UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA

MÁSTER OFICIAL EN EL SECTOR ELÉCTRICO

Master in Economics and Management of Network Industries

TESIS DE MÁSTER

Distributed Solar Thermal Energy in China: A regional analysis of building energy costs and CO2 emissions

AUTOR: **Shi WANG**

MADRID, February 2014

Autorizada la entrega de la tesis de master del alumno/a:
(Poner el nombre del alumno/a)

……………………………………………………….

EL DIRECTOR
(poner el nombre del Director)

Fdo.: ……………………… Fecha: ……/ ……/ ……

EL TUTOR
(poner el nombre del Tutor)

Fdo.: ……………………… Fecha: ……/ ……/ ……

Vº Bº del Coordinador de Tesis
(poner el nombre del Coordinador de Tesis)

Fdo.: ……………………… Fecha: ……/ ……/ ……

UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

MÁSTER OFICIAL EN EL SECTOR ELÉCTRICO

Master in Economics and Management of Network Industries

TESIS DE MÁSTER

Distributed Solar Thermal Energy in China: A regional analysis of building energy costs and CO2 emissions

AUTOR: **Shi WANG**

SUPERVISOR: **Michael STADLER**

MADRID, February 2014

SUMMARY

Energy consumed in buildings accounts for about 40% and 25% of total annual energy consumption in the United States (U.S.) and China, respectively. This paper describes a regional analysis of the potential for distributed energy resources (DER) to save energy and reduce energy costs and carbon emissions in Chinese residential buildings. The expected economic performance of DER is modeled for a multi-family residential building in different Chinese climate zones. The optimal building energy economic performance is calculated using the DER Customer Adoption Model (DER-CAM), which minimizes building energy costs for a typical reference year of operation. Several types of DER, including combined heat and power (CHP) units, solar thermal, photovoltaics (PV), and battery storage are considered in this analysis.

Estimating the economic performance of DER technologies requires knowledge of a building's end-use energy load profiles. EnergyPlus simulation software is used to estimate the annual energy performance of commercial and residential prototype buildings in the two countries. Figures ES-1 and ES-2 show energy usage intensity for residential and commercial buildings in representative and Chinese cities.

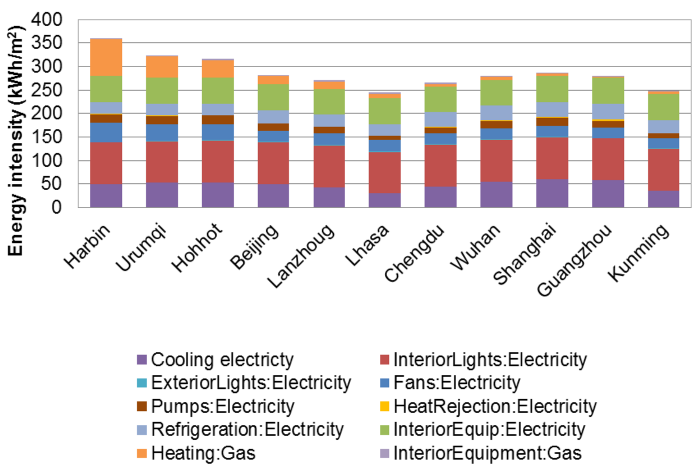


Figure ES-1 - Annual energy usage intensity of office complexes in representative U.S. cities and shopping malls in representative Chinese cities

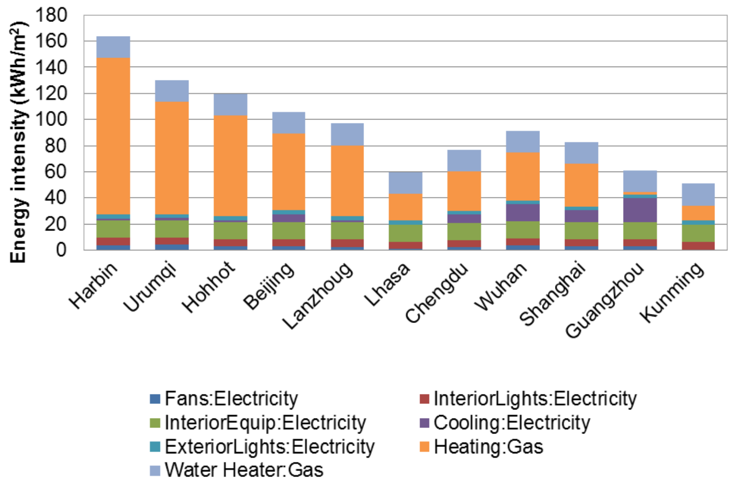


Figure ES-2 – Annual energy usage intensity of residential buildings in representative Chinese cities

This study investigates in depth the factors influencing the adoption of solar thermal technology in Chinese residential buildings. Each factor’s impact on solar thermal installation in residential buildings is evaluated through DER-CAM sensitivity analysis and the results are explained by using a sensitivity coefficient. The solar thermal variable cost ($/kW) sensitivity coefficient is affected by buildings’ heating load and the availability of solar radiation. As shown in Figure ES-3, the solar thermal variable cost sensitivity coefficient goes down with the buildings’ heating load. The Chinese city with the highest annual total heating demand, Harbin, is most sensitive to solar thermal technology cost. In contrast, Guangzhou, in southern China where heating demand is relatively low, is less sensitive to technology cost. Natural gas prices also play an important role in whether solar thermal technology is attractive. In general, solar thermal energy is attractive in places where natural gas prices are high. In the cities where natural gas prices are lower, customers are less likely to install solar thermal water heaters or other solar thermal technologies because these installations may not be cost effective.

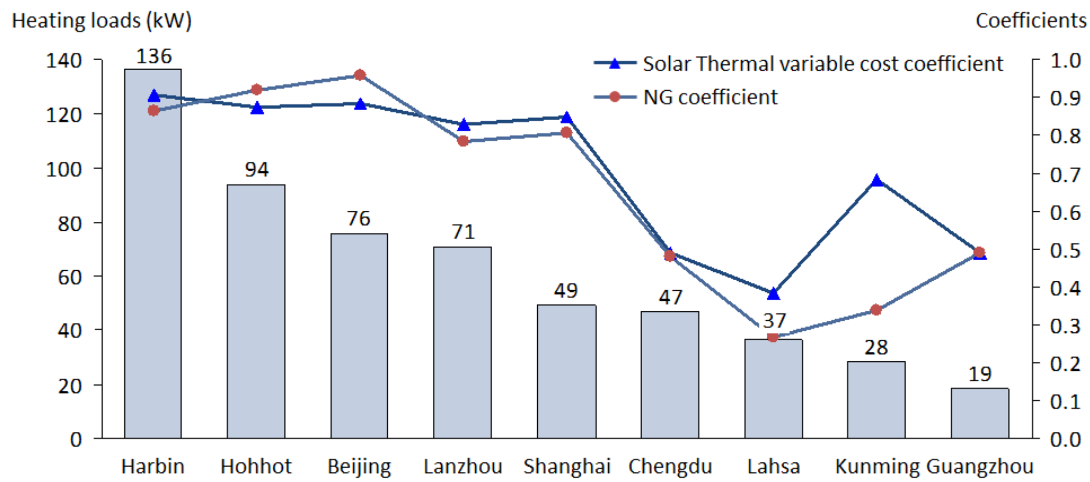


Figure ES-3 – Impact of heating load on solar thermal adoption's sensitivity to variable cost and natural gas price

Where solar radiation is ample, the price of solar technologies has less influence on whether this technology is adopted. Conversely, in places where solar radiation is limited, solar technologies will not be selected even when technology cost is low. As a result, solar thermal installation is not sensitive to technology cost. Figure ES-4 shows the rank of sensitivity coefficients of solar thermal variable cost.

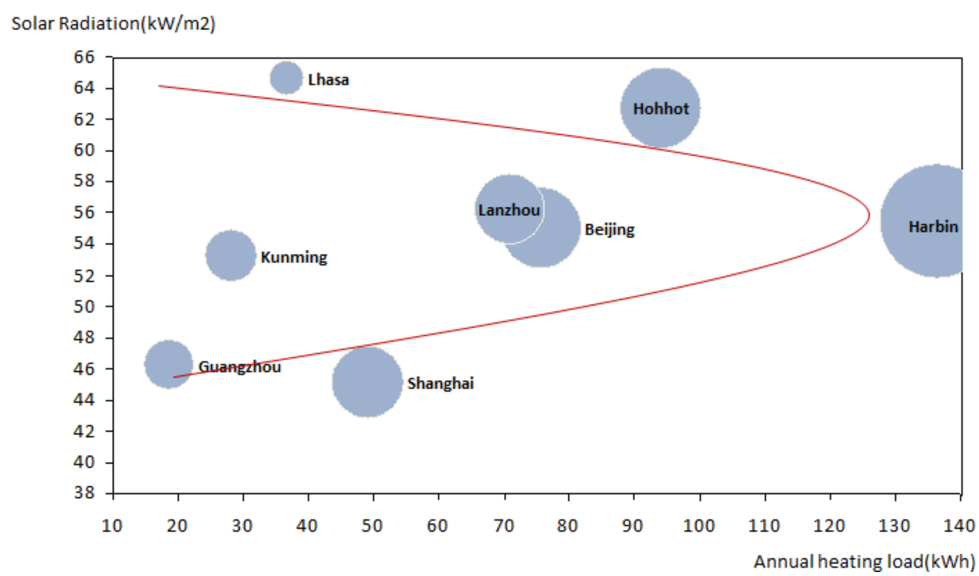


Figure ES-4 – Impact of heating load and solar radiation on solar thermal's sensitivity to variable cost

In summary, for solar thermal technology in Chinese residential buildings, the northern and eastern parts of China are more sensitive to changes in the cost of the technology. That is, if technology costs decrease in the future, residents living in these regions will be likely to adopt more solar thermal systems than those living in other regions. The southern part of China is less sensitive to technology cost. Cities like Lhasa on the Tibetan Plateau and Chengdu in the Sichuan Basin exhibit the least sensitivity to solar thermal technology costs.

Factors that may positively or negatively affect the procurement of solar thermal systems are:

- Large domestic water and space heating loads
- Abundant solar resources
- High cost of alternative energy
- Availability of area for collectors

Regression coefficients give us quantitative indicators of what will happen if technology costs decrease. In certain cities, reducing solar thermal variable cost yields promising increase of solar thermal adoption. However, the sensitivity of solar thermal adoption to its variable cost varies with building's heating load and cities solar radiation.

Solar thermal technologies compete with PV technologies in regions where prices of alternative fuels like natural gas are higher. In Guangdong, Yunnan, and Tibet provinces, it is seen more competition between these two types of solar systems if technology costs reduce or natural gas prices increase. Heat storage is the complementary technology because the combined use of solar thermal and heat storage technologies makes it possible to save the solar energy generated in the daytime for use during the evening when demand is high. Therefore, an increase in installations of one technology will boost customers' investments in the other.

Subsidies to encourage investment in solar thermal technologies should be attributed to regions sensitive to technology cost. Incentive policies, such as providing to investors a fixed amount of subsidy for each kW installed, is more effective in northern China. Prices of conventional fuels like natural gas will play an important role in customers' investment decisions. Higher natural gas prices are indirect incentives to residents to switch to solar thermal. The relationships among different distributed technologies must be considered when making policies. For example, giving incentives to both solar thermal and PV might not be effective because these two solar technologies compete for the same space, and the availability of space will limit the maximum number of solar collectors that can be installed.

TABLE OF CONTENTS

Acknowledgements

I wish to express my debt of gratitude to my thesis supervisor and director, Dr. Michael Stadler, Dr. Chris Marnay and Prof. Javier García González. They have been supportive since the day I began working on my thesis. They patiently provided the vision and advice necessary for me to complete my dissertation.

I would like to acknowledge the academic and technical support of the University of Pontificia Comillas, University of Paris-Sud XI, and European Commission particularly for the award of Erasmus Mundus Master Scholarship that provided the necessary financial support for this master program.

Special thanks to my fellow colleagues for the friendship and environment they created within this master program and for their assistance when I needed help.

LIST OF FIGURES AND TABLES

1 INTRODUCTION

Solar thermal technology uses the sun's energy, rather than fossil fuels, to generate marginal low-cost, environmentally friendly thermal energy. China is one of the largest energy consumers and producers in the world. Over 70% of its energy is provided by coal. Due to rapid economic growth, its energy demand has soared in the past decade which has caused energy shortages, environmental pollution, and ecological deterioration. The rise of demand is also the one of the key drivers for increasing fuel consumption, network expansion and renewable energy development. China has abundant solar resources, and solar thermal conversion systems have been studied for more than 20 years. The solar thermal industry has been developing rapidly in the past ten years. Meanwhile, renewable and distributed energy has caught the eyes of China's new generation of government leaders. In the country's 12th Five Year Plan, development of solar energy has been made a priority.

The purpose of this research is to assess the state of the art, and the overall prospect of buildings utilization of distributed solar thermal energy in different climate zones in China, based on economic and environmental optimizations. By taking into consideration factors like technology advances, policy directions and market trends, the goal of this study is to give investors and policy-makers in China a view of the further development of distributed solar thermal energy.

Solar power is a growing industry in China providing nearly half of world's production of solar PV and thermal panels. As the majority of products are exported, the country is trying to accelerate domestic installation. The solar powered water heater industry has been well development in China even in the absence of supporting policies between 1998 and 2008. In 2007 and 2009, two incentive policies aiming to accelerate industry development were introduced. In addition to the promising path for solar thermal water heating industry, technology has brought other possibilities. Solar thermal air conditioning and heating technologies are gradually showing their value, especially in distributed energy systems. Pilot projects have been implemented in various places in China.

The concept of the microgrid has made it possible to use heat as the energy form for transmission and storage. Solar thermal technologies can provide high temperature heat that can be used for water heating, air cooling and space heating. The combined use of solar thermal panels, absorption chillers and possibly heat storage devices can provide buildings with solar powered energy cycles. However, technologies using electricity or other fuels can also feed the demand with energy, maybe at lower cost. It has been shown in previous research that at current cost, solar thermal technology is rather competitive in residential buildings in China where the demand for domestic hot water is high, while the technology brings less benefit in commercial buildings where air conditioning demand is larger, however, solar air conditioning can be attractive given that air conditioning demand to some extent follows solar radiation cycle of the day. The SACE (solar air conditioning in Europe) project concluded that solar air conditioning has a strong potential for significant primary energy savings in Europe.

China is a country with a large territory. Tariff of purchased energy such as electricity and natural gas varies in different regions due to natural resource distribution and other factors. Provinces in the west like Tibet, Qinhai and Xinjiang receive larger amount of solar radiation, whereas in the eastern coastal areas radiation is relatively low because of cloud cover. Population density and industrial activities in the eastern and southern areas dominate total energy demand and land use. Thus, central station concentrated solar energy generation requires long distance transmission from the west to the east. Despite the lower level of radiation in the east, over 2/3 of China's total areas has abundant solar source which makes it applicable for distributed solar energy development. People living in different areas have different living habits causing varied demand patterns. Moreover, unlike in the US where states keep high level of autonomy, Chinese local government enjoys less decision making power and policies made by the central government may not perfectly apply to all the regions. Therefore, a regional analysis is of great importance.

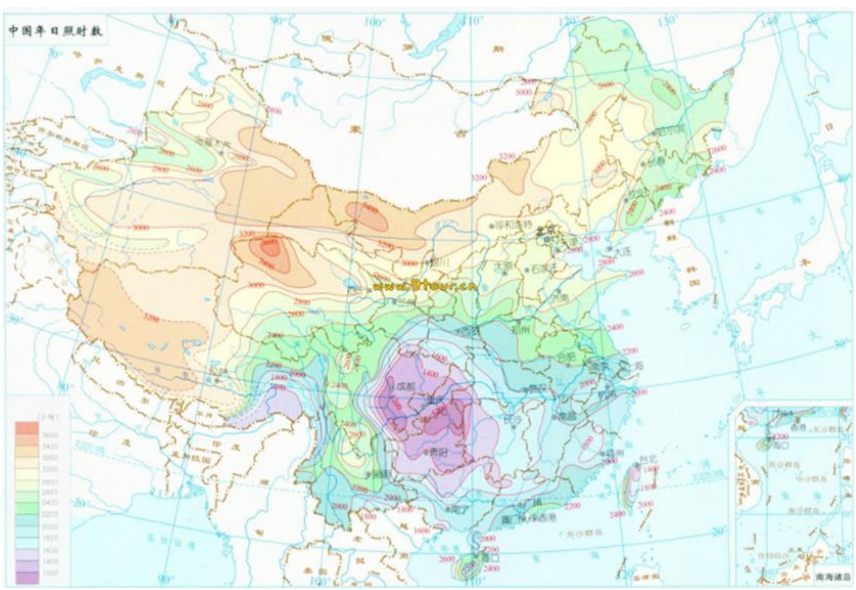


Figure-1 Distribution of China's solar energy resources

1.1 Objectives of the master thesis

The main objective is to explore the potential of solar thermal energy in distributed applications in China by conducting a regional analysis and to address the corresponding policy mechanisms to accelerate the utilization of solar thermal energy.

