# Stimulating an energy fuel transition in the residential sector of Chinese lower-tier cities

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by

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# Acknowledgements

Having lived in Shanghai during high school between 2007 and 2012, I experienced the problems of economic growth in China personally. Air pollution, otherwise called 'smog' had an impact on my daily life. I was made aware of the impact that pollution may have on health and learnt where a significant portion of air pollution came from. Since the start of my bachelor's degree at the faculty of Technology, Policy and Management I have been looking forward to ever do research about air quality in China. When the opportunity came to join research about energy consumption and air pollution in Jingmen, I knew that I found my ideal master thesis research topic. The opportunity was offered to me by 李芬. Not only did she offer me this research, she also organised the logistics for this research altogether, by taking me to several cities for research, organising meetings with stakeholders while at the same time making me feel at home at the company headquarters in Beijing. Without 李芬, none of this research was possible. From the research team at IBR Beijing I would also like to thank 彭锐, who made sure I could sleep at night by dealing with all housing-related complications I came across in Beijing.

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# Executive Summary

China is undergoing massive changes in order to tackle their carbon dioxide emissions problem. Aside from the problem of climate change, it is facing another problem – that of air pollution. The use of dirty fuels by residential households lead to emissions that are harmful to the environment, as well as to the health of citizens. In order to reduce this, local governments are tasked with inducing a change in household fuel consumption from dirty fuels (such as biomass and coal) to ones that are cleaner and more efficient, such as natural gas or electricity. The top-down hierarchy in the Chinese governance system sets targets for individual cities, while the smaller 'lower-tier' cities are left to their own devices in how to implement suitable policies in order to reach these targets. This often leads to the implementation of exclusive yet effective policies. Such policies ensure targets are reached, but also leave citizens without any fuel alternatives, or forces residents to resort to other unhealthy fuels.

The goal of this research was to investigate *how lower-tier prefectures can stimulate their residents to shift daily energy fuel demand from traditional fuel use to cleaner and more efficient fuels, while preventing the population from unwillingly reducing their total energy demand.* This had been done through a case-study research in the prefecture city of Jingmen in Hubei province. Survey research and a co-simulation model of system dynamics and an energy planning system are used to better understand citizen energy consumption behaviour in urban and rural areas.

Households in Jingmen are already consuming a significant amount of clean fuel. In the urban area, the coal and biomass users are clearly in the minority, while improvements can still be made in the rural area. Citizens are aware of the dangers coal consumption may pose, but biomass is considered a cleaner alternative as they are unaware of the dangers that biomass consumption can pose to individual health. Where the urban citizens signal that they find the effects of fuel consumption on health important, the main concern for the rural area lies in the price of fuel and convenience of consumption. Even though rural citizens are aware of the dangers that dirty fuels pose to pollution problems, the concern is overshadowed by the importance of having access to fuel in the first place.

The extent to which the research in Jingmen can be generalised to other cities in China depends on the geographical and cultural differences to Jingmen. If surveys show similar behavioural patterns, the model can be generalised for other cities after slight adjustments to model values. If larger differences are present changes in model structure is necessary. As the research focuses on policies to influence the energy consumption, the model takes a bottom-up demand-driven approach. Such an approach will always present different findings to a top-down approach due to differences in assumptions made. Although both have their own advantages, the desired approach depends on the policies that are to be investigated. The model is therefore only suitable if similar policies need to be researched.

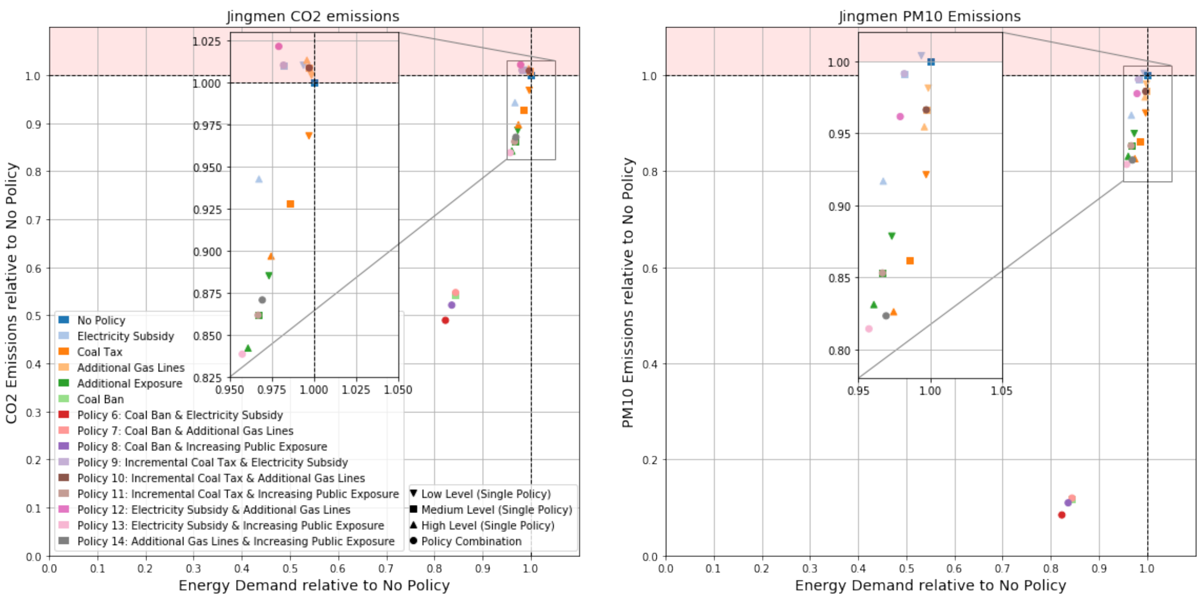
Energy consumption demand behaviour was investigated using the mechanisms of reaction to energy price level, convenience of fuel consumption, knowledge about clean and efficient energy use and willingness to making a conscious change in consumption. The research investigated the effects of policies implemented between 2020 and 2030. These policies are: (1) a ban on coal for the entire residential sector, (2) a tax on coal consumption that increases in yearly increments, (3) a subsidy on electricity consumption, (4) improving accessibility to natural gas, and (5) increasing the exposure of residents to the importance of clean and efficient energy use.

The investigation presents the following findings:

1. A ban on coal very effective in reducing emission levels but will force people to consume less energy. Without the lack of other supportive policies or alternatives available to the households, such a restriction will be detrimental to energy demand.
2. A taxation on coal consumption could be effective in the rural area. The rural area will use biomass as a substitute for the coal, which can see biomass consumption to increase. However, instead of inducing a change in behaviour, people will simply be restricted from using energy.

3. A subsidy on electricity reduce emission levels, is not very effective by itself but could instead be implemented as a supporting policy with another more restrictive policy, in order to maintain the energy demand. Reducing the electricity price will increase demand of all fuels. Therefore, implementing this policy alone will only see an increase in demand and emissions.
4. Placing additional gas pipelines at an increased rate will be mostly effective in the urban area. Increasing the convenience is very effective and therefore such a policy will see a short-term decrease of biomass and coal consumption. However, this policy is least effective policy in the rural area.
5. Exposing the population to the importance of clean fuel use can be effective if implemented correctly. As people will become more aware of the dangers of coal consumption, this fuel will likely see a reduction in usage. However, as the policy depends on the cooperation of citizens on a large scale, its actual effectiveness is uncertain and reliance on this policy is risky. The policy is most effective supplementary to another.

The following figure exhibits the policy outcomes as a graph, with the average energy demand on the x-axis, and the average emissions on the y-axis. All values are scaled relative to the 'No Policy' scenario alternative, meaning that the demand and emissions of this scenario is set at point (1, 1).




From this investigation, the following policy recommendations are made:

- **A coal ban will best reduce $CO_2$ and $PM_{10}$ emissions, but the it is more effective to do in combination with an additional supportive policy such as an increase in gas pipeline placement or an electricity subsidy.**
- **In the rural area, an incremental coal tax will be effective in reducing $PM_{10}$ emissions without impacting the energy demand. However, this policy is ineffective in reducing $CO_2$ emissions and is ineffective in the urban area altogether.**
- **A combination of an electricity subsidy with additional exposure will likely be effective but also risky as it heavily relies on the cooperation of households. The policy is effective because a subsidy will not only impact price-related measures but will also cause citizens to cooperate with the desired policy more easily.**
- **Increasing the placement of gas pipelines will have a minimal impact in the long term but could be relatively effective in order to further accelerate a shift from coal to natural gas consumption.**

# List of Abbreviations

| Abbreviation | Meaning |
|---|---|
| CCPG | Central China Power Grid |
| CPC | Communist Party of China |
| RMB | Renminbi (currency in China), also known as Yuan |
| LEAP | Long-Range Energy Alternatives Planning System |
| SD | System Dynamics |
| VBA | Visual Basic for Applications |
| API | Application Programming Interface |
| $PM_{10}$ | Particulate matter smaller than 10 micro-meters |
| $CO_2$ | Carbon Dioxide |
| SDG | Sustainable Development Goal |
| GDP | Gross Domestic Product |

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# 1. Introduction to China's emission situation

## 1.1 China's current emission situation

With the continuous growth of global energy consumption, the impact of fossil energy on environmental pollution and the global climate is becoming increasingly severe. As the largest emitter of carbon dioxide ($CO_2$) worldwide, China's total energy consumption (4.26 gigatons of coal equivalent) and $CO_2$-emissions (9.76 gigatons of $CO_2$) accounted for 23.0% and 27.5% of global energy consumption and $CO_2$-emissions in 2014 respectively (Zhou & Wang, 2018). Reasons for such high emission values are China's large population and its rapid economic growth over the past twenty years. As a country that is undergoing changes at an unprecedented pace, and one of the countries with most emission and air pollution problems in the world, a lot of research regarding emissions and air pollution is directed towards China (Y. Liang, Yu, & Wang, 2019; Shan et al., 2017; K. Wang, Wang, Li, & Wei, 2015; Yuan, Lyu, Wang, Liu, & Wu, 2018). Yet, another reason why China is the subject of such extensive research is because the research is often sponsored by the state itself. The increased funding on climate change research, and the sheer amount of sponsored papers highlight the importance placed by the Chinese state on curbing nation-wide emissions. The majority of resources have gone to research on the Beijing-Tianjin-Hebei area (the area that has suffered most from air pollution in recent years), resulting in stronger pollution control policies and a better understanding of pollution in general (Jia, 2018).

Since the Paris agreement came into effect in 2016, China has further recognised its responsibility by strengthening its environmental targets. As the current front runner in cutting $CO_2$-emissions, China is on course to reach many of its ambitious targets set (H. Wang et al., 2019). Solar farms have been installed all across the north of China and since 2013, the country has been the world's leader in solar thermal energy. From a PV capacity of under 1GW installed in 2010, China now plans to attain a PV capacity of over 200GW in 2020 (Yang, Hu, Tan, & Li, 2016). Aside from the large investments made in promoting solar energy, there has also been a heavy increase in wind power generation, from almost 45GW in 2010 to over 250GW in 2020 (Sahu, 2018). However, the increase of renewable energy does not come at the cost of a reduction in fossil fuel burning. Despite general positive trends in reducing coal consumption relative to the total energy consumption, China fails to significantly reduce its overall coal consumption and emissions continue to rise (S. Zhao & Alexandro, 2019; Climate Action Tracker, 2019). An important term when considering carbon emissions is the 'peak carbon emission value', the maximum amount of carbon dioxide a country will emit in a year. The year at which the peak carbon emission value is reached is especially important. According to commitments made during the Paris agreement, China is targeting to reach the year of 'peak carbon emission value' around 2030 (Gallagher, Zhang, Orvis, Rissman, & Liu, 2019).

Besides carbon dioxide emissions, the country is still pestered by heavy air pollution. Particles with an aerodynamic diameter less than 10μm ($PM_{10}$) particles, and especially those smaller than 2.5μm ($PM_{2.5}$) cause sincere health effects. Air pollution is estimated to be the cause of 1.1 million deaths each year (Y. Zheng et al., 2017). The quality of the air is extremely dependent on local conditions, such as weather patterns, temperature and local residential emissions. Pollution levels between individual cities can differ heavily, depending on other factors such as wind and precipitation (Vanos, Cakmak, & Kalkstein, 2015). Policies to combat 'local air pollutants' are implemented on a more local scale, while policies in combatting $CO_2$-emissions and other major greenhouse gases levels contribute to national emissions, which are therefore delegated from national planning.

In recent years, a range of policies have been implemented to curb emissions and air pollution. These policies especially take effect during periods where expected emissions are high. National policies range from temporarily reducing emissions to more permanent solutions. In accordance with the hierarchy within the Chinese national government, most policies so far have aimed providing incentives for local officials to reduce emissions in their local environment. However, aside from local incentives, China has also focused on controlling emissions through a range of policies already implemented, amongst many others, the policies include (Sandalow, 2018):

- Temporarily closing down factories during periods at which emissions are high;
- Phasing out of coal-fired power plants;
- Road space rationing (such as odd-even license plate policy of cars that are allowed to drive on certain days introduced during the 2008 Beijing Olympic Games);
- More severe criminal punishment for heavy violators of environmental policy;
- The enhancement of monitoring capabilities of emissions and usage, especially in the industrial sector;
- Targets set for renewables such as hydro, wind, solar and nuclear power;
- The development of nuclear power plants around the country;
- A national emissions trading scheme, which is expected to be fully implemented in the 2020's (to become the largest emission trading program in the world);
- The continuous expansion of a natural gas grid with importing gas from Central Asia, South-East Asia, and the Russian Far East (expected to open in 2019) to households around the country;
- Increased import of liquified natural gas (LNG);
- Connecting newly built buildings to the natural gas grid;
- Promotion of electric vehicles usage.

Many of these policies have focused on the energy, industry and transportation sector as these are responsible for the highest emissions. Residential emissions are oftentimes omitted in the policy process as sufficient data is missing and because these emissions are relatively small, especially in terms of $CO_2$. This makes reducing residential emissions less attractive to focus on, especially from a national perspective. However, curbing such emissions will allow the country to further decrease its overall emissions with just minimal loss of GDP or overall production values. Instead, using more efficient and cleaner fuels may actually be beneficial to a country's economy (Ferroukhi et al., 2016).

## 1.2 Residential emissions in China

The air pollution from residential energy consumption is harmful to the environment and citizen health. Many households use coal and/or biomass for cooking and heating purpose, Zhang and Smith (2007) state that nearly all rural residents in China use solid fuels (biomass and coal) for cooking and heating purposes. Despite the situation improving significantly since 2007, a large portion of especially rural households still use either biomass or coal as a fuel source (Pachauri & Jiang, 2008; Delang, 2016). The biomass used comes from the burning of crop residue, straw or firewood and is generally obtained by the individuals using the fuels themselves. The continued use of inefficient, dirty fuels such as coal and biomass, is a conundrum for China: current investments made for renewable electricity are less effective if citizens keep using these traditional, dirty fuels as their primary energy source. Residential emissions are responsible for a large number of health-related issues due to inefficient fuel consumption and poor household ventilation. Household air pollution is estimated to be the cause of between 350,000 and 500,000 annual premature deaths in China as a result of adverse health effects and a cause of pre-term births (Delang, 2016). Incomplete burning of these fuels leads to high indoor concentrations of air pollutants and the combustion of coal is directly responsible for sulphur dioxide emissions, as it yields acid rain and further causes soil acidification (T. J. Wang, Jin, Li, & Lam, 2000).

Prefectural governments therefore have the desire to stimulate their residents to move from traditional energy fuels such as coal and biomass consumption to more clean and efficient fuels such as electricity, or natural gas. Each household already has a minimum amount of electricity consumption, as not all daily household appliances can be powered by direct use of coal, biomass or natural gas (for example for using mobile phones, lighting, television, etc.). The substitutable products mainly concern cooking appliances and heating. An increase in electricity supply may instead come from coal-fired power plants or other fossil fuels, meaning that electricity generation is not always renewable. However, the individual prefectures are not responsible for the supply of electricity, rather the city is connected to power grids that span multiple provinces controlled by the State Grid Corporation of China (State Grid Corporation of China, n.d.).

As the cities do not exert control on the supply, the exact source of electricity falls outside their responsibility. However, if households shift their energy consumption from coal and biomass to electricity and natural gas, the consumption can be controlled: provincial/national government can then better manage what sort of fuel is used to supply the electricity, rather than citizens deciding this for themselves. Furthermore, if the electricity provider still decides to fill up the additional electricity demand with the additional burning of coal, this will occur in the controlled environment of a power plant, which are much better equipped to deal with the resultant gasses than household chimneys are (J. Zhang & Smith, 2007). As these power plants are generally located outside the direct vicinity of the citizens, it will also reduce much of the health issues caused by the burning coal or biomass.

## 1.3 Policy development and implementation in China

Undeniably, the political arena within the country plays a role in assisting China in reaching its ambitious targets set. Its ability to make radical improvements in reducing emissions cannot be seen separately from the country's political system. The People's Republic of China is ruled by a single party: The Communist Party of China (CPC), headed by their General Secretary. General long-term policy plans are developed through the use of multiple Five-Year plans.

### 1.3.1 China's Five-Year Plans

Like the name indicates, China's Five-Year Plans are a series of plans developed on a semi-decade basis in order to indicate the general direction and plans of social and economic development. The first five-year plan was developed in 1953, four years after the establishment of the People's Republic of China. The five-year plans play an essential role in mapping out strategies for economic development by setting targets for growth and reform as it currently exerts an important influence on China's economy, social life and provides guidance for its industries (Chen, Zhen, & Xin, 2017).

China's current five-year plan (Thirteenth-Five) formally came into effect in 2016 and will run until 2020. The plan is characterised by its focus on renewability and the country's environment. Such five-year plans are further prepared to ensure that long-term goals (such as those set for 2030 and 2050) will be achieved in an incremental fashion. Although such policy-making techniques are also used by other countries around the world, the amount of detail in the Chinese five-year plans, its current political system and its general methods of policy implementation ensure that desired situations will be reached using 'back-casting' techniques. Furthermore, the plans are implemented in an extremely hierarchical fashion – strategies are set up by the National Development and Reform Commission (NDRC), the Department of Climate Change as well as the National Leading Group Dealing with Climate Change, Energy Conservation and Emission Reduction. The actual implementation is then left to the provincial governments, which in turn delegate the decision-making of policies to lower level governments. Local governments need to implement their own laws and regulations and enforce them through locally assigned street-level bureaucrats (Gilley, 2012; Qi, Ma, Zhang, & Li, 2008; National Development and Reform Commission, 2008). This hierarchy ensures direct responsibility throughout the entire policy process and therefore consequences can be directly linked to individual departments that fail to reach their set goals.

### 1.3.2 Democratic and authoritarian approaches to environmental policy in China

China's political system has been tied so closely to their approach towards renewability, that China's approach to climate change has been described as 'authoritarian environmentalism'. Gilley (2012, p. 288) defines authoritarian environmentalism as a "public policy model that concentrates authority in a few executive agencies manned by capable and uncorrupted elites seeking to improve environmental outcomes". On the other hand, democratic environmentalism is defined as a "public policy model that spreads authority across several levels and agencies of government, including representative legislatures, and that encourages direct public participation from a wide cross-section of society"

(Gilley, 2012, p. 289). In other words, while authoritarian environmentalism is an effective yet exclusive policy model, the democratic counterpart can be considered less effective but more inclusive. Its effectiveness may come from the deliberate exclusion of business actors, which mostly oppose environmental action (Beeson, 2010). However, this exclusion of certain actors also comes at a cost. In order to reduce carbon emissions some policies may be implemented in order to meet last-minute targets, sometimes coming at the cost of citizen well-being. In 2011, the city of Linzhou (Henan Province) was forced to close local power plants in order to achieve energy reduction targets. Thereby leaving about 3500 households, as well as schools and hospitals, without energy (Yan, 2011). Other restrictions have included laws such as: all drivers having to leave their cars at home at least one day a week (Deng, 2017); elevators are not be used to reach the first three floors of public buildings; and that public sector employees should wear casual clothes to work in the summer (Bian, 2012). Such 'authoritarian' environmental policies could likely not be implemented in a democratic government, without facing sincere opposition from various stakeholders. The local governments that enforce these policies are also under pressure themselves as cities are required to reach their targets. As their targets are approaching their due date, such policies may be implemented more frequently in order to reduce emissions in the short term. The aim of local governments is thereby to impose local regulations so that citizens have to adopt a low-carbon lifestyle.

### 1.3.3 City tiers

The Chinese city tier system is a hierarchical classification of Chinese cities located within mainland China often used by the media in order to differentiate between different city types. There is no official list published nor are these tiers directly recognised by the national government. Therefore, the classification may vary slightly depending on the source. This research shall use the tier distinction made by the South China Morning Post (2016) which classify the cities in four tiers depending on GDP, population, as well as the 'political distance' from the central government. High-tier cities (Tier 1) are cities such as Shanghai, Beijing and Guangzhou. These cities have a disproportionately high income and population compared to other cities in the country. The cities are also in (near) direct control of the central government. Lower-tiered cities are often located in the centre or west of the country. An example of a lower-tier city (Tier 4) is the city of Jingmen in Hubei province, which has a much lower GDP, lower population and a larger political distance from the national government (South China Morning Post, 2016).

As part of the nation-wide commitment to reduce emission levels, several cities have had their energy emissions investigated in detail using energy planning modelling systems. Research on individual urban energy systems has been conducted in China in cities such as Beijing (G. Hu & Mu, 2019; Su, Chen, & Yang, 2016), Guangzhou (Ou et al., 2017) and Suzhou (S. Liang & Zhang, 2011). The authors recommend clear-cut, top-down, implementable policies, such as using other energy sources (i.e. natural gas or hydro-power instead of coal) and reducing emissions in industrial exports. However, most cities researched are of higher-tier ('Tier 1' and 'Tier 2'), while environmental research on lower-tier cities lack ('Tier 3', 'Tier 4').

As the lower-tier cities are less influential for the national GDP, these cities are at the periphery of central control (Y. Li & Wu, 2012). Top-down policy implementation occurs much less frequent in such cities, forcing them to rely on bottom-up governance much more. According to Zhao (2015), bottom-up approaches have become more frequent in Chinese governance through increased autonomy of local governments. Nearly half of the Chinese population, which live in the less developed cities are subject to bottom-up policy decision making. As national emissions and economic development depend on output from these smaller cities, effective policy implementation in these less developed areas is of utmost importance to the national government, even if they do enjoy less direct influential control from the national government than the larger cities.

## 1.4 The challenge China is facing regarding residential emissions

Residential fuel emissions are a core problem to China's overall emission levels and thereby the health of its citizens. In absolute terms, the emissions coming from individual households are substantially lower than the emissions from the other sectors. For this reason, the residential emissions often tend to be ignored in the bigger picture of emission reduction. A significant portion of research conducted has been done on the higher-tier cities, while the lower-tier cities are left to their own devices regarding policy implementation. The lack of focus on lower-tier cities is a problem since these are the cities where residential emissions relatively high, while lower levels of income and their remoteness limit the fuel alternatives available for them. Inducing a change in household fuel consumption in lower-tier Chinese cities will improve citizen health and reduce carbon dioxide emissions.

## 1.5 Report outline

**Chapter 2** further describes the research approach that will be taken. The system that is investigated is described in detail in **Chapter 3**. Subsequently, **Chapter 4** explains how the research problem is approached with relation to the actual case as well as laying out the viable demand-related policies. **Chapter 5** discusses the validation of the developed model and tests to what extent results from the research will be generalizable in a larger frame. **Chapter 6** then provides an overview of the results that come from policy analysis obtained through the simulation model. **Chapter 7** leaves room for discussion about the practicalities regarding policy implementation. Finally, **Chapter 8** closes with conclusions and recommendations for further implementation and future research.

# 2. Approach to investigating household energy use in lower-tier Chinese cities

In order to solidify a basis for research, this chapter will open with a literature review about the research that has been conducted on household energy consumption. Following this review, the main research question and several sub-questions are drawn up in **paragraph 2.2**. The different methods that are used to conduct the research are laid out in **paragraph 2.3**. **Paragraph 2.4** then establishes the scope of research. The chapter concludes with **paragraph 2.5** establishing the research as a relevant thesis subject in the Engineering and Policy Analysis programme at the Delft University of Technology.

## 2.1 Literature review on household energy consumption

The consumption of household energy and its resulting emissions has been studied using a variety of approaches. Oladokun & Odesola (2015) classify two main approaches: a top-down econometric approach and a bottom-up statistical approach. Combining a bottom-up and top-down approach is difficult as the two approaches tend to conflict with one another due to the initial assumptions that need to be made (Kavgic et al., 2010). According to Rivers & Jaccard (2005), the different approaches often end up with diverging results, which creates confusion for policy makers and thereby reduces model value. On the other hand, a single approach energy model may fail to encompass the larger picture of the problem. Top-down approaches tend to be supply-side driven, whereas bottom-up approaches are often driven by the demand-side.

### *Top-down approaches to researching household energy consumption.*

In top-down approaches such as those taken by H. Zhang & Lahr (2018) the energy consumption demand is shown to be heterogenous throughout China due to differences in geography and therefore culture, climate and availability of energy. Such an approach can provide policy advice from a top-down government perspective, such as providing better guidance to resident, or imposing taxes and subsidies. However, such approaches fail to acknowledge further impacts a change in consumption behaviour may have on the everyday life of residents. The top-down macro approach lacks concern about individual behavioural reactions that households may have to the policy. This makes it difficult to see the practical effectiveness of policies on a street-level basis. As top-down models take the supply of energy as their starting point, most research that take this approach places more focus on sectors beyond just the households, but focus on multiple sectors within an area or city (F. Dong et al., 2018; K. Y. Dong, Sun, Li, & Jiang, 2017; S. Liang & Zhang, 2011). Research in energy modelling systems provide a high level of detail about potential peak-emission research, provides clear insights, and provides a lot of freedom in mapping out the energy consumption structure of a city, area or country as a whole. However, such a top down focus lacks consideration for the socio-technical aspects related to energy consumption and carbon emissions at a household level. For this reason, research that focuses on household energy consumption often approaches the problem from a bottom-up approach instead.

### *Bottom-up approaches to researching household energy consumption*

Bottom-up approaches to mapping energy consumption generally take the energy supply as a given and research the underlying reasons behind the causes of energy demand. Such approaches can better consider the factors that drive individual households. This allows for policy advice geared towards impacting the specific households while keeping local cultures in mind. Studies in China that use such an approach find that residents are reluctant to save energy at the expense of quality of life unless they are environmentalists or under high economic pressure (Yue, Long, Liu, Liu, & Chen, 2019) and that there should be a further focus on raising public awareness so that economic incentives can play a more significant role in energy savings (S. Hu, Yan, Guo, Cui, & Dong, 2017). Jiang & O'Neill (2004), and in later research Muller & Yan (2014) consider the fuel source directly and call attention to the need for residents to move away from traditional energy fuels such as coal and biomass consumption to more clean and efficient fuels such as electricity, or natural gas. However, there is limited research that expresses how individual households can be stimulated to do this. The studies use statistical models and focus on inherent factors that drive fuel consumption such as household size, income, geographic condition and education. However, these factors are generally the underlying mechanisms that drive behaviour, not the direct cause for behaviour itself, which are factors such as the per capita energy demand, proportion of income spent on energy, climate and cultural factors, and knowledge about efficient energy use and good insulation practices, respectively.

### *Using system dynamics to model household energy consumption*

A variety of modelling approaches can be taken to investigate household energy consumption. Research that focusses on emissions of a city on a macro-scale are often approached through energy forecasting models, whereas studies related to factors of household energy consumption behaviour have a heavy inclination towards statistical analyses. Oladokun, Motawa, & Banfill (2012) highlight the importance of the underlying socio-economic environment of households for modelling energy consumption. In a system dynamic modelling study to investigate the effect of government policy to households on a micro-scale in the United Kingdom, they find that the field of energy research should combine quantitative and qualitative variables together. System dynamics has also been used for a similar purpose by Davis & Durbac (2010), who find that it is a suitable method of research that provides different insights than a mere statistical approach. In their approach they used survey data and translated this into a system dynamics model to understand the behaviour of residents in the South African Western Cape. However, this research is geared towards the general provision of energy to households rather than a focus on emission reduction.

Although bottom-up research is suitable to model energy demand patterns for households, this approach may provide limited insights in a city as a whole. Feng, Chen, & Zhang (2013) use a system dynamics model in a top-down approach, in which individual sectors are developed as sub-models, which is used to map out city-wide energy consumption and emissions. This top-down approach developed for the city of Beijing has limited attention to detail regarding household behaviour and the city of study has inherent differences with the lower-tiered cities in China. On top of that, the variety of applications for system dynamics models also limit detail about potential energy use, energy optimization and emission policy that can better be done using specialized energy modelling framework systems.

## Research gap

There is a lack of empirical data about private consumption values in China, especially lower-tiered cities have limited statistical data – let alone consumer behaviour data about energy consumption. Many households in China’s rural areas are not registered in accordance to state regulation, let alone their energy consumption. The limited focus on household behaviour is also due to the fact that the residential sector tends to use much less energy and have much lower emission levels than the other sectors do (Sheng, Cao, & Xue, 2018). This means that the individual citizen behaviour is generally not the focus of the government when looking for policies that helps build a ‘greener’ city. The approach of focusing on individual household behaviour can also be seen as too individualistic for a research to be conducted at a city-level scale. However, this lack of focus does bring about a big gap in earlier research conducted at lower-tier cities. Currently, these lower tiered cities have limited communication with the central government and little research has been done on how such traditional cities can reduce their emissions. Households in urban areas (especially in the larger cities) are becoming increasingly connected to the natural gas grid, the use of which is stimulated through convenient fuel provision at subsidized prices (Liu, Dong, Jiang, Dong, & Li, 2018). Local governments in higher-tiered cities need limited intervention methods to reduce their residential emissions as their energy fuel consumption is stimulated by national policy. This connection with the natural gas grid is possible because many urban citizens live in densely populated high-rise apartment buildings built in recent years. However, rural areas are less accessible to connection to the national gas grid. This population will continue to use coal or biomass as a primary fuel unless other alternatives become more accessible to them. Many of the rural houses are of such insufficient quality that they are unlikely to make long-term connection to the gas grid viable. On top of that, electricity is so expensive for the residents in the rural areas, that consumption is consciously minimized, the rural population tends to use a variety of other fuels for their energy demand.

The goal is to stimulate a shift towards cleaner fuels without forcing citizens to use less fuels as a result of a lack of possible and affordable alternative fuel types. This means that if consumption were to decrease, this ideally occurs through increase of citizen knowledge about the importance of fuel reduction, and their overall willingness to do so. In this situation, a single modelling approach fails to provide a complete picture in relation to actual emissions and such research generally fails to consider the city as a whole.

## 2.2 Research questions

**The objective of this research** is to provide insights for prefectural governments for the grounds upon why their citizens are using certain sources of fuels for general household energy consumption. At its base, the investigation is done using field-work research from which the general data is organized such that a quantitative model can be developed in order to attain further detail on residential behaviour. Such a model should extend to provide further policy insights for the prefectural government of a case-study city. This method can be used in order to better model energy demand, either for multiple sectors within a case-study city or for a single sector in multiple cities throughout the country. In order to investigate the research objective and attain this research goal described, the following research question is set:

*How can lower-tier prefectures in China stimulate their residents to shift daily energy fuel demand from traditional fuel use to cleaner and more efficient fuels, while preventing the population from unwillingly reducing their total energy demand?*

This main research question can be broken down into the following sub-questions:

1. What is the current attitude of households in a lower-tier Chinese city towards energy consumption, fuel choice and emissions of $CO_2$ and $PM_{10}$?
2. How can a quantifiable model of household energy consumption be developed that encompasses the attitude of households in a low tiered Chinese city?
3. To what extent can such a quantifiable model be used as a general blueprint for policy investigation in cities throughout the country?
4. Which policies can effectively reduce the $CO_2$ and $PM_{10}$ emissions with minimum impact on household lifestyle?

The first sub-question considers the current situation regarding household energy consumption. There are currently a lot of unknowns regarding residential energy consumption in smaller Chinese cities. Most of the knowledge comes from absolute quantitative figures, rather than individual behaviour that is qualitative in nature. An exploratory analysis about the current attitude of citizens in the lower-tier cities needs to be conducted in order to know what would likely incentivise households to shift from dirty fuels to more efficient ones. This research is conducted for a 'typical' case-study city, addressed in **Chapter 3**.

The insights obtained from the first sub-question can be used to conceptualize a quantitative research model. In order to do that, residential attitudes and behavioural patterns need to be translated into quantitative figures and logical relations between variables. With the conceptualisation of such a model, it is possible to consider several policies for the prefectural government that provides understanding about which policies can be considered for adjusting residential energy fuel demand. The conceptual development and policies are addressed in **Chapter 4**.

If a fully functioning quantitative model is developed, the model can be tested for discrepancies and impact assessment. Through model testing it is possible to observe the extent to which certain influences are merely present in the case-study used for this research, and what effects can be generalised for other lower-tier cities in China. These influences are investigated through model testing in **Chapter 5**.

The impact of the policies can have on energy demand and especially on reducing emission levels are investigated in **Chapter 6**. This chapter on policy results provides full insights about the potential impact the policies have on the lives of the residents in lower-tier cities. Through an analysis of all three sub-questions, the main research question can be answered in the conclusion presented in **Chapter 8**.

## 2.3 Research methods to investigating household energy consumption

### 2.3.1 Case study approach

The research will be conducted using a case study city for which the research will be performed. Using a case study for can be advantageous as it allows for using concrete data and provides a clear concrete problem for investigation. Such an investigation also allows for actual results, realistic policies, and effects of policy implementation to be investigated in greater detail. When performing a case study research, there are several techniques that could lead to the case-selection. A case study of a typical example case allows for hypothesis testing, which is -by definition- representative (Gerring, 2007). A problem with choosing a ‘typical’ case is that it is unable to be representative for more ‘diverse’ cases that could better highlight causes for distinctive behaviour. Furthermore, they may be subject to cherry picking certain aspects that purposefully conform the model being researched. For this reason, typical cases are generally descriptive in nature in order to exemplify the mean, mode or median of the larger population (Gerring, 2007).

Aside from the problems associated with the typical-example case study approach, Yin (2003) further identifies some other traditional problems with case studies. The author states that problems associated with case-study research are mainly due to traditional pre-supposed biases against this type of research, such as a lack of rigor provided in case study research and the overall time taken. Yin (2003) also identifies a further problem of generalization. It is difficult to see to what extent the results can be generalized or even in this case extrapolated to other areas. This extrapolation problem is also apparent in this research: due to its sheer size, China consists of many different areas with different climates, cultures and landscapes. Even within a city, urban and rural areas differ immensely in terms of income and energy consumption. This is further amplified by additional governmental support provided to the urban areas over rural counterparts. The task of stimulating citizens to use more clean and efficient fuels is therefore delegated to policy making at a city-level. Since cities in China vary greatly in composition, there are also large differences regarding residential fuel consumption. This means that different cities may need to implement different types of policies in order to stimulate a shift away from traditional and more harmful fuel sources.

Choosing a case-study city does not only require the choice for a city that can be used as a ‘typical case study’, but it is also important that the city under consideration is willing and able to participate in the research. As data availability is important, commitment of the city prefectural government is required. For these reasons the prefecture of Jingmen, located in the centre of Hubei province, is chosen as the typical case study city.

### 2.3.2 Survey approach

A survey approach can be used to do an exploratory analysis about the current household energy consumption of Jingmen and to obtain insights about the attitude of its residents. This approach allows for a large sample of residents to be questioned about their demographics, current energy consumption, and it allows for further investigation into the attitude of households towards energy fuel types. By obtaining a large representative sample, data analysis can be performed to better understand what the source is that shapes this attitude. Such analysed results can then be used in other quantitative research approaches to understand the underlying dynamics at play, which cause a household to pick a certain source of fuel over another one. Therefore, conclusions can be made about preferred policies and how to best guide households to use cleaner fuel sources.

Conducting a survey starts by setting up suitable questions. It is important to find a balance between the expected level of knowledge of the respondents about the topic of research and obtaining enough information to accurately describe the characteristics of the respondents (Fowler, 2013). Given the likely demographics of the target group, it is important to keep questions as simple as possible. For this reason, most questions need to be in the form of a multiple-choice question. Although this may restrict the types of questions that can be asked, the main aim of the survey is to obtain information about the behaviour of a large demographic group (a population of over a million people). The large number of respondents that is required can thereby best be achieved by making all questions as accessible as possible. This does limit the amount of analysis that can be performed on the results – methods such as Stated Preference Analysis and Q-Methodology are too impractical for the research. Surveys that incorporate such methods of questioning allow for more detailed insights but take a long time to conduct and are more difficult for the respondent to comprehend, as they require respondents to have predisposed knowledge about personal preferences and potential trade-offs. In-depth questions that require a more comprehensible answer need to be obtained through other methods.

There are several ways how the survey can be conducted, the most obvious being through approaching the respondents by electronic or personal means. Using either of these methods have clear advantages and disadvantages. Reaching out to respondents through electronic means allows for a larger audience to be reached, more remote access to responders, quicker responses, and quick data compilation (Wright, 2005). Collecting the data personally, allows for higher response rates and provides better insights into the thought process behind the respondent. This may be beneficial as it provides better insight in the actual attitude of the respondents when faced with certain questions. Furthermore, considerations need to be made in how to approach different audiences within the city. Using electronic means for data collection makes it troublesome to control the sample group and some respondents may have limited access to internet, which further complicates this approach. On the other hand, conducting the entire survey through personal means is extremely time inefficient (Jones, Baxter, & Khanduja, 2013). For these reasons an initial survey will be conducted through electronic means, after which data will be collected personally in areas that have limited access to the electronic version.

### 2.3.3 Interview methods

As part of data collection, interviews are conducted with parties involved in the decision-making processes, experts in the field of research and other stakeholders. The advantage of conducting interviews as a means of data-collection is that they are generally able to provide more in-depth information than a straightforward survey can. Due to the more personal interaction, more insights can be obtained about personal feelings and opinions, and misunderstandings can be better clarified. In order to obtain a full picture of the situation, there are three main groups that need to be questioned:

- Parties involved in the policy process such as governmental institutions may reveal information about underlying reasons of certain policy implementation – such as long-term goals of a department or the pros and cons that have been weighed throughout the decision-making process. Such interviews can be insightful as they provide a basis about how and why the situation currently is as it is, and which approaches will likely be taken in the future in order to improve the situation. Furthermore, interviewing multiple governmental agencies can provide a deeper understanding about any interdepartmental clashes in attitude or conflicting targets that may hamper policy development.
- Interviewing expert groups provides insight in the technical processes involved about the problem at hand. Especially in a socio-technical issue, it is important to further understand the technical aspects such as the data that is currently being collected by certain agencies, to what extent the current issue is present and why no technical solution has been achieved as of yet. Certain research and development departments can provide insights in what technical

developments are being worked on in order to fix the current problem and how long-term goals could be achieved through the interworking of policy and innovation.

- Interviewing on-site stakeholders such as individual residents can provide insights about the exact attitude and underlying thought process of these residents. An understanding in the local culture can be extremely helpful to obtain a deeper understanding in their behavioural patterns.

Interviews will be held with members of Jingmen's governmental departments and expert groups responsible for the research and development on an appointment basis. These parties are listed in **Appendix A**. Additionally, smaller (more informal) interviews with willing local residents are held following personal survey conduction.

### 2.3.4 Simulation modelling methods

Conducting surveys and interviews can be very insightful to understand the attitudes of different stakeholders. Yet, the deeper insights about the dynamics between actors involved can be better understood using simulation models. Simulation models allow for a variety of policy options to be investigated through a range of plausible scenarios. The approach is to develop an abstraction of the problem into a model. The quantitative and qualitative data obtained before model development can prove extremely useful to translate the problem from reality into a model as accurately as possible. In doing so it is important to clearly define the scope and scale of the problem. Some problems require the investigation of individual citizens at a detailed, low abstraction and operational level. Other studies ask for a different approach through a higher level of abstraction, desirable in order to explore the dynamics at a larger scale.

*System dynamics modelling*

System Dynamics (SD) modelling is designed to model non-linear behaviour between variables through a continuous modelling fashion. The method was originally developed by Forrester (1961) in order to observe interrelations of complex systems. The main function of SD is to construct models of complex problems and experiment with them on computers (Abbas & Bell, 1994). The technique can be used for a variety of applications, and its methodology can be used as "a practical tool policy makers can use to help solve important problems" (Sterman, 2002). Through the use of equations and feedback loops it is able to model non-linear behaviour and interdependencies between variables. The central distinction between System Dynamics modelling and other (discrete-event) modelling is its modelling of time (Ossimitz & Mrotzek, 2008). In SD, time is continuous. Time intervals are infinitesimally small, which means that the changes that occur between two time-steps in any system dynamics model should approach the limit as the time interval approaches zero, *dx/dt*. This in turn means that the underlying theme behind SD modelling is the change of state of a system rather than the state of a system itself. In practice, it is impossible to make the interval approach zero which means a (sufficiently small) time-step is chosen between which the model does its calculations as a form: $\frac{dx}{dt} \approx x_t - x_{t-1}$.

Vensim Professional 6.0 is a SD software package that allows the construction and specification of stock-and-flow diagrams, simulation of a quantified model and supports methods for qualitative and quantitative analysis and validation. It allows for visualization of results through graphs and diagrams, model testing using input sources and data connections. System variables are generally modelled using auxiliary (constant) or lookup variables as their input. Intermediate and output variables are calculated using a combination of these input variables but may also take other intermediate or output variables as their own input. Lastly its Professional version can be fully controlled using external programs such as Microsoft Visual Basic for Applications.

In this study, investigating the dynamics between aspects that govern the behaviour of different household groups is more important than pinpointing the exact households that use more or less efficient types of energy fuel. Especially establishing the dynamics between sub-systems of the problem is important to understand why groups behave the way they do. Furthermore, feedback loops are required to obtain better insights in how the population groups adapt to changes in the system over a period of time. System dynamics also allows for thorough policy evaluation and provides clear results and scenario analysis, calibration and policy optimization. Long term and indirect effects of an introduced policy can be investigated in much greater detail. For these reasons, SD can be a desired modelling tool for investigating the problem at hand.

*LEAP as an energy modelling system*

The Long-Range Energy Alternatives Planning System (LEAP), is an integrated energy-environment and scenario-based accounting modelling software developed by the Stockholm Environment Institute (Stockholm Environment Institute, 2005), used for policy and climate change mitigation assessment. It is a tool that can be used as an energy accounting (input-output) framework to model the demand and supply of energy that supports a top down as well as a bottom up approach of energy modelling – with various built-in variables and scenario options (Huang, Bor, & Peng, 2011). It can be used to model the energy usage of cities, regions or entire countries through a multi-levelled approach and thereby investigate the extraction of energy resources and the amount of resources that should be imported and exported in order to keep energy demand and supply balanced. LEAP uses discrete annual time-steps in order to do its calculations and is used to model in the medium- to long-term. LEAP can describe how energy is consumed, converted, and produced in a given region under a range of alternative assumptions on population, economic development, technology and price using linear accounting methods (Huang et al., 2011).

An energy modelling framework excels at providing a clear overview in how energy demand may shape if the key parameters are adhered to. However, providing clear key parameter values and estimates for the future is difficult. LEAP also has limited options in policy implementation and evaluation. As an input-output framework, the model input is also linear in nature. This means that longer-term dynamics of an introduced policy cannot be adequately observed. Furthermore, the system lacks possibility for thorough direct mechanisms for policy evaluation altogether. Policies could be implemented through means of scenario evaluations, but these cannot be thoroughly evaluated in how they affect residential behaviour. By using interpolations, and matching these with the city's long-term goals, the models are in danger of becoming self-fulfilling prophecies, in which the city's energy output and emissions are at a certain level because the goals indicate that the energy demand will be at a certain level. However, without the investigation of appropriate policies, the prefecture still has no clear insights in how to achieve these goals. Another problem with the LEAP model is its inability to estimate decision making and incorporate social aspects that may govern energy demand. The system is better equipped to project energy demand and supply balances of an entire city, province or country through rough approximations in energy demand, however, it is thereby insufficient in portraying the decision-making processes of any individual, or group of citizens. For this reason, a combination between a system dynamics model and an energy modelling framework such as LEAP is the most desired course of research.

*Distributed simulations*

A research using system dynamics is desired as this method can be used to look at larger consumption flows in the system and higher-order effects present in the model and certain types of behaviour has on future scenarios. However, an SD model alone may not be enough to provide knowledge about the city and its emissions as a whole. Connecting the system dynamics model to an energy planning system could allow investigation over a much broader policy space, as effects of demand-side policy effects can be observed in relation to the city as a whole. In a technical sense, no published research has been found in which a system dynamics model has been directly connected to such energy planning models for more detailed demand-side policy investigations.

Distributed simulations refer to the execution of a single simulation across multiple computing platforms. Simulations can be distributed in order to integrate different features of a simulation into a single environment (Fujimoto, 2015). A distributed simulation could be used to provide the prefecture with a clearer understanding about in how their prospected policies may affect their energy supply and provide best-practice ways in order to stimulate clean energy consumption by the citizens. A system dynamics model could be used to model the demand behaviour of the residential sector, while an energy modelling framework can use this demand behaviour to model the expected emission levels as a result of this demand.

There are multiple reasons why one would need to use a distributed simulation, these reasons include, but are not limited to:

- **Reduced development time as a result of collaborative work between developers;** The current research as a whole consists of multiple parts that are connected to one another. The different aspects of energy supply, energy transformation and energy demand for each of the industries is developed by different researchers. The residential energy demand has been developed in LEAP but is more thoroughly fleshed out on a social behavioural choice level within Vensim.
- **Geographical distribution;** Rather than geographical distribution, in this situation one should consider the sectoral distribution of the model. Subparts of the LEAP model such as those investigating the transportation and industry sectors still run as well as aspects that relate to the overall energy supply of the city. However, the change in energy demand of the residential area can be imported from the SD model, which in turn could adjust the results attained from the energy supply. The co-simulation is therefore not a replacement for the LEAP model, but rather, serves as supplementary research to it.
- **Integration of simulators that run on machines from different manufacturers;** As a continuous modelling package, Vensim allows for a wide range of model development. The package is not developed to serve a single purpose, the user has a lot of freedom in the model type and model development. On the other hand, this forces the user to have sufficient knowledge on how to use the software as all relations within need to be specified. The LEAP model is specifically developed to create energy models and therefore has a much higher ease of overall use. As both aspects are important in this research, a distributed simulation is appropriate.
- **Reusing existing models;** The current research focusses on the development of the Jingmen residential energy model. However, with a couple of tweaks, the Vensim model as well as the architecture developed in Visual Basic can be connected in the same way to LEAP models developed for other cities. On the other hand, the same Jingmen LEAP model can be expanded through the development of SD models concerning the transportation or manufacturing sectors, as these could be connected to the LEAP model too.

In this study, continuous interlinks between two modelling systems is not required, nor desired. An energy system model that encompasses emissions about all of Jingmen is insightful on its own. Developing a simulation in a way that provides insights for multiple sectors besides the residential sector is helpful. These other sectors need to remain completely unaffected by the results of the SD simulation. This means that internal model validity still upholds in other sub-models while the residential sub-model can be freely adjusted with the policies that are implemented through a distributed simulation. From this, stakeholders can obtain clear insights in how exactly policies will impact residential energy demand and emissions in comparison to the city's entire energy structure. Furthermore, it leaves clear future research in which other sectors can be investigated using SD models in a similar fashion, without compromising the total research results altogether.

A simulation system that can run on its own while also supporting a model structure that runs by interlinking an SD and a LEAP model is desired. Using such a method could examine top-down and bottom-up approaches independently, while simultaneously using both approaches supplementary to each other. The lack of inter-dependency brings the exact definition of a 'distributed simulation' into question – however this research will use term distributed simulation or co-simulation to define any simulation that uses multiple modelling systems to perform a simulation run.

## 2.4 Scope definition

In order to ensure a structured research that can be performed within the desired period of time, the research scope is defined in five aspects. These are the geographic area, the time period that will be studied for, the sector that is researched, and the fuel and emissions that are included in the research.

### Geographic

The geographic scope will limit itself solely to the prefectural city of Jingmen. This means that all energy supply or demand from outside this city is completely ignored. Any supply from outside this city is considered as imported fuel. Within Jingmen, there are two clear distinctions made: the rural and the urban area. The urban area is restricted to the boundaries of the city, while the rural area extends into the rest of the prefecture. This distinction is made because the citizens can be seen as extremely heterogeneous in terms of education, age, income and other demographic properties.

### Time

The investigation will forecast energy demand from 2015 until 2030, with data between 2010 and 2015 used for warm-up and indicative purposes. This time scope is deliberately chosen because this period stretches exactly three of China's Five-Year Plans ($13^{th}$, $14^{th}$ and $15^{th}$). Furthermore, many world-wide as well as country-wide medium-term energy goals take 2030 as their benchmark year.

### Sectoral

The research on residential behaviour is being conducted for the city of Jingmen as part of a larger encompassing research in which the entire energy structure of the city is investigated. This paper will only consider the residential sector within the city and its annual overall energy demand.

### Emission and Fuel Types

The research includes the energy from the households in general and considers their emissions alone. There are many different types of emissions which may be harmful in different ways to individuals and the environment as a whole. This research considers the general emissions in terms of carbon dioxide emissions as a measurement for the long-term larger-scale environmental harm that the fuel sources do. $PM_{10}$ particulates are used in order to measure the health effects on the residents themselves.

There are four main types of fuel that are being used by residents in Jingmen, these are:

- **Electricity:** All electricity used in a household.
- **(Natural) Gas:** A combination of both natural gas (consumed from the gas grid directly), as well as petrol gas consumed from fuel tanks that can be bought/refilled in stores.
- **Biomass:** All biological fuel sources that people use to burn directly, such as firewood, crop residue, straw, etc. This biomass is collected by the end-user directly (and is therefore free to consume).
- **Coal:** Any sort of coal (but mostly anthracite) directly used for cooking or heating purposes.

## 2.5 Relevance as an EPA master thesis subject

Over the course of the EPA-programme, the United Nations' Sustainable Development Goals (SDG's) have been heavily debated in courses such as 'EPA1101: Understanding International Grand Challenges' and 'EPA1133: Ethics and Impacts of Global Interventions'. This research will tackle multiple SDG's related to air pollution, emissions and human health. At least four of the seventeen goals include targets that directly tackle the importance of reducing emissions for the benefit of human and environmental health. 'SDG 3, good health and well-being' targets to "substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination." 'SDG 7, affordable and clean energy' is fully committed to "ensuring universal access to affordable, reliable and modern energy services". 'SDG 11, sustainable cities and communities" targets to "reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality". Lastly, 'SDG 13, climate action' stipulates the importance of taking urgent action to combat climate change and its impacts as a whole (United Nations, 2016).

The research engrains itself between the social and political areas on a city-wide level, meaning the topic is extremely relevant on a public domain. There are multiple stakeholders affected by the system of research, most importantly the residents in the urban and rural areas (both groups of citizens can be seen as two distinct groups of stakeholders) as well as multiple governmental entities in the city of Jingmen and Hubei province. Various arenas and multi-stakeholder settings have been discussed in courses such as 'EPA1424: Political Decision-making' and 'EPA1144: Actor and Strategy Models'. The problem at hand will be researched through a clear systems perspective present, as the energy consumption in the residential sector of the city will be taken as the defined system. The main decision-maker in the arena is the energy department in the prefectural government of Jingmen, who will become better informed about the energy demand behaviour of their residents, hence becoming aware of the impact several policies will have on the residential consumption and emissions.

The topic will be researched using an analytical character, in which qualitative attitudes are translated into quantitative models. The models will be developed using systems that have been directly explored in the EPA course 'EPA1341: Advanced System Dynamics'. When using such quantitative models for policy development, it is important to keep the multi-stakeholder and practical implications in mind when advising on the policy process. This has been explored in 'EPA1361 Model-based Decision-making'.

In a technical sense, the research is innovative as the co-simulation developed between two modelling systems have not been connected before. The problems associated with developing such a co-simulation have been discussed in length in 'SEN9110: Simulation Masterclass', but this research extends the theory discussed in this course by the developing such a model for research purposes.

# 3. Jingmen and the attitude of its residents to fuel demand

## 3.1 Demographics of Jingmen

As a city located the centre of one of the central provinces (Hubei province) in China, Jingmen is referred to as a city in the heart of Hubei, in the heart of China (Shenzhen Institute of Building Research [IBR], personal communication, June 13th, 2019). With a population of just under 3 million people, the city of Jingmen a city that shares many characteristics with other cities in China and attaches great importance to reducing its emissions levels and the development of non-fossil energy (IBR, personal communication, June 6th, 2019). The city is located right next to the Yangtze River, making it an "important node city of the Yangtze Economic Belt" (The People's Government of Jingmen Municipality, 2019a, paragraph 1).

The prefecture formally consists of six main districts: Dongbao, Duodao, Zhanghe, Zhongxiang, Jingshan and Shayang, with the urban city centre located around the tripoint between Dongbao, Duodao and Zhanghe. The differences between the areas are more notably differences between the urban city centre of Jingmen, and the (much larger) rural areas around the city. The urban and rural areas are extremely split in terms of GDP and connectivity - thereby also in terms of energy consumption. In 2015, just over 50% resided in the urban, but this figure continues to increase as a result of urbanization (Hubei Provincial People's Government, 2018).

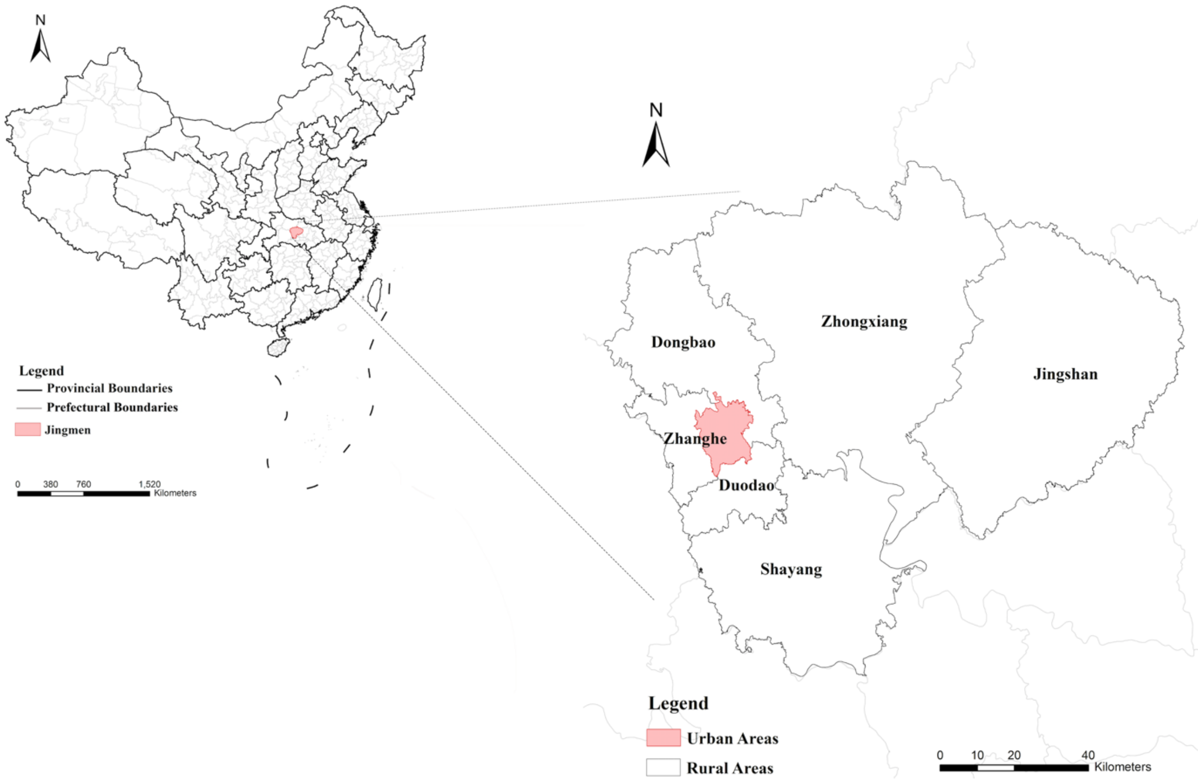


**Figure 1**: A map of the geographic location of the prefecture of Jingmen within China as well as the six main districts within the prefecture.

The map of Jingmen provided in **Figure 1**, shows that the sizes of the prefectures vary extremely throughout the country. Generally speaking, the prefectures in the west of China are much larger than those in the east. Similarly, there are large differences in economic development as well as city population size between different areas in China. As a whole, the prefecture of Jingmen contains aspects and cultures from areas all over the country and other cities can use Jingmen to draw their policies and ideas from. Its properties such as its population and GDP per capita are relatively close to that of the national average (**Figure 2** below).

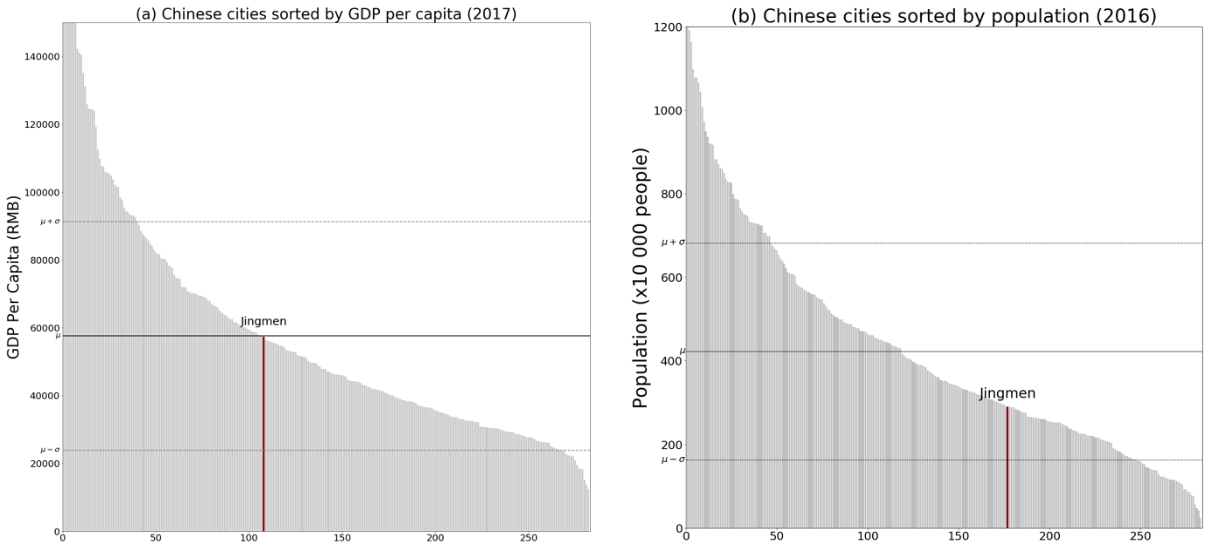


**Figure 2:** Chinese cities sorted by GDP (a) and population (b). Excluding direct-administered municipalities (Beijing, Shanghai, Tianjin, Chongqing) and special administrative regions (Hong Kong and Macao)
Statistics collected by the Shenzhen Institute of Building Research using yearbook data and survey reports (IBR, personal communication, 2019).

Aside from sharing properties with other cities throughout the country, the prefectural board of Jingmen has also expressed has high interests in reducing their $CO_2$-emissions in order to become an example city for other cities throughout the country to follow in green policy and emission reduction. Better insights in their energy consumption at present, as well as in the future are necessary in order to understand in which aspects consumption and emissions can be reduced. Jingmen's thirteenth five-year plan further stipulates the importance of a residential shift to electricity as they state their desire to implement a system to improve the electricity consumption, gas price, and time-of-use electricity price for resident (Jingmen Development and Reform Commission, 2016, paragraph 6.1).

As can be observed from the map in **Figure 1**, the actual urban area within a prefecture is relatively small. Naturally, the more prosperous urban areas are a lot more densely populated and generally have residential buildings of much higher quality. The low population-density and remoteness of the population in the rural areas make it much more difficult to provide fuel. Connecting all individual households to the natural gas grid is nearly impossible. Nonetheless, 100% of the citizens in Hubei province are connected to the electric grid so the problem of 'lack of connectivity' does not pose a major issue as the source of electricity could be seen as alternative.

Jingmen's sectoral composition in terms of GDP is 13.4%, 51.1% and 35.5% for the primary, secondary and tertiary industries respectively (The People's Government of Jingmen Municipality, 2019b). The city's manufacturing industry is very important to Jingmen and the city is an important chemical industry base in China (The People's Government of Jingmen Municipality, 2019c). However, in recent years the city is aiming to become less reliant on their industrial sector and focus on their green image with a shift towards renewability through the development of the Jingmen Green Ecological Technology Industrial City in the west of the urban city (The People's Government of Jingmen Municipality, 2016). Records from the municipality point out that residential energy demand consists of around 5-10% of the city's entire energy consumption (IBR, personal communication, 2019). Consumption of coal and biomass is estimated to consist between 30 and 40% of the residential energy consumption, which means only 1.5-2% of the total city's energy consumption comes from dirty residential fuel consumption (Jingmen Building Energy Conservation Office, 2018). Nonetheless, it is important for the city to focus on reducing this for the following reasons:

1. As an example to the rest of the country, Jingmen could work towards becoming one of the first cities in China with a clean and efficient residential energy supply.

2. The percentage can help reduce the city's overall emission levels without it costing too large of a part of the GDP, as this reduction would not directly come at the cost of its industry which is a lot more important to the city's overall GDP level.
3. Lowering residential emissions would reduce air pollution levels and with that reduce citizen health problems related to pollution.

## 3.2 Survey research and how demographics play a role in consumption

Surveys conducted in the rural and urban areas show how different the two types of areas are in their demographics and therefore citizens from either area will likely respond differently to various policies regarding energy consumption. Survey results may be slightly skewed due to different methods of data collection used for urban and rural areas. There is a large difference in sample size taken in either of the areas. However, the surveys conducted provide a general overview of the differences between the urban and rural areas. The methods of survey data collection, as well as the problem associated with it are described in **Appendix A**.

### *3.2.1 Differences in residential income between urban and rural areas*

The first problem in stimulating clean energy usage are the large discrepancies in per-capita income. There is a growing inequality in income between urban and rural areas in China (Molero-Simarro, 2017). This inequality is also reflected in the surveys conducted as the income levels in the rural areas are generally extremely low: around 50% of all surveyed respondents in the rural area (N = 31) had a yearly income of less than 30,000 RMB per year (around €3,880 in July 2019). The differences in income distribution between the rural and urban areas are shown in **Figure 3** below:

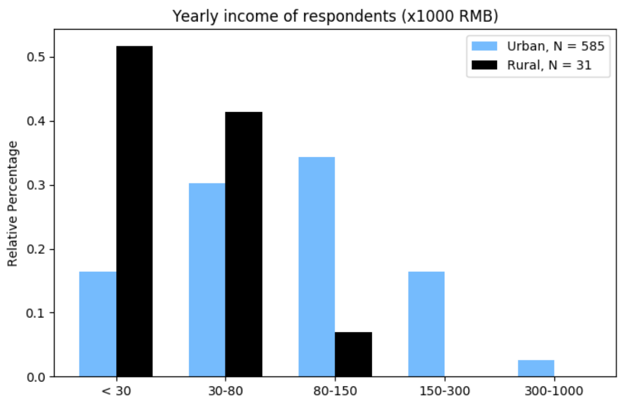


**Figure 3**: A bar chart of the income percentages (compared to all respondents from the area) of respondents.

From this, it is likely that the fuel price is much more important for the rural area than for the urban area. Policies that adjust fuel price of either supportive (subsidies) or restrictive (taxes) nature will have a very different impact: where the urban area will less affected by slight changes in fuel price, the rural area could face large shifts in terms of consumption. An increase in price of a certain type of fuel may cause rural residents to simply consume less energy altogether.

### *3.2.2 Differences in age and level of education between urban and rural areas*

Another major difference between the rural and urban areas is the age of the population. As a result of the economic development in the urban area over the rural area, many citizens from rural areas will move towards the city for employment purposes. This means that the average age of the urban population higher than that of the rural population, as can be seen in **Figure 4** below.

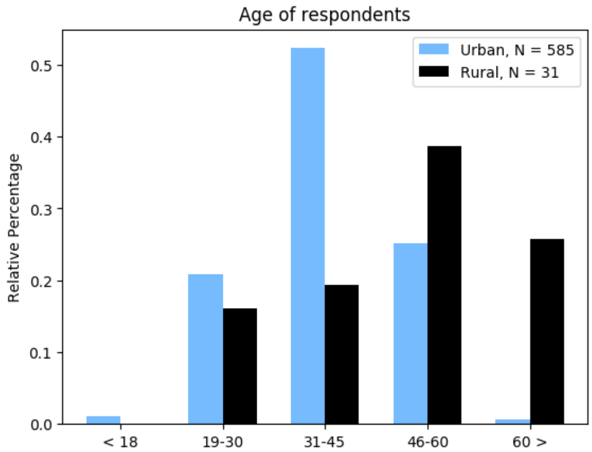


**Figure 4:** Bar chart of the age percentage (compared to all respondents from the area) of respondents.

The differences in age between the urban and rural areas may also have an effect on the type of policies that are effective. People of a more senior age may be more resistant to changing the lifestyle they had lived their entire life, while younger citizens could be more open for changing their behaviour. This further ties in with differences in the level of education, shown in **Figure 5**. According to Heckman & Yi (2012), people living in urban areas enjoy a higher level of education than those living in the countryside. The survey research supports these findings as residents in the urban are generally better educated, with nearly half of the urban respondents enjoying at least a university level of education, compared to a middle school level education that the majority of the rural respondents had. These differences are further accelerated by the different levels of income and job opportunities the urban and rural areas offer. People with a higher level of education in the rural area are more likely to relocate to the urban area as a result of the employment opportunities the city offers. This in turn may cause them to be more understanding the damages to health and environment done by harmful fuels.

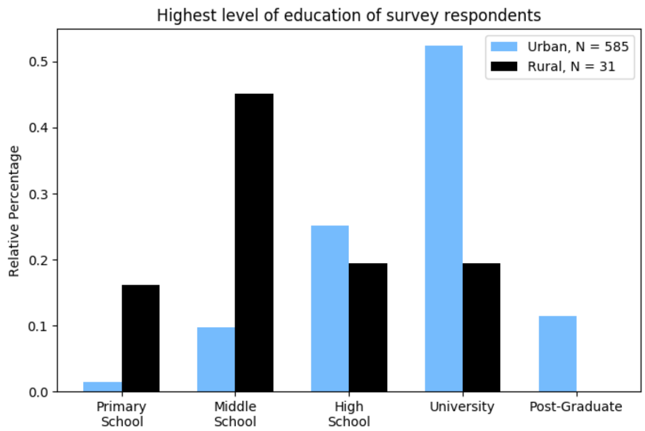


**Figure 5:** Bar chart of the education level percentage (compared to all respondents from the area) of the respondents.

### *Residential fuel consumption in urban and rural areas*

When considering the urban and rural fuel choice (**Figure 6**) it is clear that the majority of the population is already using the cleaner energy fuels. Over 60% of the people surveyed in the urban area currently uses gas for cooking and/or heating purposes, while less than 5% currently uses coal or biomass. In the rural area however, around 20% of people question admits to using coal or biomass as their main source of fuel. Having said that, it is expected that there are discrepancies in the figures obtained from the survey and the actual consumption values in Jingmen as due to geographic and time constraints, certain areas in rural Jingmen were inaccessible. According to interviews held, residents in these unexplored areas likely use coal or biomass as no other alternatives are accessible or affordable to them.

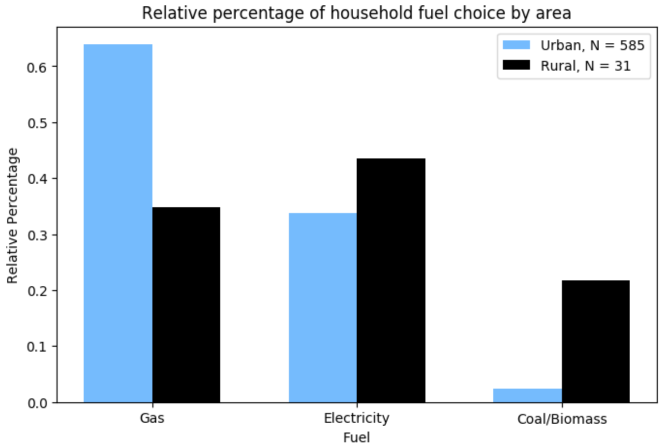


**Figure 6:** General impressions of certain fuel sources for respondents of the urban and rural areas; positive connotations are on the left side of the diagram with their antonymic keyword located opposite.

When asked exactly why people were consuming a certain type of fuel, the majority does so because it is the most convenient alternative to them (**Figure 7**). Convenience therefore seems like the most important factor in determining the fuel consumption. Only around 15% of the urban population did so because of economic considerations. This percentage is even less in the rural population. A likely reason for this is because the rural population was surveyed in person, which means that an observer effects (psychological effects where respondents modify their response because they know they are being studied) played a larger role.

