# MODELLING OF RESIDENTIAL HEAT DECARBONISATION PATHWAYS IN THE REPUBLIC OF KAZAKHSTAN

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A thesis submitted in partial fulfillment of the requirement of Nazarbayev University for the degree of Doctor of Philosophy

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**Acronyms and definitions**

| | |
|---|---|
| BaU | Business as Usual scenario |
| $CO_2$ | Carbon Dioxide |
| CHP | Combined Heat and Power Plant |
| CSRK | Committee of Statistics of the Republic of Kazakhstan |
| DH | District heating |
| EU | European Union |
| GDP | Gross Domestic Product |
| GHG | Greenhouse gases emissions |
| GWh | Gigawatt hours |
| h | Hours |
| IACOG | Information-Analytical Centre of Oil and Gas |
| IGCC | Integrated Gasification Combined Cycle |
| IMF | International Monetary Fund |
| KEGOC | Kazakhstan Electricity Grid Operating Company |
| kgoe | Kilogram of oil equivalent |
| cap | Capita |
| ktoe | Thousand tons of oil equivalent |
| km | Kilometer |
| kWh | Kilowatt hours |
| LIHC | Low income, high costs |
| LPG | Liquefied Petroleum Gas |
| mln | Million |
| ME RK | Ministry of Energy of the Republic of Kazakhstan |
| NDC | Nationally determined contribution |
| OECD | Organisation for Economic Development |
| PM | Particulate Matter |

| | |
|---|---|
| PMR | Partnership for market readiness |
| RES | Reference Energy System |
| SH | Space heating |
| TIMES | The Integrated Markal Efom System |
| TJ | Terajoules |
| TFC | Total final consumption |
| TPES | Total Primary Energy Supply |
| UNFCCC | United Nations Framework Convention on Climate Change |
| W | Watt |
| WH | Water heating |
| WHO | World Health Organisation |

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I would like to thank my mother for supporting me spiritually throughout writing this thesis and my life in general. Many thanks to my daughter, who has been driving me to work hard and never give up.

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**Declaration**

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The Thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

**Abstract**

Globally, buildings account for one third of final energy consumption and are a significant source of $CO_2$ emissions. Concerns with unsustainable use of energy in buildings, growing greenhouse gases emissions and energy poverty challenges all require effective planning, strategies and actions from policy makers. Energy systems models together with scenario analysis are widely applied tools to aid decision making in energy planning and in the assessments of technology pathways. Studies and analyses using energy systems models tend to focus on energy transition pathways and neglect energy poverty, energy affordability and local pollution. In addition, they generally do not simultaneously incorporate spatial, building type and urban/rural detail. This thesis addresses this gap, by introducing the first sub-nationally disaggregated energy system model with regional detail, representation of the building types (detached, flat) urban/rural disaggregation, and analysis of energy poverty.

The aim of this thesis is to improve the evidence base informing policy decisions regarding the energy transition. The first objective of this thesis is to build energy systems modelling capacity in Kazakhstan and use it to develop future energy systems pathways for residential energy use. The second objective is to address current limitations in energy systems modelling in addressing challenges of developing countries such as energy poverty, energy shortage, spatial and urban/rural differences. The third objective is to develop and apply suitable approaches and methods for addressing challenges with data availability and analysis.

To address limitations in data, improved Energy Balances for Kazakhstan were compiled and cross-checked with additional data.  An in-depth analysis of household fuel use and energy poverty was conducted drawing on data from the Households Survey. A detailed building stock module was incorporated into a 16-region (sub-nationally disaggregated) TIMES integrated energy systems model for Kazakhstan. Building types were disaggregated in the model to detached/flat and urban/rural using statistical data on the housing stock and building energy audit reports. Using this improved model, the most cost-effective heating technologies for different regions and building types were identified. The results can serve as a basis for National/regional strategies for residential sector policies. The approaches for model improvement and addressing data limitations can be replicated to other countries.

# 1. Introduction

## 1.1 Background

Residential emissions from space heating and cooking with solid fuels remain 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).

A number of countries continue to have 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. In 2014, the highest per capita household coal consumption in the world occurred in Poland (165 kgoe/cap), followed by Kazakhstan (157 kgoe/cap) and Mongolia (104 kgoe/cap) (Kerimray et al., 2017a).

Heating is a basic need for survival in Kazakhstan. This country is one of the coldest countries in the world together with Mongolia, Russia and Canada. Poor building insulation coupled with low access to clean fuels in some of its regions resulted in significant challenges associated with "energy poverty" in Kazakhstani households (Kerimray et al., 2017b; Atakhanova and Howie, 2013). Households that are not able to adequately heat their homes at an affordable cost or/and adequately access clean fuels are defined as energy poor. Many rural households still use solid fuels for heating purposes despite the fact that the electrification rate is 100% in the country (Atakhanova and Howie, 2013). According to an official Households Survey, 40% of surveyed households used coal, from which 77% were dwellings located in rural areas (Kerimray et al., 2016a).

The Paris Agreement, entered into force on November 4, 2016, is a key event that completes more than two decades of global negotiations on climate change prevention. The result was recognition that a low-carbon transformation of the world energy system is indeed possible, even inevitable, in context of a rapid decline in the cost of renewable energy sources and an unprecedented level of action by Governments, civil society, business and other actors. Kazakhstan ratified the Paris agreement and its nationally determined contribution (NDC) has set an unconditional target of 15% reduction in greenhouse gas emissions (GHG) by 2030 compared to 1990 levels (UNFCCC, 2016a). The Partnership for Market Readiness (PMR) Kazakhstan (2016) indicated that Kazakhstan's 15% NDC target is ambitious in the mid- and long-term period and requires explicit policy action that should make an impact by as soon as 2020. A significant emissions reduction needs to be achieved in the commercial and residential sectors with a switch from coal to cleaner alternatives to meet the NDC target (PMR Kazakhstan, 2016).

The energy transition is rarely if ever achievable without a coordinated support and regulation from the government. In some countries, a residential coal ban has been demonstrated to be an effective measure (Dockery et al., 2013), but it needs to be carefully applied in the regions with no other alternative options coupled with high poverty rates. The health benefits are generally higher than the abatement costs in the most polluted areas, and support from governments for cleaner energy can be feasible and effective if carefully designed and targeted (Kerimray et al., 2017a).

In many countries, there are support programs for building scale renewable energy installations for space heating and for retrofitting measures (IEA, 2017). In Kazakhstan there are no policy interventions currently to support the energy transition and buildings retrofit in the residential sector. The design of successful policy intervention needs quantitative assessment of possible impacts and prioritizing regions, technology types, as well as identifying optimal subsidy levels. One of the goals of this study is to provide necessary and useful information to the policy making process to address this important challenge.

## 1.2 Key objectives and novelty

The first energy models were developed in the 1960s as tools for making "informed" decisions in energy planning. The main purpose of energy system models is an assessment of energy system dynamics in medium and long-term horizon, using an *extensive technology database*. This thesis uses one of today's best known energy system modeling platforms called "TIMES" (Bhattacharyya and Timilsina, 2010; Gargiulo and Ó Gallachóir, 2013) to explore the residential sector decarbonisation pathways for Kazakhstan and to define necessary actions for achieving energy transition by accessing policy options and identifying cost effective technologies.

The focus of this research is therefore twofold. Firstly, to provide robust, knowledge-based information to inform policy makers on energy transition and emissions reduction options in the residential sector by employing advanced modeling techniques. Secondly, to contribute with the development of modelling techniques to address some of the current limitations in terms of properly representing challenges of developing countries, such as energy poverty, spatial and urban/rural differences as well as approaches for addressing challenges with data availability and analysis.

Energy systems modelling has an advantage in exploring these options as it simultaneously optimizes the supply and demand of energy, taking into account the availability of resources (e.g. gas and renewable energy, among others) and the role of infrastructure (e.g. power plants and gas network, among others) necessary for energy transition in the residential heating sector. While energy system models have comprehensive representations of the entire energy system, they mostly use an aggregated representation of the residential sector (e.g. building types, urban/rural divide and spatial split) (Yangka and Diesendorf, 2016; Sarbassov et al., 2013; Chiodi et al., 2015; Dodds, 2014). Lack of spatial disaggregation and the aggregation of demand types are two aspects that result in oversimplifications of the demand type (Fehrenbach et al., 2014). Disaggregated models (by regions, building types, urban/rural divide) can provide more balanced mid- and long-term energy system development strategies as it can provide additional insights which can be underexplored by the aggregated model.

For Kazakhstan, there have been few modelling assessments of the energy system development pathways (Kerimray et al., 2015; PMR Kazakhstan, 2016; Sarbassov et al., 2013), and they focused on energy system as a whole, without particularly focusing on the energy transition in the residential sector and without spatial, urban/rural detail.

In the developing-country context, data limitations arise as a constraint to employing energy system planning tools. The most comprehensive energy system models require a huge database and often, for developing countries, such detailed data is not available or where available, the quality may not beof high standard (Bhattacharyya and Timilsina, 2010). The inaccurate characterisation of energy systems can lead to incorrect policy suggestions, which can have implications for long-term energy system development (Bhattacharyya and Timilsina, 2010). The dynamics of economic growth and consequent energy implications are poorly understood in developing countries, which in turn results to inadequate infrastructure development or poorly adapted development (Bhattacharyya and Timilsina, 2010). For example, Kazakhstan's national statistics on energy is not harmonized with international standards (Eurostat 1998; IEA, 2007a) in terms of statistical forms, format of presentation, units and level of disaggregation (Radulov 2013; Kerimray et al. 2015). This study presents methodologies for in-depth data analysis and compilation along with a detailed review of energy supply and consumption, energy affordability and energy poverty trends. These datasets were used in the preparation of the housing stock module to be incorporated to the energy system model. The approach for data collection, analysis and cross check developed in this thesis can be useful for energy modelers in Kazakhstan and other countries to address challenges with data on the energy system.

Energy system models with sub-national regional disaggregation and with building types have been developed for Canada (Vaillancourt et al., 2014), China (Shi et al., 2016) and Denmark (Petrović and Karlsson, 2016), but they did not account for unmet demand and thermal comfort, urban/rural differences, energy affordability and air pollution. Bhattacharyya and Timilsina (2010) reviewed the suitability of energy system models for developing countries and stressed the need for better characterization of urban/rural and spatial details in the models in order to properly account for the challenges of developing countries. This study pretends to fill this gap.

The aim of this thesis is to improve the evidence-based informing policy decisions regarding the energy transition necessary to fulfill the reduction of GHG emissions committed by Kazakhstan by 2030.

The objectives of this thesis are to:

i. build energy systems modelling capacity in Kazakhstan and use it to develop future energy systems pathways for residential energy use.
ii. study current limitations in energy systems modelling in addressing challenges of developing countries such as energy poverty, spatial and urban/rural differences.
iii. develop and apply suitable approaches and methods for addressing challenges with data availability and analysis.

### 1.3 Role of collaborators

This thesis is based on my own work and was written by me, but collaborations had an important role in this research. All aspects of this thesis have received advise and been reviewed by main supervisor Professor Luis Rojas-Solórzano and co-supervisors Professor Brian P. Ó Gallachóir and Professor Mehdi Amouei Torkmahalleh. Several contributions were also received from the colleagues of the energy modeling team at National Laboratory Astana of Nazarbayev University. A full list of my collaborations and publications is contained in section 1.4.

I conducted literature review on modeling methodologies employed across the world, identified data gaps and research needs, evaluated clean energy access and energy poverty challenges. I worked on data collection on residential and non-residential sectors, the consistency cross-check of data and compilation of improved Energy Balances for Kazakhstan which serve as a key input data for TIMES model. I worked on preparation of housing stock module, its incorporation to TIMES model, implementing a number of new model inputs, dwelling stock, energy need for heating, demand projections, user constraints, energy efficiency measures and techno-economic assumptions. I ran the model, produced the results and prepared the manuscripts for publication. All the manuscripts presented in the section 1.4 were prepared by myself, with the support provided by co-authors as described below.

Suggestions and feedback on manuscripts and this Thesis were provided by my supervisors: Professor Luis Rojas-Solórzano, Professor Brian Ó Gallachóir, Professor Mehdi Amouei Torkmahalleh. Professor Philip Hopke contributed to the structure and form of the review paper (published in the "Energy for Sustainable Development" Journal). Bakytzhan Suleimenov and Igor Kolyagin supported me with the data collection on non-residential sectors necessary for maintaining TIMES model. Rocco De Miglio supported me in defining the structure of the housing stock module and its appropriate incorporation into the energy system model. Bakytzhan Suleimenov supported me with the model maintenance: he worked on non-residential sectors in the model (e.g. industry, transport, power sector). Ramil Bektineyev supported me with transferring data from the building energy audits reports (PDF files) to excel files and with preparation of database of buildings.

## 1.4 Thesis outputs

### *Journal papers*

[1] Kerimray A., Rojas-Solórzano L., Amouei Torkmahalleh M., Hopke P.H., Ó Gallachóir B. P. (2017). Coal Use for Residential Heating: Patterns, Health Implications and Lessons Learned. Energy for Sustainable Development 40C (2017) pp. 19-30

[2] Kerimray A., Suleimenov, B., Kolyagin, I. (2017) Analysis of the energy intensity of Kazakhstan: from data compilation to decomposition analysis. Energy Efficiency: 1-21. DOI: 10.1007/s12053-017-9565-9

[3] Kerimray A., De Miglio R., Rojas-Solórzano L., Ó Gallachóir, B.P.(2017). Causes of energy poverty in a cold and resource rich country. Evidence from Kazakhstan. Local Environment. DOI: 10.1080/13549839.2017.1397613

[4] Kerimray A., Suleimenov B., De Miglio R., Rojas-Solórzano L., Amouei Torkmahalleh M., Ó Gallachóir B.P. Investigating the energy transition to a coal-free residential sector in Kazakhstan using a regionally disaggregated energy systems model. Journal of Cleaner Production https://doi.org/10.1016/j.jclepro.2018.06.158

### *Chapter in a book*

*[1]* Kerimray A., Suleimenov B., De Miglio R., Rojas-Solórzano L., Ó Gallachóir B. (2018) Long-Term Climate Change Mitigation in Kazakhstan in a Post Paris Agreement Context. In: Giannakidis G., Karlsson K., Labriet M., Gallachóir B. (eds) Limiting Global Warming to Well Below 2 °C: Energy System Modelling and Policy Development. Lecture Notes in Energy, vol 64. Springer, Cham

### *Conference proceedings and presentations*

[1] Kerimray A., Bektineyev R., Rojas-Solórzano L.R. (2016). Energy efficiency options for buildings: insights from buildings energy audit reports in Kazakhstan. 4th IET Clean Energy and Technology Conference, 2016 page 23 (6) DOI: 10.1049/cp.2016.1280

[2] Kerimray A., De Miglio R., Rojas-Solórzano L., Ó Gallachóir B. (2017). Household Energy Consumption and Energy Poverty in Kazakhstan. IAEE Energy Forum. https://www.iaee.org/en/publications/newsletterdl.aspx?id=382

[3] Kerimray A., De Miglio R., Rojas-Solórzano, L., Ó Gallachóir, B. (2016) Incidence of district heating and natural gas networks on energy poverty across Kazakhstan. 1st IAEE Eurasian Conference "Energy Economics Emerging from the Caspian Region: Challenges and Opportunities". Baku, Azerbaijan http://www.iaee.org/baku2016/submissions/OnlineProceedings/Proceedings_Paper_IAEE_final.pdf

[4] Kerimray A., De Miglio R., Rojas-Solórzano L. Disaggregating housing stock in the energy system model for residential decarbonisation scenarios. World Scientific and Engineering Congress "Energy of the future: Innovative scenarios and methods for their implementation". Astana, June 19-20, 2017.

[5] Kerimray A., Energy poverty and pathways for decarbonising residential sector in Kazakhstan. Workshop "Energy - Food - Water Nexus in Kazakhstan & UK. Integrated Approach to Green Economy Transition", Astana, Kazakhstan, August 22nd, 2016

[6] Kerimray A. Bottom-up modeling of residential sector decarbonisation scenarios. International Seminar on "Towards Smart Sustainable Cities – Integrated Approaches". Astana, Kazakhstan, June 15th, 2017.

## 2. Literature review

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

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).

Figure 1shows that the highest per capita solid fuel use in 2014 occurred in Africa, China, Asia (excluding China) and OECD Europe. 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 (Kerimray et al., 2017a).

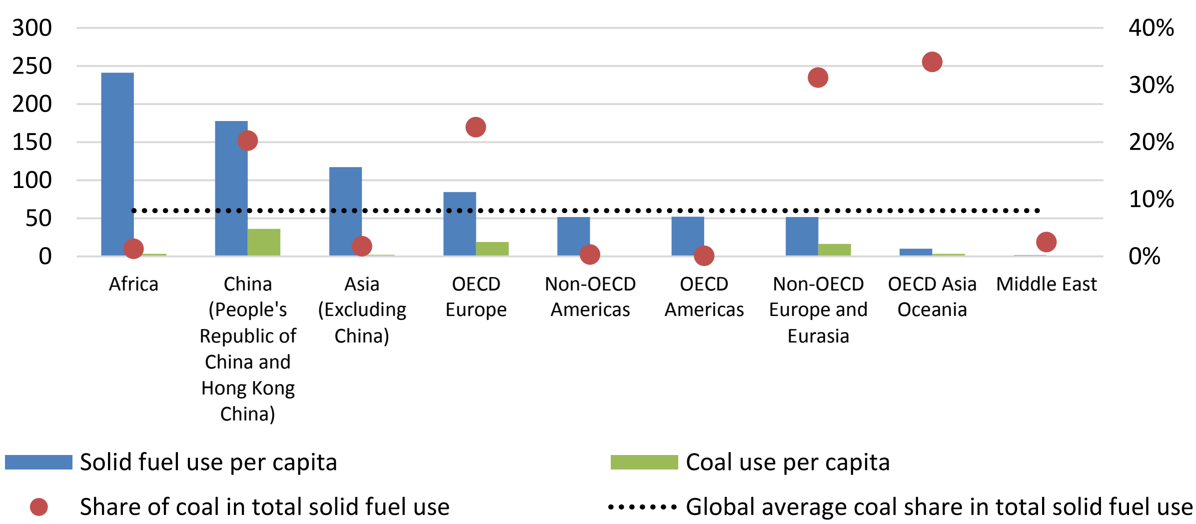



Figure 1 – Residential solid fuel and coal consumption per capita and share of coal in total solid fuels consumption by regions of the world in 2014, in kilograms oil equivalent per capita (kgoe/cap) (Kerimray et al., 2017a)

In 2014, the selected countries shown in Figure 2 represented 21% of world population and accounted for 86% of global 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. 2) (Kerimray et al., 2017a). China represented 19% of the global population and 66% of world total residential coal consumption (IEA, 2016). 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. 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, 2016b). 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.

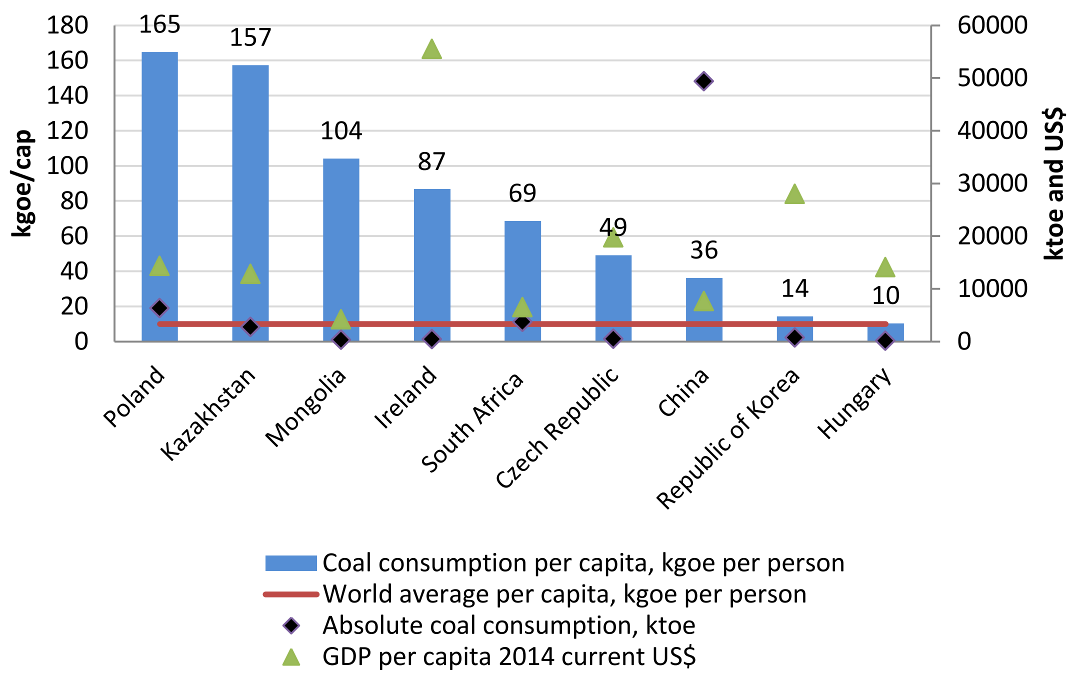



Figure 2– Residential coal consumption per capita kgoe/cap (left axis), absolute residential coal consumption ktoe (right axis), GDP per capita current US$ (right axis) in 2014 in the selected countries (Kerimray et al., 2017a)

### 2.1.1 Adverse impacts from households coal combustion

*Contribution to outdoor and indoor air pollution*

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, while there is a limited information for Czech Republic, Poland, Hungary, Kazakhstan, South Korea, and South Africa (Kerimray et al., 2017a).

Ambient air pollution is a serious concern for China. 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).

Coal and wood burning for heating contribute about 60 percent of $PM_{2.5}$ concentrations in the Mongolia's Ulaanbaatar (World Bank 2013). Ulaanbaatar (Mongolia) is the city with one of the world's worst air quality. Detected annual average of $PM_{2.5}$ fine particulate matter concentration in Ulaanbaatar exceeded WHO air quality guideline by 13 times reaching 136 $\mu g/m^3$, with peaks as high as 750 $\mu g/m^3$ during the winter.

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).

Guttikunda et al. (2013) estimated 1,000–1,500 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.

### 2.1.2 Policy Interventions

*Coal ban*

Emissions reduction from household coal heating may be achieved by behavioral changes, stove modifications or replacement, installation of chimney, and improved fuel (Kerimray et al., 2017a). 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% amongst 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.

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

*Stove replacement*

In 1983, the National Improved Stoves Program was initiated by Ministry of Agriculture of China resulted in the provision of 59.2% of rural households in China with 180 million improved stoves (Tan and Liao, 2014; Zhang and Smith, 2007). However, while all improved biomass stoves included chimneys, improved coal stoves did not specify the incorporation of chimneys, therefore resulted in higher air pollution from coal combustion (Sinton et al., 2004). Sinton et al. (2004) in its assessment of the intervention in China found that approximately in all households with different fuel/stove, $PM_4$ levels exceeded national standard of air pollution. 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).

Mongolia developed efforts to implement low-emission stoves in the market by subsidizing the equipment. With the financial support of Millennium Challenge Corporation, stove-switching project was implemented in “air pollution reduction zones” in Mongolia (World Bank, 2013). In total, 97877 low-emission stoves were sold with the subsidies of 195-319US$ each. 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). The impact of intervention programs on air quality in Ulaanbaatar was positive: monthly average $PM_{2.5}$ concentrations decreased by 20 to 40 percent in coldest winter months in 2014 compared to monthly averages in 2011 (World Bank, 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). 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 (Kerimray et al., 2017a). 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). In specific parts of China, there are pilot programs to help subsidize energy efficiency measures of farmers' homes, however for more systematic approach Chinese government is also considering voluntary design standard for rural homes (Evans et al., 2014).

*Switch to district heating or electricity*

Switching 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., 2016a) 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 and 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 large potential from a global perspective (IEA, 2007b). 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 pumps that convert electricity back into thermal energy with high efficiency may be also an option (Kerimray et al., 2017a). 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, 2007b).

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 a low level of use of biogas from biodigesters 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 modelling 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). The 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).

### 2.1.3 Conclusions on section

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-efficiency stoves. However, stove replacement interventions not always reached its targets fully, mostly because they did not account for entire energy needs of the households and behavioral issues. Additionally, home insulation is essential pre-requisite 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.