To reach the main objective, the following problems must be properly tackled.

1) How the utilization of solar thermal technologies in microgrid integration would affect overall performance? As solar thermal technologies advance and cost decreases, what is the anticipated share of solar thermal technologies in the investing decision making process of microgrid design?
2) What is the competitiveness of distributed solar technologies compared with other distributed technologies? Technologies, including CHP, solar thermal and others generate heat which can be used for water heating, space heating and air conditioning, while heat can also be provided by purchasing gas or electricity. In particular, solar thermal and PV will be in competition when roof area becomes a constraint in places with abundant solar radiation.
3) How will investment in distributed energy plans affect the CO2 emissions of the system? This problem brings into the picture environmental impacts which are key issues in the highly polluted cities of China. The tradeoff between cost and environmental benefits answers the question how policy should be made to incentivize investors as well as addressing environmental problems.
4) What are the policy implications based on the analysis at the regional level? What instruments should be considered for the implementation of these policies?

1.2 Solar thermal industry: technologies and international experience

Solar thermal is a technology for converting solar energy to thermal energy. Solar thermal collectors are classified by the United States Energy Information Administration as low, medium, or high-temperature collectors. Low-temperature collectors are flat plates generally used to heat swimming pools. Medium-temperature collectors are also usually flat plates but are used for heating water or air for residential and commercial use. High-temperature collectors concentrate sunlight using mirrors or lenses and are generally used for electric power production. Solar thermal energy is different from and much more efficient than photovoltaics, which converts solar energy directly into electricity. While existing generation facilities provide only 600 megawatts of solar thermal power worldwide in October 2009, plants for an additional 400 megawatts are under construction and development is underway for concentrated solar powe rprojects make it a total to 14,000 megawatts.

The difference between solar thermal and PV technologies lies in whether it creates electricity or heating water. While the spot efficiency of solar thermal modules is extremely efficient, well over 90 percent, compared to between 12 percent and 16 percent efficient for commercially available solar PV modules, there are other factors favoring solar thermal technology adoption.

Solar PV has a few distinct advantages:

1) It can be designed and installed on a specific customer's house, also grid tied systems have an almost unlimited demand to feed into the grid.

2) Residential systems can be cheaply designed and constructed. Systems can be fairly accurately quoted even from inspection of Google Earth.

3) The market is growing as more countries and places adopt solar PV policy and the installed costs are falling dramatically.

Solar thermal has advantages too, but some of the advantages can be disadvantages:

1) It's a mature industry and technology. Modules are cheap to manufacture and thus there are lot of manufacturers. This is good news because the systems are already cheap, it’s bad news because any significant market share increase will likely need to come from a factor other than decreased installation costs, namely higher energy costs, business model innovation, or change of local policies.

2) The technology must be tied to a specific load. This can make design more expensive because each project requires a site visit by an experienced professional and also limits system size because all energy must be consumed in the specific building.

Thus, Solar thermal makes the most sense for a very specific group of customers in the right market. For policy makers and from an energy perspective, solar thermal is a much better investment. The unsubsidized return of both technologies side-by-side favors solar thermal because for less money, it will generate more energy and offset more energy that would otherwise need to be produced.

While concentrated solar thermal heat plant technologies are well under development, distributed solar thermal energy has been developed for decades. Main applications that utilize solar thermal energy include solar water heating, air heating and air conditioning. In Europe, Over the past ten years, there was a continuous rapid uptrend in the growth rate up till 2008; followed by a decline, steeper in the first two years (2009, 2010) and then flattening out (2011, 2012). The variation in the newly installed capacity is illustrated with the blue line in the graph on figure 2. In spite of the decrease over the last four years, the annual market size has doubled, over the past decade at an average annual growth rate of 10%.

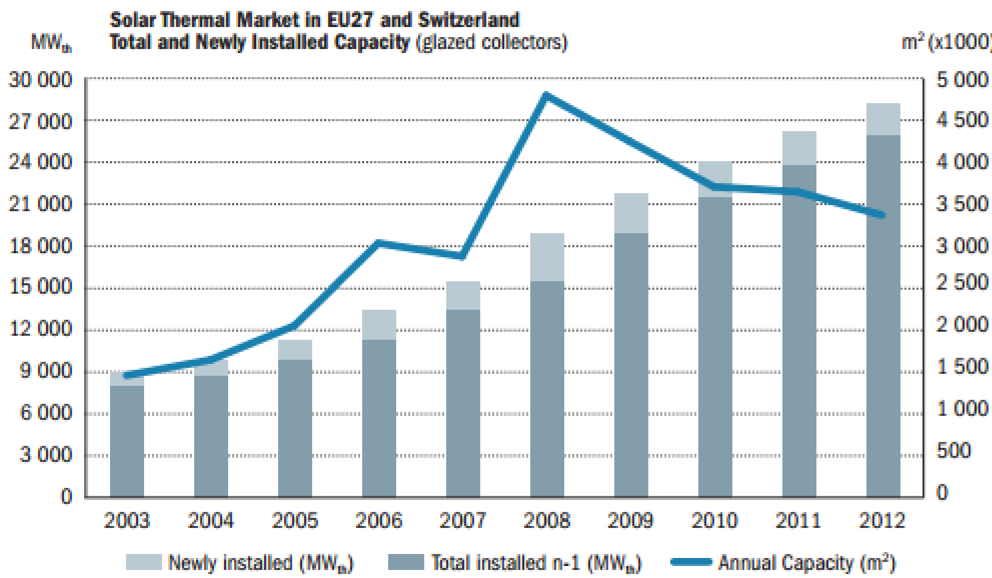


Figure-2 Solar Thermal Market EU27

2 OVERVIEW OF SOLAR THERMAL INDUSTRY IN CHINA

Compared with photovoltaic (PV) technologies, solar thermal technologies are not mature yet in China and standards are needed to standardize the market. More power was generated by solar thermal facilities than by PV facilities in 2011 worldwide. China dominates the global solar thermal market by taking up 64 to 69 percent of the existing solar heating and cooling capacity. But most of the heating capacity in China comes from solar water heaters, indicating that the industrial solar heating market is underdeveloped in China.

In 2010, China's paper making, food, tobacco, wood, chemical, pharmaceutical, textile, plastics industries consumed 450 million tons of standard coal equivalent， mainly for heating or drying.

The country is largely investing in clean energy planning as pollution has becoming an inevitable issue in front of the government. The country plans to divert its ever increasing demand of energy to clean energy solutions, and solar energy is among the top options.

2.1 Stages of development

The 1970s saw the beginning of solar thermal application in China. In late 1980s, with the introduction of flat plate collector and the development of production line of self-designed anodic oxidation selective coating, China began to manufacture flat plate solar water heater. But the progress was slow due to the problems like cost and compatibility. Major breakthroughs made in the 1990s in the technology and production of all-glass vacuum tubes enabled China to develop self-designed production line of vacuum tubes and start mass production of solar water heater with all-glass vacuum tube. It gives great momentum to the industrialization of China's solar thermal industry. With the development of economy, the demand of urban and rural residents in China for living and bathing has increased substantially. Together with electric water heater and gas water heater, solar water heater becomes one of the major products supplying hot water for domestic use.

Since the1990s, the market of solar water heater in China has maintained a rapid growth in over ten years. The annual output of solar water heater increased from 6.1 million square meters in the year 2000 to 42 million square meters in 2009, with an annual growth rate of 24%. Especially since the Renewable Energy Law took place, the application and extension of solar water heater has been greatly advanced contributed by the enforcement of national policies concerning the development of renewable energy. From 2006 to 2009, the average annual growth rate of the sales of solar water heater was kept at almost 30%.

The solar water heater industry has developed in China without incentive policies. China provided subsidies twice to seven solar water heater manufacturers for their technical transformation and industrialization projects in 2000 and 2005. However, the solar water heater industry is not listed in the national financial support catalog, so there is not stable finance sourcing, nor regular subsidy mechanism for the industry. There are no incentive policies concerning value-added tax and income tax for solar water heater industry in China. Only solar water heater companies classified as high-tech enterprises by local governments can enjoy preferential policies for high-tech enterprises. At present, two incentive policies have the greatest influence on solar water heater industry. The first one is the policy of mandatory installation of solar water heater implemented since 2007 by some local governments at provincial and municipal levels. The market under the influence of the second policy is the urban market. The carrier of the installation of solar water heaters is newly built or reconstructed buildings, which usually requires a construction cycle of two to three years from the examination and approval of the real estate project to the installation of the solar water heater, so it takes time for the effect of this policy to be seen. The second is the subsidy policy for solar water heaters in the household appliances going to the countryside scheme implemented since 2009.

2.2 The solar thermal market

The solar thermal water heater industry has been developing since late 70s. It saw a large growth in the 90s because of the advance of vacuum cube technology. Solar thermal water heater is one of the most well developed distributed energy generations in China. Up till now, residential hot water is only provided by solar thermal heater in many regions in China.

2.2.1 Potential for DER in U.S. and Chinese Buildings

For the first research task described in this thesis, to evaluate the potential for DER residential buildings in different regions of China, the Distributed Energy Resources Customer Adoption Model (DER-CAM) is used, which determines the optimal combination of technologies to supply energy needs. Modeling of distributed energy system adoption requires the following inputs: the building's end-use energy load profile, the city's solar radiation data, local electricity and natural gas tariffs, and the performance and cost of available technologies. The methodology and key assumptions used are described in the next chapter.

2.2.2 Potential of Distributed Solar Thermal Energy in Chinese Buildings

The major research task described in this thesis project is an analysis of the overall potential for utilizing distributed solar thermal energy in residential buildings in different climate zones in China to achieve optimum economic and environmental benefits. For this analysis, factors including technology advances, policy directions, and market trends were considered, with the intent of giving investors and policy makers in China a view of the development potential for distributed solar thermal energy. In China, until 2009, approximately 15 billion m^2 solar thermal collectors are installed in buildings. Figure 3 shows solar thermal installation capacity in China.

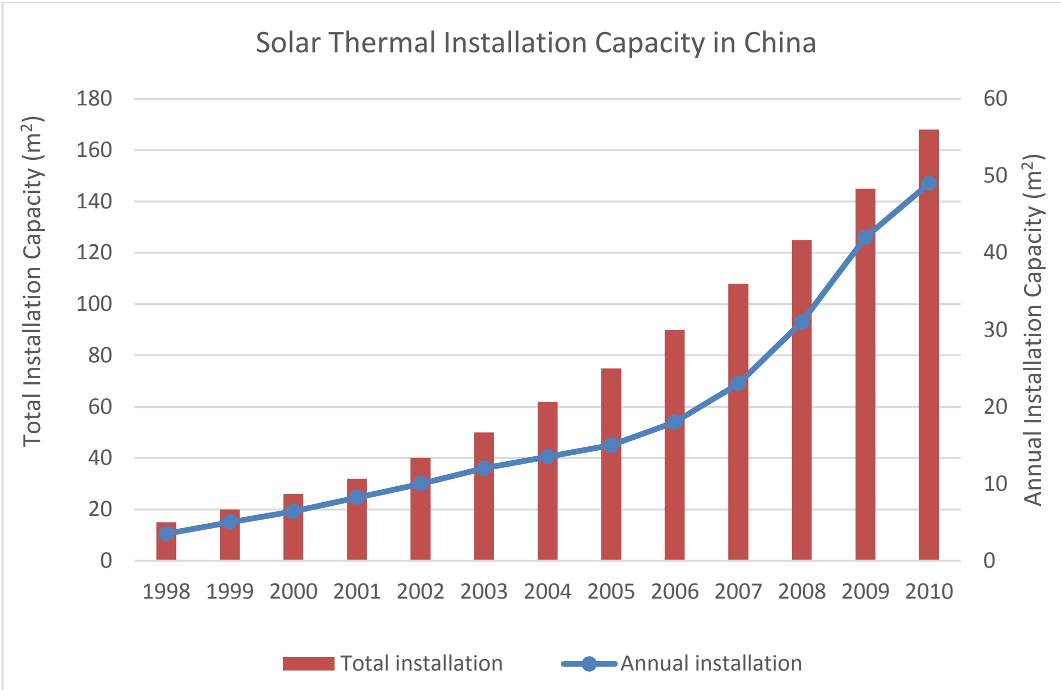


Figure 3 – Solar Thermal Installation Capacity in China

One reason for the in-depth study of the potential of solar thermal in China is that China supplies nearly half of the world's production of solar PV and thermal panels. Although the majority of products are exported, China is trying to accelerate domestic installation. The solar-powered water heater industry is well developed in China despite a lack of supporting policies between 1998 and 2008. In 2007 and 2009, two incentive policies aimed at accelerating development of the solar water heating industry were introduced. Other related technologies also show promise. Solar thermal air conditioning and heating technologies are gradually demonstrating their value, especially in distributed energy systems. Pilot projects have been implemented in various places in China[1].

The potential of solar thermal technology has blossomed as the microgrid[2] concept has made it possible to use heat as the energy form for transmission and storage. Solar thermal technologies can provide high-temperature heat that can be used for water heating, air cooling, and space heating. The combination of solar thermal panels, absorption chillers, and possibly heat-storage devices can provide buildings with solar-powered energy cycles. However, technologies using electricity or

[1] Solar thermal air conditioning means to use solar hot water to drive absorption chiller to provide chilled water for air conditioning.

[2] Microgrid means a grid system which can be operated as an island and connected with macro-grid.

other fuels can also feed demand with energy, possibly at lower cost. Previous research has shown that, at current costs, solar thermal technology is competitive in residential buildings in China where demand for domestic hot water is high, but the technology brings less benefit in commercial buildings (Wang 2011). However, solar air conditioning can be attractive because air conditioning demand to some extent follows the solar radiation cycle of the day. For example, the Solar Air-Conditioning in Europe project concluded that solar air conditioning has a strong potential to save significant primary energy in Europe.

3 METHODOLOGY

3.1 DER-CAM

The Distributed Energy Resources Customer Adoption Model (DER-CAM) is developed in Lawrence Berkeley National Laboratory for over 12 years. DER-CAM (Stadler et al.2008) is a mixed-integer linear program (MILP) written and executed in the General Algebraic Modeling System (GMAS). It is designed to minimize the total costs or total CO_2 emissions for a given modeled site for energy provision, including utility natural gas and electricity purchase, amortized capital, variable and maintenance costs for distributed generation (DG) investments. The model addresses the following issues:

1) Which is the lowest-cost combination of distributed generation technologies that a specific customer can install?
2) What is the appropriate level of installed capacity of these technologies that minimizes cost?
3) How should the installed capacity be operated so as to minimize the total customer energy bill?

In this study, costs minimization objective function is used to develop energy solutions and implement sensitivity analysis of solar thermal installation, and CO_2 minimization or multi-objective optimization will be used in CO_2 analysis in further study.

The DER-CAM approach is technology-neutral and can include energy purchases, on-site conversion, both thermal and electrical on-site renewable generation and consumption. The model requires site-specific inputs such as: energy loads, electricity and natural gas rates and tariffs, and DG investment options. Key inputs and outputs of the model are as follows.

Inputs into the model:

- Customer's end-use load profiles (typically for space heat, hot water, gas only, cooling, and electricity only)
- Customer's default electricity tariff, natural gas prices, and other relevant price data
- Capital, operating and maintenance (O&M), and fuel costs of the various available technologies, together with the interest rate on customer investment
- Basic physical characteristics of alternative generating, heat recovery and cooling technologies, including the thermal-electric ratio that determines how much residual heat is available as a function of generator electric output

Outputs to be determined by the optimization model are:

- Capacities of DG and CHP technology or combination of technologies to be installed
- When and how much of the capacity installed will be running
- Total cost of supplying the electric and heat loads.

