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Review

Coal use for residential heating: Patterns, health implications and lessons learned

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ABSTRACT

Residential coal consumption has decreased significantly since 1990 in most developed and developing countries, due to fuel switching. However, there are still countries with a high proportion of households using coal for heating purposes, in some cases with increasing coal consumption trends. This review discusses the patterns of the coal use, associated emissions, the negative impacts on health, and the policies and interventions used to limit the negative effects of high residential coal use. The patterns of residential coal use in those selected countries that account for 86% of global residential coal consumption are reviewed. Interventions in these selected countries have been accessed. It appears that the World Health Organization (WHO) may substantially underestimate the health impacts in these countries, particularly with respect to the burden of disease from household air pollution from using solid fuel for cooking as the indicator of exposure. The alternative to the WHO approach uses International Energy Agency (IEA) data because it provides the energy consumption for each country by fuel type and all household end-uses in a consistent framework. National survey data on energy and emissions also provides better metrics of exposure. Most of the assessed studies in developed countries focused on ambient air pollution, while in developing countries indoor air pollution was given primary attention (except for Mongolia). The PM concentrations within households using coal in Ireland, Mongolia, and China were compared and substantial differences were found as a result of differences in ventilation, stove design, fuel quality and stove maintenance and operation. Policy measures such as the large stove switching programs in China and Mongolia were mostly successful, but did not fully reach desired targets because of several factors. One of these key factors was the variability of human behavior and its response to the policy stimuli. Important barriers to the transition to cleaner energy alternatives are relatively low coal prices coupled with its level of supply security. Health benefits, however, are generally higher than the abatement costs in the most polluted areas, and support from governments for cleaner energy, that includes a focus on health, can be feasible and effective if carefully designed and targeted.

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Introduction

Coal has been used for residential heating for centuries. In the middle of the last century, coal use for residential heating was widespread. Today, coal burning for heat in most developed countries has diminished substantially because of the recognition of the resulting air pollution producing significant local air quality degradation. For example, the Great Smog of London in December 1952 was caused largely by smoke from household heating with coal. It caused thousands of premature deaths within a short period (Brimblecombe, 1987). Coal combustion releases toxic species including particulate matter (PM), NO_x, SO_2, CO, and Hg. Solid fuel generated PM is associated with an increased risk of adverse health outcomes, such as acute lower respiratory infections in children, chronic obstructive pulmonary disease, chronic bronchitis and lung cancer (WHO, 2014).

Residential emissions from space heating and cooking with solid fuels remains to be an important and generally unrecognized source of ambient air pollution in China and other developing countries (Liu et al., 2016; Zhi et al., 2017). The residential sector emissions are attributed to greater uncertainty than industrial emissions due to lack of activity data and lack of understanding of end-use (Archer-Nicholls et al., 2016; Zhi et al., 2017; Winijkul and Bond, 2016).

The World Health Organization (WHO) uses estimates of the populations employing solid fuels for cooking as a proxy for household air pollution in its Global Burden of Disease program since it is difficult to obtain "nationally representative samples of indoor concentrations of criteria pollutants, such as PM and carbon monoxide" (WHO, 2015a). Solid fuel combustion for space heating was not included by WHO because of the lack of routinely conducted surveys on space heating (Bonjour et al., 2013). Given this limitation, the WHO assessment of the burden of disease from household air pollution in countries with high use of solid fuels for heating may be underestimated. It is important to supplement the WHO estimates with studies investigating solid fuel use patterns for cooking and heating at national and regional scales in order to fully quantify the domestic burden of diseases. This study addresses this knowledge gap.

There remain countries with many households that burn coal for heating purposes. In cold climates, long heating seasons as well as poor ventilation are likely to produce negative adverse effects from heating with coal. However, there are few studies reviewing patterns of coal use, the associated exposure to the emissions from coal burning, their negative impact on health, and on policies and interventions to reduce these negative effects.

In this study, we investigated the patterns of global residential coal use in selected countries that represent 86% of global residential coal consumption in 2014, and reviewed the likely exposure to indoor air pollution, and the related health effects. The study also reviews policy interventions that seek to address the effects of household coal use.

Global coal use and countries selection

The International Energy Agency (IEA) data on energy balances (IEA, 2016a) were used for the analysis of global residential coal combustion trends and the selection of affected countries. In the IEA Energy Balance tables for each region/country, data in the row "Residential" and the column "coal" (IEA, 2016a) were selected. The IEA Energy Balance tables are the only source that reports energy consumption for each country in the world by fuel type and for all household end-uses, including cooking, heating, and water heating within a consistent framework. Coal consumption is derived mainly from the amounts of coal sold by companies to the population. Hence, supply and consumption are assumed to be balanced and include all of the coal use in the country. The limitation of this data source is that energy consumption is not further disaggregated to its end-uses (e.g. cooking, heating, water heating).

Fig. 1 compares (on the left axis) solid fuel use per capita with coal use per capita by regions of the world in 2014. Solid fuel use (primary solid biofuels and coal) and coal use data for each region were obtained from the IEA Energy Balance tables (IEA, 2016a). Populations by region/country were obtained from IEA indicator tables (IEA, 2016b). To obtain per capita consumption of fuels, the solid fuel or coal consumption by region/country was divided by the population of the corresponding country/region.

Fig. 2 shows the WHO assessment on percentage of population using solid fuels for cooking applied in the Global Burden of Disease as indicator of household air pollution.

Fig. 1 shows that the highest per capita solid fuel use occurred in Africa, China, Asia (excluding China) and OECD Europe. However, coal consumption in Africa, non-OECD Americas, OECD Americas, Middle East is very low since their solid fuel of choice is wood or other biomass. The highest coal share in total residential solid fuels use was reported in OECD Asia Oceania, followed by non-OECD-Europe and Eurasia, OECD Europe and China. Both WHO and IEA indicators report high solid fuel use in Africa and Asia. The WHO (2015a, b) assessment of household air pollution for OECD Europe may be underestimated because it does not consider solid fuel use for heating purposes. In addition, countries classified as high-income with a Gross National Income (GNI) of more than US$ 12,746 per capita according to the World Bank (2015) were assumed by WHO to have completed the transition to cleaner fuels since solid fuel consumption for those countries were reported to be less than 5% (WHO, 2015a).

