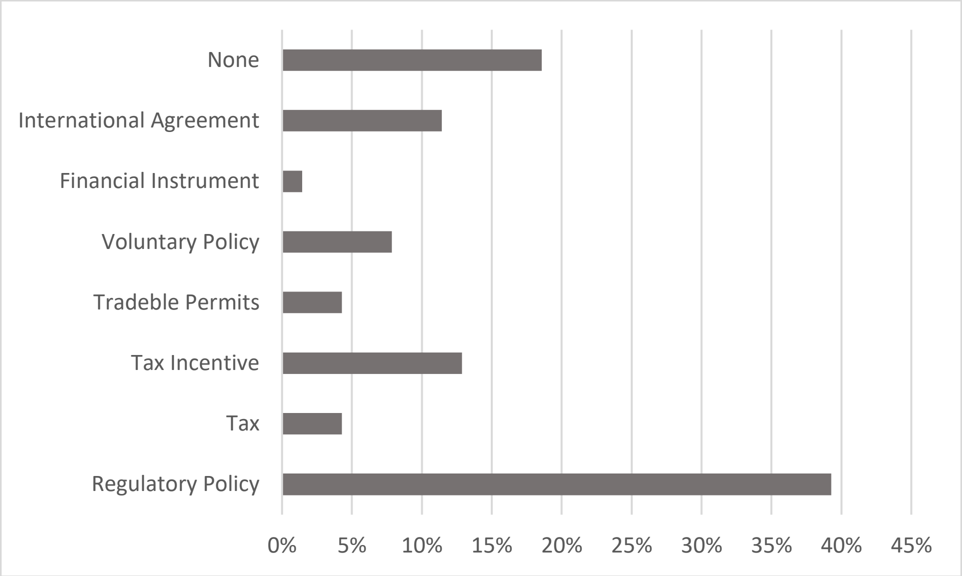
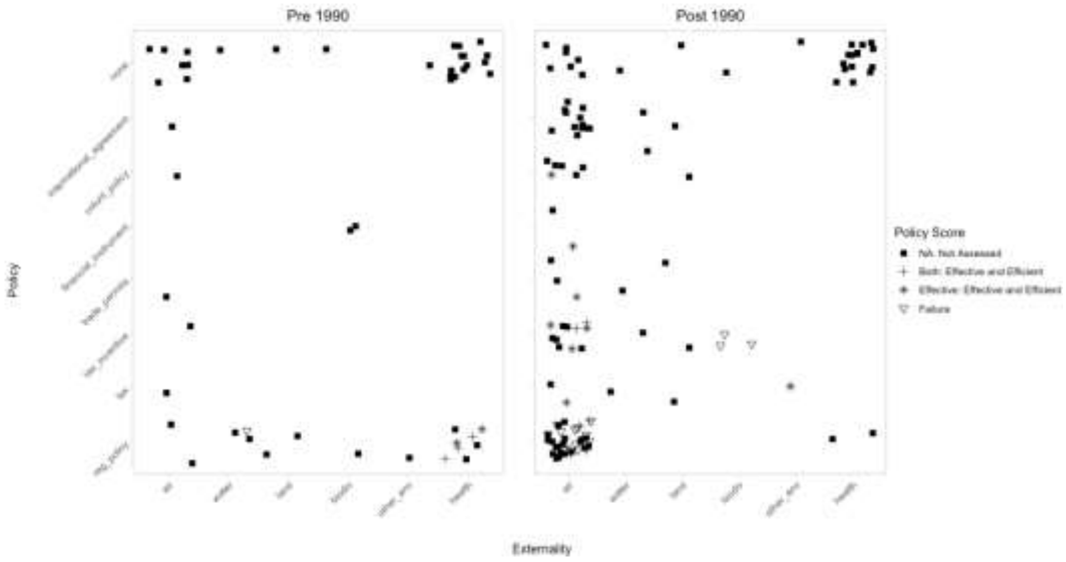


Figure 3. Policy Instruments within the dataset

Figure 4 reports the results of the cluster analysis for pre- and post-1990. On the horizontal axis the graph reports all analysed externalities and on the vertical axis policy instruments. The category "air" includes methane emissions as well as other air contaminants, "landscape" represents externalities due to abandoned mines and amenity loss-included biodiversity**,** "water" encompasses contaminants to rivers, streams and ponds, "other" refers to acid rain and other externalities. The nexus externality-policy instrument and their performance score is also displayed. Every symbol represents this combination. Different symbols indicate the success of policies in addressing coal mining externalities: * is for effective policy, + is for both effective and efficient policy. A set of studies reports no formal assessment (indicated by ■) whereas when a policy registered a failure is represented by a triangle.



Note: Air is primarily methane emission

Figure 4. Classification of studies according to externality/policy instrument and success degree pre- and post-1990

Emissions to air (primarily methane) and health impacts represent the predominant externalities that are measured and studied as retrieved in our search, and we observe an increased interest in air emission policies post-1990.

Our literature review reveals a lack of policy instruments for biodiversity loss, land use change, and water contamination. In more than 100 years of coal mining, our systematic review retrieved only six policies designed to address biodiversity loss due to coal mining. This is despite evidence that surface mining is responsible for millions of hectares of forest loss (Deikumah et al., 2014) and although biodiversity protection is recognized as an important element of sustainable development (Butt et al., 2013). Before 1990, three studies did not report any performance of the policy instruments (one command and control and two financial incentives) for biodiversity, whereas the remaining three studies, conducted post-1990, report that tax-incentives failed to protect biodiversity.

4.1 Environmental Externalities

Methane (CH_4) is the main air pollutant retrieved in our literature review. This pollutant comes from surface and underground mines and has been addressed and internalized by multiple policy instruments. Methane emissions from surface mines are usually ten times less than those from underground mines. The emission potential of mines is determined by the coal's gas content, but roughly 70% is released during extraction. Methane has a much higher radiative forcing than CO_2 and is responsible for 8-12% of all global methane emissions. Different authors report methane effects

(Cheng et al., 2011; Dessus et al., 2009, IEA, 2009b) and possible solutions (Bracmort 2011; Badarch et al., 2009; IEA, 2009a; Zhi et al., 2006; OECD & IEA, 2008). Underground and abandoned mines remain the main source of the methane emissions (Kholod et al., 2020). In the USA, abandoned mines contribute nearly 5% of total national methane emissions (EPA, 2004).

The environmental consequences of methane have only recently been regulated. Before 1990, a very small number of policies were implemented and their performance was rarely assessed. Post-1990, two clusters of policies are identified. The main cluster refers to regulatory policies and the other to innovative voluntary agreements. Regulatory policies are frequently labelled as unsatisfactory, whereas the less dense cluster of market-based instruments reveals that multiple studies report a positive assessment (mainly effective policies). The number of policies without formal assessment remains predominant. Positive examples of tax-incentive instruments for abating methane emissions which are effective and efficient were designed by the Australian and US Governments in 2000 (IEA 2009b). Voluntary energy policies are also assessed as effective instruments (Fullerton 1996; IEA 2009b; MacGill et al., 2006). Understandably, the majority of innovative instruments, which are the most recent among all other policies, like international agreements or financial instruments, lack any form of assessment. The learning message is that market-based instruments revised in this meta-analysis are successful at internalising air emission externalities but are unsatisfactory at conserving biodiversity.