The key assumptions are:

- Customer decisions are made based only on direct economic criteria. In other words, the only possible benefit is a reduction in the customer's electricity bill.
- No deterioration in output or efficiency during the lifetime of the equipment is considered. Furthermore, start-up and other ramping constraints are not included.
- Reliability and power quality benefits, as well as economies of scale in O&M costs for multiple units of the same technology are not directly taken into account.
- Possible reliability or power quality improvements accruing to customers are not considered.

DER-CAM tool is used for this study. DER-CAM has been in development by Lawrence Berkeley National Laboratory (LBNL) for more than 10 years and has been widely used to find optimal combinations of DER technologies and to perform energy-economic assessments of DER. Figure 4 shows the energy flows modeled by DER-CAM.

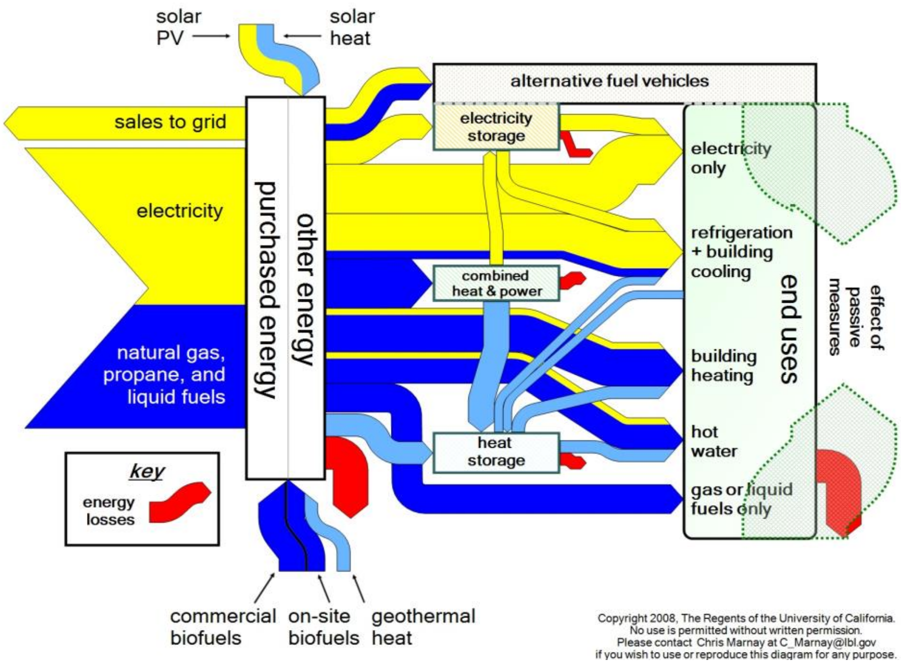


Figure 4 – Input/Output representation of DER-CAM optimization, with building energy service requirements to the right and the available energy sources to the left

DER-CAM finds the combination of supply technologies as well as the optimal operating schedule. The tool can solve the entire building energy system holistically and simultaneously in a technology-neutral manner; that is, the model seeks to minimize cost, energy use, carbon, other metrics, or a combination of metrics while considering all technology opportunities equally and equitably trading them off against each other.

3.2 Data

The distributed energy system modeling requires inputs such as a building's energy load profile, the city's solar radiation, electricity and natural gas tariffs, and the performance and costs of technologies. Data will be gathered from public industrial reports, government documents as well as LBNL database. One residential building prototype will be put into various regions to do DER-CAM optimizations.

3.2.1 Building prototype

The Chinese buildings were a seven-story, 36,000-m^2 retail shopping center with two basement floors, and a 10-story, high-rise, multi-family building. The residential prototype building was developed based on the U.S. DOE multi-family apartment prototype building along with Chinese studies of buildings that comply with China's residential building energy-efficiency standards.

The residential building is a 10-floor high-rise multi-family apartment (NREL, 2011; Field K., 2010). The floor plans of the prototype buildings are shown in Figure 5. The residential prototype building is developed based on U.S. DOE multi-family apartment prototype building, as well as Chinese studies in compliance with China's residential building energy efficiency standards (MoHURD, 2010; MoHURD, 2003). The prototype building characteristics are shown in Table 1 for Shanghai climate zone. Buildings in other climate zones are modeled with the similar internal load and lighting density, while building envelope parameters and HVAC operation schedules are determined based on Chinese commercial and residential building codes.

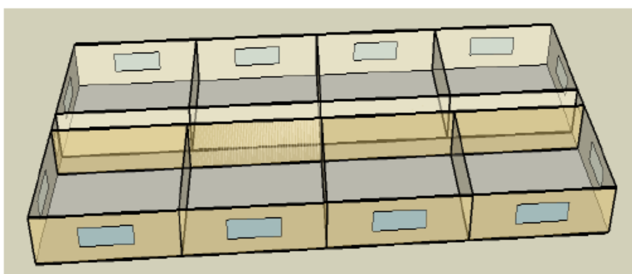


Figure-5 Residential building floor plan

The floor area is around 780m2, so 700m2 is set to be the maximum roof are for solar technologies including solar thermal and photovoltaic. Prototype residential building characteristic in Shanghai Climate zone is as follows.

Floors	10 floors above grade, 783.6m2/floor
Building Envelope	Ext-wall: U=1.0 W/m2*K
	Roof: U=0.7W/m2*K
Fenestration	Window to wall ratio=0.2
	Window: =4.0W/m2*K. SHGC=0.4
	Shading: No

Lighting	Apartment: 1.9W/m2
	Office: 10W/m2
Internal Loads	Max Apt Occupancy: 2 persons/apt
	Apt Equipment intensity: 2.3 W/m2
Infiltration	1.2 ACH
External Loads	Elevator motor capacity: 15kW
	Exterior Lighting: 1W per façade area (17.00-23.00)
Operation schedule	24/7
HVAX air sys	Room AC and EX coils, cooling COP=3.1
	OA supply rate: 20m3/(h.person)
Room temperature set point	Cooling:26; Heating:18
HVAC operation seasons	Summer season: 6/15-10/1
	Winter season:1/1-3/1,11/15-12/31

Table 1- Building Prototype

3.2.2 Load profile

It is of great importance to understand the buildings' energy load profiles to estimate the economic performance of distribute energy resources technologies in China. The annual energy performance of the residential prototype buildings is simulated in EnergyPlus (DOE,2011). The internal load of a residential building is much smaller than a retail building, and thus it is more sensitive to climate. The building prototype in Kunming (temperate climate zone) has the best energy performance, while buildings in Lhasa (cold climate zone) uses less energy compared with buildings in other cold climate regions, mainly because of the high altitude and ample solar radiation. Electricity and hot water loads vary less across all cities while heating and cooling demands vary a lot among different cities. In the cities in the northern part of China like Harbin, Urumqi and Hohhot, heating load is the majority of energy demand. In the cities in the southern part like Guangzhou and the cities in the eastern costal area like Shanghai, cooling demand is relatively high during the year.

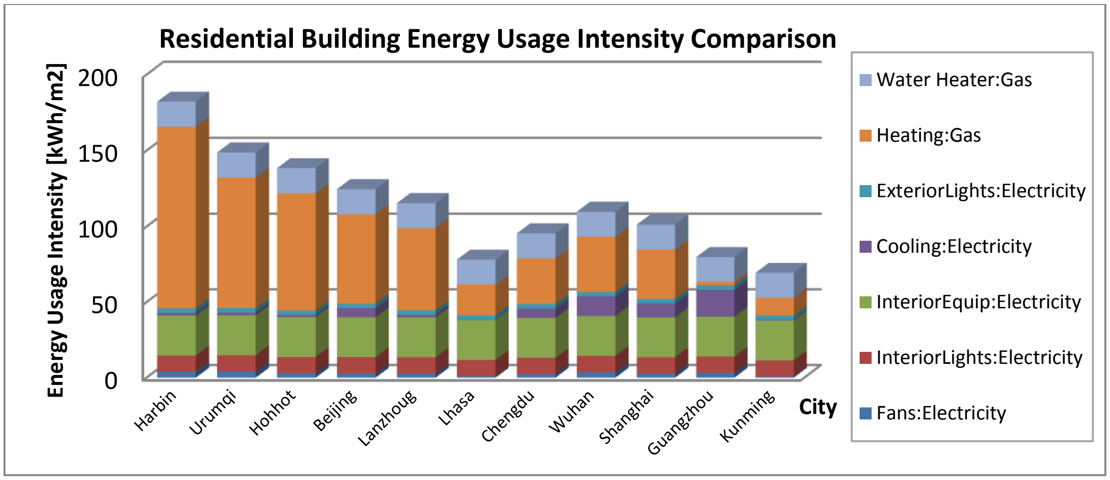


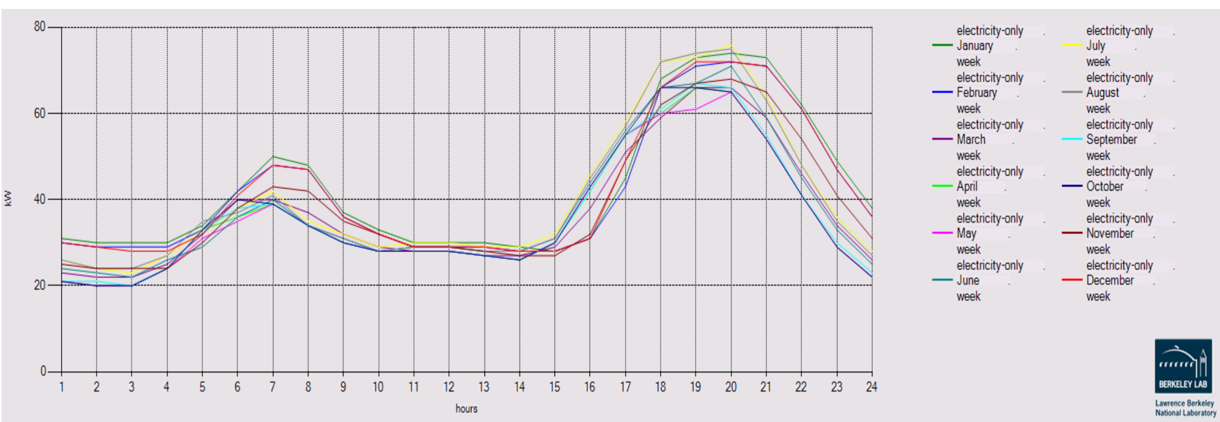
Figure-6 Residential building energy usage intensity comparison

DER-CAM requires 6 types of defined loads:

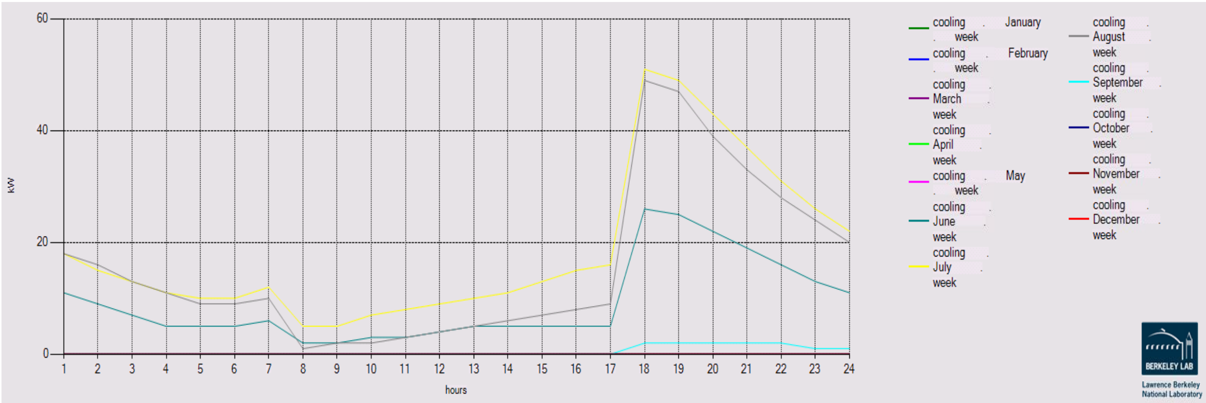
- Electricity only
- Natural gas only
- Space heating
- Water heating
- Refrigeration
- Cooling

For each of the defined load type, DER-CAM requires 24 hours data from a typical day in each month of the year. The load profile of Beijing is shown as follows. Graphs are from Webopt.

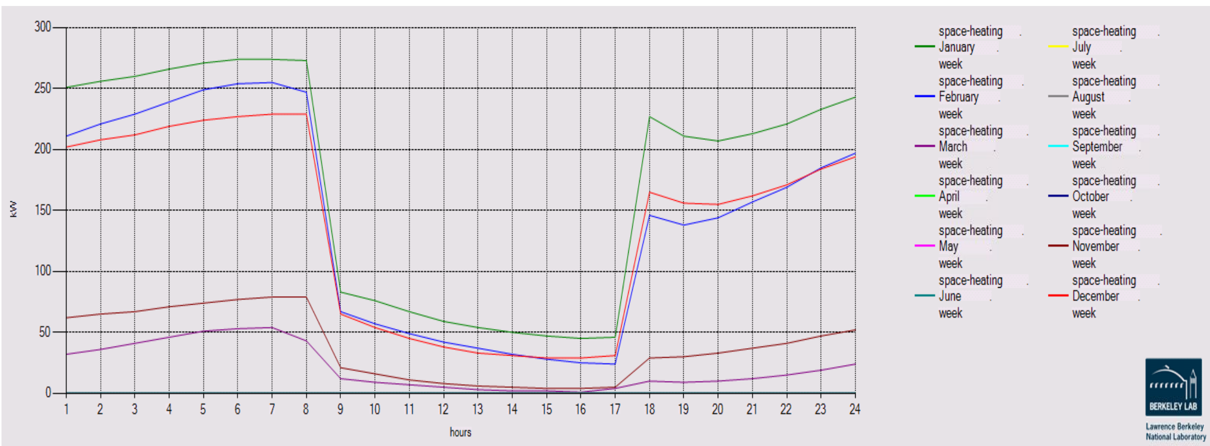
Electricity-only:



Cooling:



Space heating:



Water heating:

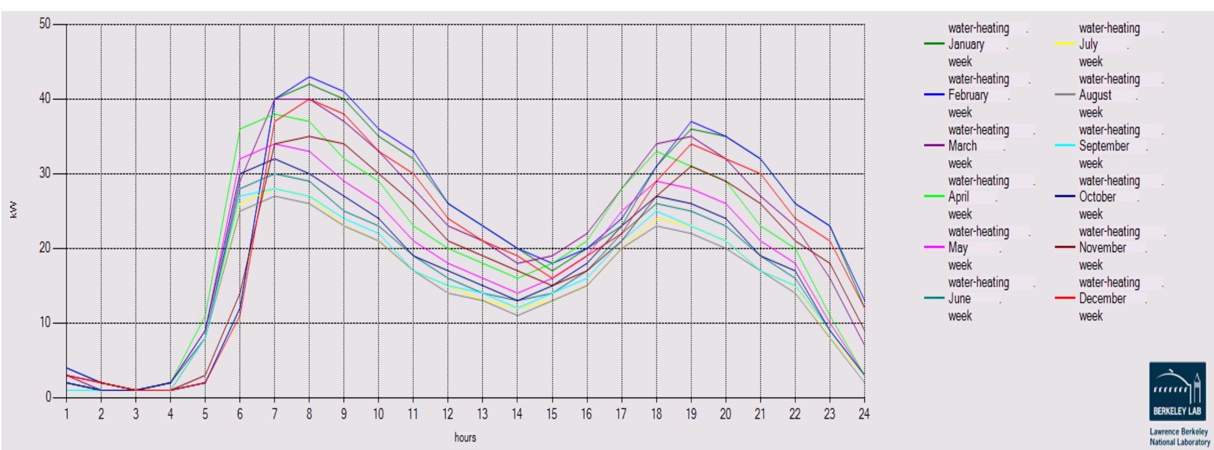


Figure-7 Load profile, Beijing, all year

For all the cities, load inputs are electricity only, space heating, and water heating and cooling. Refrigeration and natural gas only types are not defined in our load inputs. It is assumed that there will be no natural gas only or refrigeration only demand. From the load profiles, we can see that water heating and electricity only loads do not vary much during different months of the year. The peak of electricity-only demand happens at 7 a.m. in the morning and 8pm in the evening. The peak of water heating demand also happens at around 8am in the morning and 7pm in the evening. Water heating demand is higher in January than in July mainly because water temperature is lower in the winter than in summer. The cooling demand only happens in four months in summer time. July and August see the highest cooling demand while there is little cooling need in September. The peak of cooling demand happens from 5pm to 11pm in the evening due to the fact that it is a residential building prototype. The cooling load profile may change in the weekdays and weekends. A higher cooling demand is expected on the weekends. However, in our study, weekends and weekdays demands are not differentiated. Space heating load varies the most during the year. December, January and February are the months with the highest space heating demand, and space heating demand peaks in the evening mainly because the occupancy rate of residential buildings is higher in the evening and also it is much colder in the evening than in the daytime.