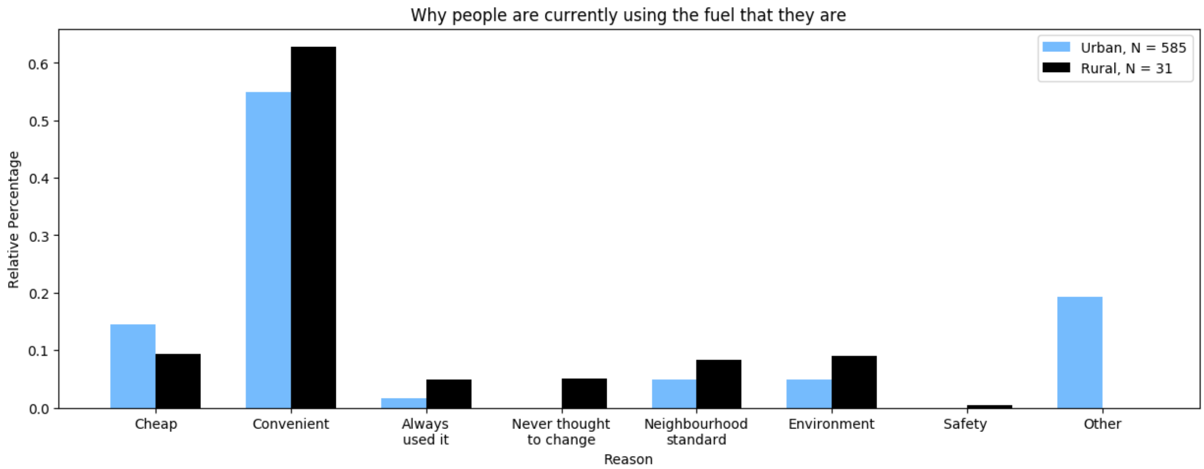


**Figure 7:** The main justification as to why people are consuming their current fuel source.

### *3.2.3 Opinions about fuel consumption in urban and rural areas*

Regardless of their own fuel choice, citizens show knowledge about the effects of certain types of fuel. Respondents were asked to pick three key terms they individually associate for each fuel type (out of a list of ten terms). **Figure 8** below shows a 'spider-diagram' where each corner represents a keyword and each colour represents a fuel type. The length of each line shows the number of people that directly associate the labelled fuel with the respective keyword. When asked about the direct attitude to a certain fuel, nearly 50% of the respondents directly associate electricity with 'expensive'. This same direct association compares to just 15% and 31% with coal and gas, respectively. Other than that, many people relate positive connotations with electricity and gas, while people present a negative attitude towards coal. The rural area generally associate biomass with positive connotations, with many indicating it as a clean fuel and unaware of the health dangers the fuel may pose.

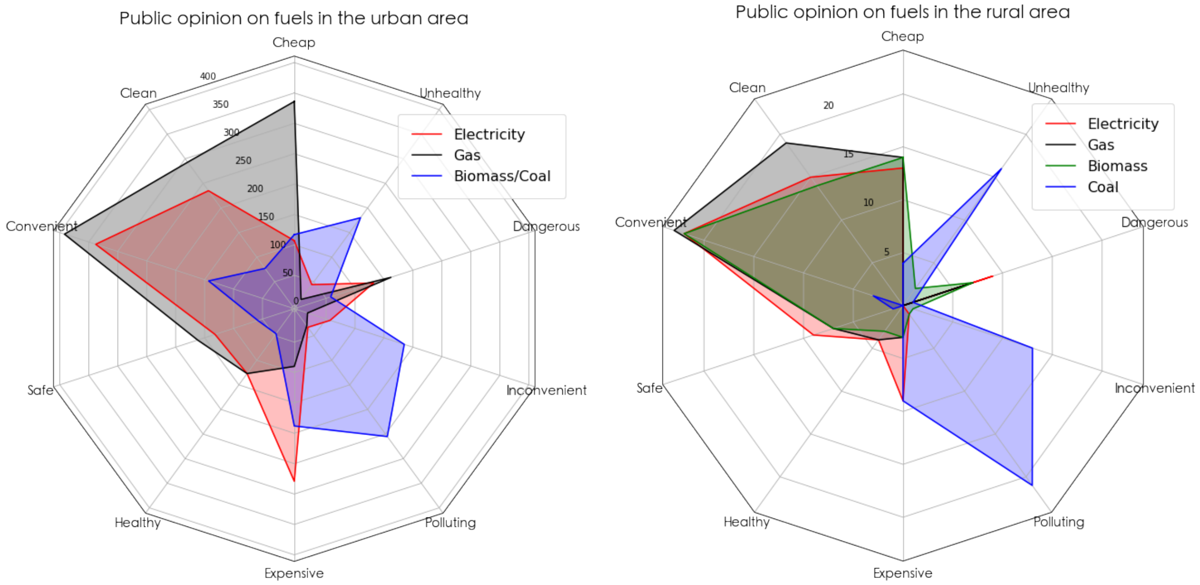


**Figure 8:** General impressions of certain fuel sources for respondents of the urban and rural areas; positive connotations are on the left side of the diagram with their antonymic keyword located opposite.

In order to get a better indication about what people find important in choosing their type of fuel, citizens were also asked the following question:

*If you decided to change fuel for cooking/heating purposes, what would be the most likely reason that would cause this change?*

The responses for this question are sorted by fuel type currently used in **Figure 9**. The majority of people in both areas indicate that price would be the cause for them changing their fuel. Biomass/coal users in both areas placed the highest importance on price. Health scores second highest in the urban area, showing that the urban area has concerns about the impact fuel consumption on their personal health. Extra convenience is not a real cause for urban residents to change their fuel. This shows that the urban area already has a very convenient fuel supply and a further focus on further improving convenience would likely be ineffective to them.

Nearly 80% of ‘dirty’ fuel users in the rural area would change if cheaper or more convenient alternatives were available. They place a high importance on improving convenience, while many already indicate that they are consuming their current fuel because it is convenient. This can indicate that people are using their current fuel out of necessity rather than out of personal preference. Furthermore, no user of biomass or coal placed any importance on health. This can mean that they are unaware or think that the fuel they are using is already healthy. However, a more likely reason is that the sheer necessity of using the fuel means that personal health is not considered. A factor such as health is an effect that plays a role in the long term. If people are consuming the fuel that they are out of necessity, having fuel in the short term is regarded as more important than effects in the long term.

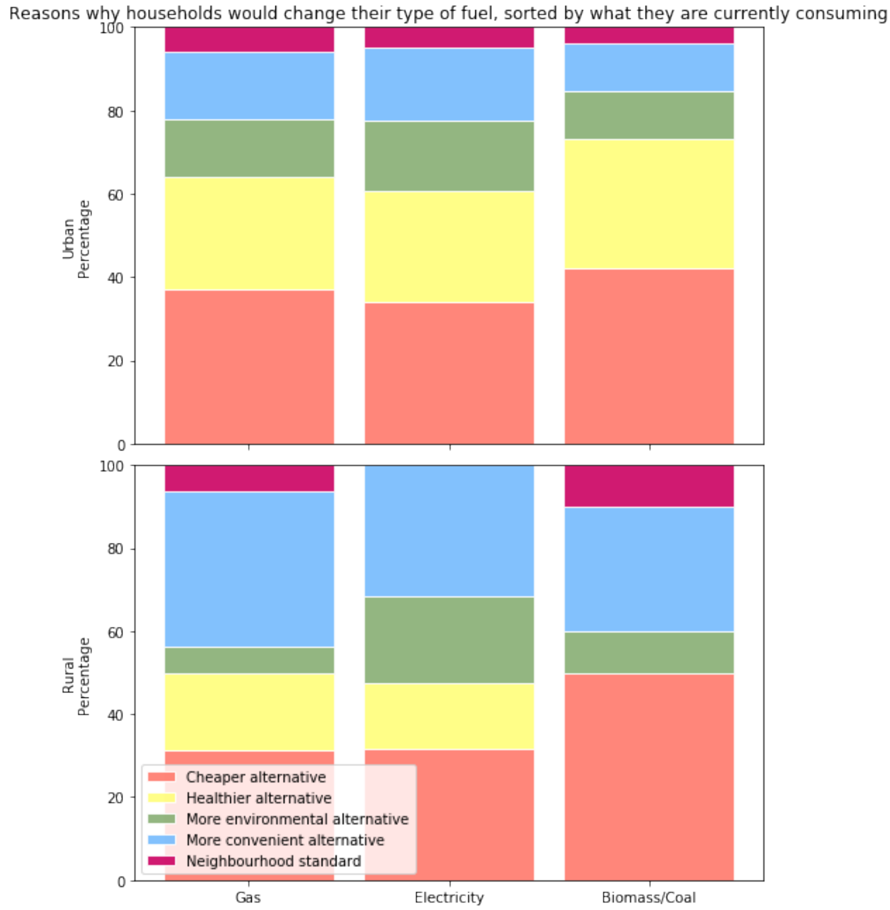


**Figure 9:** The most likely reason for changing household fuel type, sorted by the current consumption fuel type.

### *3.2.4 Residential energy expenditure in Jingmen*

When looking at the yearly amount of money spent on energy (**Figure 10**), it is clear that there is positive correlation between money spent and household size. This direct positive correlation is important as the abolishment of the one-child policy, increase in house price and aging of the general population in China can cause average household size to increase. Between 2014 and 2017, average household size in China has increased from 2.97 to 3.17 people per household (Statista, 2019). Rural families are generally larger than those in the urban area, which may give an indication that rural areas consume more energy per capita than the urban areas do. However, it is difficult to test the direct causality of this correlation. It is also possible that rural households simply consume more fuel, and because the household size is larger, energy expenditure increases as household size does too.

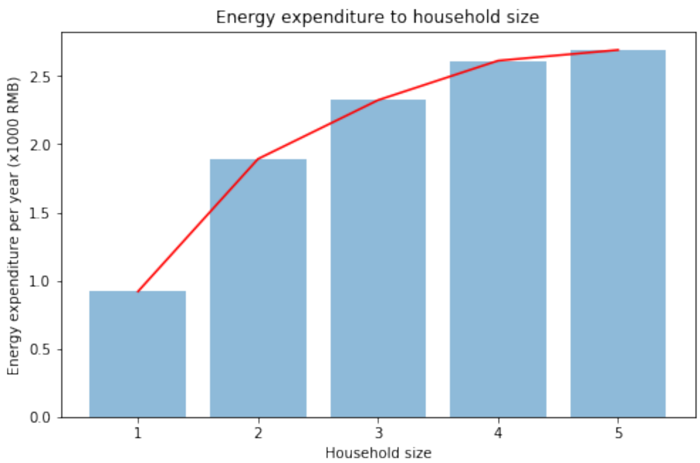


**Figure 10:** Yearly energy expenditure mapped to household size.

**Figure 11** below shows the yearly expenditure as a function of the yearly household income. Although consumption tends to increase with income, this increase does diminish as income rises further. This is because at some point, all energy consumption can be met meaning that price plays no sincere role in determining energy demand anymore. It is also clear that people spend between 2-7% of their income on energy.

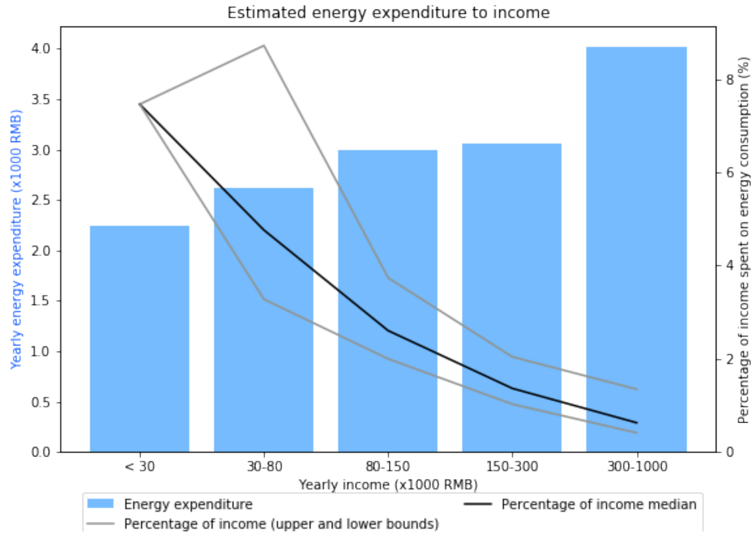


**Figure 11:** The yearly expenditure of citizens in absolute and percental terms compared to income.

The behaviour and attitudes between the urban and rural population are similar in some aspect, but very different in others. Despite both groups having similar opinions about the consumption of fuels, these opinions do not always translate into personal fuel consumption. Differences in income level, education and fuels available to them, cause differing opinions regarding fuel consumption. In the urban area there is a large consideration for health, while the rural population finds convenience a more important factor. Judging from interviews held with the local population, it is likely that many were never faced with a question regarding their energy consumption before. Despite being aware of the damages certain fuels can do, there is limited thought placed in what they, as an individual, could do to make a change. The impact an individual household has on overall emission levels is so small and 'distant' that direct effects such as price and convenience play a much larger role in choosing their fuel source.

### *3.2.5 Current attitude towards energy consumption, fuel choice and emissions of $CO_2$ and $PM_{10}$ of households in Jingmen*

Citizens in Jingmen are currently already consuming a significant amount of fuel that is considered clean. In the urban area, the coal and biomass users are clearly in the minority, while improvements can still be made in the rural area. People in both areas are already aware of the dangers coal consumption may pose, and biomass is often considered a cleaner and more convenient alternative. However, citizens are generally unaware of the dangers that biomass consumption can pose to individual health. Where the urban citizens signal that they find the effects of fuel consumption on health important, the main concern for the rural area lies in the price of fuel and convenience of consumption. Even though rural citizens are aware of the dangers that dirty fuels pose to pollution problems, the concern is overshadowed by the importance of having access to fuel in the first place.

# 4. Model conceptualisation

This chapter draws upon the modelling systems introduced in **Chapter 2** and how the residential attitudes can be translated into qualitative systems for investigation through simulations. **Paragraph 4.1** gives a brief conceptual structure of the problem within the boundaries of the LEAP model. **Paragraph 4.2** explores the household behaviour and conceptualizes this further for the system dynamics model. **Paragraph 4.3** then considers how the two models can best be linked to one another while maintaining internal model validity. **Paragraph 4.4** introducing the policies that will be investigated following the model development. The chapter closes by reflecting on the effectiveness of model development in **paragraph 4.5**.

## 4.1 LEAP model conceptualisation

A LEAP model generally consists of four main parts of an energy analysis that is used for energy analysis and emission mitigation: energy demand, energy transformation (conversion), fuel resource assessment, and environmental impact estimations (such as calculating emissions). Linking of these parts together creates insights about energy demand and environmental impact (**Figure 12**). As LEAP is linked to the environmental database, it is able to internally estimate emission values at different sections of the fuel chain, from fuel extraction, to processing, distribution down to eventual fuel usage (Shin, Park, Kim, & Shin, 2005). Through scenario comparison, the potential to save energy and minimize greenhouse gas emissions can be acquired. The scenarios can be based on national/regional targets, or through bottom-up approaches of processes such as electricity generation in terms of a per power plant investment structure, fuel intensity, and emission intensity. This can be used to make the most economically effective decisions in how to minimize carbon emissions (Cai, Wang, Wang, Zhang, & Chen, 2007).

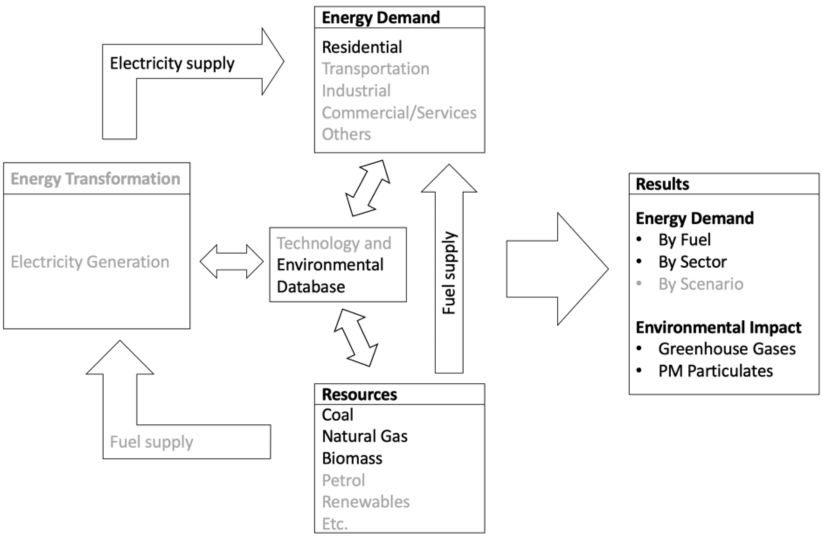


**Figure 12:** A schematic overview of a general LEAP model. Parts that are included in the model but fall outside the scope of this research are shown in grey.

Although LEAP uses built-in linear interpolation tools in order to calculate output variables, it also allows the user to input more time-varying data and further allows full support of importing Excel which can be useful when using dynamic data. LEAP's results can also be exported as datasheets which allows users to directly inspect and use its data in other applications. Moreover, LEAP's Application Programming Interface (API) functionality allows certain processes and calculations to be automated in Microsoft Scripting applications such as Microsoft Excel's Visual Basic.

The model that provides the Jingmen prefecture insights about their energy consumption is principally developed using the LEAP energy modelling tool. The energy consumption of the residential sector is modelled as a sub-model in the entire model developed for the prefecture, which (aside from the Residential sector) also includes the Transportation, Industry, Agricultural and Service sectors.

The original LEAP model has been developed in a collaborative effort that concerns multiple aspects of the emissions within Jingmen. This paragraph will only consider a general overview of the model necessary in order to understand the general model mechanics. A LEAP model is generally split up into the following parts:

1) General model assumptions*

General model assumptions mainly consider variables that are not directly connected to energy, such as GDP, GDP per capita, population, area, population density amongst others. Naturally many of these variables are important for investigating the total energy demand and supply. Many of the general model assumptions are therefore important interpolations that are considered in collaboration with city officials. However, exact values were initially only considered through expert opinion.

After survey research for the investigation of household energy consumption alone, some of these assumptions were adjusted for the current model used. The main adjustments made from the initial model as a result of the survey research were:

- The number and types of appliances citizens owned at home: this was over-estimated, especially in the rural areas.
- Household income of the urban and rural area: this was adjusted slightly to better accentuate the differences in income;
- Number of households per family: both urban and rural household size was adjusted to the average household size of both areas directly asked in the survey.

* General model assumptions have been developed in collaboration with other members in the research team.

2) Energy demand**

This part considers the entire energy demand of the city sub-divided into different sectors of the residential, services, industry, transportation and agricultural sectors. Each sector further divides into aspects of usage. The residential energy demand is divided into the different fuels. The electricity fuel is subsequently divided into lighting, and household appliances. The demand is therefore developed from a bottom-up perspective: by considering the number, type and energy usage of household appliances per household, the total electricity demand can be calculated. Similar divisions are made for the other sectors, but these fall outside the general scope of the research.
** Energy demand outside of sectors other than the residential sector had been developed by other members in the research team.

3) Energy transformation***

Now that the energy demand is established, it is important to know where this energy comes from. The energy balance will always be fulfilled, as any missing internal energy supply will be ‘imported’ from other cities. The energy transformation considers what the total industrial production of electricity is, from raw material products, and thereby also how the electricity is generated, and the amount of energy that is lost throughout the transformations.
There are four identified processes of energy transformation:

a) Petrochemical industry
b) Electricity generation
c) Heat transformations
d) Electricity transportation/distribution

However, for the scope of this research it is enough to know that there are aspects of energy supply built into the model.
*** Energy transformation has been developed by other members in the research team and transformation falls outside the general scope of the research.

## 4.2 Conceptualisation of the system dynamics model

Reducing emissions can be done in two main ways, through changing the fuel composition of the energy demand and by reducing the total energy demand. In order to reduce emissions, overall residential energy demand should not rise too much. Survey data and interviews have pointed out people are choosing their fuel type and quantity as a result of (a combination of) the following five mechanisms:

**Table 1:** an overview of the mechanisms in the system dynamics model

| **Mechanism** | **Quantity of fuel** | **Type of fuel** |
|---|---|---|
| Necessity | People need to use their fuel simply because they need heating and cooking. However, they will not use any more than that is necessary. | People use their type of energy fuel because they have no other alternative type of fuel available to them. |
| Price | People will use a certain amount of fuel because they have the means available to use this amount. If the price of fuel use is diminishable in comparison to income, people tend to use more energy. On the other hand, if fuel becomes very expensive, people will use less of it. | If the type of fuel becomes too expensive, people will start using different types of cheaper fuels available to them. On the other hand, in accordance with the energy ladder hypothesis (Hosier & Dowd, 2002), people are more likely to move over to more sophisticated types of fuel if they can afford it. |
| Convenience | If the fuel is easy to come by, people may become more wasteful, especially if money is not a sincere issue to them. | Survey data shows that convenience is one of the main reasons why people choose a specific type of fuel. |
| Knowledge | People will generally use the amount of fuel that they need. However, people can be taught to use less fuel, for example by learning how to better insulate their homes or be more efficient with their fuel use. | People can be taught on the benefits of using more efficient and cleaner types of fuel. Although most people surveyed showed considerable knowledge about the harm of coal usage, there is still limited knowledge about the health dangers biomass fuels may pose. |
| Willingness | This implies how willing people are to use more or less fuel for reasons other than described in the other mechanisms. It implies the willingness of people because they are implored to use less fuel, for example after they are made aware of the harms of using a lot of energy does to the environment. | The willingness of using a type of fuel relies on the people choosing their fuel type as a result of being more willing to spend more money or choose a less convenient fuel because they are willing to use cleaner and more efficient fuel. |

*Price*

The energy ladder hypothesis (Hosier & Dowd, 2002) proposes that as households increase in economic development, their sophistication of fuel choice will also increase. In the case of Jingmen, this would mean people will move up the ladder in their primary source of fuel from a scale of biomass, to coal, to gas and electricity if their per capita income increases. Liao et al. (2019) test whether this hypothesis also holds for China and confirm that such a ladder definitely exists in rural China. Income is an important factor for residents in deciding their fuel source.

There was a high correlation between users of biomass as their primary source of fuel and (lower) income ($P = 0.003$) which may further support the energy ladder theory. This shows that price-related factors are important in deciding which type of fuel to use as primary consumption fuel. However, it also comes to show that the absolute price of the fuel itself is not important, but rather the percentage of income spent on energy is most important. Research by Jiang & O'Neill (2004) and K. Wang et al.

(2015) points out that people are generally paying around 3-10% of their monthly income on energy. This value is further supported by survey research as indicated in **Chapter 3**, which shows that people will generally spend less than 8% of their income on energy needs. Energy expenditure generally tends to increase as income rises, but the percentage of money spent as part of their income will drop.

*Convenience*
The entire prefecture is connected to the electricity grid. As that electricity can simply be demanded through the switch of a button, electricity it is assumed to be the most convenient fuel to use. The possibility of electricity outages is left for future research (preventing electricity outages are mostly a concern for the CCPG, not for the Jingmen prefecture themselves and therefore lies outside the scope of this research). Therefore, stimulating the use of electricity cannot simply be done by improving the convenience of using electricity itself. Electricity is therefore considered to have the maximum convenience. Secondly, gas in terms of natural gas that is already connected to some households also have maximum convenience as the user faces no restrictions in consuming it. The consumption of gas from tanks, however, is considered to be less convenient as the tanks need replacing. Below gas in terms of convenience is biomass. Aside from the smoke caused by the burning of biomass, the fuel needs to be acquired and the residues need to be cleaned up after consumption. Coal is considered the least convenient in terms of usage as the residues are dirtier than those of biomass. On top of that, coal can only be acquired in stores that sell them.

*Knowledge and Willingness*
The factor of knowledge and willingness explores the knowledge that people have about the benefits of using electricity or gas may have to the environment and human health in comparison to the damaging effects of using coal or biomass. Many people may not have even considered changing their type of fuel out of health or environmental purposes. It may not concern them in their everyday life and not being confronted with the type of fuel usage will just cause them to use the same type of fuel as they always have. Latif, Omar, Bidin, & Awang (2013) and Paço & Lavrador (2017), identify that individuals with more environmental knowledge are more inclined to have more positive attitudes in reducing energy consumption. Increasing the general knowledge of the citizens may therefore be beneficial in stimulating the population to use cleaner and more efficient fuels.

However, even if the citizens have high knowledge about improving their emissions, the people will also need to make a conscious decision to choose a certain type of fuel even if this fuel may be more expensive than others. Therefore, aside from the knowledge, the willingness of the extra step people may be willing to take in order to use the desired fuel, even if this may a fuel that is more expensive or less convenient to use. People are generally more willing to use a type of fuel if they can afford this. If a smaller portion of a person's is income is spent on energy, they are more willing to pay more for their fuel.

Timestep selection
Vensim works using continuous modelling and is therefore uses differential equations in modelling its functions. It does so by using sufficiently small timesteps that allows equations of $y_t - y_{t-1}$ to approach $dy/dt$. The developed model works using time-steps of 0.0078125 on a yearly basis. This means that there are 128 time-step values in a year. This is the highest level of detail possible for a standard Vensim model – which allows more detail and the model to be used as a start for more detailed implementations in the future.

## 4.3 Conceptualisation of the co-simulation

The co-simulation is in its entirely governed by the script written in Excel VBA. This script determines which model runs at what point, is responsible for saving, exporting and importing files and values in either the Vensim as well as the LEAP model and will be responsible for policy observation. As such, the entire user interface is also set up within the Excel file in which the script is written. As can be observed in **Figure 13** below, all communication between the two models will be interlaid via the VBA script.

A schematic diagram that encompasses the full conceptualization of both simulation models can be found in **Appendix D**. Starting at the centre of the schematic diagram, it is important to determine which model to approach first. The initial model assumption is that the residential demand can always be fulfilled. Under this assumption, it is necessary to know what the energy-demand is before supply can be considered. This means that during the co-simulation, the Vensim SD model will run first.

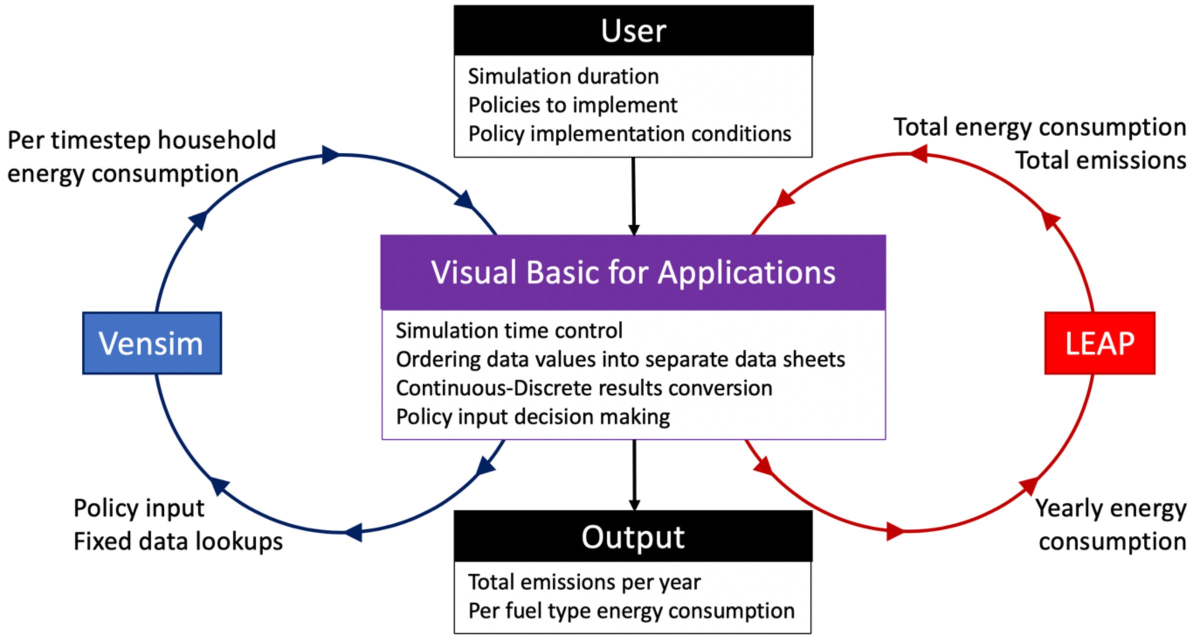


**Figure 13:** A schematic of the co-simulation run

**Specifying the model run through user input**
Before running the model, the user can select under which conditions a certain policy needs to be implemented. This can be either due to a high concentration of $CO_2$, $PM_{10}$, or starting at a specified year. The policies that can be implemented are discussed in **paragraph 4.5** below.

All experiment runs start in 2010. Each simulation has a five-year warm-up period between the years 2010 and 2015. These years are only used in the Vensim model run, the results of which are not transferred to the LEAP model. In these runs, the policies are implemented in 2020 as this is the start of the next five-year plan (Fourteenth-Five). The experiments will finish after the year 2030.

**Simulation time control**
When the user starts a model run, the VBA script first needs to create some external variables that are used to keep track of the model run and are necessary in order for the model to understand which 'federate' the model is being approached and what the general time within the model run is: a 'current time' variable. When the model starts, the 'current time' variable needs to be set to the first year of the simulation: 2015. The VBA script 'opens' the Vensim model and does a full model run is from 2010 until 2030. The years 2010 until 2015 are used to start up the Vensim model.

**Fixed data lookups and Vensim model run**
The Vensim model uses some data values and modelling assumptions as input. These values have been generated through the development of an earlier LEAP model and contain data regarding household urbanization (necessary to calculate total energy consumption) and expected electricity consumption of other appliances (necessary to calculate the total money spent on energy).

**Per timestep household energy consumption**
The main output of the Vensim model is the per timestep household energy consumption of each independent fuel, at each individual timestep.

**Ordering data values into separate sheets**

Information about energy fuel demand per year, per fuel and per area are stored within Excel files all independently created by the VBA script. Despite the entire model running from 2010 until 2030, the results used will only consider that first Vensim model run for the first year (2015) is completed. The entire model run is necessary in order to maintain internal model validity within the continuous model.

**Continuous-discrete results conversion**

A standard LEAP model operates using yearly time-steps (and may use direct linear interpolation between two years if necessary). This means that the energy and emission output is also shown on a yearly basis. As LEAP is limited to discretized slices of time, it has 128 values (each timestep from the Vensim model) to implement, in a place that only allows one (discrete) single value implementation (a single value). Each value of energy output in the Vensim model is considered the forecasted amount of energy used in the upcoming year. The average value of forecasted data for the next year will be used as using a single value (such as the first value of each year) would result in the loss of a lot of important data as 127 other data points per year would be ignored.

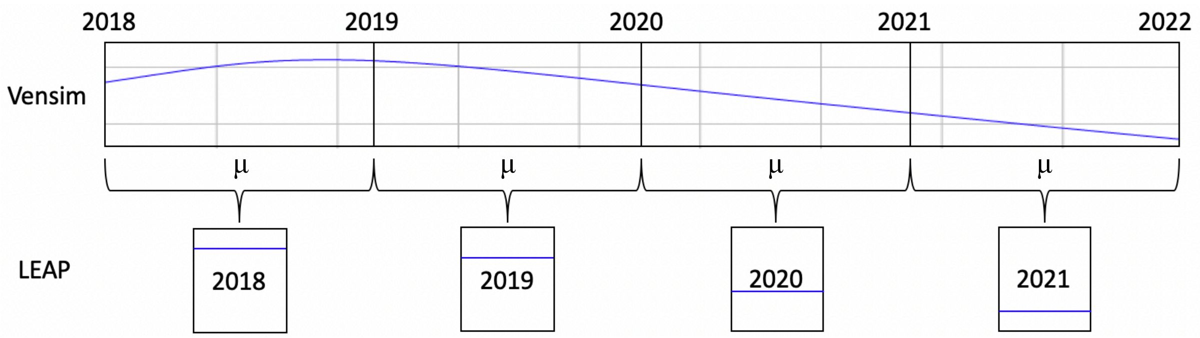


**Figure 14**: Conversion from the continuous Vensim model to the discretized LEAP model

**Yearly energy consumption and LEAP model run**

By making this continuous to discretized conversion for each individual fuel type, the LEAP model now has valid input regarding Jingmen's residential fuel demand. Using this data, the LEAP model will run and eventually output total energy demand for the rural and urban areas, as well as simulated emission results for both areas. The model can then use this data to calculate its entire energy demand, the energy supply necessary to adhere to this demand and the total emissions of the direct consumption of the demand causes.

**Total energy consumption and total emissions**

Following this model run, the VBA script will export the total energy demand from the residential sector as well as its corresponding emissions data into newly created data sheets. This investigation limits itself to $PM_{10}$ and $CO_2$ emissions caused by direct household energy consumption. The output of these data values is carefully selected and placed in individual data sheets.

**Simulation time control (2)**

After a whole simulation cycle, the energy consumption for a single year is calculated. The VBA simulation time control will increase the 'current time' by one (so after one cycle, the 'current time' will change from 2015 to 2016), after which the Vensim model is approached again. This means that the results from the run of 'current year' run in 2015 will only select the results obtained for 2015. Similarly, the energy results obtained from the run of 'current year' in 2016 will only select the results of 2016, and so forth. By combining these results for each 'current year' run, a coherent co-simulation is achieved in which the results from one model are directly influencing the other model.

**Policy input**

By specifying the exact policy to implement, and under which conditions, the VBA script will compare the current conditions of the model run to the conditions that may trigger a policy (comparing the current time and emission values).

The described procedure repeats itself for each individual year in the simulation run (15 times in a general model run). This is done because the user needs to have full control over when and how a policy is implemented. In some scenarios the user could even want to implement a policy depending on the results from the previous year. This means that policy input needs to be adaptable. The user can input the 'triggers' for policy input in the user interface. By entering the year of policy implementation, a spreadsheet within the VBA application, will change keeps track of the circumstances regarding if, and when a policy should be implemented. Every iteration, the cells within the spreadsheet are checked whether a policy should be implemented. For example, if the 'Current Time' of the model equals the year of desired policy implementation, a script will be triggered to adjust variables in another Excel sheet that keeps track of policy implementation: *PolicySheet.xls*. Each possible policy is already implemented within the Vensim model but switched off through a Boolean variable. The *PolicySheet.xls* is connected to specific variables as lookups and Booleans in the Vensim model. Implementing a policy will switch the Boolean 'on' causing the policy to be in effect. Further detail about the technicalities regarding the policy input implementation are provided in **Appendix E**.

## 4.4 Policy design

### 4.4.1 Policy overview

In order to have a better idea about the problem and policies to consider, interviews were conducted with various parties within the Jingmen prefecture. Although different stakeholders are concerned with the current situation, limited concrete policies have yet been put forth. In order to promote rural household energy transition, the Chinese government has attached great importance to clean energy supply through issuing a number of policies directed at rural electrification and gas development. However, there are tangible polices that are being examined, that are already implemented elsewhere, or are currently implemented for purposes other than emission-reduction. When designing the policies, it is important to keep in mind that their extent to which they can be investigated depend on the chosen scope as this directly excludes some policies (such as demand-driven electricity pricing) from being researched.

The policies that are investigated are explained below. Not only are these five policies desirable and in-line with the current agenda, they also observe the impact through different aspects of behaviour. Two policies affect behaviour through price-level adjustment, one policy impacts the convenience of consumption, one policy attempts to adjust behaviour through knowledge and one observes the impact of removing an alternative through legal means. Investigating policies that impact these different aspects opens up more insights regarding area-related behaviour. Conclusions can be drawn not only about the effectiveness of the policy, but also on what aspects of behaviour can best be focussed on in order to induce desirable change. Therefore, the following policies are considered:

1. **A complete ban on residential coal use**

Bans on residential coal use have been temporarily implemented in the past, especially during periods at which pollution levels were high. Due to the more local nature of air pollution, these bans themselves have mainly been implemented on a local scale. In 2014, reports announced that the larger cities in China would carry out a complete ban on coal consumption by the end of 2020 in order to curb emissions (Yeo, 2014). Although Beijing has been the only city that has formally announced the ban on coal consumption thus far, other cities will likely follow suit as the nation-wide energy transition continues. Interviews conducted seemed to indicate that the prefecture of Jingmen is preparing for a situation where a province-wide full ban on residential coal consumption could be implemented in the near future. However, no official documents concerning this policy have been released as of yet. According to interviews held with the Jingmen Development and Reform Commission, the ban would come into effect for the entire Hubei province, residents as well as companies that under the jurisdiction of the Hubei province (only some national industrial companies would be allowed to use coal within the province as they are under national jurisdiction).

2. **An (incrementally) increased price on residential coal use**

There are several ways in which the coal price can be increased (tariffs, emission trading system, natural resource price, etc.), but due to the geographic scope of this paper, their implications and direct workings will not be further discussed. However, it is worth investigating what the effects are if the price of coal is artificially increased through an ad-valorem tax. In August 2019, Chinese legislators approved a law giving local government the authority to put independent taxes on goods including coal and other fossil fuels (Stanway & Chen, 2019). A tax on coal could make the fuel so expensive that people are unwilling to any longer consume coal. The tax could be implemented in various ways (i.e. direct, gradually incremental or incrementally dependent on emission levels from the previous years or distance from emission targets). This study will consider the effects of a coal tax increased in yearly increments. A report by the IMF (Parry, Mylonas & Vernon, (2018)) highlights that a yearly incremental increase of coal taxing should be very effective in reducing emissions. According to their estimates, a tax on carbon dioxide ($CO_2$) emissions, rising by $5 per year between 2017 and 2030, significantly reduce world-wide $CO_2$ emission levels. When focusing on coal alone, Parry et al. (2014) estimate that 3.3$/GJ (around 0.025 RMB/MJ) of energy from coal combustion is necessary in order to have a significant impact on reducing emission levels. The current nation-wide coal resource tax in China is very low (0.3-5 RMB/ton) and neglects environmental cost (Shi, Tang, & Yu, 2015). A much higher tax is needed in order to have a meaningful impact. For this reason, the tax increment of 0.02 RMB/MJ per year is chosen as medium level policy.

3. **A subsidy on electricity**

As a nation, China is currently heavily investing in renewables such as wind and solar energy. One way how solar energy is currently being promoted is through China's 'Solar Energy for Poverty Alleviation Programme', announced in 2014. After a testing phase, this initiative has now been expanded for many areas across the country, including the rural areas in Jingmen. Solar panels are installed on rooftop of individual houses as well as in larger solar fields. However, rather than directly consuming the electricity obtained from the solar panels, all energy obtained from the solar panels is sent directly to the grid, after which the individual citizens can consume their electricity at a reduced price. The provision of cheaper energy at lower prices from the solar panels is currently only reserved for selected areas in the prefecture, however this policy could be expanded on a city-wide basis, which should lower the overall electricity price for the consumers. This would make the consumption of electricity household purposes more economically viable.

In 2007, the Chinese government spent over 20% of its energy subsidy on subsidizing residential electricity consumption (Lin & Jiang, 2011). Additionally, the external costs of coal consumption are estimated to constitute 23.3% of the reference price of electricity (Wang & Lin, 2017). In order to stimulate the population to reduce the consumption of bad fuels, a medium level of an electricity subsidy of 25% of the electricity price is chosen in order to investigate the effectiveness of the electricity subsidy.

4. **Increasing gas-line placement**

The placement of natural gas pipelines throughout country is currently expanding at unprecedented pace. Individual households are being connected to the gas-lines rapidly. Although many in the urban area of Jingmen are already connected to the national gas grid, a lot of the rural areas are currently deemed too remote and have houses of insufficient quality for a secure connection. However, with the rapid economic development and urbanization occurring within the country, new apartments and houses are being built, many of which are developed with a natural gas connection. Speeding up this process and increasing the placement of the natural gas may make the fuel more convenient to use as a whole and create a shift from dirty fuels to gas.

Between 2010 and 2014, the yearly increase in natural gas pipeline construction was about 9% per year (Swennen, 2017, p. 236). Due to the rapid development of natural pipelines in recent years and the potential development of a Hubei natural gas hub (Swennen, 2017, p. 242) will likely accelerate the Jingmen area at a faster rate than other areas. For this reason, an additional increase of yearly pipeline placement of 20% is chosen at medium level.

**5. Educating the public through additional exposure**

Another way to develop a shift from 'dirty' to cleaner and more efficient fuels is by better educating the general public in the dangers of dirty fuels to the environment as well as their own health. The importance of educating the public has been highlighted by (Muller & Yan, 2018; The World Bank, 2013). There are many ways educating the public this could be done, such as providing guidance through workshops and activities, media publicity and encouraging social participation in becoming green. Many people are very willing to assist the shift towards a greener environment, but do not know how. Increasing the knowledge of the people will benefit the environment not only in creating a shift from dirty to clean fuels but can also be used to teach the public about how to best reduce fuel consumption, for example through better insulation.

*Policy implementation*

The policies are connected into the Vensim model as following:

- **Coal Ban:** A variable connected to the utility of coal will be put to zero, limiting its access.
- **Coal Tax:** The total coal price equals its market price plus any additional costs of coal. These when a coal tax is implemented, these will increase.
- **Electricity Subsidy:** The total electricity price equals its market price plus any additional costs. These additional costs are normally set to zero, but when an electricity subsidy is implemented, these will decrease as a negative tax.
- **Additional Gas Line Infrastructure:** The expected gas line infrastructure is a lookup value over time. The additional gas lines policy increases this lookup rate (to a maximum of 100%).
- **Additional Exposure to Clean Energy:** Within the Knowledge and Willingness sub-model, people have an exposure to clean energy. This coefficient will be multiplied by a certain factor that increases the amount of general exposure.

### 4.4.2 Confining the policy space

Despite this research containing the number of possible policies to implement to just 5, this still leaves an enormous policy space to consider. For example, **Policy 3** (a subsidy on electricity) may be more effective when the public is better educated (**Policy 5**). Most policies considered are non-exclusive and also non-binary (there can be various heights at which a tax can be placed). The distributed method of how the research is being conducted leaves large scale exploration through Monte Carlo or Latin Hypercube policy sampling techniques for future research. For these reasons, this paper will only consider the five policies outlined in **paragraph 4.4.1** in three different categories (low, medium and high) and a combination of between two policies.

**Table 2:** an overview of the five different policies and their levels

| **Policy (Implemented in 2020)** | **Low** | **Medium** | **High** |
|---|---|---|---|
| Policy 1: Coal Ban | X | X | X |
| Policy 2: Incremental Coal Tax | 0.01 RMB/MJ/Year | 0.02 RMB/MJ/Year | 0.03 RMB/MJ/Year |
| Policy 3: Electricity Subsidy | 10% of Electricity Price | 25% of Electricity Price | 40% of Electricity Price |
| Policy 4: Additional Gas-Lines | 110% of normal increase | 120% of normal increase | 130% of normal increase |
| Policy 5: Increasing Public Exposure | 125% exposure | 150% exposure | 200% exposure |

When combining different policies, a maximum of 2 policies is to be combined. Furthermore, it is superfluous to combine policies 1 and 2 as the coal ban would make any coal tax unnecessary. **Table 3** below shows the possible combinations between the different policies. For each of the combinations, only the 'Medium' level is considered.

**Table 3:** an overview of the combined policies

| **Policy Number** | **Policy A** | **Policy B** |
|---|---|---|
| Policy 6 | Policy 1 | Policy 3 |
| Policy 7 | Policy 1 | Policy 4 |
| Policy 8 | Policy 1 | Policy 5 |
| Policy 9 | Policy 2 | Policy 3 |
| Policy 10 | Policy 2 | Policy 4 |
| Policy 11 | Policy 2 | Policy 5 |
| Policy 12 | Policy 3 | Policy 4 |
| Policy 13 | Policy 3 | Policy 5 |
| Policy 14 | Policy 4 | Policy 5 |

## 4.5 Evaluation of the model conceptualisation

In order to investigate the household energy consumption, consumption behaviour and potential emissions of $CO_2$ and $PM_{10}$, a co-simulation model has been developed. The current energy consumption and attitudes of the households have been researched through survey studies explained in **Chapter 3**. This data is subsequently used for the development of a System Dynamics model that models energy consumption using household attitudes to fuel cost in relation to income, convenience of consuming a certain type of fuel and the overall knowledge and willingness of people to consume clean fuel once they know that it is desired to do so. The translation that is made in developing a quantitative System Dynamics model from qualitative attitudes is explained in **Appendix B**, however such a translation always gives rise to modeller bias. Any initial assumption made will carry through within the model and have a potential effect to slant simulation results and policy effectiveness. For this reason, performing a model validation and a sensitivity analysis are essential in order to observe the extent to which variables have an impact on the model results. Using survey results to build the model provides further issues as it already assumes that the surveyed response groups are representative for the city as a whole and assumes that the responses are truthful.

It is apparent that a Vensim model by itself is inadequate to obtain the full picture regarding Jingmen's household emissions. For this reason, a co-simulation with LEAP has been developed, but it is ensured that both models are able to run completely separate from each other. The method of how the co-simulation is developed raises the theoretical question of whether or not the simulation is actually distributed. Although results from one model influence the run of the other model, in actuality the model runs are completely independent from one another. However, by conceptualising the model in this way and storing all model results in a structured, a full model run can be achieved by taking the 'current year' variable of each corresponding year. An important advantage of modelling this way is that it provides a near infinite policy space for the policymaker. Although the paper will only touch upon the possibilities of the policy implementation, it allows policies to be implemented for limited period, make policies depend on emission results from previous years, and it allows a direct comparison of household emissions with regards to energy supply and expected emissions in other sectors.

On the other hand, the chosen method of investigation brings about limitations in design and policies that can be evaluated. The model can only investigate policies that are directly adjustable within the model that is developed. The focus on demand-driven consumption behaviour thereby completely negates any focus on renewable energy: a policy that is essential in shaping the Chinese energy infrastructure currently and in the future. Like the rest of China, the city of Jingmen is undergoing an enormous shift from fossil fuels to renewable energy as wind power fields and solar farms are still being built within the city (IBR, personal communication, June 3rd, 2019). Such projects will have a large influence on consumer behaviour as this will show greater awareness, it could also have an impact on the industry of Jingmen altogether and adjust price levels of fuels. Excluding renewable energy from the scope of the demand-side model could therefore cause some aspects within the model to be insufficiently calculated.

Regardless, the model reflects upon patterns of behaviour that are regarded as most important by the citizens and can therefore reveals what public reactions to policy implementation the local government can expect. Furthermore, the feedback loops present can provide higher order insights regarding demand quantity and fuel type and its connection and freedom regarding policy implementation within the model can give good insights for policy recommendation. Still, it is important to know the validity of the model in comparison to reality and know what assumptions and modelling decisions are made in order to understand the circumstances under which the conclusions and recommendations are drawn.

# 5. Model validation and sensitivity analysis

This chapter explores the validity of the constructed model. This chapter will compare standard model results with expert opinion in **paragraph 5.1**. Following this model validation, a sensitivity analysis is performed to observe to what extent the final results may be affected by inaccuracies. The results of the sensitivity analysis are presented in **paragraph 5.2**. As a result of the performed analyses, **paragraph 5.3** will close the chapter by reflecting on the implications of potential inaccuracies and discrepancies on the generalization of the model.

## 5.1 Model validation through expert opinion

Model validation is done to test to what extent the developed model reflects the reality of what is being modelled. The lack of thorough statistical or census data makes it extremely difficult to perform accurate validation tests. Validating the model has become even more difficult as data values from the past and present are subject to frequent statistical modification (H. Zheng et al., 2018). This creates uncertainty, not only for future scenarios, but also in past data. An additional problem with validation of this model is the data collection. Over the course of the research, the amount of sampled data through survey analysis from the rural areas in Jingmen is insufficient to provide a definite inspection about consumption. Even a much larger sample size would be subject to continuous uncertainty about honesty (such as observer effects), lack of knowledge about personal consumption, and the distribution of the large population. The model validation will be performed by comparing the model data 'expert opinion', which are initial models developed through expected interpolation of current trends of general residential energy consumption in Chinese cities.

### Electricity consumption

The difference between the models is that one uses mere interpolated figures from expert opinions, whereas the model developed in Vensim attains the results from residential behaviour through attitudes towards fuel price, convenience of fuel use, and changes in their knowledge and willingness. The following figures will compare the comparison between the data values provided and the data sets are shown below.

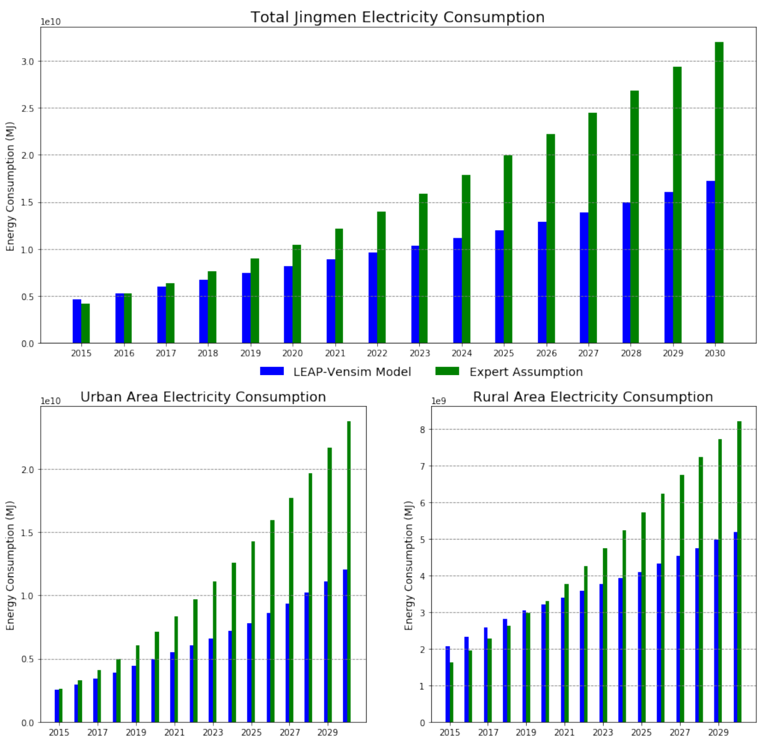


**Figure 15:** Comparison of electricity consumption in Jingmen, the co-simulation is shown in blue, the expert assumptions shown in green.

Considering electricity demand, the model shows discrepancies with the initial predictions that are mainly due to differences in the increase of electricity demand. These discrepancies are mainly because the expert assumption uses higher estimations in residential ownership of general household appliances compared to the simulation model. This over-estimation is mainly due to the direct linear interpolations taken for certain appliances, which only considers per capita income and ignores diminishing user satisfaction after ownership of a certain number of appliances – for example, owning two televisions may be more desirable than owning a single television, but it is unlikely that a household will own four televisions if income increases four-fold. These over-estimations are indicative as the survey data showed that initial user ownership is greatly over-estimated in 2019.

### Gas consumption

**Figure 16** below shows the comparison between the model and expert estimation for the consumption of gas. The simulation shows that the natural gas consumption is over-estimated in 2015, but the rate of increase in consumption is smaller than that is estimated. Where the rate of change in the simulation model is about linear, this increase in gas consumption shows nearly exponential according to the expert assumption. A reason for this is that the gas consumption seems to be dependent on convenience, which is modelled as incremental differences in utility between several types of fuel, as is further described in **Appendix B**. On the other hand, the model developed using expert opinion is highly dependent on GDP, which is assumed to increase almost exponentially.

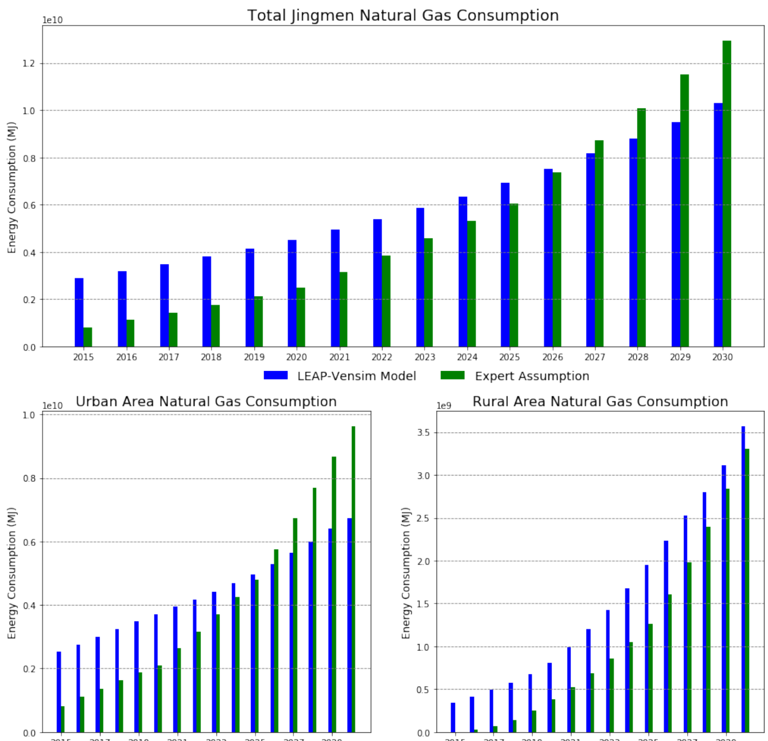


**Figure 16:** Comparison of gas consumption in Jingmen, simulation is shown in blue, expert assumptions shown in green.

Another reason for this steep increase in the rate of natural gas consumption is likely due to unintentional implemented policy bias made by the experts. As there is an awareness that China is heavily investing in furthering nation-wide natural gas consumption, this may have played a role in the assumptions made. On the other hand, the Vensim simulation model fails to acknowledge any subsidies made over the recent years, and those expected in the future but instead uses a fixed, around average price of gas for the entire model run. This means that the increase in consumption of gas is predicted is likely underestimated in the simulation model, while overestimated by the experts. This could in turn mean that the actual change that can be made through policy design for the natural gas consumption will be over-estimated using the simulated model.

### Coal consumption

The consumption of coal shows considerable differences between the developed co-simulation and expected data. The main differences however, are ascribed to the fact that field research shows that the quantity of rural coal consumption currently seems to be over-estimated, as many people in rural areas around the country are shown to be using biomass fuel (The World Bank, 2013). On the other hand, it is expected that without any intervention, the coal consumption will be increasing (in a non-policy scenario) as a result of increasing GDP and overall energy use. The inherent bias of a reducing coal consumption can be ascribed to the expectation of anti-coal consumption measures that are to be implemented.

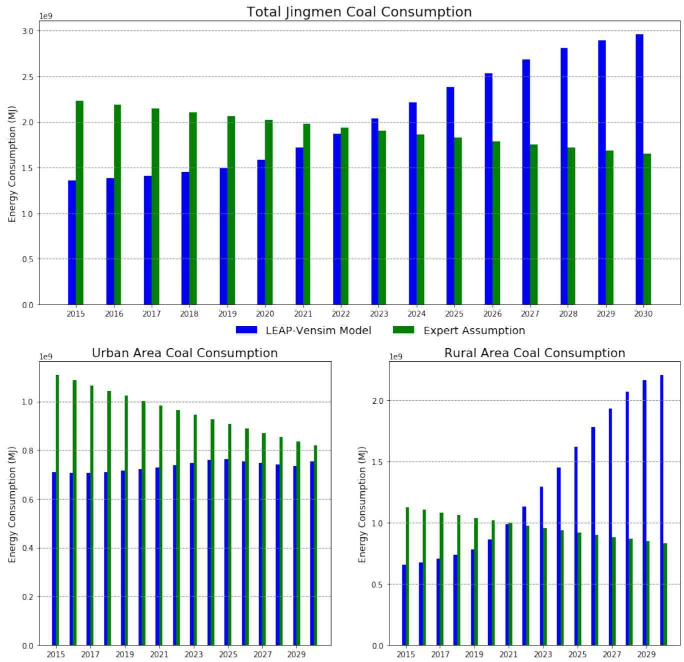


**Figure 17:** Comparison of coal consumption in Jingmen, the co-simulation is shown in blue, the expert assumptions are shown in green.

Another reason for the differences could be due to the observer bias. As a significant part of individual Chinese households may choose to burn cheaper but more harmful fuels but are unwilling to openly admit doing so out of fear for social or legal repercussions. This makes it extremely difficult to obtain an accurate figure on consumption of both biomass and coal fuels. From the survey and local interviews conducted, the consumption of biomass fuel is still rather large, something which is further supported by other research conducted in rural China (Ma & Liao, 2018; Qiu, Yan, Lei, & Sun, 2018; The World Bank, 2013).

### Biomass consumption

The difference in biomass consumption between the model and the current assumptions are therefore large, but understandable. The expert assumes that there are no urban users of biomass in their daily household. This opinion seems to be invalid; people surveyed have shown to use biomass and still see it as a viable fuel in the coming future. Moreover, the actual consumption of biomass in the urban area is over 1000 times smaller than the consumption in the rural area, meaning that its consumption in the simulation is minimal in the urban area too. The reason for these assumptions is that in both models, biomass is assumed to be gathered by the consumer rather than bought. A significant portion of the biomass are crop residue. The urban area simply has no space for any agriculture, or crops to be harvested. Hence, this underlying model assumption has a significant impact in overall model result.

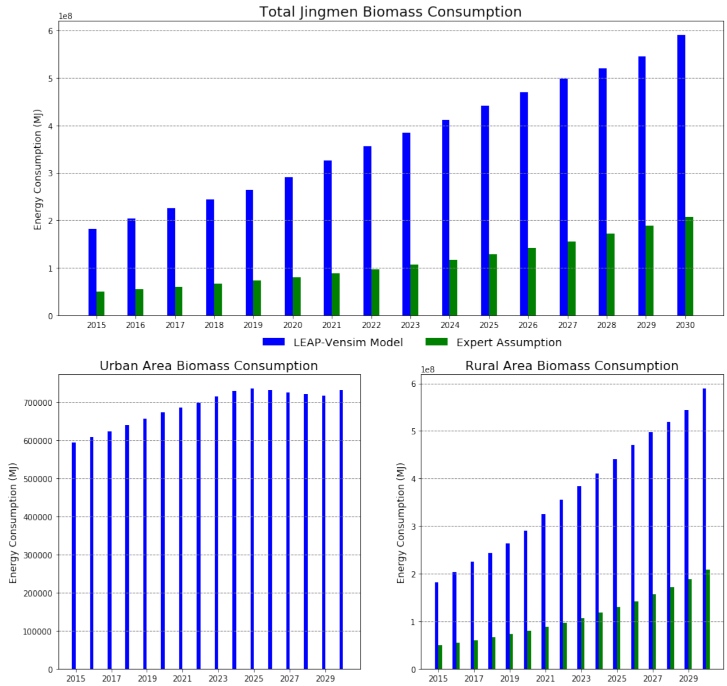


**Figure 18:** Comparison of biomass consumption in Jingmen, the simulation is shown in blue, the expert assumptions are shown in green.

## Overall energy consumption

**Figure 19** below shows the total energy consumption in Jingmen. There are large differences, mainly due to the dominance of electricity usage in the households (considering the other household appliances). This means that the model shows smaller energy consumption values than estimated by the experts.

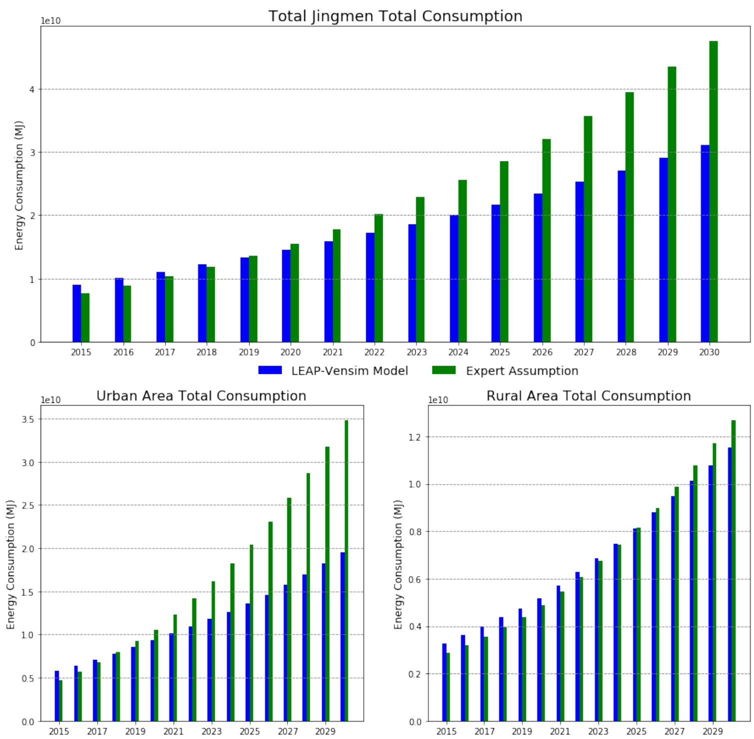


**Figure 19:** Comparison of total energy consumption in Jingmen, the simulation is shown in blue, the expert assumptions shown in green.

Even though there are still large improvements to be made to the current model if they are to conform to the initial expert estimates, the question remains whether or not real ‘improvements’ in order to classify the model as ‘valid’, especially if neither can be validated as absolute truth. Expected consumption and modelled consumption of different fuels still show significant differences. According to the model, biomass and coal consumption will increase in the future, the shift towards natural gas will be slower than assumed and the electricity use is smaller altogether. On top of that, the expert assumption shows that the reduction in coal will be mitigated in its entirety by the heavy increase in gas consumption. This behaviour is not observed in the simulation model.

The main problems regarding validation are due to differences in initial model assumptions, but these discrepancies are inherent depending on the modelling approach. Without a thorough census for all residents, it will be nearly impossible to obtain an all-encompassing regarding residential energy demand, especially if the data is subject to further modification in the future. It is desirable to observe patterns of behaviour and see how citizens will adjust their behaviour depending on policies implemented at certain times. However, in order to further investigate whether the behaviour is as expected and what reactions may occur in case there are slight discrepancies in the model assumptions, a sensitivity analysis needs to be performed.

It is important to understand the root cause for the discrepancies. The underlying differences can be due to assumptions made in model development, an entirely different modelling approach or different data used in model forecasting. The simulation model and expert opinions are based on completely different grounds. Where the experts base their results on current levels and changes in expected residential income and developmental prospects from a top-down perspective, the simulation model takes the same initial approach but place more consideration in behaviour bottom-up. As Kavgic et al. (2010) state, the different assumptions made in bottom-up (Vensim) and top-down (Expert Assumption) approaches tend to lead to diverging results. Both approaches can be considered understandable and valid, however the approach taken may solidify their own scenarios going forward. Even though the same data is used, the way the data is used in later feedback loops is different. Where the expert model took the provided data at face value, the Vensim simulation model uses the data as a form of model calibration, where the data present is ‘reconstructed’ and explained through the variables in the model. This approach turns a model used to explore values into a model that seeks to explain the reasoning behind these values. However, this does create a fundamental issue for the simulation model output, namely that it assumes that the behavioural patterns of the households stay relatively constant over time.

As an example, people with a higher level of income will use more energy, therefore as income rises, so will energy demand. This SD simulation model shows that there are other factors at play, for example, at a certain level of income, households will opt to change to cleaner and more efficient fuels. Not only because this is a healthier option, but also because this is a lot more convenient. Furthermore, people may eventually use their additional income for other purposes or investments that may allow them to use less energy such as insulated windows, thicker walls or more efficient household appliances. This would reduce household energy demand in the long term. The two approaches will predict substantially different reactions from the households during policy intervention.

## 5.2 Sensitivity analysis

As part of the model analysis it is important to see the sensitivities of certain variables in order to observe how certain influences and uncertainties within the model affect outcomes. Due to the development of the co-simulation, it is not possible to see the influences of different variables for the entire model run. Rather, the Vensim model will be run as an individual model and the influences of the different variables will be compared to what this means for overall energy demand that is the normal output for the Vensim model.

The following ten variables will be investigated for the sensitivity analysis:

- Per household average rural energy demand;
- Per household average urban energy demand;
- Total rural electricity demand for household purposes;
- Total rural gas demand for household purposes;
- Total rural coal demand for household purposes;
- Total rural biomass demand for household purposes;
- Total urban electricity demand for household purposes;
- Total urban gas demand for household purposes;
- Total urban coal demand for household purposes;
- Total urban biomass demand for household purposes.

Sensitivity analysis will be done by varying several variables simultaneously – these variables will be tweaked by category of price level, convenience, and knowledge and willingness. For each category, there will be 5000 simulation runs using Latin Hypercube sampling. All variables will be uniformly distributed between a minimum and maximum value that are around 20% lower and 20% higher than the standard values.

### *5.2.1 Sensitivity to price levels*

For investigating the sensitivity of the price levels, three values are adjusted.

**Table 4:** Price level sensitivity adjustments

| Variable | Unit | Minimal value | Normal value | Maximum value |
|---|---|---|---|---|
| Marketprice electricity | RMB/MJ | 0.120 | 0.147 | 0.180 |
| Marketprice gas | RMB/MJ | 0.030 | 0.037 | 0.050 |
| Marketprice coal | RMB/MJ | 0.015 | 0.020 | 0.025 |

The sensitivity analysis (**Figure 20**) shows that the rural area is extremely sensitive to variations in price, while the urban area shows nearly no sensitivity to the price adjustments. A slight deviation in overall price can have extreme effects in both the positive and negative directions for rural demand. This due to the high dependency on price that currently governs the choice of fuel in the rural areas. However, this in turn also means that the model values chosen for the rural areas cannot be accurately extrapolated for the distant future. The current impact of fuel price on rural energy demand may reduce if household income were to increase, or fuel price decreases in the future. On top of that, it shows that people will simply choose to not use energy if this turns out to be 'too expensive' for individual households to afford. With the lack of choice of electricity or gas provider, this can become very problematic as a continuous supply of energy is a responsibility for the government. This uncertainty further explains why the electricity price has fluctuated so little in recent years. In the past 10 years there have been only slight fluctuations in electricity price, ranging between 0.142 and 0.147 RMB/MJ (51 and 53 RMB/100 kWh) (CEIC, 2019). It is possible for large changes in electricity price to occur in short periods in China, as the electricity price changed from 0.122 RMB/MJ to 0.144 RMB/MJ between 2002 and 2007. However, this was during a period of unprecedented nation-wide economic growth.

The limited choices provided to the urban areas in terms of which fuels type to use and the inelasticity of the fuel to energy consumption is also shown in the sensitivity analysis. The higher per-capita income in the rural area means that the effect of the price has little impact on urban energy demand.

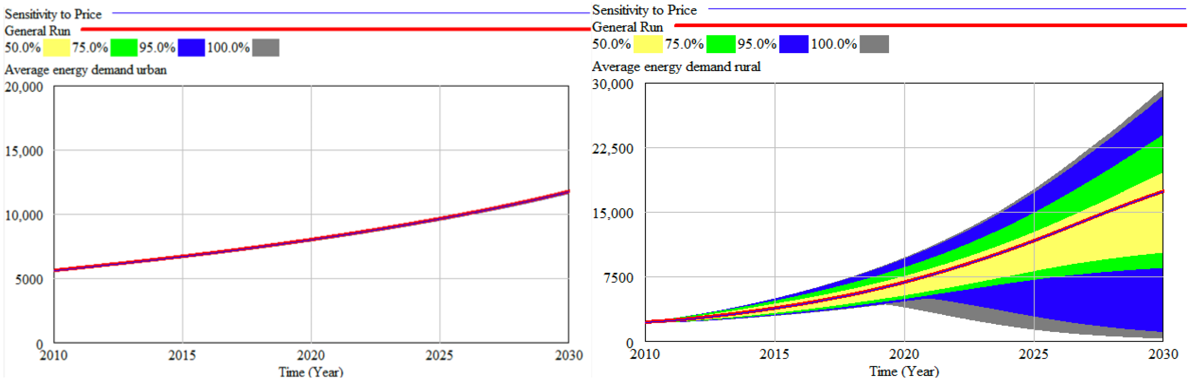

**Figure 20:** Per household average rural energy demand as sensitivity to price level (a) urban (b) rural

The electricity demand in the rural area is heavily influenced by its price. One of the reasons for this is that the consumption of other electric appliances is included in price-related considerations made by citizens, while this demand fixed regardless of price. This is because the use of these appliances is governed within the LEAP model rather than the Vensim model that is used for the sensitivity analysis. A low energy price with constant electricity consumption of other appliances will leave a huge leftover space in rural citizen budget. The high impact that price has on rural electricity consumption thereby causes demand to increase. This is further amplified by the positive feedback loops caused by an increase in knowledge about the consumption of efficient and clean fuels due to more people using clean fuels, and a reduction in availability of coal as a result of its reduced demand.

As with the energy consumption, the electricity price has nearly no impact on the electricity consumption in the urban area, except during the model warmup period. However, the differences in this five-year period seem to have no direct impact on electricity consumption later on.

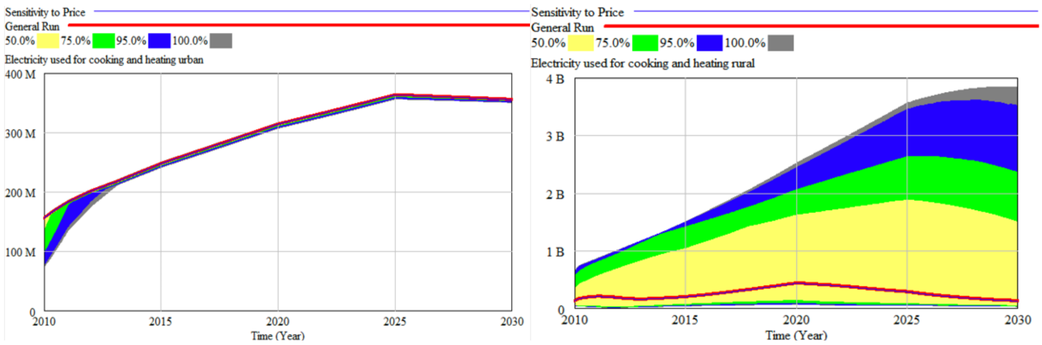

**Figure 21:** Total rural electricity demand for household purposes as sensitivity to price level (a) urban (b) rural

As with the electricity consumption, the consumption of gas in the rural area is extremely dependent on the price of gas (**Figure 22**). Although an increase in gas price will likely reduce gas consumption, it is unlikely that the gas consumption will increase a lot as a result of a reduction in gas price. The line showing the run of the current values lays outside the upper half of the 75% certainty ratio, meaning that in most tested scenarios, gas consumption is much lower than in the standard run. This shows that gas consumption is less sensitive to price level adjustments. The urban area on the other hand, shows rather stable outcomes regardless of changes in price level.