## 2.2 Review of modelling approaches for the residential sector

In addition to the multitude of options for energy transition (e.g. renewable energy, biomass, heat pumps, etc.) and for energy demand reduction (retrofit options), the optimal strategy depends on the building type, use, age, geographical and other given conditions, as well as on the goals of decision-makers (Wu et al., 2017). Energy systems modelling has an advantage in exploring these options as it simultaneously optimizes the supply and demand of energy, taking into account the availability of resources (e.g. gas and renewable energy, among others) and the role of infrastructure (e.g. power plants and gas network, among others) necessary for energy transition in the residential heating sector. While energy system models have comprehensive representations of the entire energy system, they mostly use an aggregated representation of the residential sector (e.g. building types, urban/rural divide and spatial split) (Yangka and Diesendorf, 2016; Sarbassov et al., 2013; Chiodi et al., 2015; Dodds, 2014). Incorporating a simplified housing stock model in the national (single region) energy system model of UK enabled examination of sector-specific policies while still benefiting from an internally-consistent representation of the whole energy system (Dodds, 2014). Previous studies focusing on sector specific residential analysis with energy system models employed single-region (spatially aggregated) models: for analysis of electric cooking (Yangka and Diesendorf, 2016); heat decarbonisation assessments (Dodds, 2014), electric load management (Fehrenbach et al., 2014), projections of energy services demand for residential buildings (Gouveia et al., 2012). Li et al (2016) concluded that spatial detail gives useful implications for sub-national governments and local communities, which is commonly underexplored with national single region models. Fehrenbach et al. (2014) reported that the lack of spatial disaggregation and the aggregation of demand types (whereby one building type represents several thousand real buildings) are two aspects that result in oversimplifications of the demand type.

Table 1 below provides summary on the energy system models either having spatial detail or disaggregated residential sector, or both. Energy system models with sub-national regional disaggregation and with building types have been developed for Canada, China and Denmark, but they did not account for energy poverty (unmet demand and thermal comfort), urban/rural differences, energy affordability and air pollution.

Table 1a Summary on energy system models

| Country | Spatial detail | House categories | Residential sector focus | Heating degree days ˚C-Days | Representation of dwelling stock as end-use demand (surface area) |
|---|---|---|---|---|---|
| Kazakhstan | 16 regions (administrative division) | 4 types: uban, rural, detached, multiapartment | Yes | 2700-6500 | Yes. |
| UK | Single region, national | 36 types: Urban, suburban, rural and 12 building types | Yes | 1900-2900 | No. Useful energy, PJ |
| Canada | 11 regions | Detached, attached, apartments, mobile | No | 3000-13000 | No. Useful energy, PJ |
| China | 5 climatic zones | Urban, rural | Yes | 400-5200 | Yes |
| US | 9 U.S. Census Regional Division | No | No | 0-11000 | No. Useful energy, PJ |
| Ireland | Single region, national | No | Yes (non-ETS sectors) | 2900 | No. Useful energy, PJ |
| Denmark | 2 regions | Single-family, multifamily; Age: before 1972, after 1972, new. 3 district heating areas | Yes (heat pumps) | 3400 | Yes. |
| Germany | Single region, national | 48 classes | Yes (load management) | 3300 | No. Heat demand from building stock model |
| Portugal | Single region, national | 12 types: Single, Multi-Apartment; North, South | Yes | 1400 | Yes |
| Bhutan | Single region, national | No | Yes (cooking) | N/A | No. Useful energy. |

Table 2b Summary on energy system models

| Country | Energy efficiency measures | Analysis of energy poverty[1] | GHG and local pollutants | Reference |
|---|---|---|---|---|
| Kazakhstan | Yes | Partly, unmet demand, price analysis, urban-rural | GHG and local pollutants | This study |
| UK | 17 measures | No | GHG | Dodds (2014) |
| Canada | No | No | GHG | Vaillancourt et al. (2014) |
| China | Exogenously defined building insulation standard | No. Assumption on heating habits: 100% in cold zones and 50% in warmer zones | GHG | Shi et al. (2016) |
| US | No | No | GHG and local pollutants | EPA (2013) |
| Ireland | Yes | No | GHG | Chiodi et al. (2013) |
| Denmark | Yes | No | $CO_2$ | Petrović, S. N., Karlsson, K.B. (2016) |
| Germany | 45 measures | No | $CO_2$ | Fehrenbach et al. (2014) |
| Portugal | Yes | Partly, behavior, thermal comfort | GHG | Gouveia et al. (2012) |
| Bhutan | No | No | GHG and local pollutants | Yangka and Diesendorf (2016) |

As can be seen from the Table 1, previous studies did not consider energy poverty, energy affordability and local pollution along with energy transition pathways, and they mostly do not incorporate simultaneous spatial, building type and urban/rural detail. Bhattacharyya and Timilsina (2010) reviewed the suitability of energy system models for developing countries and stressed the need for better characterization of urban/rural division and spatial distribution in the models in order to properly account for the challenges present in developing countries. This investigation aims to address this gap, by introducing the first sub-nationally

[1] Partially or fully meeting “unmet” demand (thermal comfort), analysis of urban and rural differences, analysis of energy affordability

disaggregated energy system model with regional detail, representation of the building types (detached, flat) urban/rural disaggregation, and analysis of energy poverty.

# 3. Methodology

## 3.1 Addressing the data gaps and taking stock on existing situation

### 3.1.1 Energy Balances

#### 3.1.1.1 Introduction

Energy system models require disaggregated information on the entire energy system, from the supply, to transformation to end-use. However, there is the significant uncertainty in energy consumption data, particularly in developing countries. Misleading information on the energy system and, as a consequence, incorrect modeling results and planning can lead to wrong decisions and to large costs, supply disruptions, and environmental consequences as a result (Bhattacharyya and Timilsina, 2010). Recognizing the importance of the energy in world development and the role of reliable data in modelling energy systems, the International Energy Agency (hereinafter IEA) has developed tools and methodologies for the improvement of energy statistics and reporting energy information in different countries in a single format. Kazakhstan’s national statistics on energy are not harmonised with international standards (Eurostat, 1998; IEA, 2007a) in terms of statistical forms, format of presentation, units and level of disaggregation (Radulov, 2013; Kerimray et al., 2015a). As a result, there are significant issues with GHG inventory reporting to the United Nations Framework Convention on Climate Change (UNFCCC) and with energy balance submission of Kazakhstan to the International Energy Agency’s (IEA). As an example, an inventory review report revealed that within the 2011 Energy Balance for Kazakhstan, total consumption values of coal, oil and natural gas were higher when estimated with reference approach compared with their estimate with sectoral approach by 19, 4 and 19%, respectively, which could lead to underestimation of GHG emissions from stationary combustion (Kerimray et al., 2017c).

Previous studies have not addressed the problems with current energy statistics and have mostly relied solely on energy consumption and GHG data from the UNFCCC and/or IEA (Gómez et al., 2014; Karatayev et al., 2016; Xiong et al., 2015).

This study presents results from in-depth data analysis and compilation along with a detailed review of energy trends. As a result, improved versions of the Energy Balances for Kazakhstan were compiled and cross-checked with additional data provided by the Kazakhstan Electricity Grid Operating Company (KEGOC), the Ministry of Energy of the Republic of Kazakhstan (ME RK), the Information-Analytical Centre of Oil and Gas

(IACOG) and the Committee of Statistics of the Republic of Kazakhstan (CSRK), as part of this study. The results of this study will be useful for academics and modelers of future energy and emission scenarios to cross-check and ensure the reliability of their data.

#### 3.1.1.2 Approach for compilation of energy balances and assumptions

The statistical publication Fuel Energy Balance of Kazakhstan produced annually by the Committee of Statistics of the Republic of Kazakhstan (CSRK) is the only source of information on the entire energy system: fuel and energy production, consumption, and transformation in the country for all economic sectors. Data from this publication is used to provide an inventory of the GHG emissions from the fuel combustion to the UNFCCC and the IEA. However, the energy balances reported by the CSRK do not follow the internationally used formats (Eurostat, 1998; IEA, 2007a).

For example, the CSRK reports do not illustrate commodity flows from production to final use across sectors. The formats used mean that the statistics reported are prone to double counting and the connections between sectors and uses are not immediately clear. The energy consumptions for different types of economic activity are presented in different tables, and most often, the types of economic activities have been grouped differently to the way they are in the IEA format. In addition, the way energy transformation processes are presented does not give a clear indication of fuel inputs and energy outputs. In contrast, the IEA format for illustrating energy balances offers a consistent framework for presenting data on energy use and production for all types of economic activities in a unique table (IEA, 2007a). The format ensures that double counting and/or underestimated consumption of energy is minimized. The IEA format is used worldwide and allows comparable and replicable calculation of energy indicators.

In this study, the energy balances for Kazakhstan from the Committee of Statistics of the Republic of Kazakhstan (Committee of Statistics of the Republic of Kazakhstan, 2016a) have been transferred into the IEA format using the IEA guidelines for energy statistics (IEA, 2007a). The steps taken for energy balance compilation for the period 2005–2014 were as follows (Kerimray et al., 2017c):

i. Comparison of fuels and sectors provided by the CSRK with the IEA definitions and mapping.

ii. Allocation of the data from the main tables and economic activity type tables from the CSRK report to the IEA template and identification of appropriate links between fuels, sectors and uses.
iii. Production of energy balances for each energy commodity in tables that reflect the supply of each energy resource and its consumption in physical units.
iv. Comparison of data from the CSRK with other reliable sources, and, whenever necessary, replacement of the CSRK data in the tables with more reliable data. Investigation of the causes of statistical differences and their elimination. Analysis of the efficiency of oil refineries, coke ovens, blast furnaces, gas processing plants, power generation and heat plants.
    a. Replacement of data for power plants' fuel input and energy generation with data provided by KEGOC and ME RK. Data was disaggregated as necessary by type of plant, e.g. combined heat and power plants (CHP), electricity plants, heat plants, etc.; also, by main activity or auto-producer.
    b. Replacement of data on the production, import and export of coal, oil and gas with data provided by ME RK and IACOG.

Importantly, in this study, data related to the supply side were untouched for most of the commodities, except in cases where data from the IACOG and ME RK were used (Kerimray et al., 2017b). No assumptions were made regarding the supply side; the data were obtained from local sources and assumed to be reliable. Additional information was searched for consumption sectors, if statistical difference occurred. In the energy balance report produced by the CSRK, bituminous coal is represented in one column, without further breakdown to coal classification (e.g. coking coal, other bituminous coal and sub-bituminous coal). In Kazakhstan, the calorific values of different coals can vary by 20–35%. Thus, in this study, bituminous coal was broken down into three categories: coking coal, other bituminous coal and sub-bituminous coal, with different calorific values. The data provided by ME RK for coal production by coal mines was used to determine the quantity of coal supplied for each category. The statistical differences of coal were found to correspond to 2–6% of the total production of coal, depending on the year. It was originally reported that significant amounts of coal and gas were used directly by power plants and heat plants as fuel for their own purposes; these quantities were thus re-allocated as fuel inputs to power plants since other sources (KEGOC, ME RK) had reported higher fuel inputs for these plants. The use of data provided by KEGOC and ME RK significantly improved fuel-energy balance: statistical differences for both coal and gas were reduced, disaggregation by power plants was improved, and the generation efficiencies of power and heat plants in the revised calculations became more consistent with expected values.

The Energy Balances produced by the CSRK reported losses of bituminous coal of the order of 1100– 3841 kt over the period 2007–2013. According to the instructions for respondents for the CSRK's statistical forms, these should include losses related to coal preparation, the coking industry, coal briquette production, storage and transportation, and 'non-delivery'. However, such high values of coal cannot be lost in abovementioned processes. Therefore, the quantities of coal reported as lost were redistributed to:

i. Heat plants: coal inputs were increased by taking into account heat outputs (known value) and efficiencies (around 70–80%). The efficiencies of Kazakhstan's heat plants are reported in: 'Concept of the Development of Fuel-energy Complex of the Republic of Kazakhstan by 2030' (Government of the Republic of Kazakhstan, 2014).
ii. The residential sector: quantities reallocated to the residential sector were based on the results of two surveys on household living conditions (as described below).
iii. The commercial and public services sector: the remainder of the lost coal was allocated to this sector to reduce statistical differences to 0. The allocated value varied between 0 (2006–2008) and a maximum of 335 thousand tons of oil equivalent (ktoe) in 2011. These amounts correspond to 0–6% of the total commercial and public sector energy consumption. For this sector, there is a lack of information required to verify energy consumption values.

The assumptions regarding the additional allocation of coal and biomass to the residential sector were based on the results of two surveys on household living conditions: the 'Quarterly Budget Survey of Households' and the 'Annual Household Survey' which cover 12,000 households in Kazakhstan (Kerimray et al., 2016a). These surveys were both administered by the CSRK. Households were selected by random sampling based on data from a Population Census following the 'Methodology for Constructing a Sample of Households on the Survey of Households Living Conditions' (Committee of Statistics of the Republic of Kazakhstan 2015a). The households selected were considered to be representative at both national and regional level. The surveys covered all 16 administrative regions in Kazakhstan and the number of households varied between 0.1 and 0.5% of the total in each region. Fifty-two per cent of the households surveyed were urban, and the remaining 48% were rural. The survey results show that 40% of the households surveyed use coal and 25% use firewood. Coal and biomass consumptions in the residential sector were thus estimated from data for coal and biomass expenditure (from the Household Survey) and prices. The estimates calculated indicate that in the CSRK's energy balance, the consumption of coal and biomass are potentially underestimated. Biomass was additionally added to the supply and residential sector end-use. Coal was added to residential sector from the statistical differences. In addition, the survey indicated that very few households used oil products (Kerimray et al., 2016a). In this regard, values of oil products in the residential sector in the energy balances were allocated to the transport sector. The statistical publication: 'Housing and Utilities Sector' published by Committee of Statistics of the Republic of Kazakhstan (2015b) contains data for the gas supplied to the population as reported by gas supply companies. The gas consumption reported for the residential sector was higher in the 'Housing and Utilities Sector' publication than in CSRK's energy balance. Due to remaining amounts of gas in the statistical differences, higher value for residential consumption (from the 'Housing and Utilities Sector' Publication) was taken.

#### 3.1.1.3 Analysing energy consumption trends

The energy consumption trends in Kazakhstan are closely linked to the economic development of the country (correlation coefficient between TPES and GDP for the period 2000–2014 was 0.97). Between 2000 and 2007, the country's economy experienced a rapid recovery mainly due to oil revenues: the average annual growth rate of GDP was 10%. TPES also grew steadily with an average of 7% per annum in the same period (Kerimray et al., 2017c). During 2008 and 2009, the growth of the economy slowed to 1–3% due to the world's economic crisis. In 2009, TPES fell by 9% with the largest reductions in energy usage of final consumption sectors corresponding to the transport, commercial and public and industry sectors. Because of the country's dependency on oil exports, in 2014 Kazakhstan experienced another financial crisis due to falling oil prices and a reduction in export volumes. The country's currency was later devalued by 82% in 2015, and the IMF (2015) revised its predictions for the GDP growth of Kazakhstan to 1.5% in 2015, 2.4% in 2016 and around 4% in 2020. The effect of this crisis on energy consumption in 2014 can be observed in the data for the industry and transport sectors. The highest energy consumption growth during the period from 2000 to 2014 was observed in the commercial and public sector, which grew by a factor of 3.72. This was followed by the transport (factor of 2.34) and residential (factor of 2.15) sectors. Industrial energy consumption has only grown by a factor of 1.61, and consumption in the agricultural sector has remained relatively stable.

In terms of the types of fuel and energy used, coal is dominant in TPES, although its share fell from 63% in 2000 to 49% in 2014. Coal is mainly consumed by power plants (61%) and heat plants (10%) for electricity and heat generation, respectively, as well as by households (8%) for domestic heating. In contrast, the share of gas increased from 17% in 2000 to 25% in 2014. In TFC sectors oil products dominate, and the share increased from 29 to 32% between 2000 and 2014. This can mainly be attributed to the increasing demand for oil products from road transportation sector. Gas consumption in TFC sectors increased from 1320 ktoe in 2000 to 4960 ktoe in 2014. This is in line with the expansion of gas networks in communities located along the main pipeline in Western and Southern Kazakhstan. District heating consumption remained stable during 2005–2014 (except for 2006). An expansion of the district heating system has not been carried out because the existing system was inherited from the Soviet Union and is old and inefficient (UNDP, 2013).

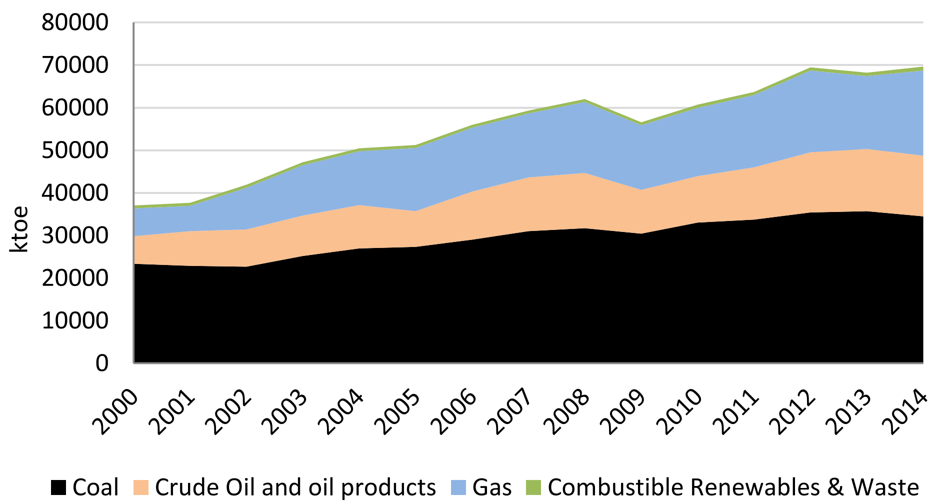
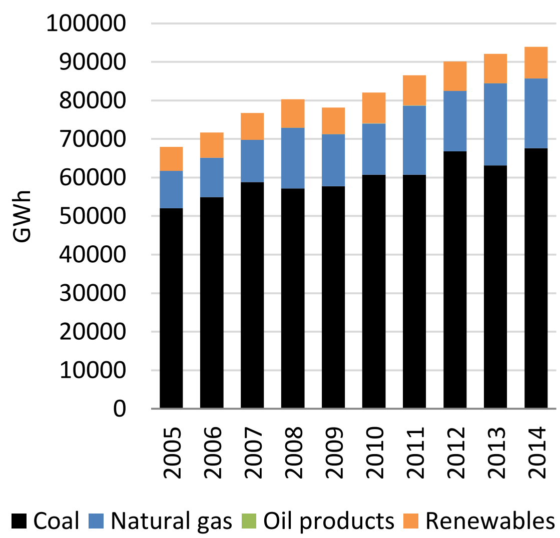



Figure 3 Total Primary Energy Supply (Kerimray et al., 2017c)

In the electricity and heat generation sector, there were no significant changes in the generation mix between 2000 and 2014, and most of the generation facilities installed during the previous century continue to operate (Figure 4). During the period 2000–2014, electricity and heat production rose at average annual growth rates of 5 and 3%, respectively. The share of coal in electricity generation fell slightly from 77% in 2005 to 71% in 2014. In contrast, gas consumption increased by 92% between 2005 and 2014, corresponding to the share in total electricity generation increasing from 14%in 2005 to 20%in 2014. A similar trend is observed in the data for heat generation.



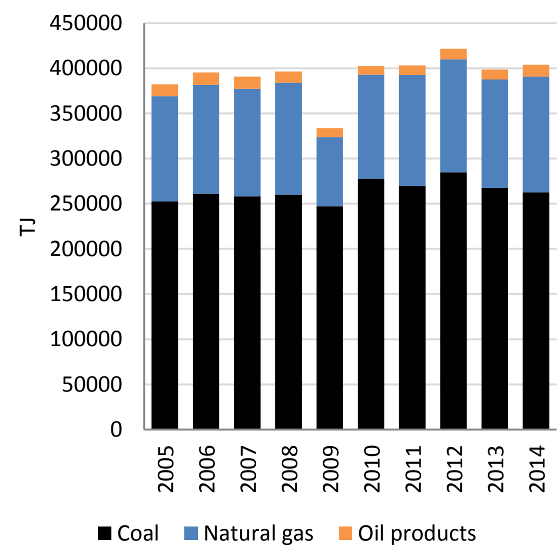




Figure 4 Electricity (left) and heat generation (right) (Kerimray et al., 2017c)

### 3.1.1.4 Conclusions

The paper authors consider this to be the first study to examine energy consumption trends in Kazakhstan for the period 2000–2014. Discrepancies in energy statistics have been reported and the energy balances for Kazakhstan were reconstructed. It was highlighted that there are large discrepancies and issues related to energy consumption data. Allocation of consumed energy to ‘not-specified’/‘other’/‘statistical differences’ introduces uncertainties which affect the monitoring of energy consumption and $CO_2$ emission trends. In this study, an attempt was made to reduce uncertainties in energy consumption by using the energy balance approach, which aims to match supply with total consumption. Additional sources of information to those used by the CSRK were employed in this study, but a number of assumptions and simplifications were still required due to a lack of information for some sectors (commercial and public sector, transport, and energy transformation processes).

The extension of gas pipeline networks to local communities has had an effect on energy usages: between2000 and 2014 the TPES of gas increased by a factor of2.15, and gas is replacing coal across almost all sectors of the economy (except agriculture and transport). However, coal continues to dominate in TPES (49% in 2014)and remains the main source of fuel for electricity (71%)and heat generation (65%) in the country. Kazakhstan has introduced a number of policies and measures domestically over the last 5–7 years to promote penetration of renewable energies and to improve energy efficiencies. However, energy consumption trend analysis has shown that changes in the energy mix are slow: renewable energy penetration is still low and there were no significant energy intensity reductions for any sectors between 2010 and 2014 (except for power and heat).

### 3.1.2 Exploring incidence of energy poverty based on data from Households Survey

#### 3.1.2.1 Background

Fuel poverty is the most commonly accepted term throughout the industrialized world to describe the inability of a household to afford basic standards of heat, power and light (Liddell et al., 2012). In developing nations however, lack of access to clean and commercial fuels is considered to indicate energy poverty (IEA, 2010). In Kazakhstan however, both terms may be applicable. In addition, Kazakhstan has a particular situation due to its resources availability, fast and uneven regional economic development, climatic conditions and large distances. There have been studies on energy poverty in post-socialist states of Eastern and Central Europe in terms of thermal comfort in houses (Buzar, 2007; Petrova, 2013) and causes of energy poverty in houses connected to district heating (Tirado Herrero and Ürge-Vorsatz, 2012), energy poverty across different demographic and income groups in the case of Hungary (Bouzarovski et al., 2016). Birol (2007) highlighted that energy poverty remains poorly researched in developing countries. Energy poverty has not been assessed and quantified for countries in transition located in Central Asia and Russia apart from preliminary estimates of energy poverty indicators in Kazakhstan among coal consumers (Atakhanova and Howie, 2013) and on the impact of district heating and natural gas network access on energy poverty (Kerimray et al., 2016a). In addition, the determinants of fuel choice and causes of energy poverty in Kazakhstan remain as an insufficiently researched area. Indeed, there is very limited understanding of the households' access to energy, energy affordability and of the linkage with household income, energy expenditure and fuel prices in the country. This knowledge gap makes it very difficult to plan policies on energy poverty alleviation, reform of tariffs, building retrofits, energy infrastructure development and reduction of indoor air pollution from solid fuel use, to name a few. This study addresses this knowledge gap.

This study presents the first comprehensive overview of households fuel use in the regions of Kazakhstan and reports causes and the extent of energy poverty based on Households Living Conditions Survey and Households Budget Survey dataset of 12000 households. Due to the large distances and uneven economic, infrastructure development and climatic conditions across the country, this study stresses the analysis of energy poverty by highlighting the differences among regions. It examines the link between household's access to clean fuels, energy affordability, fuel prices and household income in the regions of Kazakhstan.

#### 3.1.2.2 Energy poverty: metrics and quantification

The first concepts of fuel poverty were developed since late 1970s, from one of the first definitions by Isherwood and Hancock (1979) and with a more formal definition by Boardman (1991) which laid the foundations for many of the policy developments in later years. Isherwood and Hancock (1979) defined "households with high fuel expenditure as those spending more than twice the median (i.e. 12%) on fuel, light and power". For the first time 10% threshold was proposed by Boardman (1991): "[Fuel poor households] are unable to obtain an adequate level of energy services, particularly warmth, for 10 per cent of its income". Later, this indicator has been criticized for misrepresenting the trends and encompassing households that are not poor (Hills, 2012). Hills (2012) proposed "Low income, high costs" indicator of fuel poverty, according to which "households are considered fuel poor if they have required fuel costs that are above the median level and were to spend that amount they would be left with a residual income below the official poverty line". "Low income, high costs" definition was officially adopted in the United Kingdom.