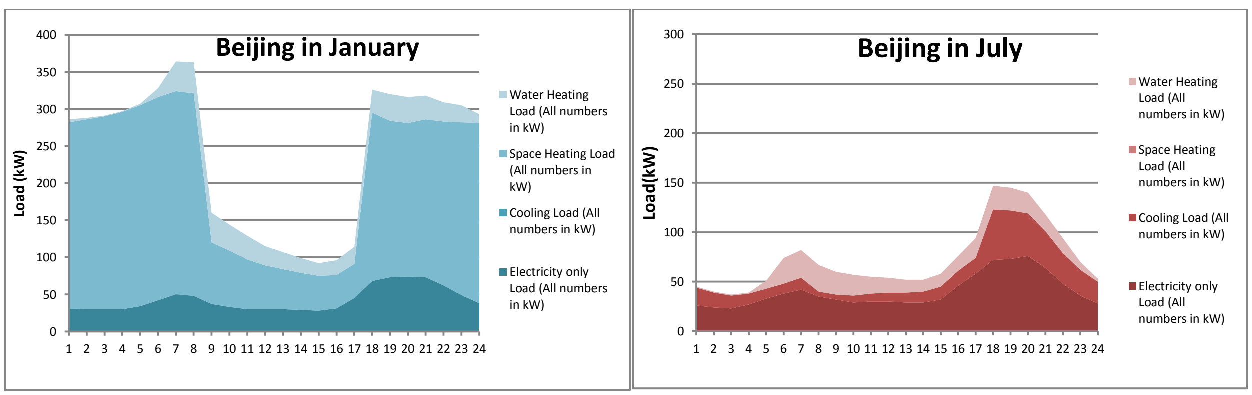


Figure-8 Load profile in a day, Beijing

Apparently, the total load is higher in winter in Beijing because of heating demand, and total load profile is quite different in different months due to the seasonal change of heating and cooling demands. For solar thermal technology, which provides heat into the system, higher heating demand gives more incentives to customers to install solar thermal technologies. However, since in summer time space heating is not required, the scheduling of solar thermal technology usage will balance and determine how much capacity is optimal for investment. This optimization will be done by DER-CAM. Also, the peak of heating demand which happen in the evening doesn't match the peak of solar radiation which happens in the daytime. Therefore, proper storage tools may be needed in combination use with solar thermal technologies.

The variation of load profile in different cities is the key point of doing sensitivity analysis in the next step of study. Whether installed capacity of solar thermal is sensitive to one or more of the independent variables depends largely on the internal characteristics of load profile of each city. The load profiles vary largely in different regions across China. In the northern part of China, heating demand is high in cities like Harbin, Urumqi and Hohhot. Most of the cities in the north are provided with public heating systems where the heating energy comes from coal burning in the winter. However, in our study, heating demand is considered not covered by public heating services. Cities in the south like Guangzhou require lower heating energy annually but present higher cooling demand. Cooling demand is also high in eastern coastal area (Shanghai, Wuhan). Even Beijing located north of yellow river.

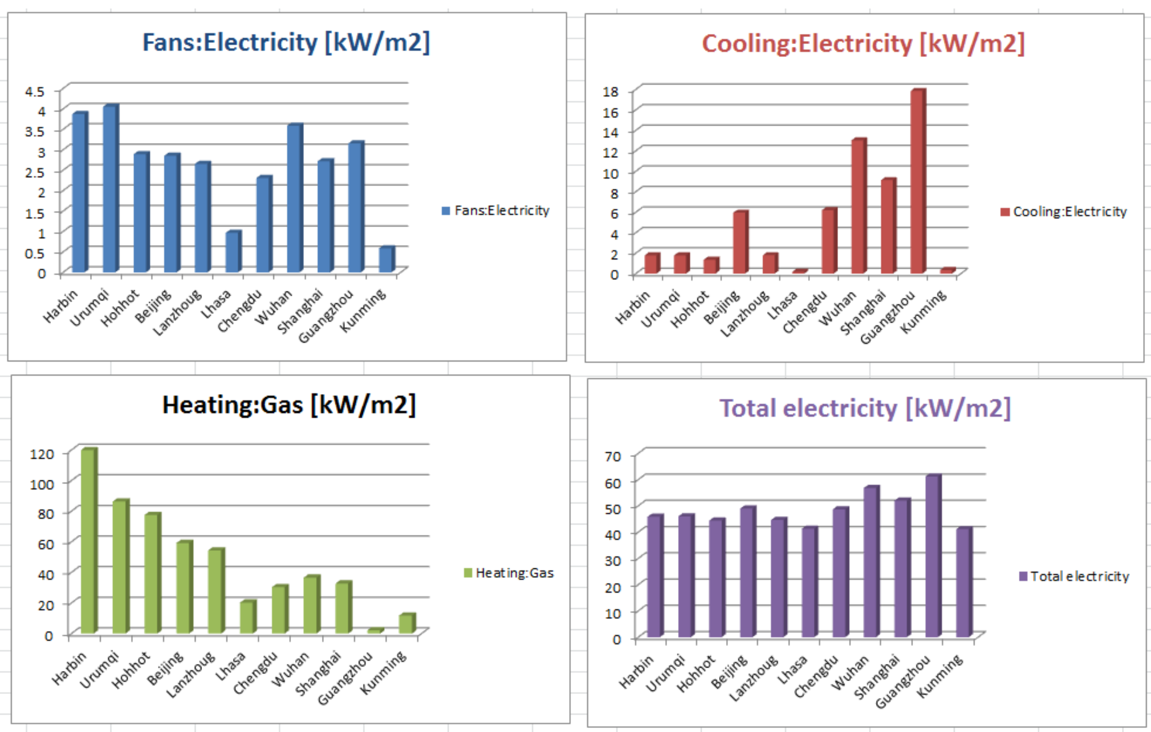


Figure-9 Load (electricity, heating, cooling, fans) 11 cities

3.2.3 Tariffs

Electricity and natural gas tariffs are key inputs to DER-CAM. The residential tariffs in all cities are shown in table $$. For residential buildings, electricity prices are set to be flat by the government. Electricity prices are higher in Guangzhou, Chengdu and Wuhan while natural gas is more expensive in Kunming and Lhasa basically because of pipeline constraints.

Cities	**Electricity prices ($/kWh)**	**Natural gas prices ($/kWh)**
Harbin	0.0797	0.0294
Beijing	0.0763	0.0301
Hohhot	0.0672	0.0267
Shanghai	0.0964	0.0367
Wuhan	0.0891	0.0372
Guangzhou	0.1000	0.0507
Chengdu	0.0900	0.0278
Kunming	0.0755	0.0852
Lhasa	0.0766	0.0852
Urumqi	0.0859	0.0201
Lanzhou	0.0797	0.0257

1$=6.4RMB

Table 2- Tariffs in 11 cities

For commercial buildings, most cities have summer and winter season rates, and cities with hydropower also have drought season, rainy season and intermediate rates, except for Hohhot and Lhasa.

Table 2 shows (for a summer day) the electricity tariffs used for Chinese commercial buildings. In China, most cities have summer and winter rates; cities with hydropower also have drought, rainy, and intermediate season rates. On a daily basis, most cities, except Hohhot and Lhasa, have peak, off-peak, and intermediate rates for commercial buildings, as shown in Figure 14. Demand charges are not very common in Chinese cities. In a city such as Shanghai, the demand charge is noncoincident with a rate of 40.5 (RMB)/kWh (6.4 $/kWh)[3]. In the residential sector, a flat tariff is common although some cities have TOU rates.

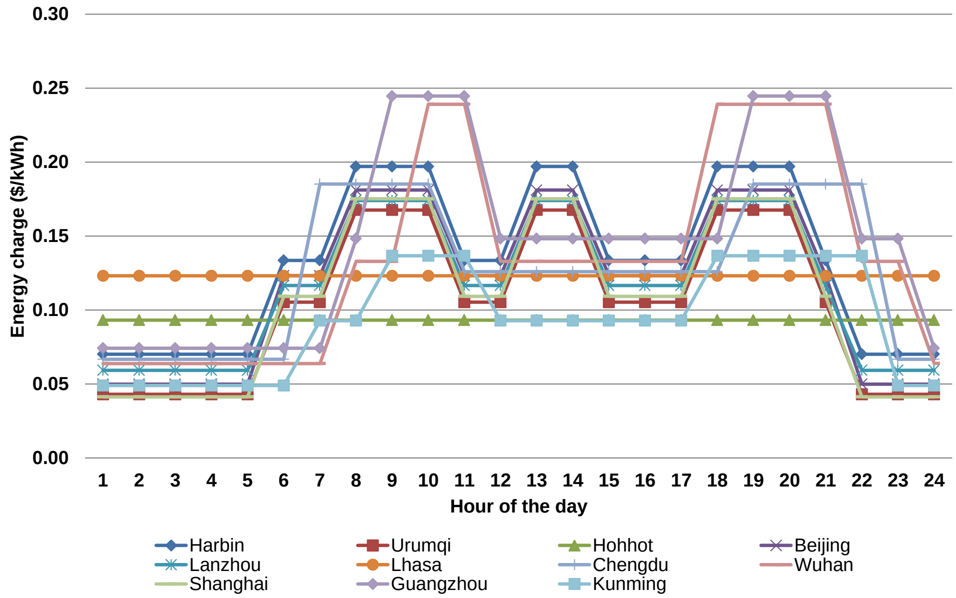


Figure 10 - Electricity tariffs for a summer day in Chinese cities

Natural gas tariffs for residential and commercial buildings and China is shown in Figures 11. In China, commercial natural gas tariffs are usually slightly higher when compared to residential tariffs in the same city. Cities in the western and central areas of China (with the exceptions of Kunming and Lhasa) have relatively lower natural gas rates than those in eastern regions. China's natural gas prices are higher overall.

[3] In this study, we use a currency conversion rate of 1 $US = 6.4 RMB.

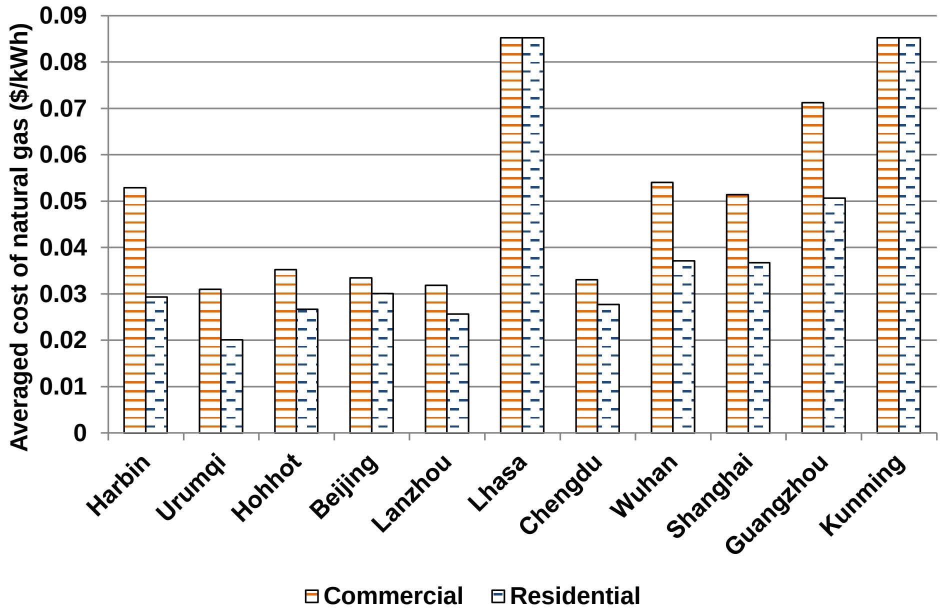


Figure 11- Chinese commercial and residential natural gas tariffs

3.2.4 Technology characteristics and other data

Technology costs

Costs and technology performances are important factors that will determine which technologies will be selected in different cities. In this study, we use the technology costs data provided by Wei's regional study of building distributed energy performance optimization for China. Government incentives and estimated technology cost in the current Chinese market are taken in to consideration. Particularly, for technologies such as PV and electricity storage devices, the final user cost after 50% government cost sharing or subsidy is used.

Technologies	**Fixed Cost [$/kW(h)]**	**Variable Cost [$/kW(h)]**	**Lifetime [years]**	**Fixed Maintenance[$/kW(h)]**
Electricity Storage	250	200	6	0
Heat Storage	2000	50	17	0
Flow Battery Energy	0	110	10	0.1
Flow Battery Power	0	1060	10	0
Absorption Chiller	20000	127	15	0.1

Refrigeration	20000	127	15	0.1
PV	0	1615	20	0.3
Solar Thermal	300	400	15	0.1
EVs1	100	5	1	0
Air Source Heat Pump	0	70	10	0.52
Ground Source Heat Pump	0	79.74	10	0.32

Table 3- Technology costs settings

Solar radiation

Solar resources are key indicator when analyzing solar thermal technologies. As China is a country with vast territory, cities in different locations enjoy varied solar isolation. The accumulated annual solar resources differ among the cities across the country as shown on Figure 12. The northwest part of the country receives more sunlight than the southeast where it is more smoggy and rainy during the year.

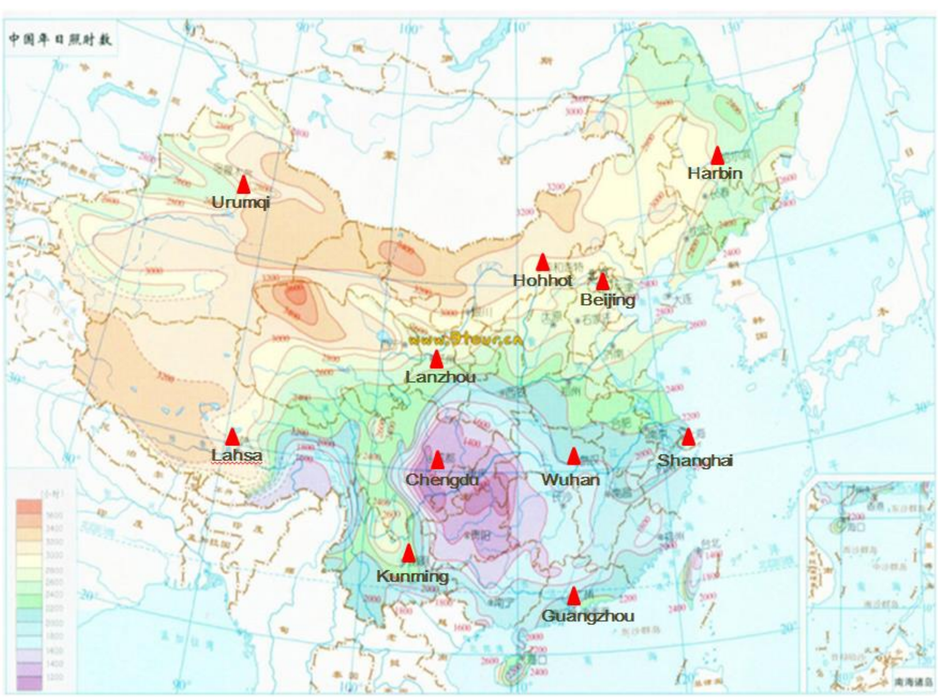


Figure 12- Daily solar radiation in July in all cities

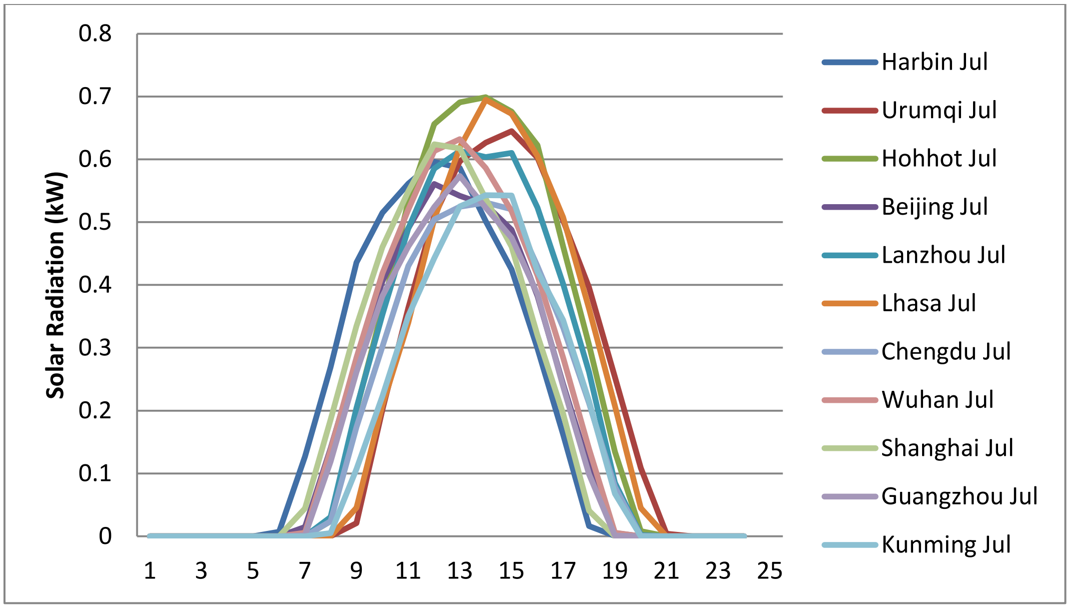


Figure 13- Daily solar radiation in January in all cities

Marginal CO2 factor

To estimate DER technologies' impact on GHG emission reduction, marginal CO2 emission factors are required as inputs to DER-CAM. The factor gives the amount of CO2 emitted when one unit of kWh of energy is generated. In this study, we use the estimated marginal CO2 factors on DER-CAM Webopt interface. The value is around 0.8 kgCO2/kWh. The number given by NDRC is a bit higher since China's electricity is mainly generated from coal. The emission factors are generally higher than those in the U.S. and other developed countries.