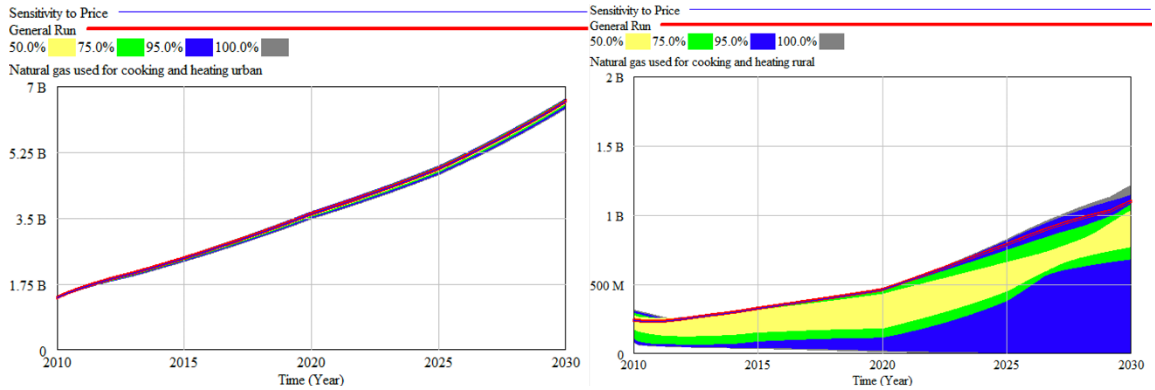


**Figure 22:** Total rural gas demand for household purposes as sensitivity to price level (a) urban (b) rural

Rural households express near-identical behaviour during fluctuations in price of coal as they do in their attitude towards gas consumption. The coal consumption seems to hit a 'ceiling' after which households will start consuming a more sophisticated fuel. This phenomena corresponds to the energy ladder model presented by Hosier & Dowd (2002). The rural area is extremely susceptible to this energy ladder model when merely considering fluctuations in price, as their current fuel choice is very dependent on price and income. The urban households show slightly more fluctuation in their coal consumption than in electricity or gas demand. The vast majority of households use gas for cooking and heating purposes, as this is a readily available and cheap option for them. Yet, lower income households in the urban areas may still be affected by price fluctuations.

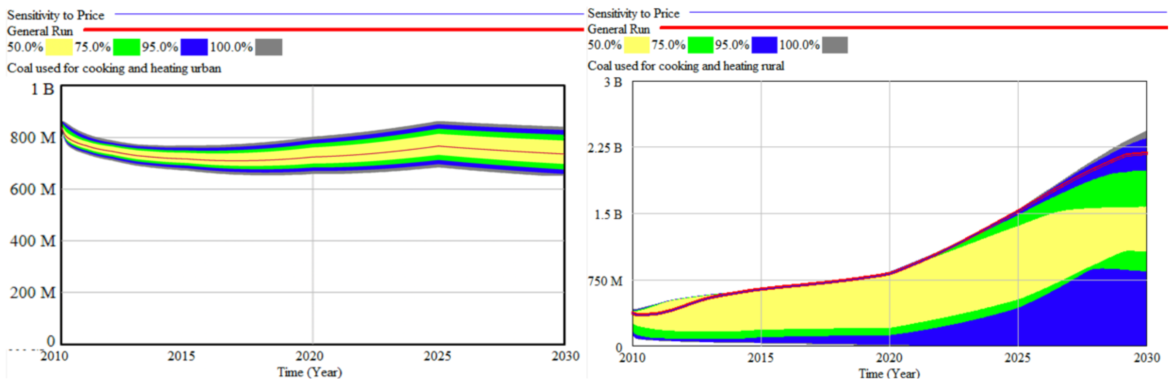


**Figure 23:** Total rural coal demand for household purposes as sensitivity to price level (a) urban (b) rural

As biomass is considered for free, the impact of changes in price level on the consumption on biomass comes from price changes of fuel sources other than biomass. These fluctuations are in accordance with the energy ladder; a decrease in fuel price of other fuels will also decrease the consumption of biomass. This can vary extremely in the rural areas, whereas the impact is limited for urban residents.

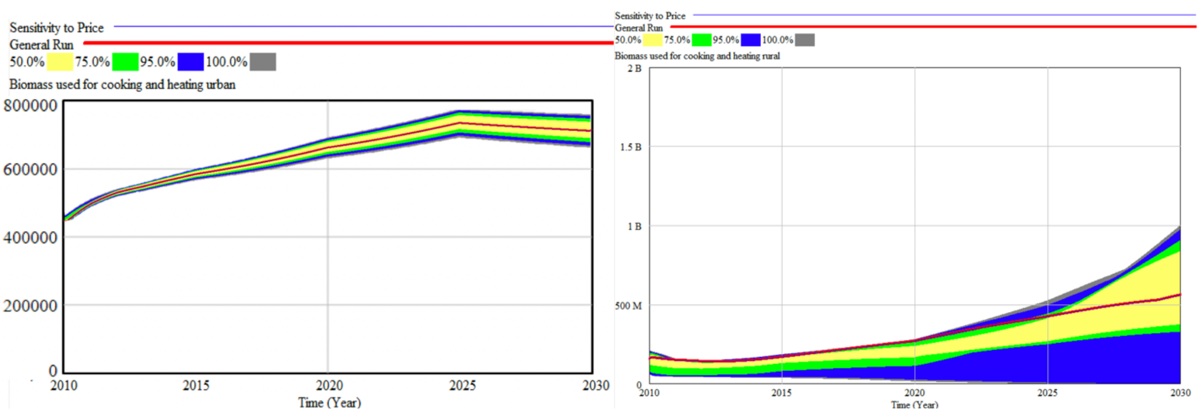


**Figure 24:** Total rural biomass demand for household purposes as sensitivity to price level (a) urban (b) rural

The high per-household energy demand in the rural area means that large changes can be incurred as a result of changes in price. It is unlikely that this will happen naturally as the national government aims to keep the energy price fixed. It is clear that the fluctuating prices will have a large impact on the rural area, while its impact on the urban area is expected to be much smaller due to the higher levels of income.

### *5.2.2 Sensitivity to convenience estimates*

To investigate the sensitivity of the model results to convenience figures, the following variables are adjusted:

**Table 5:** Convenience sensitivity adjustments

| Variable | Minimal value | Normal value | Maximum value |
|---|---|---|---|
| General convenience coal rural | 0.20 | 0.25 | 0.30 |
| General convenience coal urban | 0.24 | 0.30 | 0.36 |
| Increase convenience coal (to) biomass rural | 0.24 | 0.30 | 0.36 |
| Increase convenience coal (to) biomass urban | 0.24 | 0.30 | 0.36 |
| Increase convenience biomass (to) gas rural | 0.16 | 0.20 | 0.24 |
| Increase convenience biomass (to) gas urban | 0.16 | 0.20 | 0.24 |

The energy demand conforms in a very linear fashion to changes in convenience-related factors; the general run is largely in the centre of the 50% line, and uncertainties evenly spread. This is because there are limited dynamics within the convenience sub-model, as described in **Appendix B**.

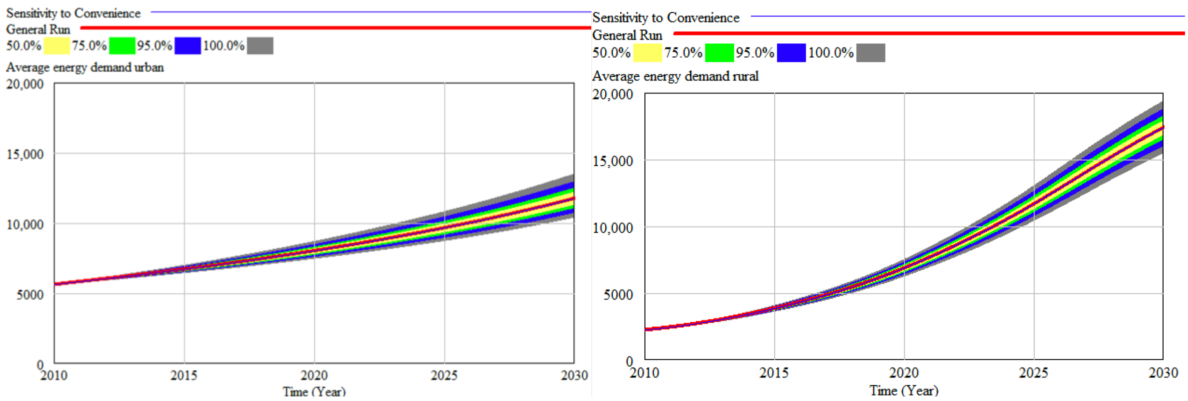


**Figure 25:** Per household average energy demand as sensitivity to convenience (a) urban (b) rural

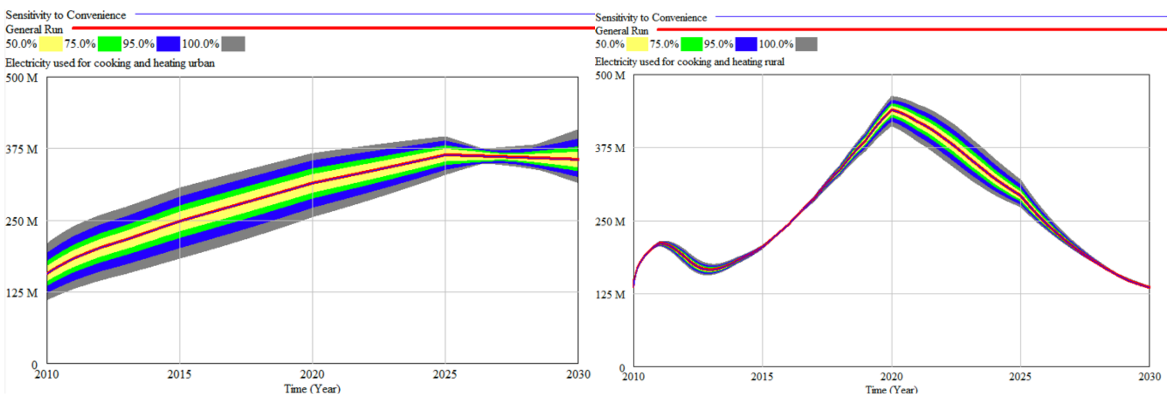


**Figure 26:** Total electricity demand for household purposes as sensitivity to convenience (a) urban (b) rural

Urban gas consumption is heavily influenced by convenience. This is because this region has a limited sensitivity to price level. Therefore, if households consume clean and efficient energy sources, they will value convenience more heavily. As electricity has a fixed (maximum) level of convenience, the urban gas consumption is extremely sensitive to its own changes in convenience. In case there is little difference between the two fuels however, households are more likely to consume natural gas as this is the cheaper alternative.

The rural areas exhibit very minimal sensitivity to adjustments of convenience-related variables. The electricity demand shown in **Figure 26b** indicates limited sensitivity, especially in early and later stages of the simulation runs. The other three fuel sources (**Figure 27b, 28b, 29b**) show a pattern that the values are directly impacted to changes, but even these adjustments are minimal. The consumption of electricity seems to peak around 2020, after which it steadily drops back to pre-2015 levels. An explanation for this is that the per-capita GDP in the rural area rises at a lower rate than the expected energy consumption, thereby making electricity relatively more expensive. Other alternatives become more desirable to use, causing a reduction in 'knowledge and willingness' to use cleaner energy fuels. Most importantly, gas becomes much more convenient to use. As a result, all incentive to use electricity is lost; it is the most expensive fuel, there is less willingness to consume clean fuels and gas has become nearly as convenient to use as electricity.

The urban area is especially affected by changes in convenience. This is likely the result of the urban area's dependence on gas. When considering the urban areas, the gas consumption (**Figure 27a**) shows a direct impact to changes. The fluctuations in the other three fuels (**Figure 26a, 28a, 29a**) are probably as a result of expected improvements in the pipe-line infrastructure in the urban area. Once this reaches a certain peak around 2026, the energy demand of other fuels seems to converge. This convergence is odd as it indicates that uncertainty reduces between 2025 and 2030. An explanation for this is that the consumption of other fuels will decrease as gas consumption becomes more convenient to use over time as a result of additional pipeline gas connections being placed in Jingmen. It is possible there is a point of convergence present which causes natural gas to be the most ideal fuel source to use in any situation.

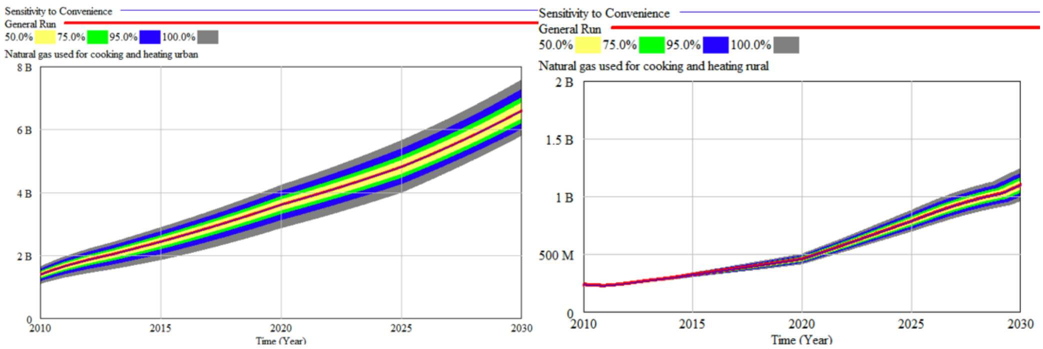


**Figure 27:** Total gas demand for household purposes as sensitivity to convenience (a) urban (b) rural

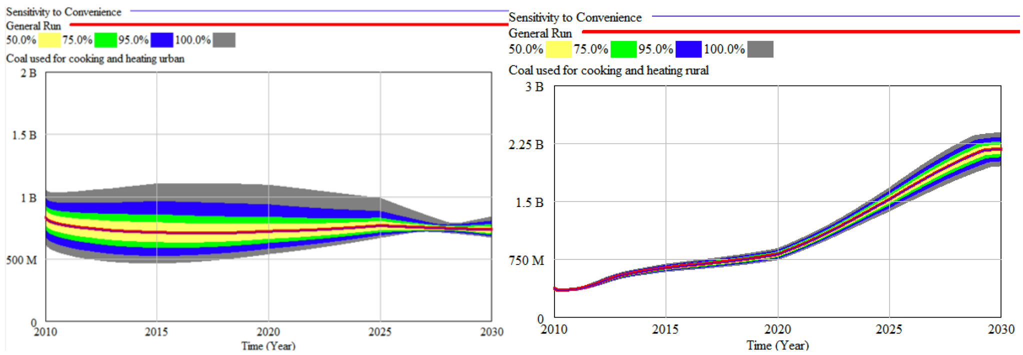


**Figure 28:** Total coal demand for household purposes as sensitivity to convenience (a) urban (b) rural

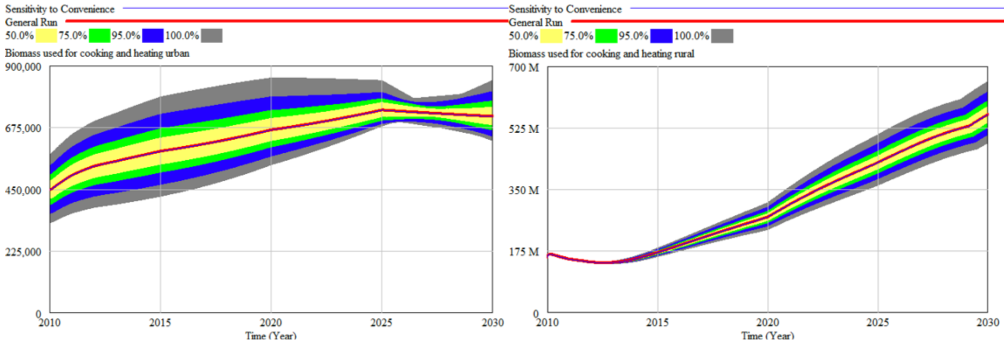


**Figure 29:** Total biomass demand for household purposes as sensitivity to convenience (a) urban (b) rural

Convenience has a lower impact in rural areas than price does, while it has a larger impact in the urban area. The fact that there is no complex dynamic process behind the gathering of the fuel sources prevents any further conclusions to be drawn in terms of convenience other than that a more convenient to use fuel will be used more frequently, ceteris paribus. The convergence taking place around the year 2026 also means that it is unlikely that fuel consumption becomes much more certain if there is a wide-spread availability of fuel alternatives.

### *5.2.3 Sensitivity to knowledge and willingness estimates*

To investigate the sensitivity of the model results to figures related to knowledge and willingness, the following variables are adjusted:

**Table 6:** Knowledge and willingness sensitivity adjustments

| Variable | Minimum value | Normal value | Maximum value |
|---|---|---|---|
| Effectiveness of learning | 0.4 | 0.5 | 0.6 |
| Effectiveness of information urban | 0.12 | 0.15 | 0.18 |
| Effectiveness of information rural | 0.08 | 0.1 | 0.12 |
| Initial knowledge | 0.48 | 0.6 | 0.72 |
| Normal exposure urban | 0.16 | 0.2 | 0.24 |
| Normal exposure rural | 0.08 | 0.1 | 0.12 |
| Social cohesion urban | 0.58 | 0.72 | 0.86 |
| Social cohesion rural | 0.54 | 0.68 | 0.82 |

The sensitivity analysis around the knowledge and willingness variables shows a very different impact between urban and rural households. Where fluctuations in the variables is likely only to decrease the consumption of the rural areas, it can more or less only increase the consumption in the urban side. This is again likely because the urban area is relatively aware of the impact their consumption has, while more growth can be achieved in the rural area.

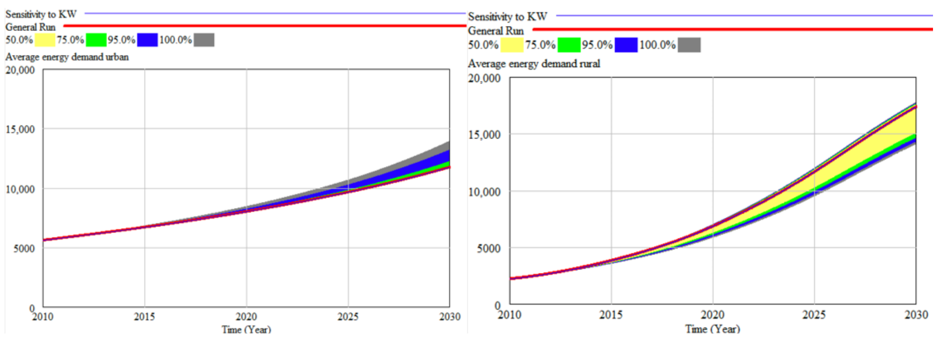


**Figure 30:** Per household average energy demand as sensitivity to knowledge and willingness (a) urban (b) rural

The consumption sensitivity of individual fuel types consumed in the rural area shows extremely interesting behaviour, namely it seems to indicate that there is an 'energy fuel ladder' in place not just in terms of price, but also in terms of knowledge and willingness. If people become more knowledgeable about fuel consumption, they are more likely to consume more efficient and clean fuel sources. The urban area on the other hand shows that this knowledge is already present: there is little room for increasing the amount of electricity and gas consumed. However, it does show that a lack of knowledge and willingness is able to increase the coal and biomass consumption with relatively large amounts.

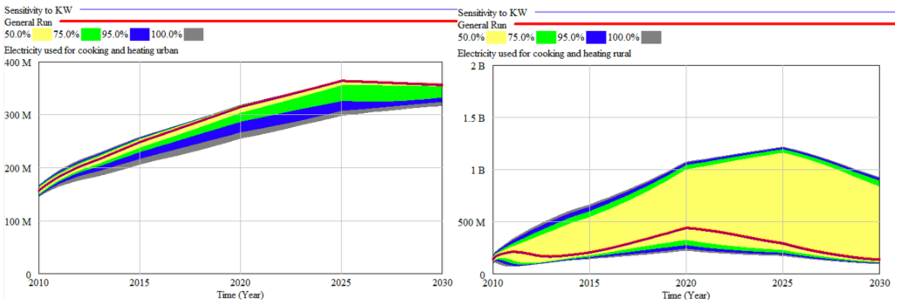


**Figure 31:** Total electricity demand for household purposes as sensitivity to knowledge and willingness (a) urban (b) rural

Even though the consumption of gas is not seen as an improvement over use of electricity in terms of knowledge and willingness (both are seen as clean fuels), the sensitivity results between electricity and gas are quite different in the rural area. Electricity demand can still increase by a lot, while gas consumption is nearly at a limit. The urban side also shows this limit with regards to consumption of natural gas, albeit with a larger quantity of demand and a higher level of certainty as is shown in **Figure 32** below. This is an indication that changing knowledge and willingness can only impact fuel consumption by a certain amount. Price and convenience have a more continuous impact.

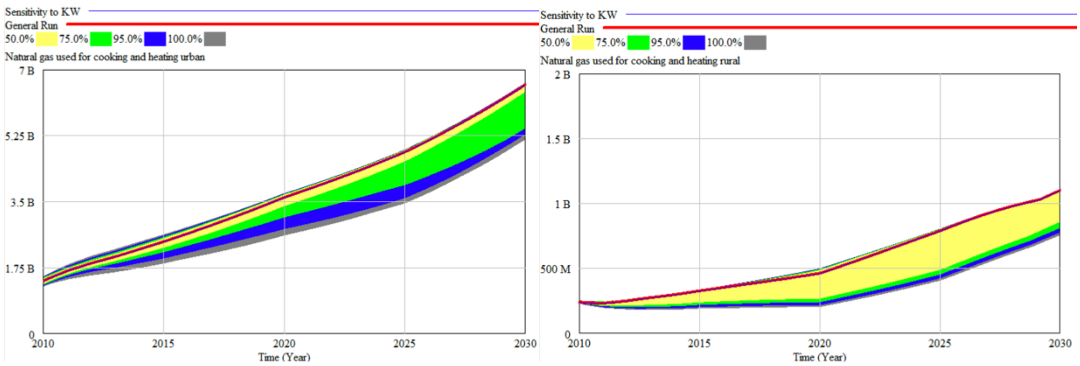


**Figure 32:** Total gas demand for household purposes as sensitivity to knowledge and willingness (a) urban (b) rural

The demand for coal and biomass (**Figures 33** and **34** respectively) is very different between the urban and rural areas. In the rural area, the consumption of coal can decrease. On the other hand, in extreme circumstances, the coal consumption in the urban area can only increase. This again shows the different levels of knowledge already present in both population groups.

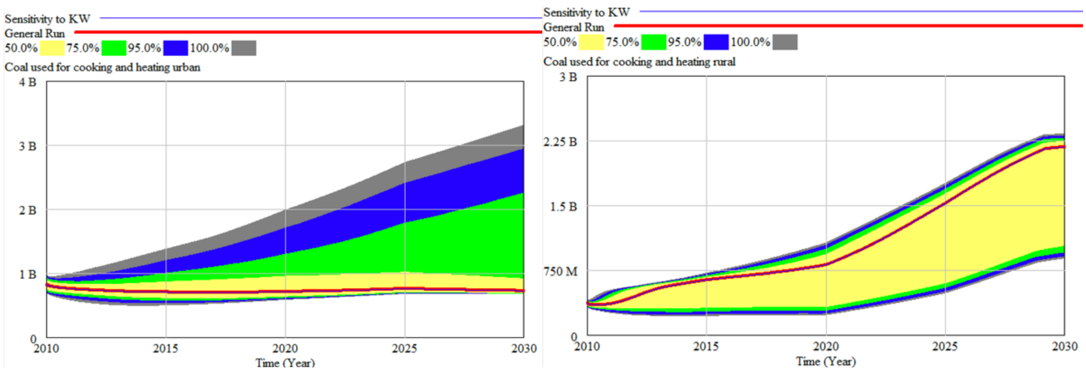


**Figure 33:** Total coal demand for household purposes as sensitivity to knowledge and willingness (a) urban (b) rural

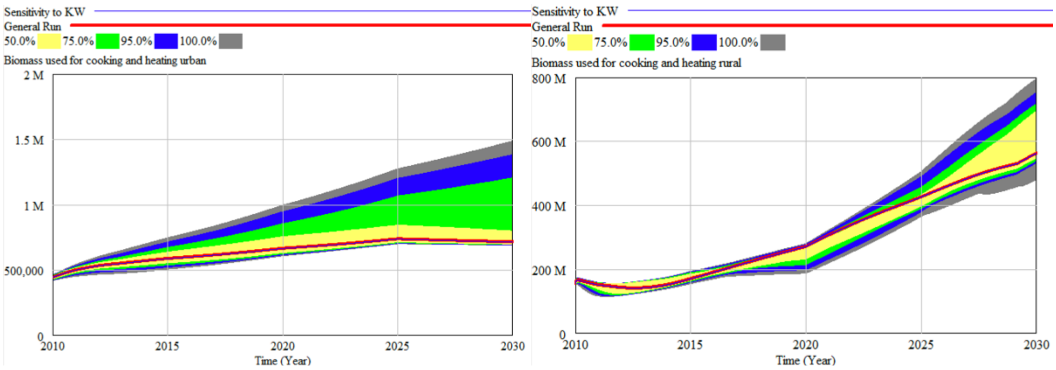


**Figure 34:** Total biomass demand for household purposes as sensitivity to knowledge and willingness (a) urban (b) rural

The sensitivity regarding knowledge and willingness shows that large gains can be made in the rural area (in terms of using electricity and gas as main source of fuel) by increasing citizen awareness. On the other hand, the urban area is only able to reduce their knowledge. However, maintaining attentiveness is still very important in order to ensure clean energy consumption.

## 5.3 Implications of discrepancies in validation for policy and model generalisation

Household energy consumption in China has been studied through various scopes, with almost each approach identifying the issue of harmful fuel consumption. Nonetheless, there is a lot of uncertainty present the data, which tends to translate itself into model development. In general modelling trends, this model proves no different. The discrepancies between the expert opinion and the model shows the glaring problem present when conducting residential energy studies in China. Despite the high level of control that the government agencies place on its citizens, absolute data about individual residential tendencies is absent. This is further complicated by modifications made in past data on a regular basis. This causes a lack of certainty for the government and experts, which transferred to research. However, rather than identifying exact values and figures for the model, its true strength lies in identifying patterns of behaviour providing insights on a by-area scale of household behaviour. Potential generalization of this model asks for adjustments will need to be made, the extent of which depends on underlying model values and modelling expectations. The usability of a generalized model depends on three aspects that this model has taken, labelled in a pyramid structure below. A different modelling approach would inherently lead to differences in model structure, for which other data values may be necessary to obtain. On the other hand, if there are minimal differences between cities, merely adjusting the data values within the model, while keeping the model structure and approach identical is adequate for policy investigation.

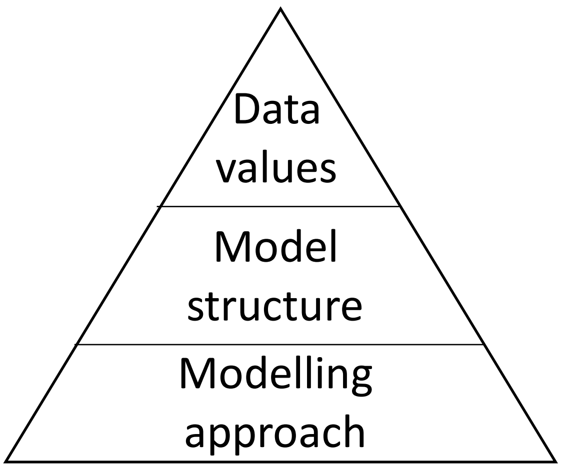


**Figure 35:** The three types of model generalization identified throughout the model development

### Explaining the discrepancies in model validation

When considering this pyramid from the bottom up, it is clear that that differences in the approach taken by the expert assumptions have led to large differences in the eventual modelling outcome in comparison to the simulation model. Differences in energy demand between the simulation model and the results coming from expert opinions initially due to differences in the modelling approaches taken. Because of top down assumptions made means that the model is open for supply-side policy intervention, while this possibility lacks for the Vensim model developed. This in turn means that calculated impacts as a result of policy implementation will have different outcomes. The model shows a much slower increase in urban gas consumption than is assumed by the expert. This is because the initial assumption is made that an increase in gas supply as a result of additional gas availability will be met with an increased demand regardless of price or other factors. The developed model on the other hand takes this as only a single aspect and assumes that residents still have an independent choice regarding fuel consumption. The disadvantage of the model is therefore this assumption that people are not restricted by fuel supply altogether.

The expert assumptions place a much higher emphasis on household size for energy consumption than the simulation model does. On the other hand, the bottom up approach shows better balance between total energy demand and changing fuel consumption as income rises. These differences will eventually have significant effects on the policies that are approached. Changes in fuel type as a result of a subsidy or tax will have a different impact. The restrictive policy will likely be less impactful under the circumstances of the expert model as a coal tax would only impact the population actually using coal but would not indicate the effect this would have on different fuel demand. On the other hand, the more individualistic approach of the bottom-up simulation model will likely over-estimate the sensitivity towards policies focused on knowledge and willingness as it shows limited considerations for choices made by society as a whole and thereby the limited impact an individual citizen has on city-wide emission levels.

Going forward from this model, it is clear that several improvements can be made. However, it is difficult to see in which direction these differences are necessary as the data values are up for modification. Due to the data dependency and uncertainty of data availability in the coming future, a better comparison can be made once figures from the Thirteenth-Five Year Plan are released. Additional survey research should be done in order to better validate the current models developed. On top of that, the simulation model does lack in adaptability going forward. An example for this is the current importance placed on price level by the rural households. An unexpected shift in household income or fuel price can radically alter the model, as is indicated by the sensitivity analysis shown earlier in **Figure 21b**. In order to convey these changes, adjustments in model structure are necessary.

### How the pyramid structure can be used for model generalisation

Depending on the policies that need to be researched, and the extent of differences between the city of study and Jingmen, an entirely different modelling approach may be desired. If there is a desire to investigate the effect of fluctuating price levels on a shorter term, model adjustments in terms of timesteps will need to be taken. For example, the current model is inadequate to consider fluctuating temperatures between summer and winter and in its current approach it is unable to consider detailed demand-level pricing policies. The model structures cooking and heating together but depending on the desires of the government and what is to be modelled one may want to split apart both aspects in order to identify even more specific policies, and even look at electricity consumption as a whole. Especially in cities where heating is not used altogether, this assumption can be ignored in its entirety. In case such impacts need to be investigated, the model needs to be re-evaluated altogether. It is possible that additional sub-models will need to be developed, or that the current sub-models are inadequate in conveying residential demand behaviour. On top of that, the policies that are approached in this model are vastly different in terms of their possibilities for implementation in comparison to policies that are implemented in other countries. Different government structures may give way to other policies that can be implemented in practice. Such could be the desirability of certain fuels, which would ask for a completely different approach, the general government structure could open up or further limit the possible choices to be made for individuals and a different model timescale could investigate more detailed policies altogether. Some outcomes that are identified as desirable (such as an increase in gas consumption), may be undesirable in other countries.

Differences in the model structure will need to be made depending on factors that need to be further considered which may have an impact on certain interrelations between variables. Depending on country and residential culture there can be differences. Such cultural differences may have an impact on whether some variables are important when determining the type of fuel considered and therefore these factors should be taken into account. For example, in a research about household energy consumption in Ethiopia, Alem, Beyene, Köhlin, & Mekonnen (2016) identified the gender of the main household member as an important factor when determining the main source of fuel. Although Liao, Chen, Tang, & Wu (2019) identified that this is not a significant factor in China, such aspects could ask for adjustments in modelling structure when using this model for generalization purposes. Additionally, the main profession of the household could be important: if a city is more dependent on agriculture, there will be more agricultural residue which can be used as biomass fuel. The accessibility to electricity can also be a lacking in some cities which would have additional implications on the modelling structure and policies can be focused on improving this factor as a means to further stimulate electricity consumption. Adjustments in model structure as well as changes in data values need to be made in order to suit this model to encompass these differences.

Despite the differences, the model shows some prospects for a model that can be more widely used for other cities in the country. The model shows little dependencies on cultural aspects in behaviour that cannot be modified for other behaviour. The main issue that prevents the model to be further expanded is the consumer choice in other countries in comparison to China. There is little room for changing the provider of fuel, which limits the directions a consumer could take in energy consumption. This allows for a more simplified model as the ways of how behaviour can be impacted is limited. This is likely to be the case for other lower-tier cities in China too, while the higher-tiered cities have less choice altogether due to the spatial planning and built-in energy supply already provided. To some extent, this can already be observed in the urban area, which also shows limited sensitivity to most adjustments of the model variables. For higher-tiered cities the model structure will be different as almost all model structure would already be pre-determined by the government, thereby making this entire research unnecessary: the residential energy consumption is in large already controlled by the government.

Naturally with the current values based off of Jingmen, many are specific to Jingmen. Although some values will be similar for other cities, further city-specific investigations area always needed depending on differences identified. Residents in other cities will have different opinions, current consumption values or ask for the necessity of completely different variables that did not need to be considered in this model. These data values need to be adjusted in order to accustom to the composition of the specific city if there are very limited differences between the city and Jingmen. These adjustments will need to be made for pretty much every other city considered. The importance of adjusting these model variables is also seen in the sensitivity analysis.

# 6. Policy results

This chapter will lay out the main results obtained from the experiments performed. The most important graphs are shown here. A full overview of all results, as well as raw data tables from the experiments conducted is shown in **Appendix G**. The results of individual policies will be presented first in **paragraph 6.1**, after which the results of the combined policies are further explored in **paragraph 6.2**. Chapter 6 continues by evaluating the practical effectiveness of the policies in **paragraph 6.3**, after which the chapter closes with a policy recommendation in **paragraph 6.4**.

## 6.1 Investigation of individual policies

### *Coal ban*

The implementation of a ban on coal in 2020 would be extremely impactful in both the urban and rural areas. The demand will immediately decline due to lack of fuel availability and abruptness of the policy. The impacts of a coal ban will be felt years later as urban and rural energy demand will increase at much lower rates compared to the 'no policy' alternative, as shown in **Figure 36** below. In the long run, urban demand will remain relatively constant. Considering consumption for cooking and heating purposes alone, a coal ban could lead to a demand reduction of 15% by 2025, which could further continue to 30% in 2030, compared to the no-policy alternative. The impact in the rural area will be much larger, which could see a reduction of 30% and 45% in 2025 and 2030 respectively.

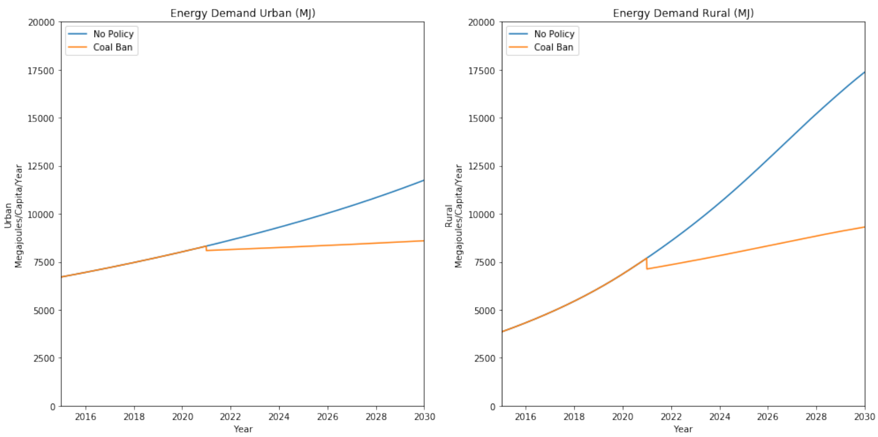


**Figure 36:** Per capita direct household fuel demand after the implementation of a coal ban in 2020 (a) urban (b) rural.

As a result of the coal ban, the emissions will reduce. Especially the $PM_{10}$ emissions will reduce to less than a third of its original value within a year. The emissions of carbon dioxide will also decline to over half its expected 'no-policy' emissions in 2030. On top of that, the expected emissions will stop increasing as fast as is expected in the 'no policy' scenario, which means that the policy will help to reach its carbon emissions peak sooner.

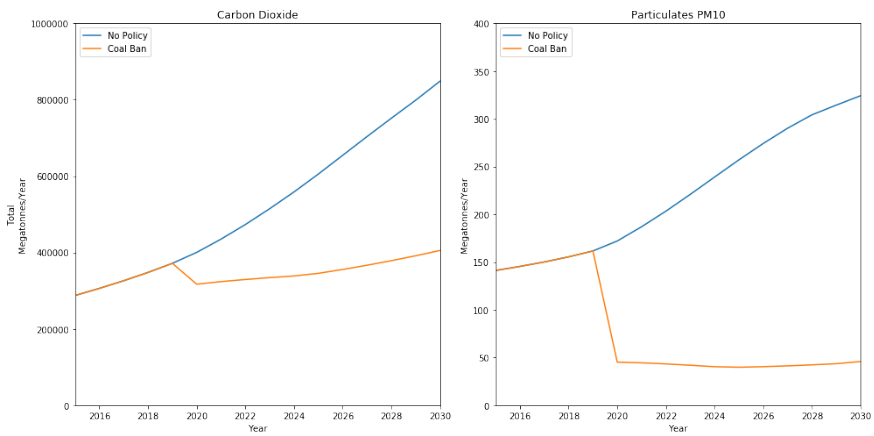


**Figure 37:** Expected carbon dioxide (a) and $PM_{10}$ particulates (b) emissions in Jingmen as a result of the coal ban in 2020.

Biomass and gas are used to compensate for the lack of coal, while demand for electricity will remain nearly unaffected, likely because it is too expensive for many to use. As **Figure 38** shows, biomass is impacted most percentagewise, seeing a direct city-wide increase of over 25% compared to the year before. In absolute terms, the gas consumption increases to around 3000TJ compared to the previous year. As gas becomes more convenient to use, a larger portion will eventually use gas to compensate for the missing coal.

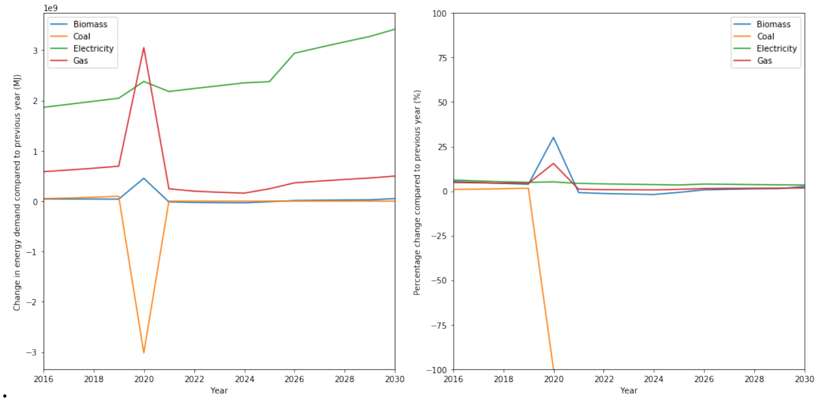


**Figure 38:** Change in demand compared to the preceding year, showing direct consumption impacts as a result of a coal ban.

The decline in energy demand is due to a high reduction of convenience and price utility rather than an increase in knowledge and willingness to reduce consumption. It can therefore be considered that this policy closely follows the perspective of an extremely 'authoritative environmentalist policy' – it is a very effective, but exclusive policy. The policy puts weight on the measure of force and enforcement through law. This makes the policy effective, yet contentious as its effectiveness lies in simply taking away a fuel choice alternative. The advantage of using this policy on the other hand is that it is a clear, and one-time policy, which creates more certainty.

*Incremental coal tax*

A coal tax will have limited effect in the urban area: a large incremental increase in coal price will lead to minimal changes in demand. This lack of response is likely because coal consumption is already low in the urban area, meaning that the overall impact it can have is minimal. Another reason is that people that are using coal are likely not doing so for monetary reasons. Making coal more expensive will therefore have limited effect, especially since it remains cheaper than gas or electricity.

In the rural area, a coal tax will have a significant impact on the overall energy demand. A substantial part of the population uses coal as people are unable to afford the cleaner alternatives. As with the coal ban policy, if coal will become less readily accessible and affordable alternatives lack, households will consume less energy. Although this reduction starts out minimal, the changes eventually add up due to the incremental tax increase. This leads to demand reductions of around 14% (low), 24% (medium) and 30% (high) in 2030 compared to the no-policy alternative.

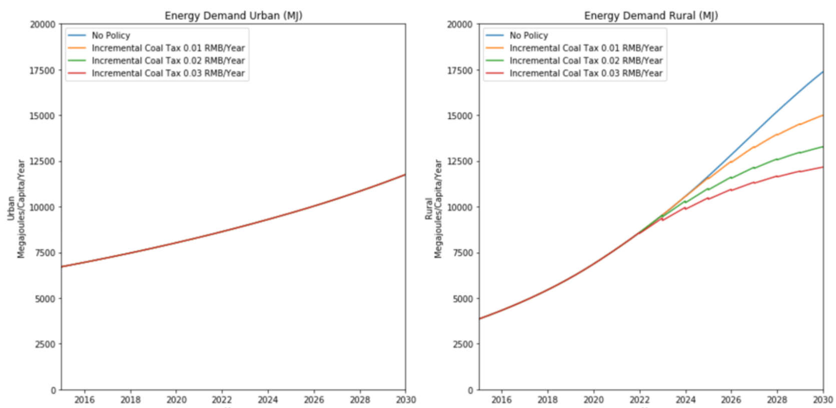


**Figure 39:** Per capita fuel demand after the implementation of an incremental coal tax starting in 2020 (a) urban (b) rural

The policy is effective in reducing $PM_{10}$ emission levels, while the effect on carbon dioxide emissions is less impactful. Even at a 'high incremental increase', there will be reductions of less than 10% and 15% in 2025 and 2030 respectively. On the other hand, a reduction of around 17% can be achieved by 2025 and as $PM_{10}$ emissions stabilize after 2025, $PM_{10}$ emissions could reduce up to 40% by 2030 if a high-level incremental coal tax is maintained.

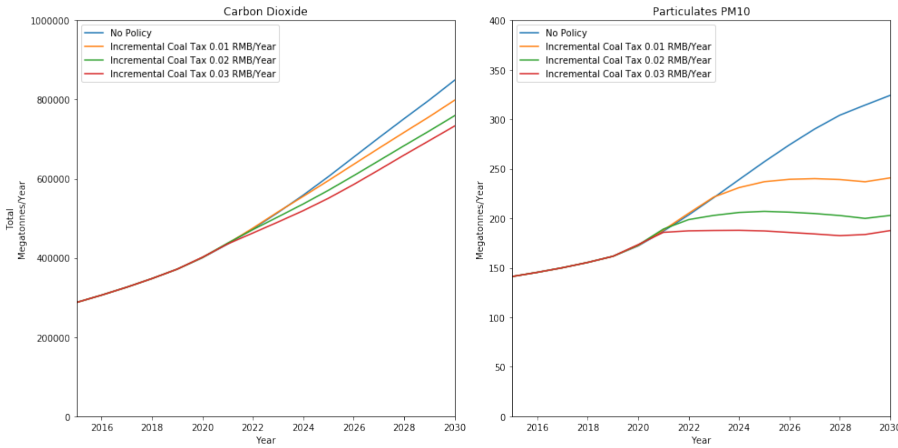


**Figure 40:** Expected $CO_2$ (a) and $PM_{10}$ (b) emissions in Jingmen as a result of an incremental coal tax starting in 2020.

A benefit for implementing this policy is that its presence will already repulse residents away from consuming coal. By putting the tax into practice households know that the burning of coal is undesirable, which further discourages its consumption in the long term. A low coal tax will therefore have a large impact already. Further increasing the coal price will have diminishing effects. This is shown by the difference in $PM_{10}$ particulates (**Figure 40b** above) between 'no policy' and the 'low level incremental coal tax', which is larger than that between a low level and a high level.

Another benefit of using an incremental coal tax is that its gradual approach will be less disruptive to energy demand, and therefore to fuel supply as well. The incremental increases give citizens time to adjust and seek out alternatives. **Figure 41b** below shows that the coal consumption in Jingmen remains relatively stable. There are no major disruptions to the demand, and the expected increase in fuel demand will be due to an increase in the cleaner fuels, while the demand for dirtier fuels is stable.

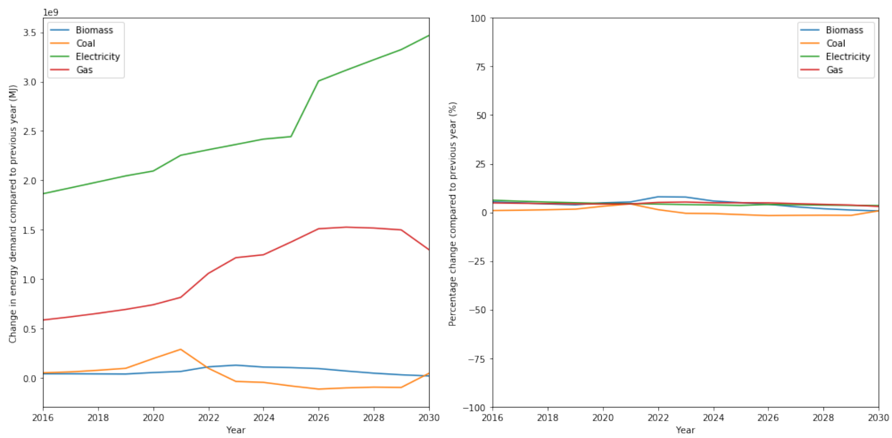


**Figure 41:** Change in demand compared to the preceding year, showing changes in consumption as a result of the incremental coal tax.

Increasing the price of coal will be more effective in preventing the overall consumption from rising while minimizing the impact on the overall energy demand. However, this addition would likely need to be much higher (than incremental increases of 0.03 RMB/MJ/year) in order to cause a further decrease in coal demand in the urban area. Although the tax is aimed at restricting coal consumption, the policy is a lot more inclusive in comparison to an outright ban on coal as it does not directly impact the energy consumption too much. It gives the citizens time to adjust their fuel consumption accordingly and also allows for a more gradual change and stability. Additionally, households that are consuming coal or biomass fuels may have sunk costs, such as a fireplace or kitchen utilities. Although these sunk costs are omitted in the model, this may also be a reason why residents are hesitant to change. A small incremental tax on coal does not directly punish citizens on their current consumption, while it discourages citizens from using the fuel in the future.

### *Reduction in electricity price*

Reducing the price of electricity will have a positive impact on energy demand in the rural area, while the demand in the urban area remains constant. The effect of the subsidy on the increase of demand shows to be directly proportional to the reduction of electricity price. This means that if the subsidy is maintained over the years, the energy demand keeps increasing at a higher rate.

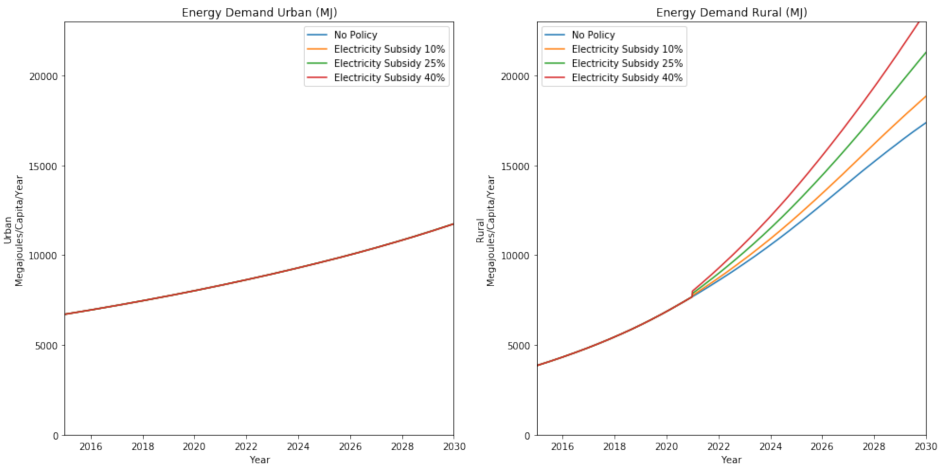


**Figure 42:** Per capita fuel demand after the implementation of an electricity subsidy starting in 2020 (a) urban (b) rural

A reduction in the electricity price will initially have a positive impact in the rural area: despite an increase in energy demand, there is a clear initial decrease in both $CO_2$ as well as $PM_{10}$ emissions. The energy demand in the urban area will be unaffected, but the composition of fuel demand will change, causing a slight decrease in $PM_{10}$, while $CO_2$-emissions remain constant. The urban area on the other hand, will see little change in terms of emission levels.

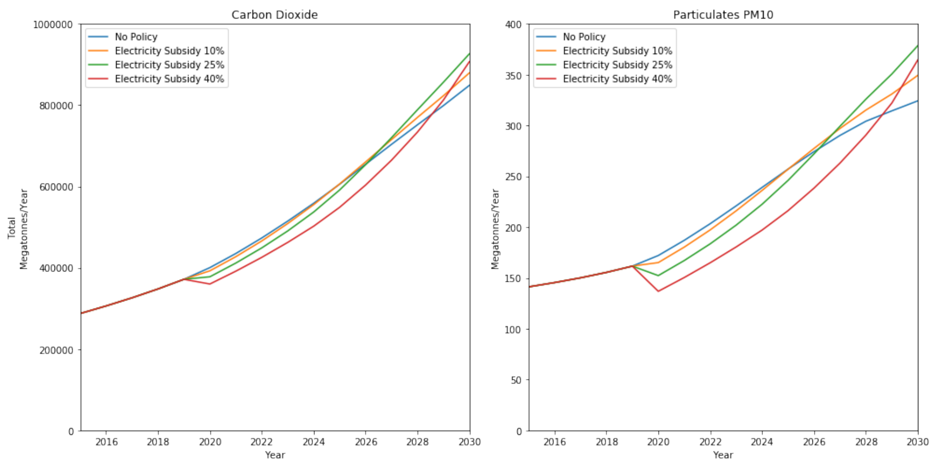


**Figure 43:** Expected $CO_2$ (a) and $PM_{10}$ (b) emissions in Jingmen as a result of an electricity subsidy starting in 2020.

This could eventually lead to higher emissions by 2030 than the 'no policy' alternative would have. An initial reduction in emissions of up to 10% can be achieved in the short term, but this will eventually increase to up to around 10-16% in $PM_{10}$ and $CO_2$ emissions. A reduction in electricity price will also reduce the price of consumption of other appliances of which the fuel is non-substitutable (such as microwaves or televisions). A price reduction means there is more money left when still using biomass or coal, which will in return lead to higher consumption overall. Especially on the moment of implementation, the effects that the policy has on the energy consumption is quite drastic, yet over time the changes seem to revert back to their original level. Although this initial reduction is desirable, it is important that the policy remains effective in the long term.

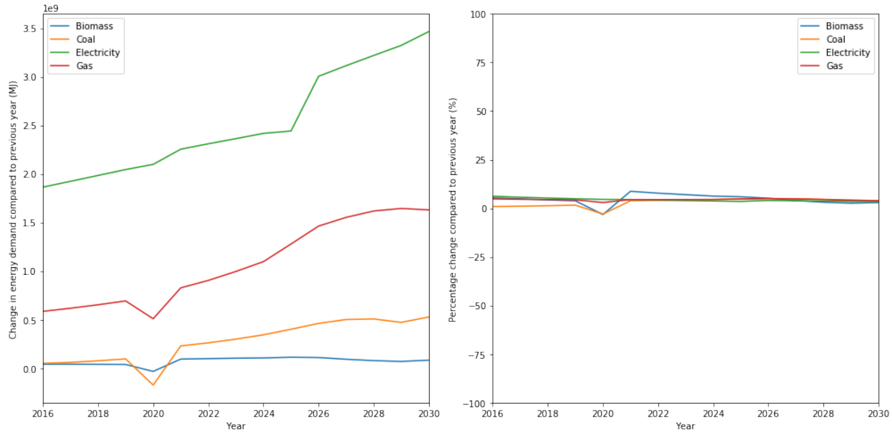


**Figure 44:** Change in demand compared to the preceding year, showing consumption changes due to the electricity subsidy.

This subsidy on electricity shows to be a typical example of 'democratic environmental policy' – it is very inclusive as the reduced price will place less restrictions on consumption. However, this policy is on its own ineffective in actually reducing emissions. For this reason, especially the method of how the subsidy is implemented is important. Aside from changing the price, it can also further raise awareness that the prefecture places on the green transition.

### *Increased placement of natural gas lines*

Increasing accessibility to natural gas has some minimal effects on energy demand. A slight increase in consumption can be ascribed to an increase in overall convenience in using the energy source. There are several reasons for this lack of direct change. Mostly, the model already expects the gas line infrastructure to improve over the course of the simulation run. Once all of the city is already connected to the grid, an additional increase has limited impact. This is especially true in the urban area where a significant part of the city is already connected. Additionally, the impact of convenience in the rural area is substantially lower, while fuel price plays a much larger role. Even if residences are connected to the national gas net, if the price is too high it will still not be consumed. The subsidy for gas could play a much larger (additional) role in this process, as currently a subsidy is provided depending on how much is consumed. However, the effects of such a policy need further investigation in its implementation.

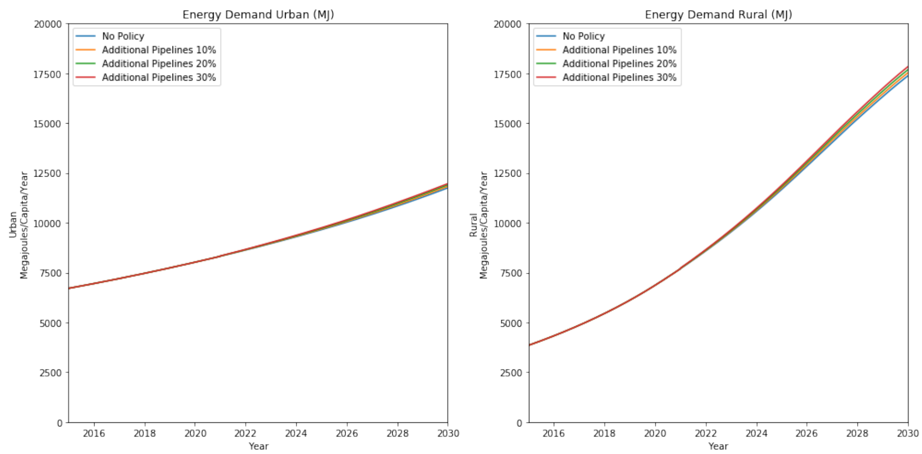


**Figure 45:** Per capita fuel demand after the implementation of additional pipelines starting in 2020 (a) urban (b) rural

With the slight change in demand, the overall emissions are also minimally impacted. Although there is an initial decline in $PM_{10}$ emissions, these eventually tend to increase slightly. This is because gas causes emissions too (albeit to a lesser extent than coal and biomass). If the consumption increases further in comparison to the other fuels, overall emissions will increase slightly.

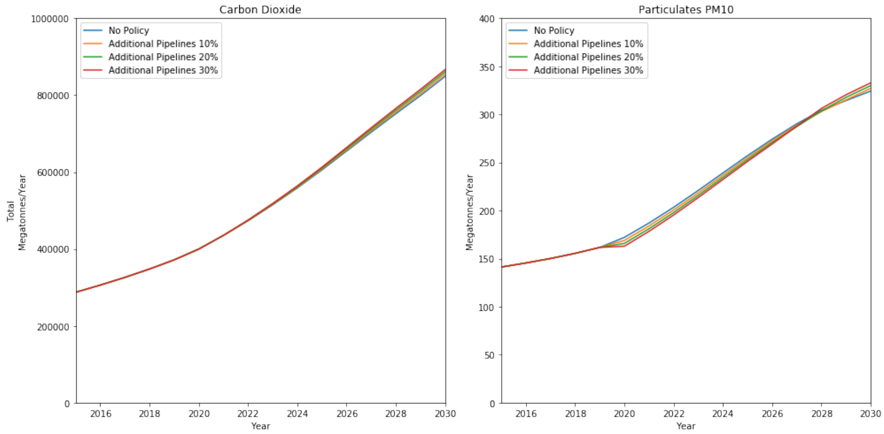


**Figure 46:** Expected $CO_2$ (a) and $PM_{10}$ (b) emissions in Jingmen as a result of additional pipelines starting in 2020.

As energy demand keeps increasing, so will the leftover biomass and coal consumption of people who still prefer to use the traditional fuels. This means that the initial decrease in consumption of these fuels will eventually recalibrate to levels of the 'no policy' alternative if implemented on its own.

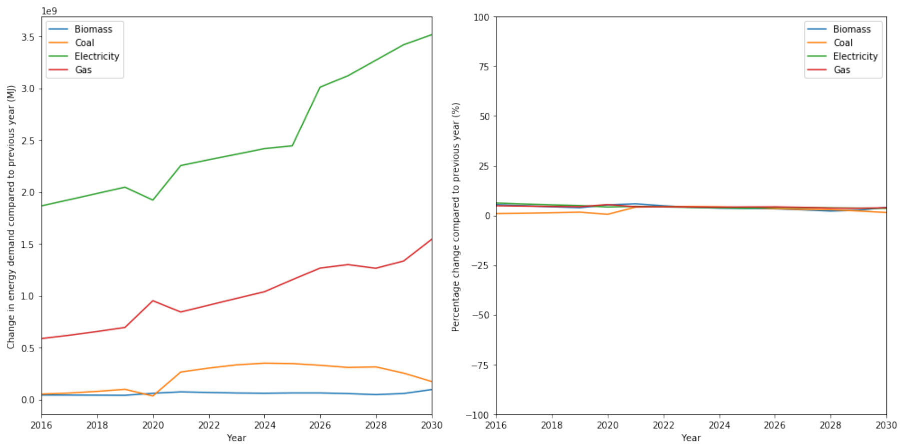


**Figure 47:** Change in demand compared to the preceding year, showing consumption changes due to additional pipelines.

This policy is not very effective by itself. At best, it will accelerate the connection of households in the city with the national gas grid. On top of that, the policy investigation leaves several unanswered questions such as whether it is even possible to connect the current residences to gas and where to even start with the increase. The policy could be effective, but it is unlikely that it should be implemented with the sole focus of reducing emission levels. Its effectiveness may lie in using it together with the other policies, amplifying its results, or as a secondary result to poverty alleviation measures. Many newly built residential areas are already being connected to the gas grid, meaning that the policy will simply accelerate this transition.

*Additional exposure to the importance of clean and efficient use of energy fuels*

The policy on increasing the exposure about the importance of using more efficient fuels has negligible effect in changing the urban demand, but will cause a reduction in energy demand in the rural area. The main reason for this is that there is most room for change possible. Some housing in the rural area are constructed by the residents themselves, whereas those in the urban area are constructed by the government-owned building companies. This provides little choice for the people in the urban area to make any additional changes to improving insulation. On the other hand, poor insulation is a reason why the rural area has a higher expected energy consumption altogether. Although the policy has some impact in reducing the energy demand, it is less impactful than the coal ban or coal tax. However, while those policies have reduced demand out of force, this policy causes the demand to decrease willingly.

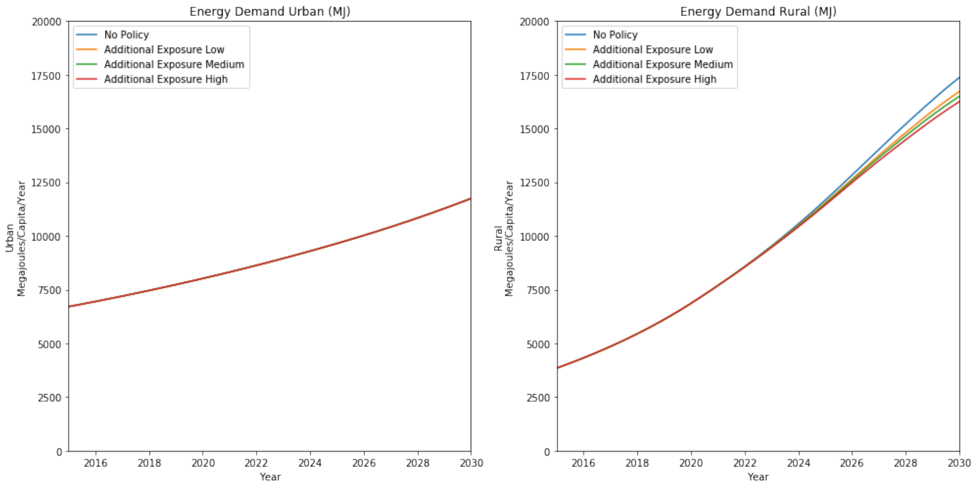


**Figure 48:** Per capita direct household fuel demand after the additional exposure starting in 2020 (a) urban (b) rural

Especially the consumption of coal sees a decrease when the policy is implemented. This decrease is compensated by an increase in biomass consumption. By 2025, biomass consumption will increase by around 25%, while coal consumption can reduce by 25-35%. This is likely because there is no change in convenience or price, while the consumption of coal is discouraged. Additionally, the gas consumption will also decrease slightly in comparison to the no policy alternative.

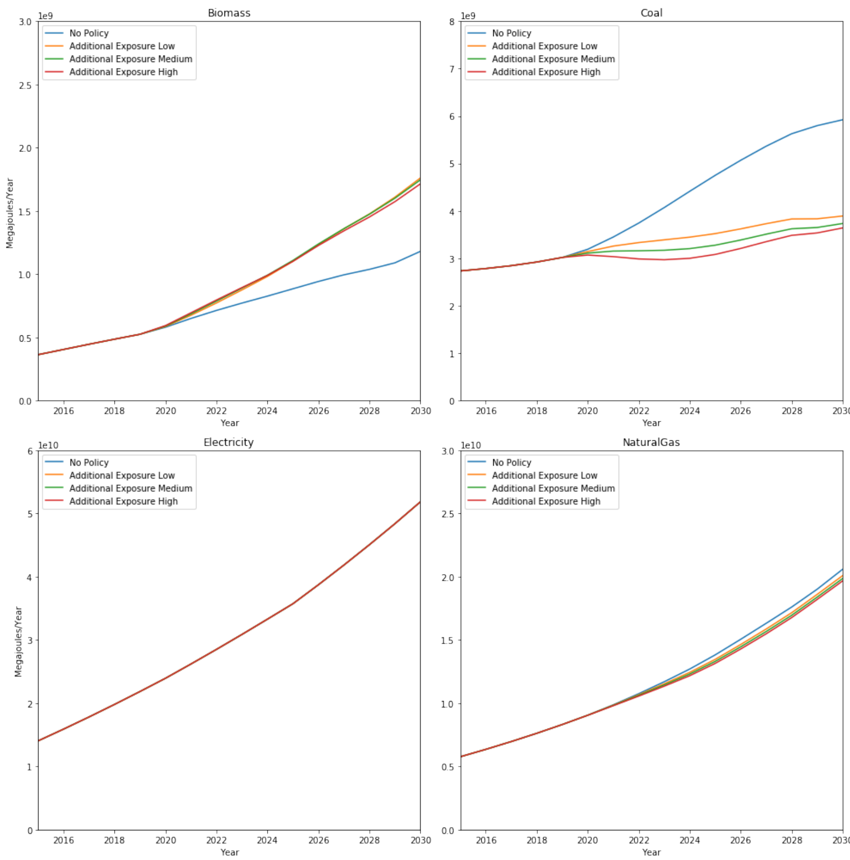


**Figure 49:** Per fuel energy demand, as a result of the additional exposure.

There is a clear decrease in emission levels, which is therefore clearly due to a change in fuel type. Even though the shift is mainly from coal towards biomass, there is a significant decrease in both carbon dioxide and $PM_{10}$ emission levels. Household $CO_2$-emissions can reduce by around 12-17% in 2025, while $PM_{10}$-emissions can reduce to around 20-25% of the expected no-policy level. These comparative reductions will be maintained to 2030. This means that the policy is quite good at achieving desired result of reducing emissions but fails to stimulate consumption of the cleaner fuels in lieu of the reduced coal demand.

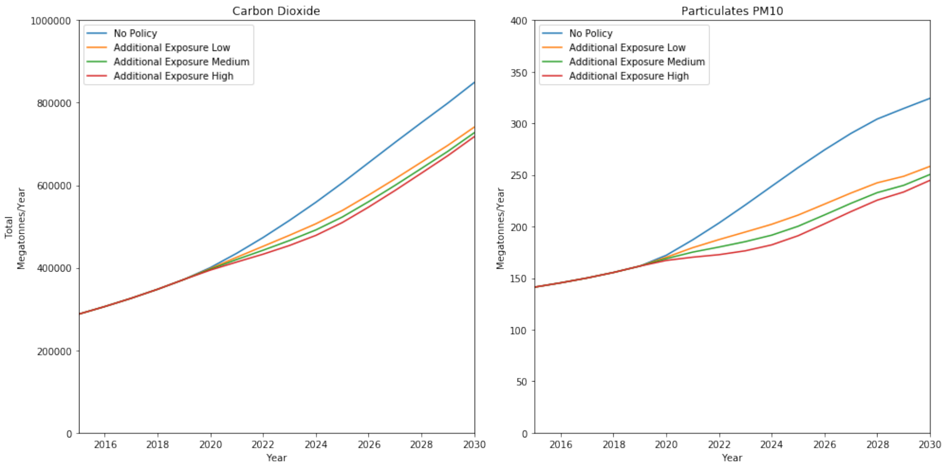


**Figure 50:** Expected $CO_2$ (a) and $PM_{10}$ (b) emissions in Jingmen as a result of additional exposure starting in 2020.

Increasing the amount of exposure to the importance of using clean energy fuels and using them efficiently will have very beneficial effects overall. Especially the rural area will be demanding lower amounts of fuel due to their more efficient use. Furthermore, this decrease in overall energy demand as well as emissions of $CO_2$ and $PM_{10}$. However, an increase in order to compensate for a reduced demand in coal, means there will still be an increased demand in biomass consumption, which causes the emissions from $PM_{10}$ particulates from biomass to increase. Regardless, this policy can prove very effective in reducing emission levels overall, while it does not exclude households from using a certain type of fuel.

### *Comparison between individual policies*

As an individual policy, the ban on coal consumption will be most effective in reducing emission levels for both, the rural as well as the urban areas in Jingmen. However, this insight is obvious as the coal consumption should, in theory, be reduced to zero. The emissions from the rural population can be reduced in various ways, but overall energy consumption should not be completely restricted.

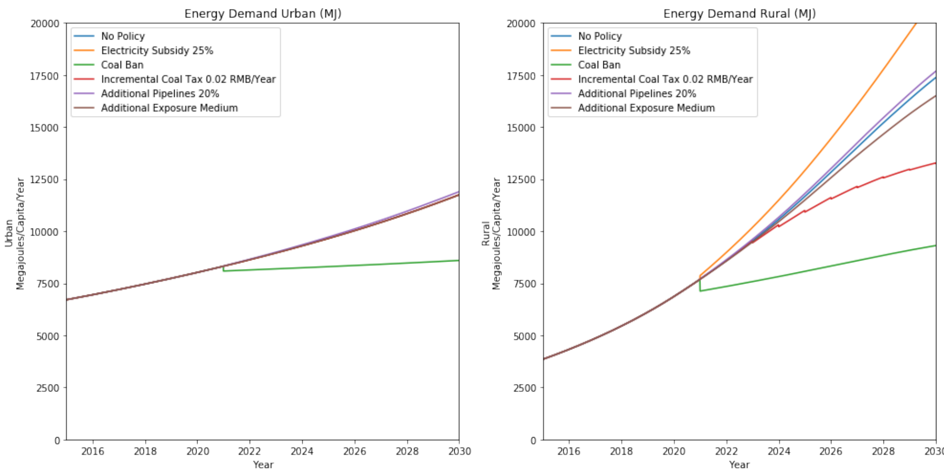


**Figure 51:** The per-capita energy demand in urban and rural areas during the individual implementation of 'medium' policies in 2020

Other than a ban on coal, an electricity subsidy will also have a direct (short-term) impact on reducing emissions, albeit to much lesser extent than the ban on coal does. Other policies such as additional exposure and a coal tax should also not be ignored as viable policies for emission reduction. These policies do not necessarily cause the emissions to reduce, but instead reduce the rate at which emissions increase as a result of expected increase in energy consumption. Such policies will therefore be helpful in reaching the peak carbon emission value sooner.

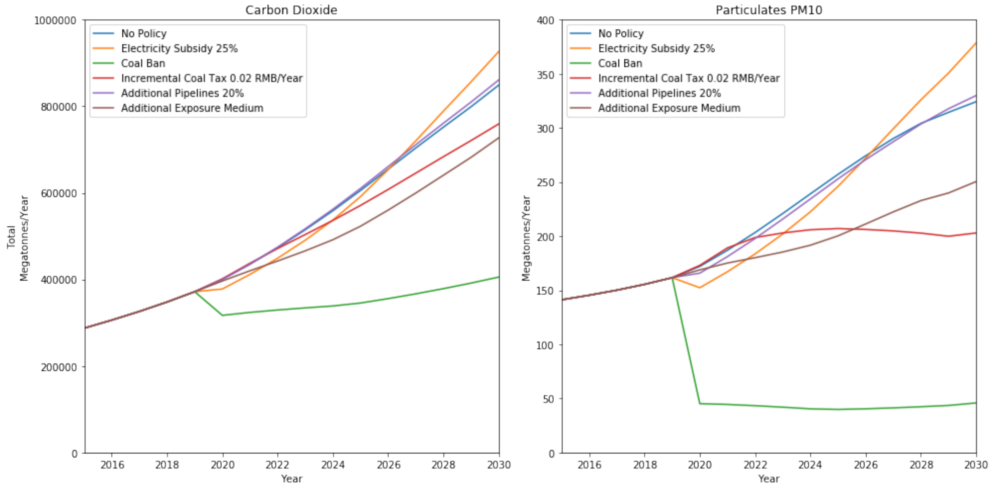


**Figure 52:** The $CO_2$ and $PM_{10}$ emissions in Jingmen during the individual implementation of 'medium' policies in 2020.

When considering the urban and rural energy consumption by fuel sort, it is clear that the coal ban will immediately be compensated by an uptake in biomass. On the other hand, the biomass consumption will decrease in the urban area in case of additional pipeline placement. In the long run, all policies (except the coal ban) have a similar demand. In the rural area, there are significant increases in biomass consumption in the short term through additional exposure and coal tax policies, while in the long run, nearly all policies (bar the coal ban policy) show an increase in biomass consumption.