Despite criticism over definition of energy poverty based on certain share of income spent on energy, it is still widely used as an official definition in some members of the European Unions, such Cyprus, Ireland, Italy, Slovakia (Pye et al., 2015). In Ireland for example, households are deemed to be experiencing fuel poverty if their annual energy bill exceeds 10% of household income (Pye et al., 2015). Eurostat collects following statistics as a proxy of energy poverty: households living in dwellings with leakages and damp walls, having arrears in accounts, unable to keep the home adequately warm or comfortable cool (Eurostat, 2014). However, the metrics used by Eurostat cannot be applied for Kazakhstan due to absence of data and Households Survey.

IEA (2010) defines energy poverty as the lack of access to clean and commercial fuels, efficient equipment and electricity and a high dependence on traditional biomass. There is a distinction drawn between definitions of energy poverty and fuel poverty since fuel poverty covers energy affordability and mostly occurs in relatively wealthy countries with cold climates, while energy poverty covers energy availability and occurs mostly in poor countries across all climates (Li et al., 2014). As an example, in China energy poverty was associated with solid fuel use (Tang and Liao, 2014). In the case of Kazakhstan both energy affordability and access to clean fuels aspects are important.

This research applies three metrics to estimate the current level of energy poverty in the country: i) 10% threshold of household income spent on energy (10% of income) ii) Hills' "Low income, high costs" (LIHC) metric and iii) IEA's lack of access to clean fuels (here the level of solid fuel dependence is used as a proxy).

With the third indicator "lack of access to clean fuels", households using coal were assumed not to have access to clean fuels and hence, be energy poor. Thus, households which used coal, regardless of the other fuels used additionally, were selected. Coal is used for any types of end-use: cooking, heating and other as the Households Survey used in this study do not differentiate the end-use of fuels and energy.

Three indicators of energy poverty were applied independently because they consider different aspects of energy poverty and use different approaches. Not all the households which have energy affordability problem may have also problem with lack of access to clean fuels and vice versa. Although, some discussion on energy poor with energy affordability and lack of access to clean fuels indicators is also present. All household energy commodities (heating fuels, LPG, electricity) were included in the estimate of total energy expenditure. Pye et al. (2015) highlighted the importance of reflecting total expenditure on energy, including electricity.

In this study "energy poverty" wording is applied for results to avoid confusion on differences between energy and fuel poverty. To distinguish energy poverty results obtained with different metrics, the clarification is provided whenever it is mentioned, such as energy poverty with "10% of income", with "lack of access to clean fuels" or with "LIHC" indicators. Due to data limitation, this investigation does not estimate the number of households that are not able to provide sufficient warmth in their homes (according to WHO recommendations).

#### 3.1.2.3 Households survey

*Household characteristics and dwelling information*

The key household characteristics from the survey observations were compared with the Population Census results conducted in 2009 (Committee of Statistics of the Republic of

Kazakhstan, 2009). Urban households represent 52% of total observations in the survey and 61% in the Population Census. The average number of persons per household is 3.6 according to the Population Census and 3.2 according to the survey.

Table 1 presents the profile of household characteristics. Average household income and total expenditure (for all household needs, including energy) in rural areas is 18%-19% lower than in urban zones. In rural areas, 70% of households live in detached houses, compared with 78% of families in urban areas living in apartments. The average living space in rural households is notably higher than in urban living spaces: 40m$^2$ in urban and 54m$^2$ in rural households.

Table 3 Profile of households characteristics: results from households survey in Kazakhstan in 2013. Survey based on 6210 urban and 5790 rural households (12000 in total).

| Profile of households characteristics | Unit | Average (Standard Deviation) | | |
|---|---|---|---|---|
| | | Total | Urban | Rural |
| Average Households size | Number of persons | 3.20 (1.57) | 4.00 (1.85) | 3.60 (1.75) |
| Average Annual Income | 1000 tenge | 1415 (841) | 1551.65 (933) | 1269 (700) |
| Average Annual Expenditure | 1000 tenge | 610.78 (408.34) | 671.62 (439) | 543.44 (361.14) |
| Average living space | m$^2$ | 46.67 (23.43) | 40.22 (20.35) | 53.60 (24.52) |

Regarding household age, the majority (80%) of surveyed households live in dwellings constructed during the Soviet Union era (i.e. before 1991), with 48% of those constructed between 1970 and 1985 (Fig. 2a). This is explained by massive construction of “standard” modular buildings in the Soviet Union during the period from 1959 to 1985. In general, rural dwelling are slightly older compared to urban dwellings. The majority of the surveyed households (94%) are owned by the occupant, with 5% being occupied by tenants and 1% owned by government authorities or other legal entities.

#### 3.1.2.4 Results of energy poverty

Despite low energy prices in Kazakhstan and energy resources availability, the results demonstrate that energy affordability aspect is an issue. Applying “10% of income” indicator depicted that 28% of surveyed households are energy poor (Figure 5). The highest share of energy poor (10% of income) population was found to be in coal dependent North and Central Kazakhstan: 62% of households in Akmola, 53% in North Kazakhstan and 51% in Kostanay regions. By contrast, energy poverty (10% of income) is much less prevalent in oil and gas rich regions: 1% in Atyrau and Mangistau and 8% in West Kazakhstan regions. This is explained by combination of low gas prices and hence low expenditures for gas, as well as higher income levels in those regions. In average, households spend 8% of their income on energy; i.e., 10% and 7% in rural and urban households, respectively.

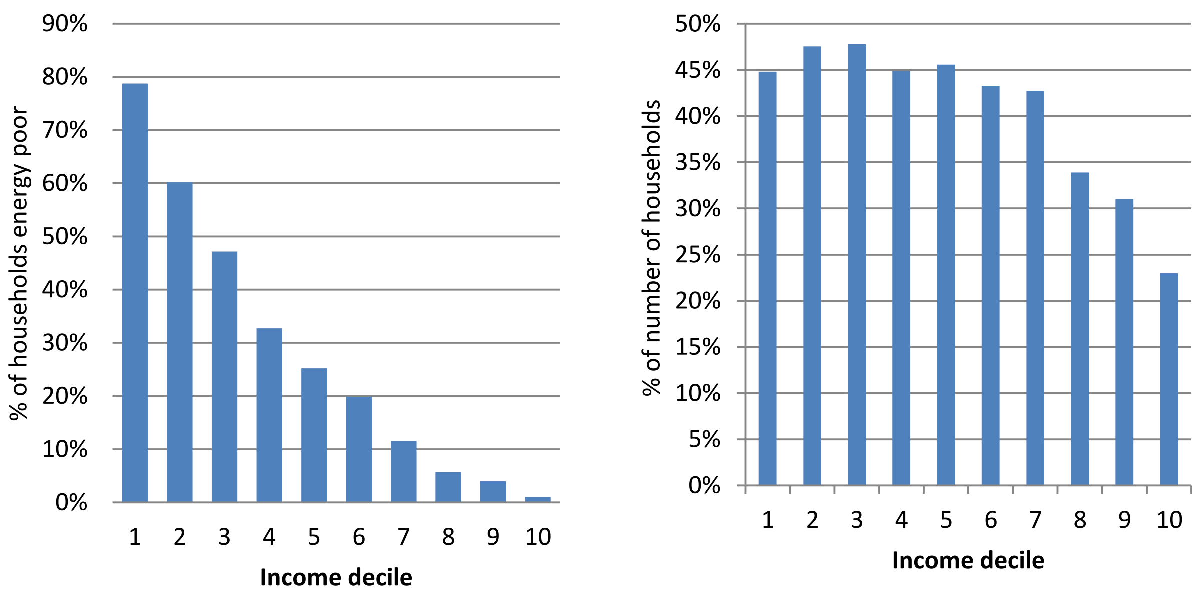



Figure 5 Share of households experiencing energy poverty in 2013 with a) “10% of income” indicator (left) and b) “lack of access to clean fuels” (right) by income deciles

LIHC energy poverty metric was applied by filtering households that spend on energy (including electricity) more than median level (82522 tenge per annum), and the income of which was below official poverty line adopted in Kazakhstan. The official poverty line in Kazakhstan is defined as 40% of minimum living wage, which comes to annual income of households of 288721 tenge[2]. The results, shown per regions in Figure 6, demonstrate that only 1% of surveyed households are energy poor according to LIHC metrics. Few number of households falling into income poverty threshold can demonstrate that low income level is not the most contributing factor to the energy poverty in Kazakhstan. All households, which are determined to be energy poor with “LIHC” indicator spend more than 10% of their income on

[2]Minimum living wage is 18797 tenge

energy, with an average 35% of share of income spend on energy. Majority (77%) of energy poor households with "LIHC indicator" use coal.

One of the factors of such low energy poverty rate could be the relatively low official poverty line in Kazakhstan (1203 UK pounds per annum). While, for example, in the UK official poverty line was 12212 UK pounds (per annum), the fuel poverty under LIHC was estimated at the level of 10.4% (Department of Energy and Climate Change, 2015). There is a clear understanding that poverty line cannot be a universal value since every country has its own level of social subsidies and remedies for low-income families´ subsistence needs.

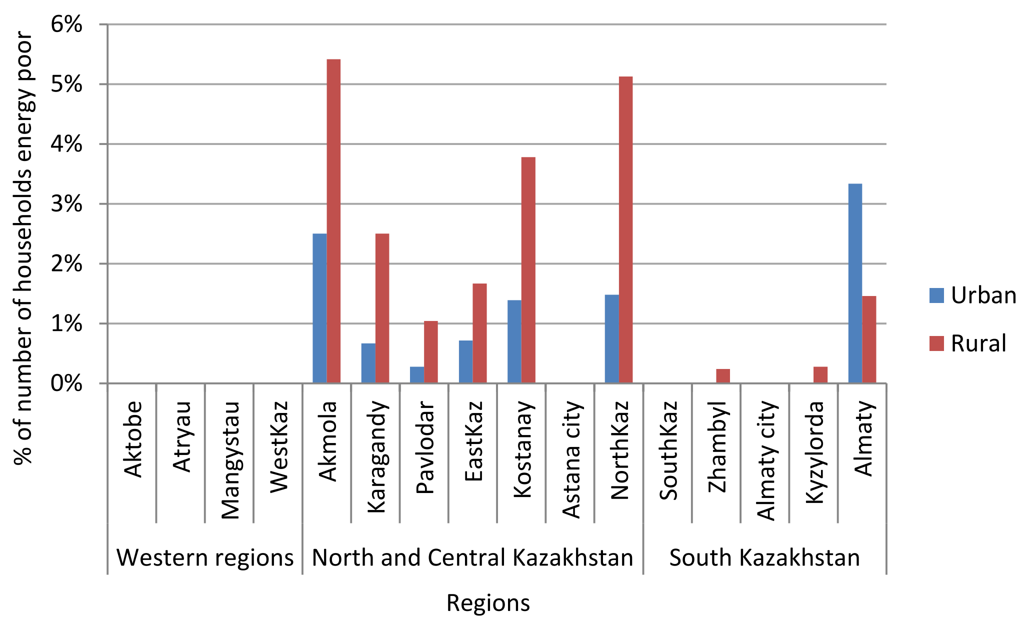



Figure 6 Share of total number of households in Kazakhstan experiencing energy poverty with LIHC indicator

Solid fuel generated particulate matter (PM) is associated with an increased risk of several health outcomes, such as acute lower respiratory infections) in children, chronic obstructive pulmonary disease, chronic bronchitis and lung cancer (WHO, 2004). The cases of deaths due to carbon monoxide poisoning in households in Kazakhstan are reported periodically during winter time in the local media, though there are no official statistics and studies on such a mortality and morbidity. The World Health Organization in its Country Profiles of Environmental Burden of Disease estimates that 9% of households use solid fuels in Kazakhstan (WHO, 2015). Comparing with 40% shown in this study, it is concluded that

WHO underestimates health effects associated to indoor air pollution in Kazakhstan. The WHO used population using solid fuels for cooking as a proxy for households air pollution in its Global Burden of Disease due to the difficulties in obtaining “nationally representative samples of indoor concentrations of criteria pollutants, such as PM and carbon monoxide”. Solid fuels for space heating were not accounted by WHO due to the absence of routinely conducted surveys on space heating (Bonjour et al, 2013). Due to this limitation, assessment of WHO on disease burden from households air pollution for the countries with high solid fuels for heating may be potentially underestimated. Future studies are needed in this regard with measurements of indoor air quality, stove combustion efficiency and room ventilation in households of Kazakhstan.

In terms of urban-rural differences (Fig.10) in energy poverty, the results demonstrate that energy poverty is prevalent in rural households with 68% of energy poor being in rural areas with “10% of income” and 77% with “lack of access to clean fuels”.

#### 3.1.2.5 Conclusions on energy poverty

This study, to the best of our knowledge, presents first comprehensive overview of households fuel use in Kazakhstan and reports causes and the extent of energy poverty based on Households Living Conditions Survey dataset of 12,000 households. It examines the link between household access to clean fuels, energy affordability, fuel prices and households income in the regions of Kazakhstan. This study applies three metrics of energy poverty: i) 10% threshold of household income spent on energy (10% of income) ii) Low income, high cost (LIHC) and iii) IEA’s lack of access to clean fuels (here the level of solid fuel dependence is used as a proxy). Finally, the current policies were evaluated and future policies were suggested.

The choice of energy poverty metrics to Kazakhstan was predetermined by data availability. The use of three indicators has resulted in varying levels of energy poverty: 40% with “lack of access to clean fuels”, 28% with “10% of income” and 1% with “LIHC” indicator. This demonstrates the complexity of energy poverty problem and different aspects leading to energy poverty problem. There is a clear understanding that energy poverty threshold cannot be a universal value since every country has its own factors for energy poverty and different thresholds for income poverty. As in case of Kazakhstan high heating needs due to climatic conditions, low coverage with gas and district heating infrastructure and regional inequalities are predominant factors. High income poverty rates was not the most important factor for energy poverty, as only few households were falling into the official poverty line as demonstrated by LIHC indicator. Further research on thermal comfort in the houses, building insulation and development of “composite” energy poverty metrics is ongoing with the aim to provide further insights about the issue.

The survey results showed large disparities in fuel uses, households income, fuel prices and energy affordability between regions of Kazakhstan. Energy prices differ considerably from region to regions due to the high distances and additional transportation and distribution costs. Households located in North Kazakhstan, Central and East Kazakhstan (except for Astana city) mainly suffer from lack of cleaner fuel options, income poverty, longer and colder winters as well as energy affordability. Providing network gas to these regions will improve the access to cleaner alternative, but high gas prices may worsen the affordability aspect. In this regard, the gas network expansion should be accompanied with energy-efficiency targeted intervention, improvement of economic condition of the region and reduction of income poverty in those regions.

## 3.2 Energy system models

### 3.2.1 Introduction

Modeling has been a tool for national energy planning since the mid-1970s and at that time it was used to understand the implications and means of coping with the first oil embargo (Nakata, 2004). There are a large number of examples of the impact of energy models on public decision-making, such as the UK and Ireland energy systems models, which have had a huge impact on climate change and renewable energy policies in these countries (Chiodi et al., 2015). Energy system models are widely applied to aid decision making in energy planning and to estimate the impact of the introduction of technologies (Nakata et al, 2011).

Energy system models are mathematical representation of the energy flows and technologies of the system, capable of studying quantitatively various options for development of the system. Long-term energy system model define investments, operation modes of the energy system, production and consumption of various goods (fuel, materials, energy services) and their prices in such a way that production is exactly equal to consumption. The main advantage of such models is that these models provide an exhaustive description of possible scenarios for development of the energy system by considering inter-temporal, inter-regional and inter-sectoral relations.

### 3.2.2 Comparison of energy system models

Energy system models can be grouped by modelling approach (top-down and bottom-up), methodology (partial equilibrium, general equilibrium or hybrid), modelling technology (optimisation, econometric and accounting) and the spatial dimension (national, regional and global) (Nakata, 2004). The bottom-up accounting type of framework has an advantage of flexibility and limited skill requirement, however this is unable to analyse price-induced effects and technology coverage is predefined. Top-down econometric models are capable of analysing price-induced effects, but have limited technology coverage. Bottom-up optimisation models have extensive technology coverage, high level of disaggregation, high data need and they are capable of analyzing price-induced effects. Table 3 below provides comparison of models by modelling approaches (Bhattacharyya and Timilsina, 2010).

Table 4 Comparison of models by modelling approaches (Bhattacharyya and Timilsina, 2010)

| Criteria | Bottom-up, optimisation | Bottom-up, accounting | Top-down, econometric | Hybrid | Electricity planning |
|---|---|---|---|---|---|
| Geographical coverage | Local to global, but mostly national | National but can be regional | National | National or global | National |
| Activity coverage | Energy system, environment, trading | Energy system, environment | Energy system, environment | Energy system, environment and energy trading | Electricity system and environment |
| Level of disaggegation | High | High | Varied | High | Not applicable |
| Technology coverage | Extensive | Extensive, but usually per-defined | Variable, but normally limited | Extensive, but usually pre-defined | Extensive |
| Data need | Extensive | Extensive but can work with limited data | High | High to extensive | Extensive |
| Skill requirement | Very high | High | Very high | Very high | Very high |
| Capacity to analyse price-induced policies | High | Does not exist | High | Normally available | Available |
| Capacity to analyse non-price policies | Good | Very good | Very good | Very good | Good |
| Rural energy | Possible but normally limited | Possible | Possible but normally limited | Possible but normally limited | Difficult |
| Informal sector | Difficult | Possible | Difficult | Possible | Difficult |
| Time horizon | Medium to long-term | Medium to long-term | Short, medium or long-term | Medium to long-term | Medium to long-term |
| Computing requirement | High end, requires commercial Linear Programming Solvers | Not demanding | Econometric software required | Could require commercial software | Requires commercial or licensed software |

This study will make use of the TIMES (The Integrate Markal-EFOM System) model generator, which is a widely-applied partial equilibrium, bottom-up, dynamic, linear programming optimization model. According to review of energy system models (Bhattacharyya and Timilsina, 2010, Gargiulo and Ó Gallachóir, 2013), TIMES/MARKAL is one of today’s best known energy system modeling platforms (Table 5).

Table 5 Comparison of bottom-up models (Bhattacharyya and Timilsina, 2010)

| Criteria | RESGEN | EFOM | MARKAL | TIMES | MESAP | LEAP |
|---|---|---|---|---|---|---|
| Approach | Optimisation | Linear Optimisation | Linear Optimisation | Optimisation | Optimisation | Accounting |
| Geographical coverage | Country | Regional and national | Country or multi-country | Local, regional, national or multicountry | National | Local to national to global |
| Activity coverage | Energy system | Energy system | Energy system | Energy system and energy trading | Energy system | Energy system and environment |
| Level of disaggregation | Pre-defined | User defined | User defined | User defined | Pre-defined sector structure | Sector structure predefined |
| Technology coverage | Good | Extensive | Extensive | Extensive | Extensive | Menu of options |
| Data need | Variable, limited to extensive | Extensive | Extensive | Extensive | Extensive | Extensive but can work with limited data |
| Skill requirement | Limited | High | High to very high | Very high | High to very high | Limited |
| Documentation | Limited | Good | Extensive | Good | Good | Extensive |
| Capability to analyses price-induced policies | Exists | Exists | Exists | Exists | Exists | Does not exist |
| Rural energy | Possible | Possible | Possible | Possible | Not known | Possible |
| Informal sector | Not possible | Not possible | Not possible | Not possible | Not possible | Possible |
| New technology addition | Difficult | Possible | Possible | Possible | Possible | Possible |
| Energy shortage | Not explicitly | Not explicitly | Not explicitly | Not explicitly | Not known | Possible explicitly |
| Subsidies | Difficult | Possible but often ignored | Possible but normally ignored | Possible but normally ignored | Not known | Not considered explicilty |
| Rural-urban divide | Possible but not covered usually | Possible but not covered usually | Possible and covered | Possible and covered | Not known | Possible and covered usually |
| Economic transition | Not covered | Not covered | Not covered | Can be covered | Not known | Usually covered through scenarios |

The advantages of TIMES/MARKAL models over other energy system models include its extensive technology coverage, user defined level of disaggregation, and capability to analyze both price and non-price induced policies. One of the disadvantages of TIMES/MARKAL models is the lack of consideration of specific features of developing countries such as informal sector, energy shortage and subsidies. This study aims to fill these gaps of TIMES models as informal sector was accounted properly by using additional data from the Households Survey. "Energy shortage" is also accounted in this study, and it is further described as "unmet demand". Subsidies were also introduced and tested in this study.

### 3.2.3 Methodology of TIMES model

The characteristics of TIMES/MARKAL models have been explained in many publications, as reported by Loulou et al. (2016) and Leo (2015). They are technology-oriented models that require information on technical and economic characteristics of various technologies within the whole energy supply and demand chain. Each model region is driven by a set of demands for energy services in all sectors including: agriculture, residential, commercial, industry and transportation.

Demands for energy services are specified by the user for the reference scenario (business as usual) and includes an own price elasticity for each service. Demand drivers (population, GDP, family units, etc.) are exogenous to the model and obtained externally, via other models or from accepted other sources. Solving the model means finding for each time period the optimal reference energy system by selecting the set of technologies and fuels that maximize the total surplus, which, in the simplest case, is equivalent to minimize the total system cost over the entire planning horizon (i.e. the optimal energy-technology pathways). Thus, the model determines the optimal mix of technologies (capacity and activity) and fuels at each period, the associated emissions, the mining and trading activities, the quantity and prices of all commodities, the equilibrium level of the demands for energy services, all in time series from the base year to the time horizon of the model.

An optimization problem formulation consists of 3 types of entities (Loulou et al., 2016):

**1.1.** *Decision variables*: endogenous quantities, to be determined by the optimisation:

VAR_CAP(r,t,p): new capacity addition (investment) for technology p, in period v and region r.

VAR_RCAP(r,v,t,p): Amount of capacity that is newly retired at period t.

VAR_DRCAP(r,v,t,p,j): Binary variables used in formulating the special early retirement equations

VAR_SCAP(r,v,t,p): Total amount of capacity that has been retired at period t and periods preceding t (see above VAR_RCAP paragraph).

CAP(r,v,t,p): installed capacity of process p, in region r and period t, optionally with vintage v.

VAR_CAP(r,t,p): total installed capacity of technology p, in region r and period t, all vintages together.

VAR_ACT(r,v,t,p,s): activity level of technology p, in region r and period t (optionally vintage v and time-slice s).

VAR_FLO(r,v,t,p,c,s): the quantity of commodity c consumed or produced by process p, in region r and period t (optionally with vintage v and time-slice s).

VAR_SIN(r,v,t,p,c,s)/VAR_SOUT(r,v,t,p,c,s): the quantity of commodity c stored or discharged by storage process p, in time-slice s, period t (optionally with vintage v), and region r.

VAR_IRE(r,v,t,p,c,s,exp) and VAR_IRE(r,v,t,p,c,s,imp): quantity of commodity c (PJ per year) sold (exp) or purchased (imp) by region r through export (resp. import) process p in period t(optionally in time-slice s)

VAR_DEM(r,t,d): demand for end-use energy service d in region r and period t.

Other variables: Several options that have been added to TIMES over the successive versions require the definition of additional variables.

**1.2.** *Objective function*: expressing the criterion to be minimized or maximized. The OBJ is to minimize the total cost of the system, which consists of the following elements: Capital costs, Operation and Maintenance costs, Costs incurred for exogenous imports and domestic resource production, Revenues from exogenous exports, Delivery costs, Taxes and Subsidies, Revenues from recuperation of embedded commodities, Salvage value and Welfare loss.