Global residential coal consumption declined by 51% between 1990 and 2014 and there are decreasing trends in most developed

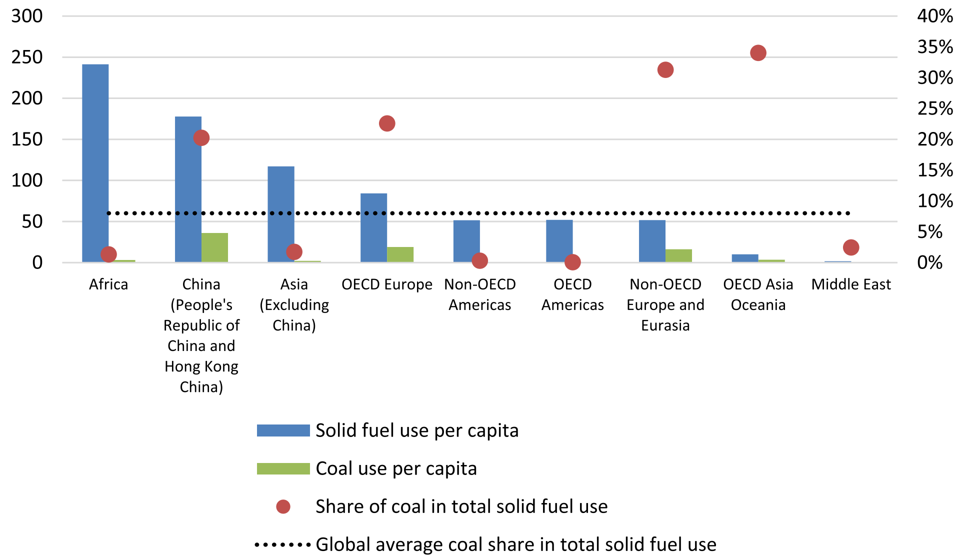

Fig. 1. Residential solid fuel and coal consumption per capita and share of coal in total solid fuels consumption by regions of the world in 2014, in kilograms oil equivalent per capita (kgOE/cap) (IEA, 2016a, b).

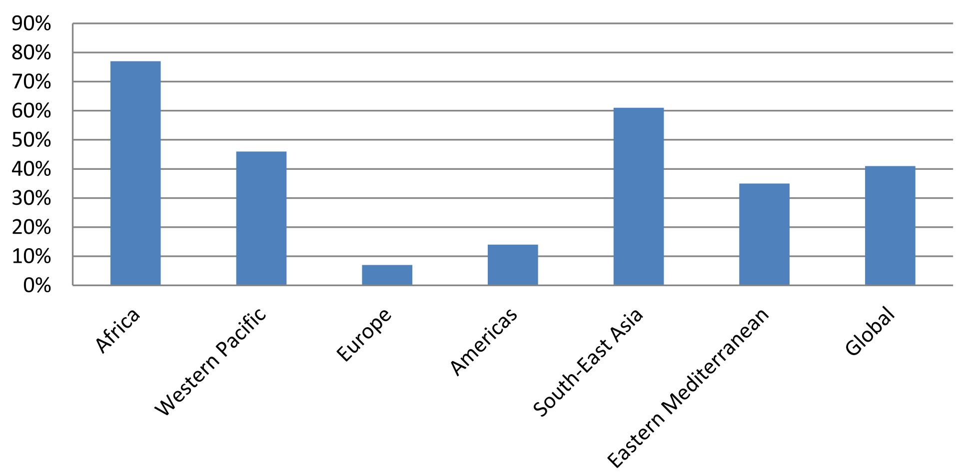

Fig. 2. Percent of population using solid fuels as employed in the WHO assessments (Bonjour et al., 2013).

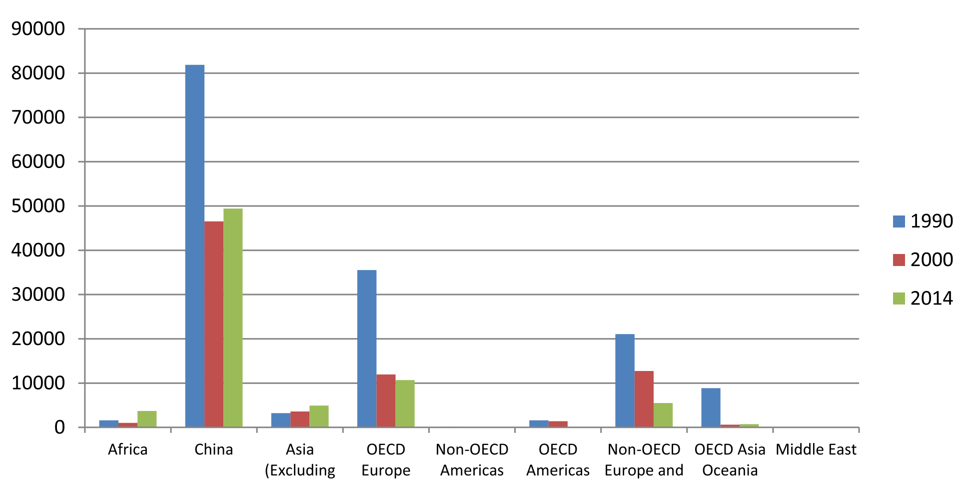

Fig. 3. Residential coal consumption trend over 1990–2014 by regions of the world, ktoe (IEA, 2016a).

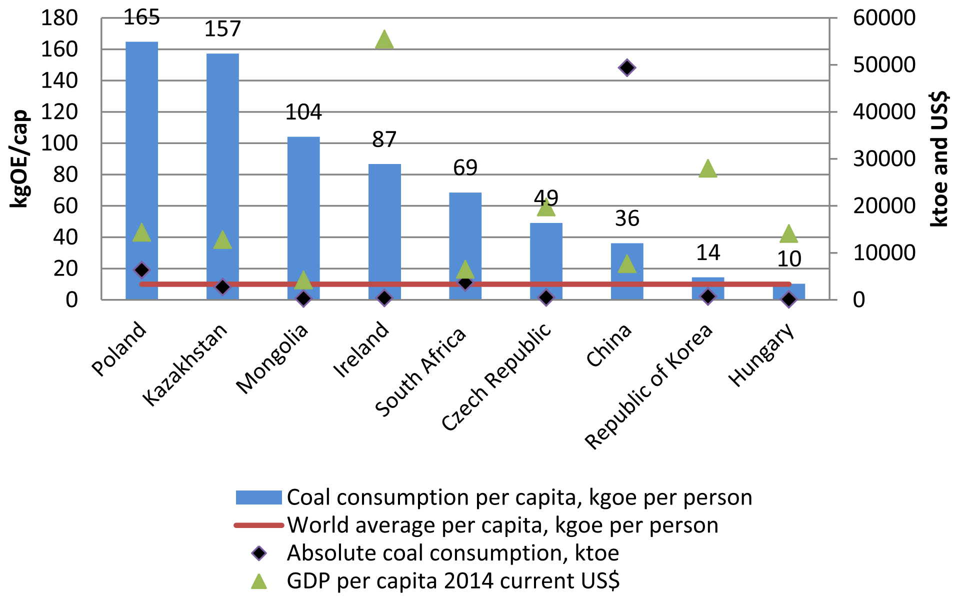

Fig. 4. Residential coal consumption per capita kgOE/cap (left axis), absolute residential coal consumption ktoe (right axis), GDP per capita current US$ (right axis) in 2014 in the selected countries (IEA, 2016a, b; World Bank, 2015).

and developing regions of the world (Fig. 3). Fuel switching has occurred due to range of changes associated with development, urbanization, electrification, education (Winijkul and Bond, 2016), policy measures such as bans on coal sales and other interventions. The only exceptions were Asia (excluding China) and Africa that increased their residential coal consumption, due to India's and South Africa's increasing residential coal consumption, respectively. The world highest coal consuming regions, China and OECD Europe, reduced household coal consumption from 1990 to 2000 by 43% and 66%, respectively.