4.2 Social Externalities

Colagiuri et al. (2012) list the main risks for coal mining communities which include higher rates of mortality from lung cancer, chronic heart, respiratory and kidney diseases, increased respiratory symptoms especially in children, and poorer self-rated health and reduced quality of life indicators. The social impacts are not only related to communities' health, but also to community life. A wide literature exists on the disadvantaged conditions of coal mining communities, e.g. for demographic measures such as marriage, fertility, human capital development, quality of life and migration (e.g. Shandro et al., 2011; Mactaggart et al., 2016). Our systematic literature review reveals that few policy instruments have been successfully implemented to mitigate negative effects at the community level.

Our results report that before 1990, the main policy instruments focused on miners' health effects were command and control and most of the policies were found to be effective and efficient in internalizing negative communities' effect. Post-1990 regulatory policies were not formally assessed. Our findings echo Li et al. (2017) and Poudyal et al. (2019) who suggest that policy instruments need to better reflect communities' subjective wellbeing.

5. Discussion of results and findings

The discussion is framed around the four research questions.

Q0: For each coal mining externality can we find a corresponding policy instruments?

Our literature review reveals that only a subset of coal mining externalities has been internalized by policy instruments. Figure 5 reports that some policy instrument/externality pairs are missing, signalling a lack of intervention. For example, post-1990, financial instruments were used for air emissions and no regulation was implemented for water, land, or biodiversity impacts. At the same time, we can expect that other policy instruments might have produced benefits for coal mining areas but are not included in this review as governments or organizations have not published the results. Our findings report that relevant global externalities (i.e. methane) have been widely regulated with a mixture of policy instruments. This reflects international attention on GHG emissions reduction strategies but our review reveals that other externalities need to be internalized (Kholod et al., 2020). Innovative mining technologies can minimize GHG emissions, making coal mining a long-term viable source of fossil fuel (Zhang et al., 2017). However, local externalities such as biodiversity loss, water quality, land use changes and communities' health problems are still overlooked which might have even more devastating consequences when multinational mining corporates operate without accounting for full coal mining externalities are not considered (Gutiérrez-Gómez, 2017). These externalities need to be incorporated in the global price of coal to support emerging economies to sustainably manage their natural capital (Cardoso, 2018) and to internalize the global and local consequences of coal mining. This would reconcile with the necessity of restoring and rehabilitating natural ecosystems for emerging countries which wish to reject the model that high-income countries have followed in the recent past (Tost et al., 2018).

Q1: What is the empirical assessment of policy instruments on the basis of criteria: effectiveness, efficiency and distributional effects?

The review shows how the assessment of policy instruments is still inadequate. Most studies (in particular those covering more recent policy instruments) do not provide any quantitative assessment. This lack of information could lead emerging economies to delay addressing coal mining externalities as they cannot benefit from the experience of developed economies. Future knowledge transfer may require international cooperation and the role of supranational organizations (Vinke de Kruijf et al., 2016). The lack of a consistent reporting of valuation methodologies has been heavily criticized by Dallimer et al. (2020).

Q2: Which are the most successful instruments for internalizing coal mining externalities?

The success of a policy instrument can be measured by its ability to be at the same time effective, efficient, and with fair effects. In this review no study scores positively for all the three measures but a subset of studies reviewed were both effective and efficient (symbol * in Fig 5). Consistent with expectation and previous studies (e.g. Goulder and Parry, 2008) market-based instruments are mainly assessed positively. The latter, could be argued, is the result of anti-state and pro market biases in the literature although we have no clear and direct evidence of such a systematic bias.

Q3. Are different countries treating coal mining externalities similarly, and can newly industrialising countries learn from experiences in high-income countries?

To answer this question we split the cluster results of Figure 5 into four groups: Europe, the USA, Australia and China (Fig. 5). A fifth group, OECD is also presented for the period post-1990. This group is independent from the USA, Europe and Australia case studies as it includes just OECD reports that jointly discussed multiple countries.

Figure 5 shows the results of a cluster analysis by country, run again pre- and post-1990. As in Figure 5, the symbol * represents effective policies, + both effective and efficient policies and ■ signal pair externality/policy instrument without any assessment. For each country, we discuss the main policy instruments adopted to mitigate coal mining externalities unfolding the findings of our literature review.

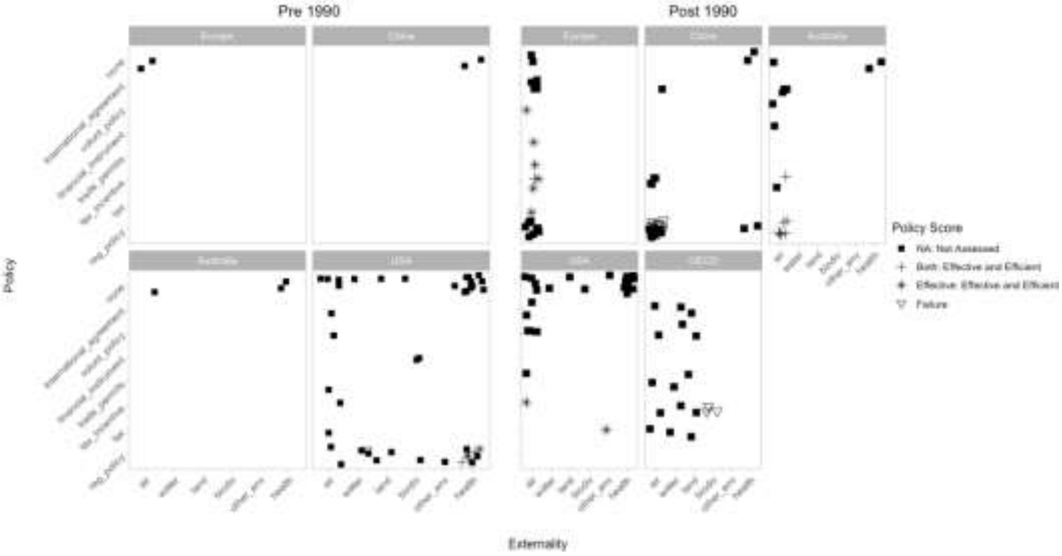


Figure 5. Classification of studies according to externality/policy instrument and success degree by country pre- and post-1990

OECD

Since 1990, many OECD countries have reduced or eliminated direct coal subsidies and lifted price controls. This process produced continuous and significant declines in coal production and favoured natural gas or less polluting fuels (OECD, 2001). In the last decade of 20th century, UK, Belgium, and Portugal removed all coal production support and the EU introduced new and more stringent environmental regulations. This is confirmed by the substantial increase in regulation post-1990; Figure 6 shows that OECD countries mainly based regulation of coal mining on market-based or innovative instruments and not command and control. Health effects on coal miners' communities appear less regulated than environmental issues and this tendency is apparent post-1990. A few policy instruments were found unsatisfactory, specifically in internalising biodiversity loss (as denoted by triangle in Figure 5). Most of the policy instruments are missing any formal assessment, however, the variety of policy instruments rejects the "one size fits all" approach to internalize externalities. The individual country analysis provides a more in-depth discussion on coal mining policy instruments.