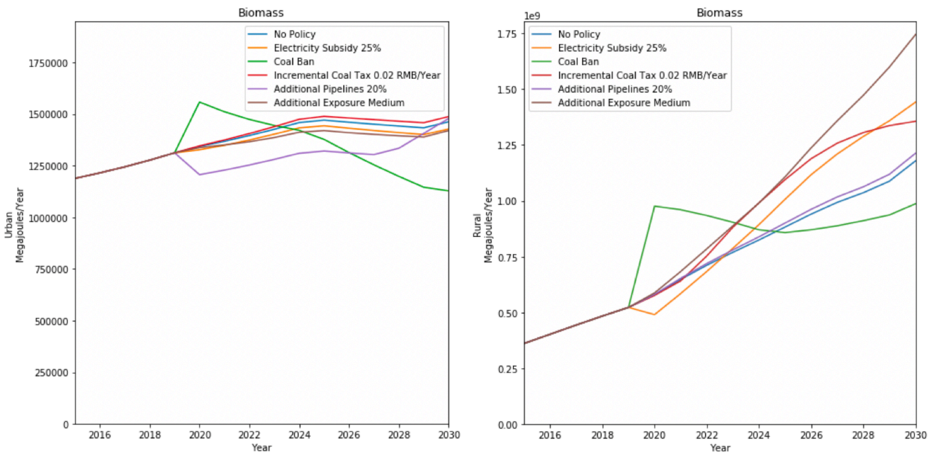


**Figure 53:** Urban (a) and rural (b) biomass demand during the individual implementation of 'medium' policies in 2020.

There are large discrepancies between urban and rural areas in coal consumption. A coal ban would diminish all coal consumption for both areas, however the other policies have substantially different effects. In the short term, increasing pipeline placement would reduce the largest amount of coal and coal in the urban area. For the rural area, this would be the electricity subsidy as well as the increase in exposure. These policies are effective in the urban area too, but to a lesser extent in reducing coal consumption. Surprisingly, the consumption of coal increases slightly after the implementation if a coal tax. This increase can be explained by speculative behaviour, or increased demand in the short term as the coal price is expected to rise further in the future. The model displays this through impacts in convenience and willingness to consume overall ever so slightly. Since there is a delay between the coal price and coal availability, there will be more coal available compared to what it should be at that price, which means that the convenience is relatively higher. Especially since the willingness to use cleaner fuels decreases as a result of the relative increase in fuel price. This increase in coal price is so little that it has no impact on the price-utility in the urban area. Altogether, this causes the consumption of coal in the urban area to slightly increase. The same coal tax does however have a very significant impact in reducing coal consumption in the rural area as the price-utility drops significantly, causing the fuel to be much less desirable to use. The policies lending support to the rural population will however cause an increase in coal consumption. This is because coal is most prominently used because of its low price, while electricity is used for other goods also. Lowering the price of electricity will leave more room for consuming more coal as discussed before.

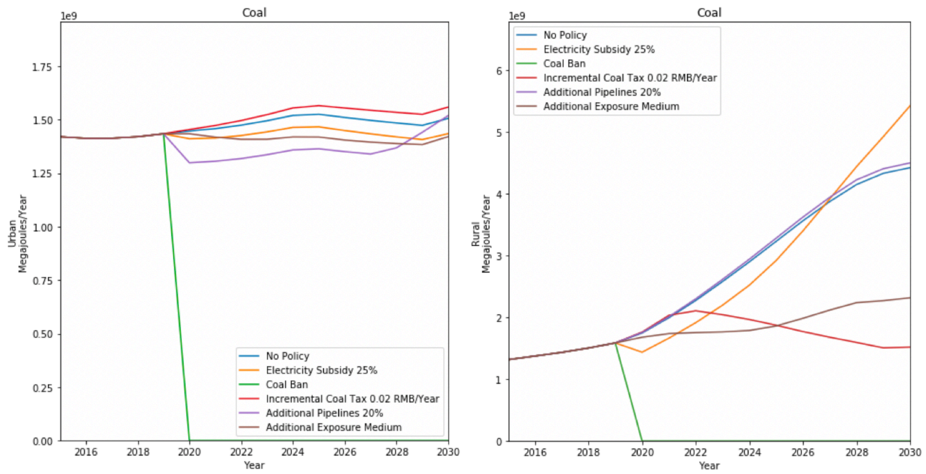


**Figure 54:** Urban (a) and rural (b) coal demand during the individual implementation of 'medium' policies in 2020.

In the urban area, only the coal ban and the additional placement of pipelines will really have an impact on the consumption of gas. However, the additional placement of pipelines policy will converge in gas consumption with the other policies. The main reason for this is that the area can only be 100% connected to natural gas. Once this full coverage is approached without policy intervention, the impact of the policy is lower. Natural gas consumption in the rural area will increase most if an electricity subsidy policy is implemented (for reasons explained above), or due to a coal tax that makes some use gas as an alternative.

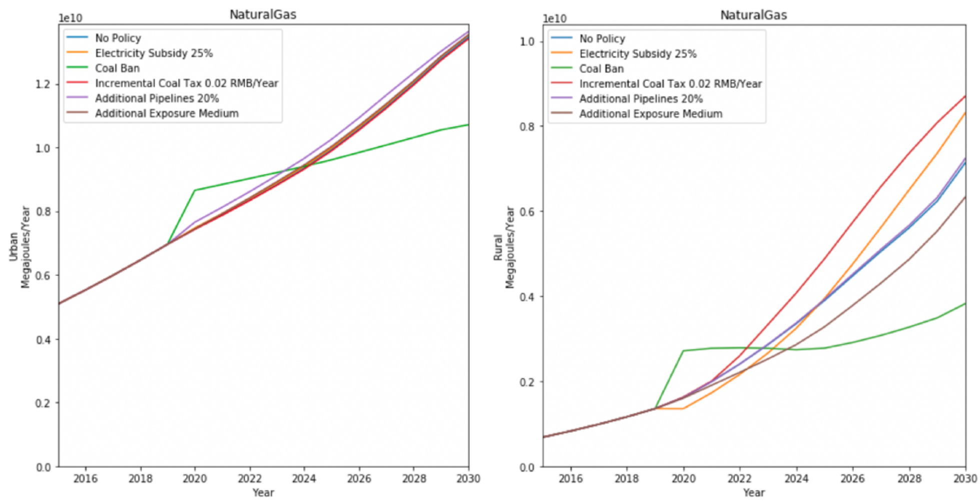


**Figure 55:** Urban (a) and rural (b) gas demand during the individual implementation of 'medium' policies in 2020.

The fact that coal is so much cheaper than its cleaner counterparts means that citizens with minimal financial means are simply restricted from using a fuel, rather than being incentivized to use alternative means. It is thereby inevitable that people will simply revert to using 'free' biomass fuels in case they are merely restricted financially or by law to consume alternatives.

The policies investigated vary drastically in their approach, and therefore also in the impact that they have. The coal ban shows to be an extreme policy which reduces fuel consumption altogether. Taking away this alternative will cause the other goods to increase in consumption for a short period, but as the consumption tends to normalize back to the original values, the overall consumption will decrease. For the urban area, supportive policies will prove most effective. Full connectivity to the gas grid will increase its consumption at the cost of coal and biomass. In the rural area however, such policies are ineffective or will even work counterproductive as these policies will be complimentary to the available resources, rather than replacements for the currently used fuels. Therefore, policies that restrict unwanted consumption are more effective in the rural area. However, this merely considers energy consumption and omits other factors and problems that may arise after the implementation of such policies.

Citizens are generally tied to consume what is available in their vicinity. This means that if certain fuels become less accessible, they cannot simply change their consumption behaviour. Although a coal ban is in theory effective in reducing carbon emissions, in practice, a coal ban could ensure that people without an option for alternatives are forced to consume their coal illegally. This could in turn lead to emission values being further obscured as people won't be likely to admit their consumption, fearing legal repercussions. In terms of health, such a policy could be even more harmful for individuals. Trying to hide coal consumption, could obstruct proper ventilation, causing further harm to individuals in the rural area who have no other alternative. Other policies such as a subsidy for electricity could create a further divide between the urban and rural areas. The urban areas consume more electricity, allowing them to benefit more from such a policy. Other policies, such as improving the exposure to the importance of responsible and clean energy consumption could lead to shaming. Survey analysis showed that people are generally aware of the fuel consumption of others in the neighbourhood. Actively advertising about the health and environmental problems of some fuels may cause people to unwillingly lose face as they cannot afford any cleaner alternatives.

## 6.2 Combined Policies

Combining two policies can have a larger impact as the effects from two policies may be able to amplify the results of one another. A combined policy composed of a restrictive and supportive policy can negate the adverse effects of one as consumption can be channelled to another fuel. The list of combined policies is as following;

Policy 6: Coal Ban combined with Electricity Subsidy
Policy 7: Coal Ban combined with Additional Gas-Lines
Policy 8: Coal Ban combined with Additional Exposure
Policy 9: Incremental Coal Tax combined with Electricity Subsidy
Policy 10: Incremental Coal Tax combined with Additional Gas-Lines
Policy 11: Incremental Coal Tax combined with Additional Exposure
Policy 12: Electricity Subsidy combined with Additional Gas-Lines
Policy 13: Electricity Subsidy combined with Additional Exposure
Policy 14: Additional Gas-Lines combined with Additional Exposure

**Figure 56** below shows the impact of the policies on energy demand. Considering this figure, it becomes clear that there are 'groups' of combined policies that can be distinguished depending on the dominance of an individual policy. As described in the previous paragraph, a policy that places an outright ban on coal is so dominant in directly affecting the overall energy demand that this has a distinct impact for the remainder of the simulation. Any permutation that includes the coal ban causes a direct reduction in energy demand. The reduction has lasting effects and will lead to a general reduction in energy consumption, in the urban as well as the rural area. Considering the energy demand of the urban area, it is clear that there are two distinguishable groups of policy combinations: those that include a coal ban, and those that don't. This policy is the only one considered that can substantially impact the consumption.

In the rural area, of the three policies that do include a coal ban, the combination with an electricity subsidy (**Policy 6**) is slightly less detrimental to rural energy demand with a reduction by 27% and 41% in 2025 and 2030 respectively. When further inspecting **Figure 56b**, it becomes clear that permutations that include the electricity subsidy are quite dominant in increasing the energy demand. This is because a significant portion of electricity consumption does not come from the heating and cooking within a household. Providing an electricity subsidy will therefore leave a lot of room for increasing overall energy consumption. The policies that include additional exposure are also dominant, albeit to a much lesser extent than the two policies previously mentioned. Policy combinations that involve additional exposure (**Policy 11, 13, 14**) reduce the energy demand in the rural area. The other two policies (incremental coal tax and additional gas-lines) show limited dominance in changing the overall energy demand. The fact that **Policy 10** leads to a slightly larger demand than the 'no policy' alternative shows that the additional pipelines take dominance in this permutation. This is surprising since the incremental coal tax showed to be very effective in reducing energy demand as an individual policy in the rural area.

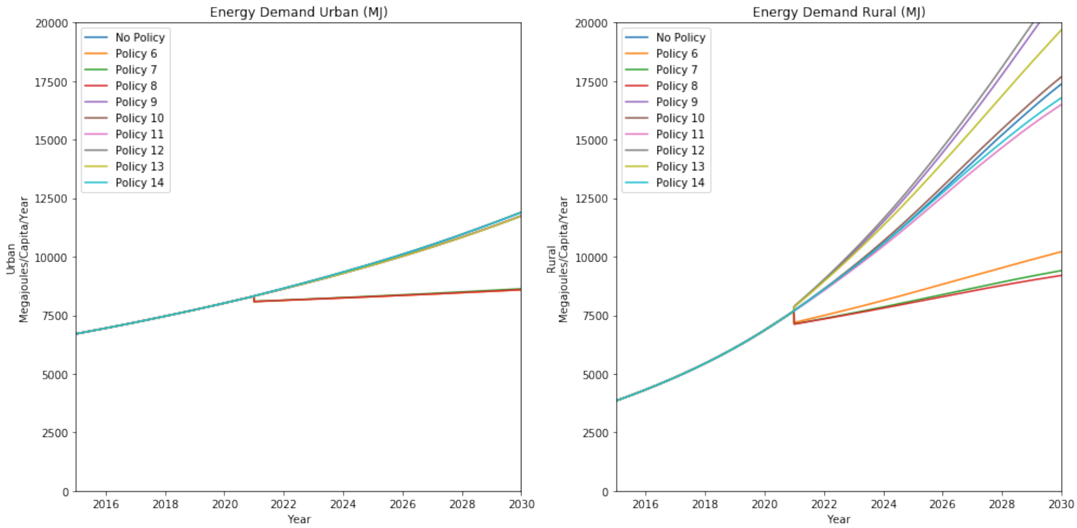


**Figure 56:** The energy demand per capita per year in urban and rural areas during implementation of the combined policies.

When looking at the emissions caused by the respective areas, there are also groups of the combined policies that can be considered. In terms of carbon dioxide emissions, the urban area splits up in the same two groups: permutations that include a coal ban, and those that don't. The coal ban reduces carbon dioxide emissions directly by up to 10%. The lower rate of increase of $CO_2$ consumption in long term caused by the coal ban, can mean a reduction of 35-40% in emissions 2030 compared to the 'no-policy' scenario. However, there is another group that can clearly be identified, especially in the short term when considering the $PM_{10}$ particulates emitted in the urban area. Policy combinations that include the increase rate of gas-line placement rapidly reduce their $PM_{10}$ emissions by about 10% compared to the 'no-policy' alternative. However, in the long term these emissions normalize to the 'no-policy' scenario. In the long term, a $PM_{10}$ emission reduction of up 10% can also be achieved by increasing exposure to the importance of clean and efficient energy consumption. This is especially effective in combination with the electricity subsidy policy.

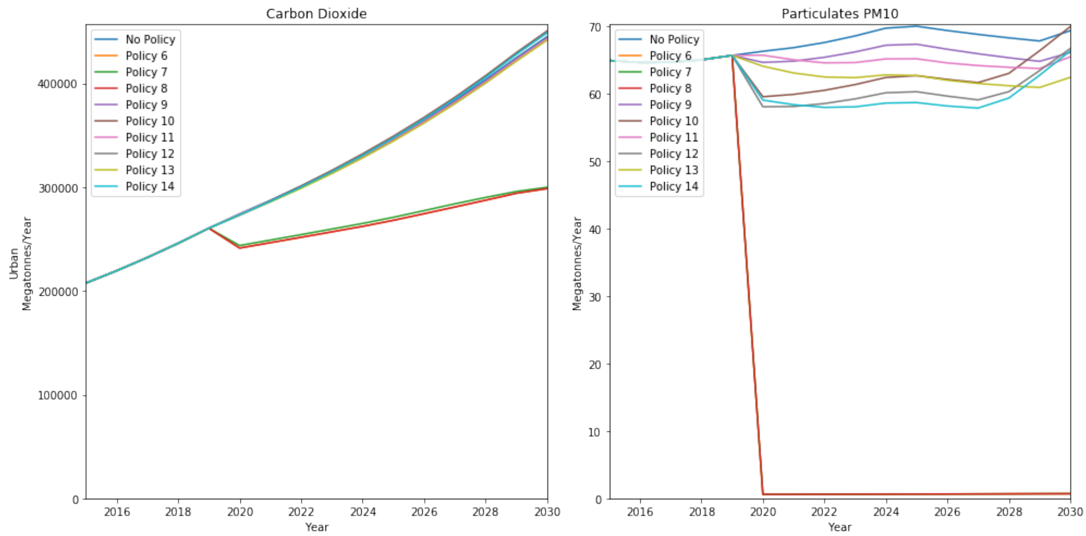


**Figure 57:** Expected $CO_2$ (a) and $PM_{10}$ (b) emissions int he urban area as a result of combined policies starting in 2020.

In the rural area, there are three main groups of policy combinations that stand out. However, most prominently, the permutation (**Policy 13**) dominated by the electricity subsidy in terms of energy demand, now shows that additional exposure can really cause a decrease in terms of emissions. The reason for this is that even though overall consumption increases due to the subsidy provided, the consumption of coal sees a heavy decline due to the exposure. This combination shows that policies can compensate one another to have a more desirable impact. In the short term, the impact of the electricity subsidy will cause a direct decrease in emission levels, however, the following increase in consumption of the undesirable fuels is negated as citizens are encouraged to shift their fuel of consumption. Additionally, it is clear that there is no clear difference between a coal tax or an electricity subsidy if combined with additional exposure, as this side of the policy can create a sincere turn away from coal consumption.

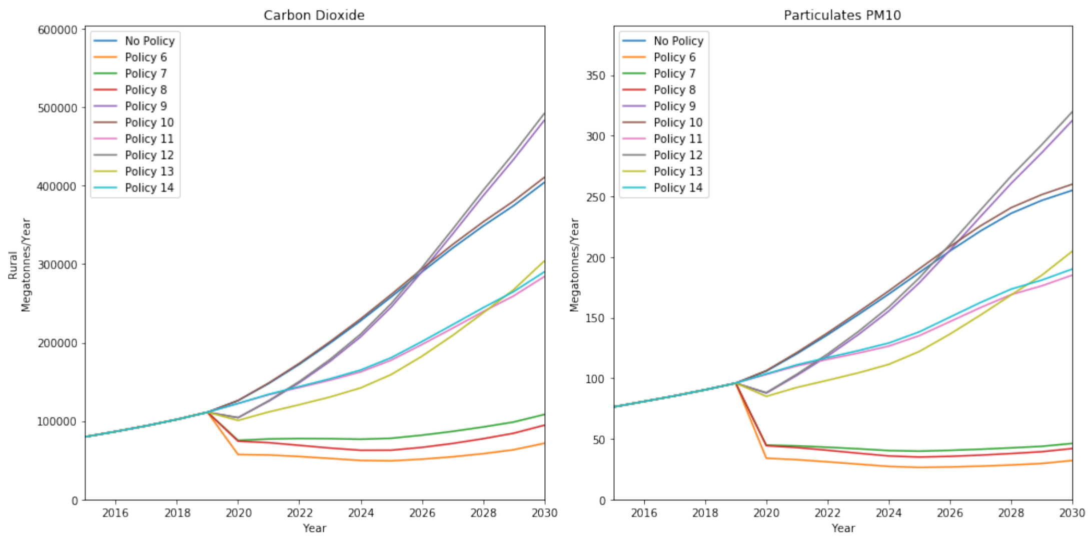


**Figure 58:** Expected $CO_2$ (a) and $PM_{10}$ (b) emissions in the rural area as a result of combined policies starting in 2020.

Of the policies investigated, combining a coal ban with a subsidy on electricity will lead to the smallest relative reduction in energy consumption, but also the largest decrease in $CO_2$ and $PM_{10}$ emissions of all policies investigated. The detriment caused by coal disappearing from available fuel sources overall is best relieved by a price reduction of its alternatives. It will have an extremely sincere and lasting impact on overall consumption. For this reason, it is unfavourable to implement this policy by itself and in the long term. Other methods of supporting individual citizens should be in order to prevent them from unwillingly reducing their energy consumption. The incremental coal tax is generally insufficient in restricting the coal consumption, causing the beneficial effects from the supportive policies to dominate consumption. On the other hand, policies that advocate for an increase in exposure for the importance of clean fuels for health and environment are very efficient in adjusting consumer behaviour, especially in combination with an additional policy.

## 6.3 Policy Evaluation

### Evaluation of the 'coal ban' policy

A ban on coal consumption will be extremely effective in reducing emissions for both, the rural and urban areas in Jingmen. This reduction will have large impacts in energy demand, especially as the other policies in the urban areas seem mostly ineffective. The coal ban is effective because it takes away a fuel alternative rather than inducing a change in household consumption behaviour. Having said that, actual impact is likely over-estimated because the model works under the assumption that consumption for non-substitutable electricity appliances remains constant. Even though consumption will drop, it will drop at much lower rates than the graphs show. The main impact is that energy demand will increase at a much lower rate. Even though it is an effective policy, an outright ban can also lead to dissatisfaction in households. The emissions from the rural population can be reduced in various ways, and it is important that overall energy consumption is not completely restricted. The coal ban will therefore be a policy that in the short term has a high level of risk in terms of citizen happiness and their financial stability. On the other hand, the potential risk in the long term is minimized. It is a one-time intervention, which afterwards only needs to be regulated, but does not lead to any real long-term changes or impacts.

### Evaluation of the 'electricity subsidy' policy

A subsidy for electricity will have a direct impact on reducing emission levels, albeit to much lesser extent than the ban on coal does. Providing a subsidy for electricity has larger scale implications: they will create uncertainty within the government as demand will fluctuate further. The current way of implementation leads to higher electricity consumption, as well as other fuels. This is because there are no underlying mechanisms in place that better promote the use of cleaner fuel. If people are unaware of the reason why they obtain the subsidy, it will not be seen as a method of inducing cleaner fuel consumption. There are other ways how electricity usage could be awarded by the Jingmen municipality while omitting the CCPG, such as a monthly discount on the purchase of electric stoves or heaters or through a buy-back of stoves that consume dirty fuels (The World Bank, 2013). The policy can therefore be more effective if combined with a policy that focusses on bringing awareness to cleaner energy consumption.

### Evaluation of the 'coal tax' policy

The fact that coal is so much cheaper than its cleaner counterparts means that citizens with minimal financial means are simply restricted from using a fuel, rather than being incentivized to use alternative means. It is thereby inevitable that people will simply revert to using 'free' biomass fuels in case they are merely restricted financially or by law to consume alternatives. However, as coal in China is still extremely cheap, a substantial increase in price is necessary in order to make a difference. Even though the investigated tax prices are substantial, its price relative to other fuels is so low that it has nearly no impact on the price-utility in the urban area. Its effect can be significant in the rural parts of Jingmen. A coal tax should therefore not be ignored as viable policies for emission reduction. The policy does not necessarily cause the emissions to reduce, but instead reduces the rate at which emissions increase as a result of expected increase in energy consumption, which will be helpful in reaching the peak carbon emission value sooner.

### Evaluation of the 'additional gas lines' policy

In the urban area, only the coal ban and the additional placement of pipelines will really have an impact on the consumption of gas. However, the additional placement of pipelines policy will converge in gas consumption with the other policies. The main reason for this is that the area can only be 100% connected to natural gas. Once this full coverage is approached without policy intervention, the impact of the policy diminishes. In the rural area, gas consumption is better promoted through the introduction of a coal tax, as this makes some use gas relatively cheaper. The additional convenience of natural gas may cause people to revert from using electricity to using gas. If gas becomes as convenient to use as electricity, and is available at a much lower price, there is no real incentive for residents to keep using electricity. This means that emissions may actually increase further in a period while consumption from renewable electricity is desired.

#### Evaluation of the 'additional exposure' policy

The policy of increased exposure is very broad with many potential factors of how to exactly bring this into practice. In the model the variable exposure to clean energy has been used as a measurement variable, but also this variable can have many implications. Therefore, more research should be done in order to investigate the practicalities of this policy.

When considering increasing the exposure of residents there are two main approaches to be taken. A lot of a lot of exposure in the short term may have a large effect in the short term, but such exposure is likely to become a 'trend', in which the effectiveness of the exposure diminishes over time. For better effectiveness, the consumption of a fuel should be a habit. For many, the type of energy that is consumed is already done so out of habit. Households are unlikely to keep changing the fuel they continuously use. This means that it is important that people decide to make a change and stick to this change. Another method could be a lower, more subtle exposure over a longer period of time. This may be more effective as it can encourage behavioural change over a period of time instead of creating a trend. The problem of this is that such lower long-term exposure may take away the awareness to other important things that are more directly at mind for the citizens such as exposure to a safer neighbourhood, road safety, recycling, etc.

This policy has higher levels of risk because there are no restrictions placed on individual citizens. This means that the government is dependent on the free will and cooperation of its citizens as a result of policy implementation. The effectiveness of such a policy is debatable especially since citizens are aware of the minimal impact, they as an individual household have on emission levels. It is uncertain whether people will change their energy consumption to the extent that they say. Drawing on experiences in other (more developed) countries, there is knowledge, however also in such countries significant improvements still need to be made. Knowing and being willing to take action does not equal taking action. Furthermore, despite the importance for citizens to become more knowledgeable about energy consumption, the government can also not expect for the citizens to make significant changes by themselves. The people cannot be expected to make the autonomous choices that the government generally makes for them. For this reason, such a policy is unlikely to be successful on its own and should always be implemented in combination with another policy.

## 6.4 Policy Recommendation

In all, the outcome of all policies investigated can be summarized by **Figures 59 and 60** below. These figures summarize all the results by taking the average energy demand between 2020 and 2030 on the x-axis, and the average $CO_2$ (**Figure 59**) and $PM_{10}$ (**Figure 60**) emissions on the y-axis. All values are scaled against the 'No Policy' scenario alternative, meaning that the demand and emissions of this scenario is set at point (1, 1).

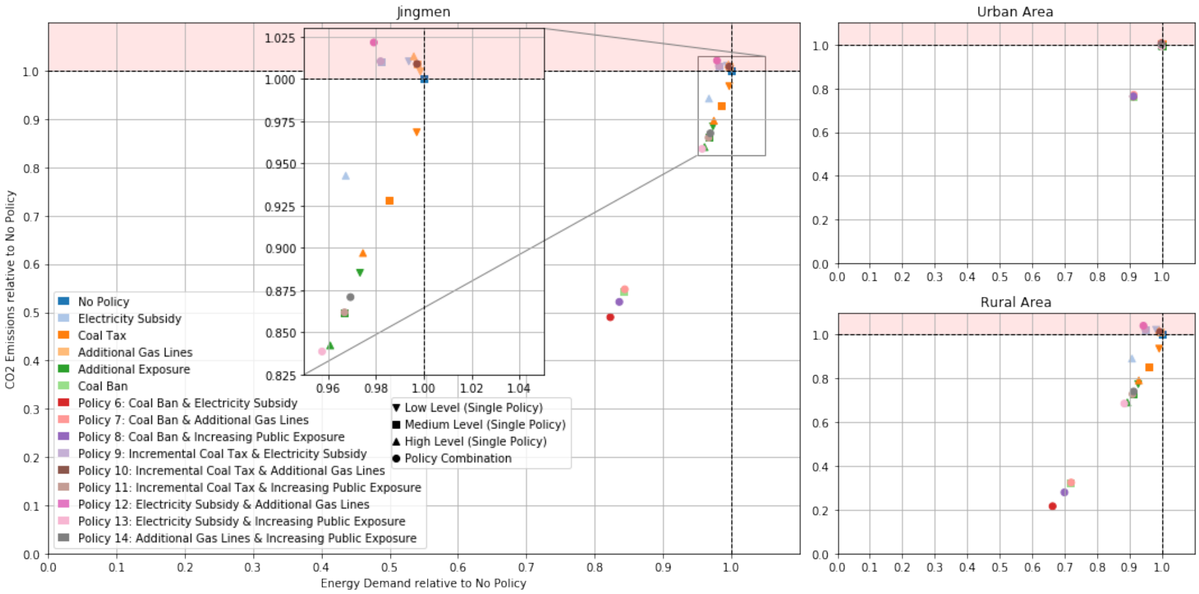


**Figure 59:** Comparison of policy results in terms of energy demand and $CO_2$ emissions, scaled to the no-policy alternative.

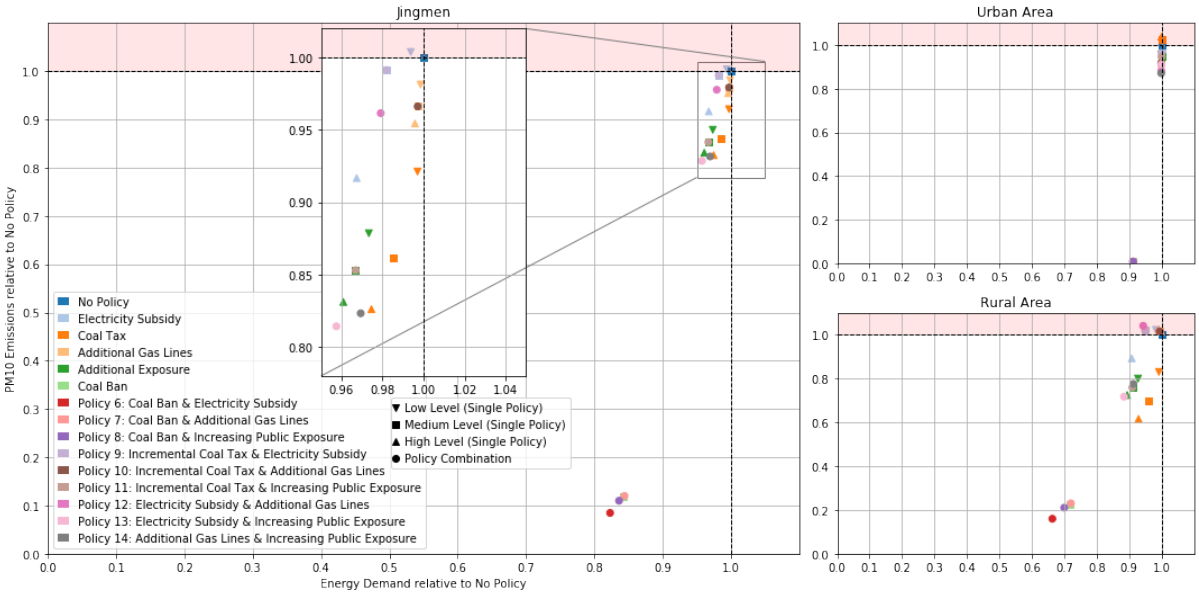


**Figure 60:** Comparison of policy results in terms of energy demand and $PM_{10}$ emissions, scaled to the no-policy alternative.

The recommended policy will eventually depend on what the policy maker deems to be an acceptable decrease in energy demand compared to the necessary reduction in $CO_2$ and $PM_{10}$ emissions. However, from this, the following policies are recommended:

- **A coal ban will best reduce $CO_2$ and $PM_{10}$ emissions, but the it is more effective to do in combination with an additional supportive policy such as an increase in gas pipeline placement or an electricity subsidy.**

- **In the rural area, an incremental coal tax will be effective in reducing $PM_{10}$ emissions without impacting the energy demand. However, this policy is ineffective in reducing $CO_2$ emissions and is ineffective in the urban area altogether.**
- **A combination of an electricity subsidy with additional exposure will likely be effective but also risky as it heavily relies on the cooperation of households. The policy is effective because a subsidy will not only impact price-related measures but will also cause citizens to cooperate with the desired policy more easily.**
- **Increasing the placement of gas pipelines will have a minimal impact in the long term but could be relatively effective in order to further accelerate a shift from coal to natural gas consumption.**

# 7. Discussion

The model has explored several possibilities for the Jingmen government to reduce its emissions and despite some interesting findings regarding what moves residents to use a specific type and quantity of energy fuel, it is important to reflect upon the practicalities involved in the research, and what the additional insights mean. Despite being well aware of the dangers of harmful fuels to health and environment, many residents did not fully consider the practical impact their individual usage could have on themselves. The minimal effect each individual believes to have on the environment and local air pollution has entrenched them into a dilemma in which they can choose to use cheap, harmful fuels or more expensive but cleaner fuels. The impact on an individual household is not bound by its own consumption, and due to the limited impacts that a single household has on the environment, individuals are inclined to behave strategically and therefore opt to use the cheaper fuels. The fact that people are mostly aware of the fuel consumption of their neighbours and peers allows them to shift their own blame towards the general population. Intervention is therefore crucial in inducing a change on energy consumption behaviour. It is important to note that such behaviour is not merely bound by consumption in lower-tier cities in China but can be observed in other democratic societies too. However, there is a fundamental difference when making this comparison, which relates to government structure and its responsibility expected from its citizens.

## Expected citizen responsibility from the government

In democratic societies, there are many stakeholders involved in decision-making processes and the population is aware that opinions will shift in the long term. As a result of the multi-actor setting, the implemented policy often ends up much different from the initial plan (Howlett, 1998). Policy windows emerge naturally as a result of the uncertainties coming from the multi-actor setting, and so it can take a long time for significant developments to occur. Government intervention is therefore not always desired, and only in situations of high necessity will the government intervene directly. Over the past years, governmental policy in The Netherlands has placed emphasis on the 'responsibilization' of its citizens (Dekker, 2019). The countries in the European Union (except for Bulgaria and Malta) have a liberalized electricity market. Citizens need to think about what energy provider they want as they make a conscious decision regarding lowest price, best offers and which provider offers clean energy alternatives. The privatization of governmental responsibilities such as choosing your energy provider forces citizens to re-evaluate our decision frequently: every energy-related commercial on the radio, every emission-related political debate on television and every unsolicited phone call by other energy providers forces citizens to reconsider their own impact on the environment. Households are expected to drive the change and the market will adjust accordingly. The responsibility is delegated to the people (eating less meat, driving electric cars, flying less) and if the citizens do not change their demand, the supplier has no incentivize to change either.

Policy decision making in China is more straightforward: despite rapid and extreme developments and all sorts of uncertainties in China, the high incentives placed on reaching targets means that these will often be reached. This makes it easier to develop policies in the long term. Policies are set from a top-down setting and distributed over several departments. Although this allows for clear-cut and effective policy implementation, the practical implementation is not always efficient as it places heavy focus on goal reaching and limited public participation (Ahlers & Schubert, 2015). Policy-windows do not appear naturally but are created by the government themselves. The governmental control over the energy market further allows for certainty in aspects such as price of electricity. This provides a lot of certainty for individual households as fluctuations in electricity price have been very limited. For individual households, the fuel they use and how much energy they consume is not a real topic of concern. There is only one choice in choosing the energy provider, that of the government. By only providing a single option of energy and gas supplier, the government takes liberty in choosing what they think is best for its citizens. In doing so, citizens are not expected to be responsible for choosing the right option in order to reduce global warming and emissions caused by their fuel consumption, leaving them to concern themselves about their individual life.

## Practical effectiveness of adjusting knowledge and willingness

Raising awareness can be effective in leading the citizens into the desired direction. This is already being done in the urban areas: as the majority of the urban population lives in high-rise apartment buildings built by companies through municipal contracts, many of these are already connected to the national natural gas grid. In turn, the citizens no longer need to place further considerations on the fuel that they use, as the more efficient and desired fuels are already the most convenient ones. This can be seen in the results presented as urban population showed heavy resilience against many of the policies. Yet, it is difficult to raise the same awareness for rural citizens. Instead of being just unaware of the direct problem and what they can do to have an impact, rural households are unaware of the fact that they are unaware. Dealing with the issue of air pollution is a task for the local government, while the central government has regulatory oversight of policy implementation through incentive mechanisms (X. Li, Yang, Wei, & Zhang, 2019). Adjusting residential behaviour accordingly is difficult because questioning government decisions is not engrained in the cultural lifestyle of the population. When asked directly, people admitted that they would change their behaviour with new knowledge and insights. The question is however, whether these people are even interested in acquiring this knowledge and insight, whether such questions are interpreted ambiguously and whether they answered sincerely or because they knew it was the right way to respond. It is unlikely that these citizens will go out of their way to further reduce their emissions as they have more important affairs to care about. The municipality will therefore need to place more emphasis in guiding and supporting these citizens accordingly if further reduction of emissions in these areas is desired. For the local government, such a policy is likely too risky as there is a dependency on citizen cooperation, especially if the incentives from the central government are highly desired. A policy such as a coal ban or coal tax can be better enforced through law and regulations and is therefore much more certain in terms of expected emission results.

The policy is also contentious in theory: there are many diverging ideas regarding energy consumption as the science behind the exact of pollution is not ubiquitous. As these cannot be accurately assessed along with the actual coal consumption of the residents, the sincerity of access to information cannot be well assessed. For example, residents can be taught about the importance of using more efficient equipment, and also about how to better insulate their housing. However, once they are expected to make a choice between the two, the question arises about which is more desirable: using less energy in the end or using cleaner fuels. These situations lend themselves to uncertainty in how residents will eventually respond to the policy, thereby hampering its effectiveness. It is therefore important to see knowledge in relation to willingness. If there is no willingness, the amount of knowledge is unimportant. The willingness is therefore essential in driving the knowledge into practical effect. In the model, the willingness of the citizens is dependent on the amount of many they spend on average on their fuels, but they can also be impacted by other factors that are unrelated to energy consumption.

In the long-term, it is difficult to observe for how effective the policy will be. Even though the policy shows promise, in reality this policy (on its own) will also show diminishing returns. People's general attention span will simply not last for ten years. Multiple ways of exposing the citizens is necessary in order to maintain knowledge about this importance in the long term, or alternatively, this policy should be implemented in the short term, after which other behavioural patterns could take over. Yet, even if people make limited direct changes in their consumption as a result of this policy, it does have additional beneficial effects that can make an impact in the long term. People will better understand the dangers to their own health and allow people to make a more conscious choice regarding their consumption. Turning people from being unknown unknown about the impact of their consumption, they at least become known unknown – which can indicate a first step to behaviour adjustment.

## Practical effectiveness of policies restricting fuel access

### *Coal Ban*

A coal ban can also have a further impact on Jingmen as a whole. Firstly, as the coal price is much lower than that of electricity and gas there will be a decrease in fuel consumption demand. This will reduce consumer spending all over the board, not only in terms of fuel consumption but also that of other goods. This can have a lasting impact on the Jingmen economy as a whole with likely lasting impacts on its economy, as well as the stability of individual residential income. Additionally, the policy will have a large impact on the industries. As the coal ban will only be enforced on local companies and residents, the larger nation-wide companies in the region are unaffected. Since a lot of coal is mined locally, with a constant supply and a lower demand as a result of the ban, price will drop. The Hubei area, and with that Jingmen, is very reliant on the steel industry. A reduced coal price can mean cheaper means of production. This will have positive benefits for the industry, but also means that the actual emissions will likely maintain. Another industry that will benefit is the actual energy generation industry. A reduced price means that more coal can be used for electricity generation. This means that the problem is not helped, but simply shifted from the residential industry to that of the energy and manufacturing industry. The cheaper coal will also mean that it will be more difficult to get these industries to move away from coal in return. Coming back to the stability of residents, this can thereby have a further negative impact. The people that are struggling financially are restricted from using coal, while the companies that have more money can continue using it, and even more of it. This could create a lack of understanding and residential dissatisfaction.

The assumption is made that a coal ban would in theory, be effective in putting the overall residential coal consumption to zero. However, the low residential density in the rural area makes enforcement of such a ban on a street level difficult. If coal is much more convenient and cheaper to use, the population will find alternative methods to use it. Enforcing a ban on the demand side will lead to people becoming less open about their energy consumption out of fear for legal repercussions. It would be nearly impossible to ensure the coal is not consumed altogether by over three million people in the city, let alone if this ban is extended on a larger scale. Enforcing a ban at the supply side will be more easily managed, especially if the initial supplier is government owned. However, this could in return give rise to black markets and lower quality coal that may be even more harmful to its users. Ensuring that the population will adhere to the ban will be especially difficult in the east of Jingmen (Jingshan) as raw coal is being harvested in mines present in this area.

In order to compensate for the coal, people will consume more biomass instead. The danger is that a shift away from coal towards biomass could be seen as a positive change. The targets set through the top-down hierarchy are mostly relate to country-wide values. As the health impacts as a result of biomass fuel usage will observed on a local scale, emphasis is placed on reducing the $CO_2$-emissions, as these figures contribute to nation-wide target.

### *Coal tax*

Another restrictive policy investigated is an incremental coal tax. The policy is ineffective in the urban area, but the mere presence of a coal tax can already lead to reduced coal consumption regardless of the tax level in the rural area. However, the problem is that this policy, like the coal ban, mostly punishes rural populations who consume the fuel out of necessity and lack of available alternatives rather than out of choice. According to Q. Liang and Wei (2012), a tax on carbon under the current social welfare system will increase residential income inequality between the urban and rural area. Zhixin and Ya, (2011) too acknowledge the dangers a carbon tax may pose on income inequality, but also state that if implemented properly it can actually promote regional economic development. A requirement for this is that the additional revenue from the carbon tax is invested within the regions that are mostly hit by the tax. In the case of Jingmen, this means that a coal tax can best be introduced in combination with another policy such as an electricity subsidy. The tax and subsidy could in essence compensate one another which could make the consumption of electricity more attractive in lieu of coal.

## Practical effectiveness of policies supporting fuel access

### *Electricity Subsidy*

Another policy that may need to be further considered before actual implementation can take place is the 'Electricity Subsidy'. The current initiative of solar panel placement is already ongoing but mostly reserved for poverty alleviation purposes. Extending this policy to encompass the energy transition may show the dedication it places on improving the overall liveability of the rural residents. As implemented in the model, the subsidy is implemented through a reduction in overall electricity price. However, in order to become even more effective, the prefecture can consider other methods of implementing this subsidy to further highlight additional factors that the government may find important. An income-dependent subsidy will put focus on poverty alleviation. This could bring more equality between the urban and rural populations. A subsidy that depends on the amount of energy demanded will place further emphasis on the importance to use electricity. An example of the use of this policy is present in the subsidy provided for natural gas users which is already in place. Making the subsidy dependent on location could be used to discourage further urbanisation from rural to urban areas, while a subsidy dependent on the members in a household size, such as the aging of the population that many cities currently face.

On the other hand, shifting this policy towards a focus on renewability and clean energy may lead to a loss of focus on the initial reason why the policy was implemented in the first place. On top of that, due to a lack of space, it would be difficult to implement such a policy directly in the urban area. Although there is a large shift going on in terms of renewability in the entire city, it is uncertain that this will actually lead to a reduction in energy price as the Jingmen municipality does not control the electricity, but the Central China Power Grid does.

The policy has further drawbacks. Firstly, depending on the type of subsidy provided it may develop discrimination between members that obtain a subsidy and those that don't. Another point of attention is that the government has the responsibility for providing the citizens with stable electricity. The current approach of the policy can provide groups of citizens electricity at a much lower price due to renewables placed in the area. However, if this policy is expanded on a larger scale, there is a larger uncertainty whether the renewables can provide enough electricity to meet the demand. In case this is not enough, the constant demand in short term may force the CCPG to upscale the supply from the industry that is currently generating electricity. This can increase the overall consumption of coal in the city. Furthermore, a short-term imbalance of supply and demand may also cause power outages. This may in turn cause the citizens to turn to alternatives that are invulnerable to such problems such as coal or biomass. Due to this responsibility of the government, the policy can also not be implemented in the short term as the coal ban or coal tax could. Households will eventually rely on the subsidy in their overall energy demand. The subsidy will need to be maintained over a prolonged period of time in order to have a relevant impact. Once the commitment has been taken to implement the policy, there is limited possibility to take the subsidy away, especially for low-income areas.

### *Additional Gas Lines*

In the current state of the rural areas in Jingmen, additional placement of natural gas pipes may not be feasible due to the state of the homes as well as the large distribution of houses. Many residential high-rises that are currently built do support the use of natural gas, however this means that population relocation is necessary in order to make the consumption viable. It is questionable whether this is feasible as well as desirable for the main purpose of using cleaner energy.

Further expanding upon the effectiveness of this policy in the long term, in China, a shift towards gas is seen as a good way to reduce emissions on a large scale. It is often seen as a necessary 'green' fuel. However, gas is not a renewable fuel, and this raises the question if such a dependency on gas is actually desired long-term, or if it is seen as an intermediary step towards a fully renewable future. Although there is currently an abundance of gas in the country, the demand for gas is also high and ever accelerating. Trade ties with Russia are currently formed, which causes a dependency on another country and other political factors far beyond the scope of this paper. However, this dependency could turn problematic in the long-term future. An example of such problems is apparent with the dependency on natural gas in The Netherlands, which is currently forced to shift away from household gas consumption. In 2019, China was the top importer of Natural Gas. There is an increased dependency on imports of natural gas – on Russia (Natural Gas imports) as well as on the USA (LNG imports) (South China Morning Post, 2018a). This reliability is difficult in times of political uncertainty. China does have its own natural gas resources, however due to technical and geographical difficulties there are problems regarding the exploitation. The gas is too deep, there is a lack of water in such areas, the gas is generally considered to be of low quality. The gas fields are mainly located in areas that are currently politically or culturally contentious (South China Sea and in the Xinjiang province) (South China Morning Post, 2018b). It is therefore unlikely that the policy can be extended into the long-term. The dependency on gas further brings technical struggles, such as resource depletion and dependency on the natural gas price. The investment has extremely large sunk costs and is combined with a high risk. For the government the supply of natural gas is risky. It is therefore unsurprising that it is looking to liberalize its natural gas market in order to minimize government responsibility (Shi & Variam, 2015).

By focusing on the supply for natural gas and the large investments made, there can be a struggle in shifting towards full renewability energy. Some regions in China have been criticized for giving too much priority to conventional sources like natural gas over the development of renewables (Stanway, 2019). Natural gas still has $CO_2$ emissions even though much lower than that of coal. This means that if this is not a long-term investment, it surely is one with a high sunk cost on this investment. Eventually a shift towards renewability is desired, and this is likely a very expensive intermediate step in order to enforce a direct turn away from coal. On the other hand, it can impede the development of renewables. This research has shown how difficult it actually is to induce a behavioural change for residents to move from damaging fuels to natural gas and electricity. This change will need to come again if there is a current focus on natural gas in an intermediate period. Eventually those residents will need to turn towards electricity completely. This will become even more difficult since gas is then the norm and seen as the most convenient fuel to use, the cheaper alternative, and by many seen as the healthy and environmental fuel to use due to the current push away from biomass and coal.

## Expected differences to energy policy implementation in the urban and rural areas

There is the clear difference in per-capita income. As income in lower-tier cities is generally much lower, a much higher proportion of income is spent on meeting basic level energy consumption. This further encourages people to use cheaper fuel, meaning it will be difficult to push the rural population to start consuming the more costly alternative. Without thorough intervention, such policies could lead to finger-pointing amongst the population rather than stimulating an effective change. Cheap fuels will remain readily available in terms of biomass, which citizens will continue to use unless clean fuel price reduces significantly. In the urban area, there is limited conscious decision-making as most residences have the relatively cheap clean alternative of natural gas that can be provided to them. Price still plays a considerable role, but people will be more understanding about top-down policy restrictions placed as a result of environmental concerns.

Driving behavioural change in the urban area is easy due to the amount of control that can be exerted on the population. There is little reflex to the investigated policies because many systems that have been examined are already nearly optimized. As urbanization rate rises, it will become increasingly important for the urban area to ensure economic development is accompanied by clean fuel consumption. For this reason, it can be expected that gas and electricity prices will remain stable. The accelerating energy transition may give rise to pricing techniques that can be further researched such as dynamic time-of-day electricity pricing or adjusting price dependent on monthly demand. However, it is questionable whether such policies will have a positive effect on the population. Such pricing levels require additional choice-behaviour that people may not desire as it creates further uncertainty regarding the energy bill at the end of the month.

There is a lot more room for the rural population to change. However, people may already be reluctant to do so. Individual rural citizens could see policies that negatively impacts them as a punishment for being less wealthy than the urban population. On the other hand, providing additional financial support will not always lead to cleaner fuel consumption, but instead cause dirty fuel consumption to increase. It is likely that the prefectural government is already aware of this, which could be an additional reason why residential energy consumption is a contentious topic in China. There is a reluctance when mentioning policies to drive support for the rural population. From a Western societal point of view, the lack of direct support for the rural population may let one to believe that they have been ‘forgotten’. However, this lack of policy is not to ignore the population altogether, but instead to ‘protect’ them. Supporting them indirectly will not work because many policies could be taken advantage of through opportunistic behaviour, while on the other hand imposing harsh, restrictive but very effective policies will only punish them for not being wealthy enough to use cleaner fuel. Individuals know that their consumption is not good for their own health, but feasible alternatives lack. For this reason, the focus is placed the urban area alone. Change in the rural area is induced through economic development or urbanization, which is why large advancements are made in the building sector.

The policies investigated vary drastically in their approach, and therefore also in the impact that they have. The coal ban shows to be an extreme policy which reduces fuel consumption altogether. Taking away this alternative will cause the other goods to increase in consumption for a short period, but as the consumption tends to normalize back to the original values, the overall consumption will decrease. For the urban area, supportive policies will prove most effective. Full connectivity to the gas grid will increase its consumption at the cost of coal and biomass. In the rural area however, such policies are ineffective or will even work counterproductive as these policies will be complimentary to the available resources, rather than replacements for the currently used fuels. Therefore, policies that restrict unwanted consumption are more effective in the rural area. However, this merely considers energy consumption and omits other factors and problems that may arise after the implementation of such policies.

Citizens are generally tied to consume what is available in their vicinity. This means that if certain fuels become less accessible, they cannot simply change their consumption behaviour. Although a coal ban is in theory effective in reducing carbon emissions, in practice, a coal ban could ensure that people without an option for alternatives are forced to consume their coal illegally. This could in turn lead to emission values being further obscured as people won’t be likely to admit their consumption, fearing legal repercussions. In terms of health, such a policy could be even more harmful for individuals. Trying to hide coal consumption, could obstruct proper ventilation, causing further harm to individuals in the rural area who have no other alternative. Other policies such as a subsidy for electricity could create a further divide between the urban and rural areas. The urban areas consume more electricity, allowing them to benefit more from such a policy. Other policies, such as improving the exposure to the importance of responsible and clean energy consumption could lead to shaming. Survey analysis showed that people are generally aware of the fuel consumption of others in the neighbourhood. Actively advertising about the health and environmental problems of some fuels may cause people to unwillingly lose face as they cannot afford any cleaner alternatives.

# 8. Conclusion, Limitations and Future Research

This research has investigated how lower-tier prefectures can stimulate their residents to shift daily energy fuel demand from traditional fuel use to cleaner and more efficient fuels, while preventing the population from unwillingly reducing their total energy demand. The research had been broken down into four sub-questions.

*The current attitude of households in a lower-tier Chinese city towards energy consumption, fuel choice and emissions of $CO_2$ and $PM_{10}$*

The urban and rural areas exhibit differing attitudes in relation to fuel consumption. Residents in both areas are aware of the potential dangers of coal, yet the harm of biomass consumption to health is unknown. While it is important for citizens to be aware of the potential harm biomass burning can cause, it is unlikely that this will have an impact on citizen health in the short term. Rural residents show larger consumption of harmful fuels. Instead of focusing on long-term effects of the harmful impact their fuel may have on health and environment, there is a larger focus on the short-term necessity of having access to fuel in the first place. For these citizens, clean alternatives often lack.

Residents in the urban area show much larger concern about what fuels can do to their health. Being located in the urban area means they are generally subject to higher levels of air pollution and they have more fuel alternatives available. Many people are already consuming cleaner fuels as these are already convenient and cheap to use. As pollution remains an issue, their concern about the environment and health remains. However, both urban and rural citizens are generally not inclined to change their habits soon and, in-line with the governmental duty of energy provision, they see it as a task of the government to come up with the policy that drives change to a cleaner environment.

*Developing a quantifiable model of household energy consumption that encompasses the attitude of households in a low tiered Chinese city*

In order to investigate the household energy consumption, consumption behaviour and potential emissions of $CO_2$ and $PM_{10}$, a co-simulation model has been developed. The SD model is divided into sub-models revolving around price level, convenience, and knowledge and willingness. This means that the model can only investigate policies that are directly adjustable within these sub-model aspects. The focus on demand-driven consumption behaviour negates any focus on renewable energy: a policy that is essential in shaping the Chinese energy infrastructure. However, the approach taken still reflect patterns of behaviour that are regarded as important by the citizens and can therefore reveal what public reaction to policy implementation the local government can expect.

*Using a quantifiable model about household energy consumption as a general blueprint for policy investigation in cities throughout the country*

The effectiveness of government intervention has been investigated through the development of a quantifiable model, using data collected in the Jingmen prefecture. The model is able to relate residential behaviour to fuel choice and consumption such that policies can be investigated. The prospects of using the model as a blueprint for the rest of the country depends on the adjustments the city of study. Cultural and geographical differences restrict the development of one all-encompassing model that is able to present accurate household behaviour. Depending on these differences, alterations in model structure may need to be made. As the strength of the model lies in showing demand patterns, policy implementation is restricted to policies that influence demand. A different model approach may be required depending on the types of policies that need to be investigated.

*Policy implementation to effectively reduce $CO_2$ and $PM_{10}$ emissions with minimum impact on household lifestyle*

A direct ban of coal will likely firstly force people to consume less energy or bring about a change to other 'cheap but dirty' alternatives such as biomass. A ban on coal very effective in reducing emission levels. A long-term coal ban can reduce $CO_2$-emissions by as much as 33% and 74% in the urban and rural areas respectively by 2030. The complete removal of coal as a fuel choice can reduce total rural energy demand by over 30% in 2025, compared to expected demand without a policy implementation. The unavoidable shift to biomass fuel will lower $CO_2$-emissions of the city but has damaging effects on people's health and air pollution will remain. Without the lack of other supportive policies or alternatives available to the households, such a restriction will be detrimental to total energy demand.

A taxation on coal consumption could be effective in the rural area. The rural area will use biomass as a substitute for the coal, which can see biomass consumption to increase by around 25% in comparison to no-policy expectations. However, if the tax does not keep increasing incrementally over the years, increasing income could eventually cause people to revert back to using coal. The price of coal is so much lower than that of the clean alternatives, meaning that the price needs to be increased many-fold for clean substitutes to become economically desirable. Instead, it will restrict households from using energy or cause them to choose biomass as an alternative.

A subsidy on electricity reduce emission levels, creating a shift towards the use of electricity as a main source of fuel in daily household use. Directly reducing the energy price is not very effective by itself but could instead be implemented as a supporting policy with another more restrictive policy, in order to maintain the energy demand. Reducing the electricity price will increase demand. As less money is spent on electricity, citizens choose to increase demand rather than shift towards other fuel sources. Therefore, implementing this policy alone will only see an increase in demand and emissions.

Placing additional gas pipelines at an increased rate will be mostly effective in the urban area. Increasing the convenience is very effective and therefore such a policy will see a short-term decrease of biomass and coal consumption by about 10%. In the long term, additional precautions need to be taken. Once the urban area is fully connected to the national gas grid, there is no additional convenience from this policy. This will eventually cause coal and biomass consumption to readjust to normal levels. However, this policy is the least effective policy in the rural area.

Exposing the population to the importance of clean fuel use can be effective if implemented correctly. As people will become more aware of the dangers of coal consumption, this fuel will likely see a reduction in usage. However, as the policy depends on the cooperation of citizens on a large scale, its actual effectiveness is uncertain. The policy shows to be more effective in the rural area than in the urban area, as people in the urban area are often already aware of the dangers of harmful fuel consumption. The policy is most effective supplementary to another.

Each policy investigated has its individual pros and cons. One policy focuses on the complete removal of a fuel, two policies focus on fuel price, one policy focuses on increasing the convenience, while another focusses on improving the knowledge and willingness of individual households. In the end, this may mean that there is no individual policy that is best to implement as the effectiveness vary in area as well as in impact on energy demand and emission results.

The following policies are recommended:

- **A coal ban will best reduce $CO_2$ and $PM_{10}$ emissions, but the it is more effective to do in combination with an additional supportive policy such as an increase in gas pipeline placement or an electricity subsidy.**
- **In the rural area, an incremental coal tax will be effective in reducing $PM_{10}$ emissions without impacting the energy demand. However, this policy is ineffective in reducing $CO_2$ emissions and is ineffective in the urban area altogether.**
- **A combination of an electricity subsidy with additional exposure will likely be effective but also risky as it heavily relies on the cooperation of households. The policy is effective because a subsidy will not only impact price-related measures but will also cause citizens to cooperate with the desired policy more easily.**
- **Increasing the placement of gas pipelines will have a minimal impact in the long term but could be relatively effective in order to further accelerate a shift from coal to natural gas consumption.**

## Limitations

The research has been conducted for two principle reasons. The first reason was to map out the residential energy structure for the citizens of a city in China with average general properties and to identify policies that would prove effective in stimulating the use of cleaner energy fuels in order to curb $CO_2$-emissions, air pollution and improve citizen health. Secondly, the research has been conducted in order to further investigate the possibility of using a distributed co-simulation that allows for policy decision making. Although this research has succeeded in investigating both, there are some limitations to the current research that need a topic of their own in the future.

**Only a single city was used for this investigation**

Behavioural patterns may differ for people in other areas throughout the country. Coal consumption is much higher in northern China, whereas general per capita fuel consumption is lower in the south.

**Only parts of the city could be questioned for survey research**

Even within the city of Jingmen, the current distinction between urban and rural areas may be up for debate. The rural area is much larger than the urban area in absolute size, while it currently has a similar (and dwindling) population. Due to limitations in statistical data, it is still not entirely clear to what extent the differences within the rural districts are. More detailed surveys throughout the city are necessary in order to do this.

**The model can only investigate urban and rural populations as different groups**

For this research the urban and rural area populations have been taken as completely different groups. However, all people within the areas are uniform. Therefore, other properties such as age, cultural ethnicity and income level are ignored. This while many policies that are currently investigated in China are dependent on properties aside from geographic location.

**The policies investigated have limited adaptability to short-term results**

The model developed for this investigation has proven to be sufficient for the policies developed, however more in-depth policy exploration has lacked. Examples are policies that consider a very short-term ban on coal depending on emission levels, or policies that loosen up once emissions have reduced. For these policies to be implemented, the feedback from the LEAP model back to the Vensim model needs to be used. Although such feedback is implemented in the simulation model, it has not been investigated in this research.

**Fluctuations in fuel price is not represented**

There is a large dependency on price level, which means that large fluctuations in price in the future may completely affect energy fuel consumption in terms of type as well as quantity. Especially natural gas is subject to high fluctuations in price as more and more gas fields within China are being discovered, and gas lines are developed with nations abroad (such as the 'Altai' and 'Power of Siberia' pipelines connected to Russian gas fields). Similarly, domestic coal prices may be affected by political changes on an international level (such as coal exports to Australia).

**Problems with model validation**

One of the largest issues faced over the course of this research is the lack of validation. The crux of the research has been to obtain better insights in how people can be stimulated in using more renewable and efficient energy fuels. It is known that the issue of residential fuel usage is a problem, however policy makers have nearly no current data that shows better insights in energy usage.

**Model does not incorporate sunk costs**

The general validity of the model can be further discussed in terms of the assumptions made that are fundamental to the model development. The first important assumption is that the sunk costs in purchasing an appliance is not considered when choosing a type of fuel. Appliances such as a cooking furnace or heater are large investments made by citizens. A reason why people are unwilling to change their source of fuel could be because they are unable to afford or unwilling to spend extra money if their current appliance is of sufficient quality in doing its job. The assumption is made that these sunk costs eventually distribute themselves over a population that is large enough.

**Cooking and heating are combined into a single purpose**

Moreover, people may be using multiple types of fuel for different purposes: although the use of electricity is included for all residents, people may use different types of fuel for cooking (for example gas) and heating (for example biomass). The assumption is made that residents only consume one certain type of fuel, as the consumption of different fuel types will likely even out over the whole of the population. However, while cooking can be considered a daily necessity, general heating may not be. It could therefore be possible that some policies may be effective for changing the fuel for cooking or heating separately.

**There is an overall lack of knowledge about the current situation**

A problem with the research is that its largely exploratory nature complicates model and data validation. There is currently insufficient centralized knowledge about the consumer behaviour of localized rural areas, such as those in parts of rural Jingmen. Expert opinion is based on vague estimates that put insufficient consideration on the underlying reasons as what moves people to consume in the fashion that they do. This means that the research conducted (such as the survey research) is partly done to expand the knowledge about such behavioural patterns. This provides new primary ideas about which (type of) policies can best be drawn upon in order to nudge residents into a certain direction in terms of energy and fuel consumption.

## Future Research Recommendations

**Examine research for other cities**

The research served the purpose of developing an example for municipal governments to investigate the effectiveness of policies to reduce consumption of inefficient and dirty fuels in the residential sector. Due to research constraints, only a single city has been examined. For this reason, it is uncertain to what extent the research can be extrapolated to other cities.

**Expand behavioural patterns**

Many residents surveyed have shown little real thought behind the reasons why they chose a certain type of fuel. This is because in many situations, the choice is already made for them, they have never thought to change, or financial constraints limit them to do so. For many, having a fuel source in the first place is much more important than the consideration whether this fuel is clean or dirty. The direct minimal necessity for fuel and how fuel consumption will alter can be further explored.

**Involving industries and other sectors**

As part of a larger research it is interesting to note the exact policies for other industries and observe how other industries cope with results obtained from the current research. For this, new system dynamics models will need to be built and connected to the current LEAP model in a similar fashion. However, this would allow for much more dynamic patterns to occur. An expansion of the energy industry may be affected by changes in demand, which in turn needs to adjust their own patterns in supplying energy – which in turn may affect other indicators such as price – which could again impact demand. Such dynamic patterns would allow for much greater complexity to be built into the model than the mere inclusion of residential energy demand and behaviour.

**Involving supply-side policies**

Including the energy supply as well as the energy demand can also provide more insights in the emissions created by the industry sector, and further allows investigation on policies that are further aimed at more renewable energy supply. This will provide the government a more comprehensive idea about which areas allow for the best improvements to made, while further considering the city’s economy. The use of renewable energy can be further expanded to individual citizens too, such as a more accurate implementation of renewable policies such as the generation of energy through residential solar panels (rather than a mere reduction of overall electricity price). The inclusion of more sub-models does, however, bring additional problems. The current simulation allows for such time-related problems to be kept to a minimum, as demand is calculated first, supply remains unaffected throughout. A more concrete way of dealing with time-related issues and the continuous versus discrete behaviour between the two models should be established before further expanding the models. In doing so, more sensible time-steps in the continuous model would also need to be defined. This is especially true when attempting to implement more detailed policies, such as dynamic peak-demand electricity pricing, or when observing general shifts in demand, for example when considering demand changes in summer versus winter periods.

# Personal Reflection

Over the past couple of months, I undertook a journey, in the literal sense as well as in my own development. My concern about the current state about the energy sector, combined with my continuous interest in simulation and modelling systems and my everlasting fascination with Chinese culture meant that this research has been an unforgettable experience.

Starting the research, it had been difficult to establish a thorough scope. The method of how the research was achieved was a little unorthodox, as the entire research project had been going on for a while before I my actual thesis research commenced. At the start of my internship, some researchers expressed their interest in further expanding upon the already existing LEAP model. Within the system, I decided to focus on a single sector, further investigating the residential sector in Jingmen. Although this is by for not the largest sector in terms of energy demand, there were sincere knowledge gaps present for the prefectural government. On top of that, I felt further attached to the residential area as the sector was most relatable for myself as an individual. Lastly, choosing this sector would allow me to learn most about the culture of the residential population in the lower-tiered cities in central China.

Conducting the research turned out to be more problematic than initially anticipated. Firstly, making the common mistake of 'trying to change the world' with a single research. I found it difficult to narrow down my scope as I often felt that I could do a little bit more than the current scope encompassed. Another problem was the fact that I was conducting research in China. Though the culture and country are not new to me, this was the first time conducting actual work in a Chinese environment. I also had little interactions with people from rural areas. Regardless, I believe that with the enormous amount I got from my colleagues in China I found my way and was able to conduct the research. The problems with this were that the municipality initially seemed to have little interest about specific research on the residential sector. In their point of view, the emissions from the residential sector were too little to specifically focus on. On top of that, a turn towards renewability would come automatically with economic development. During the interviews, government officials were very reluctant to discuss the rural population. Obtaining information about the rural population was difficult in general. After a survey was sent out and filled in by over 500 people, the insights obtained were limited. It turned out that almost every respondent lived in the urban area. After personally visiting the rural areas myself, it turned out that many residents were illiterate, did not speak standard Mandarin, were very reluctant to cooperate in the research or were unknowing about energy consumption altogether. Even though this complexified the research, such problems were also the reason why I had such interest in researching this subject about China in the first place. I believe that researchers continuously face issues like this when conducting in a foreign country, and I think that the EPA programme perfectly prepares students of learning how to deal with different, sometimes clashing cultures. As much as I enjoy modelling and simulation, I believe that this was merely a method of research to bring better and more thorough insights about the problem at hand. The biggest insights I have had over the past couple of months were how professional culture, politics and behavioural dynamics work in China.

In technical terms, this research has forced me to apply the techniques of modelling and surveying and data analysis learnt during my EPA degree through multiple, more 'out-of-the-box' methods. There were multiple challenges that I faced when setting up the survey questions for the demography chosen. For each question was important to ensure that citizens understood the question, were willing to answer it, were willing to answer it in honesty, were able to answer the question and were willing to take their time to answer the question. This did mean that the questions underwent some adjustments that eventually caused some of the knowledge that could have been attained went missing (for example almost no regression analysis could be conducted as almost every question was asked in nominal or ordinal nature). This forced me to obtain a new view and approach to survey data collection and finding methods to obtain as much information as possible while adhering to such principles. I also had to be inventive in the modelling approach. Firstly, I had to learn a whole new language, VBA, from scratch. I had no previous experience with this program, but since both the LEAP and Vensim models could be connected using VBA as an interface, this was definitely the right approach to be taken. I also had to find a way to connect the Vensim and LEAP models to each other with minimum disruption. A lot of the LEAP model had already been constructed before I started this research and therefore, I had to take care and ensure that this model maintained internal validity with and without the Vensim connection. Furthermore, some theoretical issues such as time synchronization in a continuous model needed to be worked around as there was simply no time in a master thesis to approach such an issue independently.

Over the course of the EPA programme, I found the modelling and simulation aspects much more enjoyable than the written or literature aspects of the research. This thesis was no different. A significant portion of my time (perhaps too much) was spent on model development and integrating the Vensim and LEAP models together. In hindsight, I believe that I should have started writing much earlier and simultaneously with my model development. By postponing the writing aspect of the thesis over the course of my research I may have missed some extra insights. A bigger problem of this meant that, due to the structure of my research I had way too little contact with my supervisors. Being on the other side of the world for most of the research meant that it was unnecessary to approach my supervisors for small questions. However, because I had too little to write, I also had too little to share. I believe that the biggest flaw over the course of my thesis research was the lack of contact I sought with my supervisors. Not only did this make my research unnecessarily complex, it also kept my supervisors in the dark about my thesis progress for too long. The importance of keeping up communication became especially apparent after personally meeting my supervisors early September. During these meetings I got extremely thorough and important feedback to take my insights several steps further and structure my thesis a lot better. In the future, my own communicative initiatives need to thoroughly improve in order to much better streamline the course of research.

Looking back, I feel that development I have gone through as a result from the experiences I have undertaken in the past half a year cannot be taught in the lecture hall. The practical hands-on experience working in a research environment with the possibility of meeting, interviewing and surveying individuals throughout the country has helped me develop not only in the field of research, but also as an independent individual. I thereby think that the true goal of this investigation has not merely been to pass my master thesis research, but to broaden my horizon and learn more about a culture that fascinates me, while at the same time sharing the knowledge I have learnt over the course of my period at the faculty of Technology, Policy and Management. Regardless of the eventual outcome of this thesis research, I believe I have succeeded in that perspective.

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# Appendix A – Data acquisition, analysis and limitations

## Appendix A.1 – Background about data acquisition

In order to obtain more information about citizen energy fuel behaviour, knowledge and willingness to change fuel source, field research in terms of surveys and interviews were conducted. Survey research was done on two separate occasions.

The first survey was conducted using the online messaging platform 'WeChat'. From this survey, a sample was obtained of 535 responses. However, after initial data analysis it became clear that nearly all respondents were centred around Jingmen's city centre. Although this provided useful insights, it created an extremely skewed sample, with over 95% of respondents coming from Jingmen's urban area.

Following this survey, a nearly identical survey was conducted in several rural areas within the Jingmen prefecture. During this field research it became clear that certain areas had a high illiteracy rate, high average age and low level of income. This made conducting the survey extremely difficult for several reasons:

1. Privacy of information
2. Willingness to speak to outsiders
3. Observer effect
4. Time consumption

From this, a mere 31 samples were collected. Although this (together with interviews with the local population) provided useful insights in local consumer behaviour, it was still not possible to obtain a fair sample of the rural population overall. What became apparent is that the rural population, without connection to natural gas will use the resources available to them – if cheap.

After conducting the surveys, the decision was made to mainly rely on data provided by the government in order to obtain figures related to numbers and quantities. However, survey data could still be used as a means to obtain better insights in general consumer behaviour. From the data analysed it turns out the overwhelming majority of the urban districts currently use natural gas for cooking purposes. This because the largest part of the urban areas is connected to the national grid network which currently provides natural gas at a heavily subsidized rate prices (Liu et al., 2018). For both urban and rural areas, convenience was directly identified as the most important reason why people chose their type of fuel. However, when asked what would move people to change their fuel type, many did respond they would most likely change if it were to become cheaper. This more indirect question shows that price is more of a consideration for people than they would like to admit when asked directly.

Price- and convenience-related will therefore be the most effective policies by far. Surprisingly, environmental concerns were also a very important reason that would shift the rural areas to change their fuel type. Although this phenomenon may also be caused by the observer effect, it may also show that educating the rural population in energy consumption may be a good way to helping them shift away from traditional fuel sources. A further data-related issue is a heavy reliance on expert opinions and opinions of party officials. While this research works under the assumption that the provided data is correct, it is difficult to establish the amount of pre-supposed bias and knowledge of likely policy implementation. This obscures the ability to differentiate against policy implementation and scenario analysis. For example: an expert opinion stating that residential coal consumption will decrease over the coming years may already have the presumed bias that policies will be put in place to restrict this coal consumption, rather than considering what would happen to its consumption in a 'free market'. This means that subconscious policy implementation may already occur throughout the development of the initial framework. There are also cultural issues associated with why such research has been limited, as a significant part of individual Chinese households may choose to burn cheaper but more harmful fuels but are unwilling to openly admit doing so out of fear for social or legal repercussions.

As part of data collection, interviews have been conducted with members of several commissions within the prefecture of Jingmen. These departments are the Development and Reform Commission, the Housing Construction Committee, the Transportation Committee and the Ecological Environment Bureau. Additionally, interviews were conducted with various power generation enterprises and members in the Jingmen High-Tech Industry Campus.

## Appendix A.2 – Survey Questions

1. 请问您的年龄是？

What is your age?

2. 请问您的性别是？

What is your gender?

3. 请问您的最高学历是？

What is the highest level of education you have enjoyed?

4. 请问您的家庭年收入约为？

What is your yearly income?

5. 请问目前您的家庭中共有几位家庭成员（仅考虑共同居住的家庭成员）？

How many people are in your household?

6. 请问您居住在荆门市的哪个区？

In which area (Dongbao, Shayang, Jingshan, etc.) do you live?