**1.3.** *Constraints*: equations and inequalities involving the decision variables that must be satisfied by the optimal solution:

i. *Capacity transfer*: The total available capacity is equal to the sum of investments at past and current periods plus capacity in place prior to the horizon (Equation 1 EQ_CPT(r,t,p) –Capacity transfer)

Equation 1 EQ_CPT(r,t,p) –Capacity transfer

*VAR_CAPT(r,t,p)=SUM{over all periods t' preceding ot equal to t such that*

*t-t'<LIFE(r,t'p) of VAR_NCAP(r,t',p)} + RESID(r,t,p)*

where RESID(r,t,p) is the (exogenously provided) capacity of technology p due to investments that were made prior to the initial model period and still exist in region r at time t.

ii. *Activity definition*: Equates an overall activity variable with the appropriate set of flow variables, properly weighted (Equation 2 EQ_ACTFLO (r,v,t,p,s) – Activity definition)

Equation 2 EQ_ACTFLO (r,v,t,p,s) – Activity definition

*VAR_ACT(r,v,r,p,s)= SUM{c in pcg of VAR_FLO(r,v,t,p,c,s)/ACTFLO(r,v,p,c)}*

where ACTFLO(r,v,p,c) is a conversion factor (often equal to 1) from the activity of the process to the flow of a particular commodity.

iii. *Use of capacity*: the activity of the technology may not exceed its available capacity, as specified by a user defined availability factor (AF) (Equation 3EQ_CAPACT (r,v,t,p,s) - Use of capacity)

Equation 3EQ_CAPACT (r,v,t,p,s) - Use of capacity

VAR_ACT(r,v,t,p,s)≤or=

AF(r,v,t,p,s)*PRC_CAPACT(r,p))*FR(r,s)*VAR_CAP(r,v,t,p)

Here PRC_CAPACT(r,p) is the conversion factor between units of capacity and activity (often equal to 1, except for power plants). The FR(r,s)parameter is equal to the (fractional) duration of time-slice s.

iv. *Commodity balance*: The disposition (consumption plus exports) of each commodity balances its procurement (production plus imports).

Equation 4 EQ_COMBAL(r,t,c,s) - Commodity balance

*[Sum {over all p,c ∈TOP(r,p,c,"out") of: [VAR_FLO(r,v,t,p,c,s) + VAR_SOUT(r,v,t,p,c,s)*STG_EFF(r,v,p)] } +*

*Sum {over all p,c ∈RPC_IRE(r,p,c,"imp") of :VAR_IRE(r,t,p,c,s,"imp")}+*

*Sum {over all p of: Release(r,t,p,c)*VAR_NCAP(r,t,p,c)}] * COM_IE(r,t,c,s)*

*≥ or =*

*Sum {over all p,c ∈ TOP(r,p,c,"in") of: VAR_FLO(r,v,t,p,c,s) + VAR_SIN(r,v,t,p,c,s)} +*

*Sum {over all p,c∈ RPC_IRE(r,p,c,"exp")} of: VAR_IRE(r,t,p,c,s,'exp") +*

*Sum {over all p of: Sink(r,t,p,c)*VAR_NCAP(r,t,p,c)} + FR(c,s) *VAR_DEM(c,t)*

where:

The constraint is ≥ for energy forms and = for materials and emissions (unless these defaults are overridden by the user).

TOP(r,p,c,"in/out") identifies that there is an input/output flow of commodity c into/from process p in region r;

RPC_IRE(r,p,c,"imp/exp") identifies that there is an import/export flow into/from region r of commodity c via process p;

STG_EFF(r,v,p) is the efficiency of storage process p;

COM_IE(r,t,c) is the infrastructure efficiency of commodity c;

Release(r,t,p,c) is the amount of commodity c recuperated per unit of capacity of process p dismantled (useful to represent some materials or fuels that are recuperated while dismantling a facility);

Sink(r,t,p,c) is the quantity of commodity c required per unit of new capacity of process p (useful to represent some materials or fuels consumed for the construction of a facility);

FR(s) is the fraction of the year covered by time-slice s (equal to 1 for non- time-sliced commodities).

v. *Efficiency definition*: The ratio of the sum of some of its output flows to the sum of some of its input flows is equal to a constant (efficiency).

Equation 5EQ_PTRANS(r,v,t,p,cg1,cg2,s) –Efficiency definition

*SUM{c in cg2 of : VAR_FLO(r,v,t,p,c,s )}=*

*FLO_FUNC(r,v,cg1,cg2,s) * SUM{c within cg1 of:*

*COEFF(r,v,p,cg1,c,cg2,s)*VAR_FLO(r,v,t,p,c,s)}*

where COEFF(r,v,p,cg1,c,cg2,s) takes into account the harmonization of different time-slice resolution of the flow variables, which have been omitted here for simplicity, as well as commodity-dependent transformation efficiencies.

vi. *Flow share*: Limit the flexibility, by constraining the share of each flow within its own group.

Equation 6 EQ_INSHR(c,cg,p,r,t,s) and EQ_OUTSHR(c,cg,p,r,t,s)

*VAR_FLO(c)≤,≥, =*

*FLO_SHAR(c) * Sum {over all c' in cg of: VAR_FLO(c') }*

The user may then want to limit the flexibility of the slate of outputs by means of three FLO_SHAR(c) coefficients

vii. *Peak*: There must be enough installed capacity to exceed the required capacity in the season with largest demand for commodity by a safety factor (peak reserve).

Equation 7 EQ_PEAK(r,t,c,s) - Commodity peak requirement

*Sum {over all p producing c with c=pcg of PRC_CAPACT(r,p) * Peak(r,v,p,c,s)*

** FR(s) *VAR_CAP(r,v,t,p) * VAR_ACTFLO(r,v,p,c) } +*

*Sum {over all p producing c with c≠pcg of*

*NCAP_PKCNT(r,v,p,c,s) *VAR_FLO(r,v,t,p,c,s)} +VAR_IRE(r,t,p,c,s,i)*

*≥ [1+ COM_PKRSV(r,t,c,s)] * [ Sum {over all p consuming c of*

*VAR_FLO(r,v,t,p,c,s) +VAR_IRE(r,t,p,c,s,e)}]*

COM_PKRSV(r,t,c,s) is the region-specific reserve coefficient for commodity c in time-slice s, which allows for unexpected down time of equipment, for demand at peak, and for uncertain resource availability, and
NCAP_PKCNT(r,v,p,c,s) specifies the fraction of technology p's capacity in a region r for a period t and commodity c (electricity or heat only) that is allowed to contribute to the peak load in slice s;

viii. *User constraints*: impose annual or cumulative bounds on commodities (emissions or reserves of fossil fuels), limit the share of processes in the total production of commodity; limit investment in a process (nuclear capacity), dictate a % of a fuel for electricity generation (renewable sources).

Objective function is expressed by the following equation (Loulou et al., 2016):

Equation 8

$$NPV = \sum_{r=1}^{R} \sum_{y \in YEARS} (1 + d_{r,y})^{REFYR - y} \times ANNCOST(r, y)$$

Where:

NPV - is the net present value of the total cost for all regions (the OBJ);

ANNCOST(r,y) - is the total annual cost in region r and year y;

dr,y - is the general discount rate

REFYR is the reference year for discounting

YEARS is the set of years for which there are costs (in the horizon, plus past and before years EOH;

R - is the set of regions in the area of study.

TIMES is written in a modular fashion employing the General Algebraic Modeling System (GAMS) (Loulou et al., 2016). Solver of the model are CPLEX/XPRESS. VEDA FE and VEDA-BE user interfaces handle model input and output data. VEDA-FE relies totally on templates, a collection of Excel workbooks, for all input data. VEDA-BE is used for the analysis of model results, which relies on sets (both TIMES standard sets as well as user-defined re-grouping sets defined in VEDA-BE), and user-defined tables which present the data as dynamic “cubes” or pivot tables. The model solving process may take from few seconds to several hours depending on the complexity of the model.

The complexity of the energy chains of the country is represented into a bottom-up model making use of the Reference Energy System (RES), a schematic and simplified representation of the reality. Figure below shows the generic RES which is used to describe an energy system.

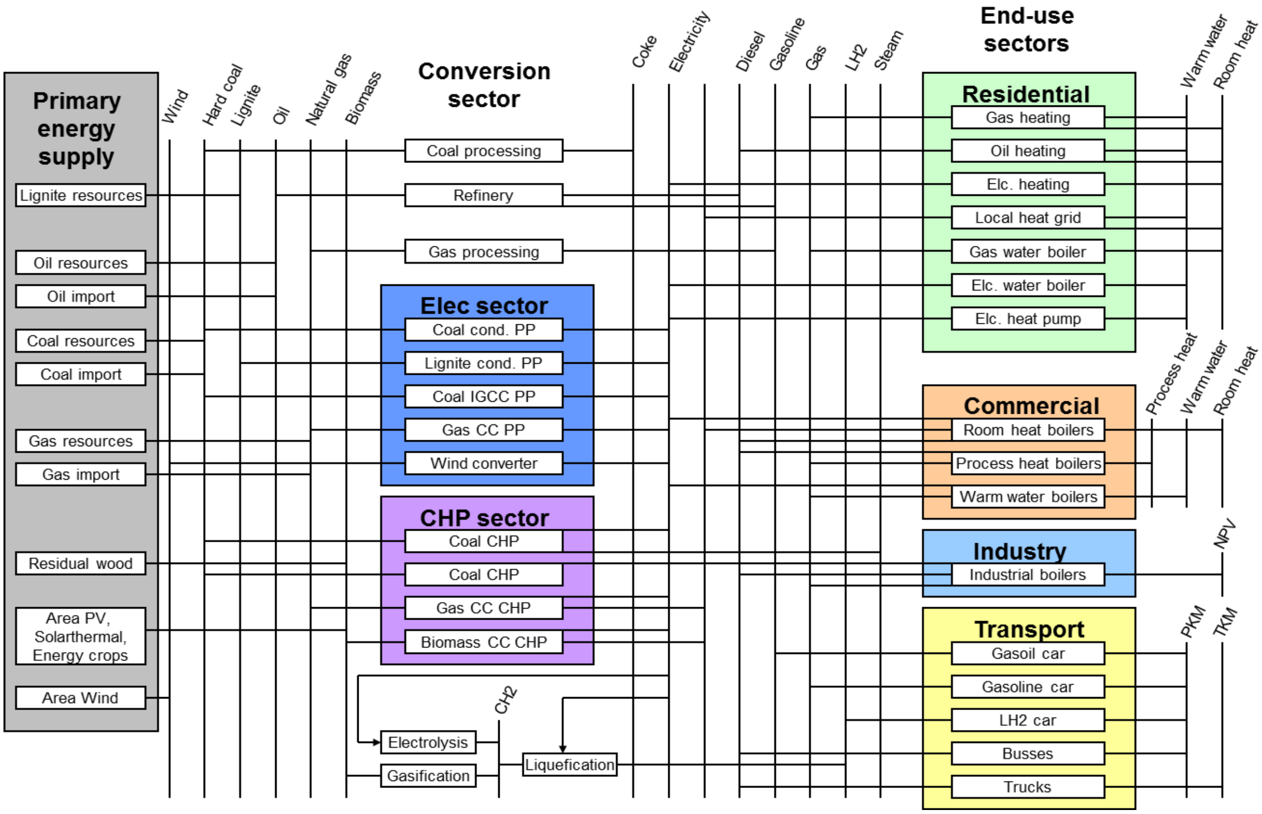



Figure 7 - The Generic Reference Energy System

## 3.3 TIMES-Kazakhstan 16 regions model

### 3.3.1 General formulation

The TIMES-Kazakhstan multi-regional model represents all steps of an energy chain region by region: from the extraction of primary resources to their supply to primary energy markets, from the transformation of primary energy carriers to their transmission and distribution to the final energy-use sectors, from use of final energy commodities to satisfying the end users demand for energy services (Suleimenov et al., 2016). The model for Kazakhstan is calibrated to the year 2011 (base year) with the data provided by the regional Energy balances (adjusted to meet local-specific indicators) (Kerimray et al., 2017b; Kazmaganbetova et al., 2016), as described in section 3.1.

The multiregional model of Kazakhstan is based on sixteen (16) structurally interconnected regional sub-models, which are allowed to trade energy forms through the existing and new "capital intensive" infrastructures (pipelines for crude oil and natural gas), through electrical grids and via land transport (oil products and coal) on the basis of synergic needs of the sub-national systems. Capacities of the existing infrastructures are used to describe the maximum level of "tradable" energy between pairs of regions; new investments are allowed to enable future extra exchanges of resources driven by exogenous plans (e.g. extension of gas network) and/or by endogenous synergies (cost-effective decisions).

The linear programing formulation of the decision problem analysed with the TIMES model for 16 regions of Kazakhstan is shown below. It makes explicit the "cumulative" (all regions) environmental constraint which is used in the framework of this study, as well as the capacity constraints for the energy trades.

Objective function is minimisation of the total system cost of "n" regions (n=16), as shown in Equation 9:

Equation 9

$$\text{Min } C = \Sigma_{j,i} \quad c_{j,i*}\, x_{j,i} + c_{j,i,k*}\, x_{j,i,k}$$

where:

$x_{j,i:}$ level of activity "i", for the energy system of region "j"
$x_{j,i,k:}$ level of activity "i", traded between the regions "j" and "k".

Demand constraints matrix for region "j" (local constraints) is shown in Equation 10:

Equation 10

$D_j * x_{j,i} \geq d_{j,i}$

Technical and market constraints matrix for the region "j" (local constraints) is shown in Equation 11:

Equation 11

$M_j * x_{j,i} \leq p_{j,i}$

Emission constraints matrix for the global system is shown in Equation 12 below:

Equation 12

$\Sigma_j E_j * x_{j,i} \leq e_i$

Capacity constraint for energy exchange "i", between the pair of regions "j" and "k" is shown in Equation 13.

Equation 13

$x_{j,i,k} \leq t_i$

### 3.3.2 System boundaries

The TIMES-Kazakhstan multi-regional model represents all steps of an energy chain region by region as shown in the Figure 7. The breakdown in end-use sectors in the model follows the energy balance detail and there is also further split across the subsectors (and services):

- Resources (primary energy supply)
    - Imports and exports of electricity, crude oil and oil products, natural gas, coal and other energy commodities.
    - Mining/Upstream: Extraction of crude oil (and natural gas liquid), natural gas (non-associated and associated) and coal (four types). This part also includes

the potential of renewable energy sources which is included in detail in the model (both for electricity production and final energy use).

- Fuel processing (conversion sector)
    - Refineries: at this stage of the model development, all the refining installations are represented by a single process which sums the capacities and productions of all the existing refineries. The total capacity of the refinery over the time horizon can be "controlled" by the users, either can be endogenously defined by the optimisation process.
    - Coke oven plants are represented by one process in the supply (upstream) sector.
    - Other secondary transformations as well as the gas pipeline system within the country are also represented.
- Electricity and heat generation
    - The electricity generation system is modelled by aggregating the existing power plants "by type" and "energy form used". Public stock (connected to the power grid) and auto-producers (industry own uses) are also split.
- Residential
    - The residential sector considers the whole dwelling stock of the country and the related needs; the following energy services demands are modelled:
        i. space heating;
        ii. water heating;
        iii. space cooling;
        iv. cooking;
        v. lighting;
        vi. refrigeration and freezing;
        vii. clothes washing;
        viii. dish washing, and
        ix. other electric (which includes TV, computers, equipment, etc).
- Commercial
    - The commercial sector includes the energy-related needs of private and public services (e.g. restaurants and hotels, shopping centres, hospitals, schools, public

offices, and other services; the following energy services demands are modelled:

i. space heating,
ii. water heating,
iii. space cooling,
iv. cooking,
v. lighting (including public lighting),
vi. refrigeration and freezing,
vii. other electric (which includes computers, equipment, etc.).

- Agriculture
  - Agriculture has no technology explicit representation (in the base year). One single process aims to describe the consumptions of different energy forms for all the agricultural activities.
- Industrial Subsectors
  - Iron and steel
  - Non-ferrous metals: broken down in
    i. aluminium,
    ii. other non-ferrous metal industries
  - Chemical industry
  - Non-metallic minerals:
    i. Cement,
    ii. Other (ceramics)
  - Paper and Printing
  - Food drink and tobacco
  - Construction
  - Mining and Quarrying
  - Other industries
- Transportation: All the transportation modes are included in the model:
  - Generic Freight Electric Train-Existing
  - Generic Passengers Train-Existing
  - Road transport
  - Two wheel transport

- Light trucks
- Heavy trucks
- Bus
- Domestic Aviation

This study aims to present improved modeling of the residential sector within the entire energy system model. The focus of this study is policies in the residential, therefore scenarios (described in the) cover residential sector only. Although, implications of those policies (scenarios) on the entire energy energy chain is discussed within the energy system modeling framework.

### 3.3.3 Demand for energy services

Demands for energy services are estimated by the model according to the following Equation 14:

Equation 14

$$\text{Demand} = \text{Constant} * \text{Driver}^{\text{Elasticity}}$$

where Elasticity is demand elasticity relatively to the given driver.

The model includes various sectors of demand for energy services (for example, industries, types of transport, household and commercial processes: washing, drying, cooking, heating, hot water supply, lighting, etc.). Each sector of demand corresponds to a specific driver. Elasticities of the demand for energy services to the drivers were inherited from the national model and assumed to be the same across the regions.

Three socio-economic drivers of energy demand were used in the model:
- GRP (Gross Regional Product);
- The population of the region;
- GRP per capita in the region.

### 3.3.4 New technology database

Technology database was inherited from the national (single region) TIMES-Kazakhstan model: the latest updated version by Nazarbayev University Research and Innovation System (Kazakhstan) under the Project funded by Partnership for Market Readiness (2015-2016). There are 59 technologies described for electricity and heat generation (e.g. coal supercritical power plant, IGCC plant, integrated gasification combined cycle plant, gas steam plant, biomass and municipal solid waste plant, wind onshore, wind offshore, nuclear plant, among others). There are 48 and 71 technology options in the residential and commercial, and public sectors, respectively (e.g. coal stove, gas water heater, washing machine, incandescent bulb, heat pump and others). In the transport sector, there are 279 technology options (e.g. LPG, diesel, gasoline, ethanol, fuel cell, light vehicles/buses/light trucks/heavy trucks/, etc.) and in the industry sector there are 38 technology options (standard pulp and paper, improved pulp and paper and others.).

The following technology databases were used for describing new technologies:

- European Commission Joint Research Centre (2014). Energy Technology Reference Indicator projections for 2010-2050. https://setis.ec.europa.eu/system/files/ETRI_2014.pdf
- IEA-ETSAP (2010-2014). E-TechDS – Energy Technology Data Source https://iea-etsap.org/index.php/energy-technology-data/energy-supply-technologies-data
- World Energy Outlook (2014). Energy efficiency in end-uses.http://www.worldenergyoutlook.org/weomodel/investmentcosts/ (cooking, lighting, appliances)
- UK Energy Research Centre University College London (2011). TIAM-UCL Global Model Documentation https://www.ucl.ac.uk/energy-models/models/tiam-ucl/tiam-ucl-manual

### 3.3.6 Gas infrastructure

The capital cost for new gas pipeline infrastructure was estimated using capital costs for recently constructed gas pipeline Beineu-Bozoi-Shymkent (Southern Kazakhstan) and it was estimated at 7mln US$/(TJ*km), which is higher than the cost of Tobol-Kokshetau-Astana (Central Kazakhstan) (6 mln US$/(TJ*km)). Potential gasification routes described in the model include all possible routes ever discussed by the Government to bring gas to non-connected regions in Central Kazakhstan (particularly capital city of Astana):

- “Saryarka” pipeline starting from south of Kazakhstan (Kyzylorda region)
- “Tobol-Kokshetau Astana” pipeline starting in the northern Kazakhstan (Kostanay region)
- “Karachaganak-Astana” pipeline starting in the North West of Kazakhstan (West Kazakhstan region)

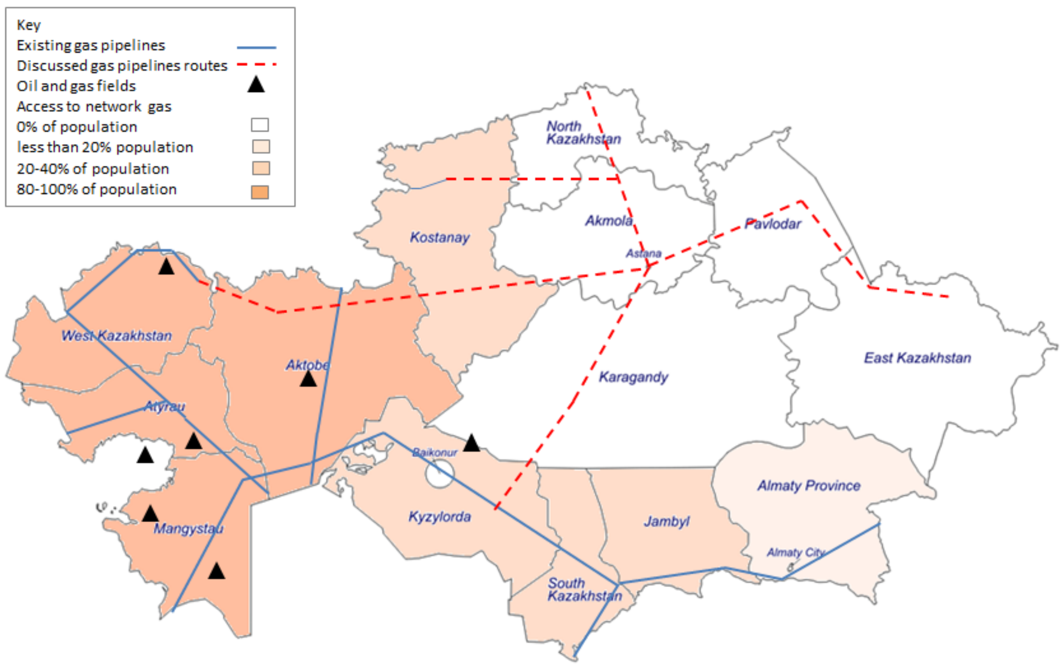



Figure 8 Existing gas pipelines and possible routes for gasification

To cover all regions of Kazakhstan, possibility for investing in the extension of gas pipeline routes (starting from the abovementioned pipelines) further to the North Kazakhstan region, East Kazakhstan, Akmola region and Karaganda region were also described.

## 3.4 Constructing housing stock module

### 3.4.1 Main steps

Housing stock module was constructed using the following steps:

i. Collection of data on surface area of residential buildings by: urban/rural, detached/flat, 16 regions, wall material and building age; estimation of average geometries of buildings by building type based on statistics of surface area and number of constructions by building type published by the Committee of Statistics of the Republic of Kazakhstan (2016b).

ii. Collection and analysis of buildings energy audit reports (Kerimray et al., 2016b), including:
    i. estimation of average heat transfer coefficients of building elements by building types.
    ii. estimation of costs of retrofitting measures.
    iii. heat transfer coefficients of refurbished building elements.
iii. Calculation of the theoretical heating need by building type and by region based on ISO 13790 “Thermal performance of buildings and building components”. Heating-Degree-Days and heating season duration by regions of Kazakhstan was obtained from the Building Code “Energy consumption and thermal protection of buildings” (СН РК 2.04-21-2004).
iv. Assessment of energy saving from retrofitting measures by building type estimated as a difference between the theoretical heating need and heating need after retrofit measure.
v. Comparison of theoretical heating consumption in the base year (2011) with energy statistics on actual energy consumption, assuming occupancy rate and calibrating the model
vi. Representation of dwelling stock by types and energy efficiency measures by types in the model

### 3.4.2 Analysis of housing stock

The share of the surface area by building types is different from region to region in Kazakhstan (Figure 9). As an example, colder climate regions have average share of flats in the dwelling stock of 70%, while it is 42% in the warmer regions.

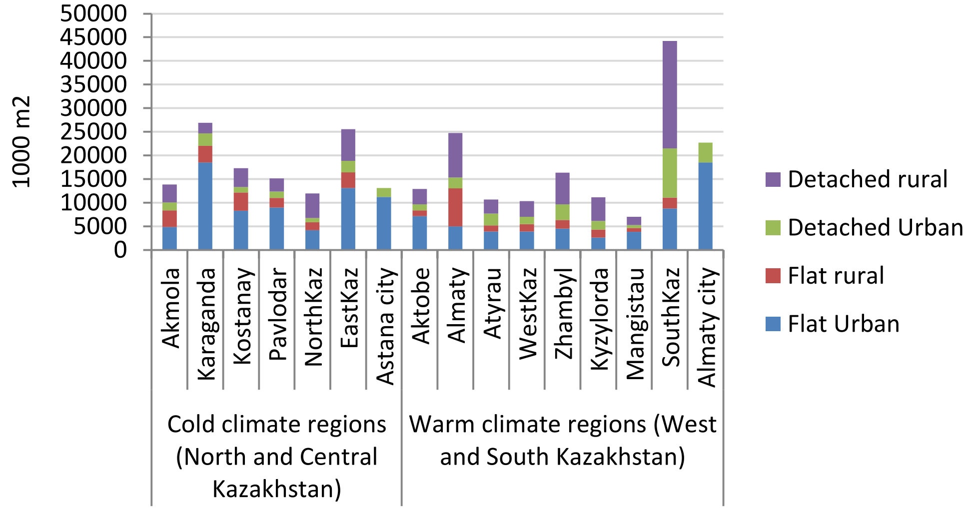



Figure 9Living surface area of residential dwelling stock in Kazakhstan 2011 (base year) (Committee of Statistics of the Republic of Kazakhstan, 2016b)

### 3.4.3 Heat transfer coefficients of building elements

Buildings energy audit reports (586 in total) conducted by accredited energy auditing companies across all regions of Kazakhstan were collected to estimate the heat transfer coefficients of building elements (walls, windows, floors, roofs and doors) by building types. A comparison of the average heat transfer coefficient of building elements between Kazakhstan and Finland (similar climatic conditions) showed that buildings in Kazakhstan have poorer insulation properties. U values for wall, ceiling, floor and windows are presented in the Table 6.