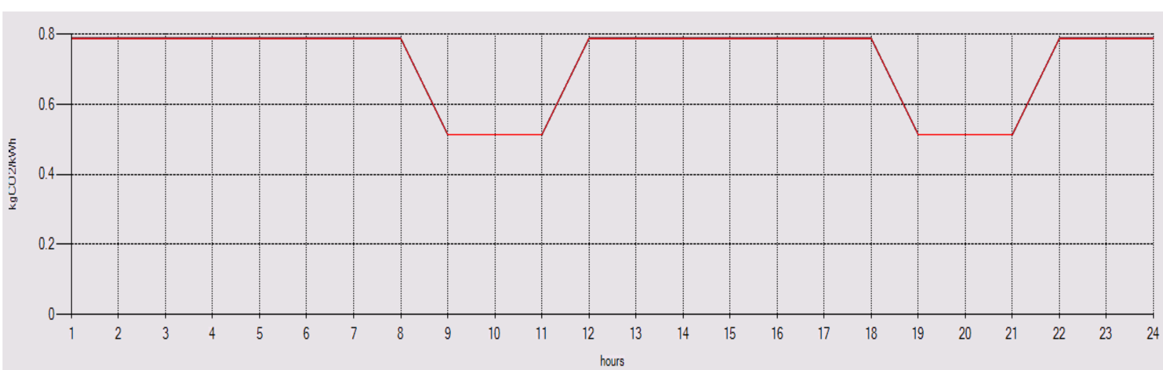


Figure 14- CO2 emission factor

3.3 The automatic large volume DER-CAM runs model

To conduct sensitivity analysis, 90 scenarios are tested on 11 cities. Taking into consideration the original scenarios, around 1000 DER-CAM runs need to be done. Thus, an automatic large volume DER-CAM run tool requires to be developed. A large volume DER-CAM runs model was developed thereafter based on Excel visual basic for applications (VBA). The VBA coding deals with one city at a time to conduct 90 runs on the same building prototype, and it contains 6 steps in the main module, including functions like exporting fixed and variable data, running basecase case, calling DER-CAM and read DER-CAM outputs back to Excel sheets. Firstly, fixed data, that is the data varies according to different cities like solar data, temperature, are exported as parameters to DER-CAM GAMS file. Secondly, 6 variables are exported to GAMS by GDX file according to different scenarios. A GDX file is a file that stores the values of one or more GAMS symbols such as sets, parameters variables and equations. GDX files can be used to prepare data for a GAMS model, present results of a GAMS model, store results of the same model using different parameters etc. After step 6 reading output data from DER-CAM to Excel, VBA will loop back to step 2 because these 6 variables are the ones that will change values in every scenario. In step 3 and 4, basecase DER-CAM run is conducted, and *Annual Total Energy Costs* figure is extracted and put into GDX file as options parameter. In the basecase DER-CAM runs, no investment on distributed energy technologies choice is activated, and the annual total energy costs is basically purchasing all energy demand from the grid or other fuels. This figure is then set as the *Basecase Cost* in the next DER-CAM run which takes into consideration distributed energy technologies utilizations and optimize investments and scheduling energy dispatches. The Basecase Cost parameter is required to set a baseline for optimization process and also calculating annual savings for the provided optimized solution. In step 5, DER-CAM is called by VB using GAMS application programming interfaces, and selected output data are obtained by GDX file including continuous and discrete technologies installed capacities, annual total energy costs, annual CO2 emission and annual total savings. In the last step in each scenario, outputs are read from GDX file to Excel sheet.

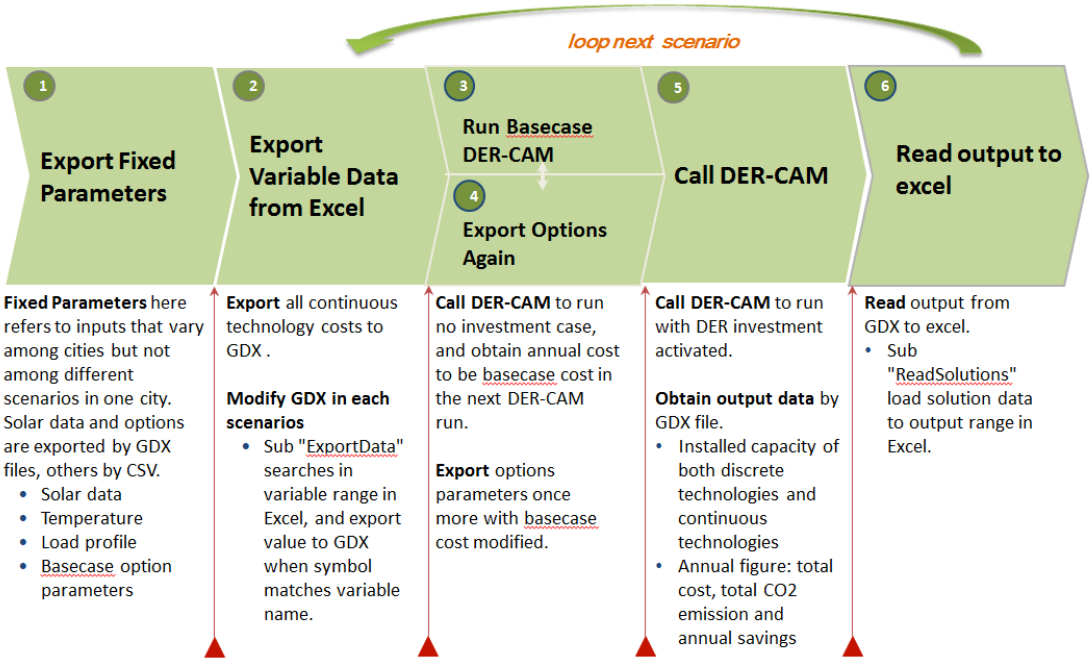


Figure 15- Automatic sensitivity DER-CAM runs process

Theoretically, this model can run DER-CAM simulations as many times as the user set to be. However, in this research 90 scenarios runs are conducted based on statistical reasons. The sample size should be 15 times larger than number of variables to be statistically significant for analysis. The next graph shows the Excel interface with large volume DER-CAM runs model. The upper left side of the window is the original technology costs settings and tariff figures. It is marked yellow when the parameter is a variable figure. On the very left are scenario numbers and then the six variables figures change according to different scenarios. On the right are all the output figures including continuous technology installations, annual figures and discrete technology type and installed capacities. The solar thermal installation capacity is marked red when maximum area for solar thermal and photovoltaic reaches its maximum limitation which is 700 m2 in this research.

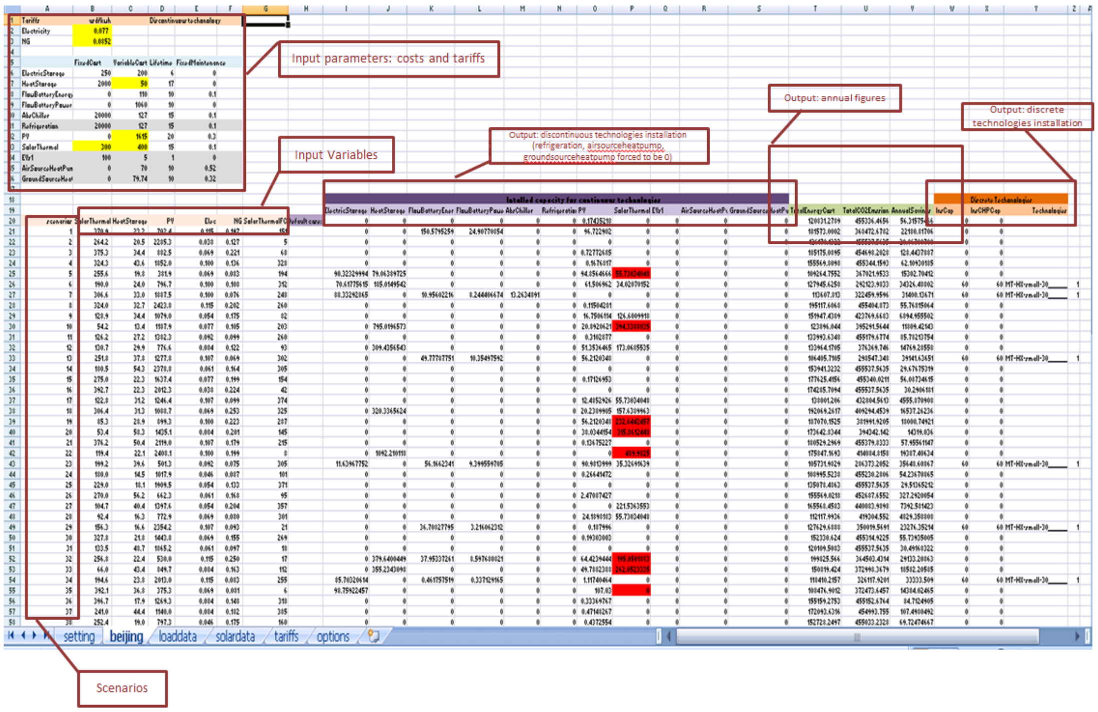


Figure 16- Large volume DER-CAM runs interface

The large volume DER-CAM runs model is implemented on the same building prototype in 11 cities that located in different climate zones in China. The original costs and tariffs settings are shown in the table with four technologies disabled in the simulation.

Tariffs	usd/kwh
Electricity	0.076
NG	0.0301

	FixedCost	VariableCost	Lifetime	FixedMaintenance
ElectricStorage	250	200	6	0
HeatStorage	2000	50	17	0
FlowBatteryEnergy	0	110	10	0.1
FlowBatteryPower	0	1060	10	0
AbsChiller	20000	127	15	0.1

Refrigeration	20000	127	15	0.1
PV	0	1615	20	0.3
SolarThermal	300	400	15	0.1
EVs1	100	5	1	0
AirSourceHeatPump	0	70	10	0.52
GroundSourceHeatPump	0	79.74	10	0.32

Table 4 -Original costs and tariff setting for Beijing

Scenarios inputs are decided by random numbers within a certain range shown in the table. The varying range is set based on current costs of each technology and lowered due to anticipated cost reduce in the future. Electricity and natural gas tariffs are set by coefficients which defines the varying range be multiplying the coefficient to the current tariff value. Natural gas price is expected to have more rises in the near future due to the country's willingness to shift energy dependency from coal to natural gas. Random scenarios inputs are generated by excel random number generator function.

Technology costs and tariff coefficient generation		
Varibles	Max	Min
Solar Thermal	400	50
HeatStorage	60	10
PV	2500	300
ElecTariff coefficient	1.5	0.5
NGTariff coefficient	3	0.8
SolarThermalFC	400	0

Table 5- Sensitivity analysis variable range

3.4 Stata and statistical analysis

After collecting data from 90 runs in 11 cities, a linear regression is conducted on these data using Stata as the tool. Stata is an integrated statistical package that provides data analysis, data management and graphics. The linear regression model is the most widely used econometric model. It specifies the conditional mean of a response variable y as a linear function of k independent variables:

$$\mathrm{E}[\mathrm{y}|x_1, x_2, \dots, x_k] = \beta_1 x_1 + \cdots + \beta_k x_k$$

The regression is used to estimate the unknown effect of changing one variable over another (Stock and Watson, 2003). The βs are fixed parameters; the linear regression model predicts the average value of y in the population for different values of x_1, x_2,…x_k

The key assumptions when using multiple linear regression models is

- There is a linear relationship between two variables (i.e. x and y)
- This relationship is additive (i.e. y=$x_1 + x_2 + \cdots + x_n$)

In this solar thermal potential study, the dependent variable is solar thermal installed capacity given by DER-CAM optimization solutions. The independent variables are the ones are chosen based on previous analysis, which are solar thermal fixed and variable costs, heat storage costs, photovoltaic costs, electricity and natural gas prices.

$$\begin{aligned} &InstalledSolarThermalCapacity \\ &\qquad = \beta_1 * SolarThermalVarCost + \beta_2 * HeatStorageCost + \beta_3 * PVCost + \beta_4 \\ &\qquad * ElectricityTariff + \beta_5 * NaturalGasTariff + \beta_6 * SolarThermalFixedCost \end{aligned}$$

The βs in the equation reflect the how sensible the installed solar thermal capacity is to each of the independent variables. In theory, they vary in different cities due to load profile and climate characteristics. The signs of βs represent the impact, positive or negative; the independent variables have on the dependent variable. If β is positive, the corresponding independent variable will have a positive impact the Y, which means that with the independent variable increasing, the solar thermal installed capacity will increase as well. Within all six variables, the PV cost is expected to have positive impact on solar thermal installed capacity, because the rise of PV cost will reduce the installed capacity for PV technology, and it might cause an increase of solar thermal installation when maximum roof area for installed solar technologies are met. If β is negative, the impact of independent variable on Y is negative. The expected impact of solar thermal variable and fixed costs is negative since solar thermal technology will be less competitive if its cost increases while other technologies' costs remain unchanged.

4 RESULTS AND ANALYSIS

4.1 DER-CAM results

Table 6 shows the DER-CAM results for Beijing and Guanzhou for a building prototype introduced in the last chapter with 700m2 roof areas. The inflation rate is set to be 5%. As shown in the results, Beijing is better off with investment on distributed energy resources compared with Guangzhou. However, Guangzhou sees more installation of heat storage and solar technologies.

		Beijing	Guangzhou
Total energy cost	No investment	48236$	54760$
	With DER	47751$	54945$
CO2 emissions	No investment	379529kg	345930kg
	With DER	328248kg	281942kg
Electricity storage		0	0
Heat storage		0	77.4kW
Flow battery energy		0	0
Flow battery power		0	0
Absorption chiller		0	1.2kW
PV		33.2kW(217.2m2)	44.8kW(293m2)
Solar thermal		26.2kW(37.4m2)	66.9kW(95.5m2)

Table 6- DER-CAM results, Beijing & Guangzhou

With initial settings, the DER-CAM results show most cities install photovoltaics of the range of 30-40 kW, while 5 of the cities would adopt solar thermal energy. Hohhot, Beijing and Wuhan would adopt 30-45 kW of solar thermal. Lhasa and Kunming would adopt over 150kW. The result is not surprising since Lhasa and Kunming are the cities receive highest amount of solar radiation during the year. As under current technology costs and other settings, solar thermal is much more competitive at places with high solar resources, and less competitive to photovoltaics at places where solar radiation is medium.