Australia

Inspecting more closely governmental attitudes, we observe some similarities between Australia and Europe both pre- and post-1990. Air emissions have been widely addressed and in 2013 the government report (Australia's Sixth National Communication on Climate Change) revealed that methane emissions were responsible for 30% of all emissions, of which coal mining was responsible for 83% (Department of Industry, Innovation, Climate Change, Science, Research and Tertiary Education, 2013). The mix of policy instruments adopted differs from those in Europe as they mainly invested in command and control. Before 1990, Australia and Europe mainly addressed air emissions through international agreement and voluntary instruments. Post-1990, Australia has mainly invested in regulations and less intensively than Europe in market-based instruments (e.g. permits). A successful initiative in Australia is the '13% Queensland Gas Scheme' launched in 2005 and valid for 15 years. This scheme forces energy producers to source 13% of electricity from emitted gases. This has resulted in methane capture and the current percentage of electricity from methane gas is 18%, 5% more than the target. Another initiative is the 'Coal Sector Assistance Package' which encourages innovation in coal production including to reduce methane emissions. The Government provides $38.5 million to industry to fund innovative projects. Several Australian initiatives to internalize externalities due to air emissions have been found successful and might represent good practice for other coal producing countries (Cronshaw, & Grafton, 2016; MacGill et al., 2006).

Europe

Post-1990 air emissions are the main externalities addressed and differently from Australia, European countries have adopted a variety of policy instruments. Coal methane emissions represent 5% of the total European Union methane emissions, of which Germany produced 42% of the total, Spain 27%, UK 17%, and France 11% (AEA, 1998). EU tackled methane emissions in the so called 'Climate and Energy Package' (2007) and EU methane emission strategy COM 663 (2020) (together with other GHG emissions strategies). The EU regulation does not tackle coal mine methane (CMM) directly but leaves national governments to promote the reduction of methane.

In the 1990s, UK and Germany started to capture CMM and now Germany captures more than 70% of CMM compared to only 30% in the UK. Germany utilised a market-based instrument, the feed-in-tariff, to incentivise the use of methane as a renewable energy. This policy was introduced in 1990 and reviewed in 2004 and 2006. The feed-in tariff has an important distributive effect, whereby CMM producers are compensated from electricity consumers to provide clean energy from methane emissions; the cost of negative externalities is internalized in electricity prices and consumers bear the cost of this externality. The policy provides a long-term price deal and promotes investments in CMM projects, such as reducing methane emissions from abandoned coal mines. In the UK, the emphasis is on methane control and flaring rather than energy recovery. Whilst this regulatory policy is successful in reducing methane emissions in a cost-effective way, it discourages the capture and use of methane as energy source. The UK also has a methane Emission Trading Scheme from active coal mines, however, the scheme excludes abandoned mines although they represent a significant source of pollution. In April 2002, another market-based policy introduced is the exemption of CMM from the Climate Change Levy. However, this market-based policy instrument has not promoted investments in electricity generation technologies.

The USA

The internalization of coal mining externalities in the US started before 1990 and it has evolved post-1990. Initially, methane emissions were regulated only for health and safety reasons Since 1994 CMM has been regulated for environmental reasons in the 'Coalbed Methane Outreach Program'. This voluntary program was signed by mining companies to reduce methane emissions. State administrations could also offer tax incentives (shifting the burden on the general taxpayer) to attract investments and stimulate the recovery and use of CMM. The CMM recovery policy produces distributive effects, whereby electricity producers are subsidised to invest in technology innovations by means of compensation from electricity users. In the period 1994-2009, the US Environmental Protection Agency (US EPA, 2011) reported that the coal mining industry was able to capture and use 81% of methane emissions. Direct revenues were estimated at $150-350 million without accounting for the environmental benefits of CMM reduction. Despite this policy success, the results of the cluster analysis in Figure 5 suggests that there are significant cases where the performance of air emission policy instruments is unknown, as signalled by many ■ symbols. In 2004, the US EPA launched and started administering the 'Methane-to-Markets Partnership' or 'Global Methane Initiative'. The program is an international voluntary initiative which sets guidelines for CMM. It also supports innovative technologies and projects that promote the capture and reuse of methane around the world. Currently 41 countries plus the European Commission contribute to the 'Global Methane Initiative'. Unfortunately, the benefits of this long-lasting initiative have not been measured yet.

In general, the USA, in contrast to Europe and Australia, has also dedicated attention to other coal mining externalities such as social health impacts, water, land use changes and biodiversity loss. Social and health consequences are particularly relevant in policy interventions as coal miner communities are experiencing several health side effects (Mactaggart et al., 2016; Hendryx and Holland, 2016; Hendryx et al., 2011; Ahern et al., 2011, Shandro et al., 2011). The most common policy instrument is regulatory policy with four federal Acts, issued pre-1990. These Acts enforced standards to improve mining techniques and reduce impacts on surrounding communities: the SMCRA regulation issued in 1977 for all coal mining processes; the Clean Water Act (1977); the National Environmental Policy Act (1969); and the Administrative Procedure Act (1946).

The first two Acts provide substantive standards for regulating surface mining, whereas the last two Acts are procedural statutes that guide enforcement of the laws. Kaneva (2010) reviews these regulations and a key conclusion is that there is a lack of stringent enforcement weakening policy success in reducing negative externalities. For example, in 1997, 75% of the active surface mines in West Virginia were being operated in violation of state and federal laws.

China

As an emerging economy China is increasingly addressing many of the commonest externalities of coal mining (Qi et al., 2019). Indeed, before 1990 no Chinese policy was dedicated to air emissions. Post-1990, CMM is regulated by several laws mainly for safety reasons, but China is committed to recover and use CMM in the short run for environmental and energy reasons. Currently, China is the largest emitter of CMM, but the 'Mineral Resource Law' (revised in 1996) made important changes in the management of coal resources (Miller et al., 2019). In the last decade, small mines, operating under low safety standards and environmental conditions, were closed. As CMM is defined as an associated mineral of coal, China financially subsidizes its recovery. This tax-incentive was crucial to reduce the coal mine air emissions. In 2005, the 'Five Year Plan 2006-2010' aimed at draining 5 billion m^3 of methane (draining efficiency of 40%) and utilizing 3 billion m^3 (efficiency of 60%) by 2010. Cheng et al. (2011) present the results of the program and report that the drained CMM successfully reached the target but the utilization rate was unsatisfactory. However, this policy is considered not fully evaluated and therefore received a ■ in Figure 6. In June 2006, the report on 'Opinions on Speeding up CBM/CMM Extraction and Utilization' was issued with guiding principles to capture methane emissions before mining activities can start. Key aspects of this policy are: CMM draining is compulsory for coal mining activity, in case of significant problems, the mining activity must be suspended, and coal mine owners and operators have legal responsibilities to ensure that the CMM standards are met.