Table 6 Average U values by building age in Kazakhstan and Finland (adapted using data from the building energy audit reports) (Kerimray et al., 2016b)

| U values, $W/m^2K$ | Walls | Ceilings | Floors | Windows | Doors |
|---|---|---|---|---|---|
| Kazakhstan | | | | | |
| before 1969 | 1.01 | 0.70 | 0.64 | 2.32 | 3.55 |
| 1970-1979 | 1.11 | 0.72 | 0.72 | 2.24 | 3.62 |
| 1980-1989 | 1.19 | 0.72 | 0.60 | 2.24 | 3.21 |

| | | | | | |
|---|---|---|---|---|---|
| 1990-1999 | 1.13 | 0.66 | 0.59 | 2.20 | 3.69 |
| 2000-2014 | 1.22 | 0.62 | 0.72 | 1.92 | 1.66 |
| Finland | | | | | |
| before 1969 | 0.56 | 0.38 | 0.45 | 2.2 | N/A |
| 1970-1979 | 0.41 | 0.29 | 0.37 | 2.05 | N/A |
| 1980-1989 | 0.29 | 0.23 | 0.33 | 1.75 | N/A |
| 1990-1999 | 0.28 | 0.22 | 0.32 | 1.75 | N/A |
| 2000-2014 | 0.26 | 0.18 | 0.28 | 1.5 | N/A |

### 3.4.3 Heating need

The heating need calculation methodology follows ISO 13790 "Thermal performance of buildings and building components". The energy need for space heating is calculated according to Equation 15 below:

Equation 15

$$Q_{H,n} = Q_{H,ls} - \eta_{H,gn} \cdot Q_{H,gn}$$

Where $Q_{H,n}$ is the building energy need for heating, in kWh per year; $Q_{H,ls}$ is the total heat transfer for the heating mode, in kWh per year; $Q_{H,gn}$ are the total heat gains for the heating mode, in kWh per year; $\eta_{H,gn}$ is the dimensionless gain utilisation factor. The total heat transfer, $Q_L$, of the building zone for a given calculation period, is given by Equation 16 below:

Equation 16

$$Q_{ls} = Q_{tr} + Q_{ve}$$

$Q_{ls}$ is the total heat transfer, in kWh;
$Q_{tr}$ is the total heat transfer by transmission, in kWh;
$Q_{ve}$ is the total heat transfer by ventilation, in kWh

Input data used for heating need assessment is presented in the Table 7. Reference values for Kazakhstan ENSI EAB (Software for building energy auditors), building energy audit reports and assumptions were used to complete Table 7.

Table 7 Summary of input data for the assessment of energy need for heating

| Parameter | Unit of measurement | Value |
|---|---|---|
| Total solar gain, g | - | 0.5 |
| Infiltration | 1/h | 0.5 |
| Indoor temperature $\theta I,H$ | ˚C | 21 |
| Heating hours | Hours/day | 24 |
| Heat capacity C'm | $Wh/m^2K$ | 72 |
| Lighting operating period | h/week | 84 |
| Average power of lighting | $W/m^2$ | 3.5 |
| Various exploitable equipment operating period | h/week | 72 |
| Various exploitable equipment average power | $W/m^2$ | 2 |
| Metabolic heat from men | W/person | 93 |
| Metabolic heat from women | W/person | 79 |
| Metabolic heat from kids | W/person | 70 |
| Time present indoors for men | h/day | 12 |
| Time present indoors for women | h/day | 24 |
| Time present indoors for kids | h/day | 24 |

The resulting estimated heating need is presented in Figure 10. There are significant variations in heating needs from region to region of Kazakhstan which are determined by differences in climatic conditions (heating-degree-days). Due to the differences in the “Surface Area to Volume Ratio” there are also differences in heating need between flats and detached houses within the same climatic conditions. The highest heating need occurs in detached rural houses in Northern Kazakhstan which require 450-500 $kWh/m^2$ per year. Large variations of heating needs between climatic zones of Kazakhstan and type of buildings construction prove that quantitative assessments, future scenarios and policy actions for technology mix should account for these uneven initial conditions.

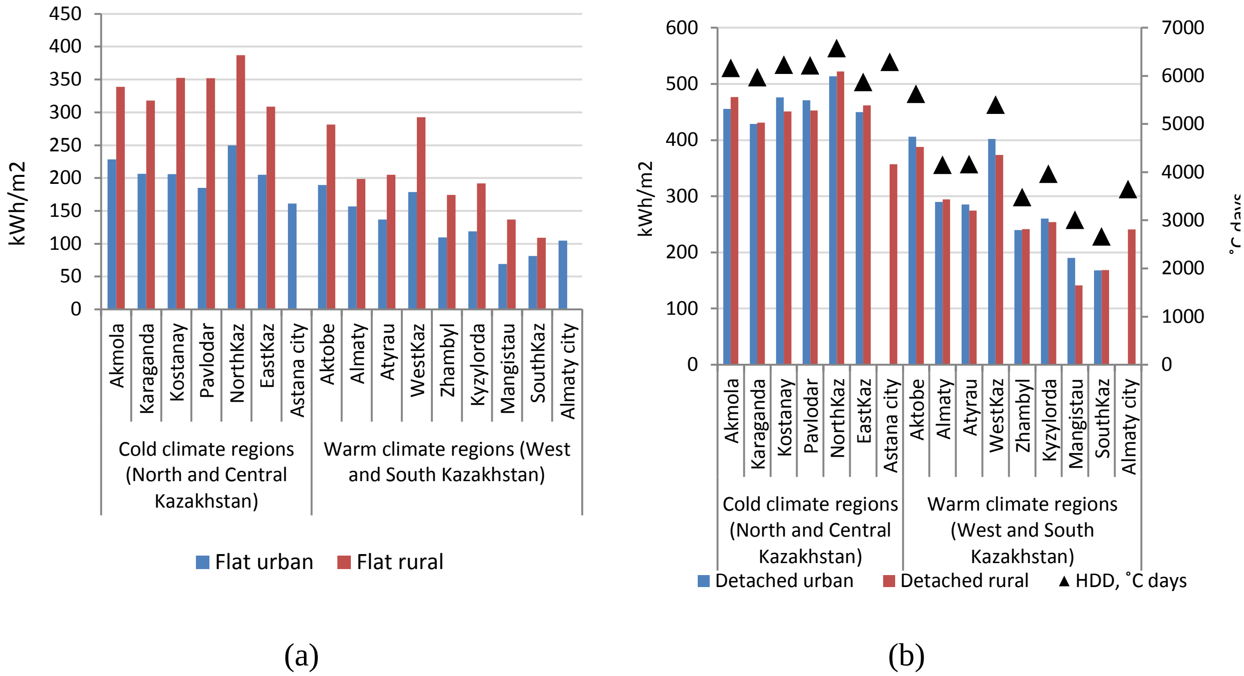



Figure 10 Estimated heating need a) flat (left axis); and b) detached buildings (left axis) and Heating-Degree-Days (right)

### 3.4.4 Retrofitting measures

The retrofitting measures that are represented in the model, with corresponding saving potentials and costs are summarized in Table 8. The data was obtained from the Reference values for Kazakhstan ENSI EAB (Software for building energy auditors) and building energy audit reports.

Table 8 Building envelope retrofit measures (adapted from Kerimray et al, 2016b)

| Measure | Building envelope | | | | |
|---|---|---|---|---|---|
| | New windows | Wall insulation | Ceiling | Floor | Door |
| Short description | Replacement of old windows with new plastic | 50 mm insulation made of polystyrene or mineral wool with the outer layer of plaster | 150 mm cellulose fiber insulation | Insulation made of polystyrene or mineral wool with the outer layer of plaster | Insulated metal door with a door closer |
| U value, $W/m^2K$ | 1.60 | 0.65 | 0.17 | 0.35 | 1.66 |
| Total cost, $US\$/m^2$ (per area of insulated element) | 153 | 19 | 10 | 3 | 420 |

### 3.4.5 "Unmet" demand and occupancy rate

The theoretical heating need is influenced by factors such as households' occupant behavior and equipment utilization. A difference exists between theoretical and actual heating needs as households are not constantly occupied and thereby, not always heated. Even if it is occupied, not all the household area is heated to the same indoor temperature (Gouveia et al., 2012). Due to relatively high energy costs and low incomes, householders may not heat their homes to the sufficient comfort level, resulting in "unmet" demand (energy poverty).

The stock component (occupancy rate) was assumed to be 81% (national average) in the absence of studies on occupancy and indoor temperature. The resulting "unmet" demand (corrected with 81% occupancy rate) was estimated to be 24906 TJ or 13% of total heating need (based on actual data) in the base year 2011. The highest values of "unmet" demand were in coal based regions: North Kazakhstan (32% of theoretical heating need), Akmola (25%) and East Kazakhstan (21%). In the base year heating need was calibrated in accordance with actual heating needs (based on energy statistics), while it was assumed that in all scenarios entire "unmet" demand is satisfied by 2030. Future studies should be conducted to better quantify "unmet demand" based on Households Survey data of thermal comfort, indoor air temperature, behavioral issues. The "unmet demand" and "occupancy" rate values are presented in the Figure 11.

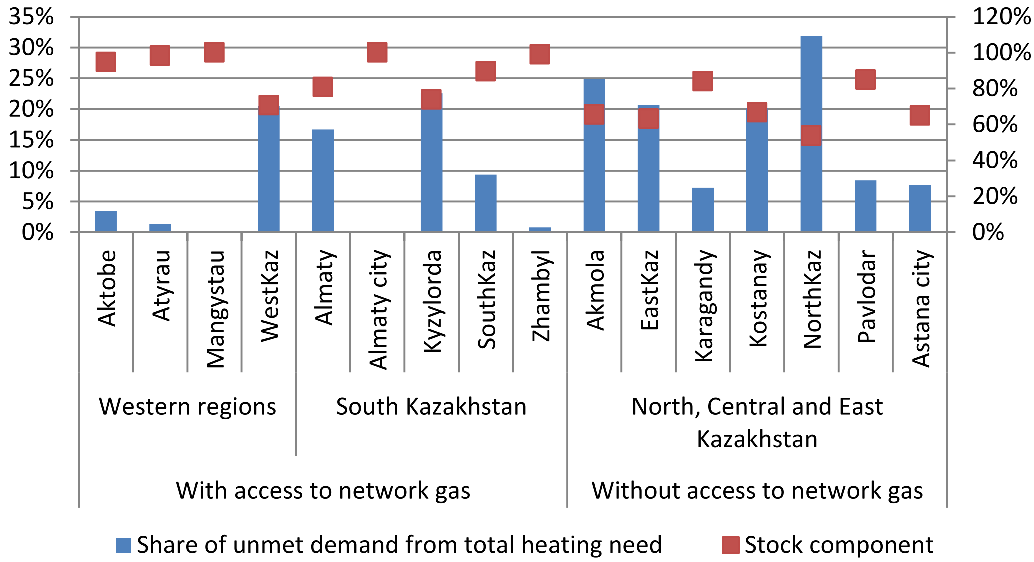



Figure 11 Share of unmet demand to theoretical heating need of the region and assumed stock component.

### 3.4.6 Model representation

The demand for residential heating is represented in this improved TIMES model by heated surface area by 4*3 types: flat/detached, urban/rural, and new/existing/passive (Figure 12). New buildings and passive houses have different heating needs compared to existing dwellings.

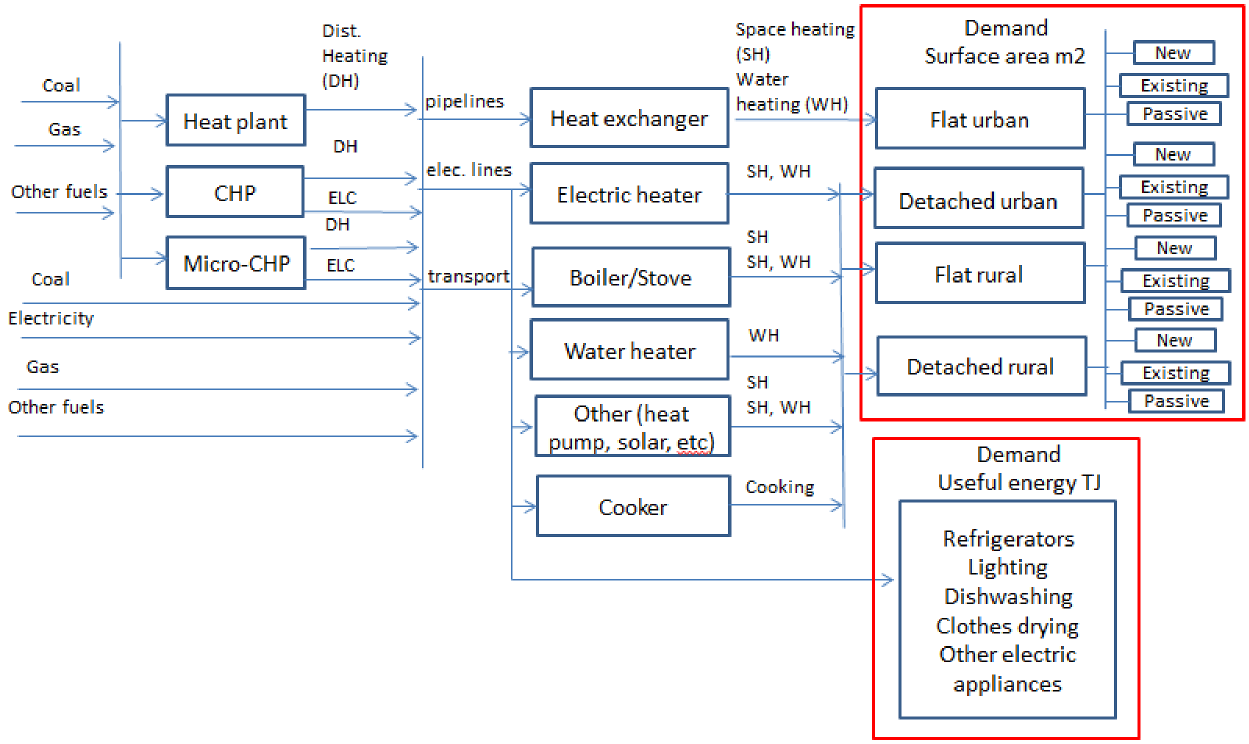



Figure 12 Residential sector structure in revised version of the TIMES-Kazakhstan multi-regional model

According to the Law "On energy saving and energy efficiency" adopted in 2012, all new buildings must not be less than Class C (normal). Thus, at a minimum, the heating need should be less than the "normal" heating (class C) need values determined by construction norms of the Republic of Kazakhstan СНРК 2.04-21-2004. For all scenarios in the model, it was assumed that new buildings do not have less than Class C heating needs.

The emission coefficients for air pollutants (NOx, CO, SOx, PM2.5) were obtained from EMEP/EEA air pollutant emission inventory guidebook (EMEP/EEA, 2016). GHG emission factors were obtained from the Kazakhstan's inventory submission to the UNFCCC.

### 3.4.7 Demand drivers

The total amount of heated area served, which is a driver of the demand for space heating, water heating and cooking is presented in Figure 13. In the estimates of future area of the dwelling stock by 2030, it is assumed that the current ratio between the growth rates of various types of housing stock (by regions, urban/rural, detached/flat) is maintained. This ratio between the growth rates of various types of housing stock (by regions, urban/rural, detached/flat) is obtained on the basis of historical data for 2008-2015. The total annual increase in living space is calibrated according to statistical data for 2015 and total annual increase corresponds with the parameters of the State Program "Affordable Housing - 2020": about 7-8 million m$^2$ of new areas annually.

The fastest growth rates, based on these estimates, are observed in urban detached houses, with an almost 3-fold increase by 2030, compared to 2011. The housing stock in rural areas is growing slowly due to the rapid urbanization. The total area of the housing stock is projected to increase by 1.5 times by 2030 compared to the level of 2011.

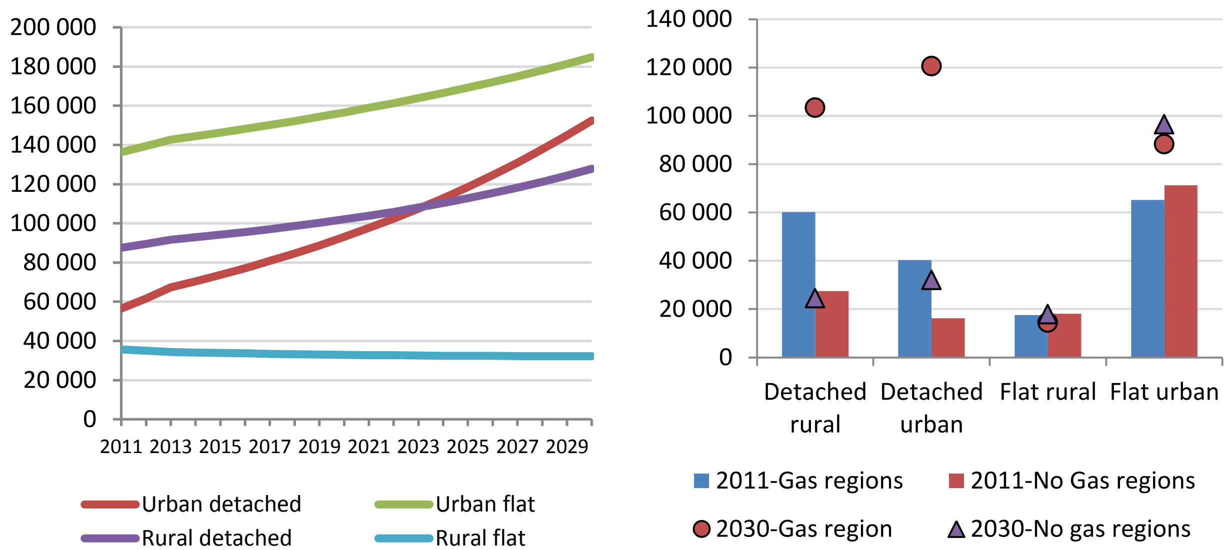



Figure 13 Projected total area of dwelling stock a) by type and b) by regions and by type, thousand m$^2$

## 3.5 Sensitivity analysis

There are many uncertainties that can affect the delivery and cost of the energy transition, such as economic growth and structural change, delivery capacity (including financing), technology costs and behavioral change (Pye et al., 2015).The most common approach for dealing with uncertainty in large-scale energy modelling, is by performing a local sensitivity analysis investigating how uncertainty on a model output can be apportioned to different levels of uncertainty in the model for a given input (Saltelli and Annoni, 2010). Sensitivity analyses entitle multiple runs of the model and are very time consuming. However, sensitivity analyses can contribute to increase in the robustness perception of the modelling analysis (Chiodi et al., 2015). Nonetheless, single-variable sensitivity analysis has been criticized for failing to fully capture the importance and impact of uncertainties of multiple input variables (Pye et al., 2015). Accounting for simultaneous uncertainties for the multiple input parameters in our current model, would provide probability distributions to assess the level of risk of a given answer, but this analysis could only be achieved at the expense of random combinations of thousands or even hundreds of thousands of scenarios given the large number of input parameters in the current model. The time required for one model run is from 20 to 30 minutes with a processor Intel(R) Core(TM) i5-4690 CPU @ 3.50GHz (4 CPUs) and memory of 8192MB RAM. Hence this would be very time consuming. Moreover, there is a lack of available and reliable data on those future uncertainties for Kazakhstan, and therefore, constructing probability distributions of uncertainties of future energy system of Kazakhstan is a task for future studies. Hence, in our model, a single-input variable uncertainty is analyzed at each time in the local sensitivity analysis here presented.

Kazakhstan fully supplies its own energy sources (coal, gas and oil) and thus, prices for fossil fuels are independent of other countries, but rather on local transportation costs and distances between supplier and consumers (Kazenergy, 2015). Distances between regions and associated transportation costs were considered in our model using trade matrices. In this regard, fuel prices were not incorporated in the sensitivity analysis.

In this study, 4 main scenarios were supplemented by 64 other “sensitivity” runs to study how the results would change with alternate assumptions on the costs of district heating network, network gas pipeline and Combined Heat and Power Plants (CHP). These technologies are “key” in satisfying demand for heating in Kazakhstan in the present and future energy system.

Costs were varied from 80% to 120% (with 10 %'age point steps) from the base assumption costs of 100%.

## 4. Energy transition scenarios

### 4.1 Energy transition in the residential sector

Least Cost Solution (BaU) case was tested to identify optimal configuration of the energy system without any policy intervention. A gradual phase out on coal use in the residential sector was imposed on the model and then compared between cases with subsidized and with unsubsidized clean technologies and retrofit measures. This allows us to compare the impact and efficiency of clean energy technologies and the retrofit subsidization and to identify cost-effective technology options by building type and by region (with and without subsidization), which can be helpful in designing targeted policy intervention as well as infrastructure planning (gas pipeline, district heating). Scenarios with and without constraints on gas pipeline construction were also investigated and compared with other cases since the construction of gas pipelines to non-gasified regions is capital intensive (due to large distances) and can be postponed or cancelled. Scenarios analyzed in this study are presented in the Table 9.

Table 9 Definition of energy transition scenarios to be explored

| Scenario name | Definition |
|---|---|
| BaU | Least cost solution for the system. No constraints on the use of coal use, no subsidies for cleaner technologies. |
| Coal-ban | Phase out of coal use in the residential sector (40% reduction of coal use by 2020 and 100% reduction by 2030 compared to the level of 2011). |
| Coal-ban-subs | - Subsidies on the capacity for cleaner alternatives: micro-CHP (biogas, biomass, natural gas), heat pumps and solar space heaters in the amount of 70% of the investment cost.<br>- Subsidies for the retrofit measures (50% of the cost): wall, roof, floor, loft, door, windows. |
| Coal-ban-subs-no-gas | The same as in "BAN+subsidies" scenario, but construction of new network gas pipeline to the northern and central Kazakhstan is not allowed. |

#### 4.1.1 Choosing level of subsidies

Different levels of capital costs subsidies for cleaner technologies were also compared with the model: from 30% to 100% of the investment cost. Subsidy levels of up to 50% lead to a maximum of only a 1-2% of penetration of subsidized technologies in satisfying the useful energy demand for heating (without constraining network gas). Higher subsidy levels of 60%, 70%, 80%, 90% led to up to 5%, 8%, 12%, 19% penetration of subsidized technologies respectively (depending on the building type, without constraining network gas). A 100% subsidy lead to up to 80% of penetration of subsidized technologies even without constraining network gas. In this study, 70% of subsidization level has been tested.

In Mongolia's Ulaanbaatar an 85-93% subsidy level were offered for low emission stove (World Bank, 2014; World Bank, 2013). Thus, low emission stoves were not offered for free. One of the conclusions of intervention program in Mongolia was that subsidy arrangements should ensure stoves are sold to people who will use and maintain them (World Bank, 2013).

# 5. Results

This chapter presents all the main results of the model. The comparison of the aggregated and disaggregated version of the model has been made. Analysis of residential sector decarbonisation and system level decarbonisation is presented. Following results are presented: energy consumption by fuels and by regions, useful energy demand by building types, marginal price for heating, energy efficiency and greenhouse gases and air pollutants emissions. Using improved model, most cost-effective heating technologies for different regions and building types were identified. The thesis makes comparisons with and without subsidies for cleaner technologies as well as with and without possibility for extension of the gas pipeline. Results of the sensitivity analysis are summarized in the Table .

## 5.1 Energy transition in the residential sector

### 5.1.1 Energy consumption and fuel mix

Coal remains the main fuel for heating in rural detached houses in the regions without gas availability in the absence of policy interventions (BaU) (Figure 14). Total coal consumption however, reduces by 27% in 2030 compared to the base year level in BaU. This is because in some regions with a gas network, particularly in the southern parts, there is switch from coal to gas in the least cost case (BaU) (Figure 15), even without any interventions. This occurs as a result of long distances from coal mines, relatively high coal price (in gas regions), as well as lower combustion efficiency of coal stove compared to gas boilers. As an example, the average price of coal in South of Kazakhstan (with access to gas) was 48% higher than the price in the Northern and Central Kazakhstan (without gas), due to the additional transportation and distribution costs (Committee of Statistics of the Republic of Kazakhstan, 2015).