In this study, the nine countries with the higher per capita residential coal consumption were selected (according to IEA Energy Balances statistics for 2014). The selected countries are Poland, Kazakhstan, Mongolia, Ireland, South Africa, Czech Republic, China, Republic of Korea and Hungary. For Ireland, IEA data for coal consumption includes peat, which accounts for approx. 50% of residential 'coal' consumption. In 2014, the highest per capita household coal consumption occurred in Poland (165 kgoe/cap), followed by Kazakhstan (157 kgoe/cap) and Mongolia (104 kgoe/cap) (Fig. 4, IEA, 2016a, b). GDP per capita by country presented in Fig. 4 was obtained from World Bank (2015). In 2014, the countries shown in Fig. 4 represented 21% of world population and accounted for 86% of global residential coal consumption. China represented 19% of the global population and 66% of world total residential coal consumption (IEA, 2016a).

Patterns and determinants of residential coal consumption in the selected countries

Coal consumption trends and importance of coal industry

Most of the selected countries were coal producers and collectively were responsible for 55% of global coal production in 2014 and owned 25% of global coal proven reserves. China, South Africa, Poland and Kazakhstan are the biggest coal producers (Table 1). Coal represents significant share in the total domestic energy consumption for most of the countries and selected countries collectively consumed 60% of global coal consumption in 2014. Countries use mostly domestically produced coal with the exception of South Korea, Ireland and Hungary. Coal provides secure and affordable energy and it is expected that coal will continue to play significant role in the future power generation mix of Poland (Gawlik and Mokrzycki, 2016), Mongolia (Punsalmaagiin and Sodovyn, 2012), Kazakhstan (Government of the Republic of Kazakhstan, 2014), South Africa (UNFCCC, 2016). In the case of Ireland, this 'coal' production quantified by the IEA captures the indigenous peat production, which is mostly used for electricity generation (Tuohy et al., 2009). Due to low competitiveness of Kazakhstan's coal in the world export markets (due to its low quality), domestic power generation is expected to be its main consumer of coal. Coal industry is an important economic activity in the northern and central Kazakhstan and closure of coal mines is not expected.

Table 1
Production and consumption of coal (IEA, 2016a), coal reserves in the selected countries (BP, 2016).

Country	Production of coal in 2014, thousand tons of oil equivalent	Total primary consumption of coal in 2014, thousand tons of oil equivalent	Share of coal in total primary energy consumption in 2014	Share of total coal consumption in residential energy in 2014	Total proved reserves at end 2015, million tons	Reserves to production ratio
Poland	54,034	49,313	52%	13%	5465	40
Kazakhstan	49,940	37,035	48%	7%	33,600	316
Mongolia	13,186	3829	71%	8%	2520	103
Ireland	971	2006	16%	20%		
South Africa	147,451	102,071	69%	4%	30,156	120
Czech Republic	16,934	15,878	39%	3%	1052	23
China	1,889,588	2,011,501	66%	2%	114,500	31
Republic of Korea	778	81,669	30%	1%	126	71
Hungary	1588	2202	10%	5%	1660	180
World	3,976,142	3,918,491	29%	2%	891,531.0	114

Five out of nine selected countries reduced their residential coal consumption substantially from 1990 to 2014 by factors of 16.5, 11.9, 6.2, 3.6, and 1.7 in Hungary, South Korea, Czech Republic, Ireland, and China, respectively (IEA, 2016a). Over the period 2000–2014, residential coal consumption in China increased by 6% (IEA, 2016a) due to increasing consumption of coal in the northern part of the country (Li et al., 2017). In China, the type of solid fuel consumed was highly correlated with local fuel availability, with large use of coal in the provinces with coal availability (Duan et al., 2014). In Poland, residential coal consumption reduced slightly (by 14% from 1990 to 2014), with a clear declining trend observed only in the later years (2012–2014). The main reasons restraining reduction of residential coal use in Poland are availability of local coal resources, security of gas supply issues, gas price and energy poverty (Stala-Szlugaj, 2016). In Czech Republic the price of coal for heating was 1.7, 2.5, and 4.3 times lower than biomass pellets, natural gas, and electricity, respectively (Karásek and Pavlica, 2016). In Kazakhstan, Mongolia and South Africa residential coal consumption has grown from 1990 to 2014. In these three countries availability of relatively inexpensive coal from local mines (BP, 2016) and the lack of reliable and affordable supply of cleaner alternatives (Kerimray et al., 2016; World Bank, 2009) contributed to higher coal consumption.

Households survey data

In the selected countries, household energy surveys/census was performed in Ireland, Poland, South Africa, and China, with only limited data available for the other countries. Household surveys confirm high coal use by households in the selected countries (except for South Africa).

Coal was used in 9.6% and approximately 50% of all households in Ireland (SEAI, 2013) and Poland (Central Statistical Office, 2014), respectively. In Poland 70% of single-family houses are heated with coal (Institute of Environmental Economics, 2014). In Czech Republic coal is mainly used in rural areas and 29% of the heating demand in rural areas is satisfied by coal (Meirmans, 2013). These numbers show that the WHO assumption (WHO, 2015a, b) in Ireland, Poland, and Czech Republic that less than 5% of population use solid fuels are underestimation.

The Survey demonstrated that 16.7% and 11.3% of Chinese households used coal for heating and cooking, respectively (Duan et al., 2014). WHO (2015b) estimated 45% of population use solid fuels in China which is comparable to the 43.4% obtained from the survey in China (Duan et al., 2014). Urban-rural differences were vast, with urban residents using cleaner fuels, while rural residents mainly relied on traditional biomass and coal (Duan et al., 2014). There was a negative correlation between proportion of households using solid fuels and income levels (Duan et al., 2014).

The Households Survey 2013 in South Africa showed that 1.5% of all surveyed households used coal for heating and 0.4% for cooking as a main source of energy (Energy Department, 2012; Statistics South Africa, 2014). These values contradict the Energy Balance of South Africa (IEA, 2016a) that states that 22% of residential energy consumption is coal in 2014, and that the country is one of the highest per capita residential coal consumption rates in the world.

Coal and wood burning for heating of individual residences in *ger* (traditional Mongolian nomadic tent-like dwelling) areas are deemed essential for survival in Ulaanbaatar (the capital of Mongolia), the coldest capital in the world. The survey conducted by World Bank (2013) in Ulaanbaatar has shown that 98% of surveyed households in ger areas used coal as a heating fuel, with most of these households being relatively poor (World Bank, 2009). Around 40% of the Mongolian population lives in Ulaanbaatar and there were no studies in other regions of Mongolia. WHO (2015b) estimated 63% of the population use solid fuels in Mongolia.

In Kazakhstan, 40% among surveyed households used coal in 2013 (Kerimray et al., 2016). Most of the households using coal in Kazakhstan were in rural regions where natural gas and district heating is unavailable. This study suggests that the assessment of WHO (2015b) that 9% of the population use solid fuels in Kazakhstan is an underestimate.

Coal use in combination with other fuels

Coal is rarely used alone, but is often used in combination with other fuels. In Mongolia almost all households used coal as the main heating fuel and firewood is used as a supplement (World Bank, 2013). In Ulaanbaatar during the summer, 83% of households use electricity for cooking, while during winter, they switch to solid fuels for heating and cooking (Ulaanbaatar Clean Air Project, 2015). In Kazakhstan, there is a minority of households that use only one type of fuel during the year. Coal and firewood are used for heating during the cold seasons in Kazakhstan, while LPG is used throughout the year for cooking. In China on average, 2.6 fuel types were used per households during the summer and 1.9 fuel types during the winter (Edwards et al., 2007). During the winter, the number of households using biomass and LPG fell, and number of coal users rose (Edwards et al., 2007). In Poland, only a small number of households use only coal (6.4%) or only wood (6.2%). Most households used both coal and wood together or interchangeably, with wood used in warmer periods and coal used in colder ones (Central Statistical Office, 2014).