The IEA (2009) commented that many coal mine producers have installed the draining system and the new standards have been successful in reducing coal mine externalities, however, a formal assessment of this regulation was not found in our review. In 2007, the government launched another initiative 'Notice on CMM Price Management' which established that the price of CMM can be freely negotiated. At the same time, the Ministry of Finance issued the 'Executing Opinions on Subsidizing CMM Development and Utilization Enterprises'. This market-based instrument financially subsidized any enterprise engaged in CMM to be used on-site or marketed for residential use or as a chemical feedstock. In 2008, the Ministry of Environmental Protection issued an 'Emission Standard of CMM'. This new standard dictated rules for CMM draining systems, methane dilution and transport of lower concentration. Details about the effects of the recent Chinese regulations are still missing and Khan and Chang (2018) raise the need for more transparency and a comprehensive analysis of environmental effectiveness of Chinese policy interventions. Figure 5 confirms that the Chinese government presents an interest in coal mining communities (health) higher than Europe and Australia (Ming-Xiao et al., 2011; He et al., 2020). We acknowledge that this might be just a time effect, as Chinese interventions are recent and possibly better reported than in other analysed countries.

In responding to our Q3, we observe a diversity of policy instruments used to tackle coal mining externalities by countries. The first result of our analysis is the lack of assessment for many of policy instruments. Looking vertically at the countries' panel in Figure 6, we observe predominantly air emission and health externalities policies except for the OECD and USA; these countries also addressed other externalities although with disappointing results. Europe reports examples of satisfactory and unsatisfactory air emission policies and a lack of policy actions for coal mining communities. Australia and China have both invested in regulatory instruments although Australia has effective and efficient policies whereas China has negative or missing assessments. Although the choice and feasibility of policy instruments reflects cultural and institutional traditions and capacity, this review suggests that new coal mining countries such as China can gain effective and efficient reduction in coal mining externalities using market-based or innovative instruments as implemented in other nations.

6. Conclusions

The sustainable pathway for energy production requires a broader awareness of all fossil fuel externalities. Coal mining and its externalities have a very long history and government interventions vary in their ability to mitigate social and environmental impacts. Coal remains an important future source of the energy mix for many economies and this paper poses questions about the overall ability of policy instruments to mitigate the coal mining externalities. Combining a systematic literature review (including of grey literature) and cluster analysis we analyse the nexus of coal mining externalities and policy instruments to investigate successful policy responses for sustainable coal mining activities. We conclude that coal mining externalities (Q0) are still only partially researched (as noted in Dallimer et al., 2020) and in addition we observe several "neglected" externalities that are not policy regulated. We refer to local impacts such as forest and biodiversity loss, water contamination, which are increasingly regarded as crucial components of sustainability and might need ad hoc policy interventions (Borie et al., 2020; Dallimer et al., 2020). While environmental coal mining externalities present primarily local impacts, these detrimental effects can impinge on global ambitions for biodiversity conservation set by the IPBES (Borie et al., 2020) and the UN Sustainable Development Goals. Furthermore, the lack of regulation for coal mining environmental externalities raises concerns for the possible consequences of emerging markets for new mines for cobalt and lithium (Nkulu et al., 2018).

Emerging economies are endowed with coal reserves and biodiversity hotspots (e.g. Colombia) and coal represents a fundamental asset for their development plans. However, some of these countries wish not to repeat the pattern of economic development followed by mature economies (as noted in Borie et al., 2020) and a set of best practices to handle coal mining externalities might be useful. Our assessment of policy instrument performance (Q1) provides insight about the most promising policy instruments to internalize coal mining externalities, but a formal quantitative assessment of these policies is frequently missing. This is particularly worrying for emerging countries that would possibly benefit from best practices elsewhere in the world (Cardoso and Turhan, 2018).

The cluster analysis reveals that the most common policy instrument remains command and control (regulation policies) but post-1990 the number of market-based instruments has increased. As expected from economic theory the results (of Q2) confirm that on average market based and innovative instruments are efficient. Market based instruments (i.e. feed-in tariff in Germany) and innovative instruments (i.e. voluntary programs in US) provide clear examples of distributional effects: in both cases CMM emissions are internalized in the price of electricity and consumers compensate producers who invest in the capture and utilization of methane. This result encourages scholars and policy makers to further investigate the distributional effects of any energy transition policy (Sovacool, 2016).

Details of the findings of our literature review are deployed in the country analysis (Q3) and the brief description of some of the successful policies aimed at highlighting the peculiarities of each national context that reduces the scope for a "one size fits all" approach (as stressed in Borie et al., 2020). For example, voluntary programmes are unlikely to be successful in all situations. In some cases, knowledge transfer may require the presence of supernational organizations and/or international cooperation (as noted in Vinke de Kruijk et al., 2016). In general, economists agree that the effectiveness of a single policy instrument depends also on the institutional capacity. Therefore, we can expect that if some countries share similar economic and institutional settings, policy instruments can be successfully transferred from one country to another but further study is needed.

The lack of assessment for distributional issues represents a serious defect for most of the reviewed studies. In fact, multiple air emission policies are efficacious and efficient although doubt remains on their distributional effects across groups and regions. The long-term effects of energy transition policies deserve further research as also suggested by Gellert and Ciccantell (2020). Coal mining externalities could also be mitigated by technology innovations as confirmed by CMM capture and use strategies.

Summarizing similarities and differences among countries (Q3) is not straightforward. In response to international pressure to control greenhouse gas emissions we note that methane emissions is the main externality tackled in all countries. Whereas in the UK, emphasis has been mainly on controlling methane emissions, Germany has subsidised producers to exploit methane as a renewable energy source. Australia has been even bolder by encouraging innovative policy options that rely on industry initiatives. Finally, the USA has relied on a mix of voluntary agreements and tax incentives to attract investments in the recovery and use of methane. China, not surprisingly, has extensively used regulations to impose standards and thus control methane emissions. However, more recently it too has moved towards market-oriented policies for promoting methane use, although a proper assessment of such policies is still lacking.

Social health effects on coal mining communities have been given less attention by published studies.. The US provides examples of successful policy interventions for coal mining communities' pre-1990. China and Australia have adopted a variety of policy instruments to reduce coal communities' externalities, but a formal assessment of these policies is still missing.

References

AEA Technology Environment, (1998). Options to Reduce Methane Emissions (Final Report). Harwell.

Ahern, M. M., Hendryx, M., Conley, J., Fedorko, E., Ducatman, A., &Zullig, K. J. (2011). The association between mountaintop mining and birth defects among live births in central Appalachia, 1996–2003. Environmental research, 111(6), 838-846.