In the scenario where coal is banned, it is mainly substituted with natural gas, district heating and electricity (in areas where no gas pipeline is available) (Figure 14). In addition, higher efficient technologies and retrofit measures are utilized, which results in the reduction of residential energy consumption by 9% in coal-ban and 15% in Coal-ban-subs scenario in 2030 compared to BaU scenario.

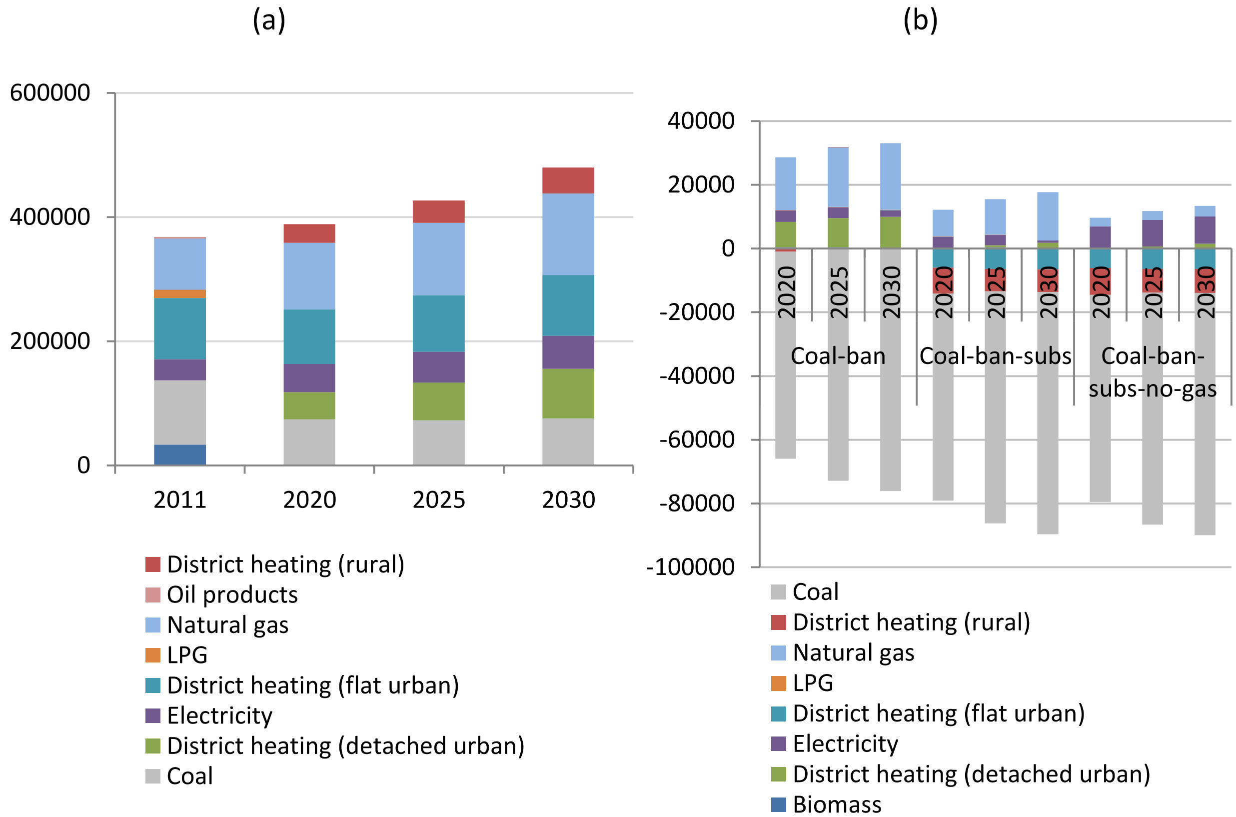



Figure 14 Energy consumption in the residential by 2030 in BaU scenario, TJ b) Difference in energy consumption between alternative and BAU scenarios (TJ)

Regions with high coal use (including some regions in the South) have the highest savings from retrofit measures when coal is banned and subsidies offered (Figure 15b).

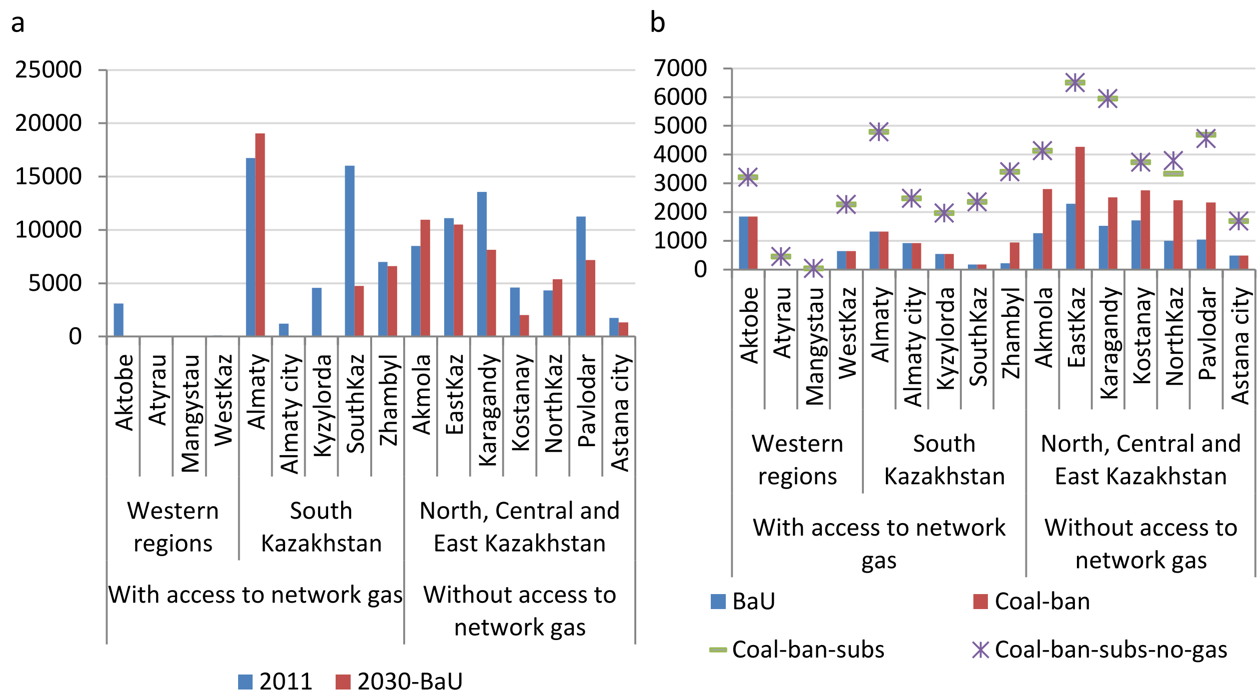



Figure 15 Regional results - a) Residential coal consumption by regions of Kazakhstan in BaU scenario, TJ[3] b) Useful energy reduced by retrofit measures, TJ

### 5.1.2 Useful energy demand

The declining demand for useful energy in rural flats (contrasting with the increasing trend for most other building types) is explained by low demand growth for rural flats combined with high retrofit measures penetration for this building category (Figure 16, Figure 17).

[3] Kostanay region is the only region located in the North Kazakhstan with access to network gas, it supplied from Russia via SWAP agreements

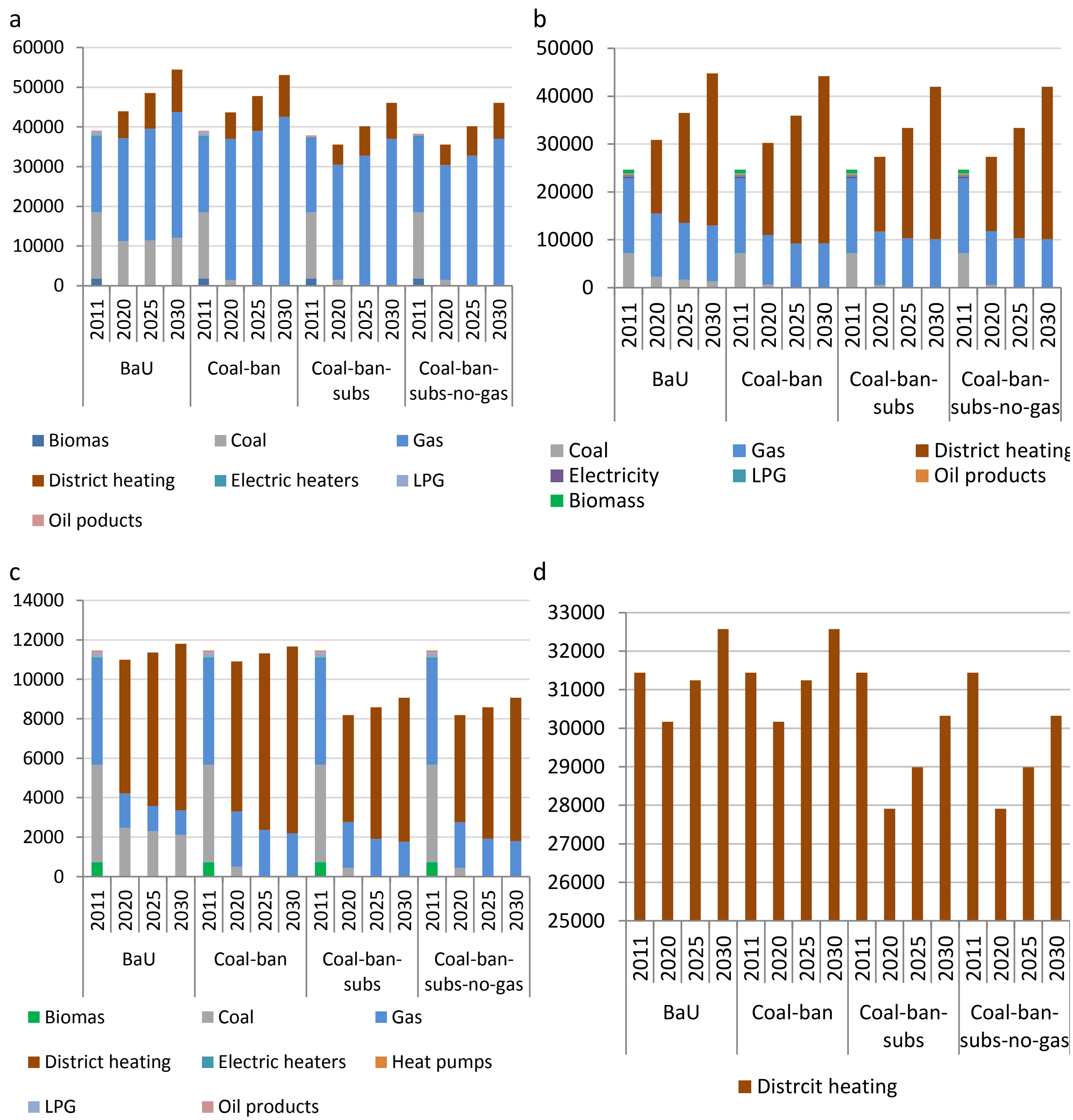



Figure 16 Useful energy for space heating by technology for regions with gas network availability, TJ a) detached rural, b) detached urban, c) flat rural, d) flat urban

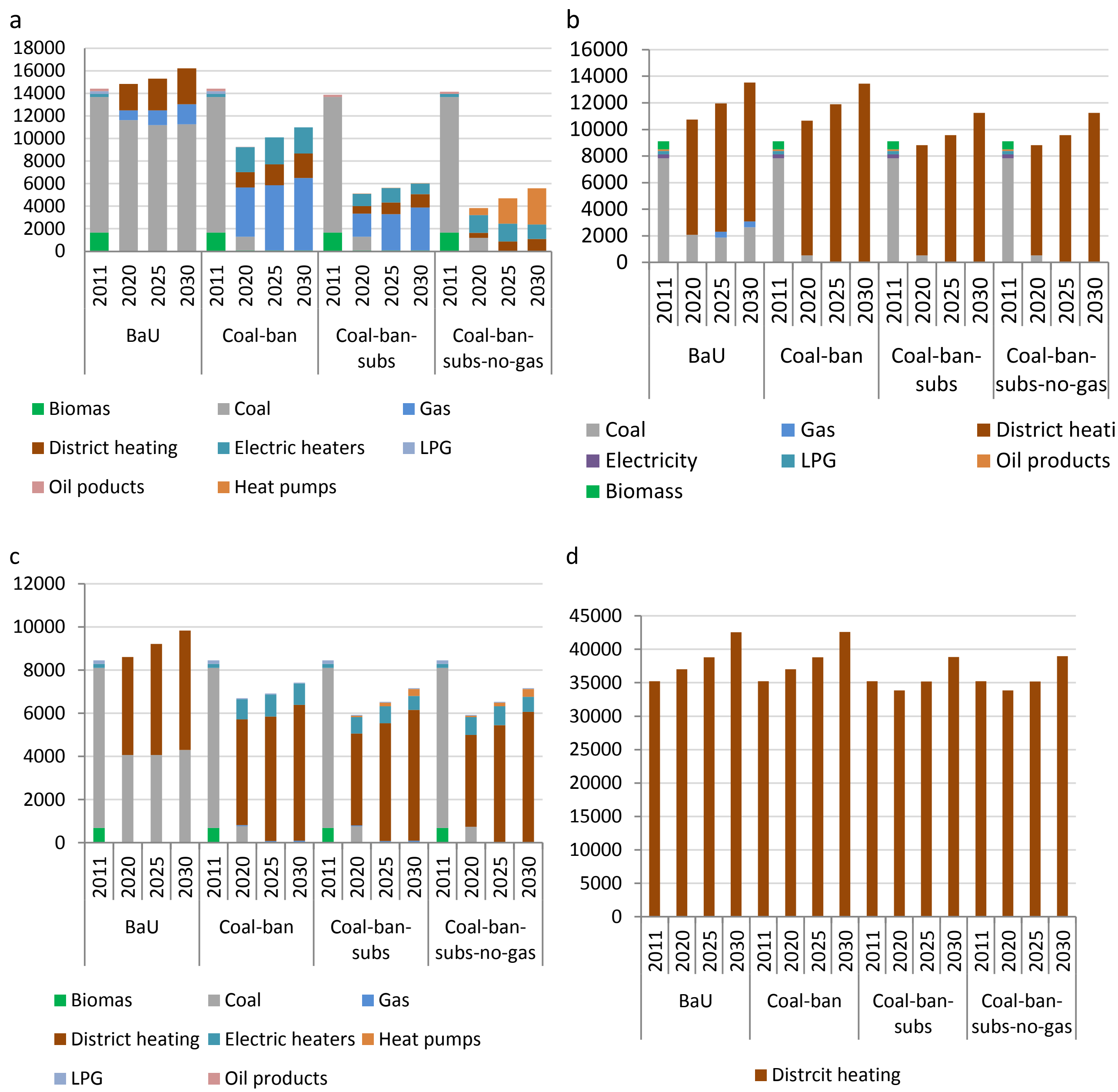



Figure 17 Useful energy for space heating by technology for regions without gas network availability a) detached rural, b) detached urban, c) flat rural, d) flat urban

The model selects district heating for most of the flats and detached houses in urban locations (Figure 16, Figure 17). Even with additional subsidies for cleaner alternatives (e.g. solar space heaters, heat pumps, micro-CHP), network gas and district heating are the most economically feasible. Imposing constraints on constructing gas pipelines (to the regions without gas) results in wide utilization of heat pumps in detached rural houses (Coal-ban-subs-no-gas), with some consumption of district heating and electricity (Figure 17c).

### 5.1.3 Energy efficiency

Subsidized cleaner technologies are not widely utilized in Coal-ban-subs scenario, compared with network gas and district heating. However, there is significantly a higher use of retrofit measures when subsidies are offered (Coal-ban-subs) compared to the case without subsidies (Coal-ban) (Figure 18). There are significant differences in the share of retrofit measures between regions with gas and without gas, with notably higher penetration of retrofit measures in the locations affected by the coal ban. Detached rural houses in regions without the gas network in particular reduce useful energy demand by up to 76% when coal is banned and subsidies offered (no network gas). Rural flats in the regions without network gas achieve energy savings up to 39% when the subsidies are offered (Figure 18).

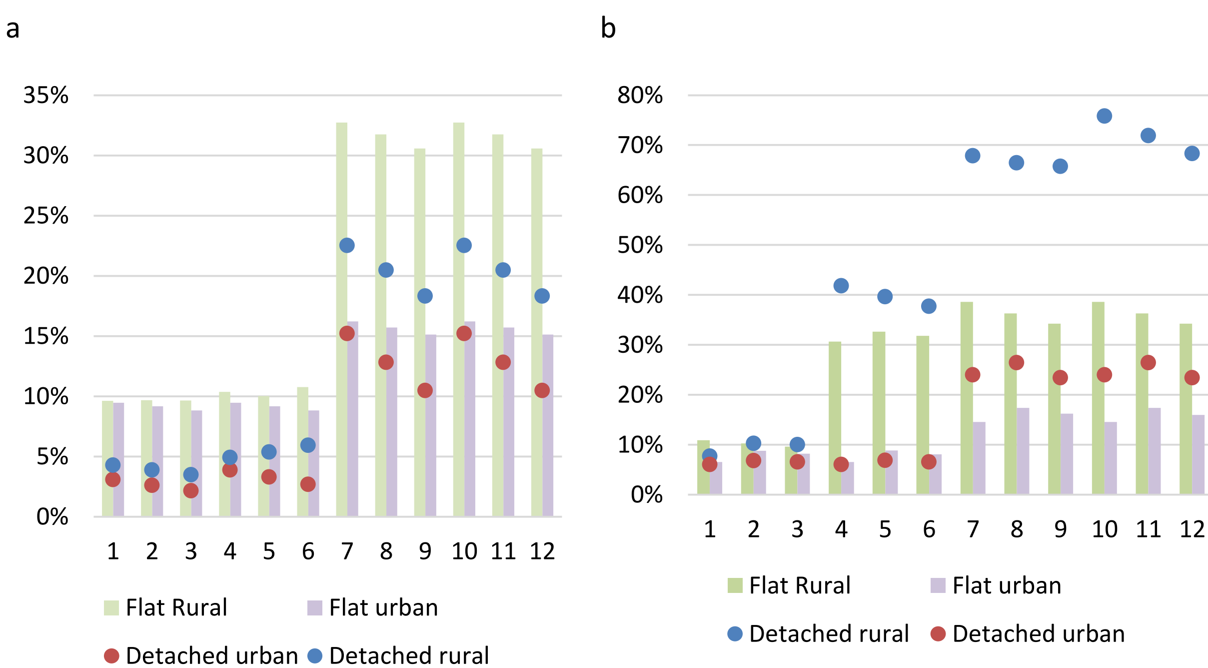



Figure 18 Share of useful energy for space heating reduced by retrofit measures, a) regions with gas b) regions without gas

### 5.1.4 Energy poverty, marginal price for heating

The coal ban has only minor impacts for urban locations (due low use of coal in urban locations), but significantly impacts on rural locations on fuel mix and price of useful energy for heating (Figure 19). Thus, the coal ban results in an increase in the marginal price of useful energy for heating in detached rural houses by 171%, 199%, 184% by 2020, 2025, 2030 respectively in Coal-ban compared to BaU (as in case of coal-based Akmola region). Offering subsidies reduces the marginal price of useful energy for heating by 10%, 21%, 13%, respectively (rural detached, no gas regions) in Coal-ban-subs compared to Coal-ban.

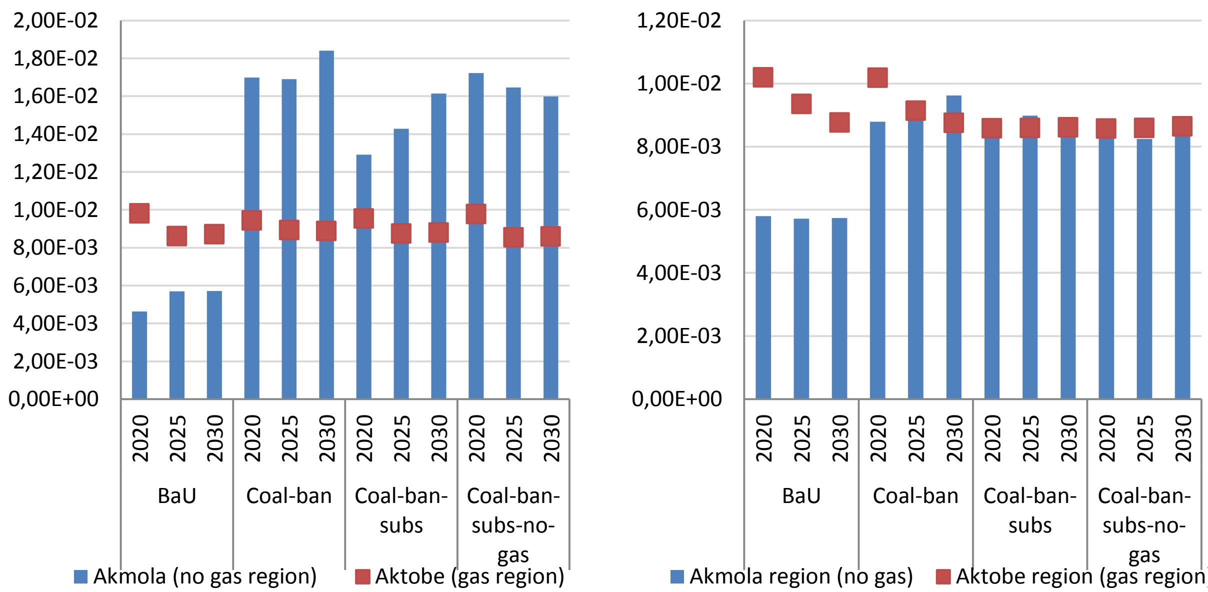



Figure 19 Marginal price of useful energy for heating a) detached rural, b) flat rural, US$/MJ

### 5.1.5 Emissions

#### 5.1.5.1 Residential sector emissions

The low combustion efficiency in the coal stoves and absence of pollutant controls results in the emissions of pollutants, posing adverse health challenges. Without any measures (BaU), NOx and $SO_x$ are projected to increase by 4% and 7%, respectively, in 2030 compared to the base year level. The coal ban results in a nearly 100% reduction of residential emissions of CO, $PM_{2.5}$ and $SO_x$ in 2030 compared to base year level (Figure 20). In addition, $NO_x$ and $CO_2$ emissions can be reduced by 65% and 56%, respectively in 2030 compared to the base year level.

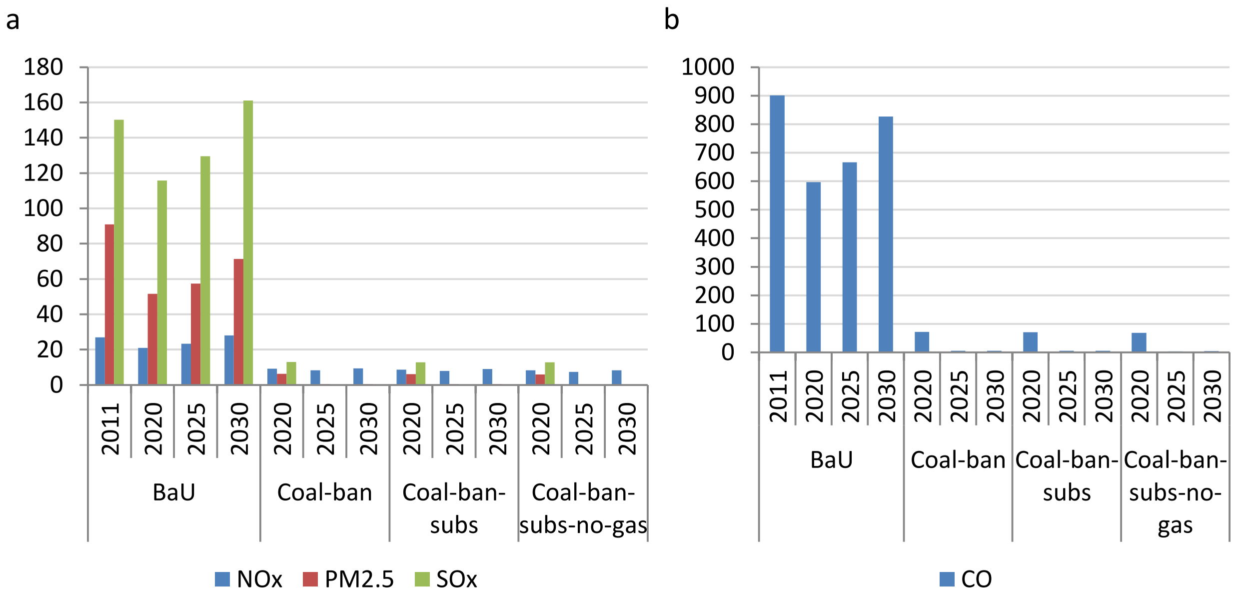



Figure 20 Residential sector emissions of a) $PM_{2.5,}$ $NO_x$, $SO_x$, b) CO

#### 5.1.5.2 Emissions from the entire energy system

When considering the overall energy system emissions (power plants, heat plants and residential sector), there is a considerable reduction in $PM_{2.5}$ and CO by 95% and 97% in coal-ban scenario in 2030 compared to the base year level. This is because of lower efficiency of fuel combustion in the residential stoves (products of incomplete combustion) compared to industrial boilers in the power plants. However, this is not the case for other emissions. There is only 2-6% reduction (residential sector and supply side) of $CO_2$, $NO_x$, $SO_x$ in the coal-ban scenario compared to BaU. Here the additional electricity generation from coal offsets much of the emissions avoided in the residential sector. If pollutant controls were installed in the power plants (which is not accounted in the model), the emissions reductions could be even more significant.