7. 请问您的日常能源相关支出（包括煤气、电、煤炭、柴薪）占您月收入的比例约为？

What is your monthly expenditure on energy (fuels)?

8. 您日常烹饪主要使用的能源是？

What energy fuel do you use for cooking purposes?

9. 您为何主要选择该能源烹饪？

What is the main reason why you use this source of fuel for cooking purposes?

10. 您日常取暖主要使用的能源是？

What energy fuel do you use for heating purposes?

11. 您为何主要选择该能源取暖？

What is the main reason why you use this source of fuel for heating purposes?

12. 您的家庭拥有以下哪些设备？

Which of the following equipment do you own (computer, mobile phone, air conditioning, etc.)

13. 您知道您的邻居使用哪种能源进行烹饪或取暖吗？

Are you aware of the fuels used by your neighbours for cooking and heating purposes?

14. 您愿意为日常能源（包括煤气、电、煤炭、柴薪）支付的费用最多占月收入的比?

What is the most you would be willing to spend on energy?

15. 如果您知道支付额外费用将有利于环保，您愿意吗？如果愿意，您能够接受支付多少额外费用？

If you were to be asked for an additional amount of money in order to compensate for the environment, how much would you be willing to spend?

16. 如果您决定改变烹饪/取暖所使用的能源，以下哪项会是您做出改变的主要原因？

If you decided to change fuel for cooking/heating purposes, what would be the most likely reason that would cause this change?

17. 您对使用电进行烹饪/取暖的主要印象是（请选择三项）
18. 您对使用煤气/天然气进行烹饪/取暖的主要印象是（请选择三项）
19. 您对使用煤炭进行烹饪/取暖的主要印象是（请选择三项）
20. 您对使用煤炭进行烹饪/取暖的主要印象是（请选择三项）

贵 便宜 环保 污染 便利 不便 危险 安全 健康 不健康

What is your impression about using electricity (17), gas (18) and coal (19) for cooking/heating purposes? Select three of the following:

Expensive, cheap, environmental, polluting, convenient, inconvenient, dangerous, safe, healthy, unhealthy

21. 您是否了解使用煤炭对环境的影响？

Are you aware of the effect that consumption of coal has on the environment?

# Appendix B – Vensim implementation

## Appendix B.1 – General model description

The Vensim model is developed as a multinomial logit/choice model with the utility function dependent on the mechanisms described. The utility for each fuel is taken as the percentage of households that are using a certain type of fuel as their main source of household fuel for purposes such as cooking and heating. The value is then multiplied by the total energy demand per household to obtain the total fuel demand of each fuel. The 'causal loop' model of the sub-models developed is shown in **Figure B1** below. As price is identified as the main cause of choice, the price sub-model shows to be the main driver for the other sub-models too. The output results of the three sub-models of Price, Convenience, and Knowledge and Willingness combine together into the Utility sub-model, which calculates the overall utility for each of the fuel type. The results from the utility are then converted into actual energy demand.

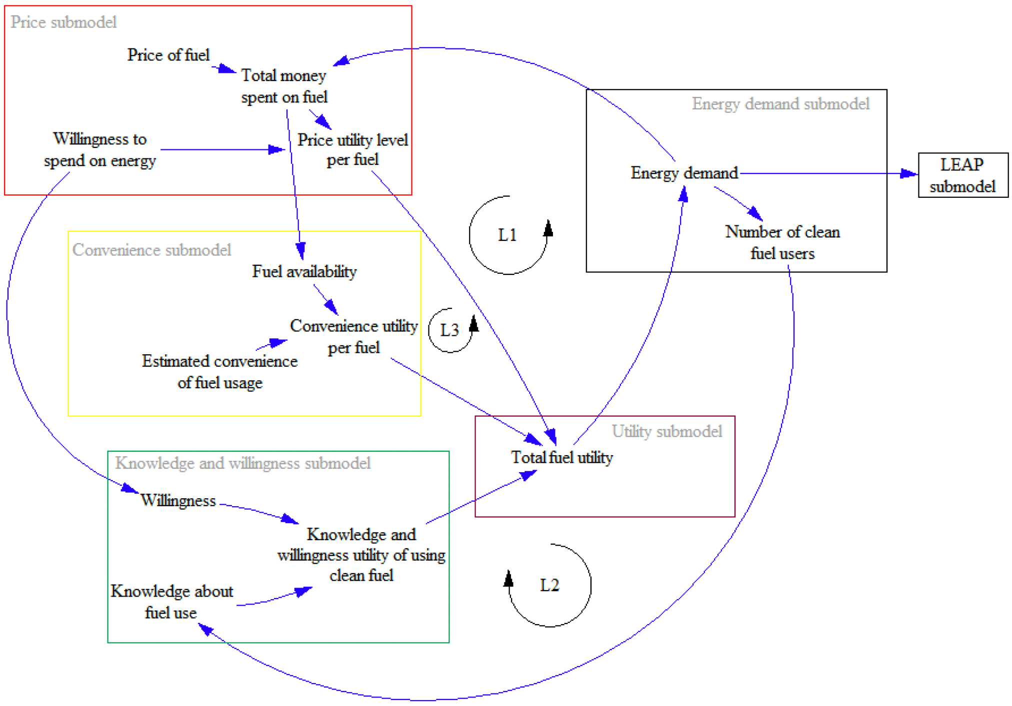



**Figure B1:** A general overview of the system dynamics model used to simulate user energy demand

There are three main 'loops' within this model:
**L1:** 'Higher energy demand leads to more money spent' – A destructive/balancing feedback loop: Considering the proportion of income spent on the fuels. The higher the price utility (i.e. the lower the price is), the higher the utility for using the fuel, which increases the energy demand. A higher demand will in turn mean a larger portion of income is spent on fuel, thereby decreasing the utility of using such an amount of fuel.
**L2:** 'Users spread the knowledge' – A positive feedback loop: If there are more users of cleaner fuels, the knowledge about responsible fuel use will increase, thereby increasing the amount of people using the cleaner fuels.
**L3:** 'Market responds to demand' – A positive feedback loop: if there is more money spent on coal, it means there is more money to be made for individual stores to sell coal. In turn, this causes more stores to open and sell coal. This increases the convenience for people to buy coal, thereby increasing the demand for the fuel.

## Appendix B.2 – The structure of the Vensim model

*Formulaic Variables*

The table given below provides a general overview of the most important variables used in the model. Most variables are accompanied by subscripts; these are further explained in-text.

| Variable | Explanation |
|---|---|
| e | Electricity (often used as a subscript) |
| cl | Coal (often used as a subscript) |
| g (ng, pg) | Gas (natural gas, petrol gas) (often used as a subscript) |
| b | Biomass (often used as a subscript) |
| c, α, β, ξ, x, n, Θ | General coefficient and factor terms |
| P | Price |
| C | Convenience |
| K | Knowledge |
| W | Willingness |
| KW | Combined variable of knowledge and willingness |
| CP | Combined variable of convenience and price |
| u | Total utility |
| U | Relative utility |
| Fr | Fraction (accompanied with subscripts explaining the type of fractions) |
| f | Fuel (often used as a subscript) |
| t | Time (often used as a subscript) |
| r | Region (Rural or Urban) (often used as a subscript) |
| D | Total fuel demand |
| d | Demand per household |
| Y | Income spent |
| N | Number of households |
| A | Surface area |

*Utility sub-model*

Literature investigating population fuel choice often investigates fuel preferences using Multinomial Logit Models (Alem et al., 2016; Hosier & Dowd, 2002; Liao et al., 2019). This type of choice modelling considers the utility of each available choice by calculating its logarithmic fraction to of the sum of utility of all choices possible. In this situation, the utility of each individual type of fuel available is considered as a fraction of the combined utility of all fuel types available. This in turn means that the sum of all available fuels equals to 1. The relative utility of each individual fuel can be seen as the proportion of the total population that is using a certain type of fuel.

The utility of each available fuel is a function of the mechanisms of price, convenience, knowledge and willingness described below. Each of these mechanisms are described in their individual sub-models below, however, each sub-model will output a KPI value between 0 and 1, where 1 stands for the most positive value (such as lowest price, highest convenience, highest knowledge and highest willingness), while 0 represents the lowest possible. In order to obtain the utility of each fuel type, the sub-model KPI's are multiplied by a coefficient ($c$) representing their relative importance in determining the type of fuel. Although these coefficients are calibrated later, an indication of their value is obtained through survey research. Each individual fuel also consists of a further fuel-dependent term ($\alpha$) which is also multiplied by all KPI's – this term represents all other considerations people make aside from fuel price, convenience, knowledge and willingness. Such considerations may include that people may have never thought about switching their fuel, the fact that their house is too ingrained with the current fuel technology to switch, or the unwillingness to purchase new appliances. Lastly, a calibrated error term ($\xi$) is added to each of the utilities to compensate for other assumptions made such as the limited choice of which fuel types available. This provides the following function for each fuel type (e – electricity, g – natural gas, cl – coal, b – biomass):

$$\ln(u_{e,t,r}) = \frac{c_P P_e + c_C C_e + c_{KW} KW_e}{c_P + c_C + c_{KW}} + \alpha_e (P_e + C_e + KW_e) + \xi_e$$

$$\ln(u_{g,t,r}) = \frac{c_P P_g + c_C C_g + c_{KW} KW_g}{c_P + c_C + c_{KW}} + \alpha_g (P_g + C_g + KW_g) + \xi_g$$

$$\ln(u_{cl,t,r}) = \frac{c_P P_{cl} + c_C C_{cl} + c_{KW} (1 - KW_{cl})}{c_P + c_C + c_{KW}} + \alpha_{cl} (P_{cl} + C_{cl} + (1 - KW_{cl})) + \xi_{cl}$$

$$\ln(u_{b,t,r}) = \frac{c_P P_b + c_C C_b + c_{KW} (1 - \beta KW_b)}{c_P + c_C + c_{KW}} + \alpha_b (P_b + C_b + (1 - \beta KW_b)) + \xi_b$$

Notice that the formulas for the dirty fuels are different from the fuels considered clean, as knowledge and willingness hereby have a negative effect on the total utility. As biomass is considered less harmful than coal, a factor considering the harmfulness of biomass in comparison to coal (β) is multiplied by the knowledge and willingness factors.

Subsequently, the relative utility of each fuel type is calculated using:

$$U_{f,t,r} = \frac{u_{f,t,r}}{\sum_{i=0}^{4} u_{f_i,t,r}}$$

The utility sub-model further calculates the CP-factor and KW-factor, which are used in the energy demand sub-model. These values are calculated as following:

$$x_{CP,r,t} = Delay3\left( \frac{\sum_{i=0}^{4} \left( \frac{c_C C_{f_i} + c_P P_{f_i}}{c_C + c_P} \right)}{4}, \frac{1}{12} \right)$$

$$x_{KW,r,t} = Delay3\left( c_{KW} KW, \frac{1}{12} \right)$$

For each factor there is a third-order delay, as it is estimated it will take a month before people will adjust their consumption quantity (as a result of the monthly energy bill).

#### *Energy demand sub-model*

The actual demand for energy variable represents the expected average amount of energy a family will be using for cooking and heating purposes in the upcoming year. It is modelled as a stock variable as there is a high dependence on the energy consumed in the previous timestep. The stock of actual energy demand has an influx as a result of the convenience and price total utility variables of all fuels combined (CP-inflow). A higher level of convenience would mean people are more likely to use more fuel. Cheaper energy would also mean that people are more likely to consume more energy. On the other hand, the energy demand stock has an outflow, which is related to the knowledge and willingness variables. This determines how people are willing to use less fuel because they are more 'aware' of using less of it and willing to use less of it because they are implored to do so out of altruistic reasons for the environment (KW-outflow).

The CP-inflow and the KW-outflow are dependent on the current expected average amount of energy as the flows represent a percental change in demand. Furthermore, aside from their indicated names (Convenience and Price, and Knowledge and Willingness) they depend on a minimum threshold value that needs to be reached in order for any effect to take place. If this threshold value is not reached, the flows will turn out to be negative. For convenience and price, residents will use less energy if the combined factor of convenience and price is less than they are willing to put in. On the other hand, a decrease in knowledge and willingness about saving energy will lead to an increase of energy consumption (i.e. a negative KW-outflow).

The average energy demand is therefore modelled as following:

$$d_{r,t} = d_{r,t-1} + \frac{dd_r}{dt}$$

$$\frac{dd_r}{dt} = CP_{in,r,t} - KW_{out,r,t}$$

$$CP_{in,r,t} = d_{r,t-1} \cdot (x_{CP,r,t} - x_{\min,CP,r})^3$$

$$KW_{out,r,t} = d_{r,t-1} \cdot (x_{KW,r,t} - x_{\min,KW,r})^3$$

With $D_r$ describing the average expected per household energy demand for region *r* (urban or rural).

There is a difference however, in willingly and unwillingly reducing energy demand. Although people may want to reduce their energy demand, they should not be forced to do so as this would have sincere negative impacts in their overall liveability. If energy demand is to be reduced, this should therefore occur through a positive outflow (using the knowledge and willingness variables), not through a negative inflow (using the price and convenience variables).

This value is subsequently divided to all different fuels and multiplied by the proportion of the population that is using a certain type of energy fuel, multiplied by the total number of households in the area (rural or urban). This gives a total amount of fuel demand for an individual fuel.

$$D_{f,r,t} = N_{f,r,t} \cdot d_{r,t}$$

Where $D_,$ indicates the total demand of fuel, while N indicates the total number of households that are demanding that specific fuel.

$$N_{f,r,t} = U_{f,r,t} \cdot N_{r,t}$$

The sub-model further calculates the total demand for ‘clean’ fuel by dividing the amount of demand for electricity and natural gas by the total energy demand in the area.

$$P_{clean,r,t} = \frac{D_{e,r,t} + D_{g,r,t}}{D_{r,t}}$$

*Price sub-model*

The price sub-model concerns itself solely with the prices of fuel and the people’s opinions with relation to using a certain type of fuel. The market-price for each individual fuel in China is estimated per megajoule. However, it is important to note that the absolute price of the fuel is not extremely important, but rather its price with relation to the other fuels that are available, as well as the proportion of income that is spent using a certain type of fuel.

Without policy, the market-price (per MJ) is taken as the price people will need to pay for their fuel. This value is subsequently multiplied by the average energy demand and divided by the GDP/capita to provide the proportion of income that is paid when using a certain type of fuel:

In which P signifies the proportion of income spent, D stands for the average demand per household, and Y is the fuel price (in RMB/MJ).

The price portion of the utility of the fuel is subsequently calculated as following:

$$Fr_{income,f,t,r} = \frac{D_{t,r} Y_{f,t,r}}{GDP / capita_{t,r}}$$

However, the utility from price is not (inversely) linear to the percentage of income paid. The more people pay for their fuel, the less and less likely people are to choose a more expensive fuel. From this, assumption, the following formula is used to calculate price-related utility:

$$P_{f,t,r} = \min\left(1, \max\left(0, c_{pe} \cdot \ln\left(\frac{Fr_{income,max}}{Fr_{income,f,t,r}}\right)\right)\right)$$

Note that the price-related utility factor will remain 0 unless $Fr_{income}$ becomes larger than $Fr_{income,max}$. Furthermore, the value will generally stay smaller than 1, unless $Fr_{income,max} > e * Fr_{income}$, after which it will assume a maximum price-related utility value of 1. In this model, the assumption is made that biomass is free and therefore has a maximum price-related utility of 1 ($Y_{b,t,r} = 0$) as by people using this type of fuel will most likely collect the firewood themselves.

The value $c_{pe}$ is a coefficient that concerns the coefficient that mimics price-elasticity of the fuel source. However, here it concerns the additional reduction in utility as a result of the increase in price. It is likely that this value largely relates to the convenience of the type of fuel ($c_{pe} = f(C_f)$), however as this relationship will again ask for further coefficients, this value will be assumed to be a constant fuel-related coefficient on its own.

*Convenience sub-model*

The convenience sub-model mainly concerns itself with the convenience of buying and selling coal as well as the convenience of using natural gas. This is because the assumption is made that every individual is connected to the national electricity grid, which has a maximum relative convenience of 1.

In case a household is fully connected to the national gas grid network, the convenience is, just like the convenience of electricity equal to 1. However, not the entire city is connected to the gas network. This means that the standard convenience of using natural gas is equal to the proportion of households that are connected to the gas grid network. Furthermore, for the people not connected by the gas network there is a convenience value of using gas from propane tanks. This provides the following equation for the convenience of natural gas:

$$C_{g,t,r} = Fr_{connected} + C_{pg}\left(1 - Fr_{connected}\right)$$

On top of that, it is difficult to estimate what exactly the convenience of the use of biomass is, but it is definitely true that $0 < C_{biomass} < C_{pg}$, as the use of biomass is considered a lot less convenient than propane gas. As people generally tend to collect firewood by themselves, the convenience for using biomass is dependent on two factors. Firstly, the amount of time and effort people are putting into finding the fuel (for example the effort for chopping down trees). Secondly, it depends on the amount of dirt the firewood gives, such as the ash that the timber leaves behind after being used. Also, survey data analysis has shown that the use of biomass is assumed to more convenient than that of coal. This is most likely because it leaves less dirt behind after use. This means that the convenience of using propane gas can be considered as following:

$$C_{pg} = C_b + \Delta C_{b \to pg}$$
$$C_b = C_{cl} + \Delta C_{cl \to b}$$

It is important to note that although the value of $\Delta C_{b \to pg}$ is definitely larger than 0, that of $\Delta C_{cl \to b}$ is not necessarily larger than 0, but is assumed to be. Lastly, the convenience of coal is estimated to be dependent on the number of stores in the city area that are selling such coals for fuel burning, as well as a standard coefficient that incorporates the general nuisance that people notice when using coal as a fuel.

$$C_{cl,r,t} = c_{0,r}\left(c_d \frac{n_{stores,r,t}}{A_r}\right)$$
$$n_{stores,r,t} = n_{stores,r,t-1} + n_{new,r,t} - n_{closing,r,t}$$
$$n_{new,r,t} = c_{ne,r} Delay1\left(Fr_{cl,income,r,t}, 1\right)$$
$$Fr_{cl,income,r,t} = \frac{TS_{cl,r,t}}{n_{stores,r,t} \cdot GDP / capita_{r,t}}$$
$$n_{closing,r,t} = c_{ce,r} Delay1\left(1 - Fr_{cl,income,r,t}, 1\right)$$

Here, A represents the size of the Jingmen area (rural or urban), while $c_d$ represents the coefficient that determines the importance of distance to the nearest store that sells coal in relation to the convenience, and $c_0$ stands for the overall lack of convenience coal may provide due to dirt and other nuisances. The number of stores in the area depends on the income people are looking to achieve from selling coal. If there is a high coal demand – i.e. a lot of money is spent on coal, represented by high value of $TS_{cl,r,t}$, then the possible fraction of income per store is high. If this value is high in relation to the GDP/capita of the area, more new stores will open. If demand falls however, then stores will close down. This is tied in with an elasticity coefficient that determines when the income is of such a value that new stores will open. Furthermore, both the new stores and closing stores are delayed by one year of a third order.

*Knowledge and Willingness sub-model*

The knowledge sub-model part for using cleaner and less energy is modelled using learning-by-searching and learning-by-doing mechanisms. These mechanisms are modelled after Bildik, Daalen, Yü, Ortt, & Thissen (2015) and Struben & Sterman (2008). These models model the general knowledge and willingness of people in a neighbourhood to adopt a new technology as a stock-variable.

The ‘amount’ of knowledge is determined by the yearly gain and loss of knowledge, these variables depend on the amount of people that are currently using ‘clean’ energy. The main drivers of this model is the loop in which ‘clean energy’ becomes the ‘talk of the town’, i.e. people are becoming aware of the importance because it is being talked about. It concerns the ‘social cohesion’ amongst members in the urban and rural areas as well as the general information about energy usage provided from information outlets. The general values are gauged using on survey results using the following questions:

“Are you aware of the type of fuel used by the people in your environment for cooking and heating purposes?”

“Are you aware the effects of coal have on the environment?”

The general loss of knowledge is due to a lack of overall exposure and general decay as people’s interests are shifting away over time. Naturally, the effect of the importance of clean energy depends mostly on the amount of people are currently using the clean energy as these people will drive the model in the first place. If there are not enough people who have adopted the clean energy, then the feedback loop will diminish, and the ‘knowledge and willingness’ of people to adopt the technology will die down as a result of lack of knowledge.

The difference with the model developed by Bildik, van Daalen, Yü, Ortt, & Thissen (2015) however, is that the assumption is made that the ‘talk of the town’ from people is stimulated by information outlets rather than. Information about reducing energy demand and using cleaner fuels will take higher effect if current knowledge is considered low, actual energy demand is higher than the currently forecasted energy demand and if the current energy demand is low.

The stock-variable of ‘Knowledge of using less and clean energy’ is therefore affected by the flows that indicate a ‘Knowledge gain’ and a ‘Knowledge loss’. The initial knowledge ($K_{t=0}$) is estimated using survey results. This provides the following formulas:

$$K_{t,r} = K_{t-1,r} + \frac{dK_r}{d_t}$$

$$\frac{dK_r}{dt} = k_{in,t,r} - k_{out,t,r}$$

$$k_{in,t,r} = c_{learning} \cdot (1 - K_{t-1,r}) \cdot (E_{soc,t,r} + E_{info,t,r})$$

$$E_{soc,t,r} = c_{soc} \cdot K_{t-1,r} \cdot Fr_{clean,r,t}$$

$$E_{info,t,r} = c_{info} \cdot Delay1(1 - K_{t-1,r}, 1) \cdot (Delay1(Fr_{demand,t,r}, 1) + (1 - Fr_{clean,t,r}))$$

$$F_{demand,t,r} = \frac{D_{r,t}}{D_{forecast,r,t}}$$

$$k_{out,t,r} = \Theta_0 \frac{\exp(-4\varepsilon(K_{t-1,r} - n_{ex,r})}{1 + \exp(-4\varepsilon(K_{t-1,r} - n_{ex,r})}$$

In the formulas above, *c* are coefficients that are estimated and further calibrated. $E_{soc}$ represents the exposure to using less and cleaner energy through social exposure, while $E_{info}$ represents the exposure through information outlets. The social exposure depends on the current amount of people using clean energy as well as the current knowledge that people already possess. As it takes time for data about energy consumption to be gathered and information outlets to inform about consumption behaviour, there is a standard delay built into this function. The delay concerns the dependence on the (lack of) knowledge the residents currently have as well as data about current energy demand values to be gathered: $F_{demand}$. This value concerns the fraction of energy demand in the region, compared to the currently forecasted demand values used for planning. In case demand is higher than the forecasted amount, information about reducing energy demand will therefore be broadcasted. The loss of knowledge is modelled as modelled by by Bildik, van Daalen, Yü, Ortt, & Thissen (2015). Here, $\Theta_0$ concerns the maximum general rate of knowledge decay, ε stands for the slope of knowledge decay at a given time and $n_{ex}$ general exposure value. It is assumed that value $\varepsilon = 1/n_{ex,r}$, which normalizes the elasticity of familiarity decay to exposure at 1.

No matter how knowledgeable people are about the importance of clean and efficient energy types, this will have no effect on demand unless people are willing to put this knowledge to use – in terms of willingness. The overall factor of knowledge and willingness is therefore decided by a knowledge sub-sub-model and a willingness sub-sub-model. The willingness part mainly depends on the proportion of income spent as well as a factor that determines the overall willingness. Other areas that may include the willingness of people to use less and cleaner energy are already incorporated in the 'knowledge' sub-sub-model and therefore do not need to be included again – these are factors such as peer pressure (determined through social cohesion). This willingness to adopt therefore mostly depends on the amount of money people are currently already spending on their energy as a portion of their maximum willingness to spend on energy. As described earlier, this maximum amount is around 3-10% of the total income of the people but is standard set at 5% as the model only considers the use of energy for cooking and heating purposes.

This leads to the following formulas for the willingness sub-sub-model:

$$W_{t,r} = c_{sW}\left(\max\left(0, \frac{Fr_{income,max} - Fr_{income,t-1,r}}{Fr_{income,max}}\right)\right)$$

$$KW_{t,r} = K_{t,r} \cdot W_{t,r}$$

In which $c_{sW}$ is a coefficient which considers the importance that income proportion has on general willingness. The willingness value is limited to remain positive as the assumption is made that people won't purposefully go out of their way with other motives than convenience and price, to consume less efficient fuels because they need to spend a larger proportion of their income on this.

# Appendix C – LEAP sub-model development

The LEAP sub-model has been developed as a whole, with further consideration for all sectors, including the residential sector. Only the development of the residential sector shall be discussed in this paragraph. There are two main aspects to consider: Key Assumptions (assumptions that count for the entire model, such as population size, GDP, etc.) and the modelling for the Residential Energy Demand.

*Key Assumptions **

* As the Key Assumptions govern the entire model as a whole, they were in large made by other researchers, however they are stated as they form a vital part to the overall LEAP sub-model.

### Input Parameters

Within the model, the following Key Assumptions made are shown in **Figure C1** – all of which are divided between urban and rural estimations.

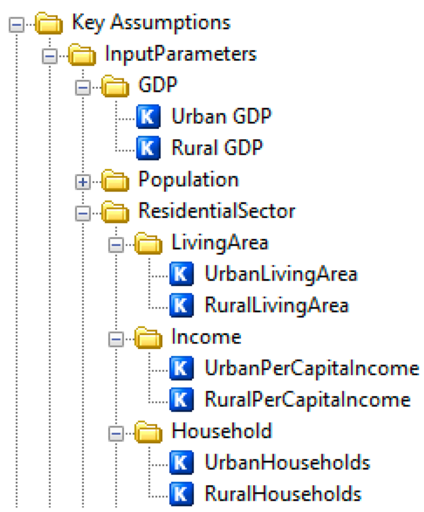



**Figure C1:** an overview of the 'Key Assumptions' entries

**Population**

Before 2015, the rural population has seen a massive decline, which is compensated by an almost equal incline in the urban population. For the upcoming years from 2015 until 2030, the city-wide population is assumed to be unchanged, but migration is expected to occur from the rural to the urban areas.

**Living area (living space)**

Due to the larger economic development in the urban area, the living space will in large increase.

**GDP and (Per Capita) Income**

- In effect, one of the two is superfluous as the per capita income is simply considered to be the GDP for an area divided by the population.
- It is estimated that the GDP will rise at unprecedented pace. These estimations are made by looking at the GDP in 2010 and comparing them to the levels in 2015 while also considering the general target GDP made in the 12$^{th}$ Five-Year Plan. The GDP and income at 2015 levels are then compared to the targets in 2020; these targets and estimations are further extrapolated linearly for 2025 and 2030. However, China has experienced enormous economic growth in recent years, and it is questionable if this growth be maintained in the future.

**Number of households**

This variable is superfluous as the extrapolations for population is simply divided by the current estimated number of people per household: 3.1 in the urban area, opposed to 3.8 in rural areas. However, in the overall model, it is at times more useful to calculate the per-household energy rather than by population.

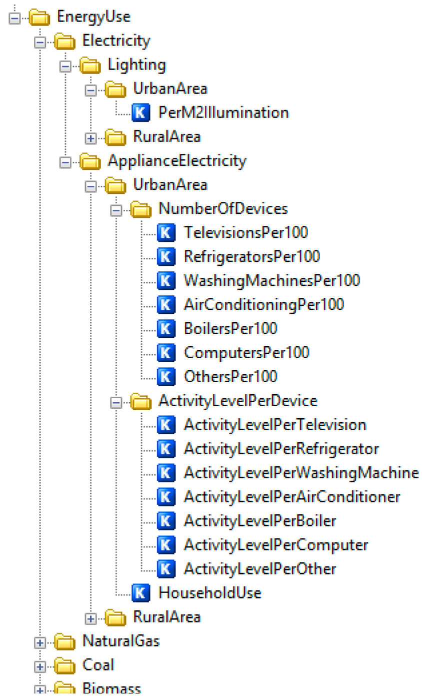



**Figure C2:** an overview of the 'Energy Use' under the 'Key Assumptions' entries

**Energy Use**

The energy use for each of the fuels is explored in terms of Activity Level (per square meter usage). This is where the energy values for each individual fuel source in the Vensim model are imported directly. The exception being the usage of electricity. Electricity is also used for lighting as well as other devices that cannot be powered by other fuel sources, such as televisions, refrigerators, washing machines, etc. The use of electricity for cooking and heating purposes is imported from the Vensim model under the HouseholdUse branch. The other values were all results taken from the survey research conducted in which the question was asked "Which of the following appliances do you own". In turn, the amount of each appliances per 100 entries was considered. Although this may be subject to double entries (as two people from the same household could have filled in the survey), it provides a good estimate as to the ownership of individuals. These values are subsequently extrapolated to compensate for the expected income growth. The activity level for each appliance is assumed constant until 2030, so possible improvements for energy efficiency are considered using the 'Sectoral Index' discussed below. The assumption is made that each household has one additional piece of equipment unaccounted for, the activity level of which is equal to the average of all other appliances. These appliances could range from (a combination of) a water kettle, freezer, mobile phone charger, electric fan, etc.

### Derived Variables

**Figure C3** provides an overview of the 'derived variables. These are variables that have been derived from the intial input parameters discussed previously. Most of these variables are created in order to ease the development process in the overall model formulaic input and bare no true significance to the development of the overall model. However, it is important to consider the PerM2 energy usage for each of the fuel types. The Activity Level variables inputted from the Vensim model are here divided by the area of each of the urban and rural areas. This provides information about the energy intensity for each of the fuel sources. This is not done for the electric appliances as the total energy usage of the appliances is already calculated in the initial input.

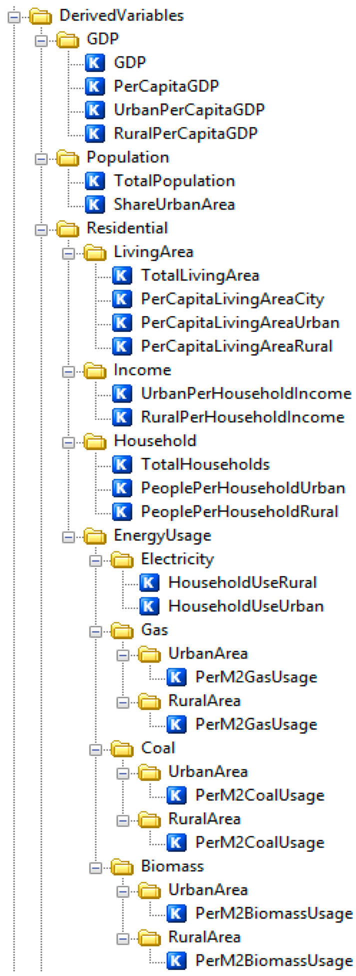


**Figure C3:** an overview of the 'Derived Variables under the Key Assumptions'

### Sectoral Index Variables

The sectoral index variables have little representation in the model as a whole, other than stipulate the relative power consumption intensity of each respective sector. Currently, each sector has an equal power consumption intensity, but the industrial sector will likely consume more in the future, while other sectors will consume less as they become slightly more efficient. It is expected that the appliances in the households will become 5% more efficient in 2030 as opposed to 2015.

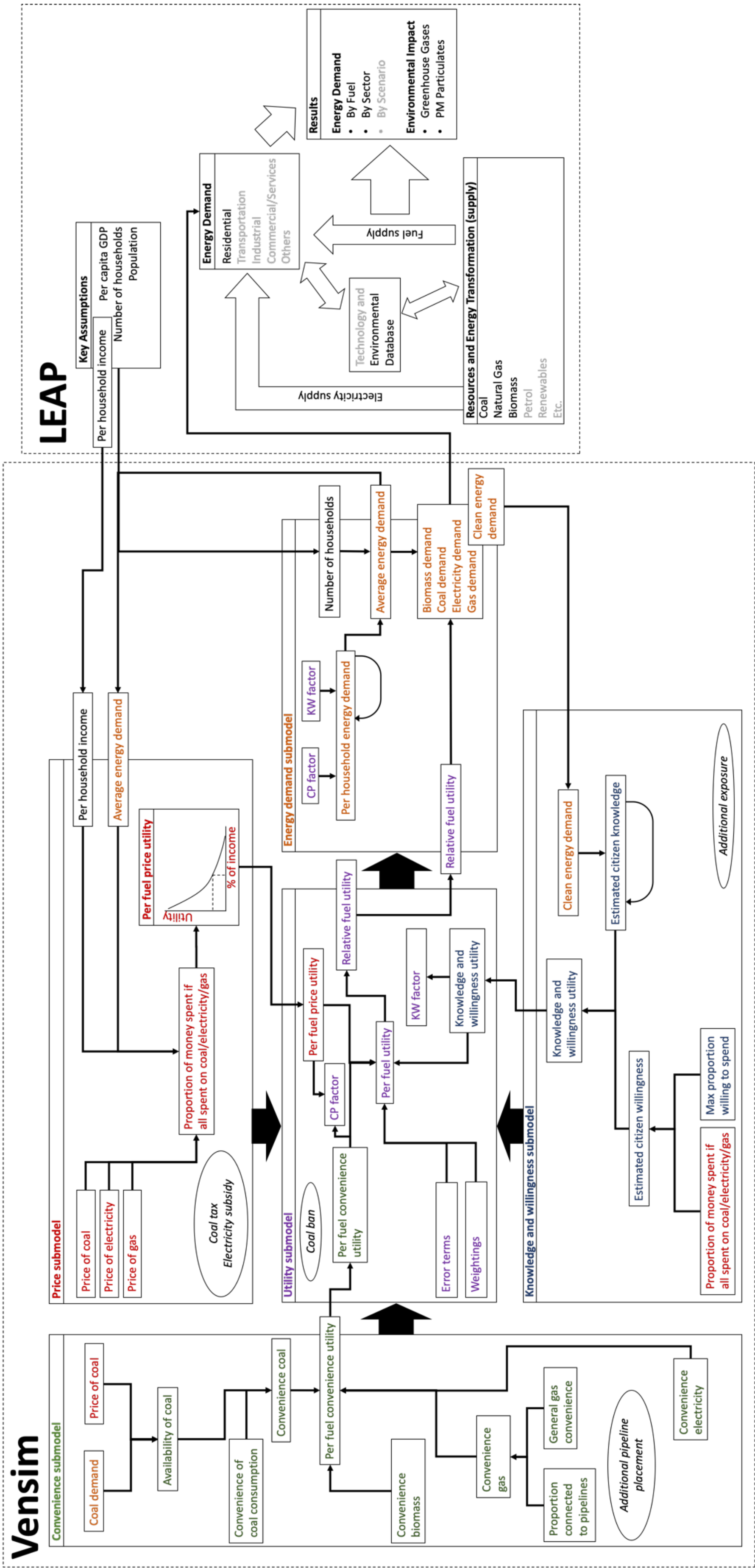
### *Residential Energy Demand*

In calculating the residential energy demand, LEAP considers the per square meter fuel intensity and multiplies it by the total amount of square meters of living space in the area (Activity Level multiplied by the Final Energy Intensity). In doing so, it calculates the total amount of gas, coal, electricity and biomass used in the rural and urban areas. Aside from that, the environmental effects of each individual fuel are established as shown in **Figure C4** below. This is done using key figures that are already inherent in the LEAP model software, which uses IPCC assessment data. Other data values have been adjusted in accordance to the overall research project. As these input variables are entered per unit energy consumed (also for the industrial and transportation sectors) and as such, they have been entered by other members in the research team.

| Branch | Effect | Expression | Units | Per | Method |
|---|---|---|---|---|---|
| Carbon Monoxide | Carbon Monoxide (CO) | 2000 | Kilogramme | Terajoule | Per unit energy consumed |
| Methane | Methane (CH4) | 300 | Kilogramme | Terajoule | Per unit energy consumed |
| Non Methane Volatil | Non Methane Volatile Organi | 200 | Kilogramme | Terajoule | Per unit energy consumed |
| Nitrogen Oxides | Nitrogen Oxides (NOx) | Key\DerivedVariables\排放\生活\氮氧化物{NOx}\排放系数 {标准量}\煤炭[千克/吨标煤]/10 | Kilogramme | Tonnes of Coal Equi | Per unit energy consumed |
| Total_ Suspended Pa | Tot Suspended Particulates ( | 2.24 | Gramme | Megajoule | Per unit energy consumed |
| Nitrous Oxide | Nitrous Oxide (N2O) | 1.4 | Kilogramme | Terajoule | Per unit energy consumed |
| Carbon Dioxide | Carbon Dioxide (CO2) | 25.8 * FractionOxidized * (CO2/C) | Metric Tonne | Terajoule | Per unit energy consumed |
| Sulfur Dioxide | Sulfur Dioxide (SO2) | Key\DerivedVariables\排放\生活\二氧化硫{SO2}\排放系数 {标准量}\煤炭[千克/吨标煤] | Kilogramme | Tonnes of Coal Equi | Per unit energy consumed |
| Particulates PM10 | Particulates PM10 (PM10) | Key\DerivedVariables\排放\生活\PM10\排放系数{标准量}\煤炭[千克/吨标煤] | Kilogramme | Tonnes of Coal Equi | Per unit energy consumed |

**Figure C4:** an example of the energy impacts per unit coal consumed as an example of energy demand entry.

# Appendix D – Combined Model Structure



# Appendix E – VBA, model interface and its internal structure

## Appendix E.1 – Software used

The model run has been successfully tested on Windows 7 (as a VirtualMachine on MacOSX 10.14 Mojave) as well as on Windows 10. The software packages used are LEAP 2018.0.1.18, Vensim DSS Single Precision (x32) and Microsoft Excel (Microsoft Office Professional Plus 2010 – 32-bit).

## Appendix E.2 – Visual Basic for Applications

Microsoft Visual Basic for Applications (VBA) is an event-driven programming language often used alongside other Microsoft Office applications. The main benefits of using VBA is that it allows users to fully automate operations. VBA is especially used in collaboration with Microsoft Excel as a way to automate certain spreadsheet functions (Roy, Deursen, & Hermans, 2019). The development environment can be accessed through any Microsoft Application itself under the 'Developer' tab (Microsoft Excel Professional Plus 2010, **Figure E1** below) and the written script is saved as part of the file that is used to access the script (such as .xls or .xlsx, when using Microsoft Excel to write the script).

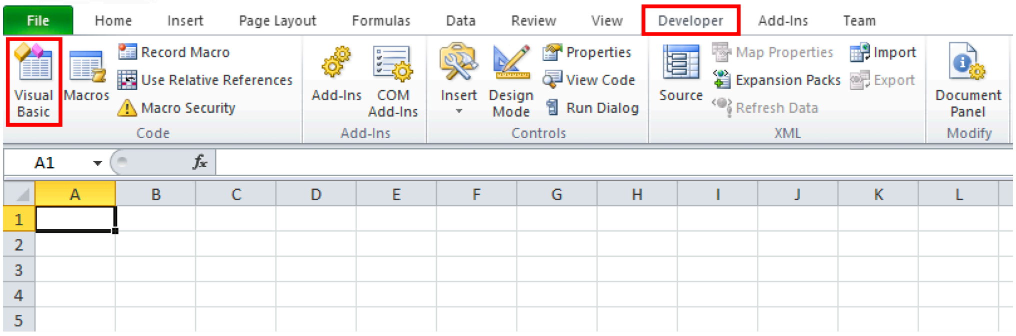



**Figure E1:** How to access the Visual Basic for Applications Development Environment in Microsoft Excel Professional Plus 2010

Alongside Microsoft Office applications, VBA script further allows individual developers to create scripts/libraries that allow for external control of such applications. Both the developers of LEAP and Vensim have developed corresponding functionalities, which means that LEAP as well as Vensim can be fully controlled using the VBA script. Interaction between LEAP/Vensim and the script written in Excel occurs using OLE Automation, in which the application objects create an OLE link with the application. Using this automation, the VBA script can open, run and modify LEAP and Vensim models. Aside from that, as LEAP and Vensim are both able to directly import and export data from and to Microsoft Excel, VBA can be used to inspect output data over the course of the simulation runs. Its control over the LEAP and Vensim models can then be used for dynamic model adjustment as a result of the output. Although the code is run from the environment of one Excel file, its power extends to opening, closing, modifying, creating and even deleting other files too. Therefore, VBA has a lot of freedom in creating new files from data obtained from Vensim or LEAP model runs. Lastly, as VBA is inherent within the Microsoft packages, these automated commands could be called upon through a user-friendly entry form in which a user can specify model details and run a model simply by clicking a button.

## Appendix E.3 – Model Interface

The user opening the model application *ModelApplication.xls* will not directly open an Excel spreadsheet, but will be greeted with a 'Form' structured as an application.

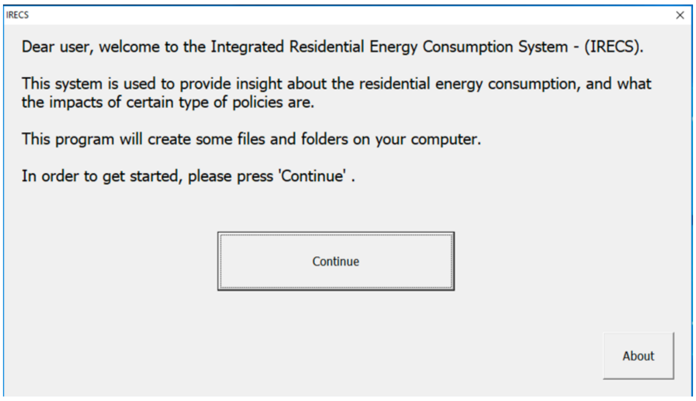



**Figure E2:** Start-up user interface of the model application

Pressing continue confronts the user with the initial basic input, asking the user until which year the model should run. As the general model run is until 2030, this is set as the general standard, however the user is able to reduce this until 2016.

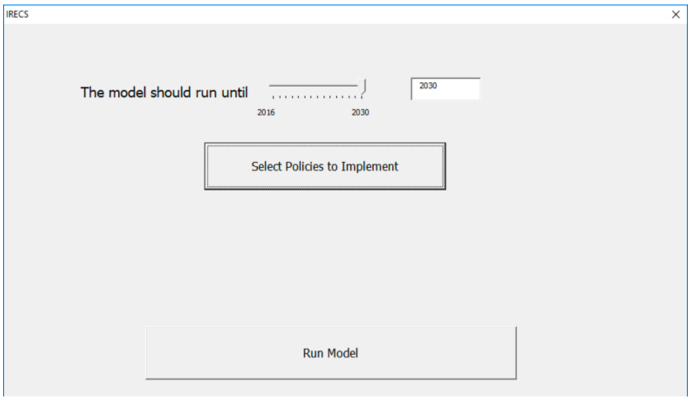



**Figure E3:** Indicating model time duration screen in the model application

If the user chooses to 'Select Policies to Implement', the user is confronted with the following screen. On this screen, the user can select one of several available policies to implement. The application does not (yet) support combined policies. During the model research, these policies have been implemented manually. When selecting a policy, the user can select the height of a specific policy in a pop-up window.

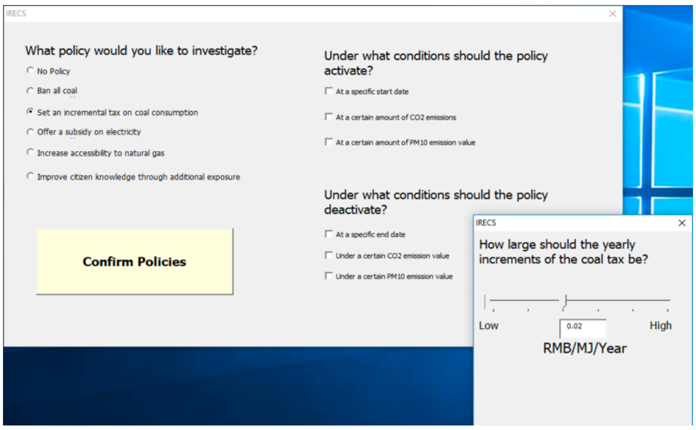



**Figure E4:** Policy implementation screen in the model application

The user can then select when exactly the policy should be implemented. For activation and deactivation of the policy, there are three options: (de)activate at a specific start date, at a certain amount of $CO_2$ emissions or a certain amount of $PM_{10}$ emissions. The user can select multiple options for (de)activation. If multiple options are selected, the policy will be (de)activated as soon as one of the conditions is met.

In order to confirm the policies, the user can simply press the ‘Confirm Policies’ button. This will save the selected policies and return the user to the previous screen, where the user can click on the ‘Run Model’ button. If this button is pressed before the ‘Select Policies to Implement’ is selected then the same input levers as the most recent model run are selected. When selecting ‘Run Model’ the user is shown a progress bar indicating how much of the simulation has run. One full model run (from 2015 to 2030) should take just under 15 minutes the model run, as the run for a single year takes around 50 seconds. The user is also able to abort the simulation, but the software will only respond to this function at specific instances in the model run.

## Appendix E.4 – Internal model structure

The entire model run takes place from Microsoft Excel. Opening the file directly opens a form that instructs the user how to start their model run. Starting a model run triggers the main function developed in Visual Basic for Applications (VBA). The first thing that happens once the model run has started is that several Vensim files are deleted if they are in place. This is done in order to ensure there are no error messages in terms of overwriting previous files. All Vensim files created over the course of the model run are stored in a specific folder. This folder (including all its Vensim file contents from previous runs) is deleted using the following function:

```
CreateObject("Scripting.FileSystemObject").DeleteFolder "C:\Users\EPA\Desktop\JingmenModel\VensimOutput"
```

The folder is then recreated by accessing the following function:

```
Sub CreateVensimFolder()
    Dim fdObj As Object
    Application.ScreenUpdating = False
    Set fdObj = CreateObject("Scripting.FileSystemObject")
    fdObj.CreateFolder (ActiveWorkbook.Path & "\VensimOutput")
    Application.ScreenUpdating = True

End Sub
```

A variable is created in order to keep up with the current time within the model run. As each simulation starts in 2015, this variable is initially set to 2015.

```
Dim CurrentTime As Integer
CurrentTime = 2015
```

Additionally, the *ModelApplication.xls* file is activated. This is the main Excel file that is accessed by the user when opening the application. All code that govern the entire model run is written in the 'Developer' VBA tab of this file. The spreadsheet of this Excel file contains all information that govern the run and stores all data that the user enters in the form presented upon opening, such as what policy to implement, under what conditions to implement the policies, what emissions levels have been so far individually, as well as those from the previous year, and until what year the model is supposed to run. Despite it being activated, it is immediately minimized and hidden from the user.

The user has entered the specific year until which the simulation will run in the application. This value is stored in 'Cell G2' of *ModelApplication.xls*. This variable is subsequently read by the script as *MaxTime*.

```
MaxTime = Worksheets("ModelCoupling").Cells(2, 7)
```

Before the actual models can start running, there is one Excel spreadsheet that must be deleted. If data is written in an Excel spreadsheet, the VBA script will overwrite cells that are not empty. However, all other cells will remain unchanged. The file *PolicySheet.xls* contains data about what policies to implement at which specific time. Data concerning the policy implementation file is written continuously as the model run progresses. This file is read by Vensim and used as a lookup for certain variables. However, if this file contains data from previous runs, this data will also be read. It is therefore essential that this sheet is completely deleted at the start of a model run, and re-created at a later stage.

```
DeleteFile (ActiveWorkbook.Path & "\PolicySheet.xls")
```

Following this, the function enters a loop that encompasses the entirety of the simulation run. The loop will continue to run until the *CurrentTime* variable equals the *MaxTime* variable, i.e. the loop will be exited once the final year of the simulation has been reached.
The loop runs as following:

```
While CurrentTime <= MaxTime
    UpdateProgress CurrentTime
    Run_Vensim (CurrentTime)
    Load_Into_LEAP (CurrentTime)
    LEAP_To_Excel (CurrentTime)
    CurrentTime = CurrentTime + 1
    Workbooks("ModelApplication.xls").Activate
    SumEmissions (CurrentTime)
    CloseWorkbooks
Wend
```

### UpdateProgress

This function merely exists to keep the user of the application up to date with the model run. The application displays a progress bar which is updated with the argument of the function (*CurrentTime*, or *CT*).

```
Sub UpdateProgress(CT)
    StartScreen.ProgressBar1.Value = CT
    Workbooks("ModelApplication.xls").Activate
End Sub
```

### Run_Vensim

Firstly, the published model is approached and the run within this published model is set up in the correct folder with the *CurrentTime* variable set at the end of the file name. Furthermore, in order to make sure that errors do not temper with a model run, if there is no model found then the model run is simply ignored.

```
Set wb = Workbooks("ModelApplication.xls")
Set ws = Worksheets("ModelCoupling")
result = vensim_command("SPECIAL>LOADMODEL|" & wb.Path & "ModelFinal.vpm")
result = vensim_command("SIMULATE>CHGFILE")
result = vensim_command("SIMULATE>DATA")
result = vensim_command("SIMULATE>RUNNAME|" & wb.Path & "\VensimOutput\ModelRun" & CT)
```

As the *PolicySheet.xls* file is deleted at the start of the model run, it needs to be re-created. Furthermore, the policies are added as column headers and the years 2010 – 2015 are inserted into the first six rows. These years are used to start-up the model. However, as there is no policy that can be inserted in these years, the policy input will be zero.

```
If CT = 2015 Then
Add_Workbook ("PolicySheet.xls")
Worksheets("Sheet1").Cells(1, 1) = "Time"
Worksheets("Sheet1").Cells(1, 2) = "Policy Lever"
Worksheets("Sheet1").Cells(1, 3) = "Coal Tax Boolean"
Worksheets("Sheet1").Cells(1, 4) = "Coal Tax Price Urban"
Worksheets("Sheet1").Cells(1, 5) = "Coal Tax Price Rural"
Worksheets("Sheet1").Cells(1, 6) = "Coal Ban Urban"
Worksheets("Sheet1").Cells(1, 7) = "Coal Ban Rural"
Worksheets("Sheet1").Cells(1, 8) = "Electricity Subsidy Urban"
Worksheets("Sheet1").Cells(1, 9) = "Electricity Subsidy Rural"
Worksheets("Sheet1").Cells(1, 10) = "Natural Gas Subsidy Urban"
Worksheets("Sheet1").Cells(1, 11) = "Natural Gas Subsidy Rural"
Worksheets("Sheet1").Cells(1, 12) = "Additional Natural Gas Connectivity Urban"
Worksheets("Sheet1").Cells(1, 13) = "Additional Natural Gas Connectivity Rural"
Worksheets("Sheet1").Cells(1, 14) = "Additional Exposure Urban"
Worksheets("Sheet1").Cells(1, 15) = "Additional Exposure Rural"
For x = 1 To 6
    Worksheets("Sheet1").Cells(x + 1, 1) = CT - 6 + x
    For j = 2 To 15
    Worksheets("Sheet1").Cells(x + 1, j) = 0
    Next
    Next
ActiveWorkbook.Save
ActiveWorkbook.Close
End If
```

Depending on the *CurrentTime* variable, it is possible that a policy will be implemented. The policy to implement is stated at 'Cell G4' in the *ModelApplication.xls* spreadsheet. The conditions that determine when the policy is to be implemented are given at 'Cell G5' and 'Cell I5' (if the conditions are related to the year), or the cells between D10:G11 (if the conditions are related to $CO_2$ or $PM_{10}$ emissions from the previous year. Note that a policy will not be implemented until the 'Current Time' variable is equal to the desired conditions of the policy implementation period: i.e. if a policy needs to be implemented in 2018, this will not occur until the Current Time variable is equal to 2018.

Each policy has a certain ID number. In case that a policy needs to be implemented, this ID number will be set in the *Policy Lever* column of the *PolicySheet.xls* spreadsheet. The *Policy Lever* will change as soon as the policy is implemented for the first time in the run. Furthermore, the size of the policy (such as the height of the tax) is given in the columns that follow. The implementation of the coal ban in urban and rural areas on the Policy Sheet is shown below.

| Time | Policy Lever | Coal Tax Price Urban | Coal Tax Price Rural | Coal Ban Urban | Coal Ban Rural |
|---|---|---|---|---|---|
| 2017.984 | 0 | 0 | 0 | 0 | 0 |
| 2017.992 | 0 | 0 | 0 | 0 | 0 |
| 2018 | 2 | 0 | 0 | 1 | 1 |
| 2018.008 | 2 | 0 | 0 | 1 | 1 |
| 2018.016 | 2 | 0 | 0 | 1 | 1 |
| 2018.023 | 2 | 0 | 0 | 1 | 1 |

In the Vensim model, every year consists of 128 timesteps. As a policy in the model can currently only be implemented over the course of a full year, each year in the entry (that follows the first five years of model warm-up) to display for the policy lookup. The reason why this is done is further explained in **Appendix E5** (model verification). The file will only write the model results up until the end of the *CurrentTime*. For example, when running the model over *CurrentTime* = 2018, all years following 2018 are not yet entered in the Policy Sheet. As Vensim variables perform their lookup, they will continue using the variables that are entered last. This means that all years following 2018 in the *CurrentTime* run of 2018 will all have the same policy implemented as the policy that is present at the end of the year. Once the policies are implemented, in the Excel sheet (so that the Vensi variables will be able to use them as lookup variables, the Vensim model is ready to run.

```
result = vensim_command("MENU>RUN")
```

Following the run, the variables for output will be exported into a unique Excel Sheet, called *ByFuelResultXXXX.xls*, in which *XXXX* is the *CurrentTime*. This is done by taking the model run results and accessing specific variables for each individual timestep. These variables are accessed from within the exported ModelRun*XXXX.vdf* file. The results for each timestep are placed underneath one another.

In exporting the file, the user is able to specify how many variables should be exported and therefore also what the time interval between data points is. The data as well as the simulation time of the exported data are saved in single arrays, for example:

*vensim_get_data("MainRun.vdf", "Electricity used for household use urban", "time", rval1(1), tval1(1), 2700)*

Is used to export the data from "Electricity used for household use urban", in which rval(1) represents the data point, tval(1) represents the time, and 2700 represents the maximum number of values that are exported for each (i.e. the maximum size of the array). After the values are successfully exported, they need to be converted in order to be imported accordingly.

| Year | Electricity Demand U | Electricity Demand R | Gas Demand Urb | Gas Demand Ru | Biomass Demand Ur | Biomass Demand Ru | Coal Demand Rural (MJ) | Coal Demand Rural (MJ) |
|---|---|---|---|---|---|---|---|---|
| 2017.977 | 287168992 | 335361824 | 3103159296 | 404166304 | 629710.0625 | 232039392 | 707452736 | 732737088 |
| 2017.984 | 287272544 | 335697216 | 3105026816 | 404390368 | 629835.0625 | 232204480 | 707477632 | 733037312 |
| 2017.992 | 287376512 | 336031776 | 3106893568 | 404614816 | 629961.5625 | 232369568 | 707503360 | 733338560 |
| 2018 | 347358720 | 589790400 | 3756280832 | 709857088 | 761326.9375 | 407733184 | 0 | 0 |
| 2018.008 | 347466528 | 550058624 | 3758155776 | 736031616 | 761645.25 | 422312576 | 0 | 0 |

In order to adjust this spreadsheet to a spreadsheet that is readable for the LEAP model, the average value for each year must be taken. The average values are then placed into a different spreadsheet, called *VenResultsXXXX.xls*. These averages are taken using the following code:

```
Set wbExternal1 = Workbooks.Open(Application.ThisWorkbook.Path & "\Results\ByFuelResults" & CT & ".xls")
Set wbExternal3 = Workbooks("VenResults" & CT & ".xls")
For x = 2010 To 2030
    wbExternal3.Worksheets("Sheet1").Cells(x - 2008, 1).Value = x
    For i = 2 To 9
    Set FuelResults = wbExternal1.Worksheets("Sheet1").Range(Cells((2 + (x - 2010) * 128), i), Cells(129 + ((x - 2010) * 128), i))
    wbExternal3.Worksheets("Sheet1").Cells(x - 2008, i).Value = Application.WorksheetFunction.Average(FuelResults)
    Next
Next
```

The code takes a range of values, *FuelResults* which are values in a range of exactly 128 values, starting from one year until the end of the year and stores the average in the 'next' row. This creates a spreadsheet of the average energy demand of an entire year, for each individual fuel for rural and urban areas. Finalizing this spreadsheet marks the end of the Vensim side of the loop.

### Load_Into_LEAP

The converted averages are now ready to be exported into LEAP. However, the LEAP API in VBA runs differently than that of Vensim does. Instead of running the application directly using code, the LEAP API allows the model to be opened and adjusted using VBA indirectly. Firstly, the correct model needs to be opened. In order to place the variables into the right 'branches', the Analysis view must be open:

```
Set l = CreateObject("LEAP.LEAPApplication")
l.ActiveArea = "JingmenModel"
l.ActiveView = "Analysis"
```

In order to import the variables accordingly, firstly the correct LEAP model needs to be open and in the right view (Analysis view), which allows for edits. Then, within VBA a specific variable can be changed by specifying the exact 'Branch' (i.e. pathname) to the variable that is to be adjusted. The expression of the variable is then changed by making it equal to a string that could also be entered within LEAP directly. By directing the variable to the exact columns where the results from the Vensim run (after conversion into the mean year) had just exported its own results into, the right fuel demand quantity for the right fuel is specified. Each individual fuel lookup is then placed in their corresponding 'Activity Level' key assumption branch as following:

*l.Branches("Key Assumptions\InputParameters\ResidentialSector\EnergyUse\Electricity\ApplianceElectricity\UrbanArea\HouseholdUse").Variable("Activity Level").Expression = "ReadFromExcel(" & Application.ThisWorkbook.Path & "\Results\VenResults" & CT & ".xls, a2:a22, b2:b22)"*

Once this function is performed for each of the eight branches (four fuels, for both rural and urban areas), the LEAP model is ready to run. However, before a full LEAP run commences, the model links need to be updated (in order to prevent error messages presented at later stages in the model run). This is done by sending keystrokes to the LEAP application while it is active.

```
Public Sub Run_LEAP()
Appl = "LEAP: JingmenModel"
AppActivate Appl
SendKeysForResults
sendKey "^S", 10
SendKeys "% n"
End Sub
Private Sub SendKeysForResults()
    sendKey "%", 50
    sendKey "A", 50
    sendKey "f", 50
    sendKey "~", 50
    sendKey "~", 50

    sendKey "%", 50
    sendKey "A", 50
    sendKey "f", 50
    sendKey "f", 50
    sendKey "~", 50
    sendKey "~", 50
End Sub
Public Sub sendKey(ByRef key As String, ByRef waitMS As Integer)
    On Error GoTo errHandeler
    Dim endTime As Single
    waitMS = Abs(waitMS)
    endTime = (Timer + (waitMS / 1000))
    Do While Timer <= endTime
        DoEvents
    Loop
    SendKeys key
    Exit Sub
errHandeler:
End Sub
```

The LEAP model generally runs directly when the 'Results' view is opened. However, simply opening the 'Results' view will trigger errors and/or message boxes. As some input results are changed, the user needs to agree to such changes. In order to get around these messages (as they prevent a smooth model run), a forced recalculation of the model, as well as a force refresh with all Excel links are performed. This can be done manually by accessing the "Area" menu in the toolbar and then clicking "Force Refresh of Excel Links" and "Force Whole Area to Recalculate", as is shown in **Figure 17**. This manual approach is circumvented by sending keys to the actual LEAP application. By sending the keys: *"alt, a, f, Enter, Enter"*, all links with Excel are refreshed. Similarly, *"alt, a, f, f, Enter, Enter"* forces the whole area to recalculate. The LEAP model has now successfully run, and the Results view is subsequently opened automatically. In order to ensure that each key is processed correctly, the application is given 50 milliseconds to process each keystroke before advancing to the next one. Immediately after this is performed, the LEAP screen is minimized in order to show as little background calculations as possible to the user of the application. If this is not done, the user will see the following screen (the one displayed below shows a coal ban implemented in 2018 and 2019 alone).

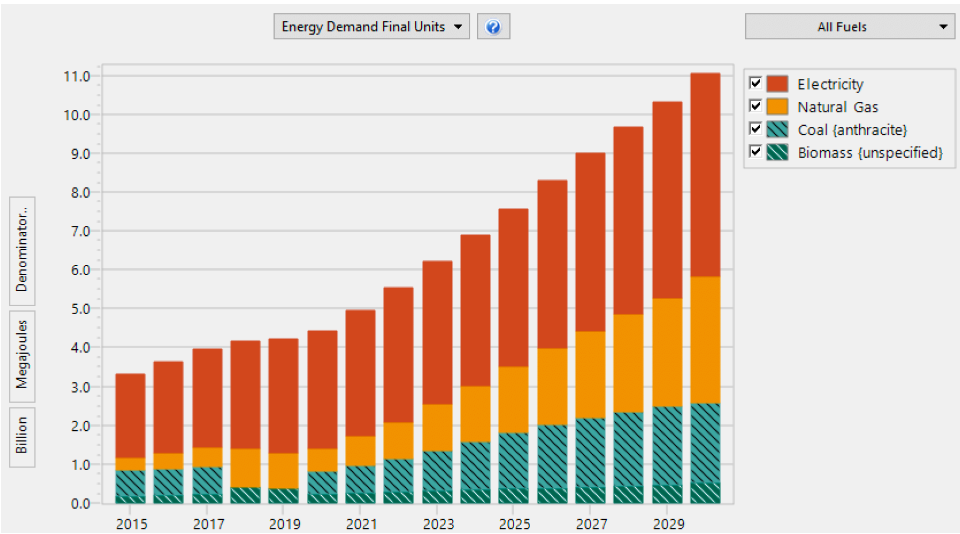



**Figure E5:** An overview of the results of a coal ban implemented in 2018 and 2019.

### LEAP_To_Excel

As soon as these results have been calculated, all necessary results are exported. This is done by exporting specific branches in the model. However, as the LEAP model also consists of other industries and sectors in Jingmen, going through all branches of the model to select the correct one takes an extremely long time. Therefore, the specific ID variables of the desired emissions and energy consumption values are selected specifcally and placed manually into a list. VBA will subsequently cycle through this list and place each output variable in another newly created Excel file: *LEAPResultsXXXX.xls*. The results concerning Energy Demand are placed in *Sheet1*, whereas results concerning emissions are in *Sheet2*.

| Year | Branch | Value (MJ) |
|---|---|---|
| 2015 | Demand | 1.84E+11 |
| 2015 | Demand\ResidentialUse | 9.1E+09 |
| 2015 | Demand\ResidentialUse\UrbanArea | 5.78E+09 |
| 2015 | Demand\ResidentialUse\UrbanArea\Electricity | 2.53E+09 |
| 2015 | Demand\ResidentialUse\UrbanArea\Electricity\Lighting | 4.39E+08 |
| 2015 | Demand\ResidentialUse\UrbanArea\Electricity\HouseholdAppliances | 2.09E+09 |
| 2015 | Demand\ResidentialUse\UrbanArea\NaturalGas | 2.54E+09 |
| 2015 | Demand\ResidentialUse\UrbanArea\Coal | 7.1E+08 |
| 2015 | Demand\ResidentialUse\UrbanArea\Biomass | 594215 |

| Year | Branch | Value (Metric Tonne) |
|---|---|---|
| 2015 | Demand\ResidentialUse\UrbanArea\NaturalGas\NaturalGas\Carbon Monoxide | 127.1034547 |
| 2015 | Demand\ResidentialUse\UrbanArea\NaturalGas\NaturalGas\Methane | 12.71034547 |
| 2015 | Demand\ResidentialUse\UrbanArea\NaturalGas\NaturalGas\Non Methane Volatile Organic Compounds | 12.71034547 |
| 2015 | Demand\ResidentialUse\UrbanArea\NaturalGas\NaturalGas\Nitrogen Oxides | 6.196630348 |
| 2015 | Demand\ResidentialUse\UrbanArea\NaturalGas\NaturalGas\Nitrous Oxide | 0.254206909 |
| 2015 | Demand\ResidentialUse\UrbanArea\NaturalGas\NaturalGas\Sulfur Dioxide | 7.307025676 |

### SumEmissions

Finally, the most important results are also exported into the *ModelApplication.xls* file. These are results concerning the $CO_2$ and $PM_{10}$ emissions. This is necessary in case the user has the desire to implement a policy depending on emission values from the previous year. The values can then be used to make a comparison to the observed emissions and the maximum/minimum emission for policy implementation/deimplementation.

Once this is done, the *CurrentTime* variable increases by 1 and the entire loop (approaching the Vensim model) is repeated until the final year of the implementation (*MaxYear*) is reached.

## Appendix E.5 – Verification of the co-simulation model structure

*Verification of time discrepancies*

Although System Dynamics is a continuous modelling technique, it still uses discretized 'time steps' in performing its calculations. On the other hand, LEAP reads and writes data only in a discretized yearly fashion- a time step far too large in System Dynamics. Issues arising time-steps in a continuous and largely discrete model became more apparent when verifying the system. There were two ways in which such time-related issues were observed. Firstly, in terms of communicating results from Vensim towards LEAP, and secondly when implementing LEAP policies into Vensim.

*Time discrepancies in policy implementation*

Policies initially seemed to be implemented a year later than they should have been implemented. However, it turns out that an interpolation occurs within the first year of policy implementation (for an unexplained reason). **Figure E6** below shows the 'Policy Sheet' used throughout the simulation (edited for clarity). This sheet is responsible for noting down which policy is to be implemented at which time, and by how much (for example what the height of a coal tax should be). The 'Policy Lever' column indicates which policy is to be implemented. The columns that follow (in this figure, the Coal Ban Urban and Coal Ban Rural columns) show how Vensim has observed and implemented the policy as a result of the change in the Policy Lever. The figure shows that a complete ban of coal (indicated by the implementation of the 'Policy 2' Lever) is implemented in 2020. According to the feedback provided by Vensim however, the coal ban has not been fully implemented until 2021.

When further investigating this phenomenon by considering the per 'time-step' implementation of the coal ban, it becomes apparent that the Vensim Lookup Function will automatically implement the policy over the course of a year. Therefore, when considering a complete ban on coal starting in 2020, after half a year the 'coal ban lever' equals 0.5, meaning that the ban is only 'half' implemented.

| Time | Policy Lever | Coal Ban Urban | Coal Ban Rural |
|---|---|---|---|
| 2010 | 0 | 0 | 0 |
| 2011 | 0 | 0 | 0 |
| 2012 | 0 | 0 | 0 |
| 2013 | 0 | 0 | 0 |
| 2014 | 0 | 0 | 0 |
| 2015 | 0 | 0 | 0 |
| 2016 | 0 | 0 | 0 |
| 2017 | 0 | 0 | 0 |
| 2018 | 0 | 0 | 0 |
| 2019 | 0 | 0 | 0 |
| 2020 | 2 | 0 | 0 |
| 2021 | 2 | 1 | 1 |
| 2022 | 2 | 1 | 1 |
| 2023 | 2 | 1 | 1 |
| 2024 | 2 | 1 | 1 |
| 2025 | 2 | 1 | 1 |
| 2026 | 2 | 1 | 1 |
| 2027 | 2 | 1 | 1 |
| 2028 | 2 | 1 | 1 |
| 2029 | 2 | 1 | 1 |

| Time | Coal Ban Urban |
|---|---|
| 2020 | 0 |
| 2020.031 | 0.03125 |
| 2020.063 | 0.0625 |
| 2020.094 | 0.09375 |
| 2020.125 | 0.125 |
| 2020.156 | 0.15625 |
| 2020.188 | 0.1875 |
| 2020.219 | 0.21875 |
| 2020.25 | 0.25 |
| 2020.281 | 0.28125 |
| 2020.313 | 0.3125 |
| 2020.344 | 0.34375 |
| 2020.375 | 0.375 |
| 2020.406 | 0.40625 |
| 2020.438 | 0.4375 |
| 2020.469 | 0.46875 |
| 2020.5 | 0.5 |
| 2020.531 | 0.53125 |
| 2020.563 | 0.5625 |
| 2020.594 | 0.59375 |
| 2020.625 | 0.625 |
| 2020.656 | 0.65625 |
| 2020.688 | 0.6875 |
| 2020.719 | 0.71875 |
| 2020.75 | 0.75 |
| 2020.781 | 0.78125 |
| 2020.813 | 0.8125 |
| 2020.844 | 0.84375 |
| 2020.875 | 0.875 |
| 2020.906 | 0.90625 |
| 2020.938 | 0.9375 |
| 2020.969 | 0.96875 |
| 2021 | 1 |

**Figure E6:** The implementation of the coal ban as observed in the Policy Sheet and as interpreted by Vensim

This has even further implications when implementing a policy such as the incremental tax on coal consumption. A policy that increments until year *y-1* and a policy that increments until year *y* should have identical results up until year *y-1*. However, the way how Vensim handles lookups in Excel creates problems when working with such increments. **Figure E7** below shows the different increments of the coal tax implementation. The price increases in yearly increments of 0.02 and stops incrementing at start of the year represented by the label of the line. The lines should therefore follow each other up in a coherent fashion. The figure shows three different types of behaviour. Line 1 (Grey) shows an implementation in 2018 (single increment of 0.02) desired exactly at timestep as soon as 2018 starts. When observing the following increment, 2019 (Green, two increments of 0.02), the first increment takes a whole year to be implemented (from 2017 to 2018, linearly). The following increment shows a direct implementation at the start of 2019. The implementations of the other two increments that follow (one that stops in 2020 and one that stops in 2021), exhibit linear interpolation from year 2017 until their given year.

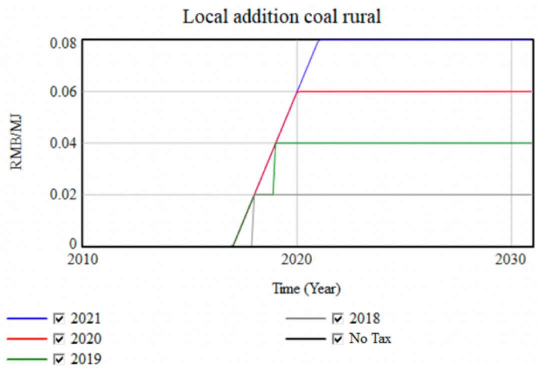



**Figure E7:** An example of Vensim's inconsequential method of data reading

This slight difference of stepwise incrementation in comparison for a policy to be implemented over the course of a year, has sincere implications behaviour. In order to fix this issue, the Policy Sheet is adjusted specify the implementation of a policy at each single time-step rather than implementing the lookup for each year.