Type of coal

The properties of coal vary from country to country depending on its local availability (Fig. 5). For example, Ireland uses mostly peat (which according to the IEA categorization of fuels, is effectively considered as a type of coal), while in Poland, Kazakhstan, China, and South Africa, bituminous coal prevails as shown in Fig. 5. In China, the properties of household coal vary dramatically across the country according to the character of local coal deposits (Zhang and Smith, 2007). In Mongolia, domestically produced lignite is used by households, while bituminous coal produced in the country is mainly exported to China. Coal briquettes are subsidized in Korea as these are considered fuels for very lowest income households for heating and cooking needs (Park, 2013).

End-uses of coal and climatic conditions

Heating represents the highest end-use share of coal in all of the countries for which data are available (41–81%) (Fig. 6). Cooking was the second major use of coal consumption in South Africa and China (22% and 40% of the end-use of coal, respectively) while in Poland, Ireland and Kazakhstan, water heating was the second highest use.

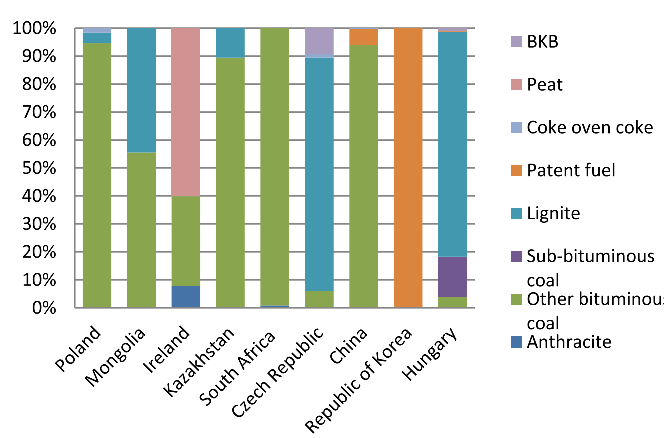

Fig. 5. Coal split by type in the selected countries (IEA, 2016a).

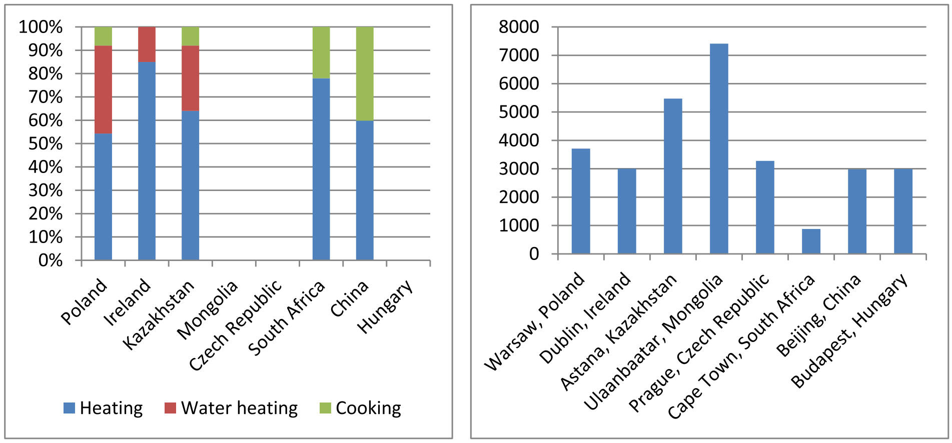

Fig. 6. Residential coal split by end-use (Central Statistical Office, 2014; SEAI, 2013; Sarbassov et al., 2013; Duan et al., 2014) and (b) Heating-Degree-Days [°C-days] in capital cities (NASA, 2008).

These selected countries are relatively cold, with typical number heating-degree-days reaching 3000 °C-days (except for South Africa) and very cold in the cases of Kazakhstan (5472 °C-days in Astana) and Mongolia (7410 °C-days in Ulaanbaatar) (Fig. 6b). In Kazakhstan, Mongolia, Poland, Hungary, and Ireland, where the heating season lasts for up to 8 months, heating is one of the basic needs for living (SEAI, 2013; Chwieduk, 1997; World Bank, 2009; Unger and Makra, 2007). China is a large country with several climatic zones and different heating needs. The heating period in cold areas (northeast and west) can last for as long as 200 days, while in other areas it might be around 90 days (IRENA, 2014). In South Africa, which is the warmest among selected countries, one third of surveyed households in South Africa did not use any energy source for heating.

Table 2 compares percentage of households using coal from national surveys and WHO percentage of population using solid fuels, as well as, heating technologies in the selected counties.

Based on the population using coal from the Households Surveys, it was estimated that at least 243.8 million people use coal in the selected countries, representing 86% of the global residential coal consumption in 2014. Most of the population is located in China (218.3 mln), followed by Poland (16.4 mln), Kazakhstan (6.9 mln) and Mongolia (1 mln).

Exposure assessment and health effects

Due to low combustion efficiency and/or poor fuel quality, lack of pollutant reduction control and regulation, emissions from household coal combustion have significant adverse impacts on outdoor and indoor air qualities (Li et al., 2017; Guttikunda et al., 2013; Institute of Environmental Economics, 2014). The most comprehensive studies on exposure assessment and health effects were found in China. There is a large population using solid fuels in China and China accounted for 66% of the global residential coal consumption. There were limited or nearly absent studies on exposure and health effects for large populations in Czech Republic, Poland, Hungary, Kazakhstan, South Korea, and South Africa. This study did not consider indoor air pollution studies that focus only on cooking and only on biomass, although it may include studies, that compared exposure from biomass with coal and cooking with heating.

Indoor air quality and contribution to outdoor air pollution

China

Previous studies assessing the effect of stove replacement program in China have demonstrated that the indoor pollutant concentrations

Table 2
Households using coal and heating technology in the selected countries.

	Percentage of households using coal (national, regional surveys)[a]	WHO Percentage of population using solid fuels, 2013 (WHO, 2015b)	Heating technology
Poland	42.5% (Central Statistical Office, 2014)	<5%	58.9% manual coal fired boilers 8% automatic coal fired boilers 13.7% biomass, wood boiler/fireplace 13.5% gas boiler 5.9% district heating, electricity and other (Institute of Environment Economics, 2014)[b]
Mongolia	No estimates at the national scale 98% in ger areas of Ulaanbaatar (World Bank, 2013)	63%	"Traditional" stove (88%), of which 85% metal or cast iron; improved stove (2%); small LPB (9%) (World Bank, 2013)[c]
Ireland	9.6% (SEAI, 2013)	<5%	43% oil fired boilers 33% gas fired boilers 8.5% electric heating 9.6% solid fuel open fire or stove (SEAI, 2013)
Kazakhstan	40% (Kerimray et al., 2016)	9%	N/A
South Africa	1.5% (Energy Department, 2012)	12%	N/A
Czech Republic	11% in two surveyed districts (Baker et al., 2006)	<5%	N/A
China	16.7% for heating (Duan et al., 2014)	45%	Kang is a heated brick bed used for heating and cooking, widely used in rural areas. Generally efficiency is less than 20% (He et al., 2014)
Republic of Korea	N/A	<5%	N/A
Hungary	N/A	11%	N/A