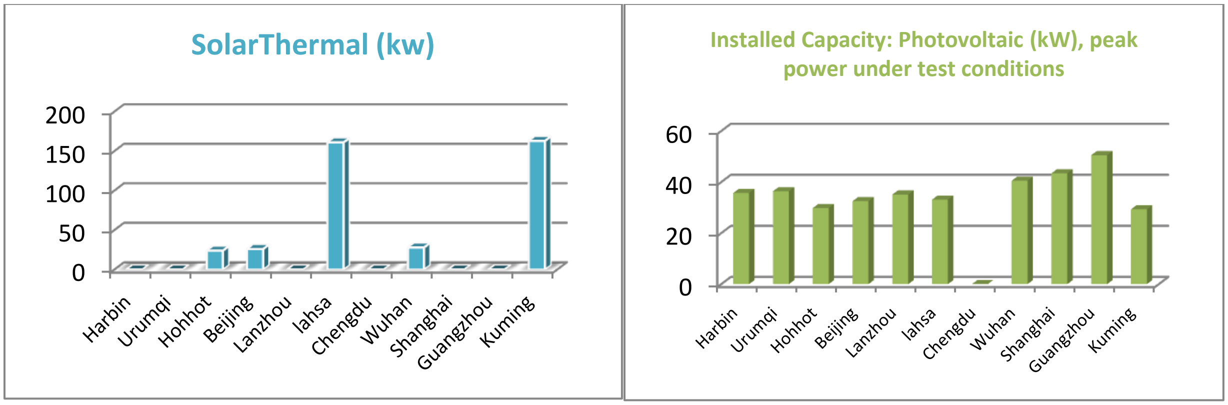


Figure 17- Installed solar capacity, DER-CAM results

4.2 The sensitivity analysis

In the case of Kunming, the regressions results generate the coefficients for each variable. All variables are significant on 1% level except solar thermal fixed cost is significant on 5% level. All the independent variables explain 77.3% of the variances of solar thermal installed capacity. Multiple linear regression results give the coefficients of each independent variable which to some extent reflect how sensitive the installed capacity of solar thermal is to each of the variable.

$$\begin{aligned} InstalledSolarThermalCapacity \\ &= -0.673 * SolarThermalVarCost - 1.825 * HeatStorageCost + 0.053 * PVCost \\ &- 1801 * ElectricityTariff + 1654 * NaturalGasTariff + 0.130 \\ &* SolarThermalFixedCost \end{aligned}$$

The coefficient for solar thermal variable cost is negative as anticipated because the increase of cost will end up a decrease of solar thermal utilization. The value means that a 10$ reduce of variable cost will cause 6.73kW increase of installation in Kunming. The coefficient of heat storage cost is -1.825 which means that solar thermal installation will decrease 18.25kW when the cost of heat storage cost increases 10$. The difference of the coefficients doesn't define the significance of impact of the variable to the dependent variable. Heat storage cost coefficient is larger in absolute value than solar thermal variable cost mainly because original heat storage cost is 50$ while solar thermal variable cost is 400$. 10$ decrease of cost is 20% change on heat storage cost while it is 2.5% change on solar thermal costs. PV cost coefficient is positive as anticipated because PV is in competition position with solar thermal when maximum available area for solar technologies becomes a constraint.

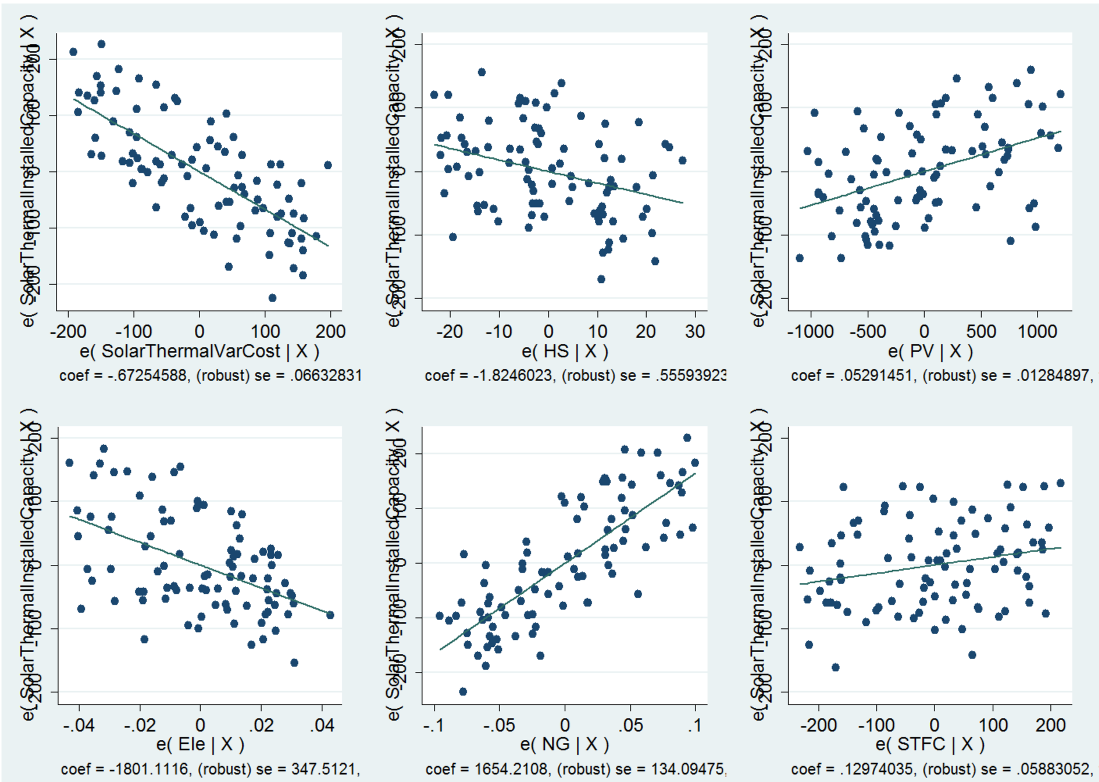


Figure 18- Coefficient for solar thermal variable cost, Kunming

Stata shows that how each variable linearly impacts the dependent variable installed solar thermal capacity, and it also shows how significant the impacts are. In the case of Kunming, natural gas price and solar thermal variable cost are the factors most significantly affect solar thermal installation. Other factors are less significant because they are indirectly affecting solar thermal installation. For instance, the selection of heat storage technology and installed capacity sees a strong correlation with solar thermal installation which will be discussed in the next chapter. Over produced heat from solar thermal collectors in the day time requires storage tool to be used in the night. The combination use of solar thermal and heat storage technologies makes the use of solar resources more efficient. Therefore, how sensitive installed capacity of solar thermal to heat storage cost depends mostly on how strong is the correlation between solar thermal and heat storage installations. In the case of Kunming, the coefficient of PV to solar thermal installation is significant on 1% level. The significance level of PV cost coefficient is based on whether the maximum area for solar technologies constraint is reached. The more this constraint is hit, the more significant impact the cost of PV will have on solar thermal installation. Natural gas price has a direct influence on solar thermal installation as solar thermal variable costs, because natural gas is the alternative energy option for heating loads. Thus, the significance level of natural gas price, the same as solar thermal variable cost, is high in all the cities.

All multiple linear regressions results are shown in the next table.

	Beijing	**Shanghai**	**Guangzhou**	**Chengdu**	**Lahsa**	**Kunming**
Solar Thermal Variable Cost	-0.884*** 0.085	-0.848*** 0.093	-0.615*** 0.062	-0.489*** 0.068	-0.384*** 0.030	-0.685*** 0.066
Heat Storage Cost	-1.008* 0.552	-0.618 0.535	-1.161** 0.473	-0.828** 0.393	-1.330*** 0.220	-1.854*** 0.552
PV cost	0.007 0.127	0.023* 0.014	0.033*** 0.009	0.0004 0.010	0.059*** 0.006	0.052*** 0.013
Electricity	-285.5 344.1	-655.7** 275.8	-964.8*** 220.2	540.9** 221.2	-1605.3*** 168.3	-1840.9*** 343.1
Natural Gas	4794.7*** 393.1	4025.5*** 359.6	2447.4*** 186.7	2408.9*** 399.8	1340.6*** 73.6	1699.1*** 131.2
Solar Thermal Fixed Cost	-0.028 0.063	0.023 0.071	0.003 0.046	-0.079* 0.043	0.064** 0.028	0.127** 0.059
R square	77.5%	74.4%	78.3%	62.2%	90.1%	77.3%
	Hohhot	**Harbin**	**Lanzhou**	**Wuhan**	**Urumqi**	
Solar Thermal Variable Cost	-0.874*** 0.0885	-0.905*** 0.0866	-0.830*** 0.0878	-0.742*** 0.840	-0.322*** 0.072	
Heat Storage Cost	-1.658** 0.5443	-1.711*** 0.600	-0.981* 0.503	-1.378** 0.613	-0.308 0.482	
PV cost	-0.015 0.0147	-0.012 0.0146	-0.0032 0.0146	-0.0005 0.015	-0.002 0.007	
Electricity	181.5 460.3	198.48 395.2	358.4 371.6	396.2 291.2	133.4 149.9	

Natural Gas	4596.5*** 493.6	4321.6** * 470.6	3920.8*** 467.1	2279.3** * 351.0	2052.8*** 417.8
Solar Thermal Fixed Cost	-0.0365 0.080	-0.046 0.081	-0.013 0.075	-0.100 0.070	0.018 0.031
R Square	71.1%	79.8%	68.3%	64.7%	49.7%

In each cell: coefficient / Robust Std. Error

* Significant at the 0.10 level.

** Significant at the 0.05 level.

*** Significant at the 0.01 level.

Table 7- Sensitivity results

Comparing the coefficients among different cities gives an idea of intrinsic characteristics of city load and solar resources as well as providing quantitative implications for policy makers. For the overall model, about over 70% of the variances of dependent variable *installed capacity for solar thermal* are explained by all the six independent variables, which is indicated by R square. R square shows the amount of variances of Y explained by the variables. In the case of Beijing, the model explains 77.5% of the variance in solar thermal installation. The R square reflects how well the model works in each city. The city with best data performance is Lhasa. Chengdu, Urumqi, Lanzhou and Wuhan are the cities with an R square less than 70%.

Solar thermal variable costs and natural gas price are statistically significant at the 0.01 level in all the cities due to the fact that these two factors are directly impacting solar thermal technology. Solar thermal fixed cost is almost irrelevant in all the cities except for Lhasa and Kunming where there are sufficient solar resources and high natural gas prices. Since the fixed cost is set to be 300$ while variable cost for 1 additional kW is 400$, solar thermal fixed cost only counts for a small portion of total cost resulting in that fixed cost does not significantly impact installed capacity.

4.2.1 Solar thermal variable cost coefficient

The solar thermal variable cost coefficient β_1 in equation $$ is one of the most important factors for installed solar thermal capacity. It tells how much more solar thermal will be installed if the cost reduces in the future as the technology develops. It also gives policy makers ideas quantitatively to incentivize customers to install distributed energy technologies especially solar thermal technology in this case.

$$
\begin{aligned}
&InstalledSolarThermalCapacity \\
&\qquad = \boldsymbol{\beta_1} * SolarThermalVarCost + \beta_2 * HeatStorageCost + \beta_3 * PVCost + \beta_4 \\
&\qquad * ElectricityTariff + \beta_5 * NaturalGasTariff + \beta_6 * SolarThermalFixedCost
\end{aligned}
$$

The coefficient β_1 is the result of linear regressions. As in the case of Beijing and Kunming, the slope of linear relationship between solar thermal variable cost and solar thermal installed capacity differs with Beijing steeper, which means that the dependent variable is more sensitive to cost in Beijing than Kunming.

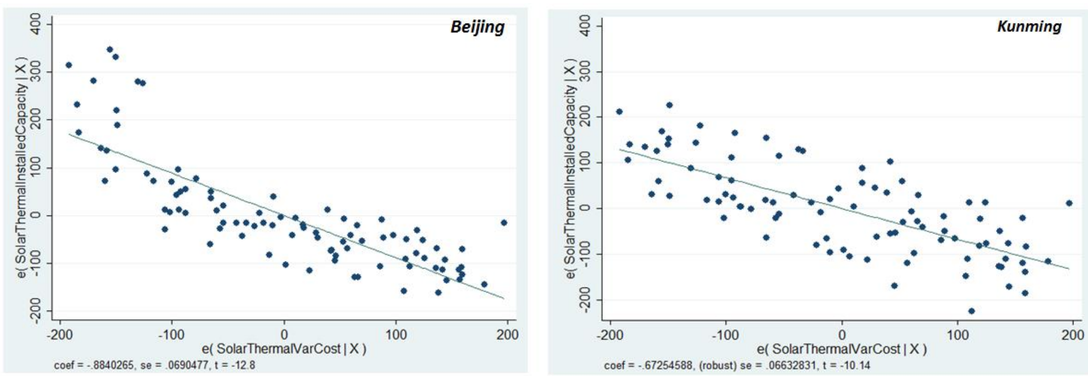


Figure 19- coefficient β_1 comparison, Beijing & Kunming

From regression results given by Stata, Harbin is most sensitive to solar thermal variable cost which means that a decrease of technology cost will boost the sales most in Harbin. 5 other cities, Wuhan, Beijing, Hohhot, Lanzhou and Shanghai have a coefficient around 0.8. A 10$ per kW subsidy in these cities will increase an 8kW installation in our residential building prototype. Urumqi and Lhasa are least sensitive to solar thermal variable cost. However, the model only explains 49.7% of variances in the case of Urumqi, so the real sensitivity may differ from what we get from this data set. The comparison of coefficients among cities provides the information of expected outcome of increase of solar thermal installations when technology cost reduces in the future or government subsidies are expected. In the presence of cost reduce; Harbin will see more solar thermal technology selection whereas Lhasa will see less change of installed capacity.

It is shown in fig && solar thermal variable cost coefficients and space and hot water heating load in 7 cities where the R square is more than 70% which we considered sufficient set of data. As total heating load (annual space heating and hot water demand) goes down in the cities, solar thermal variable cost coefficient goes down accordingly as heating energy is a major part of energy provided by solar thermal technologies. In residential buildings, the load profile gives a high demand for hot water and space heating demand as compared with commercial buildings. The city with the highest annual total heating demand, Harbin in this case, is most sensitive to solar thermal technology cost. Whereas Guangzhou, the city in the south part of China where heating demand is relatively low, is less sensitive to technology cost, because even with a large reduce of cost solar thermal won't be installed or the increase of installation won't see big difference simply due to the fact that there is not that much heating demand. An exception is Lahsa. The heating demand in Lahsa is medium, but the technology cost coefficient is the lowest in all cities. It is because Lahsa receives the largest amount of solar radiation in all parts of China. Solar technologies are very competitive in Tibet due to the redundant solar resources.

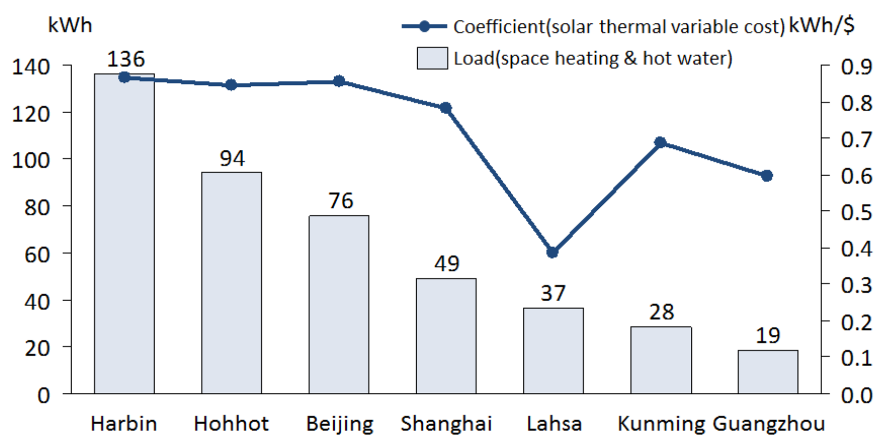


Figure 20- Coefficient β_1 , 7 cities

When there is high solar radiation in a city, solar technologies will be selected no matter the price of the technology. Thus, solar thermal installation will be less sensitive in regions where solar resource is redundant. On the other hand, in the places where there is very low solar radiation, solar technologies will not be selected even when technology cost is very low. As a result, solar thermal installation will not be sensitive to technology cost as well. As shown in graph$$$, the area represents the rank of solar thermal variable coefficients. In cities like Lahsa and Guangzhou, where solar radiation is the highest and lowest respectively, β_1 coefficient is smaller because solar thermal technology will either be selected or not preferred regardless to a certain degree of solar thermal technology cost. Taking also into consideration influences of the annual heating load, the sensitivity to technology cost can be approximately explained by the combination influences of both heating demand and solar radiation level. City like Harbin, where receives medium solar radiation and high heating load, is most sensitive to technology cost. Other elements may also play a role in affecting the sensitivity of solar thermal installation on technology cost. The competitiveness of other technologies is one of them.