Badarch, M. and Namkhainyam, B. (2009) "Methane recovery and utilization opportunities". *Ulaanbaatar*,

Boden, Leslie I. (1977). "Underground coal mining accidents and government enforcement of safety regulations". *Dissertation. Massachusetts Institute of Technology.*

Borie, M., Gustafsson, K. M., Obermeister, N., Turnhout, E., & Bridgewater, P. (2020). Institutionalising reflexivity? Transformative learning and the Intergovernmental science-policy Platform on Biodiversity and Ecosystem Services (IPBES). *Environmental Science & Policy*, 110, 71-76.

Boyer, C. M., et al. (1990). "Methane emissions from coal mining: issues and opportunities for reduction*". United States Environmental Protection Agency, Air and Radiation (EPA).*

BP. (2018). BP statistical review of world energy: coal. BP Statistical Review, London, UK, accessed July 7, 2019.

Bracmort, K. (2011). Methane Capture: Options for Greenhouse Gas Emission Reduction. DIANE Publishing.

Butt, N., Beyer, H. L., Bennett, J. R., Biggs, D., Maggini, R., Mills, M., ... & Possingham, H. P. (2013). Biodiversity risks from fossil fuel extraction. *Science*, 342(6157), 425-426.

Cardoso, A., &Turhan, E. (2018). Examining new geographies of coal: Dissenting energyscapes in Colombia and Turkey. *Applied energy*, 224, 398-408.

Cheng, Yuan-Ping, Lei Wang, and Xiao-Lei Zhang (2011). "Environmental impact of coal mine methane emissions and responding strategies in China." *International Journal of Greenhouse Gas Control* 5.1: 157-166.

Chichilnisky, Graciela, and Geoffrey Heal. (1994) "Who should abate carbon emissions?: An international viewpoint." *Economics Letters* 44.4: 443-449.

Chichilnisky, Graciela, and Geoffrey Heal, eds. (2000) "Environmental markets: Equity and efficiency*". Columbia University Press.*

Colagiuri, Ruth, Johanne Cochrane, and Seham Girgis. (2012) "Health and social harms of coal mining in local communities". Beyond Zero Emissions,

Commission of the European Communities. "Strategy Paper for reducing Methane Emissions", (1996), Brussels.

Cronshaw, I., & Grafton, R. Q. (2016). A tale of two states: Development and regulation of coal bed methane extraction in Queensland and New South Wales, Australia. Resources Policy, 50, 253-263.

Dallimer, M., Martin-Ortega, J., Rendon, O., Afionis, S., Bark, R., Gordon, I. J., & Paavola, J. (2020). Taking stock of the empirical evidence on the insurance value of ecosystems. Ecological Economics, 167, 106451.

Darmstadter, Joel, and Brian Kropp. (1997) "Productivity Changes in US Coal Mining". *Resources for the Future*,

Deikumah, J. P., McAlpine, C. A., &Maron, M. (2014). Mining matrix effects on West African rainforest birds. Biological Conservation, 169, 334-343.

Department Of Industry, Innovation, Climate Change, Science, Research and Tertiary Education, (2013). "Australia's Sixth National Communication on Climate Change - A report under the United Nations Framework Convention on Climate Change", Australia.

Dessus, B., Laponche, B. And Le Treut, H., (2009). "The importance of a methane reduction policy for the 21stcentury".

Di Matteo, M., Ferrini, S. and Talia, V., (2015) "An analysis of the effects of policies: the case of coal". FESSUD wp 80.

EPA, (1999). US Methane Emissions 1990–2020: Inventories, Projections, and Opportunities for Reductions. *United States Environmental Protection Agency, Air and Radiation*, 1999.

EPA, (2008). Coalbed Methane Outreach Program (Promoting Coal Mine Methane Recovery and Use). *United States Environmental Protection Agency, Air and Radiation*, 2008.

Epstein, P. R., Buonocore, J. J., Eckerle, K., Hendryx, M., Stout Iii, B. M., Heinberg, R., ...&Doshi, S. K. (2011). Full cost accounting for the life cycle of coal. *Annals of the New York academy of sciences*, 1219(1), 73.

EUROPEAN COMMISSION *(2013)*. "European Commission Global Methane Reduction Actions", Belgium.

Fullerton, Don. "Why have separate environmental taxes?" (1996) *Tax policy and the Economy* 10 : 33-70.

Galetovic, A., and. Muñoz C. M. (2013) "Wind, coal, and the cost of environmental externalities." *Energy policy* 62: 1385-1391.

Gellert, Paul K., and Paul S. Ciccantell. (2020). Coal's Persistence in the Capitalist World-Economy: Against Teleology in Energy "Transition" Narratives. *Sociology of Development* 6, no. 2: 194-221.

Giam, X., Olden, J. D., &Simberloff, D. (2018). Impact of coal mining on stream biodiversity in the US and its regulatory implications. *Nature Sustainability*, 1(4), 176-183

Goulder, L. H., and ParryIan WH (2008). Instrument choice in environmental policy. *Review of environmental economics and policy* 2.2: 152-174.

Gutiérrez-Gómez, L. (2017). Mining in Colombia: Tracing the harm of neoliberal policies and practices. In *Environmental Crime in Latin America* (pp. 85-113). Palgrave Macmillan, London.

He, G., Lin, J., Zhang, Y., Zhang, W., Larangeira, G., Zhang, C., ...& Yang, F. (2020). Enabling a rapid and just transition away from coal in China. One Earth, 3(2), 187-194.

Hendryx, M. (2009) "Mortality from heart, respiratory, and kidney disease in coal mining areas of Appalachia." *International archives of occupational and environmental health* 82.2: 243-249.

Hendryx, M. (2010). "Poverty and mortality disparities in central Appalachia: mountaintop mining and environmental justice." *Journal of Health Disparities Research and Practice* 4.3: 6.

Hendryx, Michael, and Melissa M. Ahern. (2008). "Relations between health indicators and residential proximity to coal mining in West Virginia." *American Journal of Public Health* 98.4: 669-671.

Hendryx, Michael, and Melissa M. Ahern. (2009) "Mortality in Appalachian coal mining regions: the value of statistical life lost." *Public Health Reports* 124.4: 541-550.

Hendryx, Michael, Melissa M. Ahern, and Timothy R. Nurkiewicz. (2007) "Hospitalization patterns associated with Appalachian coal mining." *Journal of Toxicology and Environmental Health, Part A*70.24: 2064-2070.

Hendryx, Michael, Kathryn O'Donnell, and Kimberly Horn. (2008) "Lung cancer mortality is elevated in coal-mining areas of Appalachia." *Lung Cancer* 62.1: 1-7.

Hendryx, M., & Holland, B. (2016). Unintended consequences of the Clean Air Act: Mortality rates in Appalachian coal mining communities. Environmental Science & Policy, 63, 1-6

Hendryx, Michael, and Keith J. Zullig. (2009). "Higher coronary heart disease and heart attack morbidity in Appalachian coal mining regions." *Preventive Medicine* 49.5: 355-359.