### *Verification for policy implementation*

The implementation of a policy at a certain year must have no effects on previous years. The implementation of a policy at year *y*, must have no effect on any simulation run while the year is before year *y*. **Figure E8** below illustrates the effects of a tax on the consumption of coal, increasing with yearly increments of 0.02 RMB/MJ in the years labelled by the line in the legend.

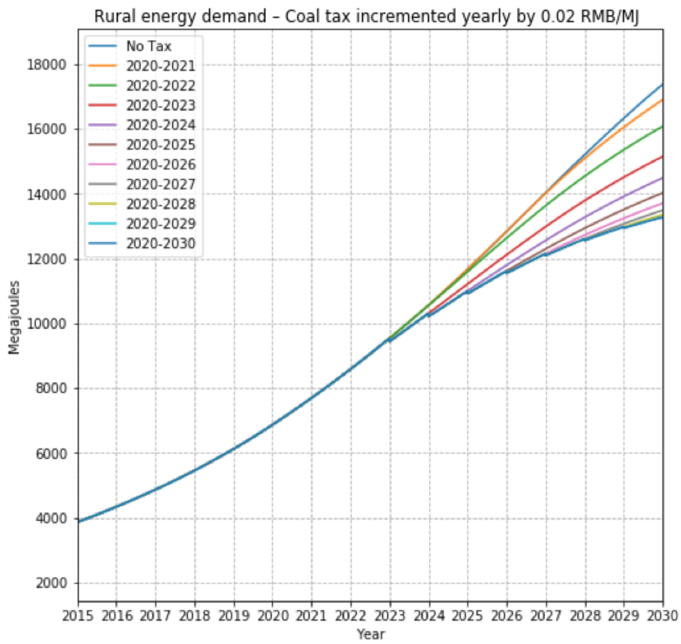



**Figure E8:** Rural energy demand with a coal tax implemented in 0.02 RMB/MJ increments from 2020 until the year indicated by the legend. The image shows coherent validity between all policies.

As the increments keep increasing on a yearly basis, the lines start to diverge. Each experiment that keeps increasing its increment up to a certain year, must show exactly the same behaviour as all other lines that have also increased their increment up to that same year. Divergence can only take place once a simulation run stops its increments while other experiments keep incrementing their coal tax on a yearly basis. This is exactly the case as is shown in **Figure E8**, solidifying that a clean interaction between the two systems, as well as the policy implementation, is verified.

# Appendix F – Model Assumptions

*Household Related Assumptions*

- The number of households for each region concerns a lookup function which considers the urbanization rate that is estimated in collaboration with the Jingmen planning bureau;
- Households have a fixed minimum electricity demand for the use of appliances such as washing machines, refrigerators and lighting. This demand is determined by the LEAP model and are therefore pre-determined. The cost of this electricity is part of the overall money spent on energy;
- Urban and rural households are considered to separate non-connected areas. This means that people in one area cannot obtain fuel that could be relatively cheaper in another;
- Households have a fixed size equal to the average number of citizens per household living in the area;
- Household per capita GDP is a fixed pre-determined lookup determined by expected GDP growth in each area.

*Fuel Related Assumptions*

- As fuels are converted to effective megajoules before usage in the model, it is assumed that each fuel source requires the same quantity (in megajoules) for consumption. This is because there is a direct link between joules and calories (which is the amount of energy needed to raise the temperature of 1 gram of water through 1$^{o}$C). One megajoule of coal is therefore just as effective as one megajoule of electricity;
- The fuel prices are fixed as following:

| | |
|---|---|
| Price of Biomass: | 0.000 RMB/MJ |
| Price of Coal: | 0.020 RMB/MJ |
| Price of Gas: | 0.037 RMB/MJ |
| Price of Electricity: | 0.147 RMB/MJ |

- As the model is demand-driven, fuel can never run out. Demand can always be satisfied. This also means that there are no power outages in the model;
- In a no-policy scenario, citizens have access to all four types of fuel;
- Gas, sometimes referred to as Natural Gas encompasses all gas-related consumption, including LNG, and propane fuel tanks.
- People consume electricity from the CCPG – they will not generate their own electricity;
- The number of stores selling coal are solely dependent on the expected amount of revenue the sales generate;

*Emission Related Assumptions*

- Emissions are calculated from fuel consumption per individual area;
- Only household emissions are taken into consideration;
- Emissions cannot move between areas and all emissions from outside Jingmen are ignored.
- Biomass generates no $CO_2$ emissions. This is because the $CO_2$ emissions from biomass is contentious. China generally regards biomass consumption as a CO2-neutral fuel as the source replaces the amount of $CO_2$ that comes from burning it many-fold throughout its lifespan.

Other Assumptions

- There is no inflation – this relates to the assumption that prices will not change;
- The practical function of the policies described work as intended: a ban on coal will therefore mean that coal is completely non-accessible, people will not upset the law;
- All policies take effect starting on the 1$^{st}$ of January in the given year that they are implemented.

- Households do not adjust their individual consumption as a result of factors other than Price, Convenience and Knowledge and Willingness. Thus, household consumption is independent of emissions;
- Urbanisation phenomena are and governed by the LEAP model, this means that the urbanisation practices are independent of fuel consumption;
- Sunk costs are not included in the model not be considered. The assumption is made that people will be able to switch between two fuel types without any additional costs, for example the cost of an electric heater;

# Appendix G – Model Results

This appendix provides all obtained results from the policies implemented. As stated, all policies are implemented in 2020 until the end of the model run in 2030. The results from the simulation were analysed in Python.

## Appendix G.1 – Policy: Coal Ban

The results in the following charts are obtained from a coal ban policy implemented in 2020. The charts on the left give the total yearly energy demand for each of the areas (urban at the top, rural at the bottom). The graphs in the middle are the CP in graphs. This is the rate of increase of energy demand as a result of increased utility in convenience and price. The KW out graphs on the right-hand side are the rate of decrease in energy demand as a result of increased and knowledge and willingness to reduce energy emissions.

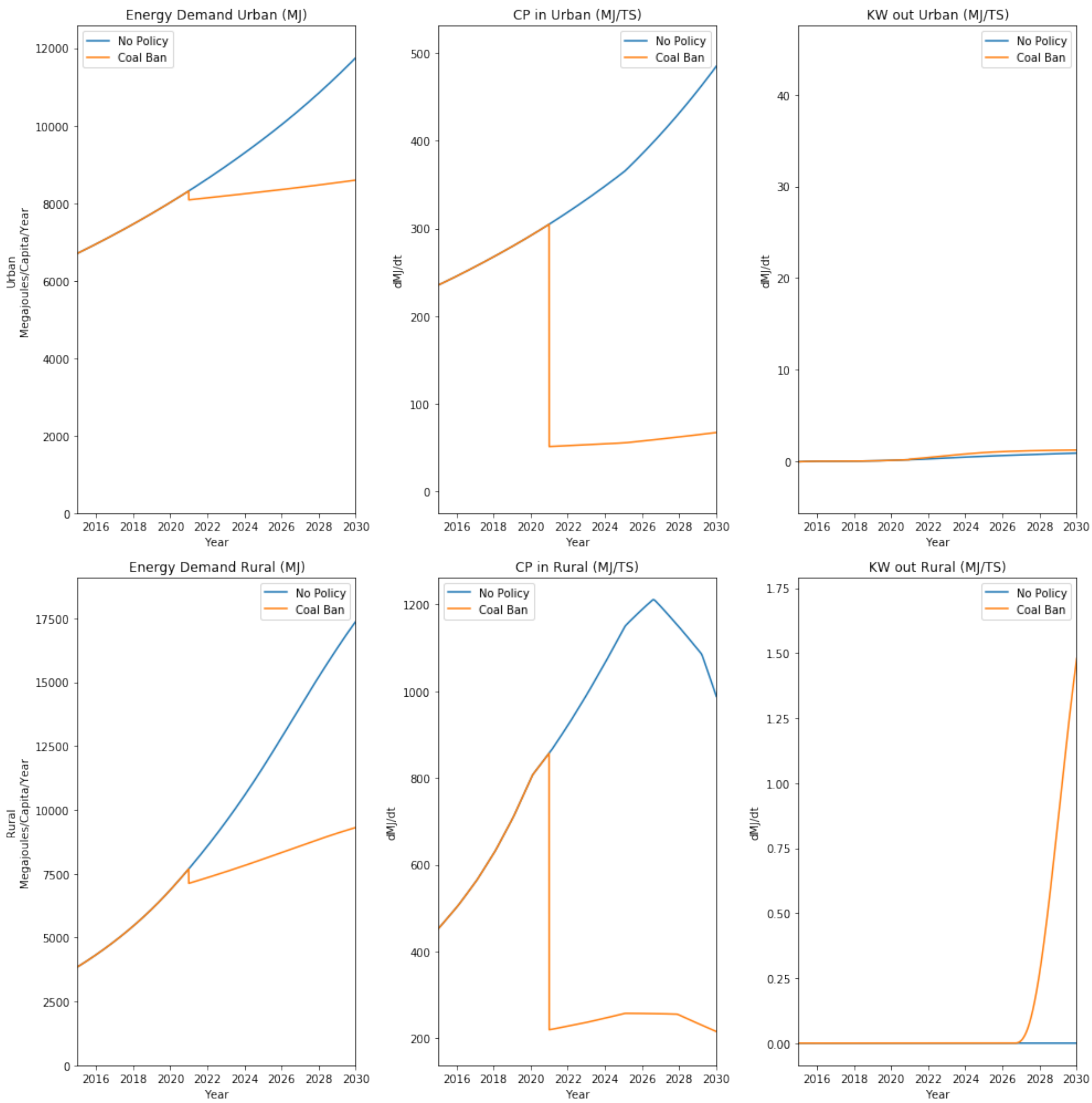



**Figure G1:** The energy demand per household as well as the rate of change of energy demand for the urban and rural areas as a result of the coal ban.

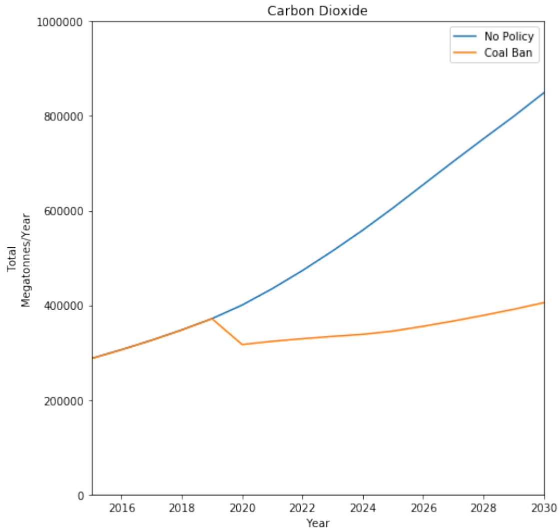



**Figure G2:** The total carbon dioxide and $PM_{10}$ particulates emissions in the coal ban scenario in Jingmen.

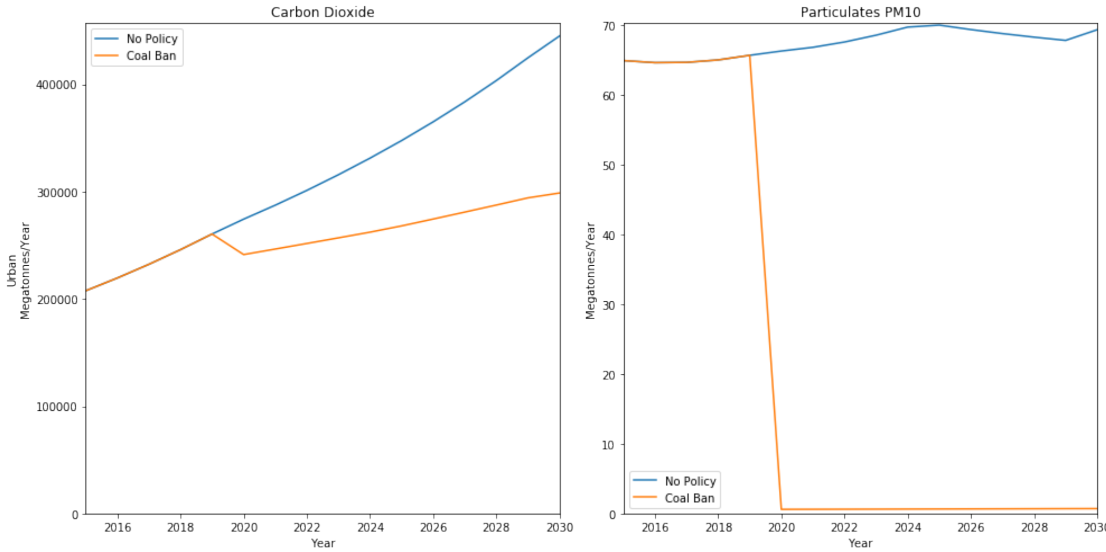



**Figure G3:** The total carbon dioxide and $PM_{10}$ particulates emissions in the coal ban scenario in the urban area.

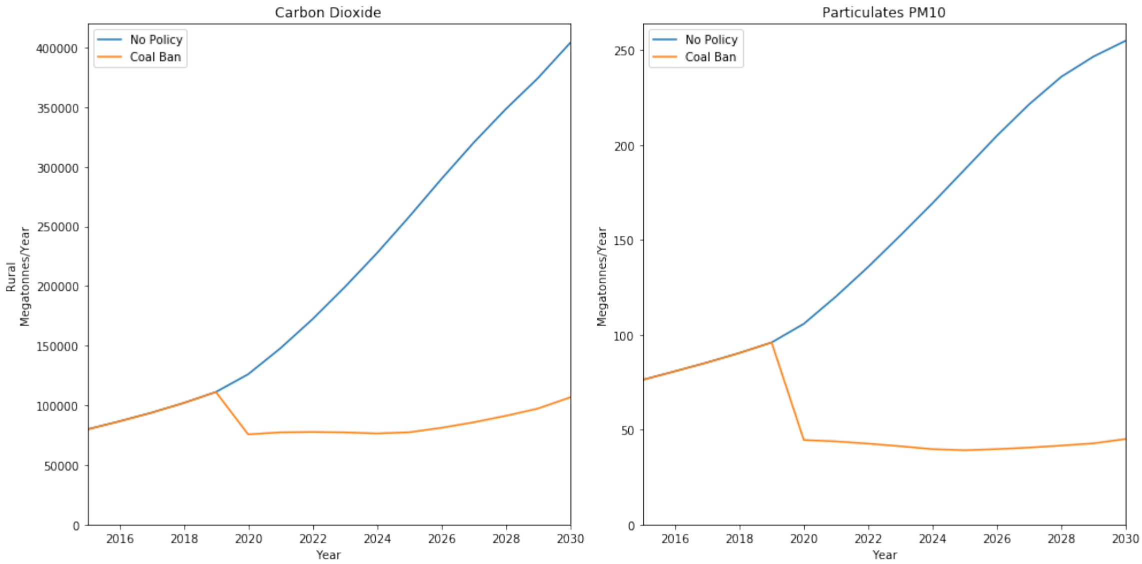



**Figure G4:** The total carbon dioxide and $PM_{10}$ particulates emissions in the coal ban scenario in the rural area.

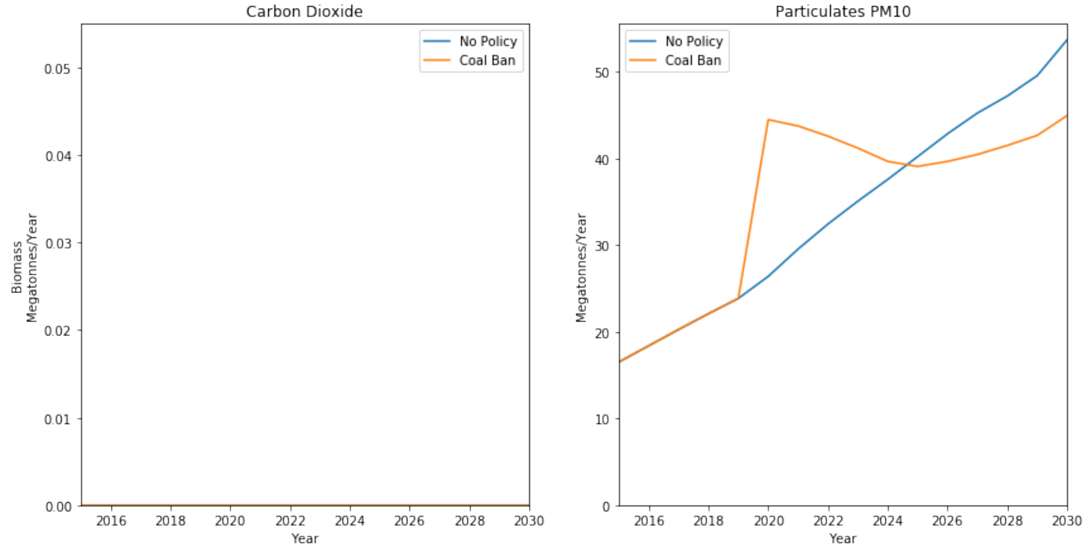



**Figure G5:** The total carbon dioxide and $PM_{10}$ emissions coming from biomass consumption in the coal ban scenario.

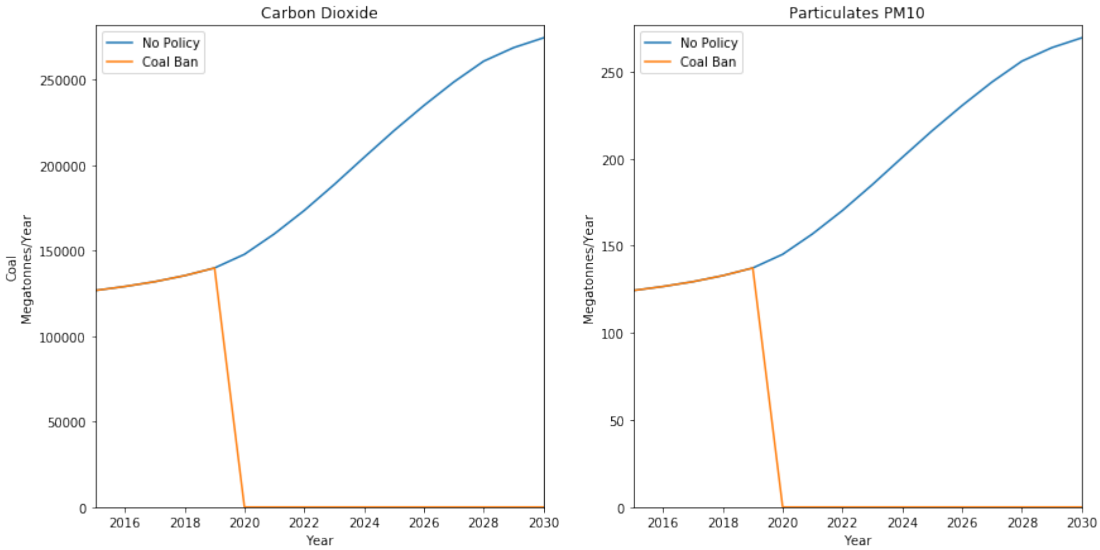



**Figure G6:** The total carbon dioxide and $PM_{10}$ emissions coming from coal consumption in the coal ban scenario.

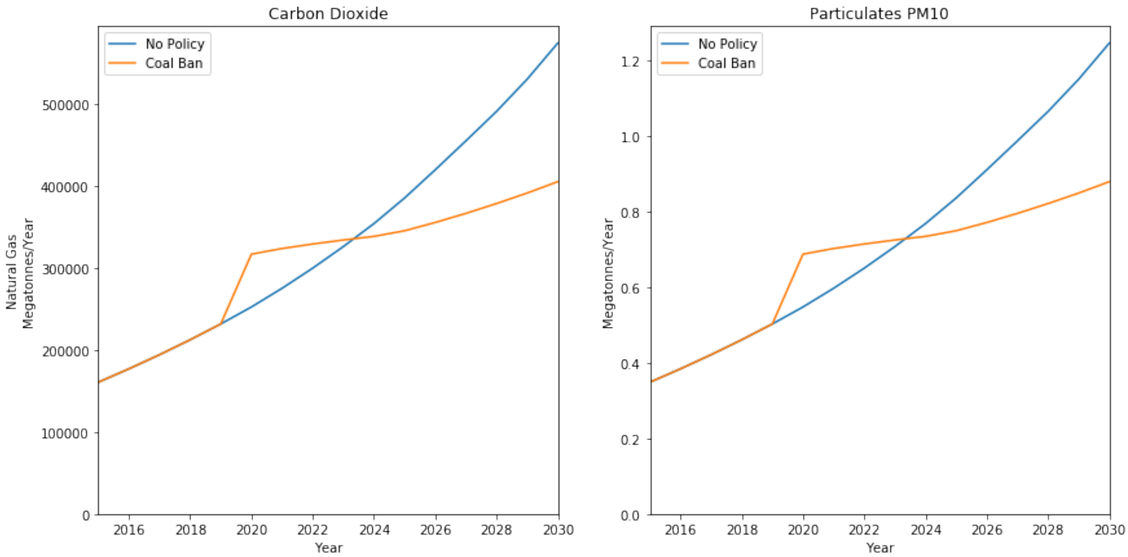



**Figure G7:** The total carbon dioxide and $PM_{10}$ emissions coming from gas consumption in the coal ban scenario.

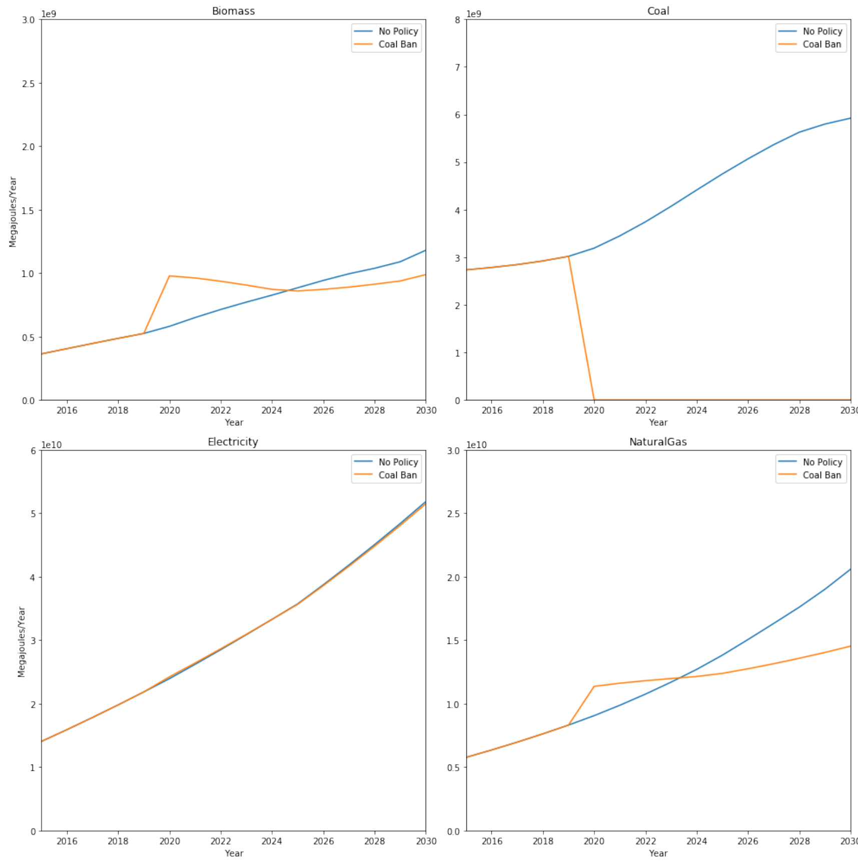



**Figure G8:** The total energy consumption of each individual energy fuel in Jingmen during the coal ban scenario.

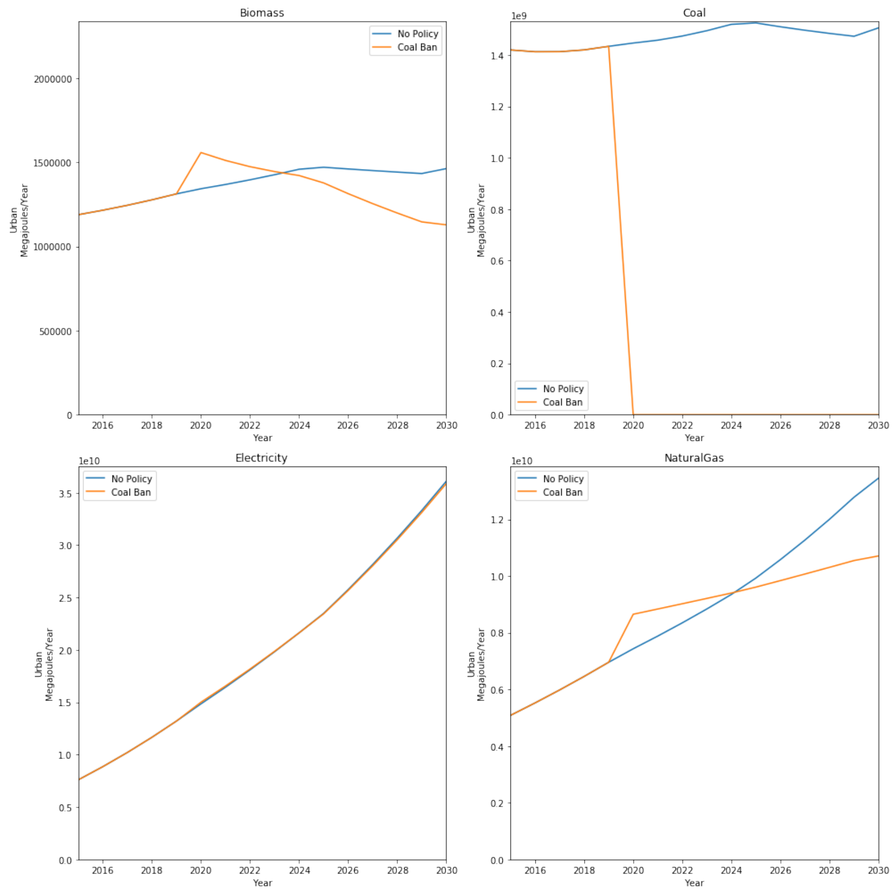



**Figure G9:** The total energy consumption in Jingmen's urban area during the coal ban scenario.

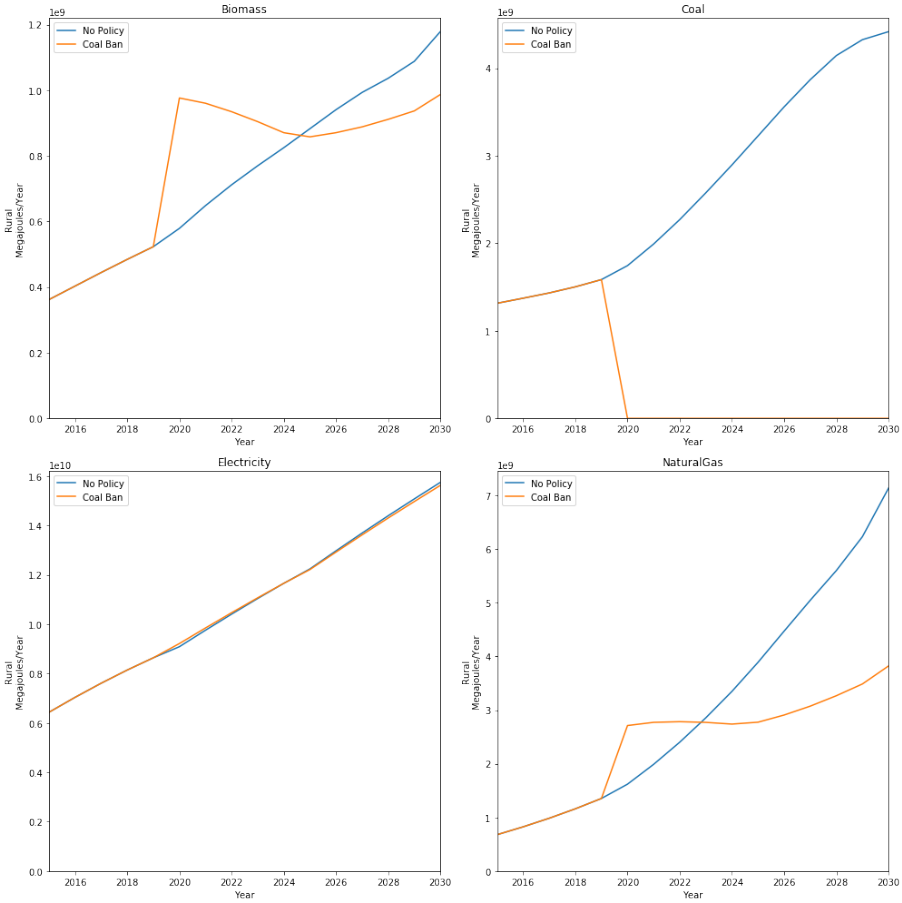


**Figure G10:** The total energy consumption in Jingmen's rural area during the coal ban scenario.

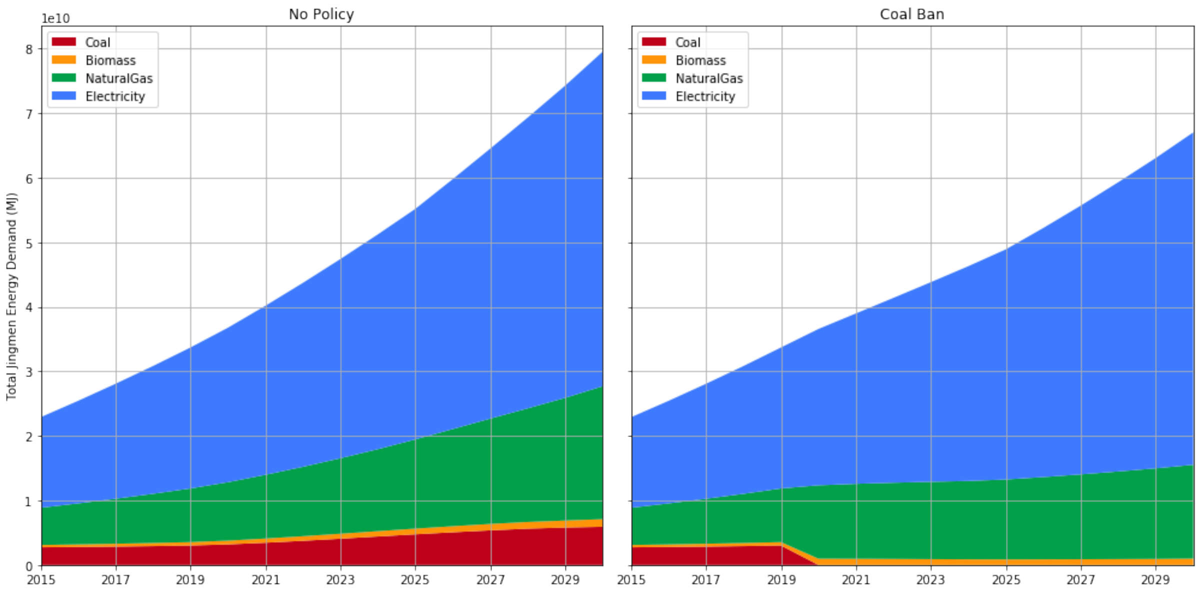


**Figure G11:** The total energy consumption in Jingmen during the coal ban scenario visualized in a stacked area chart.

## Appendix G.2 – Policy: Incremental Coal Tax

The results in the following charts are obtained from the incremental coal tax policy implemented in 2020. The charts on the left give the total yearly energy demand for each of the areas (urban at the top, rural at the bottom). The graphs in the middle are the CP in graphs. This is the rate of increase of energy demand as a result of increased utility in convenience and price. The KW out graphs on the right-hand side are the rate of decrease in energy demand as a result of increased and knowledge and willingness to reduce energy emissions.

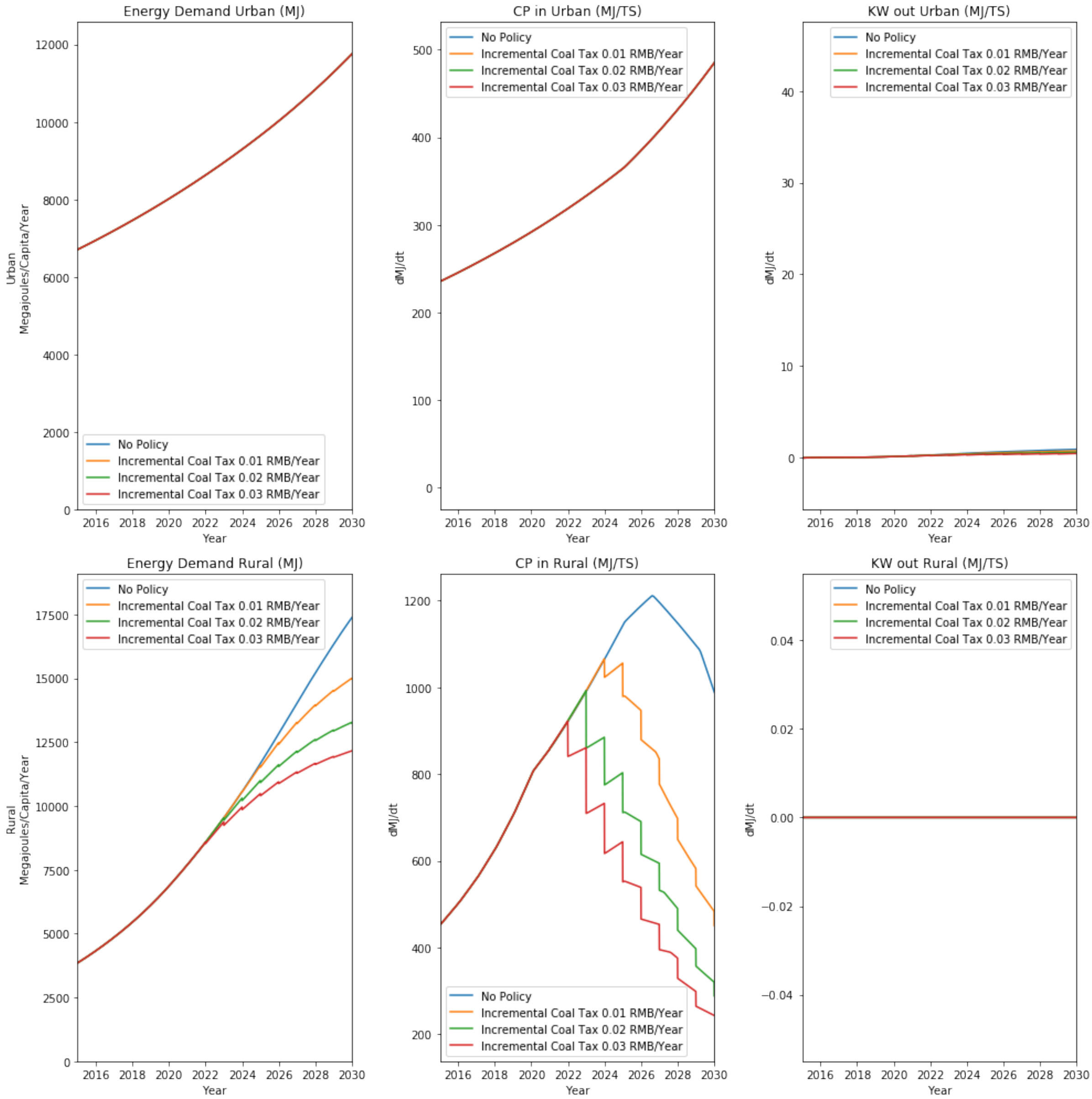



**Figure G12:** The energy demand per household as well as the rate of change of energy demand for the urban and rural areas as a result of the incremental coal tax.

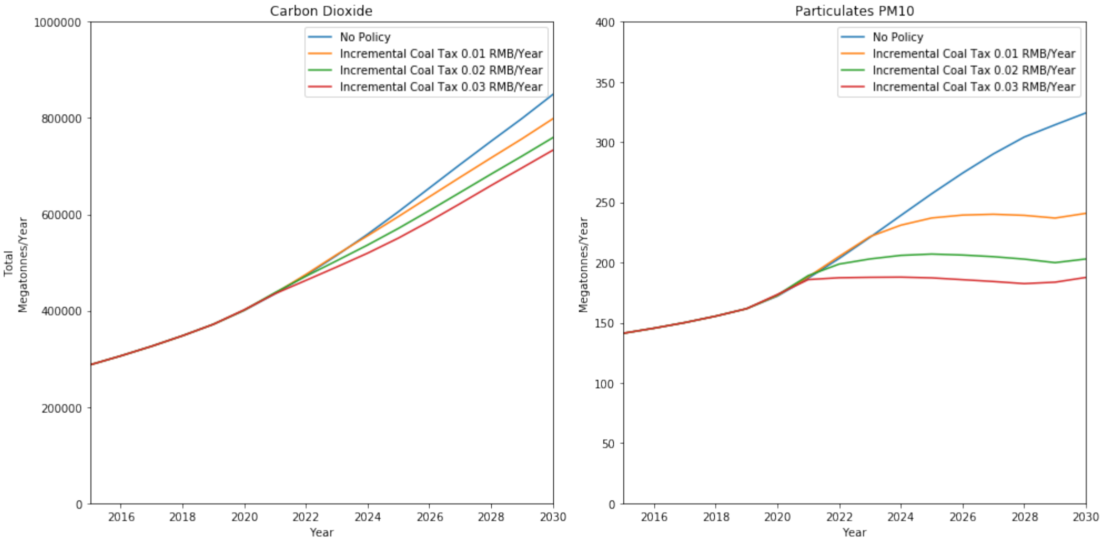



**Figure G13:** The total carbon dioxide and $PM_{10}$ particulates emissions in the incremental coal tax scenario in Jingmen.

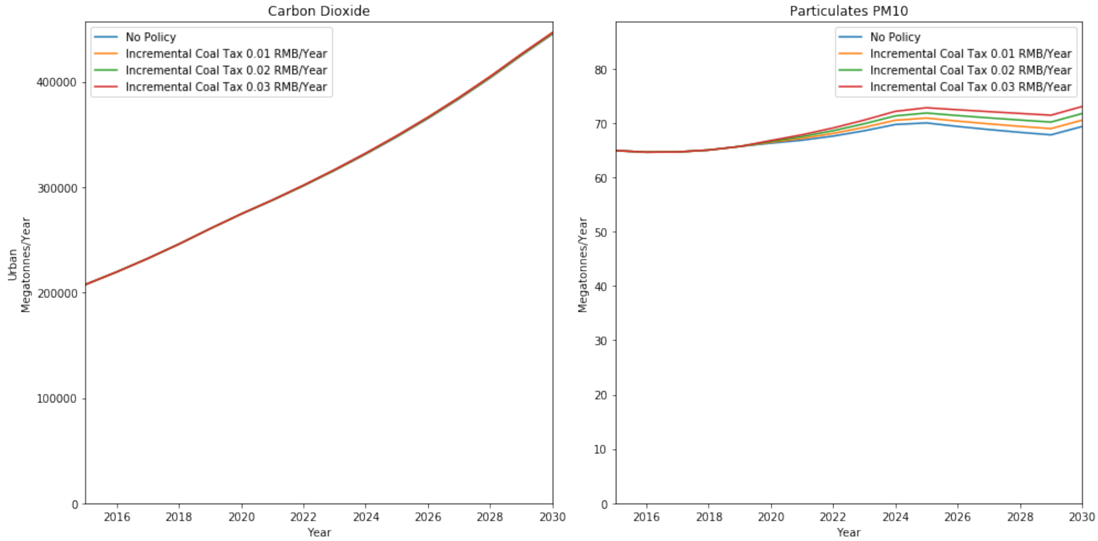



**Figure G14:** The total carbon dioxide and $PM_{10}$ particulates emissions in the incremental coal tax scenario in the urban area.

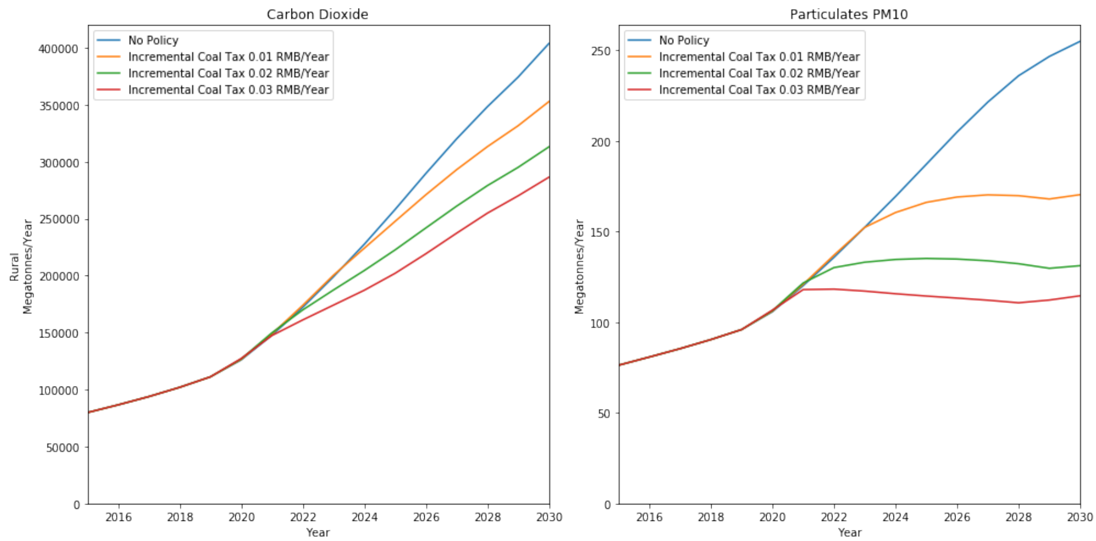



**Figure G15:** The total carbon dioxide and $PM_{10}$ particulates emissions in the incremental coal tax scenario in the rural area.

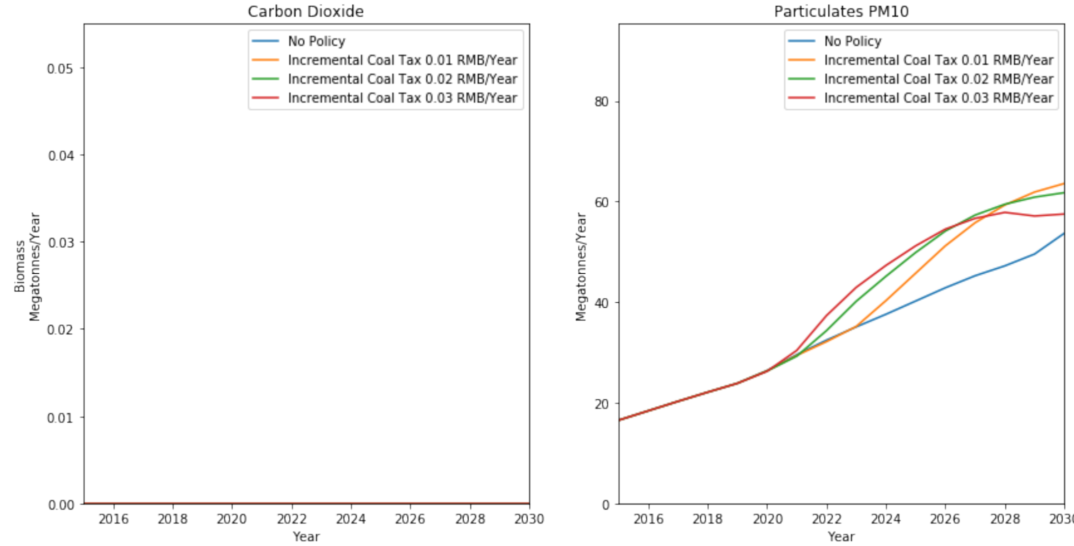



**Figure G16:** The total carbon dioxide and $PM_{10}$ particulates emissions coming from biomass consumption in the incremental coal tax scenario.

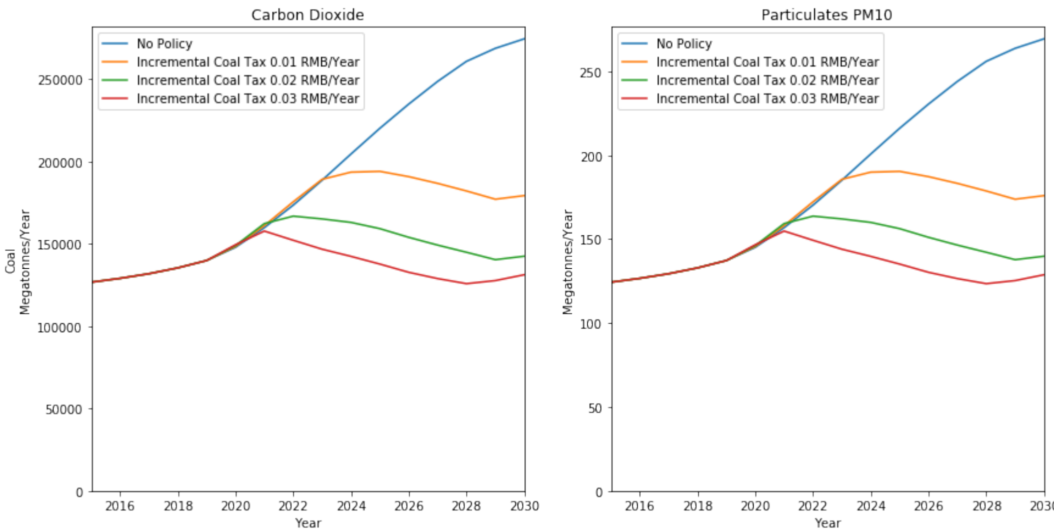



**Figure G17:** The total carbon dioxide and $PM_{10}$ particulates emissions coming from coal consumption in the incremental coal tax scenario.

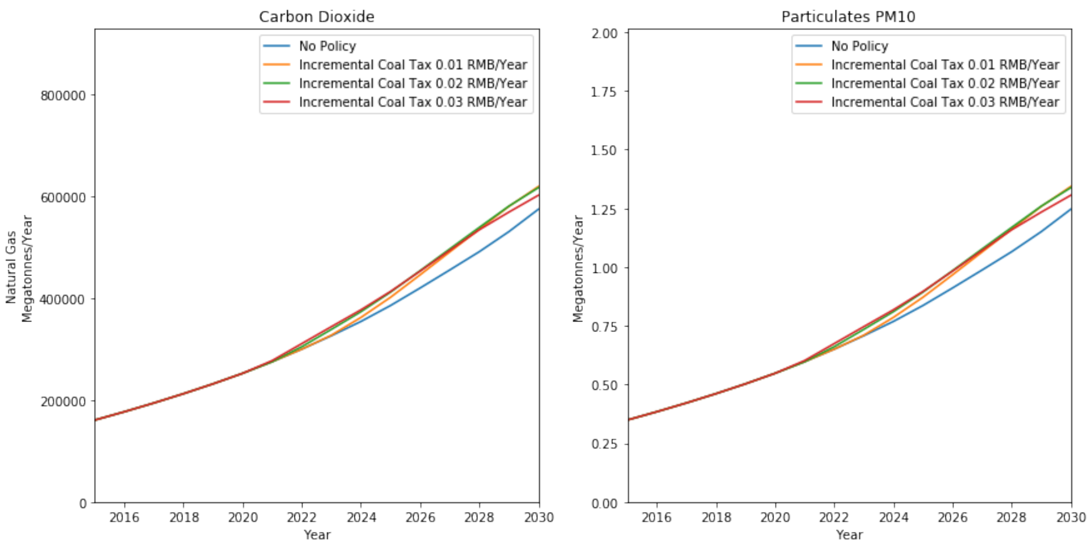


**Figure G18:** The total carbon dioxide and $PM_{10}$ particulates emissions coming from gas consumption in the incremental coal tax scenario.

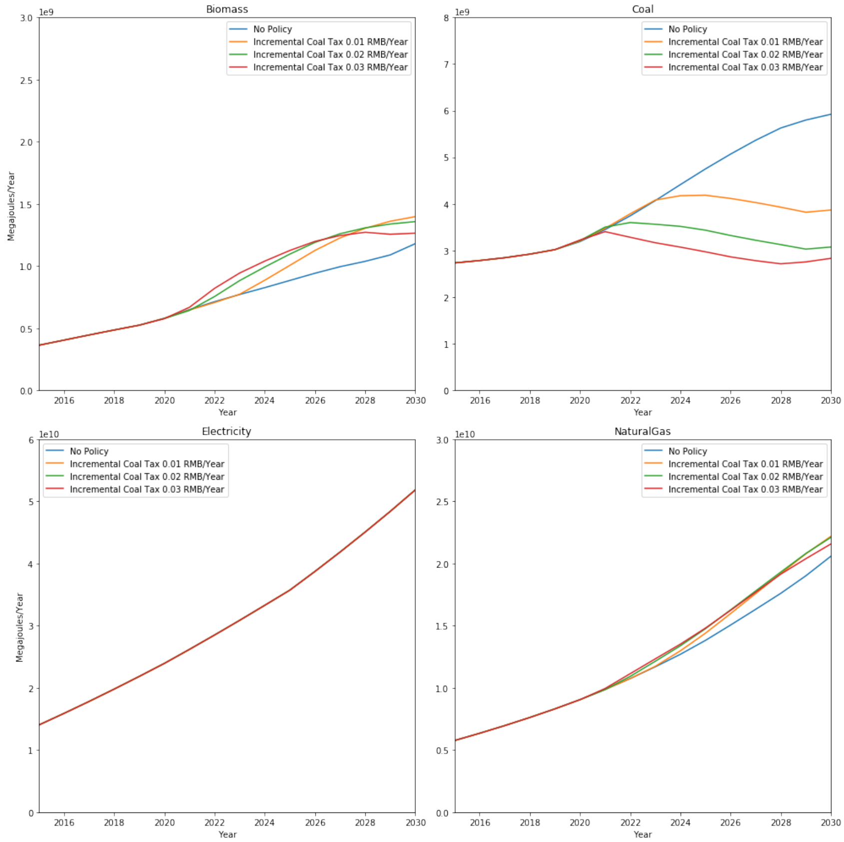



**Figure G19:** The energy consumption of each individual energy fuel in Jingmen during the incremental coal tax scenario.

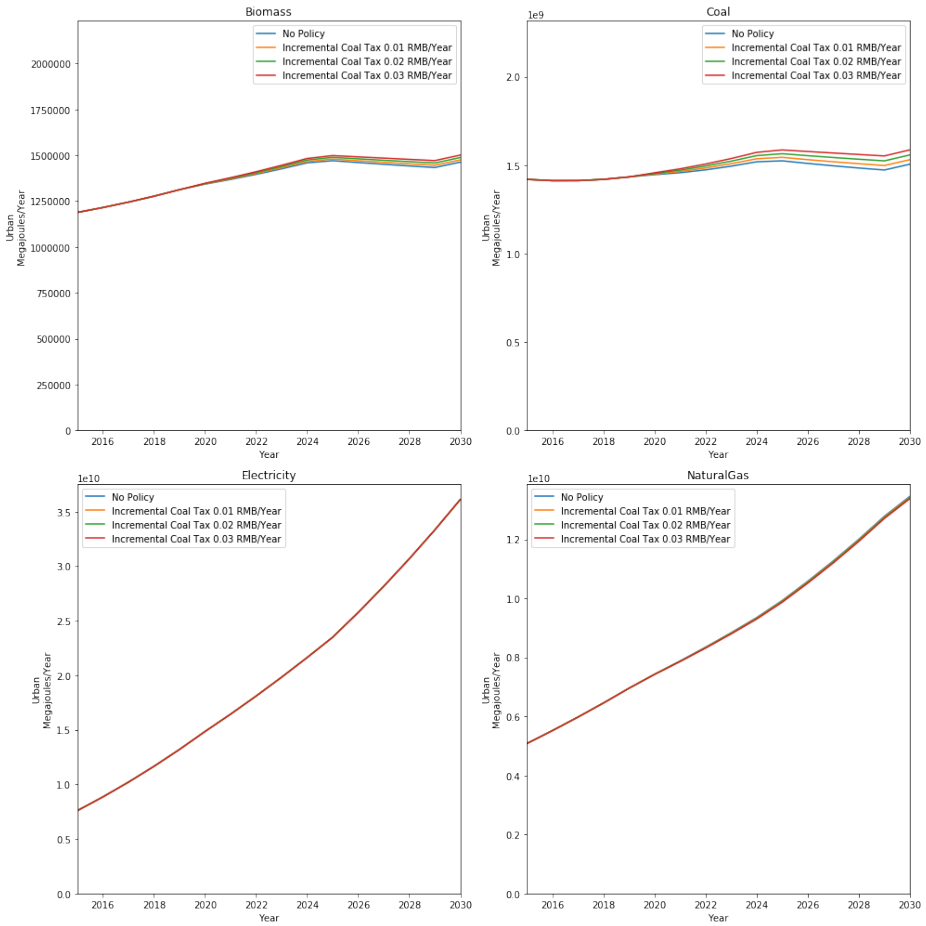



**Figure G20:** The total energy consumption in Jingmen's urban area during the incremental coal tax scenario.

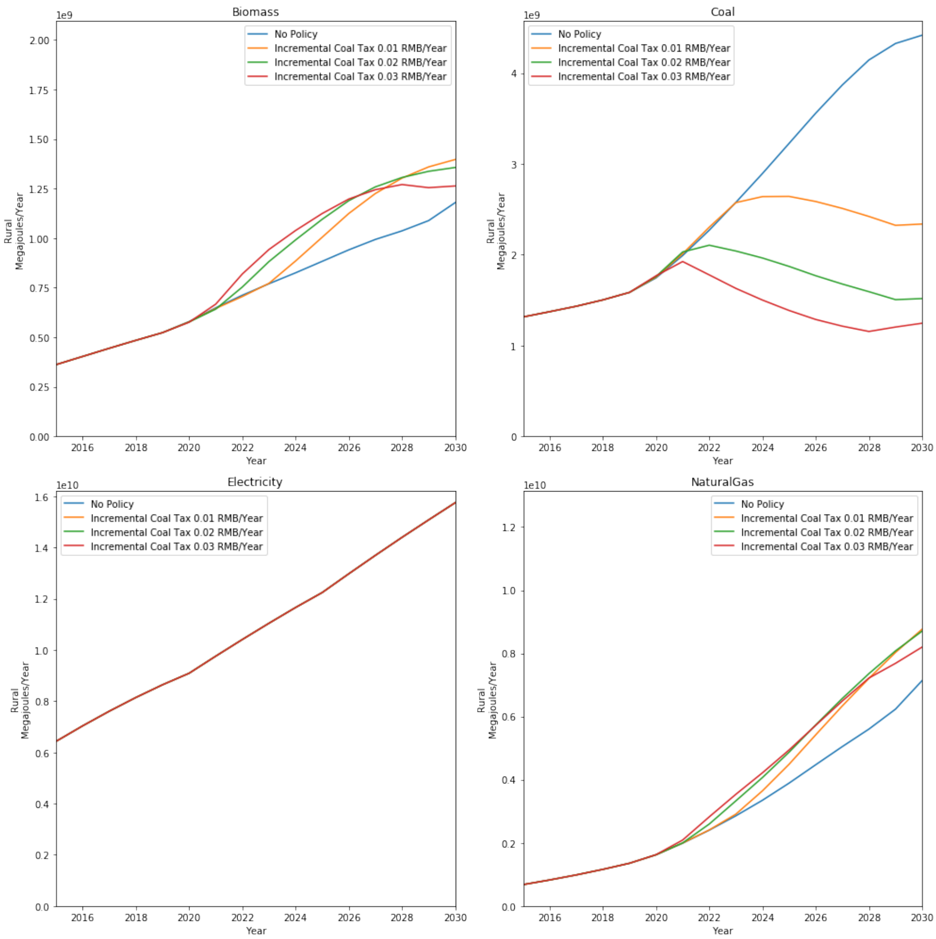


**Figure G21:** The total energy consumption in Jingmen's rural area during the incremental coal tax scenario.

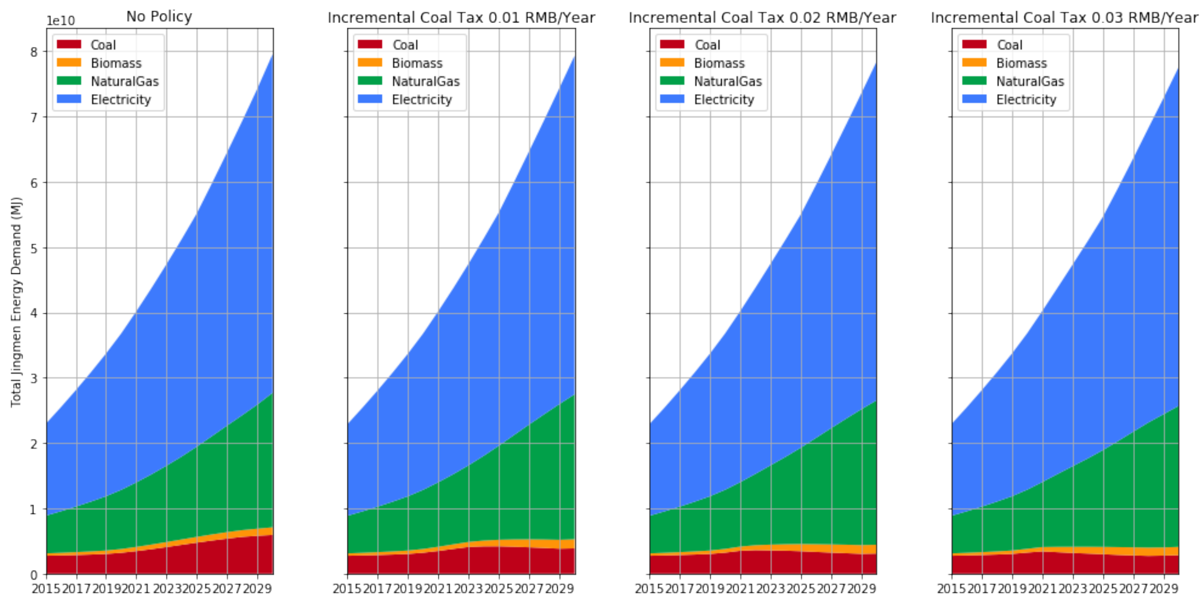


**Figure G22:** The energy consumption in Jingmen during the incremental coal tax scenario visualized in a stacked area chart.

## Appendix G.3 – Policy: Electricity Subsidy

The results in the following charts are obtained from the electricity subsidy policy implemented in 2020. The charts on the left give the total yearly energy demand for each of the areas (urban at the top, rural at the bottom). The graphs in the middle are the CP in graphs. This is the rate of increase of energy demand as a result of increased utility in convenience and price. The KW out graphs on the right-hand side are the rate of decrease in energy demand as a result of increased and knowledge and willingness to reduce energy emissions.

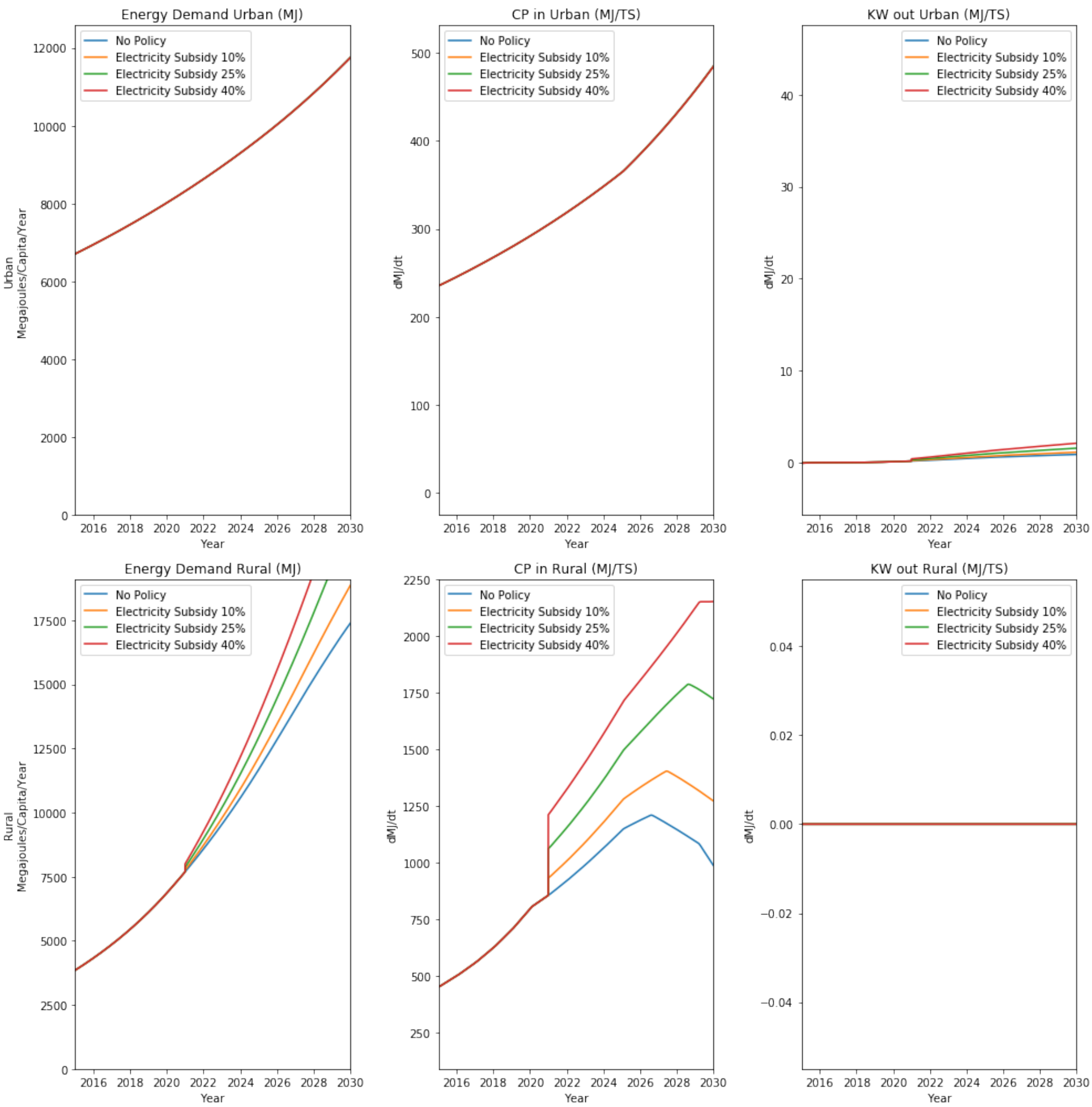



**Figure G23:** The energy demand per household as well as the rate of change of energy demand for the urban and rural areas as a result of the electricity subsidy.

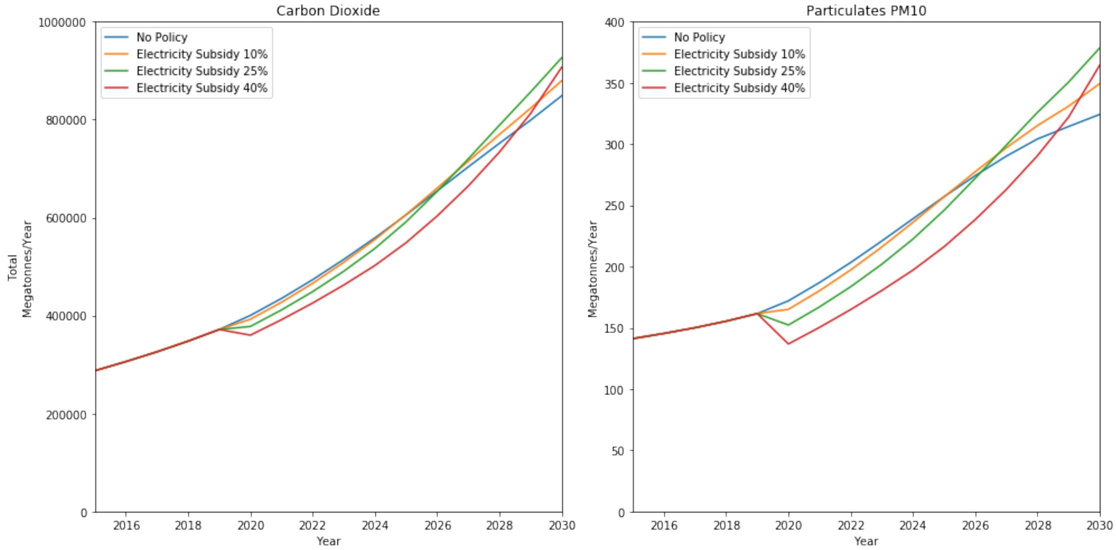



**Figure G24:** The total carbon dioxide and $PM_{10}$ particulates emissions in the electricity subsidy scenario in Jingmen.

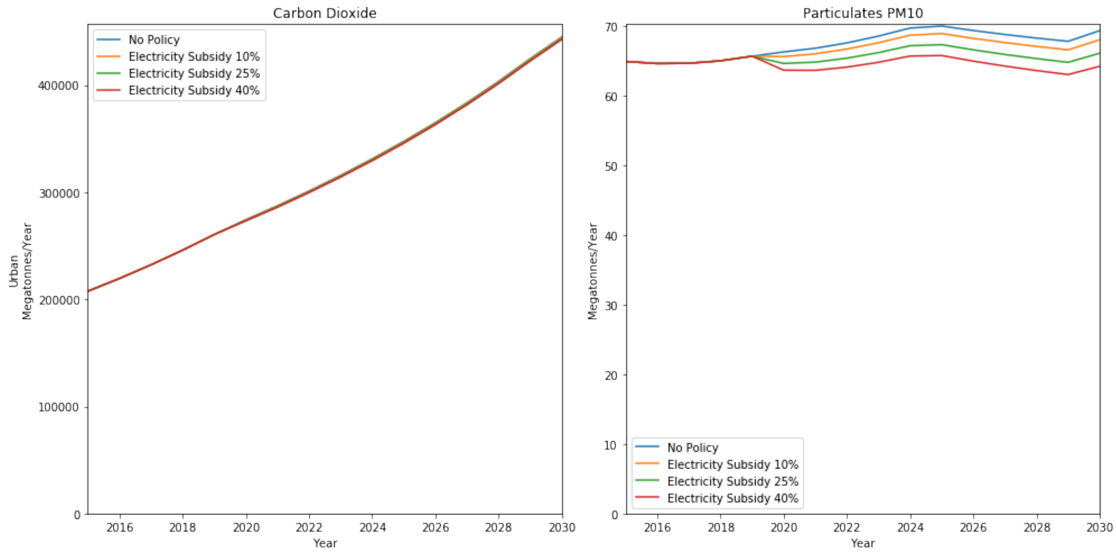



**Figure G25:** The total carbon dioxide and $PM_{10}$ particulates emissions in the electricity subsidy scenario in the urban area.

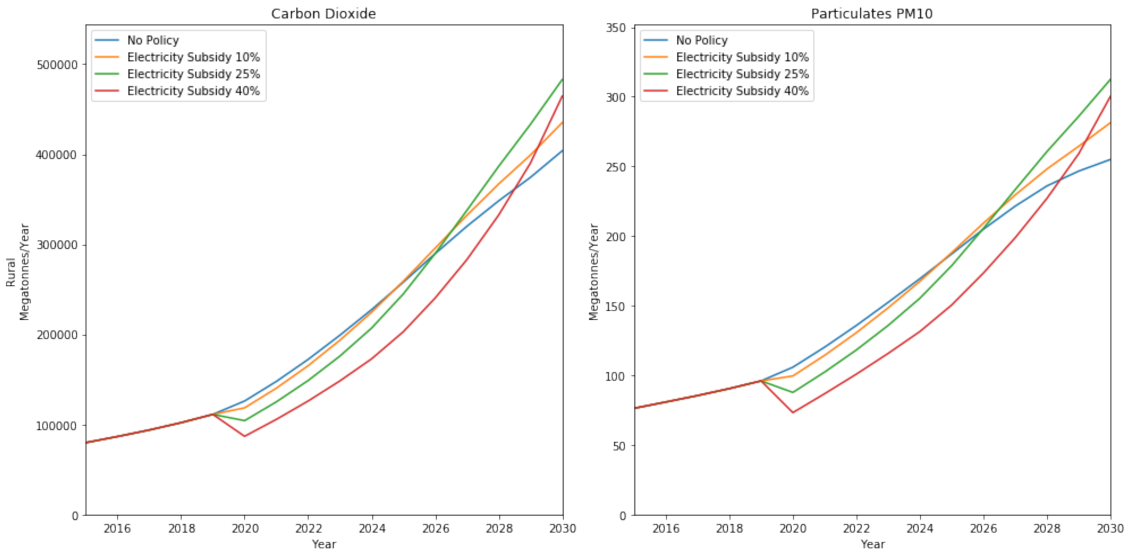



**Figure G26:** The total carbon dioxide and $PM_{10}$ particulates emissions in the electricity subsidy scenario in the rural area.

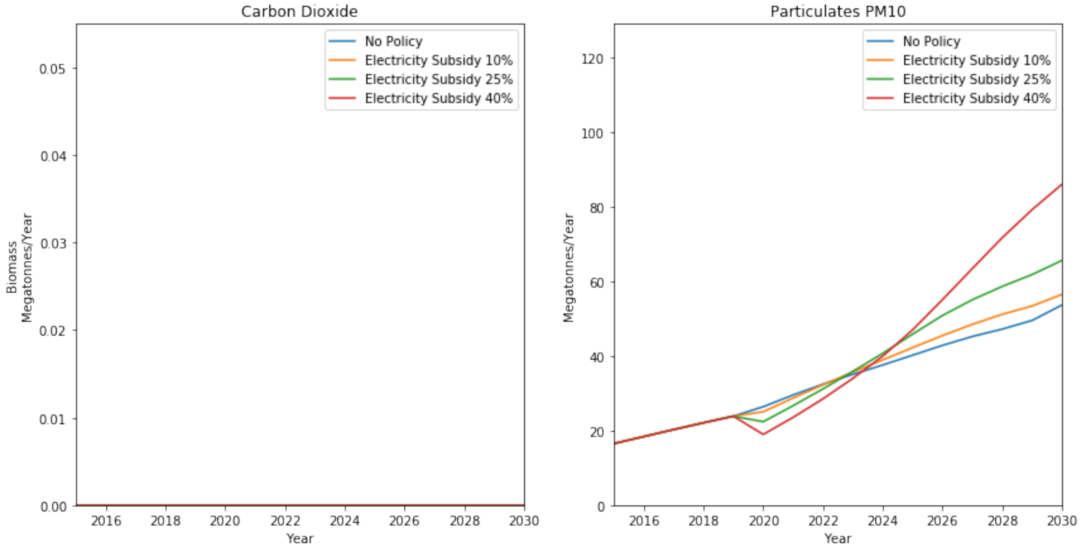



**Figure G27:** The carbon dioxide and $PM_{10}$ emissions coming from biomass consumption in the electricity subsidy scenario.