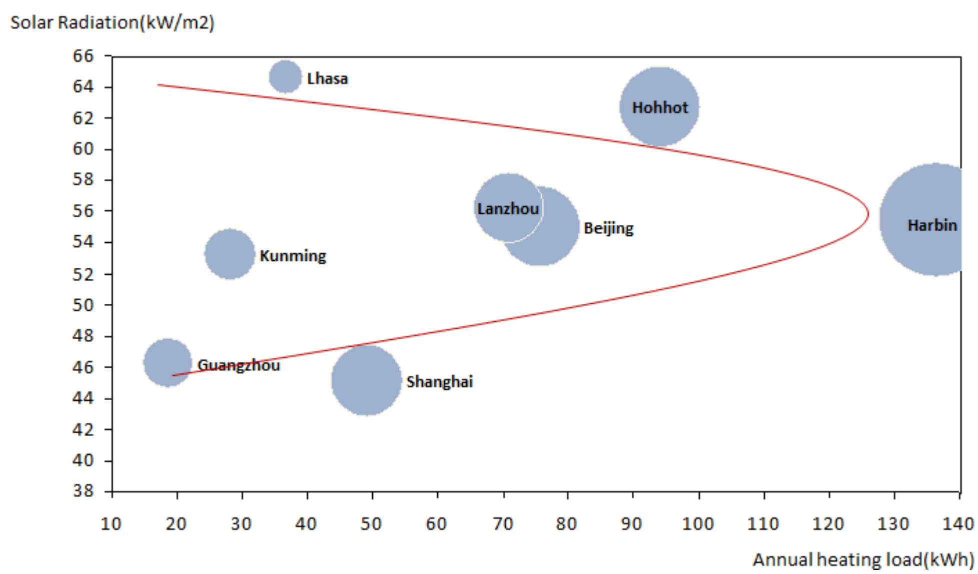


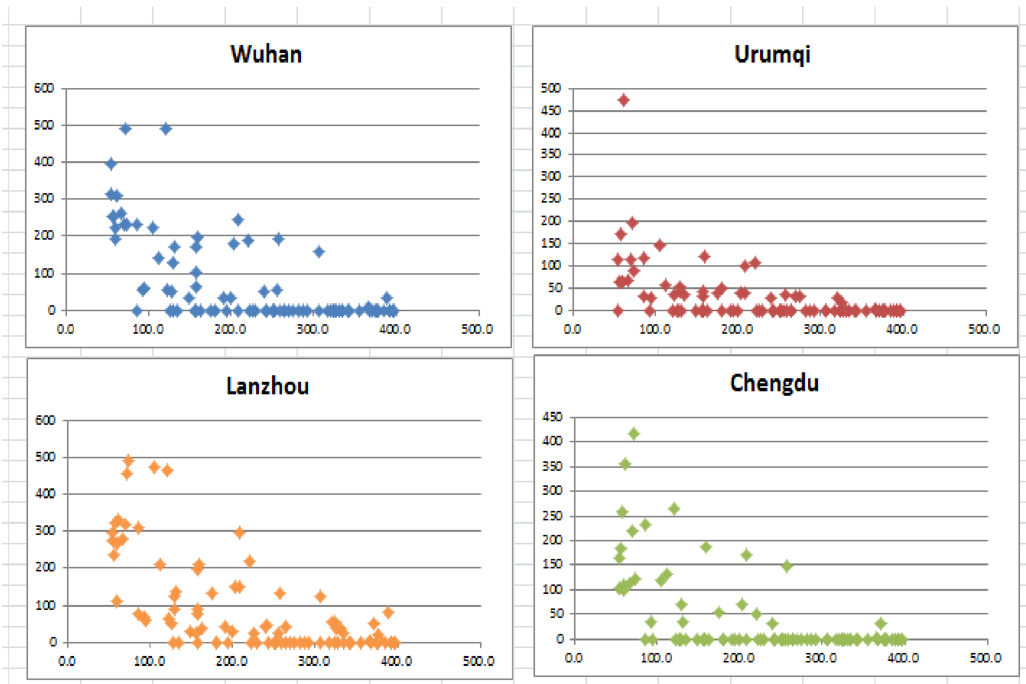
Figure 21- Impact of heating load and solar radiation on solar thermal's sensitivity to variable cost

There are 4 cities where the data we get from Stata regression model shows explaining of variances of dependent variables less than 70%. These 4 cities are Lanzhou, Urumqi, Chengdu and Wuhan. The β_1 coefficients we get from regression results in these 4 cities may not well explain the true sensitivity of technology cost. In Urumqi, the heating demand is relatively high and solar radiation is medium. The city should be very sensitive to solar thermal technology cost. However, regression results tell us that the β_1 coefficient is -0.322 which is even lower than Lahsa. The regression model only explains 49.7% of variances of solar thermal installation.

	Harbin	Beijing	Hohhot	Lanzhou	Kunming	Urumqi	Lahsa	Chengdu	Guangzhou	Shanghai	Wuhan
Coefficient	-0.905	-0.884	-0.874	-0.830	-0.685	-0.322	-0.384	-0.489	-0.615	-0.848	-0.842
R square	79.8%	77.5%	71.1%	68.3%	77.3%	49.7%	90.1%	62.3%	78.3%	74.4%	64.7%

Table 8- Solar radiation coefficients

Why the model works better in some cities than others? It is very necessary to take a deep look into these 4 cities and see the reason why our regression model doesn't fit well in these places. For instance, in Lanzhou, if we eliminate all the data with zero installation, there will be 55 observations left. We analyze these 55 data and can get an R square of 73.9%. However, 55 observations are not statistically enough for analyzing 6 variables. The result of solar thermal variable cost coefficient will change from -0.830 to -0.854, which means with a larger data base or lower range of variables, the β_1 coefficient may show a bigger figure in Lanzhou. The city may be more sensitive to solar thermal variable cost than expected in our model. It also means that a certain threshold may exist when the dependent variable becomes sensitive to solar thermal technology cost. In the case of Chengdu, before technology cost goes down to 300$, there is almost no solar thermal installation.



X: solar thermal variable costs ($)

Y: solar thermal installation (kW)

Figure 22- The non-linear effect of solar thermal variable costs coefficients

In all 4 cities, there are larger amount of zero installation in the data set. For example, in Urumqi, there are 55 cases where solar thermal installation is zero in a total of 90 scenarios. These zero installations greatly affect the performance of regression model because one of the assumptions of multiple linear regressions is the linear relationship between the dependent and independent variables. The non-linearity caused by zero installations is the main reason why the regression model doesn't work well in there 4 cities. For further analysis, the non-linearity indicates:

- R square is smaller in these 4 cities (Landzhou, Urumqi, Wuhan, Chengdu) mainly because too many 0 installation of solar thermal increases non-linearity.
- A certain threshold may exist before Y becomes sensitive to X.
- Out of all the cities, Chengdu receives least average solar radiation annually, which means, even with cost reduce; solar thermal technologies won't be sufficiently competitive simply because of short of solar radiation.
- Annual solar radiation is in average level in Wuhan and Urumqi, but both cities receive less sunlight in winter time when heating demand is higher.
- Bases on current price (400$), directly subsidy on solar thermal cost may not see large increase of installation quickly in these 4 cities.

4.2.2 Natural Gas Prices

In the regression results from all cities, natural gas prices play a greatly important role in solar thermal technology utilizations because natural gas is the alternative fuel choice for heating loads. In general, places where natural gas prices are high will have a higher installation of solar thermal technology. In the cities where natural gas prices are lower, customers are less likely to install solar thermal water heaters or other solar thermal technologies simply because it may not be an economical investing decision. However, the sensitivity of natural gas price to solar thermal installed capacity is a key figure in analyzing the impact of a change of natural gas price is on solar thermal market. With the natural gas price goes up, a more optimistic solar thermal market forecast can be expected. A same amount of natural gas price change may end up different outcomes in different regions. Some regions are more sensitive to natural gas price changes. If the region is cold in winter and heating demand is high, it will be more sensitive to natural gas prices. The natural gas setting point price is also a key factor in the sensitivity analyses. In the city where natural gas price is already very high, like Kunming, if the natural gas price goes up a bit, it may not affect very much customers' choice of solar thermal installations.

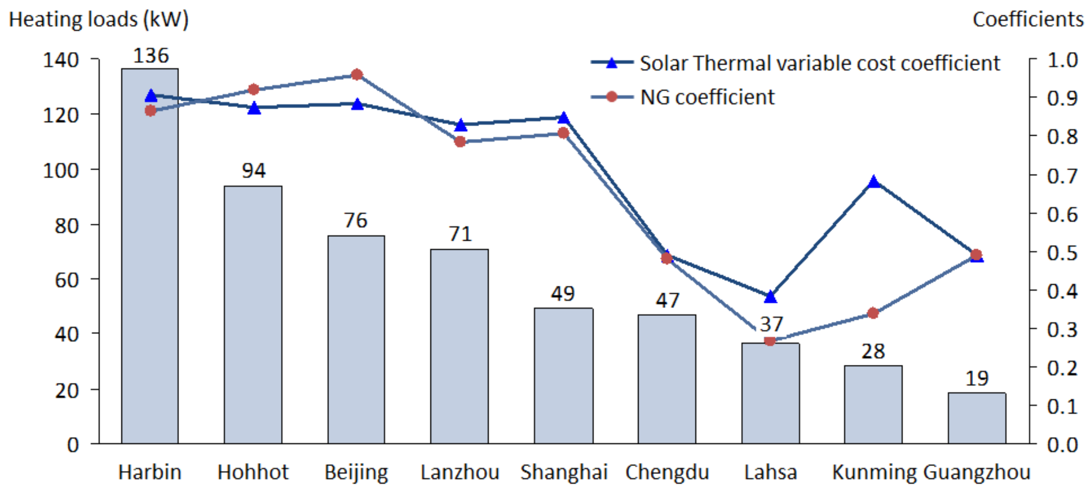


Figure 23- Natural gas tariff coefficients

4.2.3 Heat Storage Cost

Heat storage is the technology that store heat when there is redundant generation and release heat when demand is high. As solar thermal technologies only generate heat in the day time when the collectors receive solar radiation, it cannot fulfill the demand that happens in the evening. The efficiency of solar thermal technologies changes in the day time according to temperature and solar resources as well. The peak of heat provision from solar thermal technology probably doesn't match the peak heating demand. Most of the solar thermal water heater products that can be found in the market are designed with a heat storage tank. The design is for storing hot water in the day time so that it can be used later in the evening or early next morning. The efficiency of those heat storage tanks is a key figure when it comes to the total efficiency of a solar thermal water heater. Because of the nature of solar technologies, the combination use of heat storage and solar technologies is of great importance. Therefore, there is expected to be great correlation between solar thermal technology installation and heat storage installation. When there is large amount of heat generated by solar thermal, it's more efficient to use storage tools to keep the heat and use them when demand is high. In our regression results, 7 cities out of 11 show a significant impact of heat storage cost on solar thermal installation. The correlation between the installations of heat storage and solar thermal technologies implies that heat storage cost will have an impact on solar thermal installation. With lower heat storage cost, more solar thermal will be installed. Thus the heat storage coefficient is anticipated to be negative.

	Guangzhou	Chengdu	Kunming	Hohhot	Lahsa	Harbin	Wuhan
Heat Storage	-1.161** 0.473	-0.828** 0.393	- 1.854*** 0.552	-1.658** 0.5443	- 1.330*** 0.220	- 1.711*** 0.600	-1.378** 0.613

Table 9- Heat storage coefficients

The correlations between solar thermal and heat storage installation can be seen from data generated from large volume DER-CAM runs model. In almost all the cities, there can be seen a positive linear relation between solar thermal installed capacity and heat storage installed capacity.

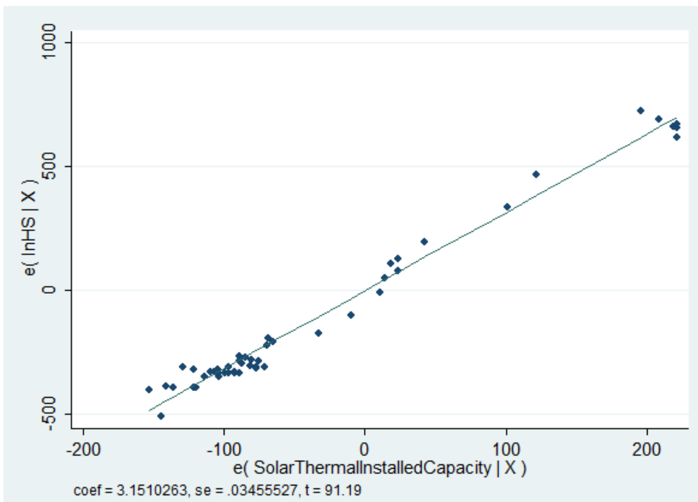


Figure 24- The correlation between installed heat storage capacity and installed solar thermal capacity, Kunming case

How solar thermal installed capacity is affected by heat storage cost depends highly on how strong the correlation is between heat storage installation and solar thermal installation. In city like Kunming, the correlation is stronger when compared with Guangzhou as shown in graph $$. As a results, the heat storage cost coefficient in Kunming is higher (in absolute value) than that in Guangzhou. The solar thermal installed capacity is more sensitive to heat storage technology cost in Kunming than Guangzhou, which means that the change of heat storage cost will make a bigger different on solar thermal installed capacity in Kunming. Moreover, the cost reduce of heat storage may boost the utilization of solar thermal technologies because of the correlation, and vice visa. In the regions where correlation is stronger, it’s possible to put incentive policies on heat storage technology to boost the utilization of solar thermal technology.

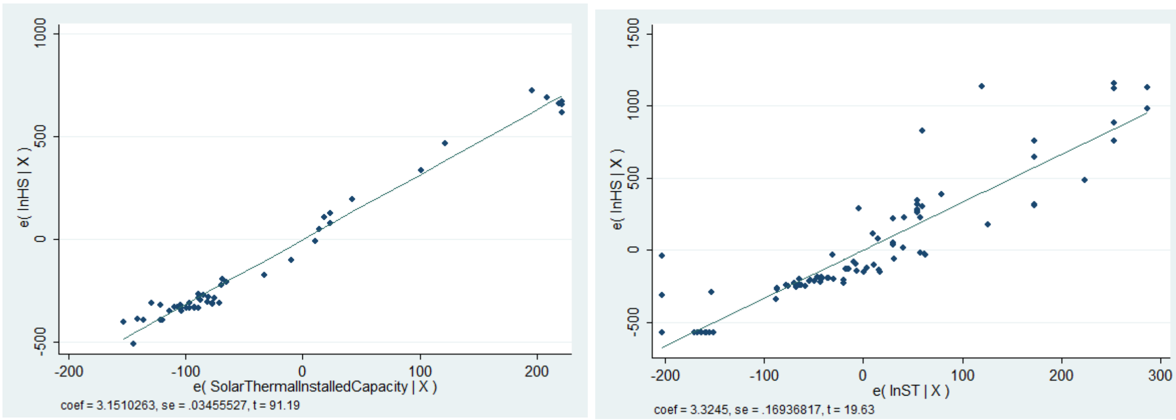


Figure 25- Correlation between solar thermal and heat storage installations in Kunming (left) and Guangzhou (right)

4.3 PV vs. Solar Thermal

PV and solar thermal technologies both convert solar energy into other useable forms. PV technology converts solar resources to electricity, and solar thermal technology converts solar energy to heat. Electricity generated by PV will feed electrical-only demands as well as demands like cooling (i.e., via a traditional electric air conditioner), space heating (via electric heating devices), and water heating. Heat generated by solar thermal technologies can be used for space heating and water heating. It can also be used in absorption chillers to meet cooling demand. Because both technologies use solar resources as input, they will likely be used more heavily in regions with large amounts of solar radiation. Each building prototype has a limited area where solar collectors can be installed, so these two solar technologies might compete for this limited space. Thus, a policy of encouraging one technology might discourage the other because of space limitations.