Hendryx, Michael, et al. (2012). "Self-reported cancer rates in two rural areas of West Virginia with and without mountaintop coal mining." *Journal of community health* 37.2: 320-327.

IEA (2009). "Cleaner Coal in China"*,* Paris.

IEA (2009a). "Coal Mine Methane in China: A Budding Asset with the Potential to Bloom"*,* Paris.

IEA (2009b). "Coal Mine Methane in Russia"*,* Paris.

IEA (2012). "Key World Energy Statistics", Paris.

Jakob, M., Steckel, J. C., Jotzo, F., Sovacool, B. K., Cornelsen, L., Chandra, R., ...& Robins, N. (2020). The future of coal in a carbon-constrained climate. *Nature Climate Change*, 10(8), 704-707.

Kaneva, D. (2010). Let's Face Facts, These Mountains Won't Grow Back: Reducing the Environmental Impact of Mountaintop Removal Coal Mining in Appalachia. *Wm. & Mary Envtl. L. &Pol'y Rev.* 35: 931.

Khan, M. I., & Chang, Y. C. (2018). Environmental challenges and current practices in China—a thorough analysis. *Sustainability*, 10(7), 2547.

Kholod, N., Evans, M., Pilcher, R. C., Roshchanka, V., Ruiz, F., Coté, M., & Collings, R. (2020). Global methane emissions from coal mining to continue growing even with declining coal production. *Journal of Cleaner Production*, 256, 120489.

Lewis-Beck, Michael S., and John R. Alford (1980). Can government regulate safety? The coal mine example. *American Political Science Review* 74.3 (1980): 745-756.

Li, Q., Stoeckl, N., King, D., & Gyuris, E. (2017). Exploring the impacts of coal mining on host communities in Shanxi, China–using subjective data. *Resources Policy*, 53, 125-134.

Lofaso, Anne Marie. "What We Owe Our Coal Miners." (2011) *Harv. L. &Pol'y Rev.* 5 (2011): 87.

MacGill, I., Outhred, H., & Nolles, K. (2006). Some design lessons from market-based greenhouse gas regulation in the restructured Australian electricity industry. *Energy Policy*, 34(1), 11-25.

Mactaggart, F., McDermott, L., Tynan, A., & Gericke, C. (2016). Examining health and well-being outcomes associated with mining activity in rural communities of high-income countries: A systematic review. *Australian Journal of Rural Health*, 24(4), 230-237.

Matheis, M. (2016). Local economic impacts of coal mining in the United States 1870 to 1970. The Journal of Economic History, 76(4), 1152-1181.

Miller, S. M., Michalak, A. M., Detmers, R. G., Hasekamp, O. P., Bruhwiler, L. M., & Schwietzke, S. (2019). China's coal mine methane regulations have not curbed growing emissions. *Nature communications*, 10(1), 1-8.

Ming-Xiao W., Zhang Tao, Xie Miao-Rong, Zhang Bin, Jia Ming-Qiu (2011). "Analysis of national coal-mining accident data in China, 2001–2008." *Public Health Reports*126.2: 270-275.

Nkulu, C. B. L., Casas, L., Haufroid, V., De Putter, T., Saenen, N. D., Kayembe-Kitenge, T., ...& Nemery, B. (2018). Sustainability of artisanal mining of cobalt in DR Congo. *Nature Sustainability*, 1(9), 495-504.

OECD (2000). "The potential for using tax instruments to address greenhouse gases: CH4, N20, HFCs, PFCs and SF6". *OECD Publication*, France

OECD (2001). "Environmentally related taxes in OECD countries. Issues and Strategies". *OECD Publication*, France

OECD (2008). "An OECD Framework for Effective and Efficient Environmental Policies. (Meeting of the Environment Policy Committee (EPOC) at Ministerial Level Environment and Global Competitiveness)". *OECD Publication*, France

OECD (2010). "Environmental taxation: A Guide for Policy Makers". *OECD Publication*, France

OECD (2012). "Environmental outlook to 2050". *OECD Publication*, France.

OECD & IEA (2008). "Energy Technology Perspectives". *OECD Publication*, France.

Owen, A. D. (2006). Renewable energy: Externality costs as market barriers. *Energy Policy* 34.5: 632-642.

Pearce, D. W., & Turner, R. K. (1990). Economics of natural resources and the environment. JHU Press.

Perman, Roger. "Natural resource and environmental economics". (2003) *Pearson Education.*

Pigou, A.C., (1920), "The economics of welfare", MacMillan

Poudyal, N. C., Gyawali, B. R., & Simon, M. (2019). Local residents' views of surface mining: Perceived impacts, subjective well-being, and support for regulations in southern Appalachia. *Journal of Cleaner Production*, 217, 530-540.

Qi, R., Liu, T., Jia, Q., Sun, L., & Liu, J. (2019). Simulating the sustainable effect of green mining construction policies on coal mining industry of China. *Journal of Cleaner Production*, 226, 392-406.

Rentier, G., Lelieveldt, H., & Kramer, G. J. (2019). Varieties of coal-fired power phase-out across Europe. *Energy Policy*, 132, 620-632.

Sovacool, B. K. (2016). How long will it take? Conceptualizing the temporal dynamics of energy transitions. *Energy Research & Social Science*, 13, 202-215.

Shandro, J. A., Veiga, M. M., Shoveller, J., Scoble, M., & Koehoorn, M. (2011). Perspectives on community health issues and the mining boom–bust cycle. *Resources Policy*, 36(2), 178-186.

Smil, V. (2010). Energy Myths and Realities: Bringing Science to the Energy Policy Debates. Praeger.

Steenblik, R. P., & Coroyannakis, P. (1995). Reform of coal policies in Western and Central Europe: Implications for the environment. *Energy Policy* 23.6: 537-553.

Tiwary, R. K. (2001). Environmental impact of coal mining on water regime and its management. *Water, Air, and Soil Pollution*, 132(1-2), 185-199.

Tost, M., Hitch, M., Chandurkar, V., Moser, P., & Feiel, S. (2018). The state of environmental sustainability considerations in mining. *Journal of Cleaner Production*, 182, 969-977.

Vinke-de Kruijf, J., & Pahl-Wostl, C. (2016). A multi-level perspective on learning about climate change adaptation through international cooperation. *Environmental Science & Policy*, 66, 242-249.

Weeks, James L., and Maier Fox, (1983) Fatality rates and regulatory policies in bituminous coal mining, United States, 1959-1981. *American Journal of Public Health* 73.11: 1278-1280.

York, R., & Bell, S. E. (2019). Energy transitions or additions?: Why a transition from fossil fuels requires more than the growth of renewable energy. *Energy Research & Social Science*, 51, 40-43.