[a] In Ireland, South Africa, China the coal use as a primary source for energy use is reported, remaining countries did not specify.
[b] The results of survey of single family houses.
[c] LPB is referred to small furnace connected to a low-pressure hot water distribution system including radiators.

from solid fuel use in most provinces of China still exceed the Chinese Indoor Air Quality standard (150 μg/m^3) (Sinton et al., 2004; Edwards et al., 2007). Heating was found to be an important source of indoor air pollution exposure, especially in the northern provinces with colder climates (Jin et al., 2006). Edwards et al. (2007) found that in most cases, PM_4 concentrations were considerably higher in winter than those in summer. This is likely due to decreased ventilation in homes combined with increased fuel use during winter. Composition and concentration of indoor air pollutants varied depending on fuel type and quality, stove design, absence or presence of ventilation, layout of the house (Peabody et al., 2005; Sinton et al., 2004). In China, there are a number of fuel types and a variety of stove designs (Sinton et al., 2004), as well as regional differences in housing design, behavior, and climate (Li et al., 2017; Jin et al., 2006). Thus, despite of number of studies on indoor air quality in China the results are difficult to compare and generalize (Li et al., 2017; Zhang and Smith, 2007).

Mestl et al. (2007a) estimated exposure to PM_{10} from indoor air pollution by different demographic groups in China using available literature on measurements of particulate air pollution (which meet certain criteria) combined with time activity patterns. The results demonstrated high exposure to indoor air pollution in China. For the rural population, exposure was estimated to be 750 μg/m^3 (±100) and 680 μg/m^3 (±65) in the south and north respectively. In southern and northern cities average exposure is estimated at 340 μg/m^3 (±55) and 440 μg/m^3 (±40).

Ambient air pollution is a serious concern for China. China has succeeded in reducing PM levels substantially, but further reductions remain a challenge due to growing economy and energy demand. It is still common for Chinese cities to not attain their air quality standards, especially during winter when high pollution is more frequent. In 2015, air quality standards were exceeded during 105 days during the year in 74 key cities of China (Clean Air Asia, 2016). Households coal and biomass combustion have significant contribution to ambient air quality in China, particularly in the regions with high solid fuels use. Relative contributions of residential sector emissions to ambient air pollution have increased in China due to the strict pollutant control for industrial boilers and lack of household-level emission controls or regulations (Li et al., 2017). Household relative contributions of CO, $PM_{2.5}$, BC, and PAH emissions in all anthropogenic sources are 30%, 30%, 45%, and 60% in mainland China, respectively (Li et al., 2017).

Mongolia

The WHO listed Ulaanbaatar as having one of the world's worst air quality. Given the severity of the problem in Ulaanbaatar, there have been studies conducted on air quality monitoring, health effects assessment and interventions in Ulaanbaatar since 2000s. Guttikunda et al. (2013) estimated that detected annual average of $PM_{2.5}$ fine particulate matter concentration in Ulaanbaatar exceeded WHO air quality guideline by 13 times reaching 136 μg/m^3, with peaks as high as 750 μg/m^3 during the winter. Coal and wood burning for heating contribute about 60% of $PM_{2.5}$ concentrations in Ulaanbaatar (World Bank, 2013). In ger areas of Ulaanbaatar, annual average $PM_{2.5}$ was even higher and it was 200–350 μg/m^3, exceeding WHO limit 17–35 times (Sustainable Development Department of the East Asia and Pacific Region, 2011). It was estimated that to achieve compliance with the Mongolian Air Quality Standard (annual average $PM_{2.5}$ - 25 μg/m^3) in Ulaanbaatar, ger area heating, heat-only boilers and suspended soil yields would need to reduce emissions by 94% (Sustainable Development Department of the East Asia and Pacific Region, 2011). In contrast to many developing countries where indoor air pollution is more severe than outdoor pollution, in Ulaanbaatar, PM has been attributed to release from stove chimneys, which result in less severe indoor air pollution. Concentrations of PM_{10} and $PM_{2.5}$ measured indoor were 3–7 and 3–5 times lower than outdoor air pollution levels (Sustainable Development Department of the East Asia and Pacific Region, 2011), although air quality in houses with improved stoves is still 2–3 times the WHO recommended values (0.15 mg/m^3).

Ireland, Poland and Czech Republic

Most of the studies in developed countries investigated the contribution of different sources to outdoor air pollution, with few investigating indoor air quality. The study in Ireland demonstrated that indoor air quality, in the homes burning solid fuels in stoves, was good and well below WHO air quality guidelines, indicating that there is good ventilation and generally well designed and maintained stoves (Semple et al., 2012). Weighted 24-hour average $PM_{2.5}$ concentrations were found in homes that burned peat to be 11 μg/m^3 and coal 7 μg/m^3. These concentrations are much lower than those reported in China where mean 24-hour concentration of 223 μg/m^3 for "improved" stoves, 197 μg/m^3 for coal stoves and 185 μg/m^3 for gas stove were found (Sinton et al., 2004).

Previous studies demonstrated that heating with wood and coal were the major source of outdoor PM in rural areas in Czech Republic, Poland's Krakow, and in some regions of Ireland (Braniš and Domasová, 2003; Schwarz et al., 2016; Junninen et al., 2009; Samek, 2016; Wenger, 2015).

Poland has been recognized as a country with the worst air quality among European Union countries. Air quality norms for particulate matter concentrations are exceeded in 83% of air monitoring areas in Poland (Institute of Environmental Economics, 2014). The concentrations of PM_{10} and $PM_{2.5}$ during winter were even three times higher (depending on the city) than in the warmer seasons. Mean concentrations of benzo[*a*]pyrene in Poland exceeded EU norms by a factor of 5 (Institute of Environmental Economics, 2014). Heating with old, inefficient coal boilers often with low quality coal in Poland has been the major source of PM (52%), polycyclic aromatic hydrocarbons (87%), heavy metals, and dioxins (Institute of Environmental Economics, 2014).

Health effects

There is a strong evidence of adverse health impact from household solid fuel consumption in China, including lung cancer, respiratory illnesses, acute respiratory infections and chronic obstructive pulmonary disease, as well as lung function and immune system impairment (Zhang and Smith, 2007). In some Chinese provinces, coal has high concentrations of toxic elements such as arsenic and fluorine and there are "endemic" health impacts such as arsenosis and fluorosis (Zhang and Smith, 2007).

It was estimated that 37% of all premature deaths due to ambient $PM_{2.5}$ exposure across China is attributable to emissions from the residential sector, with 159,000 and 182,000 premature deaths from heating and cooking emissions, respectively (Archer-Nicholls et al., 2016).