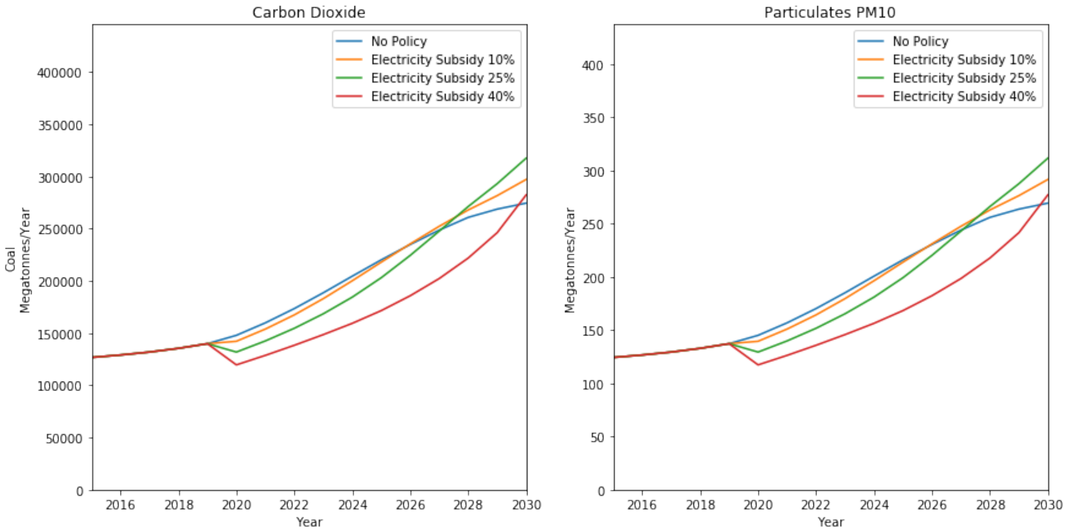



**Figure G28:** The carbon dioxide and $PM_{10}$ emissions coming from coal consumption in the electricity subsidy scenario.

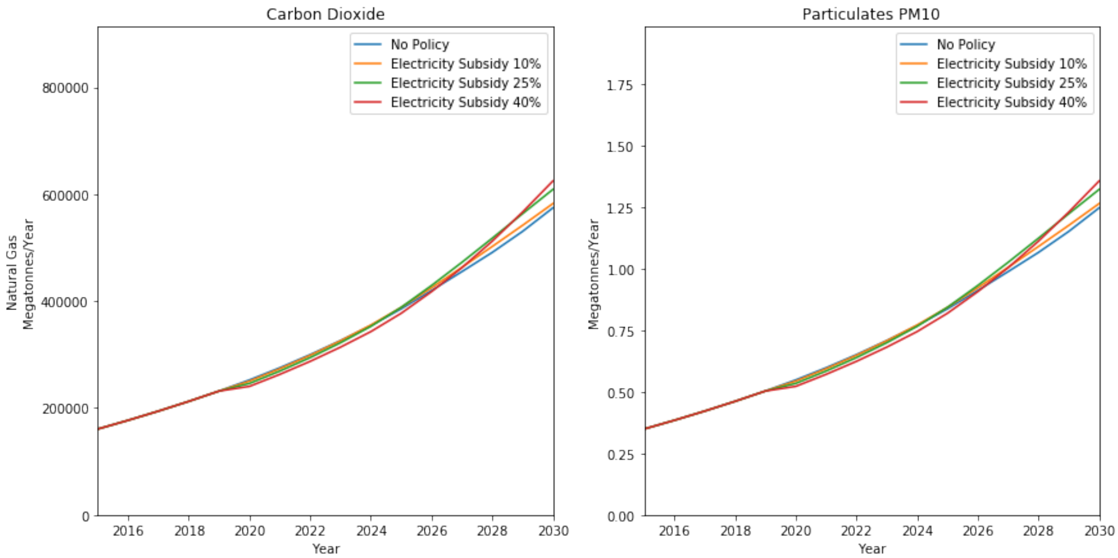



**Figure G29:** The carbon dioxide and $PM_{10}$ emissions coming from gas consumption in the electricity subsidy scenario.

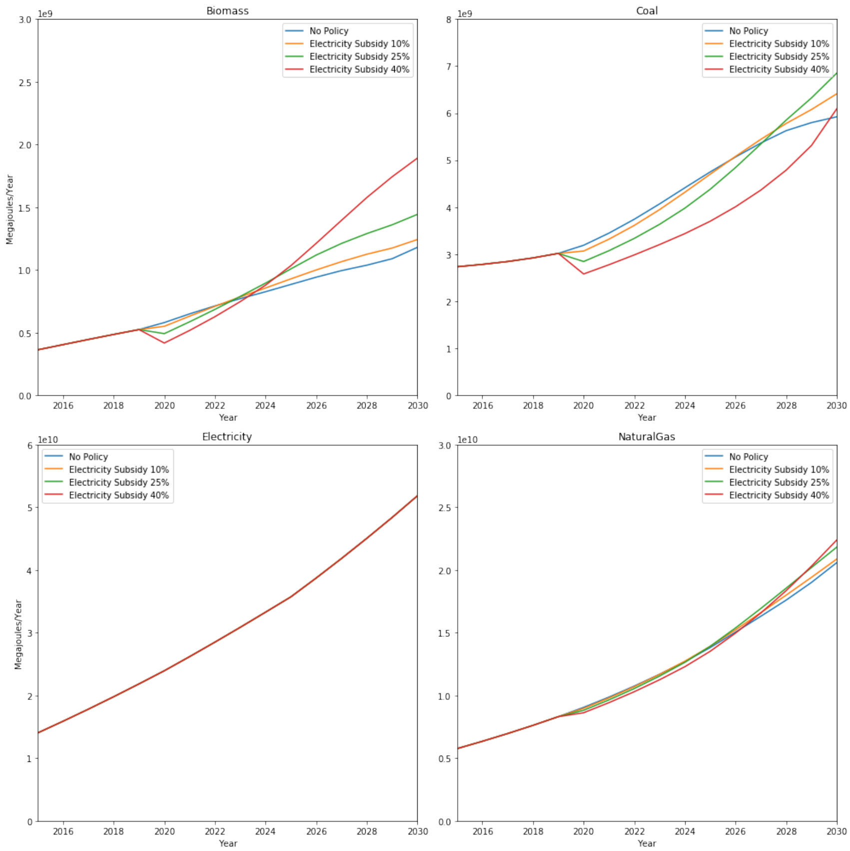



**Figure G30:** The total energy consumption of each individual energy fuel in Jingmen during the electricity subsidy scenario.

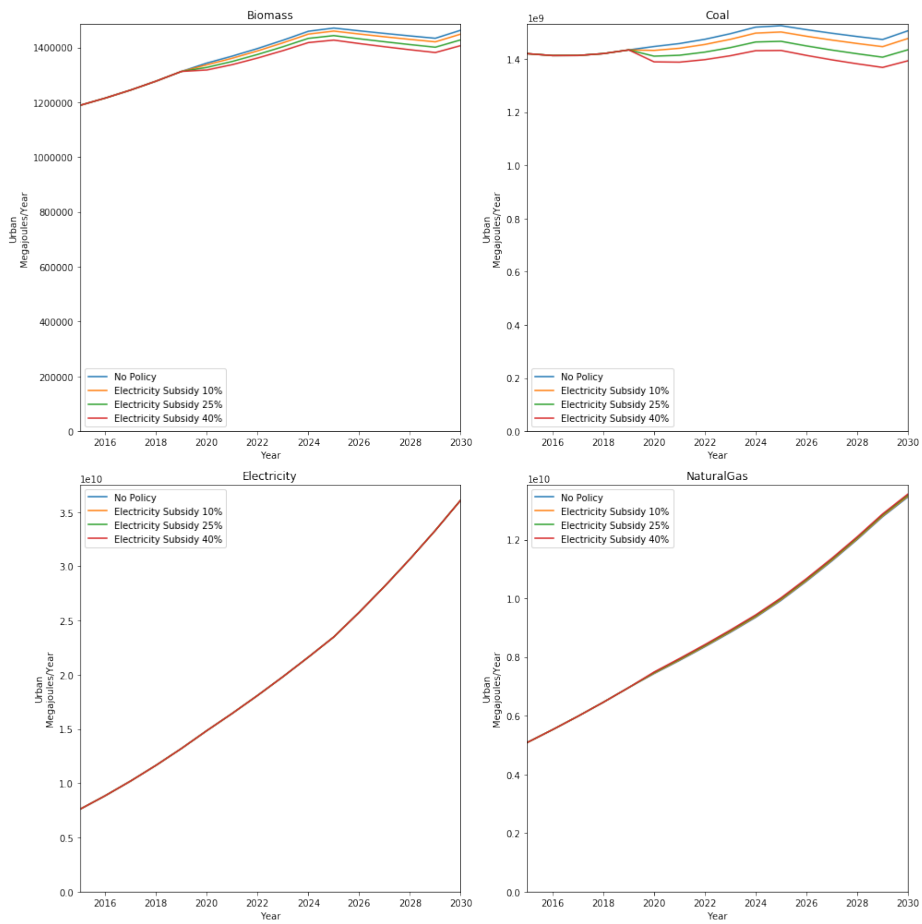



**Figure F31:** The total energy consumption in Jingmen's urban area during the electricity subsidy scenario.

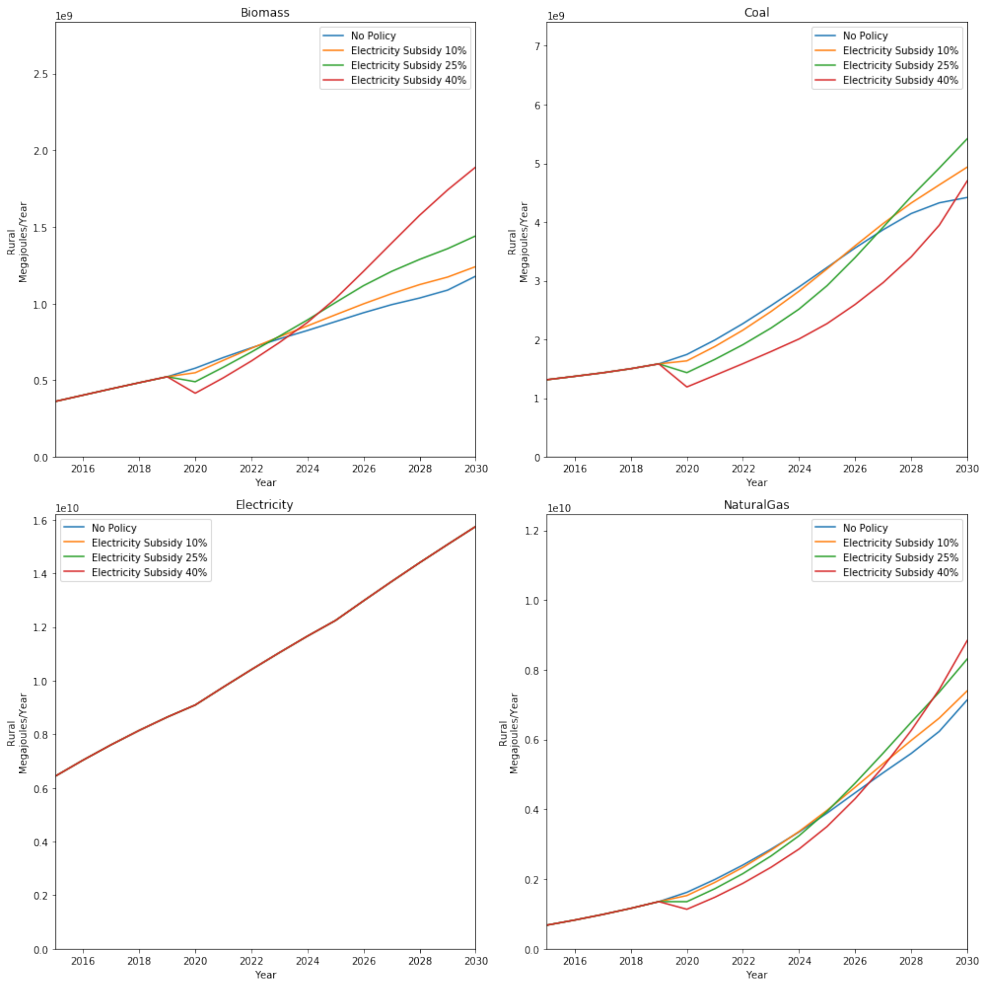



**Figure G32:** The total energy consumption in Jingmen's rural area during the electricity subsidy scenario.

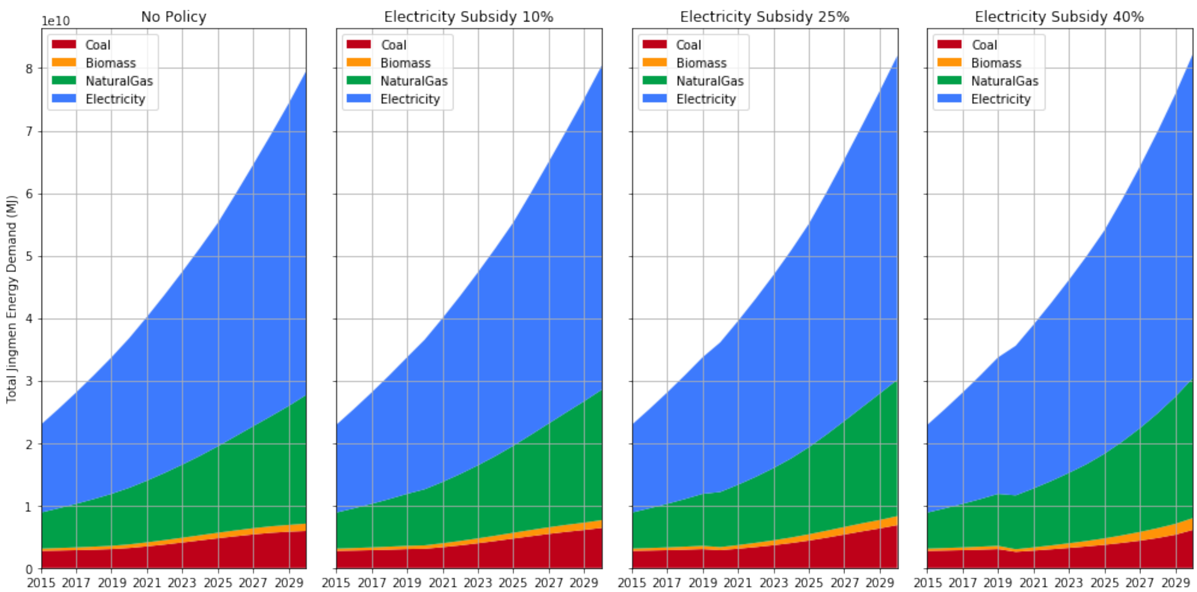



**Figure G33:** The energy consumption in Jingmen during the electricity subsidy scenario visualized in a stacked area chart.

## Appendix G.4 – Policy: Additional Pipelines

The results in the following charts are obtained from the additional pipeline policy implemented in 2020. The charts on the left give the total yearly energy demand for each of the areas (urban at the top, rural at the bottom). The graphs in the middle are the CP in graphs. This is the rate of increase of energy demand as a result of increased utility in convenience and price. The KW out graphs on the right-hand side are the rate of decrease in energy demand as a result of increased and knowledge and willingness to reduce energy emissions.

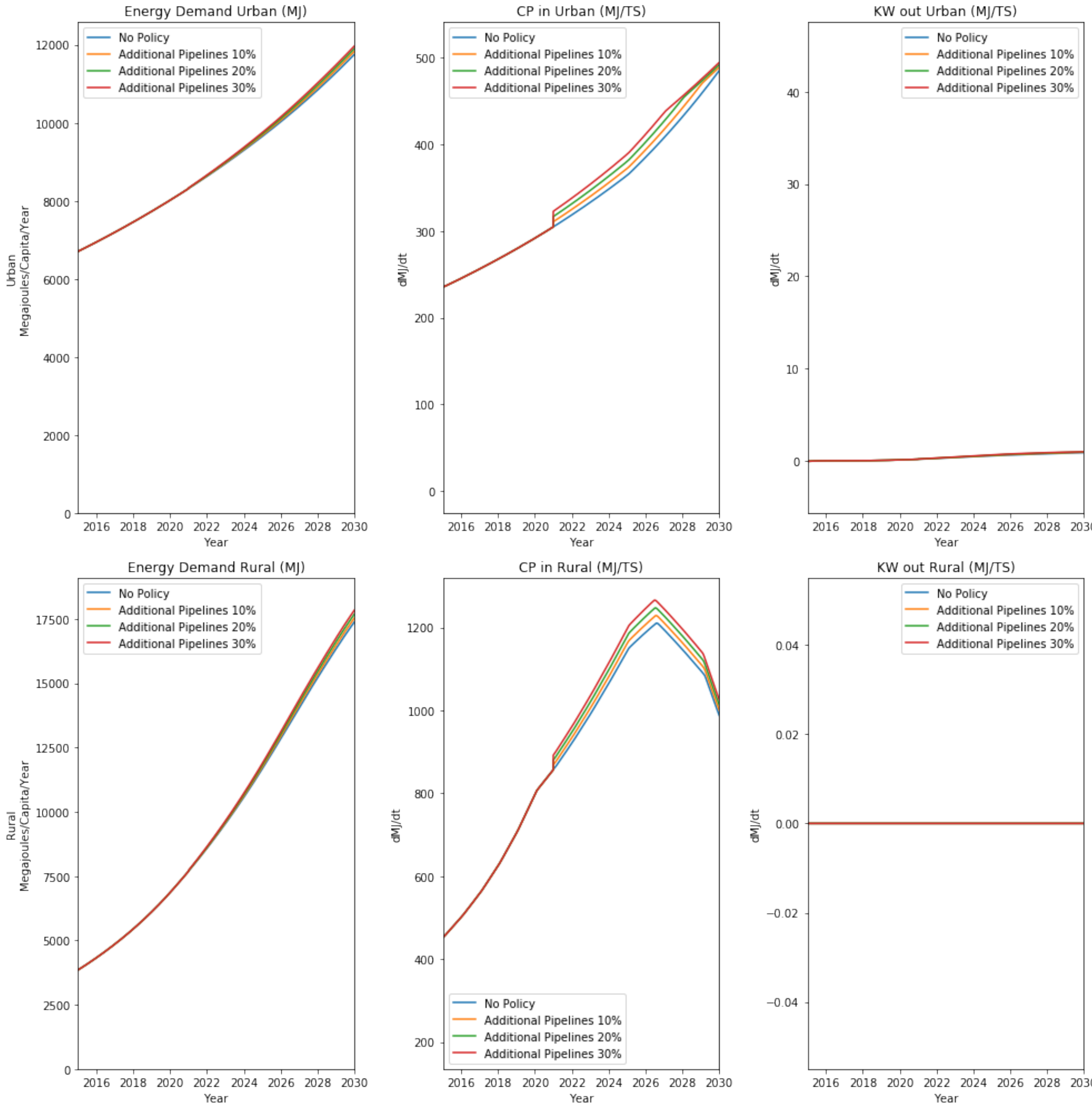



**Figure G34:** The energy demand per household as well as the rate of change of energy demand for the urban and rural areas as a result of the additional pipeline.

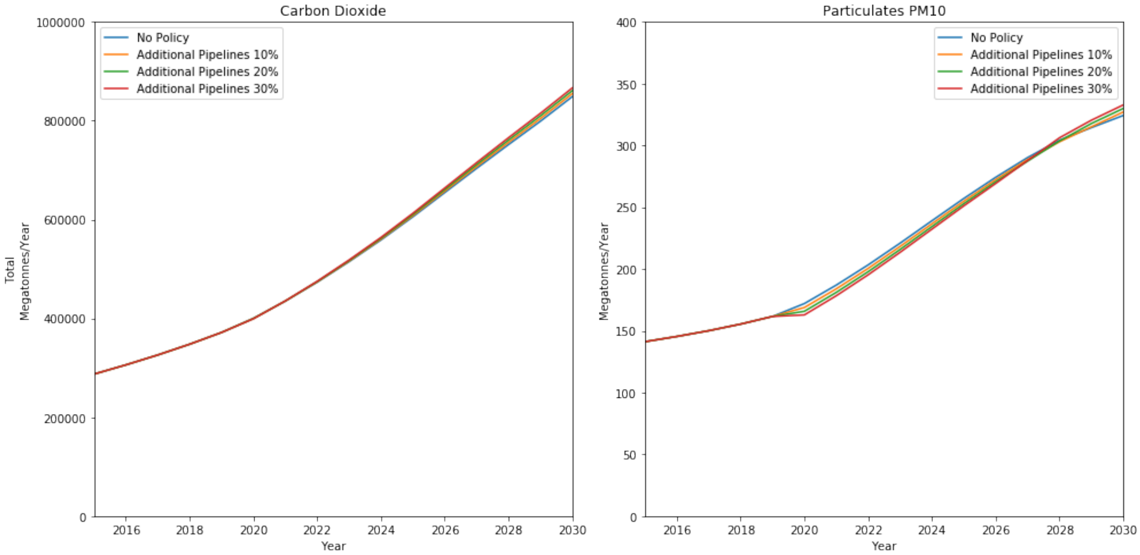



**Figure G35:** The total carbon dioxide and $PM_{10}$ particulates emissions in the additional pipeline scenario in Jingmen.

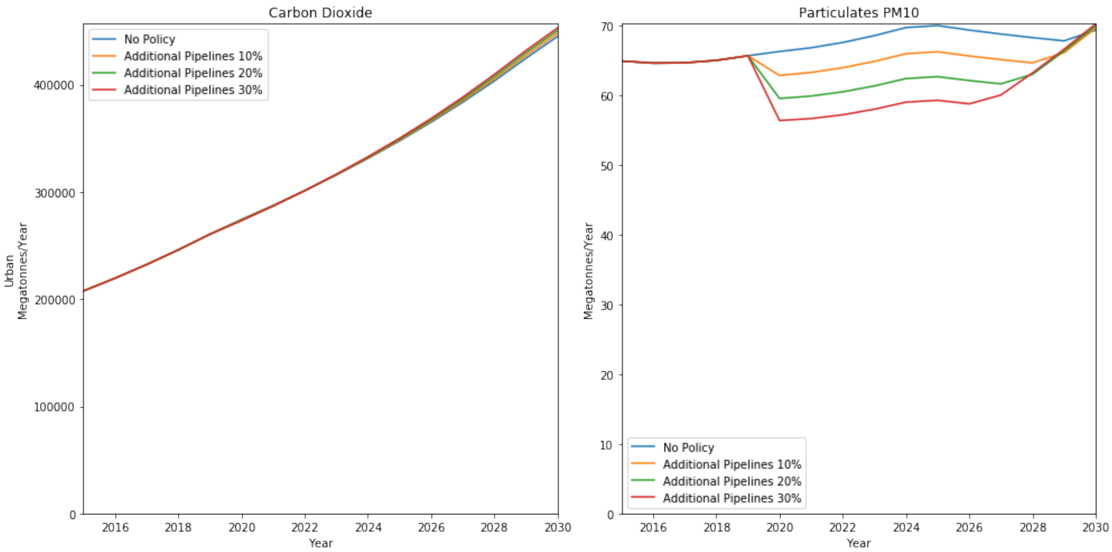



**Figure G36:** The total carbon dioxide and $PM_{10}$ particulates emissions in the additional pipeline scenario in the urban area.

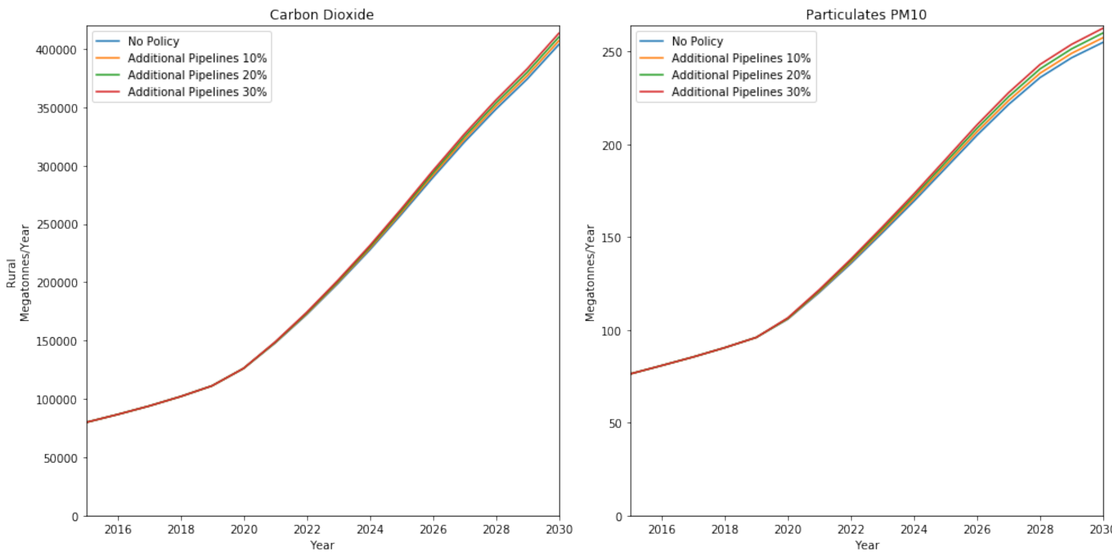



**Figure G37:** The total carbon dioxide and $PM_{10}$ particulates emissions in the additional pipeline scenario in the rural area.

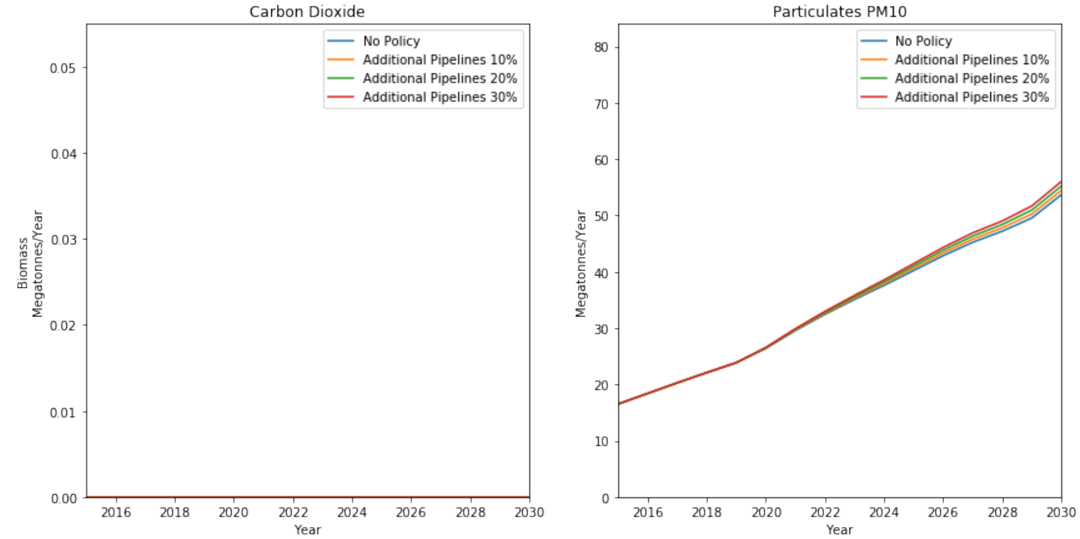



**Figure G38:** The total carbon dioxide and $PM_{10}$ particulates emissions coming from biomass consumption in the additional pipeline scenario.

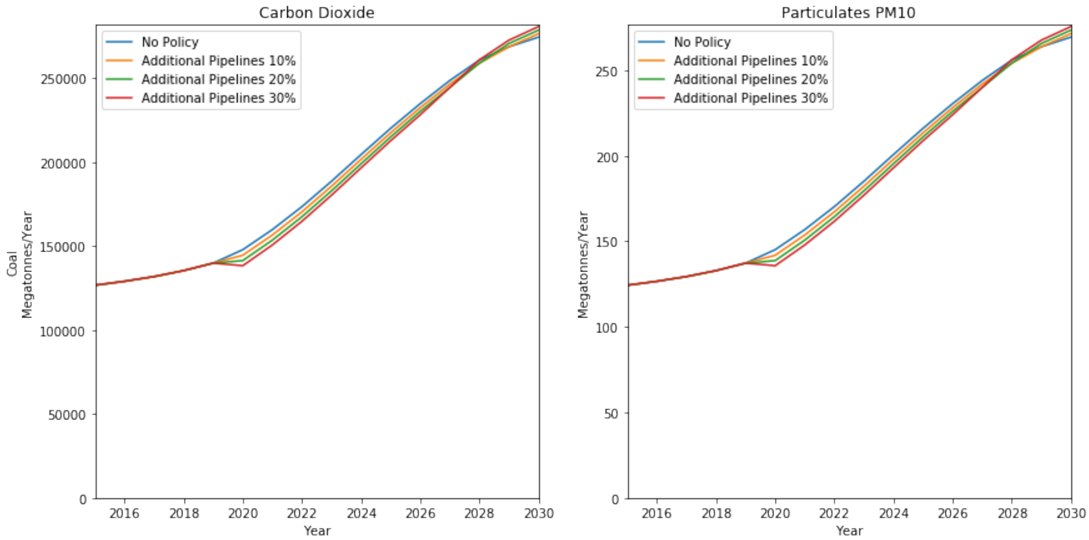



**Figure G39:** The total carbon dioxide and $PM_{10}$ particulates emissions coming from coal consumption in the additional pipeline scenario.

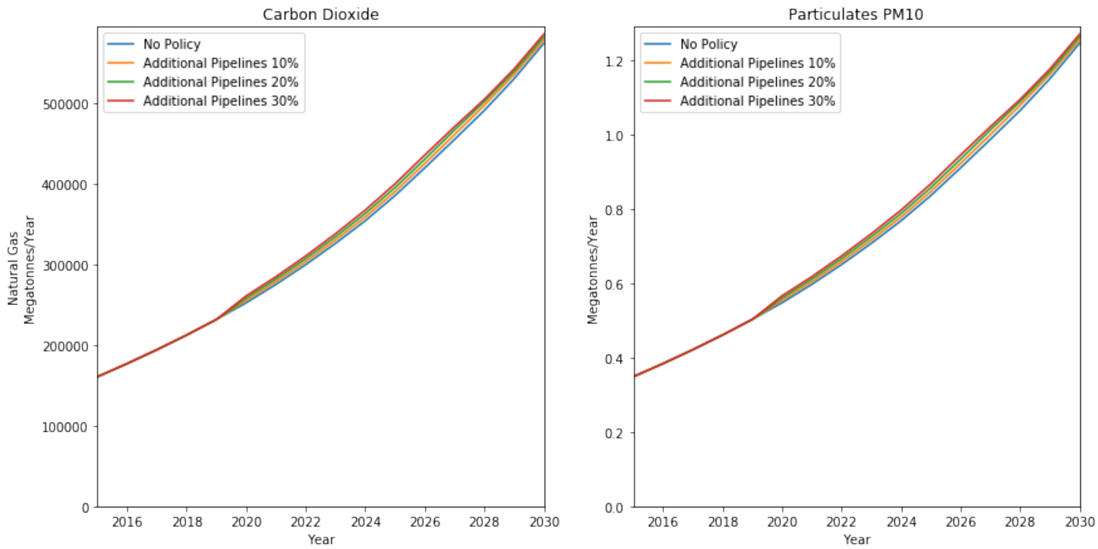



**Figure G40:** The carbon dioxide and $PM_{10}$ emissions coming from gas consumption in the additional pipeline scenario.

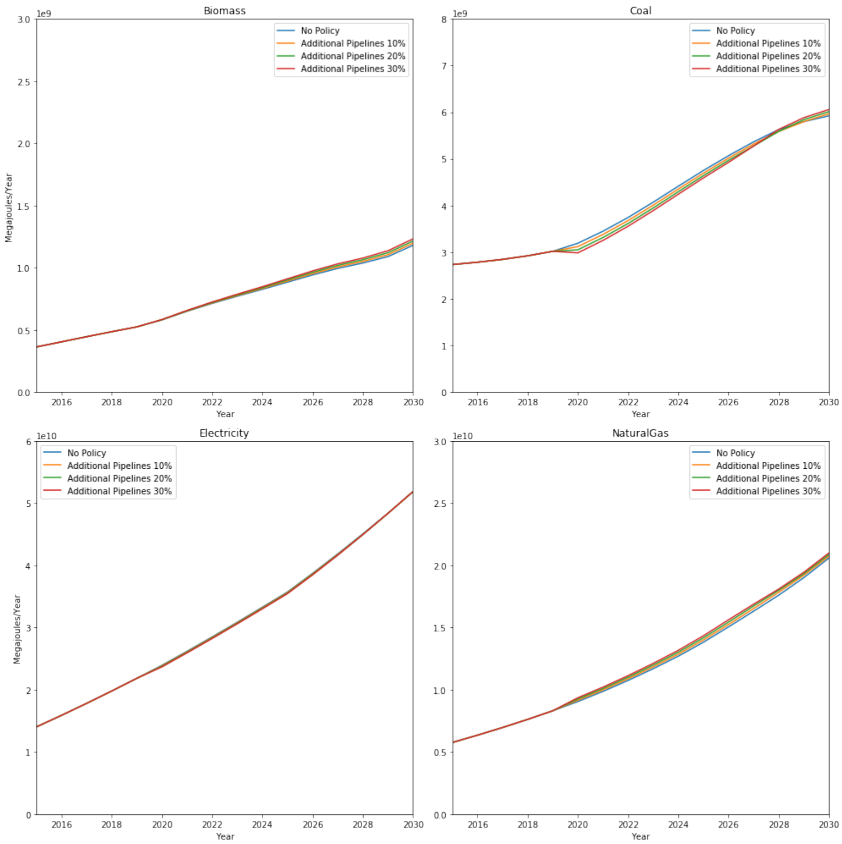



**Figure G41:** The energy consumption of each individual energy fuel in Jingmen during the additional pipeline scenario.

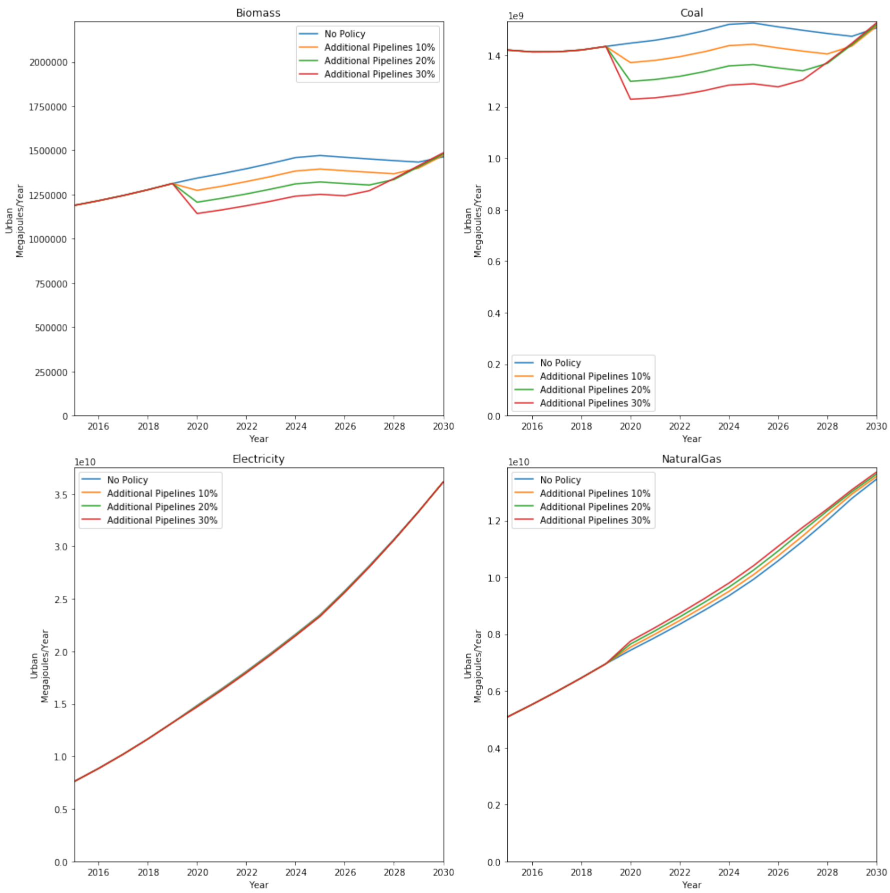



**Figure G42:** The total energy consumption in Jingmen's urban area during the additional pipeline scenario.

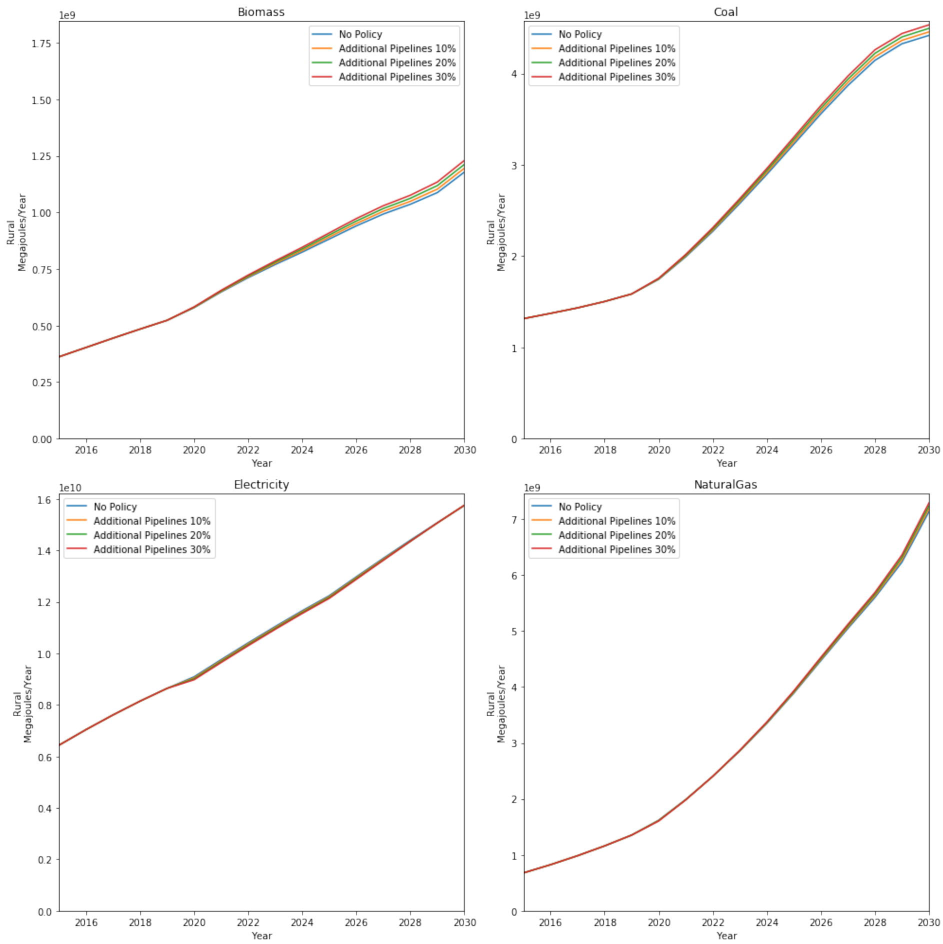



**Figure G43:** The total energy consumption in Jingmen's rural area during the additional pipeline scenario.

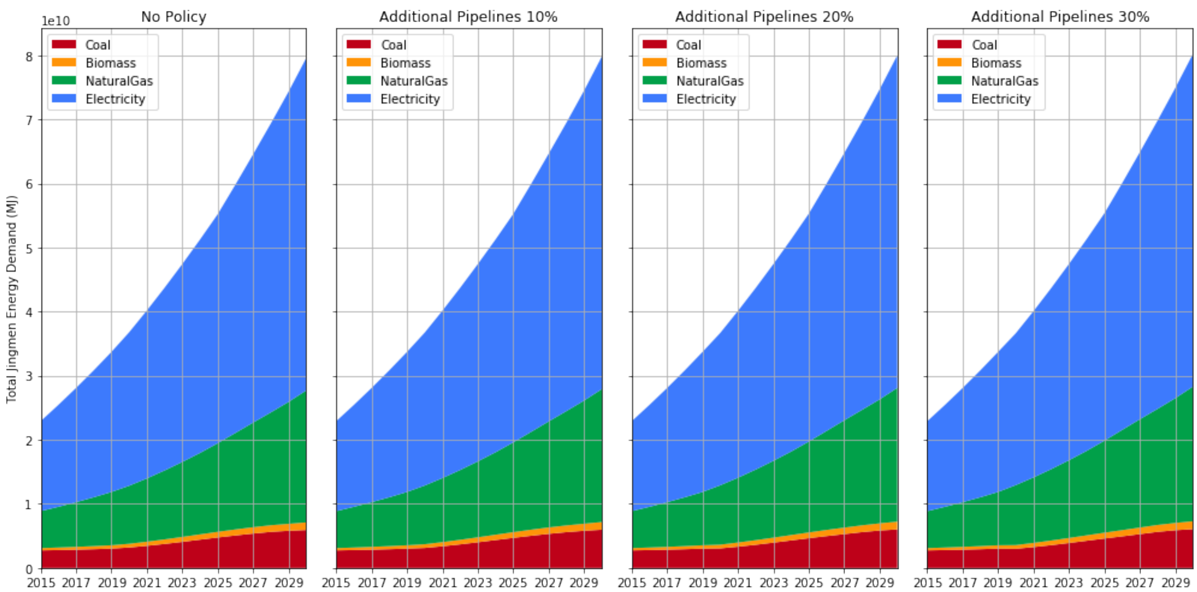



**Figure G44:** The energy consumption in Jingmen during the additional pipeline scenario visualized in a stacked area chart.

## Appendix G.5 – Policy: Additional Exposure

The results in the following charts are obtained from the additional exposure policy implemented in 2020. The charts on the left give the total yearly energy demand for each of the areas (urban at the top, rural at the bottom). The graphs in the middle are the CP in graphs. This is the rate of increase of energy demand as a result of increased utility in convenience and price. The KW out graphs on the right-hand side are the rate of decrease in energy demand as a result of increased and knowledge and willingness to reduce energy emissions.

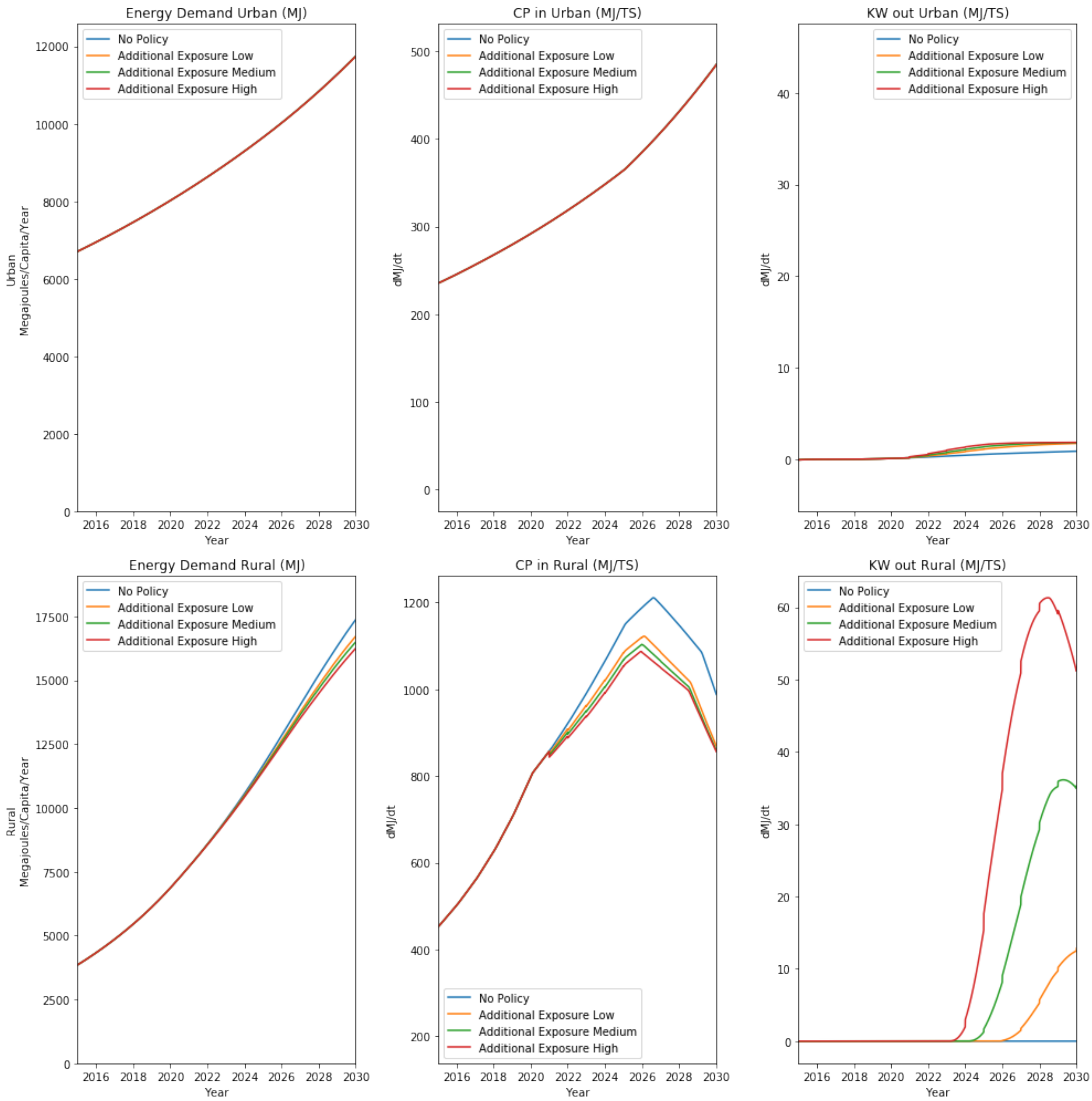



**Figure G45:** The energy demand per household as well as the rate of change of energy demand for the urban and rural areas as a result of the additional exposure.

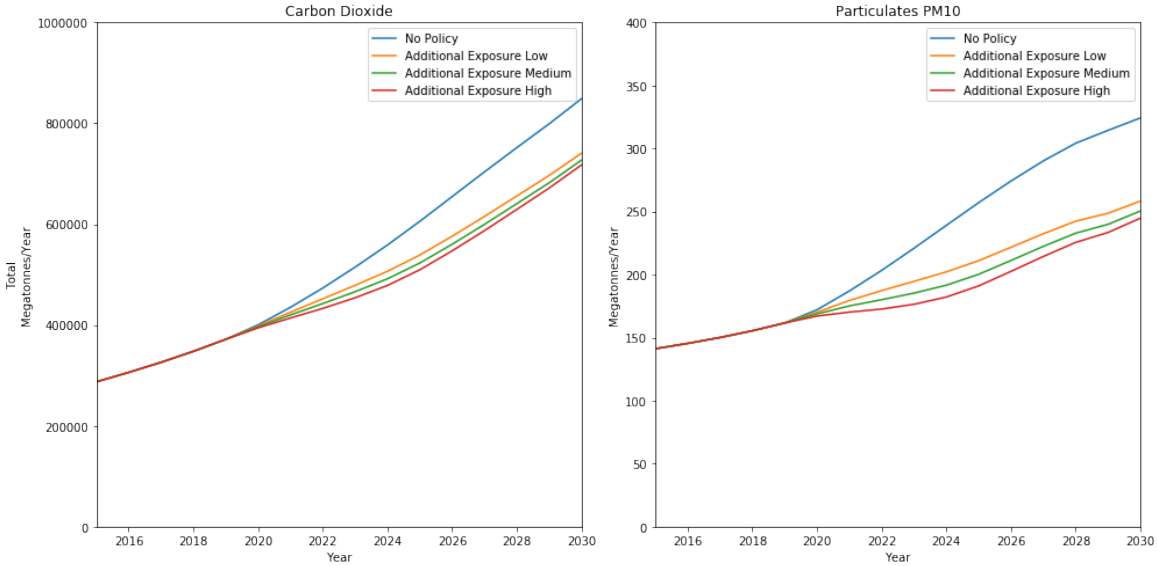



**Figure G46:** The total carbon dioxide and $PM_{10}$ particulates emissions in the additional exposure scenario in Jingmen.

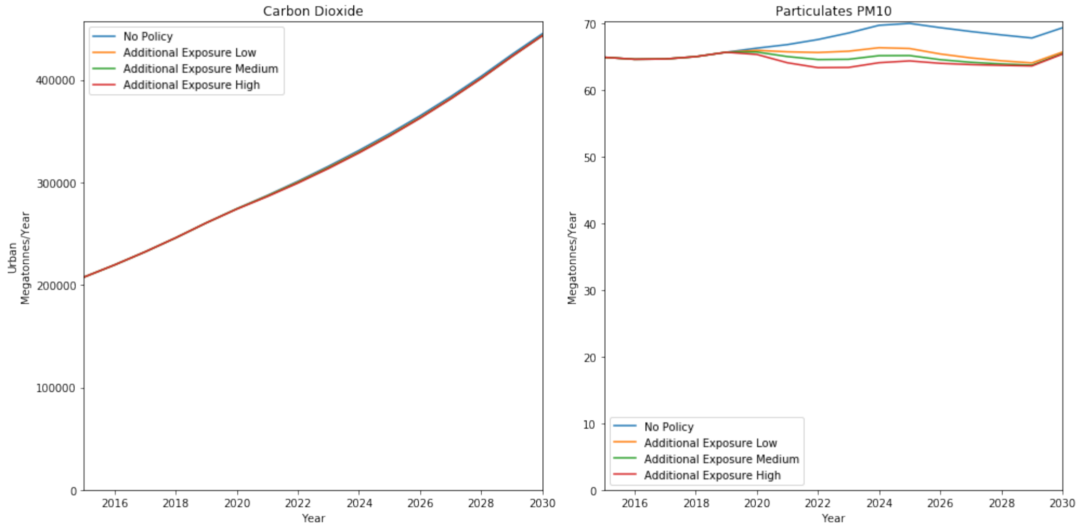



**Figure G47:** The total carbon dioxide and $PM_{10}$ particulates emissions in the additional exposure scenario in the urban area.

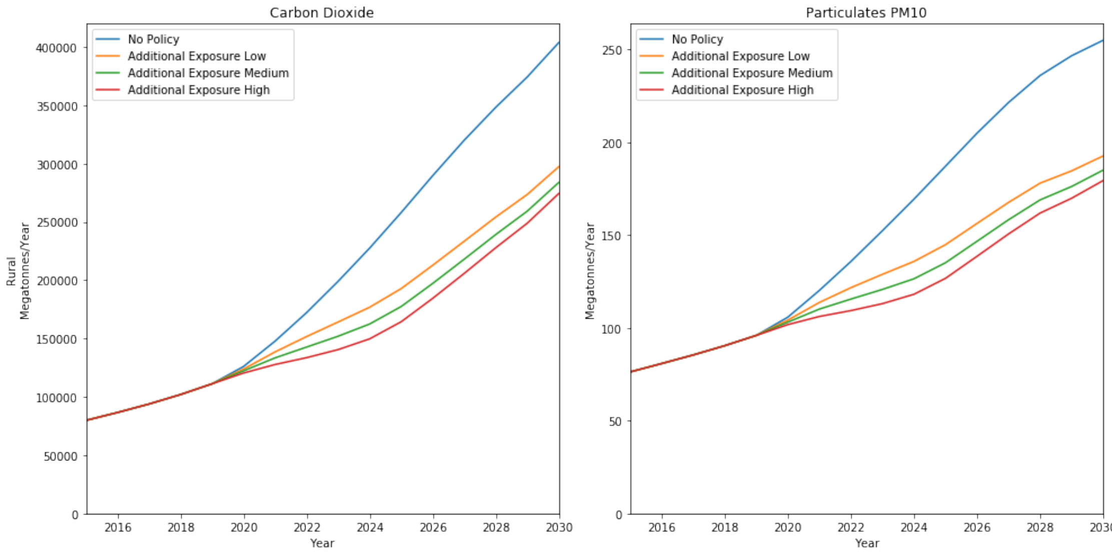



**Figure G48:** The total carbon dioxide and $PM_{10}$ particulates emissions in the additional exposure scenario in the rural area.

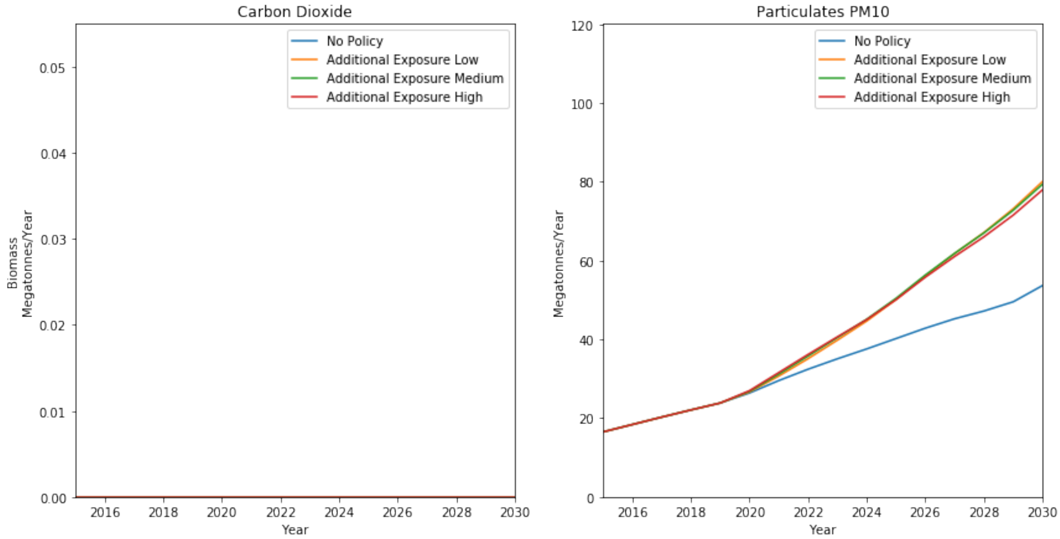



**Figure G49:** The carbon dioxide and $PM_{10}$ emissions coming from biomass consumption in the additional exposure scenario.

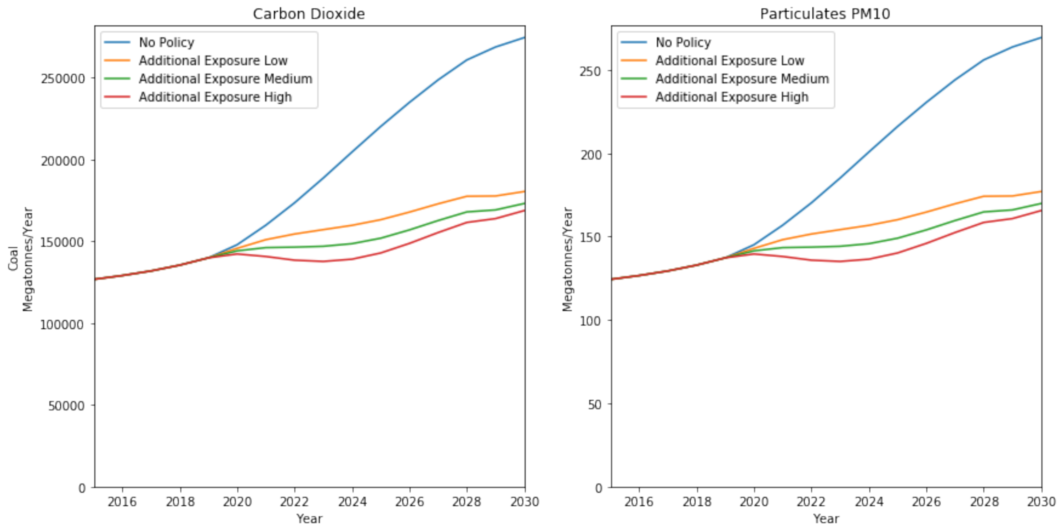



**Figure G50:** The total carbon dioxide and $PM_{10}$ particulates emissions coming from coal consumption in the additional exposure scenario.

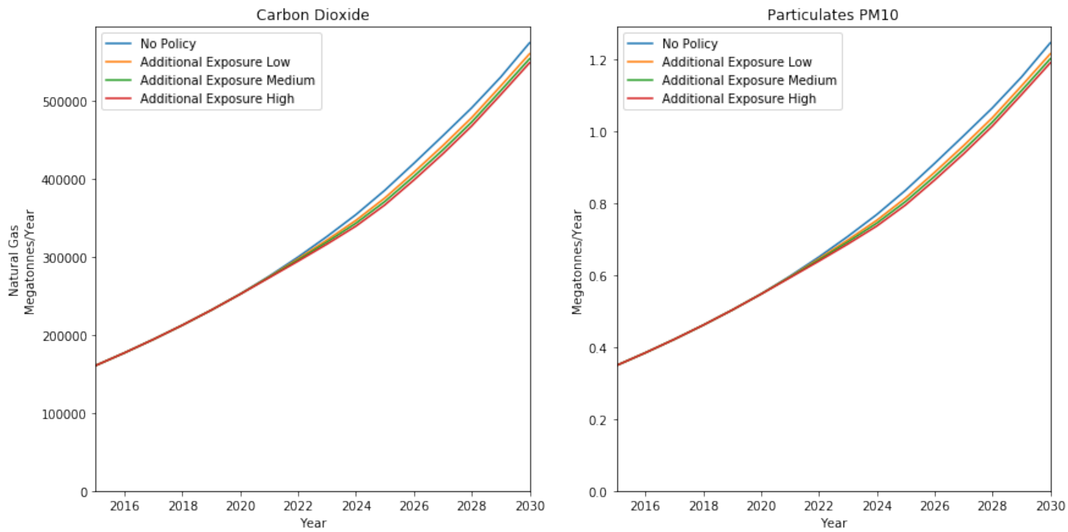



**Figure G51:** The total carbon dioxide and $PM_{10}$ particulates emissions coming from gas consumption in the additional exposure scenario.

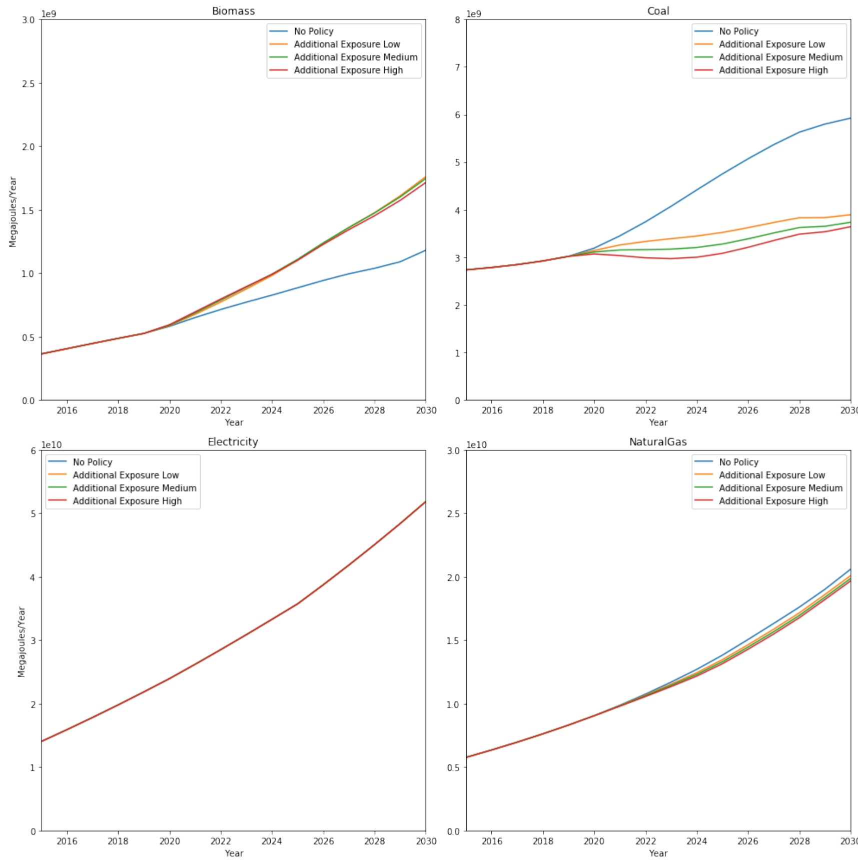



**Figure G52:** The energy consumption of each individual energy fuel in Jingmen during the additional exposure scenario.

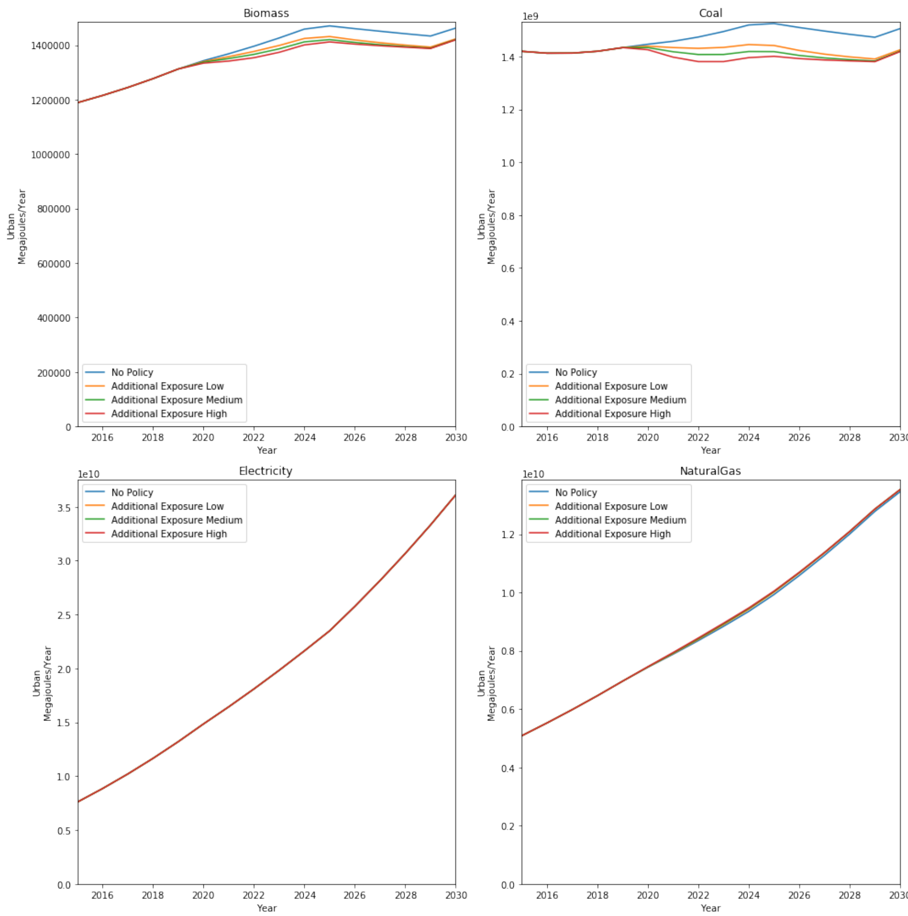


**Figure G53:** The energy consumption in Jingmen's urban area during the additional exposure scenario.

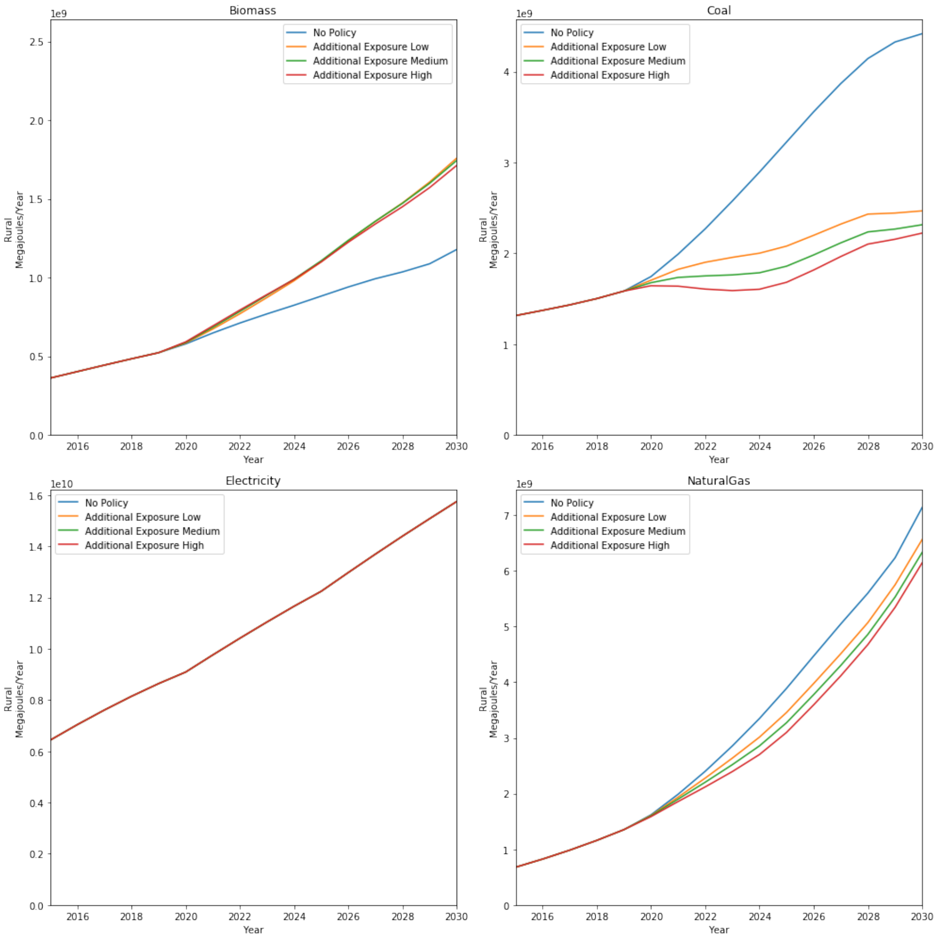



**Figure G54:** The total energy consumption in Jingmen's rural area during the additional exposure scenario.

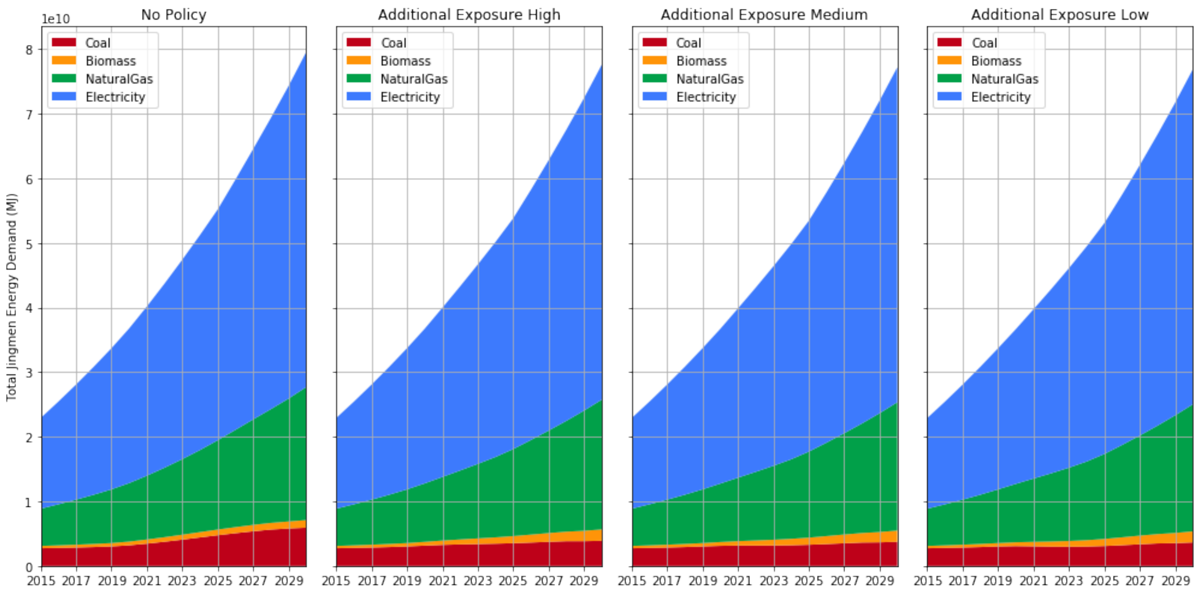



**Figure G55:** The energy consumption in Jingmen during the additional exposure scenario visualized in a stacked area chart.

## Appendix G.6 – Policy comparison

The results in the following charts are obtained from the additional exposure policy implemented in 2020. The charts on the left give the total yearly energy demand for each of the areas (urban at the top, rural at the bottom). The graphs in the middle are the CP in graphs. This is the rate of increase of energy demand as a result of increased utility in convenience and price. The KW out graphs on the right-hand side show the rate of decrease in energy demand as a result of increased and knowledge and willingness to reduce energy emissions.