Zhang, J., Zhang, Q., Spearing, A. S., Miao, X., Guo, S., & Sun, Q. (2017). Green coal mining technique integrating mining-dressing-gas draining-backfilling-mining. *International Journal of Mining Science and Technology*, 27(1), 17-27.

Zhi, L., Totten, M., & Chou, P. (2006). Spurring innovations for clean energy and water protection in China: An opportunity to advance security and harmonious development. *China Environment Series*, 61.

823

Supplementary materials

A1. Literature Review

The objective of the systematic literature review was to identify those studies that provide a quantitative and/or qualitative assessment of the policies addressed to coal mining externalities. The coal mining externalities were initially retrieved in Epstein et al. (2011) where initial estimates of damage are assigned from a literature review in US $ 2008. We report the derived estimates in Table A.1.1.

Table A.1.1. Total cost of externalities for coal life cycle externalities in $2008. Source: modified from Espstein et al. (2011) Table 3, page 91.

MINING AND EXTRACTION	Landscape impacts	$162,934,529	0.05%
	Methane	$2,052,254,783	0.62%
	Public health impacts	$74,612,823,575	22.38%
TRANSPORTATION	Coal transport Impacts	$1,807,500,000	0.54%
COMBUSTION	Air Impact in combustion	$187,473,345,794	56.24%
	Health Impacts form Mercury Emissions	$5,522,500,000	1.66%
	GHG Emission	$61,724,314,549	18.52%
TOTAL		$333,355,673,230	1.0000

From these estimates we could draw Figure A.1.1 where the grey box identifies the mining costs and the black box the consumption costs.

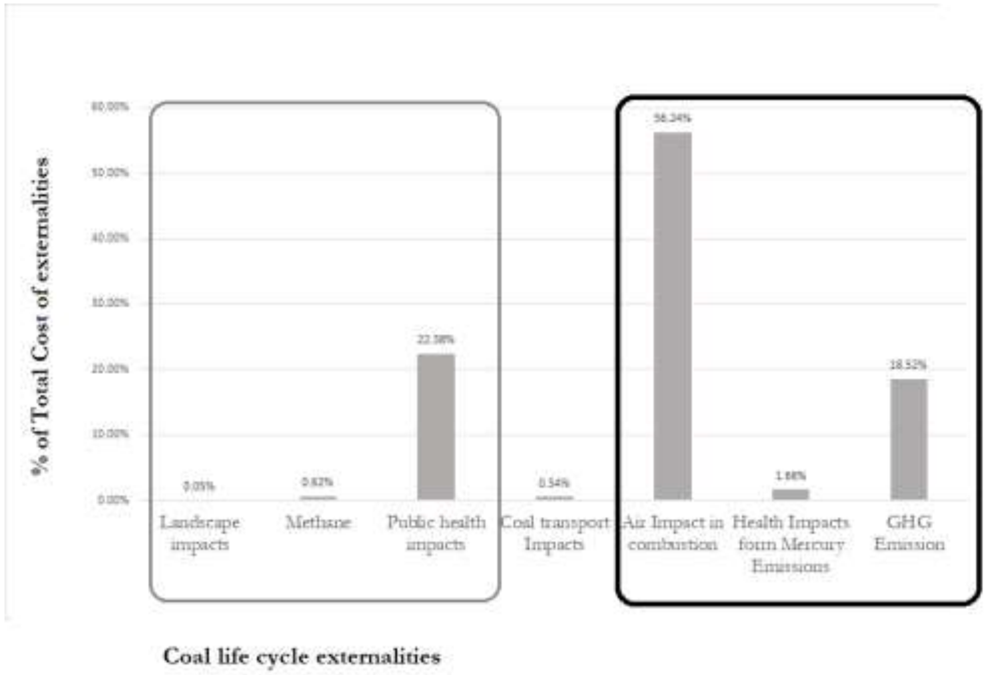


Figure A.1.1. Percentage of total cost of externalities for coal life cycle externalities. Source: modified from Espstein et al. (2011)

The literature review was conducted through a web search routine. Both advanced Google and Google Scholar search interface were used to gather published and grey literature on coal mining externalities and policy instruments. A set of rules were introduced to systematically interrogate the world wide web. The search rules were the following:

- Keywords driven search: the search string jointly included externalities (@) and Policy options (*);
- Search and results in English;
- Different web page domains: multiple domains were chosen to collect information from the most relevant organizations including World Bank, U.S. Environmental Protection Agency, U.S. Energy Information Administration, etc. in addition to nation domains.

Details of the web search are reported in Table A1: the first column indicates the general string used to run the web search routine, the second column contains the set of policy options alternatively considered in the search string, the third column summarizes the analysed externalities taken into account, the last column shows different web domains.

Table A.1.2. Web search strings used in web search routine

Key word strings	***Policy options*	*@ Externalities*	*Web domains*
Quantitative assessment of effects of (*) to damages from coal surface mines/underground mines/ abandoned mines to (@);	Pigouvian taxation (tax), charges, subsidies (tax incentive), tradable permits, voluntary actions/policies, command and control policies, regulation, international agreements, environmental bonds (financial instruments)	biodiversity loss; methane emissions (air); emissions fires (air); water contamination; particulate emissions (air); sludge slurry ponds (water); mortality morbidity health coal communities miners (health)	.org; .gov; .ue; gov.uk; gov.au; .cn; .ch

Note: In parenthesis we report the classification used in the cluster analyses

Two independent researchers (two of the authors) were dedicated to this task. From the literature review a dataset of studies was created with a score of performance in efficiency, efficacy and distribution concerns. A study could include one or more policies and for each policy the researchers assign a score of performance as detailed in A2.

The final dataset aims at including coal mining externalities addressed with one or more policy instruments and an assessment of the efficiency, effectiveness and distributional effects of the policy. Ideally the assessment methods of policy instruments should be based on quantitative transparent approached (such as cost-benefit analysis, cost effectiveness analysis, impact evaluation etc.), however the literature review shows that only qualitative assessment is widely available. Consequently, the assessment of policy instruments for coal mining externalities is based mainly on qualitative information derived by each study.

The resulting papers from the literature search were included in the final dataset of 140 studies. Studies from the USA represent 40% of all retrieved studies, France 30%, Australia 6%, China 6%, Belgium 5%, UK 5%, and the remaining studies are OECD reports covering multiple countries. Figure A.1.2 reports the proportion of externalities.