Mestl et al. (2007b) argued that fuel-based approach applied by WHO underestimates health effects. Using linear exposure–response functions, Mestl et al. (2007b) estimated that 3.5 million people die prematurely due to indoor air pollution in China each year. This value is much higher than the WHO estimate of 0.42 million (0.548 million in the later WHO assessment (WHO, 2009)). The differences were attributed to the fact that linear exposure–response relationships most likely tends to overestimate the effects and also that WHO results were limited to respiratory disease while Mestl et al. (2007b) estimated "all-cause-mortality". Large differences in the assessments of excess premature deaths from indoor air pollution associated with solid fuel use suggest the need for further studies on exposure and health impact from indoor air pollution of population of China.

Air pollution represents a major threat to public health in Ulaanbaatar, Mongolia. An epidemiological study demonstrated statistically significant associations between cardiovascular mortality and coarse particles with a one-day lag (Sustainable Development Department of the East Asia and Pacific Region, 2011). There were strong statistical correlations between ambient air pollutants and spontaneous abortion (Enkhmaa et al., 2014). Guttikunda et al. (2013) estimated 1000–1500 premature deaths per year due to outdoor air pollution in Ulaanbaatar. The ratio of premature deaths caused by respiratory and cardiovascular diseases over total premature deaths have steadily increased in Mongolia (Sumiya, 2016). Allen et al. (2013) estimated that 29% of cardiopulmonary deaths and 40% of lung cancer deaths were attributed to outdoor air pollution.

Deaths due to carbon monoxide poisoning in households in Kazakhstan are reported periodically during winter in the local media (Tengrinews, 2014; Inform, 2015). However, there are no official statistics or studies of such mortality.

Since the health impacts were small and few people were exposed, indoor air pollution from solid fuels was not considered to be a major public health issue in Ireland (Galea et al., 2013). Excess winter mortality due to fuel poverty however has been quantified for Ireland (Zeka et al., 2014) and is estimated to account for 2800 deaths per annum. Households that used coal and also experienced energy poverty have less economic capacity for the investment required to address energy poverty.

In South Africa, studies have produced estimates of the health effects from indoor air pollution. Acute Lower Respiratory Infections among children were associated with the exposure to indoor air pollution caused by using polluting fuels (Barnes et al., 2009). Indoor air pollution in South Africa was estimated to be responsible for up to 1400 child deaths annually. Using the WHO comparative risk assessment methodology, Norman et al. (2007) estimated respiratory illness from indoor air pollution and found that exposure to indoor air pollution caused 2489 deaths in 2000 in South Africa and 60.9 DALYs/1000cap, with the later revision of the assessment (Norman et al., 2010).

Table 3 summarizes the contributions to outdoor pollution, indoor air quality, health impact estimated by WHO and other sources in the selected countries.

Policy interventions

Emissions reduction from household coal heating may be achieved by behavioral changes, stove modifications or replacement, installation of chimney, and improved fuel. Simple behavior changes such as burning outdoors when possible (cooking and water heating) rather than burning indoors, ensuring adequate ventilation, reducing the amounts of time spent near the fires were found to reduce PM_{10} by 57% and CO by 31% among households that burned indoor fires. (Barnes et al., 2011). Other behavioral changes that affect indoor air pollution exposure include how fuels are prepared and fires are kindled, and how appliances are maintained (Barnes et al., 2011). There are also high investment in infrastructure measures such as switching to LPG, pipeline gas, electric heating and district heating. Stove replacement and/or better solid fuels are sometimes considered as transitional measures (World Bank, 2014), while in the longer term switching to cleaner alternatives is suggested to achieve significant emissions reductions (Zhi et al., 2017). However, lack of access to cleaner options and/or high cost of cleaner alternatives (particularly for distant rural areas with generally lower income levels) and limited security of supply restrain the energy transition. Often such a transition is not achievable without coordinated support and regulation from the government.

Ban on coal

Most developed countries have either banned or greatly restricted household coal use to mitigate its effects on urban ambient pollution

Table 3
Contribution to outdoor pollution, indoor air quality and health impact in the selected countries.

	Contribution to outdoor pollution	Indoor air quality	WHO health effect from indoor air pollution, deaths/year (WHO, 2009)	Health risks from indoor air pollution, other studies[a]
Poland	More than half of PM_{10} was attributed to residential heating by coal combustion in small stoves and boilers in Krakow (Junninen et al., 2009)	N/A	–	N/A
Mongolia	Coal and wood burning for heating contribute about 60% of $PM_{2.5}$ concentrations in Ulaanbaatar (World Bank, 2013)	Annual average concentration of PM_{10} 117 μg/m^3 and $PM_{2.5}$ 55 μg/m^3 (Sustainable Development Department of the East Asia and Pacific Region, 2011)	300	N/A
Ireland	50% and 75% of wintertime $PM_{2.5}$ is resulting from solid fuel burning in Cork City and in Enniscorthy and Killarney (Wenger, 2015)	Average 24-hour time weighted average levels of $PM_{2.5}$ were found in homes that burned peat 11 μg/m^3, coal (7 μg/m^3) (Semple et al., 2012)	–	21 additional annual cases of all-cause mortality, 55 of chronic bronchitis, and 30,100 and 38,000 annual lower respiratory symptom days (including cough) and restricted activity days respectively (Galea et al., 2013)
Kazakhstan	N/A	N/A	100	N/A
South Africa	N/A	N/A	3200	2489 deaths in 2000 in South Africa and 60.9 DALYs/1000cap (Norman et al., 2007), with the later revision of the assessment (Norman et al., 2010)
Czech Republic	Household heating is a major source of emissions of PM_{10}. It produces roughly 40% of PM (European Environmental Agency, 2015)	N/A	–	Higher frequency of lower respiratory Illness in children from homes heated by coal (Baker et al., 2006)
China	Household relative contributions of CO, $PM_{2.5}$, BC, and PAH emissions in all anthropogenic sources are 30%, 30%, 45%, and 60% in mainland China, respectively (Li et al., 2017)	Median population weighted exposure 620 μg/m^3 (Mestl et al., 2007a)	548,900	3.5 million premature deaths due to indoor air pollution (Mestl et al., 2007b)
Republic of Korea	N/A	N/A	–	N/A
Hungary	70% of outdoor air pollution is caused by household heating systems (Hungarian Energy Efficiency Institute, 2017)	N/A	–	N/A

[a] Studies estimating health risks from outdoor air pollution were not included in this Table.

(WHO, 2014). Bans on coal sales are known to be an effective measure to tackle air pollution. Clancy et al. (2002) found that average PM concentrations have declined by 70%. Approximately 116 fewer respiratory deaths and 243 fewer cardiovascular deaths per year were found in Dublin after coal sales were banned. Results by Dockery et al. (2013) confirmed the decrease in respiratory mortality after the 1990 ban.

To improve air quality, the ban on smoky coal marketing, sale and distribution in Ireland was extended to other cities and towns with over 15,000 people. In 2015 it was announced that ban on smoky coal will be extended to the entire country in a maximum timeframe of three years.

To tackle severe air pollution problem in Krakow and surrounding areas of southern Poland, the Law on Environment Protection was passed in 2013. This law bans coal use for heating purposes (Ricardo Energy and Environment, 2016). A transitional period of five years was set from the approval of the law. It is expected, that the fuel ban will be implemented by other cities of Poland with similar problems.