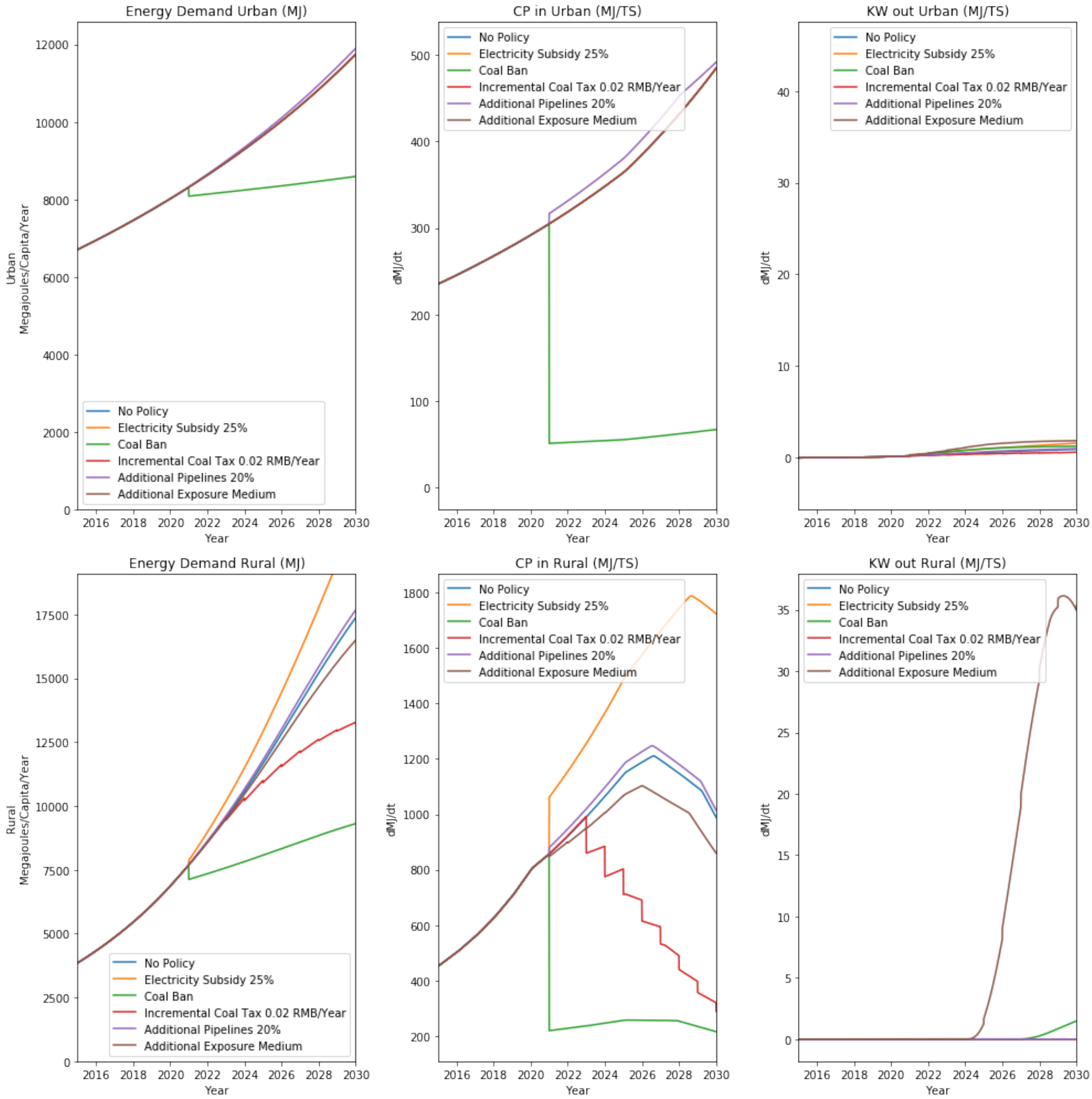



**Figure G56:** The energy demand per household as well as the rate of change of energy demand for the urban and rural areas as a result of the medium scenario levels of each individual policy.

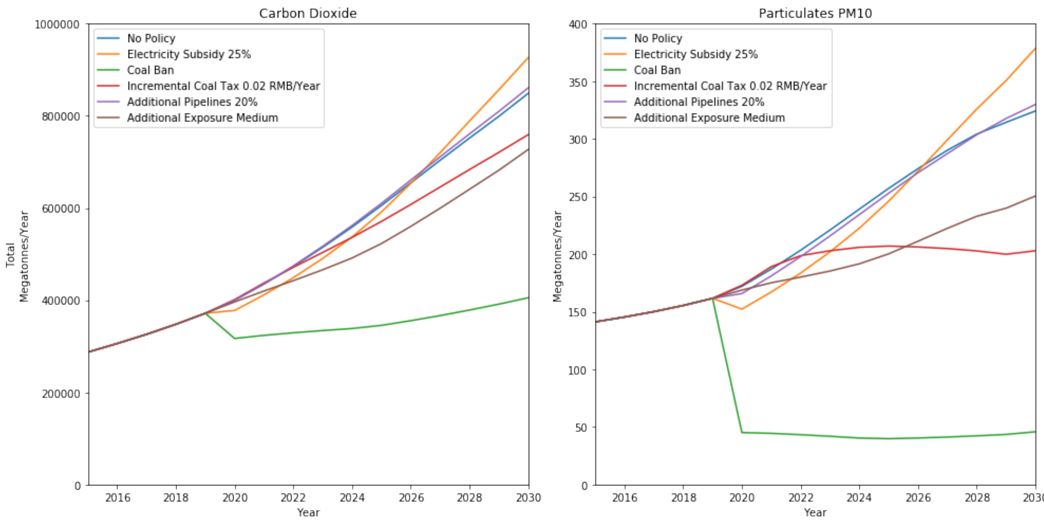



**Figure F57:** The total carbon dioxide and $PM_{10}$ particulates emissions in the medium scenario levels of each individual policy in Jingmen.

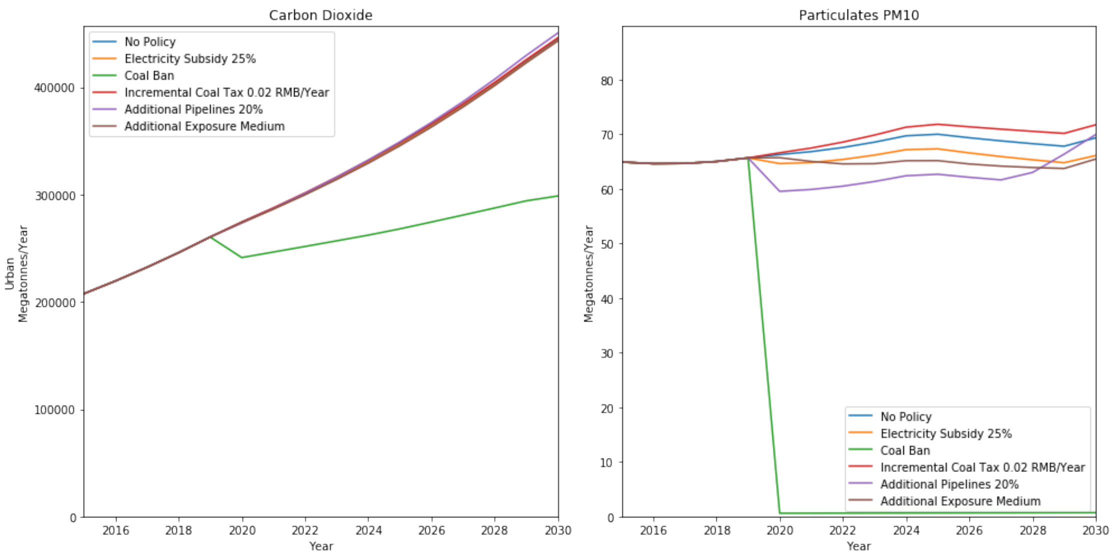



**Figure G58:** The total carbon dioxide and $PM_{10}$ particulates emissions in the medium scenario levels of each individual policy in the urban area.

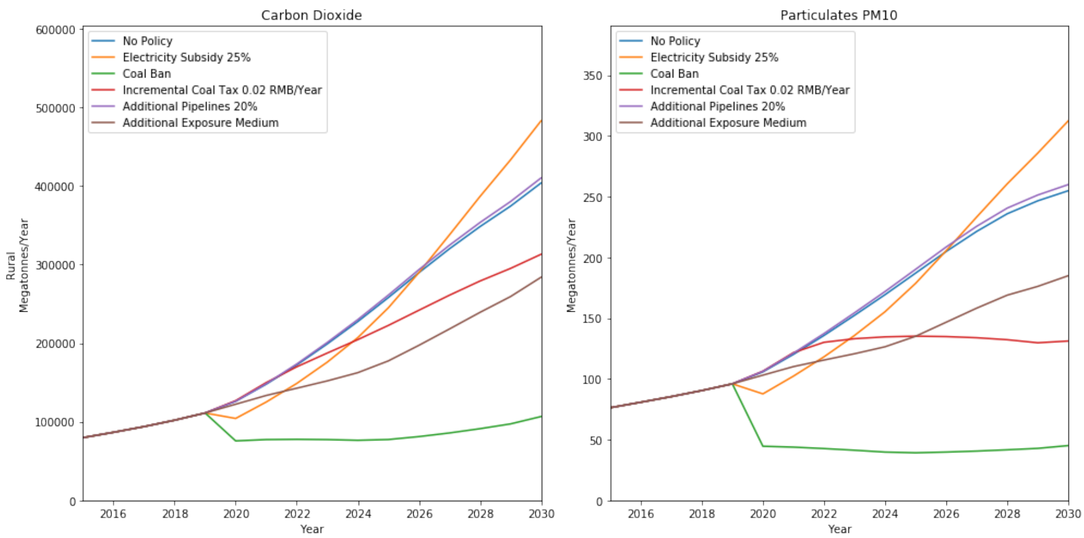



**Figure G59:** The total carbon dioxide and $PM_{10}$ particulates emissions in the medium scenario levels of each individual policy in the rural area.

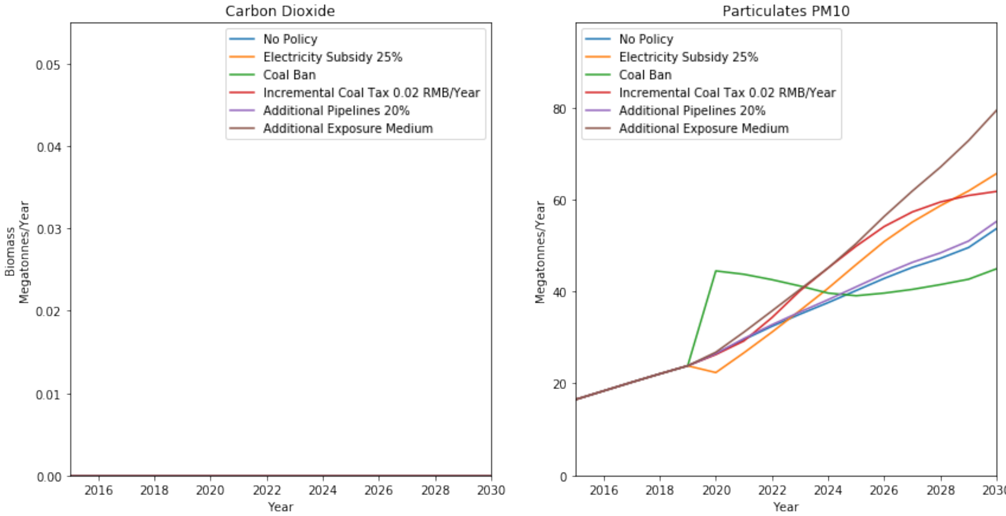



**Figure G60:** The total carbon dioxide and $PM_{10}$ particulates emissions coming from biomass consumption in the medium scenario levels of each individual policy.

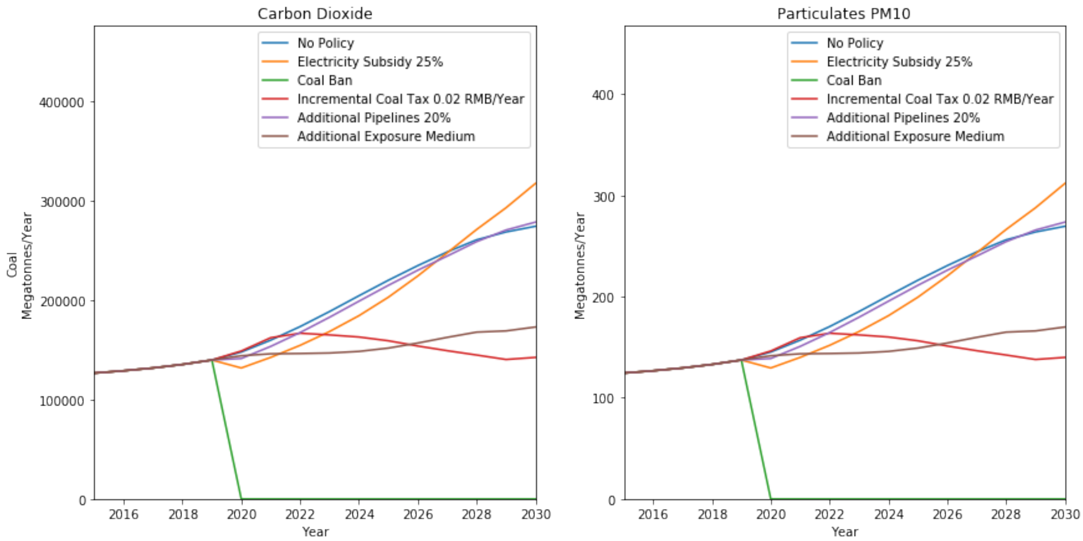



**Figure G61:** The total carbon dioxide and $PM_{10}$ particulates emissions coming from coal consumption in the medium scenario levels of each individual policy.

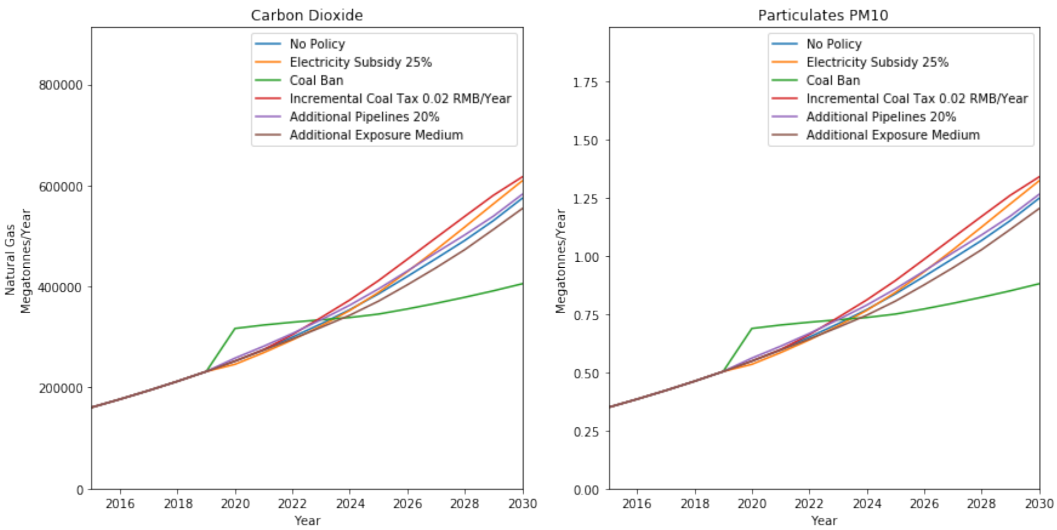



**Figure G62:** The total carbon dioxide and $PM_{10}$ particulates emissions coming from gas consumption in the medium scenario levels of each individual policy.

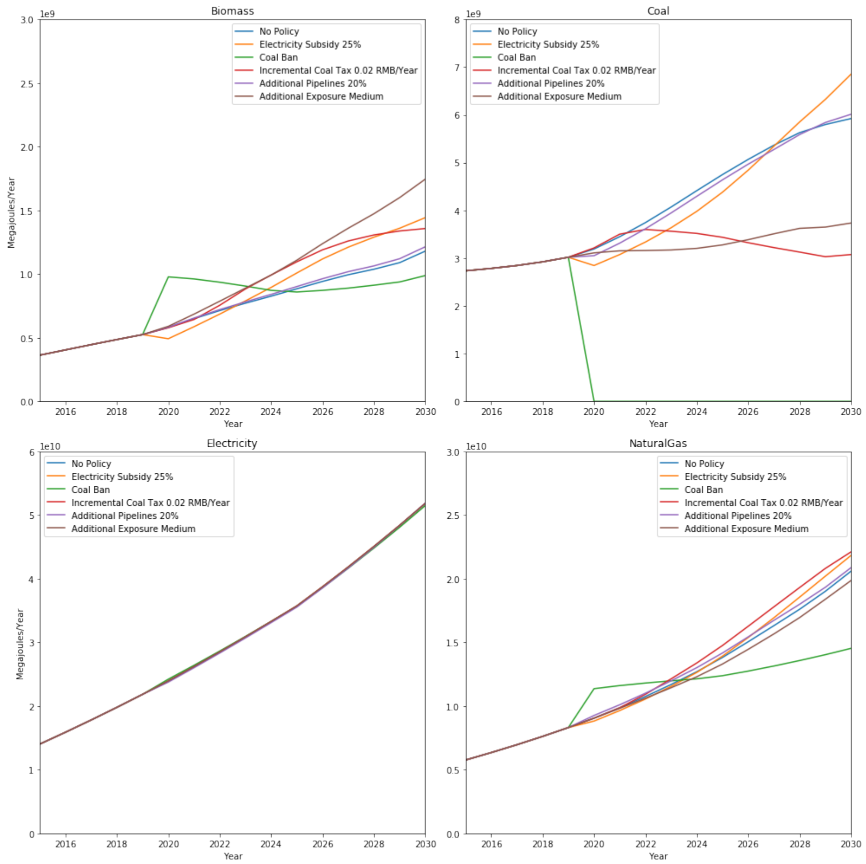



**Figure G63:** The energy consumption of each energy fuel in Jingmen during the medium scenario levels of each policy.

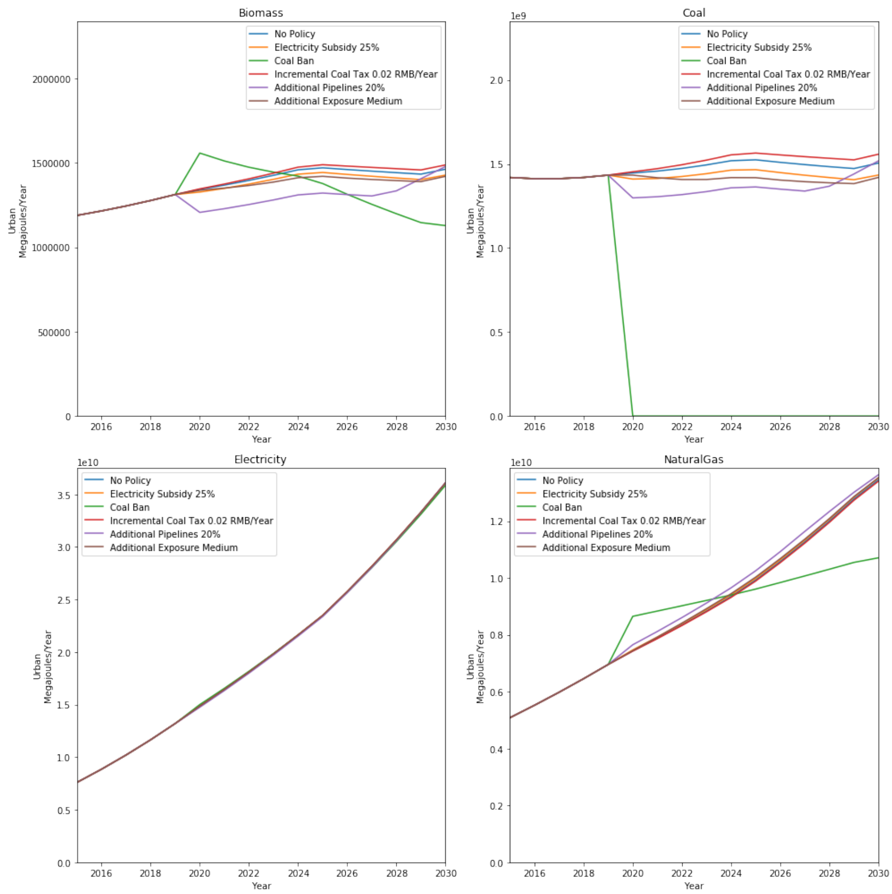



**Figure G64:** The energy consumption in Jingmen's urban area during the medium scenario levels of each individual policy.

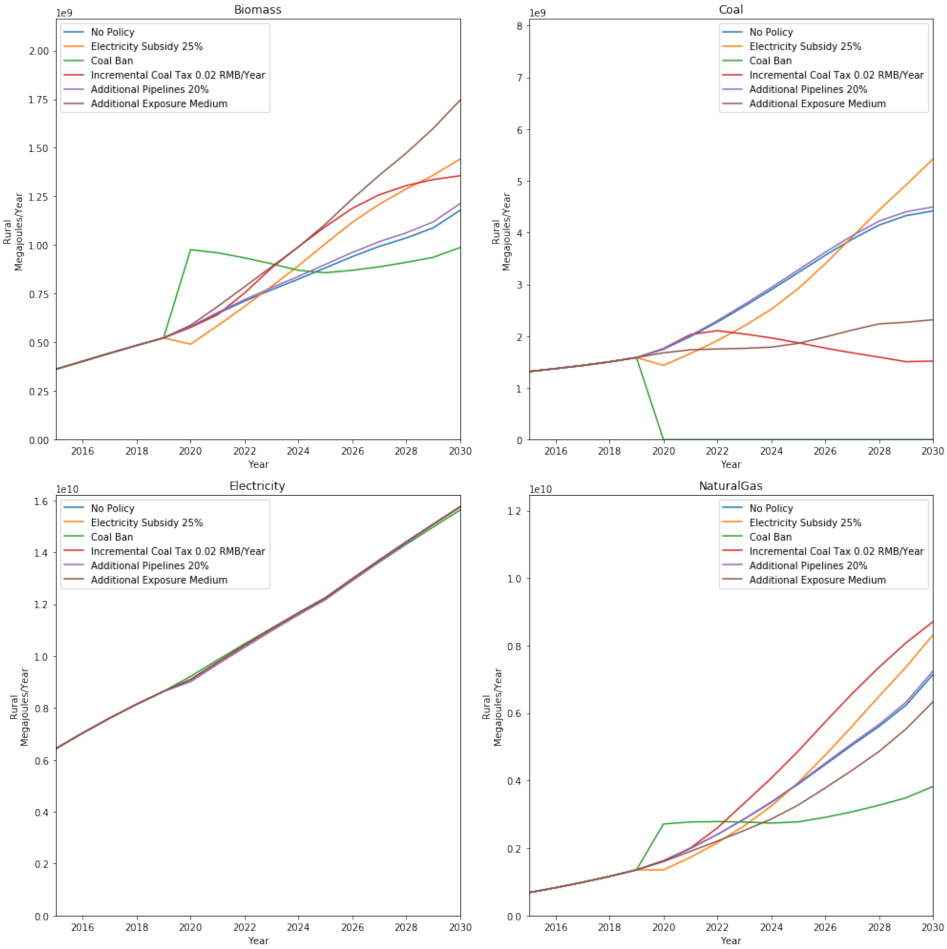



**Figure G65:** The energy consumption in Jingmen's rural area during the medium scenario levels of each individual policy.

# Appendix G.7 – Overview of all combined policy results

The results in the following charts are obtained from combined policies designed in **paragraph 5.5.2**, all of which were implemented in 2020. **Table G1** below indicates what policy combination each of the policies indicate in the charts provided below.

**Table G1:** an overview of the combined policies

| Policy Number | Policy A | Policy B |
|---|---|---|
| Policy 6 | Policy 1: Coal Ban | Policy 3: Electricity Subsidy |
| Policy 7 | Policy 1: Coal Ban | Policy 4: Additional Gas Lines |
| Policy 8 | Policy 1: Coal Ban | Policy 5: Increasing Public Exposure |
| Policy 9 | Policy 2: Incremental Coal Tax | Policy 3: Electricity Subsidy |
| Policy 10 | Policy 2: Incremental Coal Tax | Policy 4: Additional Gas-Lines |
| Policy 11 | Policy 2: Incremental Coal Tax | Policy 5: Increasing Public Exposure |
| Policy 12 | Policy 3: Electricity Subsidy | Policy 4: Additional Gas-Lines |
| Policy 13 | Policy 3: Electricity Subsidy | Policy 5: Increasing Public Exposure |
| Policy 14 | Policy 4: Additional Gas-Lines | Policy 5: Increasing Public Exposure |

The charts on the left give the total yearly energy demand for each of the areas (urban at the top, rural at the bottom). The graphs in the middle are the CP in graphs. This is the rate of increase of energy demand as a result of increased utility in convenience and price. The KW out graphs on the right-hand side are the rate of decrease in energy demand as a result of increased and knowledge and willingness to reduce energy emissions.

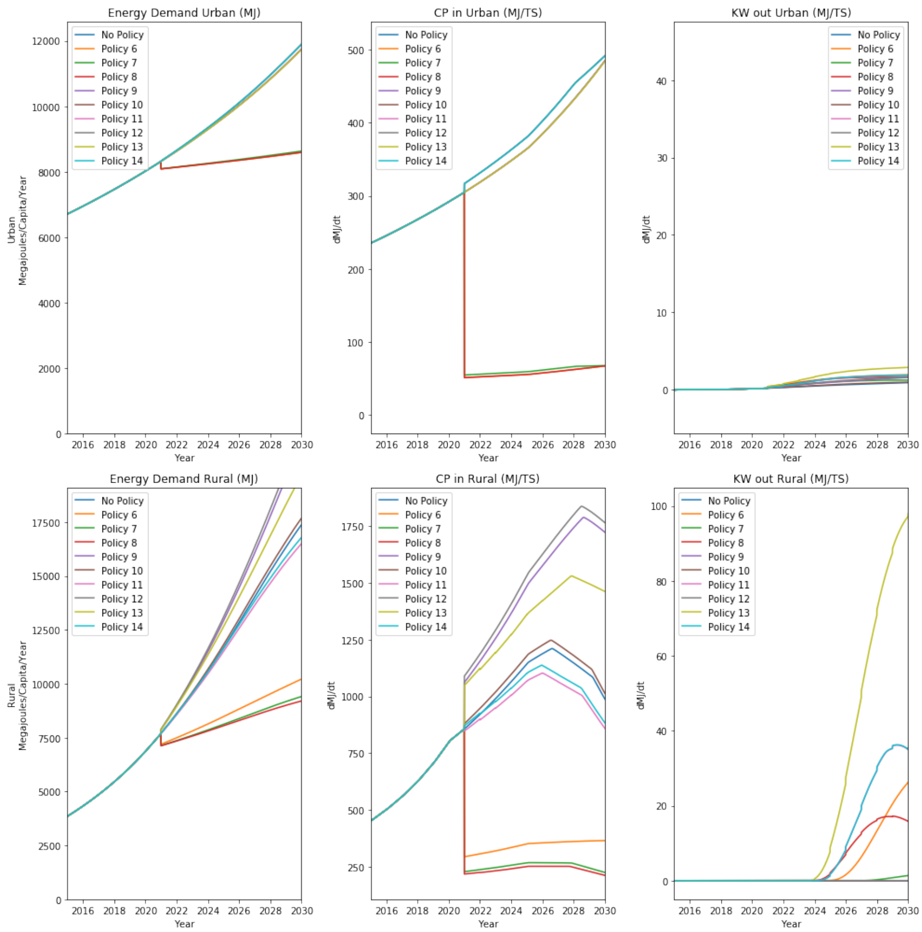



**Figure G66:** The energy demand per household as well as the rate of change of energy demand for the urban and rural areas as a result of the combined policy scenarios.

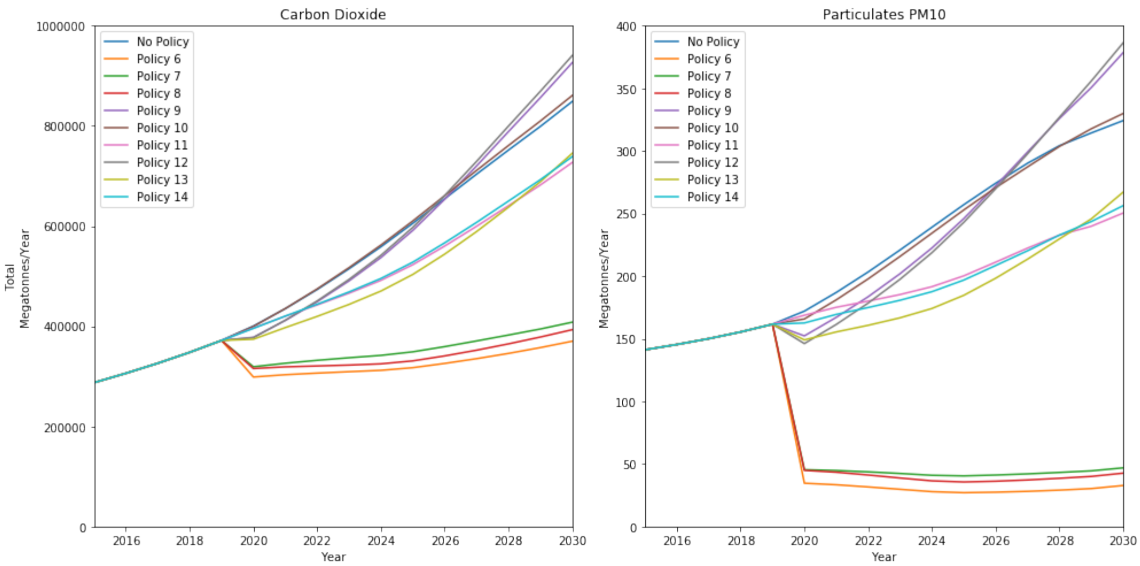



**Figure G67:** The total carbon dioxide and $PM_{10}$ particulates emissions in the combined policy scenarios in Jingmen.

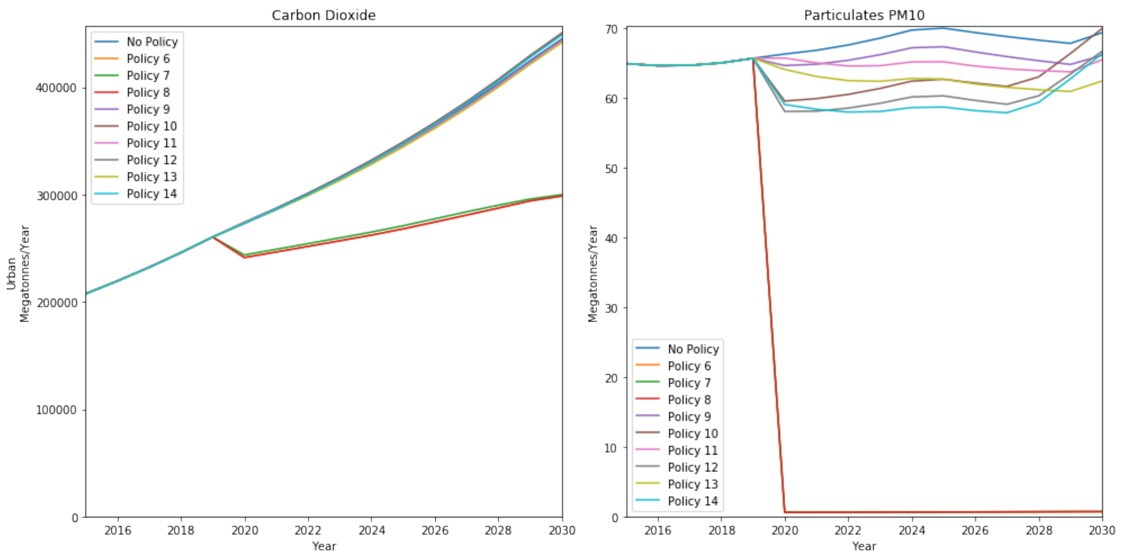



**Figure G68:** The total carbon dioxide and $PM_{10}$ particulates emissions in the combined policy scenarios in the urban area.

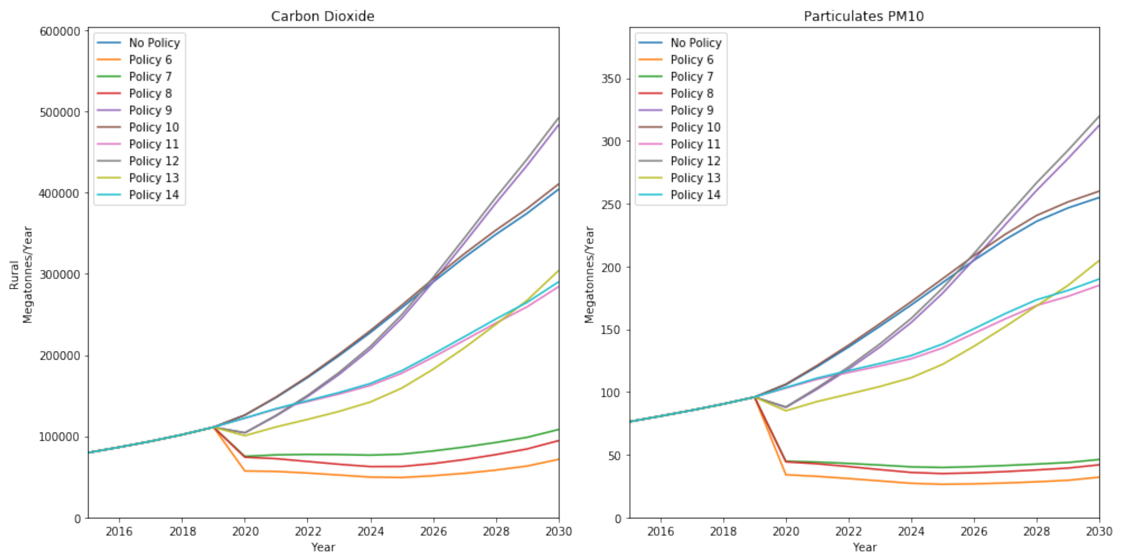



**Figure G69:** The total carbon dioxide and $PM_{10}$ particulates emissions in the combined policy scenarios in the rural area.

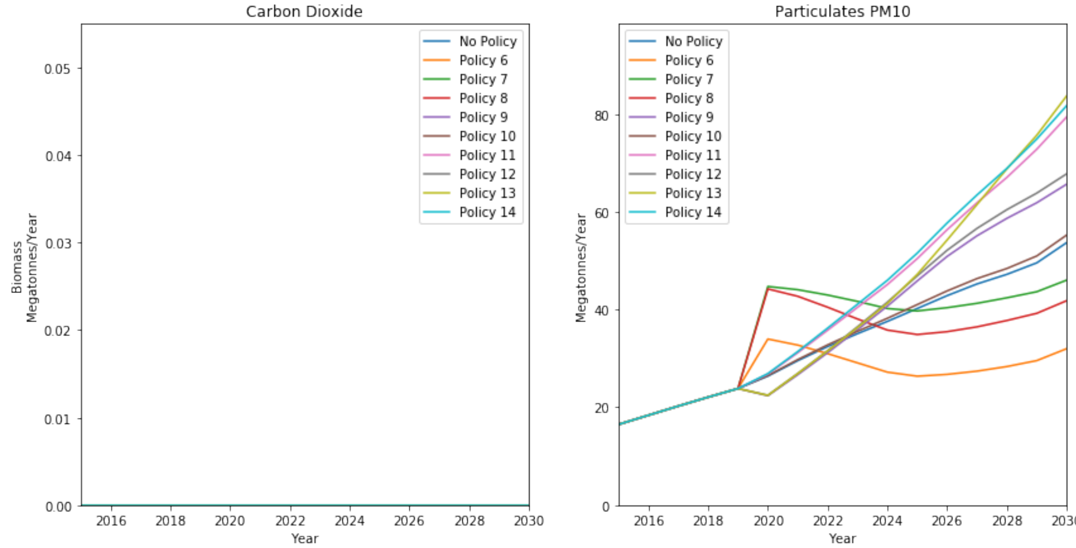



**Figure G70:** The carbon dioxide and $PM_{10}$ emissions coming from biomass consumption in the combined policy scenarios.

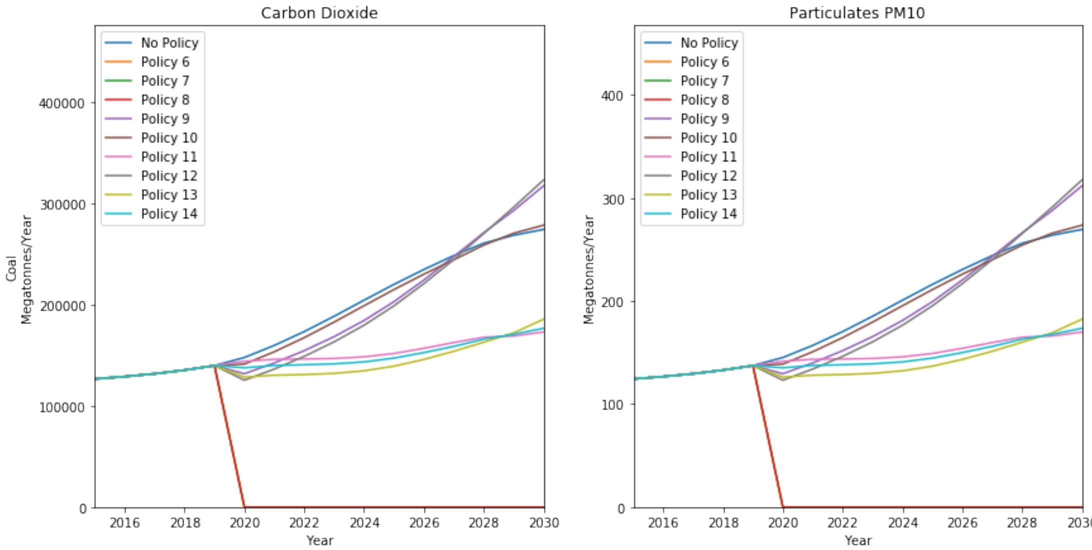



**Figure G71:** The carbon dioxide and $PM_{10}$ emissions coming from coal consumption in the combined policy scenarios.

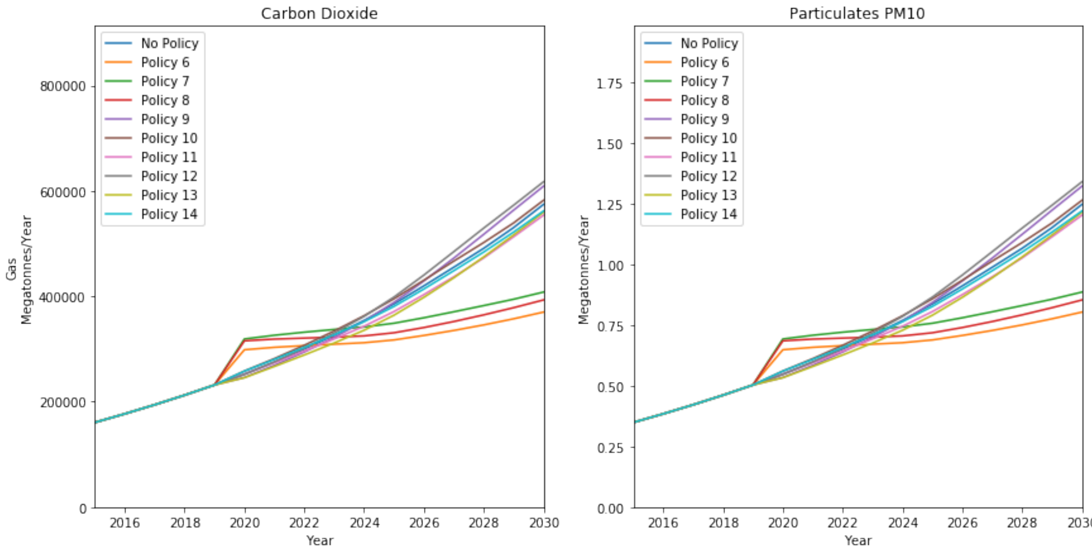



**Figure G72:** The carbon dioxide and $PM_{10}$ emissions coming from gas consumption in the combined policy scenarios.

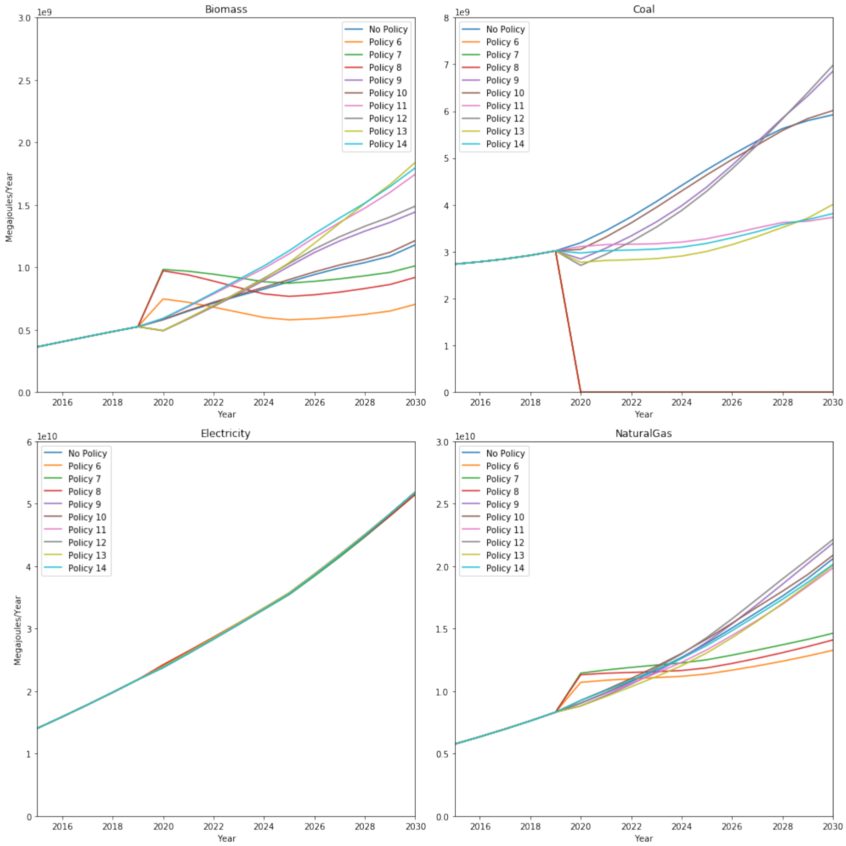



**Figure G73:** The total energy consumption of each individual energy fuel in Jingmen during the combined policy scenarios.

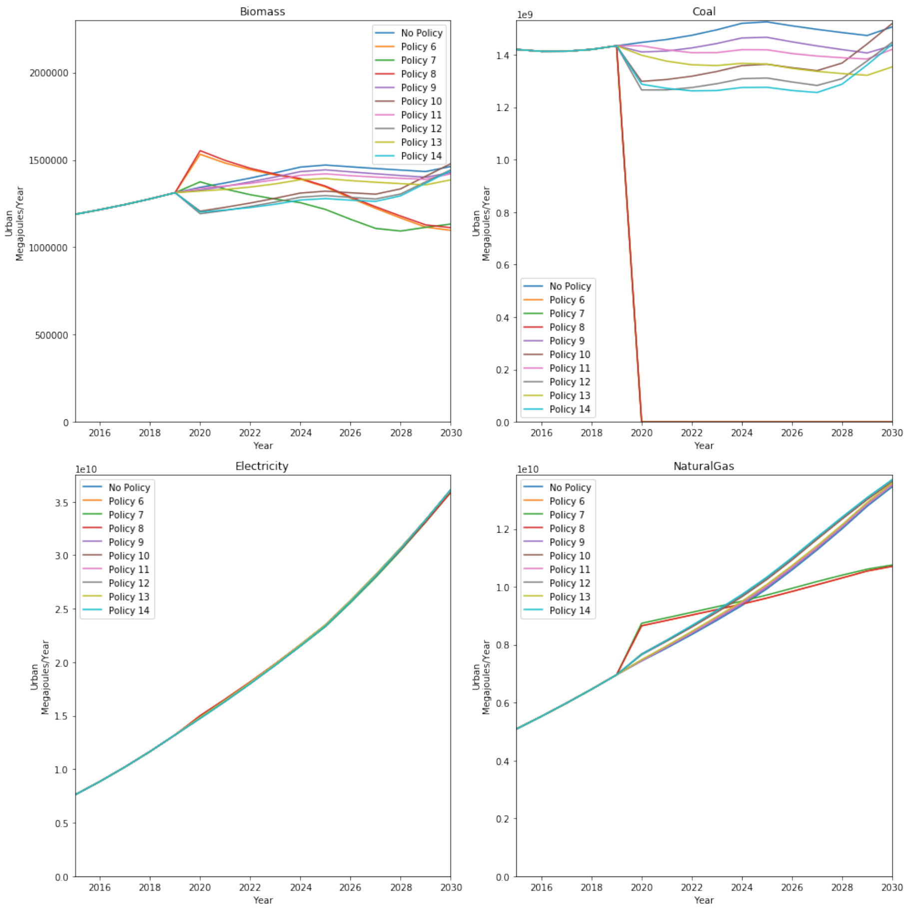



**Figure G74:** The total energy consumption in Jingmen's urban area during the combined policy scenarios.

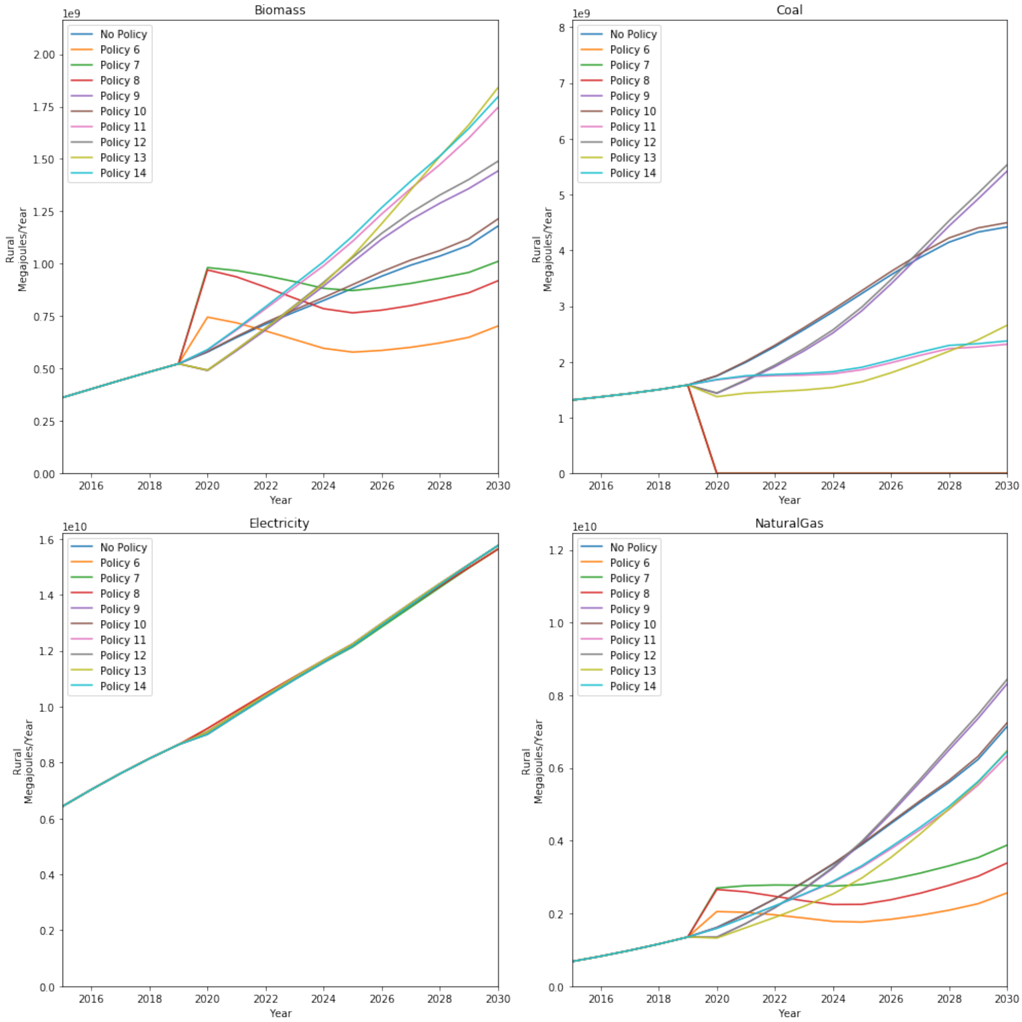



**Figure G75:** The energy consumption in Jingmen’s rural area during the combined policy scenarios.

## Appendix G.8 – Raw experimental data figures

The raw data results from all medium-level policies for the years 2025 and 2030 are shown in the tables below. All policies are implemented in the year 2020 and stay implemented until the year 2030.

NP: No policy;
CB: Coal Ban;
CT: Incremental Coal Tax (0.02 RMB/MJ/Year);
ES: Electricity Subsidy (25%);
AP: Additional Pipeline Infrastructure (20%);
AE: Additional Exposure (Medium Level, 50%)

**Table G2:** Urban demand in absolute terms

| | Total Urban (MJ) | | Biomass (MJ) | | Coal (MJ) | | Gas (MJ) | | Electricity (MJ) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2025 | 2030 | 2025 | 2030 | 2025 | 2030 | 2025 | 2030 | 2025 | 2030 |
| NP | 3.49E+10 | 5.11E+10 | 1.47E+06 | 1.46E+06 | 1.52E+09 | 1.51E+09 | 9.93E+09 | 1.35E+10 | 2.35E+10 | 3.61E+10 |
| CB | 3.31E+10 | 4.66E+10 | 1.38E+06 | 1.13E+06 | 0.00E+00 | 0.00E+00 | 9.61E+09 | 1.07E+10 | 2.34E+10 | 3.59E+10 |
| CT | 3.49E+10 | 5.11E+10 | 1.49E+06 | 1.49E+06 | 1.56E+09 | 1.56E+09 | 9.89E+09 | 1.34E+10 | 2.35E+10 | 3.61E+10 |
| ES | 3.49E+10 | 5.11E+10 | 1.44E+06 | 1.43E+06 | 1.47E+09 | 1.43E+09 | 9.99E+09 | 1.35E+10 | 2.35E+10 | 3.61E+10 |
| AP | 3.50E+10 | 5.13E+10 | 1.32E+06 | 1.48E+06 | 1.36E+09 | 1.52E+09 | 1.03E+10 | 1.36E+10 | 2.34E+10 | 3.61E+10 |
| AE | 3.49E+10 | 5.11E+10 | 1.42E+06 | 1.42E+06 | 1.42E+09 | 1.42E+09 | 1.00E+10 | 1.35E+10 | 2.35E+10 | 3.61E+10 |
| P6 | 3.31E+10 | 4.66E+10 | 1.35E+06 | 1.10E+06 | 0.00E+00 | 0.00E+00 | 9.61E+09 | 1.07E+10 | 2.34E+10 | 3.59E+10 |
| P7 | 3.30E+10 | 4.66E+10 | 1.22E+06 | 1.13E+06 | 0.00E+00 | 0.00E+00 | 9.72E+09 | 1.08E+10 | 2.33E+10 | 3.59E+10 |
| P8 | 3.31E+10 | 4.66E+10 | 1.35E+06 | 1.11E+06 | 0.00E+00 | 0.00E+00 | 9.61E+09 | 1.07E+10 | 2.34E+10 | 3.59E+10 |
| P9 | 3.49E+10 | 5.11E+10 | 1.44E+06 | 1.43E+06 | 1.47E+09 | 1.43E+09 | 9.99E+09 | 1.35E+10 | 2.35E+10 | 3.61E+10 |
| P10 | 3.50E+10 | 5.13E+10 | 1.32E+06 | 1.48E+06 | 1.36E+09 | 1.52E+09 | 1.03E+10 | 1.36E+10 | 2.34E+10 | 3.61E+10 |
| P11 | 3.49E+10 | 5.11E+10 | 1.42E+06 | 1.42E+06 | 1.42E+09 | 1.42E+09 | 1.00E+10 | 1.35E+10 | 2.35E+10 | 3.61E+10 |
| P12 | 3.50E+10 | 5.13E+10 | 1.30E+06 | 1.44E+06 | 1.31E+09 | 1.45E+09 | 1.03E+10 | 1.37E+10 | 2.34E+10 | 3.61E+10 |
| P13 | 3.49E+10 | 5.10E+10 | 1.39E+06 | 1.39E+06 | 1.36E+09 | 1.35E+09 | 1.01E+10 | 1.36E+10 | 2.35E+10 | 3.61E+10 |
| P14 | 3.50E+10 | 5.13E+10 | 1.28E+06 | 1.44E+06 | 1.28E+09 | 1.44E+09 | 1.03E+10 | 1.37E+10 | 2.34E+10 | 3.61E+10 |

**Table G3:** Rural demand in absolute terms

| | Total Rural (MJ) | | Biomass (MJ) | | Coal (MJ) | | Gas (MJ) | | Electricity (MJ) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2025 | 2030 | 2025 | 2030 | 2025 | 2030 | 2025 | 2030 | 2025 | 2030 |
| NP | 2.02E+10 | 2.85E+10 | 8.83E+08 | 1.18E+09 | 3.23E+09 | 4.42E+09 | 3.89E+09 | 7.14E+09 | 1.22E+10 | 1.58E+10 |
| CB | 1.59E+10 | 2.04E+10 | 8.58E+08 | 9.87E+08 | 0.00E+00 | 0.00E+00 | 2.78E+09 | 3.82E+09 | 1.22E+10 | 1.56E+10 |
| CT | 2.01E+10 | 2.73E+10 | 1.09E+09 | 1.36E+09 | 1.87E+09 | 1.52E+09 | 4.87E+09 | 8.70E+09 | 1.22E+10 | 1.58E+10 |
| ES | 2.01E+10 | 3.09E+10 | 1.01E+09 | 1.44E+09 | 2.92E+09 | 5.42E+09 | 3.94E+09 | 8.31E+09 | 1.22E+10 | 1.58E+10 |
| AP | 2.03E+10 | 2.87E+10 | 9.01E+08 | 1.21E+09 | 3.28E+09 | 4.49E+09 | 3.92E+09 | 7.24E+09 | 1.22E+10 | 1.58E+10 |
| AE | 1.85E+10 | 2.61E+10 | 1.11E+09 | 1.74E+09 | 1.86E+09 | 2.32E+09 | 3.27E+09 | 6.33E+09 | 1.22E+10 | 1.58E+10 |
| P6 | 1.46E+10 | 1.89E+10 | 5.79E+08 | 7.03E+08 | 0.00E+00 | 0.00E+00 | 1.76E+09 | 2.56E+09 | 1.22E+10 | 1.56E+10 |
| P7 | 1.58E+10 | 2.05E+10 | 8.72E+08 | 1.01E+09 | 0.00E+00 | 0.00E+00 | 2.79E+09 | 3.88E+09 | 1.21E+10 | 1.56E+10 |
| P8 | 1.52E+10 | 1.99E+10 | 7.66E+08 | 9.18E+08 | 0.00E+00 | 0.00E+00 | 2.25E+09 | 3.39E+09 | 1.22E+10 | 1.56E+10 |
| P9 | 2.01E+10 | 3.09E+10 | 1.01E+09 | 1.44E+09 | 2.92E+09 | 5.42E+09 | 3.94E+09 | 8.31E+09 | 1.22E+10 | 1.58E+10 |
| P10 | 2.03E+10 | 2.87E+10 | 9.01E+08 | 1.21E+09 | 3.28E+09 | 4.49E+09 | 3.92E+09 | 7.24E+09 | 1.22E+10 | 1.58E+10 |
| P11 | 1.85E+10 | 2.61E+10 | 1.11E+09 | 1.74E+09 | 1.86E+09 | 2.32E+09 | 3.27E+09 | 6.33E+09 | 1.22E+10 | 1.58E+10 |
| P12 | 2.02E+10 | 3.12E+10 | 1.03E+09 | 1.49E+09 | 2.98E+09 | 5.53E+09 | 3.99E+09 | 8.44E+09 | 1.22E+10 | 1.58E+10 |
| P13 | 1.79E+10 | 2.67E+10 | 1.04E+09 | 1.84E+09 | 1.64E+09 | 2.65E+09 | 2.98E+09 | 6.48E+09 | 1.22E+10 | 1.58E+10 |
| P14 | 1.85E+10 | 2.64E+10 | 1.13E+09 | 1.79E+09 | 1.90E+09 | 2.37E+09 | 3.31E+09 | 6.45E+09 | 1.22E+10 | 1.58E+10 |

**Table G4:** Urban demand in percentual terms compared to the no-policy alternative

| | Total Urban | | Biomass | | Coal | | Gas | | Electricity | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2025 | 2030 | 2025 | 2030 | 2025 | 2030 | 2025 | 2030 | 2025 | 2030 |
| CB | 95% | 91% | 94% | 77% | 0% | 0% | 97% | 80% | 100% | 99% |
| CT | 100% | 100% | 101% | 102% | 103% | 103% | 100% | 100% | 100% | 100% |
| ES | 100% | 100% | 98% | 98% | 96% | 95% | 101% | 100% | 100% | 100% |
| AP | 100% | 100% | 90% | 101% | 89% | 101% | 103% | 101% | 100% | 100% |
| AE | 100% | 100% | 97% | 97% | 93% | 94% | 101% | 101% | 100% | 100% |
| P6 | 95% | 91% | 91% | 75% | 0% | 0% | 97% | 80% | 100% | 99% |
| P7 | 95% | 91% | 83% | 77% | 0% | 0% | 98% | 80% | 99% | 99% |
| P8 | 95% | 91% | 92% | 76% | 0% | 0% | 97% | 80% | 100% | 99% |
| P9 | 100% | 100% | 98% | 98% | 96% | 95% | 101% | 100% | 100% | 100% |
| P10 | 100% | 100% | 90% | 101% | 89% | 101% | 103% | 101% | 100% | 100% |
| P11 | 100% | 100% | 97% | 97% | 93% | 94% | 101% | 101% | 100% | 100% |
| P12 | 100% | 100% | 88% | 99% | 86% | 96% | 104% | 102% | 100% | 100% |
| P13 | 100% | 100% | 95% | 95% | 89% | 90% | 102% | 101% | 100% | 100% |
| P14 | 100% | 100% | 87% | 98% | 84% | 96% | 104% | 102% | 100% | 100% |

**Table G5:** Rural demand in percentual terms compared to the no-policy alternative

| | Total Rural | | Biomass | | Coal | | Gas | | Electricity | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2025 | 2030 | 2025 | 2030 | 2025 | 2030 | 2025 | 2030 | 2025 | 2030 |
| CB | 69% | 54% | 97% | 84% | 0% | 0% | 71% | 54% | 100% | 99% |
| CT | 94% | 76% | 124% | 115% | 58% | 34% | 125% | 122% | 100% | 100% |
| ES | 111% | 123% | 114% | 122% | 90% | 123% | 101% | 116% | 100% | 100% |
| AP | 101% | 102% | 102% | 103% | 102% | 102% | 101% | 101% | 99% | 100% |
| AE | 99% | 95% | 125% | 148% | 58% | 52% | 84% | 89% | 100% | 100% |
| P6 | 73% | 59% | 66% | 60% | 0% | 0% | 45% | 36% | 100% | 99% |
| P7 | 70% | 54% | 99% | 86% | 0% | 0% | 72% | 54% | 99% | 99% |
| P8 | 69% | 53% | 87% | 78% | 0% | 0% | 58% | 47% | 100% | 99% |
| P9 | 111% | 123% | 114% | 122% | 90% | 123% | 101% | 116% | 100% | 100% |
| P10 | 101% | 102% | 102% | 103% | 102% | 102% | 101% | 101% | 99% | 100% |
| P11 | 99% | 95% | 125% | 148% | 58% | 52% | 84% | 89% | 100% | 100% |
| P12 | 112% | 125% | 117% | 126% | 92% | 125% | 102% | 118% | 99% | 100% |
| P13 | 108% | 113% | 117% | 156% | 51% | 60% | 76% | 91% | 100% | 100% |
| P14 | 100% | 97% | 128% | 152% | 59% | 54% | 85% | 90% | 99% | 100% |

**Table G6:** Percental urban and rural $CO_2$ and $PM_{10}$ emissions compared to the no-policy alternative

| | Urban $CO_2$ | | Rural $CO_2$ | | Urban $PM_{10}$ | | Rural $PM_{10}$ | |
|---|---|---|---|---|---|---|---|---|
| | 2025 | 2030 | 2025 | 2030 | 2025 | 2030 | 2025 | 2030 |
| NP | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| CB | 77% | 67% | 30% | 26% | 1% | 1% | 21% | 18% |
| CT | 100% | 100% | 86% | 78% | 103% | 103% | 72% | 51% |
| ES | 100% | 100% | 95% | 120% | 96% | 95% | 95% | 123% |
| AP | 100% | 101% | 101% | 102% | 90% | 101% | 102% | 102% |
| AE | 99% | 100% | 69% | 70% | 93% | 94% | 72% | 73% |
| P6 | 77% | 67% | 19% | 18% | 1% | 1% | 14% | 13% |
| P7 | 78% | 67% | 30% | 27% | 1% | 1% | 21% | 18% |
| P8 | 77% | 67% | 24% | 23% | 1% | 1% | 19% | 16% |
| P9 | 100% | 100% | 95% | 120% | 96% | 95% | 95% | 123% |
| P10 | 100% | 101% | 101% | 102% | 90% | 101% | 102% | 102% |
| P11 | 99% | 100% | 69% | 70% | 93% | 94% | 72% | 73% |
| P12 | 100% | 101% | 97% | 122% | 86% | 96% | 98% | 125% |
| P13 | 99% | 99% | 62% | 75% | 90% | 90% | 65% | 80% |
| P14 | 100% | 101% | 70% | 72% | 84% | 96% | 74% | 75% |

# Appendix H – Vensim model values

While some variables in the Vensim model can be taken from historical data and literature (such as fuel price, GDP and population), most values in the Vensim model are qualitative 'feelings' of individual households. Quantifying these values in a model is a necessary yet difficult task. However, for many variables the actual value is not as important as its relative value with regards to other figures. The qualitative Vensim model values have been based using three methods: if possible, they were based on survey data results. If this was deemed too impractical, the variables had been adjusted depending on educated estimations. During these estimations, attempts were made in keeping variables between rural and urban areas practical and in relation to one another in order to maintain homogeneity in the model. Lastly, error terms were calibrated in using yearbook data, data from Jingmen's energy balance that is originally used in the LEAP model, and estimations for the consumption between 2015 and 2018. This is done because the LEAP model had been developed using interpolations (short and long term) with the use of expert opinions from the city itself and other estimated data, despite formal data not being available. By including the estimates from the past years into the calibrations it allows the data to take a better approach in accordance with expert expectations into the future. During the standard model run, the following variables are used:

| Variable name | Value | Variable Explanation | Reason |
|---|---|---|---|
| Biomass harmfulness coefficient | 0.2 | Coefficient that portrays how harmful biomass is in comparison to coal; | Coal is considered a lot more harmful than biomass because of its direct impact on the environment. The danger of biomass to the environment is debatable. Although no real literature has been found to establish the comparative harmfulness between coal and biomass, the IPCC base in the LEAP model shows that the per MJ impact of biomass at 20-Year Global Warming Potential is about 20% of that of coal. |
| Coal stores elasticity rural | 10 | How many stores will close down and open up as a result of lower income these stores provide for shopkeepers; | Both rural and urban coal stores have a value of 'elasticity'. However, it is difficult to assign a variable to this. |
| Coal stores elasticity urban | 10 | | |
| Distance coefficient | 0.6 | The inconvenience that having to travel for fuel brings along. A distance coefficient of 1 describes that it is no extra inconvenience to travel in comparison to having the fuel delivered (like electricity). | For both urban and rural areas the value is placed at 0.6 because there is some inconvenience in having to travel for obtaining fuel, however this is mostly dependent on the distance to the nearest store. Therefore, the lack of convenience is more judged by the consumption of coal than is by the additional inconvenience for travelling of an individual by itself. |
| Effectiveness of learning rural | 0.5 | Describes what fraction of information provided to the public is retained by the public's knowledge in making conscious decisions about their fuel use. | No direct value can be placed on how effectively the people in rural and urban area will learn. The amount of knowledge people initially have is based on survey results, but this has limited impact on how effectively they draw in new information. |
| Effectiveness of learning urban | 0.5 | | |

| | | | |
|---|---|---|---|
| General information effectiveness urban | 0.15 | Describes what the effectiveness is of providing general information to the public (such as informative posters and articles about hazards of using coal and biomass) | New information would likely be more effective in the urban area than in the rural area because they place higher importance on long term effects such as the impact of fuels on health. |
| General information effectiveness rural | 0.1 | | |
| General convenience coal rural | 0.3 | The general convenience that the burning coal brings along, such as coal dust | Consuming coal is a considered a little more convenient in the rural area than in the urban area. This is because the urban area has little room for general ventilation since a larger population lives in high-rise apartment buildings. This is the consumption of mere coal by itself, and not the additional inconvenience caused by having to obtain the coal in the first place. It is estimated that the consumption of biomass is a little more convenient than coal because burning leaves slightly less long-lasting harmful materials. Hence, the convenience of biomass is set to be 0.2 higher than coal. However, both fuels still score relatively low in overall convenience as they both give off undesirable materials after consumption. This is not present in using gas. Using gaseous fuel tanks increases convenience by 0.3 as the fuel is a lot cleaner. However, every so often it needs replacing. Gas from the natural gas grid directly connected to the houses and electricity consumption both have a maximum convenience of 1. |
| General convenience coal urban | 0.25 | | |
| Increase convenience coal biomass rural | 0.2 | Describes what the additional convenience is in using biomass over coal. | |
| Increase convenience coal biomass urban | 0.2 | | |
| Increase convenience biomass gas rural | 0.3 | Describes what the additional convenience is in using gas over biomass. | |
| Increase convenience biomass gas rural | 0.3 | | |
| Initial number of stores rural | 1000 | Estimated number of stores that sell fuel in a specific area. | As it is in no way possible to know the exact number of stores that sell coal in the neighbourhood, both are initially set as 1000. This means that there is a higher density of stores in the urban area as this is a lot smaller. |
| Initial number of stores urban | 1000 | | |
| Maximum decay rate urban | 0.6 | The decay in knowledge as a result of loss of interest and information not being provided at a constant rate. | It is estimated that the maximum decay rate in the urban area is slightly higher than that in the rural area because of the 'lifestyle speed' and busyness in the urban area. |
| Maximum decay rate rural | 0.5 | | |
| Min CP value urban | 0.5 | The minimum value of a combined price-convenience factor necessary in order to cause people to demand more energy | It is estimated that many people in the urban area already consume a near maximum amount of energy. Convenience and price utilities need to increase much more in order to have a meaningful impact in overall energy demand. |
| Min CP value rural | 0.3 | | |
| Min KW value urban | 0.3 | The minimum value of a combined knowledge-willingness factor necessary in order to cause people to demand less energy | People in the urban area are much more likely to reduce their energy as a result of increased knowledge and willingness than people in the rural area. |
| Min KW value rural | 0.6 | | |

| | | | |
|---|---|---|---|
| Convenience weight urban | 0.7 | Importance of convenience in determining the overall fuel utility | Both urban and rural areas place high importance to convenience, however as price weighs most importantly in a factor between 0 and 1, it is expected that relative to price, convenience weighs higher in the urban area than in the rural area due to the difference in income levels. |
| Convenience weight rural | 0.5 | | |
| Knowledge and willingness weight rural | 0.25 | Importance of knowledge and willingness in determining the overall fuel utility | Knowledge and willingness is set as 1/4$^{th}$ the importance of that of price. It is not a final determining factor, but it is important especially since the willingness incorporates factors of price. |
| Knowledge and willingness weight urban | 0.25 | | |
| Price weight rural | 1 | Importance of price in determining the overall fuel utility | Both in the urban and rural areas price is assumed to be the most important factor. |
| Price weight urban | 1 | | |
| Willingness value rural | 1.5 | Importance of willingness as a factor in determining the overall knowledge and willingness | The willingness value determines how important the final impact of knowledge is on the utility of the variable as a whole. In the rural area, this factor is much higher: even if people have a high level of knowledge about effective energy consumption, it is less likely to have a high impact on consumption because of the higher costs of the clean fuels. |
| Willingness value urban | 0.4 | | |
| Standard rural biomass coefficient | -0.5 | Factor error coefficient term when determining the utility of each fuel. These variables have been calibrated to available data. | Each of the standard coefficients are terms that are multiplied by the price, convenience and knowledge-willingness variables. This means that these coefficients can be seen as time-dependent error terms that further amplify or temper the effect of the terms on each of the fuel utility function. The values can be seen as individual fuel-dependent factors that the model has been considered too little or too much by the model.<br><br>It is important to note that the urban and rural coefficients are completely independent from one another, the fuels should be seen in relation to the other fuel coefficients in the same area. The coefficients in the urban area are overall much higher than those in the rural area. The consumption of electricity, coal and gas is further amplified. The effects in the rural area on the other hand are generally diminished.<br>The harmful fuels in the rural area have a negative value, which indicates that over the period of the simulation the actual utility of consuming such fuels is actually much lower than initially anticipated. |
| Standard urban biomass coefficient | 0 | | |
| Standard rural electricity coefficient | 2.75 | | |
| Standard urban electricity coefficient | 2.5 | | |
| Standard rural gas coefficient | -0.5 | | |
| Standard urban gas coefficient | 3 | | |
| Standard rural coal coefficient | -1.5 | | |
| Standard urban coal coefficient | 2.5 | | |
| Urban coal error term | 3 | Fixed constant error term when | These error terms are fixed, meaning that they create the anchor points of the |

| | | | |
|---|---|---|---|
| Urban electricity error term | 0.25 | determining the utility of each fuel. These variables have been calibrated between logical figures. | utility for each individual fuel. High error terms do not necessarily mean that the model is wrong, but rather that the base value is higher or lower than provided in the model. These terms can therefore be seen as the terms which fix the height of the demand, rather than the slope of the curves. |
| Urban biomass error term | 0 | | |
| Urban gas error term | 2 | | |
| Rural coal error term | 3 | | |
| Rural electricity error term | -2.75 | | |
| Rural biomass error term | 3 | | |
| Rural gas error term | 3.5 | | |