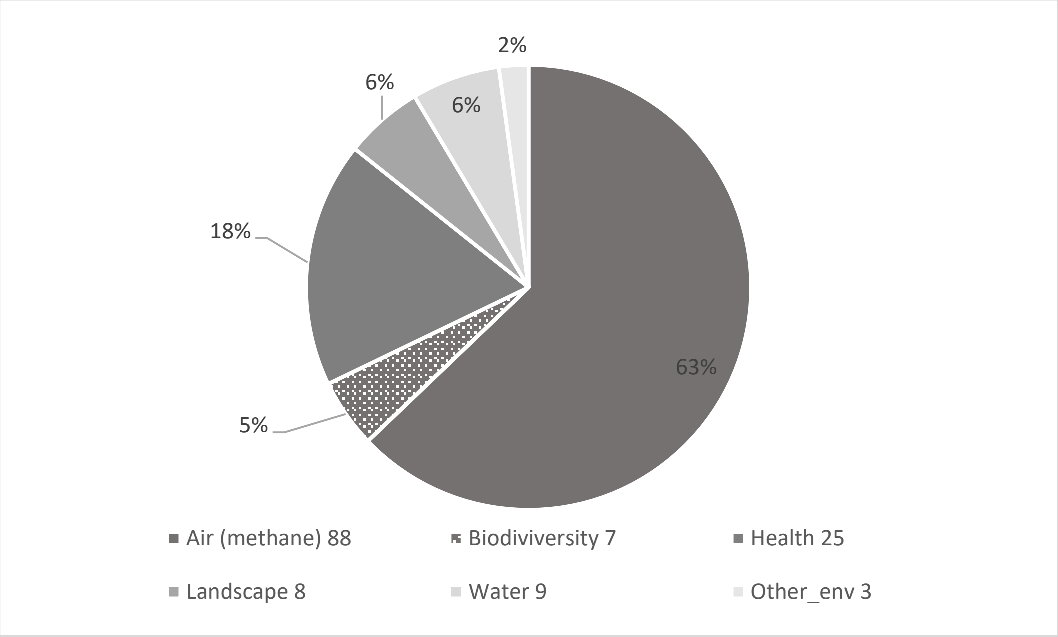


Figure A.1.3. Externalities

A2. Policy evaluation criteria

Quantitative measures of policy strategies are ideally the best form of assessment, however, when quantitative measures are not available, qualitative assessment of policy instruments is the most often used proxy among researchers. Every policy was assessed individually, and the performance score is a dummy variable for effective, efficient and distributionally fair. An example of qualitative information researched in the documents is the following:

> *"since its launch in 1994 through 2009, CMOP (coalbed methane outreach program) has assisted the coal mining industry in successfully increasing its methane recovery by 50 percent. These emissions reductions are due to active underground mines recovering and utilizing drained gas. In 2009, the U.S. coal mining industry recovered and used about 81 percent of all drained CMM.*
>
> *Between 1994 and 2009, U.S. CMM emissions reductions have effectively removed the equivalent of more than 263 million metric tons of carbon dioxide from the atmosphere. These avoided emissions are equivalent to 654 billion cubic feet of methane—588 from active underground mines and the remaining 66 from abandoned underground mines.*

These emissions reductions have had an important economic impact as well. CMM gas sales nationally generated between $150 million and $350 million in revenue in recent years, depending on natural gas prices" (EPA, Coalbed Methane Outreach Program, 2011)

This policy was classified in the dataset as effective for reaching the goal of increasing methane recovery by 50 percent and efficient for its important economic impact in terms of revenue effects. A contrary example is represented by Cathie Bird and Landon Medley for Strip-mine Issues Committee of Statewide Organizing for Community empowerment (formerly, Save Our Cumberland Mountains) (2010) where we can read that:

"(…) various analysts, pundits and stakeholders agree only on two things: the future of the Clean Water Act is uncertain, and it's going to take a long time to clear the muddy waters of small stream protection. […] continuing challenges to the reach of federal jurisdiction until citizen's rights to a clean and healthy environment are amended to the U.S. Constitution. >>.

In this case the policy instrument is commented as uncertain and away from effectiveness or efficiency. Many other studies failed to report any measure of performance. Surprisingly, none of the revised studies assesses the distributional effect of the policy instruments. Multiple studies provided only information about qualitative or quantitative assessment of coal mining impacts on local, regional and global economy, without mention environmental and social externalities. The present paper reports the summary of the qualitative assessment of studies conducted in this systematic literature review.

A3. Cluster analysis

Analyse of the data with Cluster Analysis Technique

The Cluster Analysis is a classification method which identifies groups of observations that are similar to each other for some aspects/factors/characteristics.

There are different procedures to divide cases in groups, depending on the size of dataset and the nature of variables. In the present paper we use a two-step process, applying firstly a hierarchical clustering and then a partitioning clustering.

The underlying idea of clustering data according to a hierarchical method is that at the beginning every point in the data set represents a unique group/cluster. The algorithm then successively merge clusters, by measuring the "distance"/ "proximity" or the "dissimilarity"/"similarity" between data points, until there is one big cluster containing all the data.

The similarities between elements are computed for all attributes classified in the dataset. In our dataset variables are all categorical and the similarity is defined on qualitative factors such as year of study, externality addressed etc. So, two studies that present diverse characteristics are classified as dissimilar and all the pairwise dissimilar distances are reported in the dissimilarity matrix. Once the dissimilarity matrix is computed, a distance criterion can be set to start clustering studies. In our case the general dissimilarity coefficient is the Gower Distance that measures the distance between element i and j, considering the weighted mean of the contributions of each variable. Specifically:

$$d_{ij} = d(i,j) = \sum_{k=1}^{p} w_k \delta(ij;k) d(ij,k) \Bigg/ \sum_{k=1}^{p} w_k \delta(ij,k)$$

Where:

$d_{ij}$is a weighted mean of d(ij,k) with weights $w_k\delta$(ij;k);

w_k = weight[k];

δ(ij;k) is 0 or 1,

d(ij,k), the k-th variable contribution to the total distance, is a distance between x[i,k] and x[j,k]

The 0-1 weight δ(ij,k) becomes zero when the variable x[,k] is missing in either or both rows (i and j), or when the variable is asymmetric binary and both values are zero. In all other situations it is 1.

The contribution d(ij,k) of a nominal or binary variable to the total dissimilarity is 0 if both values are equal, 1 otherwise. The contribution of other variables is the absolute differences of both values, divided by the total range of that variable.

As the individual contributions d(ij,k) are in [0,1], the dissimilarity d_{ij} will remain in this range. If all weights $w_k\delta$ (ij;k) are zero, the dissimilarity cannot be calculated.

Accounting for all Gower measures between elements, the algorithm merges similar and close elements until one unique cluster is formed.

The process goes ahead merging point by point, then cluster by cluster. Distance between clusters is then calculated according to the method *average*, in other words the distance between two clusters is the average of the Gower measures between the points in one cluster and the points in the other cluster. From the dissimilarity matrix and Gower measures we can plot a tree diagram (dendogram), where hierarchical clusters are represented. This tree presents results from different groups sharing similar characteristics in one big group of elements. At this stage the number of potential groups is visible, and the portioning cluster can be applied. The portioning aims to separate the observations using the shared characteristics of the studies. More similar studies will belong to the same cluster, unique studies will remain as single cluster. The number of clusters is decided by the analysist and in our case, we run two cluster analyses (pre- and post-1990), dividing the results by countries. Results obtained from each cluster analysis represent the most typical characteristics of observations in our dataset of policy instruments and externalities for coal mining.