China National Action Plan on Air Pollution Prevention and Control (2013–2017) sets a cap on annual coal consumption by 2020 as a core strategy to address the ambient air pollution in China (Jin et al., 2016). Key air pollution areas (Beijing-Tianjin-Hebei area, the Yangtze River Delta and the Pearl River Delta) are required to cap coal consumption by 2017 (Jin et al., 2016). The cap is on overall coal consumption, including power generation, industry and households. Although, Liu et al. (2016) suggest that air pollution control strategies in China mainly focus on the power, transport, and industrial sectors, with residential sector being mostly ignored.

Stove replacement

Stove improvements may contribute to even higher emissions reduction than switching to cleaner fuels, due to unavailability or unaffordability of other alternative fuels (Winijkul and Bond, 2016). The largest and the most successful improved stove program ever conducted in the world happened in China, called National Improved Stove Program (NISP) in which nearly a billion rural Chinese citizens benefited from fuel efficiency during 1980s to 1990s (Edwards et al., 2007; Sinton et al., 2004). Since the Program was focusing mainly on biomass users (due to biomass shortages), subsidies were rarely offered for coal stoves and amounts were generally lower than for biomass users (Sinton et al., 2004). Large post-intervention studies by Edwards et al. (2007) and Sinton et al. (2004) demonstrated that efficiency improvements were lower than expected (mean efficiency 14% compared to target value 20–30%) and air quality was still poorer than national air quality standard (150 μg/m^3). Significant differences in PM_4 concentrations between improved stoves and traditional stoves were only observed for biomass fuel combinations. This reduction was mostly because majority of biomass stoves had chimneys (95%), while only 38% of coal stoves were equipped with chimneys (Sinton et al., 2004). The elevated PM concentrations were attributed to households with improved biomass stoves and chimneys commonly also having portable coal stoves without chimneys, and/or additional fires being lit in the kitchen for other cooking or water heating tasks (Sinton et al., 2004; Edwards et al., 2007). There are multiple uses of energy for cooking, heating, and food drying, which cannot be simply stopped (Jin et al., 2006). The most important lesson was that providing improved cooking stoves is not sufficient (Sinton et al., 2004) and intervention programs must take all of the household energy needs into account and determine how alternative technologies can serve for all the intended purposes (Jin et al., 2006).

Stove switching programs in Ulaanbaatar have been recognized as being successful and contributed to improved ambient air quality (World Bank, 2014). In 2011 in partnership with Millennium Challenge Corporation, MCA-Mongolia introduced the stove subsidy for the use of more energy efficient stoves (Millennium Challenge Corporation, 2014). A total of 103,255 low-emission stoves were sold with subsidies (Millennium Challenge Corporation, 2014). Although, expected indicators in terms of emissions reduction and reduction of fuel expenditure were not achieved fully (by 100%), there were improvements in outdoor and indoor air quality. Households with the improved stoves had 65% lower emissions of $PM_{2.5}$ and 16% lower CO emissions compared to traditional stoves (Social Impact, 2014). Importantly, there were no significant reductions in daily coal consumption in households with improved stoves that were associated with the low compliance with operation instructions with cold starts and top lighting procedures (Social Impact, 2014). However, improved stove owners kept their homes up to 2 °C warmer in spite of using approximately the same quantities of coal daily (Social Impact, 2014). In 2013, another stove switching campaign was launched by the Municipality of Ulaanbaatar, supported by the Clean Air Foundation and the UBCAP project (World Bank, 2014). The goal was disseminating 45,000 improved stoves. In 2014, the penetration rate of improved stoves was 65% of the estimated market of 208,400 stoves in gers/houses (World Bank, 2014). The impact of intervention programs on air quality in Ulaanbaatar was positive: monthly average $PM_{2.5}$ concentrations decreased by 20 to 40 % in coldest winter months in 2014 compared to monthly averages in 2011 (World Bank, 2014). Successful stove switching program should account for available technologies and fuels, supply chain capacities, market demand segments, user preferences, incentives and regulations (World Bank, 2014).

In 2012–2013, the Ministry of Environment and the region of Moravia-Silesia (Czech Republic) offered financial help to households to replace old solid fuel stoves with new, low-emission, automatic boilers to improve air quality. Changing manually stoked coal boiler to an automated stoker boiler reduced coal consumption by 32% (Pechrová and Kolářová, 2014).

Home insulation

Better insulation in buildings brings fuel savings, GHG emissions reductions, and improves air quality through reduced fuel consumption (Institute of Environment Economics, 2014; Ricardo Energy and Environment, 2016). It was estimated that 70% of single-family buildings in Poland have no thermal insulation or their insulation layers are insuffient (Institute of Environment Economics, 2014). Typical single-family house from the 1970s in Poland reduced its seasonal heat demand by 50% after thermal modernization (Institute of Environment Economics, 2014).

The importance of home insulation in achieving emissions reductions was demonstrated in the post intervention study of stove replacement program in Mongolia (Social Impact, 2014). Improved stove owners in gers with three or more layers of felt insulation used 2.2 kg less coal each day than traditional stove owners with the same level of insulation. One of the recommendations of the impact evaluation study was that stoves interventions should enable simultaneous insulation measures to encourage compliance with cold start instructions (Social Impact, 2014).

In Ireland, Poland, Hungary, Czech Republic there are loans/subsidies for residential buildings for conducting refurbishment measures (IEA, 2017). In Hungary 41% of households already finished energy efficiency improvement projects in the past 5 years (Hungarian Energy Efficiency Institute, 2017). In Ireland, more than 300,000 households (representing nearly 20% of permanently occupied dwellings) have accessed financial supports and retrofitted their homes (Scheer et al., 2016). There has been substantial progress in energy efficiency in buildings in urban areas of China, however rural buildings are still inefficient (Evans et al., 2014). In specific parts of China, there are pilot programs to help subsidize energy efficiency of farmers' homes, however for more systematic approach Chinese government is also considering voluntary design standard for rural homes (Evans et al., 2014).

Access to clean energy

Natural gas

Residential natural gas consumption in China has increased tenfold over 2000 to 2014 (IEA, 2016a). China has abundant conventional natural gas resources (Hu and Dong, 2015), and it aims to increase its production from conventional and unconventional resources even further to improve gas security (IRENA, 2014). Replacing household coal with natural gas has already been implemented in Beijing, and there is potential to expand the use of natural gas to many cities and suburban areas with increasing import from Russia and development of shale gas reserves in China (Liu et al., 2016). There were limiting factors such as supply security and high cost which caused projects to switch from coal to gas in power plants (except for Beijing) to be cancelled or suspended in China (Jin et al., 2016).

Kazakhstan is a resource rich country, with gas reserves mainly concentrated in its western regions. In Kazakhstan, there has been expansion of distribution gas pipelines in the regions near the main pipelines in western and southern Kazakhstan. However, construction of pipelines to non-gasified regions of Kazakhstan in which 33% of Kazakhstan's population are located is still under discussion. Large distances, low population densities, high investment costs, and low economic profitability are the primary obstacles for increasing gas access to those regions (Kerimray et al., 2016).

In Poland, Hungary, Czech Republic, Ireland, South Korea and South Africa natural gas is mostly imported (IEA, 2016a). Dependence on exporting countries and negotiated price contribute to security of natural gas supplies and its affordability. In Poland, gas cost and supply security are considered to be the main challenges in switching from coal to gas (Stala-Szlugaj, 2016).