### 5.1.6 Sensitivity analysis

Table 9 demonstrates the results of the sensitivity analysis for combinations of varying three input variables. The results of the sensitivity analysis (on the costs of district heating network, network gas pipeline and Combined Heat and Power Plants (CHP)) demonstrate that there is a minimum impact on the total system cost (less than 0.8%) and total final consumption (less than 1%). District heating consumption reduces by a maximum of 2.2% (compared to base case) in the case with simultaneous increase of the costs of CHP and heat network ( Table ). Marginal price for heating increases at maximum by 2.7% in the case of simultaneous increase of the costs of CHP and heat network. With an increased cost for gas pipeline (by 20%) and reduced CHP cost (by 20%), gas consumption declines by 3.6% (compared to 100% case). While in an opposite case (lower cost for gas pipeline and higher CHP cost by 20%), gas consumption increases by 2.9%. Thus, the sensitivity analysis demonstrated that changing input parameters for "key" technologies have little impact on resulting fuel mix.

The Figure 21, Figure 22 and Figure 23 below demonstrate tornado charts with the impact of varying (one-by-one) three input variables on the different outputs of the model (sorted by the impact and normalized to a maximum impact value).

Total system cost was affected by gas network cost (Figure 21a). As expected, increase of the costs results in higher system cost and visa-versa. Total residential energy consumption, marginal price for heating, district heating and gas consumption were mostly affected by the cost of CHP and heat plants (compared to other parameters).

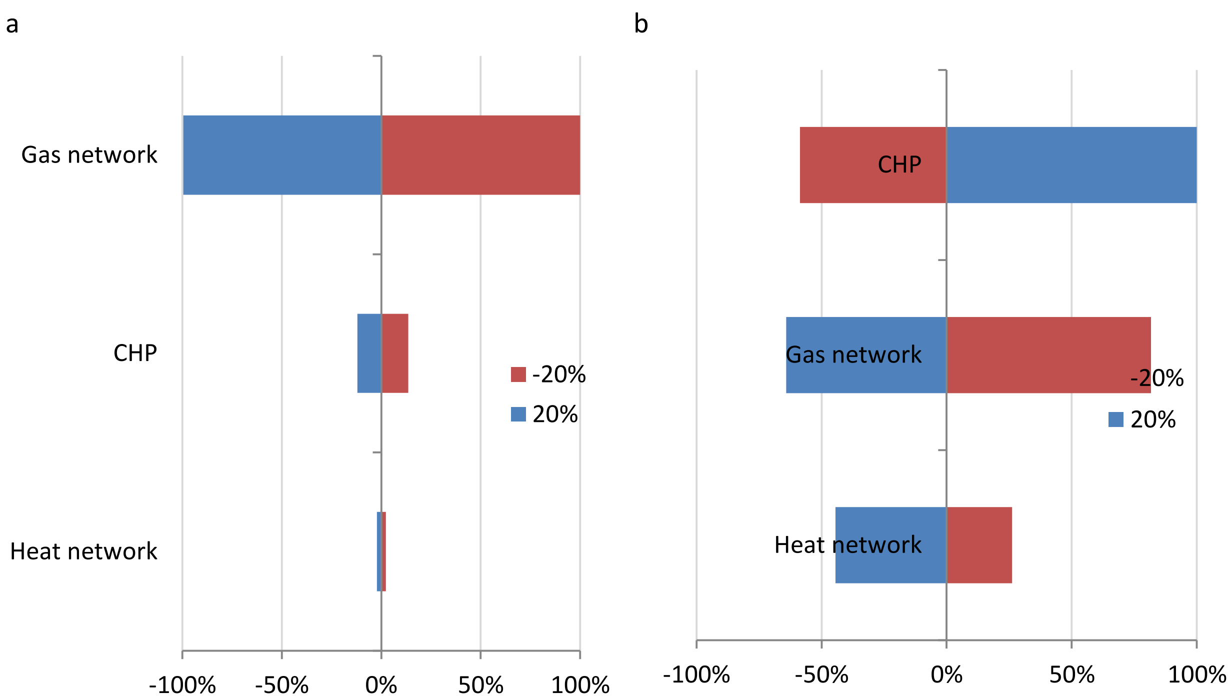



Figure 21 Tornado chart of the impact of varying investment cost for heat network, gas network and CHP and heat plants on the a) total system cost b) total residential energy consumption in 2030

a b

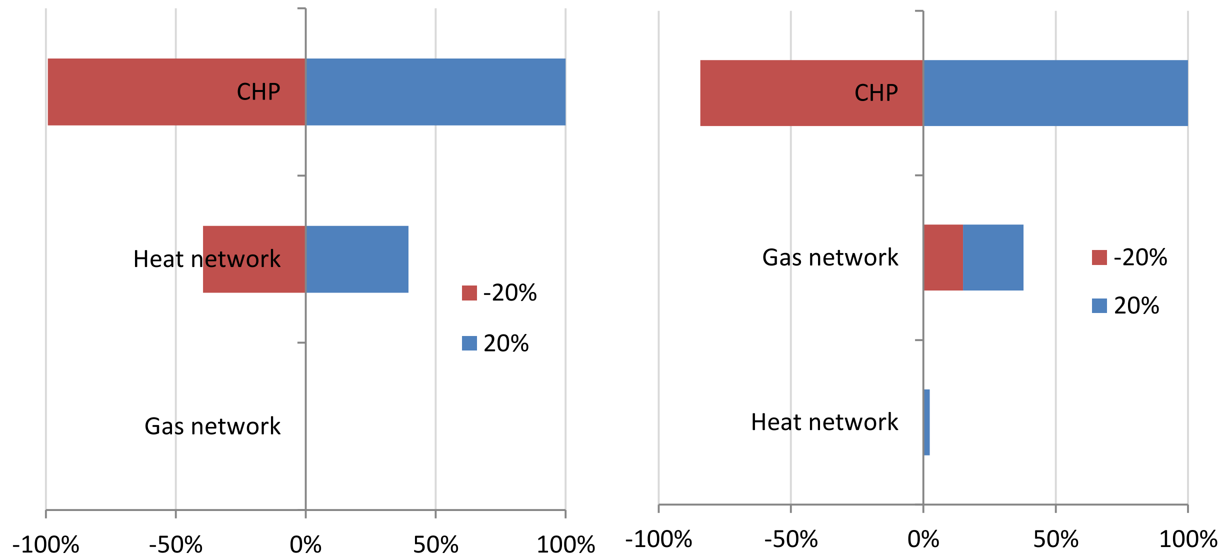



Figure 22 Tornado chart of the impact of varying investment cost for heat network, gas network and CHP and heat plants on the marginal price for heating in 2030 a) Akmola region b) Aktobe region

a b

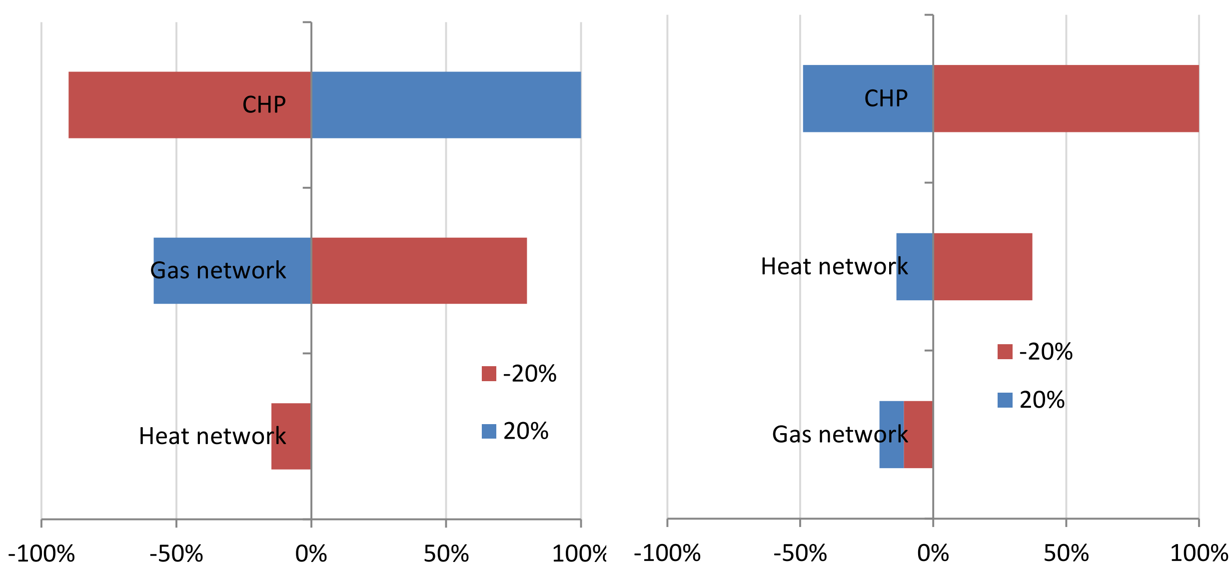



Figure 23 Tornado chart of the impact of varying investment cost for heat network, gas network and CHP and heat plants on a) gas consumption b) district heating consumption in 2030

Table 9 Results of sensitivity analysis to alternate assumptions on key technologies

| Total residential energy consumption, TJ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| CHP | | -20% | | | | -10% | | | |
| Gas network | | -20% | -10% | 10% | 20% | -20% | -10% | 10% | 20% |
| Heat network | -20% | 441473 | 441318 | 441159 | 440721 | 440325 | 440127 | 439857 | 439454 |
| | -10% | 441451 | 441303 | 441151 | 440367 | 439551 | 439534 | 439145 | 438904 |
| | 10% | 440460 | 440315 | 440138 | 439713 | 438382 | 438129 | 437866 | 437510 |
| | 20% | 440085 | 439937 | 439761 | 439336 | 438344 | 438134 | 437859 | 437499 |
| Residential gas consumption, TJ | | | | | | | | | |
| CHP | | -20% | | | | -10% | | | |
| Gas network | | -20% | -10% | 10% | 20% | -20% | -10% | 10% | 20% |
| Heat network | -20% | 153074 | 151386 | 150457 | 147627 | 153911 | 152241 | 150839 | 148608 |
| | -10% | 153159 | 151472 | 150578 | 147662 | 154046 | 152376 | 151014 | 148743 |
| | 10% | 153173 | 151486 | 150577 | 147748 | 154045 | 152414 | 151012 | 148742 |
| | 20% | 153203 | 151515 | 150592 | 147763 | 154139 | 152469 | 151012 | 148742 |
| Residential district heating consumption, TJ | | | | | | | | | |
| CHP | | -20% | | | | -10% | | | |
| Gas network | | -20% | -10% | 10% | 20% | -20% | -10% | 10% | 20% |
| Heat network | -20% | 233828 | 233899 | 233950 | 233967 | 231870 | 231880 | 231865 | 231793 |
| | -10% | 233721 | 233799 | 233821 | 233581 | 231006 | 231224 | 231049 | 231178 |
| | 10% | 232715 | 232796 | 232809 | 232840 | 229922 | 229839 | 229831 | 229844 |
| | 20% | 232358 | 232438 | 232465 | 232496 | 229791 | 229791 | 229824 | 229834 |
| Marginal prices for useful energy, mln US$ 2013 | | | | | | | | | |
| CHP | | -20% | | | | -10% | | | |
| Gas network | | -20% | -10% | 10% | 20% | -20% | -10% | 10% | 20% |
| Heat network | -20% | 0.237 | 0.236 | 0.236 | 0.236 | 0.237 | 0.237 | 0.237 | 0.237 |
| | -10% | 0.238 | 0.237 | 0.237 | 0.237 | 0.238 | 0.237 | 0.238 | 0.237 |
| | 10% | 0.239 | 0.238 | 0.238 | 0.238 | 0.239 | 0.238 | 0.239 | 0.239 |
| | 20% | 0.239 | 0.238 | 0.239 | 0.239 | 0.239 | 0.239 | 0.240 | 0.239 |
| Total system cost, mln US$ 2013 | | | | | | | | | |
| CHP | | -20% | | | | -10% | | | |
| Gas network | | -20% | -10% | 10% | 20% | -20% | -10% | 10% | 20% |
| Heat network | -20% | 497580 | 499101 | 502144 | 503664 | 497725 | 499248 | 502290 | 503810 |
| | -10% | 497612 | 499135 | 502178 | 503697 | 497759 | 499281 | 502324 | 503843 |
| | 10% | 497679 | 499201 | 502244 | 503763 | 497825 | 499347 | 502390 | 503909 |
| | 20% | 497711 | 499234 | 502277 | 503796 | 497857 | 499380 | 502422 | 503941 |

Table 9 Results of sensitivity analysis to alternate assumptions on key technologies

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Total residential energy consumption, TJ | | | | | | | | | |
| CHP | | 10% | | | | 20% | | | |
| Gas network | | -20% | -10% | 10% | 20% | -20% | -10% | 10% | 20% |
| Heat network | -20% | 437616 | 437396 | 437396 | 437396 | 435828 | 435786 | 435738 | 435433 |
| | -10% | 437211 | 437211 | 436784 | 436519 | 435727 | 435687 | 435739 | 435434 |
| | 10% | 437081 | 436430 | 436421 | 436137 | 435708 | 435668 | 435643 | 435416 |
| | 20% | 436847 | 436252 | 436239 | 435970 | 435458 | 435418 | 435366 | 435159 |
| Residential gas consumption, TJ | | | | | | | | | |
| CHP | | 10% | | | | 20% | | | |
| Gas network | | -20% | -10% | 10% | 20% | -20% | -10% | 10% | 20% |
| Heat network | -20% | 157075 | 155353 | 155353 | 155353 | 157539 | 157245 | 154073 | 151704 |
| | -10% | 155356 | 155356 | 151765 | 150440 | 157528 | 157245 | 154080 | 151711 |
| | 10% | 157086 | 155704 | 151791 | 150466 | 157528 | 157245 | 154319 | 151673 |
| | 20% | 157092 | 155697 | 151784 | 150459 | 157528 | 157248 | 154410 | 151486 |
| Residential district heating consumption, TJ | | | | | | | | | |
| CHP | | 10% | | | | 20% | | | |
| Gas network | | -20% | -10% | 10% | 20% | -20% | -10% | 10% | 20% |
| Heat network | -20% | 227035 | 227048 | 227048 | 227048 | 224876 | 224874 | 225840 | 226430 |
| | -10% | 226887 | 226887 | 228397 | 228397 | 224786 | 224785 | 225834 | 226424 |
| | 10% | 226532 | 225746 | 228035 | 228015 | 224767 | 224766 | 225557 | 226444 |
| | 20% | 226292 | 225585 | 227874 | 227866 | 224517 | 224516 | 225208 | 226317 |
| Marginal prices for useful energy, mln US$ 2013 | | | | | | | | | |
| CHP | | 10% | | | | 20% | | | |
| Gas network | | -20% | -10% | 10% | 20% | -20% | -10% | 10% | 20% |
| Heat network | -20% | 0.241 | 0.242 | 0.242 | 0.242 | 0.244 | 0.245 | 0.244 | 0.244 |
| | -10% | 0.242 | 0.242 | 0.242 | 0.242 | 0.245 | 0.245 | 0.245 | 0.245 |
| | 10% | 0.243 | 0.243 | 0.243 | 0.244 | 0.246 | 0.247 | 0.246 | 0.246 |
| | 20% | 0.244 | 0.244 | 0.244 | 0.244 | 0.247 | 0.247 | 0.246 | 0.247 |
| Total system cost, mln US$ 2013 | | | | | | | | | |
| CHP | | 10% | | | | 20% | | | |
| Gas network | | -20% | -10% | 10% | 20% | -20% | -10% | 10% | 20% |
| Heat network | -20% | 497931 | 499456 | 499456 | 499456 | 498014 | 499539 | 502583 | 504104 |
| | -10% | 499488 | 499488 | 502531 | 504051 | 498046 | 499571 | 502616 | 504136 |
| | 10% | 498029 | 499553 | 502596 | 504116 | 498111 | 499636 | 502681 | 504201 |
| | 20% | 498061 | 499585 | 502628 | 504148 | 498143 | 499668 | 502713 | 504233 |

### 5.1.7 Discussion

#### 5.1.7.1 Data analysis

Within the same building category, heating needs may vary by up to 4 times from the warmest region to coldest region as a result of climatic differences; while within same region, heating need may vary by up to 2.5 times as a result of different building category.

"Unmet" demand values were highest in the regions without gas availability, indicating potentially high "energy poverty" incidence. This is not accounted in the official statistics and strategic planning. It is well known, that insufficient thermal comfort in homes leads to health impacts, with excess winter deaths (Howelson and Hogan, 2005; Bull et al. 2010). Accounting for severe climatic conditions in Kazakhstan, the consequences in terms of health impact can be very high. In this study it was assumed that in all scenarios entire "unmet" demand is satisfied. However, the model can be improved with more robust policy analysis of tackling "unmet demand" once the data on thermal comfort and occupancy from Households Survey in Kazakhstan's buildings will be obtained.

#### 5.1.7.2 Temporal resolution

Long-term energy system models are useful for improving understanding of the long-term development of energy systems, but often they are not able to take into account short-term changes (Deane et al, 2012). As regards to heating demand, it has an annual temporal resolution (Section 3.4.3). Heating demand is estimated based on degree-day of the heating period - an indicator equal to the multiplication of the difference in the temperature of the internal air and the daily-average outside air temperature for the duration of the heating period. Heating-Degree-Days and heating season duration by regions of Kazakhstan was obtained from the Construction Norms "Energy consumption and thermal protection of buildings". This approach accounted for sum of the average monthly temperatures of each region and duration of the heating period. Duration of the heating period is defined as the period when the outside temperature is less than 8° C. In Kazakhstan there are severe winters with 6-7 months of heating period with an average temperature of heating period between +1° C to -9° C. District heating is provided almost without shut-downs throughout the heating period. Operation of heating boilers (fossil fuel) does not have unpredictable character (as renewable energies), they are considered as reliable in satisfying peak loads. For long-term planning of energy policies and measures, annual approximation of the heating demand can be adequate as further breakdown by the time interval of the existing model can lead to an increase in the simulation time and the requirement for computing power. Future studies should concentrate on city-level optimal management of district heating systems with a possibility of integration of industrial waste heat, heat storage, cogeneration plants and renewable energy with detailed temporal representation (including peak demands).

Electric load management may require high temporal resolution. The model employed in this study takes into account the peak and seasonal features of the generation and consumption of electricity. There is a temporal division into 3 seasons (winter, summer, off-season), and 3 periods (day, night, peak). Large-scale introduction of variable renewable energy sources requires high temporal resolution because of the need for accounting of technical operational parameters such as minimum generation level, limited rump rate, minimum up and down time, startup costs (Deane et al., 2012). One approach to address this issue is coupling of a short-term high-resolution model to a long-term low-resolution model. From the households survey it can be observed that electricity is rarely used for heating purposes in Kazakhstan (Kerimray et al., 2017b). When introducing a large share of renewable electricity in Kazakhstan, a significant problem will remain with the provision of heat for the population during the long and severe winter period. The modelling results demonstrated that renewable electricity is not part of the solution for residential coal-free energy transition. Introduction of the large shares of renewable electricity in Kazakhstan is challenging due to its inefficiency in satisfying heat demand compared to cogeneration plants, heat plants and individual heating systems. Thus, high temporal (hourly, minute) resolution for electricity is not implemented in the existing model.

#### 5.1.7.3 Linearity and economies of scale

A linear input-to-output relationship implies that each represented technology may be implemented at any capacity without consideration of economies of scale (Loulou et al., 2016). In reality, technology is usually available in discrete sizes. It may happen that the model's solution shows some technology's capacity at an unrealistically small size. The scope of TIMES application is usually national context and thus, capacities are large enough that small capacities are unlikely to occur. When the model is applied is a small region, by introducing integer variables, certain capacities can be allowed only in multiples of a given size (Loulou et al., 2016). Mixed Integer Linear Programming greatly increases solution time and thus, must be applied sparingly (Loulou et al., 2016). Therefore, in this study MIP is not applied.

#### 5.1.7.4 Technological development

The costs of technologies can reduce over time due to economies of scale and other factors such as learning-by-doing, continued research and development. In the energy system models, capital cost of technology over time can be described in three ways:

a) assuming no technological change over time
b) use exogenous forecasts of technological development
c) endogenise technological change into the model by using technology and experience learning curve (Anandarajah and McDowall, 2015).

The second approach is the most widely used in the energy system models and it employs exogenous forecasts of technological development to represent technology improvements. Even though third approach is considered as improved for modeling technologies, uncertainties remain relating to the learning rate and changes to the learning rate over the time. Another shortcoming of the third approach is that cost reduction has been modelled with a single factor (learning rate), while it depends on many factors, which can be local specific.

In Kazakhstan, most of the energy technology is imported as there is nearly no production of energy technologies. There are no studies in the literature which describe the change of technology cost in Kazakhstan and factors determining this change. In this study exogenous forecasts of technological development were used in the model from European Commission Joint Research Centre (2014) “Energy Technology Reference Indicator projections for 2010-2050”. Thus, the technology cost is not endogenous to the model and it does not vary with its utilization. The economy of scale is partly accounted in the model as district heating technologies have different costs and technical parameters from the individual heating technologies. Capital costs for the construction of heating networks were split to urban/rural and detached/flat.

#### 5.1.7.4 Model results

The results of this study suggest that the energy efficiency potential in buildings is very high in Kazakhstan and retrofit subsidies can be effective in most building types in reducing demand for heating and serve as a key step in any of the energy transition pathways. Retrofit measures are highly used in rural houses and in coal regions, with up to 76% of reduction of useful energy for space heating, indicating high potential for solving energy poverty problem. Implementation of retrofit measures is known to be effective strategy in reducing energy costs and alleviating energy poverty (Patterson, 2016).

The model results suggest that when coal is banned, networked gas is the most viable solution for rural detached houses, while for most other building categories district heating has been chosen. District heating is very common in Kazakhstan and 63% of housing stock in urban areas is already connected to central heating network. District heating can be environmentally clean and energy efficient when it is well managed: efficient cogeneration, clean sources of fuels (e.g. gas, biomass), and efficient distribution.

Kazakhstan has considerable gas supply potential, as it has significant gas reserves (Kazenergy, 2015). The existing gas infrastructure system was part of the former Soviet Union gas transmission system and mainly served as transit of natural gas flows from Turkmenistan and Uzbekistan to Russia and Europe. Several possible routes for providing a gas to capital Astana city (with further extension to northern and eastern locations) have been proposed in the past. It was estimated that constructing the new processing plant and the pipeline connecting it with Astana would cost $3.7 billion and over $4.1 billion, respectively (Kazenergy, 2015). However, to date (2017), the investment decision for constructing of a gas pipeline to northern and central regions has not been yet made. The most important barrier for constructing gas pipeline is its relatively high cost due to the long distances involved. Domestic gas prices in Kazakhstan are regulated at the consumer level and they are lower than those in Russia and significantly lower than EU gas prices (Kazenergy, 2015). Therefore, the cost recovery of gas pipeline has been questioned and it was considered as social project and thus, to be funded by the budget of the Government. The future of the construction of gas pipeline largely relies on a strong political will to implement pricing reforms and/or allocation of funding from the Government.