Switch to district heating or electricity

Switch to electric heating or district heating can achieve emissions reduction compared to residential stoves in the cases when power is generated in highly efficient power plants or heat-only plants with pollution control devices such as dust precipitation, desulphurization and denitrification. As a part of solving air pollution problem in China it was suggested to support the development of highly efficient coal based power plants for supplying more electricity to rural households in China (Zhi et al., 2017). Due to the high heating demand and relatively high price of electricity, it was not used widely as a heating source in Poland (3% of all households) (Central Statistical Office, 2014), Kazakhstan (Kerimray et al., 2016) and Mongolia (World Bank, 2009). Even at the cheaper nighttime rates, the monthly heating bill for electricity will be twice of the expense of coal in the case of Mongolia (World Bank, 2009).

The main challenges for connection of ger areas in Ulaanbaatar to district heating are high infrastructure costs, high losses in the distribution lines from house to house (World Bank, 2009). The same challenges can be also referred to connecting rural areas in Kazakhstan to district heating, due to low population density, large distances and prevalence of detached houses in rural areas. It has been demonstrated in Ulaanbaatar that most of the pollution abatement measures and even high investment infrastructure measures with switching to electric heating bring net benefit when accounting for the resulting health benefits due to reduced exposure to pollutant emissions (Sustainable Development Department of the East Asia and Pacific Region, 2011).

Renewable and alternative energy for space heating

Renewable energy heating has been considered as a “sleeping giant” of potentials from a global perspective (IEA, 2007). There are renewable technologies using solar, biomass and geothermal resources available for heating purposes. Since most of the selected countries have 100% electrification rate, heat pump that converts electricity back into thermal energy with high efficiency may be also an option. However, high capital and installation cost of technology, variability of solar irradiation (and necessity for heat storage), feedstock supply for bioenergy and limited locations with high-temperature geothermal resources are the barriers restraining the widespread market penetration of renewable and alternative energy heating (IEA, 2007).

China is a global leader in renewable energy. China's 12th Five Year Plan identified renewables as an emerging strategic industry and adopted targets for thermal applications of renewable energy sources: biogas, solar thermal and geothermal energy (IRENA, 2014). Analysis conducted by International Renewable Energy Agency (IRENA) demonstrated that accounting for investments and subsidies necessary to achieve 26% share for modern renewable energy in China will bring net savings of between USD 55 and USD 228 billion per year to China's economy due to improved health and reduced CO_2 emissions. To achieve high penetration of renewable energy sources in the end-use sectors in China, particularly for space heating in buildings, subsidies are needed to make them “competitive” compared with fossil fuel technologies (IRENA, 2014). China has had ambitious biomass support program, which resulted in China accounting for 90% of biogas installations worldwide, with around 35 million units in operation in 2010 and 5 million new units added every year (IRENA, 2014). The evaluation of the overall effect of subsidy program demonstrated that low level of use of biogas digester despite the high number of installations (Sun et al., 2014). Sun et al. (2014) suggested that biogas subsidies have possibly not been targeted effectively at households that would actually prefer to use biogas energy. In Ireland, future scenarios for energy use in the residential sector within a least cost modeling framework point to an increase in biogas along with electricity for residential heating, displacing not only coal but also oil (Chiodi et al., 2013).

In Korea, Czech Republic, Poland and Ireland, there are support programs for building scale renewable energy installations for space heating (IEA, 2017). Institute of Environmental Economics (2014) suggested that the subsidy program in Poland was not sufficient to improve air quality due to the growing availability of new sources resulting from the lack of emission standards. While in Kazakhstan, South Africa and Mongolia, renewable energy support policy mainly focuses on power supply and to the best of our knowledge, there were no support policies for building scale space heating renewable and alternative technologies.

The evaluation of economic and environmental output of the Green Investment Scheme in the Czech Republic by Karásek and Pavlica (2016) clearly demonstrates the need for subsidizing cleaner sources for heating. The exchange of former heating with fossil fuels to heating with biomass, as well as heat pumps was found to be beneficial in terms of achieving lowest emissions abatement cost (total costs per unit of GHG emissions reduction) (Karásek and Pavlica, 2016). However, switching from fossil fuel stove to biomass boiler or heat pump did not achieve payback of investments due to lower prices of fossil fuels (Karásek and Pavlica, 2016). Solar thermal had long payback period of investment (19 years) since they mainly covered water-heating demand rather than space heating (Karásek and Pavlica, 2016).

The interventions in the selected countries are summarized in Table 4.

Conclusions

Global residential coal consumption is steadily declining. However, coal is still a major household fuel in some countries. Since coal is mostly burned domestically with low efficiency, it results in significant adverse impacts on outdoor and indoor air quality, which in turn lead to severe health impacts. Availability of coal and security of its supply, relatively inexpensive price and lack of other affordable alternatives are primarily the reasons restraining transition to cleaner option. Interventions have been successful in reducing the adverse effects of low efficient stoves. However, stove replacement interventions not always reached its targets fully, mostly because they did not account entire energy needs of the households and behavioral issues. Additionally, home insulation is

Table 4
Interventions in the countries considered.

Country[a]	Interventions/policies
Poland	"KAWKA" – "Liquidation of low emission supporting increased energy efficiency and development of distributed renewable energy resources" Program (IEA, 2017)
	Ban on coal for heating needs in Krakow (Ricardo Energy and Environment, 2016)
Ireland	The Greener Homes Scheme (IEA, 2017)
	Ban on smoky call extended across Ireland since 2018 (Department of the Environment, Community and Local Government, 2015)
Czech Republic	Subsidies for replacing old solid fuel stoves (Pechrová and Kolářová, 2014; Prague Daily Monitor, 2017)
	Green Investment Scheme: NEW GREEN SAVINGS 2014+ (IEA, 2017)
	Boiler efficiency requirements and emissions standards (Institute of Environmental Economics, 2014)
Hungary	Establishment of an off-take and support scheme for green heat (Deputy Secretariat of State for Green Economy Development and Climate Policy for the Ministry of National Development, 2010)
Kazakhstan	Expansion of gas network in the regions where main pipelines is in place (Kerimray et al., 2016)
Mongolia	Ulaanbaatar Clean Air Project (subsidies for low emissions stove) (World Bank, 2013)
South Africa	N/A
China	Cap on overall annual coal consumption by 2020 (Jin et al., 2016)
	Key pollution areas are required to cap overall coal consumption by 2017 (Jin et al., 2016).
	Subsidies for the installation of small-scale biogas digesters (Sun et al., 2014)
	Investment subsidy for large scale biogas projects (IRENA, 2014)
	Renewable energy development fund (Sun et al., 2014)
Korea	Home Subsidy Program (IEA, 2017)

[a] National specific interventions and policies were described. European Directives applicable for Poland, Ireland, Czech Republic and Hungary were not presented in the Table.

essential prerequisite for any intervention in poorly insulated homes in cold climate regions.

Health benefits are mostly higher than the costs of most of the cleaner alternatives in the regions with severe air pollution problems. There are mature renewable technologies for space heating available, but they require targeted financial support from the governments. Further research on evaluation of support programs of renewable and alternative heat technologies at building scale is needed to estimate their technical and economic viability. For some of the countries with high households coal consumption, there is still lack of nationally representative data on patterns of households coal use, indoor air quality and health impacts.

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