Investment costs of renewable/alternative sources of heat are still high, and they are not affordable for many households in Kazakhstan. The results of this study indicate that offering subsidies/grants to coal users in rural areas for installing heat pumps with retrofits is an optimal strategy for eliminating coal consumption, if the construction of gas pipeline is delayed or cancelled. As our model suggests, at first, the regions with no access to gas (North and Central Kazakhstan) should be targeted, as they are mostly affected by energy poverty (Kerimray et al., 2017b).

#### 5.1.7.5 Energy system effect

Existing power plants and combined heat and power plants in Kazakhstan generate large emissions due to the use of low-quality coal and inadequate pollution control equipment in power plants and district heating plants (Government of the Republic of Kazakhstan, 2013). Kazakhstan emissions standards for coal plants (with installed capacity exceeding 200 MW) exceed European thresholds by more than 10 times for PM, more than 10% for $NO_x$ and by more than 2.5 times for $SO_x$ (Government of the Republic of Kazakhstan, 2013). Most of the existing coal power plants do not comply with Kazakhstan standards on emissions. The model results demonstrated that there are practically no reductions of $CO_2$, $NO_x$, $SO_x$ achieved when coal is banned in the residential sector with the entire energy system emissions accounted. Additional electricity generation from coal offsets much of the emissions avoided in the residential sector because no constraint on emissions were imposed for the supply side (power plants and heat plants) within this study.

In this study, the implications of the policies in the residential sector (coal ban in the residential sector) were tested within the entire energy system modeling framework, which allows to quantify the impact at the overall system level (emissions, energy infrastructure). Results proved that the system boundaries for considering energy transition in the residential sector play an important role. Supply side energy infrastructure such as network gas pipeline and district heating system played a major role in the residential sector energy transition. As a result, policies in the residential sector (e.g. coal ban) may not result in the reductions of some air pollutants (products of complete fuel combustion) at the systems level. This may imply that additional policies and measures have to be undertaken in the supply side of the energy system (reducing emissions at power plants and heat plants). With an improved modeling framework proposed in this study, supply side policies can be further evaluated in future studies.

#### 5.1.7.6 Challenges for energy transition and implementation strategies for energy transition

The review of international experiences of policy interventions showed that offering cleaner technologies alone was not fully effective, since many households continued to employ dirty technologies/fuels (Sinton et al., 2004, Sun et al., 2014). Households in China continued to use portable coal stoves for other cooking or water heating tasks even after installing improved stoves (Sinton et al., 2004). Sun et al. (2014) concluded that the failure of biogas subsidy program in China was because of wealthier households in rich regions have been included in the program, while low-income households in poorer areas should be targeted as they are more likely to use biogas energy. Proper targeting of intervention program should be a key for successful implementation strategy of energy transition in Kazakhstan.

Most developed countries have either banned or greatly restricted household coal use (Kerimray et al., 2017a). Usually transitional period of several years is given. The ban on coal implies ban on marketing, sale and distribution for households, so that households are not able to find coal on the market and are forced to switch to other alternatives. Thus, for Kazakhstan, it is recommended to follow similar approach by banning marketing, sale and distribution of coal. Transitional period of 5 year can be given. Additionally, the ban may be implemented initially for some regions (e.g. Astana and Almaty cities), with further extension to other regions.

Coal ban alone may have a significant impact on energy affordability of households in Kazakhstan. According to the Households Survey, 28% of households in Kazakhstan spent more than 10% of their income of energy and majority (65%) of those households were those using coal (Kerimray et al., 2017b). Modeling results depicted that coal ban results in an increase in the marginal price of useful energy for heating in detached rural houses by 184% in 2030 respectively compared to BaU (Figure 19), while offering subsidies reduces the marginal price of useful energy for heating by 13%. As an example, the capital cost of heat pump ranges from 1100 to 1700 Euro 2013/kWhth depending on its type (European Commission Joint Research Centre, 2014), which is mostly unaffordable for Kazakhstan’s coal users, especially located in rural areas. Retrofitting measures such as insulation of walls, roofs, replacement of windows are also capital intensive (Kerimray et al., 2016). National average monthly income of household per capita in 2015 was 367 USD (Committee of Statistics of the

Republic of Kazakhstan, 2017), and for coal users it was even lower by 10% compared to the national average (Kerimray et al., 2017b). Thus, many households in Kazakhstan may not afford to invest in the expensive clean heating technology (e.g. heat pump, solar heaters), and in the retrofitting measures without financial support tools. As an example, in India, the key barrier identified to the deployment of the rural biogas was the upfront installation cost of the biogas plant (Mittal et al., 2018). In many countries (e.g. Korea, Poland, Ireland, etc.) there are support programs for building scale renewable energy installations for space heating and retrofitting measures (IEA, 2017). It is not effective to provide consumer subsidies while dirty stoves/fuels are still allowed with no plan to phase them out (World Bank, 2014). Subsidy arrangements should consider that the use of a final consumer's price that is not too low (or free) to ensure stoves are sold to people who will use and maintain it (World Bank, 2013). In this regard, combination of coal ban with consumer subsidy has to be implemented in Kazakhstan.

Based on empirical evidence among rural households in Tanzania, it was concluded that access to alternative choices of stoves, different payment mechanisms and a longer trial period were important for increasing rate of adoption of improved cooking stoves (Kulindwa et al., 2018). Thus, in Kazakhstan, different payment mechanism can be offered for the subsidized technology: credit, cash or free. Additionally, alternative choices of technologies (e.g. heat pumps, solar water heater, new windows, wall insulation, etc) can be offered accounting for consumer's preferences. Offering technology for cash at harvest time can increase its penetration level in rural areas (due seasonal income from agricultural activities), as Kulindwa et al. (2018) concluded.

The results of this study demonstrated that coal users in rural areas should be fist targeted within the Intervention Program. According to the model results (coal-ban-subs-no-gas), the total amount of allocated subsidies (at the rate of 70% of the technology cost) amounted by up to 165.8 mln $USD_{2013}$ by 2030 and it constitutes 32% and 8% of the current state social and health care expenditures, respectively (Committee of Statistics of the Republic of Kazakhstan, 2016c). This is a considerable expenditure for the Government, therefore the costs and benefits have to be well justified. Unsustainable energy use in households is one of the indoor and outdoor air pollution sources. In Kazakhstan, prevalence of chronic obstructive pulmonary disease (COPD) was 39.2 per 1000 (which is much higher compared to Ukraine and

Azerbaijan) likely due to poor ecological conditions (Nugmanova et al., 2018). Particulate matter pollution in Kazakhstan causes approximately 2,800 premature deaths and costs the economy over US$1.3 billion annually (or 0.9% of GDP) in terms of increased health care costs (World Bank and Ministry of Environment and Water Resources of the Republic of Kazakhstan, 2013).

Key funding source for this targeted subsidy program could be savings from the phase-out of the energy subsidies. Currently, Government subsidizes investments in the development and modernisation of energy infrastructure, operating and maintenance of generating capacities, it also provides tax concessions and privileges for energy companies (OECD, 2014). Energy subsidies keep end-user prices low and ensures that they are not reflective of the full cost of service provision. It was estimated that subsidies for energy amounted to USD 5.85 billion in 2011 equivalent to 3.3% of GDP of Kazakhstan (OECD, 2014). Removing these energy subsidies is necessary for attracting investments in infrastructure and generating capacities, which is currently mostly obsolete and inefficient. Additionally, energy subsidy for energy suppliers may not be effective for tackling challenges of energy poverty and energy transition as it promotes ineffective energy consumption across population and supports wealthier population located in urban areas having access to energy infrastructure. While removing subsidies for energy suppliers, differentiated tariff methodology for electricity and district heating can be applied, which can be well-designed to reduce the burden to the low-income households and to provide incentives for efficient energy consumption.  Thus, in urban locations energy transition can be promoted by energy market reforms and price signals, while some of the savings from phase-out of energy subsidies can be directed to the targeted support to coal users in rural areas.

### 5.2 Comparing with the results of the single-region model

#### 5.2.1 Description of the single region model

For the purposes of comparison, the TIMES-Kazakhstan single-region model, further named as "aggregated" model, was used. The model was updated in 2015-2016 to access impacts of different mitigation policies under the project funded by the World Bank Partnership for Market Readiness. The aggregated model for Kazakhstan represents entire energy system (similar to TIMES 16 regions model). Following energy services demands in the residential sector are modelled: space heating; water heating; space cooling; cooking; lighting; refrigeration and freezing; clothes washing; dish washing, and other electric (which includes TV, computers, equipment, etc).

There is no disaggregation to urban/rural and flat/multiapartment buildings in the aggregated model (Figure 24). Thus, the difference between two models is not only spatial resolution, but also representation of the residential sector and residential energy demand.

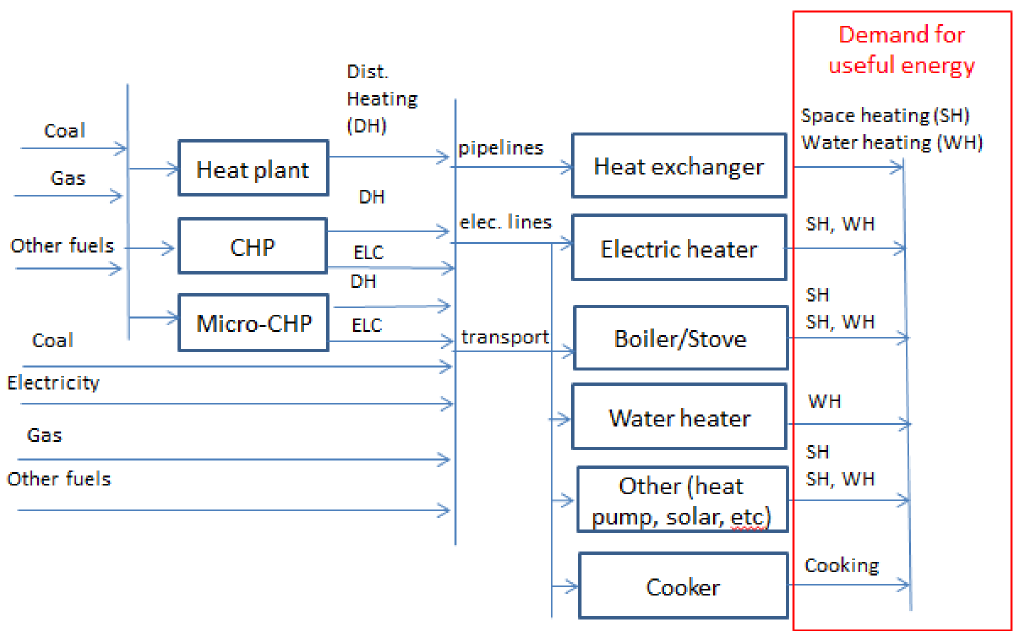



Figure 24- Representation of the residential sector in the aggregated model

Driver of the demand for residential heating is population (Table 10) in the aggregated model. Correlation factor of the demand for heating to the driver has been inherited from the global model (the Former Soviet Union region), due to the absence of the data from studies for Kazakhstan.

Table 10 Projection of the driver (2011=1)

| Driver | 2011 | 2012 | 2013 | 2014 | 2016 | 2018 | 2020 | 2022 | 2025 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|
| Population | 1.00 | 1.01 | 1.03 | 1.05 | 1.08 | 1.11 | 1.14 | 1.17 | 1.20 | 1.26 |

Energy poverty and unmet demand are not explicitly represented in the aggregated model. Energy consumption in the residential sector is calibrated according to the Energy Balance for Kazakhstan (Kerimray et al, 2017c).

Scenario with coal ban on the residential sector was compared between two models.

### 5.2.2 Demand for heating

The projected demand for heating in TIMES-Kazakhstan (single-region) model and TIMES-Kazakhstan 16 regions model is shown in the Figure 25 below.

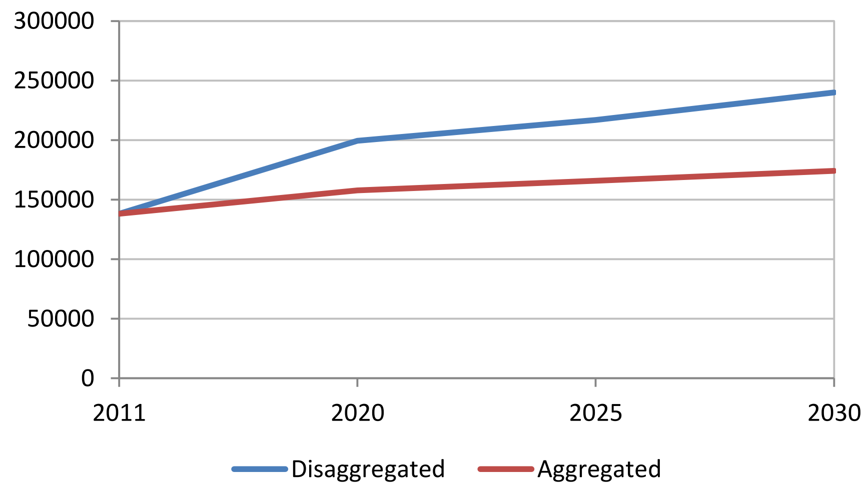



Figure 25 Demand for heating, TJ

The average annual growth rate of the demand for heating during the period 2011-2030 is 3% in the aggregated model and 6% in the disaggregated model. This difference occurs due to change of the drivers for heating demand: population (with corresponding correlation factor) in the national model and dwelling stock in the regional model. Dwelling stock was projected to increase by 57% by 2030 (compared to 2011 level), while population was projected to increase by 26% by 2030 (compared to 2011 level).

### 5.2.3 Total energy consumption and useful energy

Total residential energy consumption in 2030 is 9% higher in the disaggregated model than in the aggregated model. The fuel mix is considerably different. As an example, consumption of district heating is 70% higher in the disaggregated model compared to the aggregated model. While natural gas consumption is 11% lower in the disaggregated model compared to the aggregated model (Figure 26).

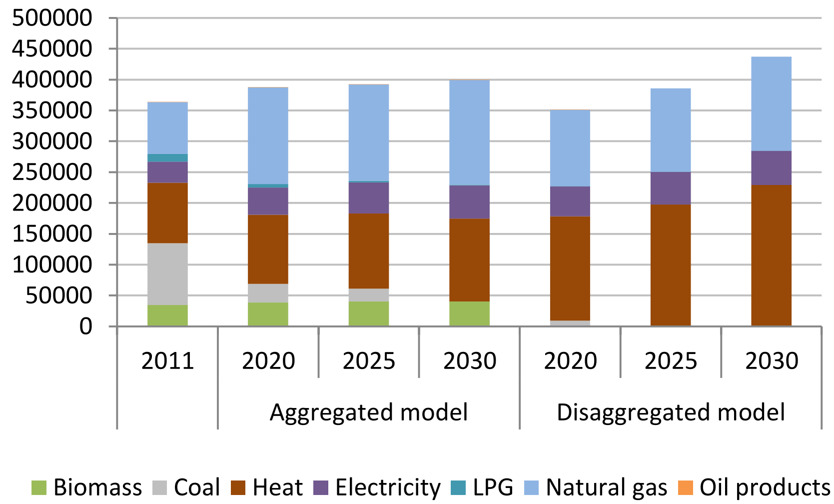



Figure 26 Total consumption of fuels in the aggregated and disaggregated model, TJ

Insulation measures are not chosen in the aggregated model. District heating (52% share in useful demand), natural gas (29%), electric heaters (11%) and heat pumps (6%) satisfy demand for heating (Figure 27).

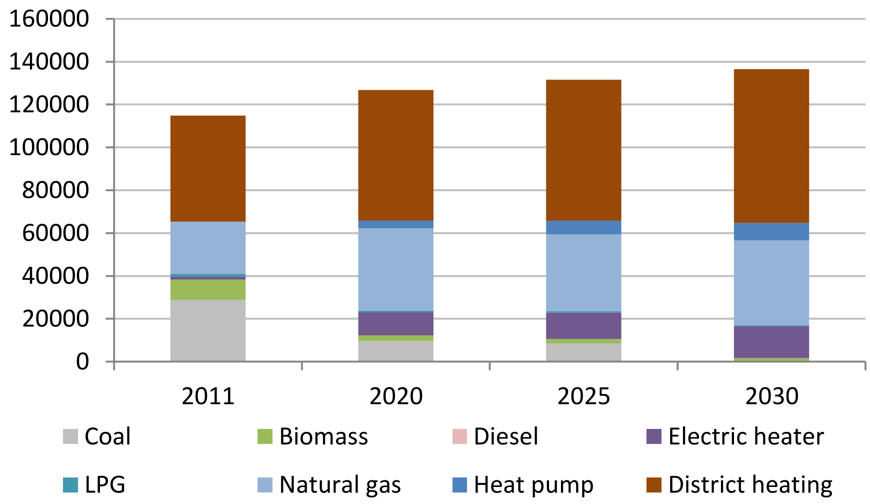



Figure 27 Useful energy for space heating by technology in the aggregated model, TJ

### 5.2.4 Discussion

The disaggregated model gives more useful insights on energy transition pathway and implications of policies, as it accounts for building categories and regions. Accounting for these differences is important as within the same building category, heating needs may vary by up to 4 times from the warmest region to coldest region as a result of climatic differences; while within same region, heating need may vary by up to 2.5 times as a result of different building category (Figure 10).

Demand for heating varies considerably (by 38%) between two models as a result of changing the methodology for its estimation. Population served as a driver for heating demand in the aggregated model. Due to the relatively low growth rate of population (compared to the surface area, households income and households energy consumption), using population as a driver for heating demand may potentially lead to underestimated values of heating demand. Additionally, correlation factor (elasticity) of the demand for heating to the population was not available for Kazakhstan. Methodology for determining heating demand was improved in the disaggregated model as surface area of dwelling stock was used as a driver of the demand. The association between surface area of dwelling stock and heating need was described in the disaggregated model according to the ISO 13790 “Thermal performance of buildings and building components”. The projection of the surface area of the dwelling stock (in the disaggregated model)is obtained from the State Program "Affordable Housing - 2020".

“Unmet” demand was quantified and accounted in the demand for heating in the disaggregated model. This was not accounted in the aggregated model.  Due to the differences in the model structure and projected useful energy demand, the results of the two models are different. As an example, consumption of district heating is 70% higher in the disaggregated model compared to the aggregated model.

# 6 Conclusions

## 6.1 Conclusions on methodology and modeling results

This study presents a strategic modeling framework for residential sector that addresses current limitations of energy system models in terms of properly representing particular challenges of developing countries, such as energy poverty, spatial and urban/rural differences. The model was used to evaluate optimal configuration of a coal-free residential sector in Kazakhstan and impact of subsidies for cleaner technologies.

Approaches for addressing challenges with data availability and analysis have been presented in this study: compilation and verification of energy balances, households survey analysis, quantification of energy poverty. These datasets were used in the preparation of the housing stock module and was incorporated to the energy system model.

The analysis has shown that there are substantial differences in heating demand by building types (up to 2.5 times) and regions (up to 4 times).The disaggregated model provided more useful insights on energy transition pathway by regions and by building types. Comparing aggregated and disaggregated versions of the model showed that resulting energy consumption varied substantially as a result of different model structure, particularly on methodology of demand representation.

The results demonstrated that constructing infrastructure for providing district heating and network gas coupled with significant energy efficiency measures are the least cost solutions for coal-free heating in Kazakhstan. Retrofitting measures are used by all building types, but they play a crucial role in reducing heating demand in coal dependent buildings, when a coal ban is introduced. In urban, densely populated areas, district heating systems provide the most optimal solution. For flats, combining district heating with energy efficiency is almost the single optimal solution. Without a gas pipeline option to non-gas supplied regions, ground-source heat pumps satisfy most of the demand for heating in rural locations coupled with extensive building retrofits.

The coal ban alone may have a significant impact on energy affordability (as there was significant impact on marginal price for heating). Subsidies for clean technologies should be primarily targeted to rural population relying on coal, while retrofit measures can be offered for all building types. Coal ban in the residential sector almost completely eliminates emissions of $PM_{2.5}$ and CO from the residential sector. For achieving reductions in $CO_2$, $NO_x$, $SO_x$, additional measures are needed in the supply side (e.g. pollutant controls, cleaner fuels).

The approaches for addressing data limitations and model construction can be replicated to other countries.

## 6.2 Implications for policy makers

### 6.2.1 Lessons learned from the international experience

Coal is still a major household fuel in some countries, including Kazakhstan. 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. Health benefits are mostly higher than the costs of most of the cleaner alternatives in the regions with severe air pollution problems. 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. Most developed countries have either banned or greatly restricted household coal use to mitigate its effects on urban ambient pollution. Therefore, pathways for gradual phase-out of coal use and its substitution with other alternatives have been investigated in this study.

### 6.2.2 Energy poverty

The "energy poverty" problem is not officially defined in Kazakhstan and currently there are no specific policies and measures to tackle energy poverty in Kazakhstan. Approaches, findings, indicators of energy poverty employed in this study can be used for formulation of relevant policies. In this study, employing three indicators of energy poverty resulted in different results, demonstrating the complexity of energy poverty problem and different aspects leading to energy poverty problem. Energy poverty threshold cannot be a universal value since every country has its own factors for energy poverty. As in case of Kazakhstan high heating needs due to climatic conditions, low coverage with gas and district heating infrastructure and regional inequalities are predominant factors of energy poverty. The analysis of the households survey in this study demonstrated there is a high incidence of energy poverty in Kazakhstan both in terms of energy affordability and lack of clean fuel options. It was also demonstrated that "unmet" demand value was 13% of total national heating demand in the base year, with higher prevalence in coal regions. Therefore energy planning should account for satisfying entire energy demand without neglecting "unmet" demand (energy poverty).

### 6.2.3 Coal-free residential sector strategy

It was demonstrated that building retrofit measures play an important role in the coal-free residential sector strategy, especially for households those affected by coal ban. Thus, awareness raising campaigns, providing access to finance for building retrofits (e.g. reduced interest rates), and targeted support on building retrofit for energy poor have to be the key initial steps for residential sector transformation strategy.

To attract private investments in the gas and district heating infrastructure (as well as energy efficiency), Government should transform energy sector from the existing regulated energy prices to utilizing market tools and allowing prices to rise in order to reflect the necessary investments. This inevitably will affect energy affordability of households. Monitoring of energy poverty indicators (including energy affordability) can assist in developing effective support policy to low-income households, thus preventing negative social consequences of rising energy prices.

Renewable/alternative sources of heat are not yet affordable for many households in Kazakhstan, especially those located in rural areas. If the construction of gas pipeline is delayed or cancelled, Government should launch targeted subsidies/grants to coal users in rural areas for installing heat pumps with retrofits. The regions with no access to gas should be targeted first, as they are mostly affected by energy poverty. The modeling results can serve as a basis for national intervention program/strategy for residential sector and energy poverty reduction.

Measures in the residential sector only may not be sufficient for reduction of some emissions ($CO_2$, $NO_x$, $SO_2$) from the energy system. Emissions from the supply side (power and heat plants) can be reduced by development and implementation of emissions standards close to EU norms, retrofitting and installation of filters at plants, as well as switching existing coal-fired power plants to gas.

### 6.2.4 Energy statistics

Recommendations for improvement of energy statistics include an urgent need to move towards harmonisation of its energy statistics with internationally recognized standards in order to better monitor and plan energy system transformations and climate change mitigation measures. Changes should be made not only in the questionnaires, instructions and reporting formats used but also stricter penalties should be introduced for providing incorrect data and for poor control over the data provided by companies.

### 6.2.5 Energy modeling

Energy models are useful for informing policy makers on optimal energy system and sectoral development pathways. Analyses based on technology rich energy models should be promoted and deployed in the country, to provide different views and pathways on the energy system development and to provide verification and comparison of the results.

## 6.3 Further research

The key limitations of this study are that the occupancy rate and indoor air temperature parameters had to be estimated and simplified, due to the lack of surveys and data. Future studies should concentrate on households survey of these parameters and behavioral issues, as well as epidemiological studies quantifying health impacts. Future research should be conducted to reduce costs and increase efficiency of heating technology options for remote cold climate regions. Uncertainty to multiple variables simultaneously also needs to be modelled.

There are no previous studies on the historical trends of heating-degree-days in the regions of Kazakhstan, which can serve as a basis for the sensitivity analysis of model results on varying climatic conditions. There is a need for studies of historical and future heating-degree-days taking into account climate change impact. Sensitivity analysis of model results can be conducted on varying climatic conditions (heating-degree-days).

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