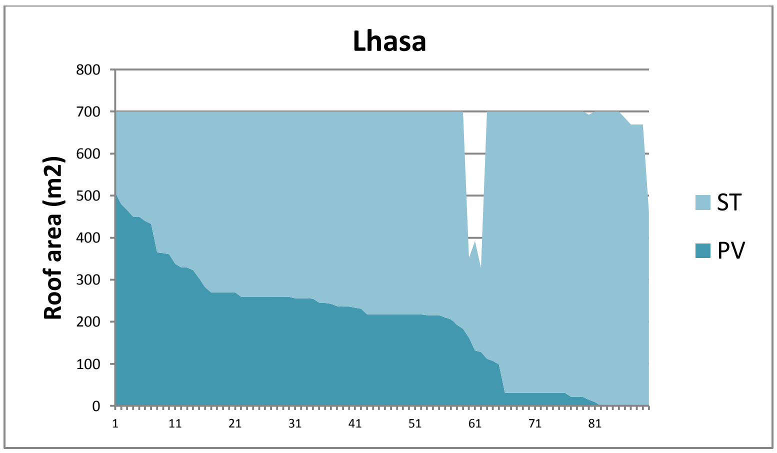
In this research, it is found that in three cities – Lhasa, Kunming, and Guangzhou – there is significant competition between PV and solar thermal. Table 14 shows the number of scenarios in which the maximum space for both PV and solar thermal (700 m^2) is reached. In 81 out of 90 cases in Lhasa, all available space for solar technologies is occupied.

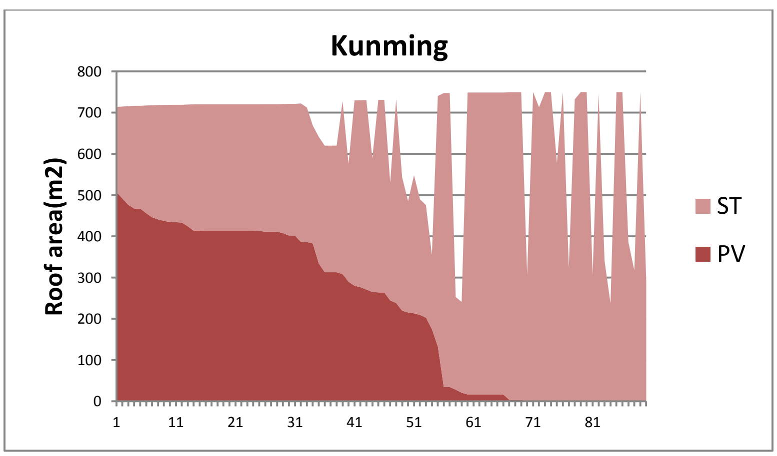
Number of scenarios when max space becomes a constraint (total 90 for each city)

	Harbin	Beijing	Hohhot	Shanghai	Wuhan	Lanzhou	Lahsa	Chengdu	Kunming	Urumqi	Guangzhou
Number of Scenarios	20	23	23	30	18	19	81	15	65	19	46

Table 10 – Number of cases in which the maximum space for solar technologies is used

The competitiveness of PV and solar thermal differs in the three cities. When lack of roof area becomes a constraint (i.e., the maximum, 700 m^2, is used), Kunming will see more PV installations (200-400) than Lhasa (100-300) (Figure 33). PV is more competitive in Guangzhou because heating demand there is lower.





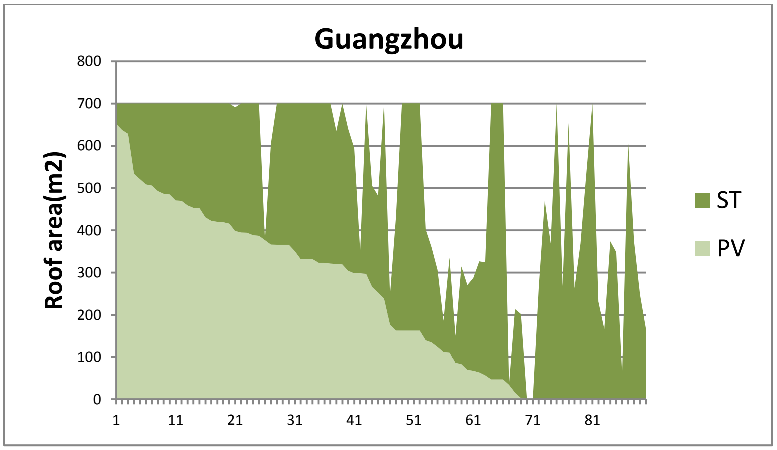


Figure 26 – Roof area constraints on solar thermal and PV technology installation in four Chinese cities

4.4 Additional analysis

4.4.1 Total annual costs and incentives

Annual savings reflect customers' incentive to invest on DER technologies. The more the adoption of one technology decreases the annual total energy cost, the more motivations for users to invest in this technology. Thus, the sensitivity analysis of annual costs to all the technology costs provides us implications for policy making. As in Figure 27, some technologies (PV and Absorption Chiller in the case of Shanghai) will impact more on annual savings than others. Therefore, adding incentive policies to these technologies will give more efficient results.

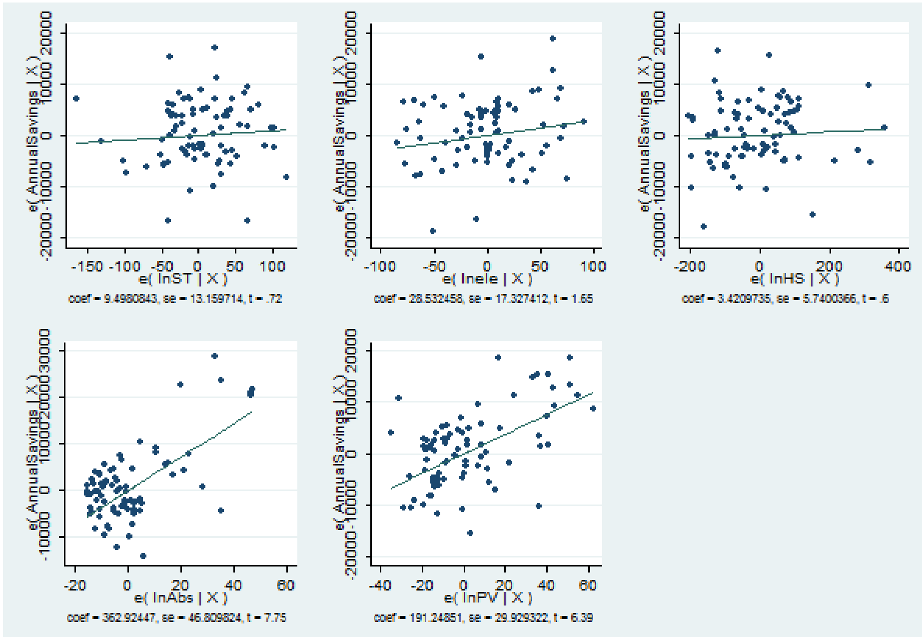


Figure 27- Total annual costs, Shanghai

4.4.2 CO2 emissions

The sensitivity analysis towards CO2 emissions and tariffs and technology costs provides us the idea which variable would have higher influence on the environmental effects. As shown in Figure 28, Subsidizing PV makes more sense to control CO2 emissions. When PV cost decreases, annual CO2 emission decreases with a steeper rate and higher significance level compare with solar thermal technology costs.

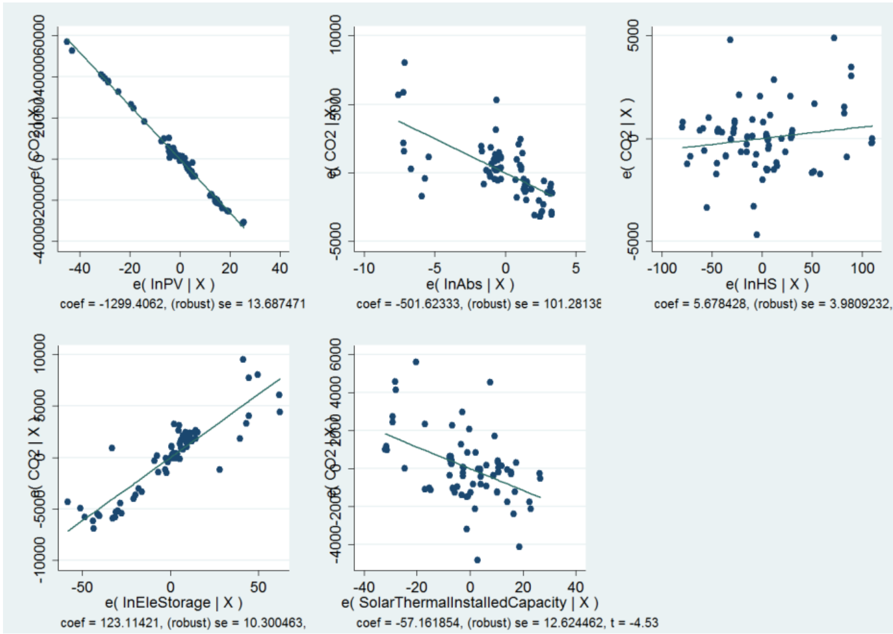


Figure 28- CO2 emission sensitivity analysis, Kunming

4.4.3 Policy implications

When Procuring Solar Thermal Systems, it makes a better investment when the city have:

- Large water heating loads.
- High cost of backup energy.
- Abundant solar resources.
- Area for collectors.

Thus, for incentive policies, the government should make into consideration the following points:

- Regional difference. Cities solar thermal installation is more sensitive to technology cost (Harbin, Hohhot, Beijing, Shanghai)
- Increase of natural gas price gives incentive indirectly
- Subsidizing on technology cost of PV provide more incentive than solar thermal
- Competing technology is PV and complementary technology is heat storage
- For green gas policies: it is more efficient investing on PV. Taking into consideration technology costs (PV: 1600$, solar thermal 400$), for same amount of CO2 reduction (2 tons), PV will cost 2500$ while solar thermal costs 14000$ in Kunming.

1. SUMMARY AND CONCLUSIONS

This study analyzed the economic and environmental viability of DER in prototype buildings in selected Chinese cities, with special in-depth examination of solar thermal technologies in China.

If technology characteristics are fixed, the structure and prices of electricity tariffs as well as the cost of natural gas are the most important factors determining whether DER is likely to be adopted; these factors have a stronger influence on the attractiveness of DER than does climate. The Chinese residential flat tariffs are generally not conducive to adoption of CHP and storage technologies; however, higher electricity prices can stimulate investments in solar PV. Solar thermal is also largely attractive in the residential context. In Northern China, the price of coal-fired district residential heating makes CHP systems not cost effective.

For solar thermal technology in Chinese residential buildings, the northern and eastern parts of China are more sensitive to changes in the cost of the technology. That is, if technology costs decrease in the future, residents living in these regions will be likely to adopt more solar thermal systems than those living in other regions. The southern part of China is less sensitive to technology cost. Cities like Lhasa on the Tibetan Plateau and Chengdu in the Sichuan Basin exhibit the least sensitivity to solar thermal technology costs.

Factors that may positively or negatively affect the procurement of solar thermal systems are:

- Large domestic hot water and space heating loads
- Abundant solar resources
- High cost of back-up energy
- Availability of area for collectors

Regression coefficients give us quantitative indicators of what will happen if technology costs decrease. In certain cities, reducing solar thermal variable cost yields promising increase of solar thermal adoption. However, the sensitivity of solar thermal adoption to its variable cost varies with building's heating load and cities solar radiation.

Solar thermal technologies compete with PV technologies in regions where prices of back-up fuels like natural gas are higher. In Guangdong, Yunnan, and Tibet provinces, more competition exists between these two types of solar systems if technology costs reduce or natural gas prices increase. Heat storage is the complementary technology because the combined use of solar thermal and heat storage technologies makes it possible to save the solar energy generated in the daytime for use during the evening when demand is high. Therefore, an increase in installations of one technology will boost customers’ investments in the other.

Subsidies to encourage investment in solar thermal technologies should be attributed to regions sensitive to technology cost. Incentive policies, such as providing to investors a fixed amount of subsidy for each kW installed, is more effective in northern China. Prices of conventional fuels like natural gas will play an important role in customers’ investment decisions. Higher natural gas prices are indirect incentives to residents to switch to solar thermal. The relationships among different distributed technologies must be considered when making policies. For example, giving incentives to both solar thermal and PV might not be effective because these two solar technologies compete for the same space, and the availability of space will limit the maximum number of solar collectors that can be installed.

5 REFERENCES

[1] U.S. Department of Energy (DOE), Energy Efficiency & Renewable Energy. 2012. Buildings Energy Data book – Energy Supply, 2012. Available online at: http://buildingsdatabook.eren.doe.gov/ChapterIntro6.aspx

[2] U.S. Department of Energy (DOE), U.S. Energy Information Administration (EIA). 2012. Annual Energy Outlook 2012 with projections to 2035. DOE/EIA-0383(2012), Washington D.C. Available online at: www.eia.gov/forecasts/aeo

[3] Goldstein, L., B. Hedman, D. Knowles, S. I. Friedman, R. Woods, T. Schweizer. 2003. Gas-Fired Distributed Energy Resource Characterizations. Golden CO: National Renewable Energy Resource Laboratory Report TP-620-34783.

[4] Stadler, M., C. Marnay, A. Siddiqui, H. Aki, J. Lai. 2010. Control of Greenhouse Gas Emissions by Optimal DER Technology Investment and Energy Management in Zero-Net-Energy Buildings. European Transactions on Electrical Power, Special Issue on Microgrids and Energy Management. Volume 21, Issue 2, on-line ISSN: 1546-3109. Also Berkeley CA: Lawrence Berkeley National Laboratory Report LBNL-2692E, available online at: http://der.lbl.gov/publications.

[5] C. Marnay, M. Stadler, A. Siddiqui, N. DeForest, J. Donadee, P. Bhattacharya, J. Lai. 2011. Applications of Optimal Building Energy System Selection and Operation. Microgen'II: Second International Conference of Microgeneration and Related Technologies, Glasgow, Scotland. Also, Berkeley CA: Lawrence Berkeley National Laboratory Report LBNL-4764E, available online at: http://der.lbl.gov/publications.

[6] M. Stadler, C. Marnay, A. Siddiqui, J. Lai, B. Coffey and H. Aki, Effect of Heat and Electricity Storage and Reliability on Microgrid Viability: A Study of Commercial Buildings in California and New York States, Rep. LBNL-1334E, Berkeley, 2009. Available online at: http://der.lbl.gov/publications

[7] U.S. Department of Energy (U.S, DOE), Energy Efficiency & Renewable Energy, Building Technologies Program. 2010. Guide to Determining Climate Regions by County. Building America Best Practices Series, Volume 7.1 Pacific Northwest National Laboratory and the Oak Ridge

National Laboratory Report PNNL-17211, available online at: http://www1.eere.energy.gov/buildings/.

[8] Feng, W., N. Zhou, C. Marnay, M, Stadler, J. Lai, Q. Liu, R. Fan. 2012. Building Distributed Energy Performance Optimization for China - a Regional Analysis of Building Energy Costs and CO_2 Emissions. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove CA. Also, Berkeley CA: Lawrence Berkeley National Laboratory Report LBNL - 81770, available online at: http://der.lbl.gov/publications.

[9] Levine, M., W. Feng, J. Ke, T. Hong, N. Zhou, Y. Pan. 2012. A Retrofit Tool for Improving Energy Efficiency of Commercial Buildings. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove CA. Also, Berkeley CA: Lawrence Berkeley National Laboratory Report LBNL.

[10] Hong, T. 2009. A close look at the China Design Standard for Energy Efficiency of Public Buildings. Energy and Buildings, Vol. 41 (4): 426–435.

[11] U.S. Department of Energy (DOE). 2011. EnergyPlus. Available online at: http://apps1.eere.energy.gov/buildings/energyplus/.

[12] National Renewable Energy Laboratory (NREL). 2012. PVWatts - A Performance Calculator for Grid-Connected PV Systems, Available online at: http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/..

[13] Energy Solutions Center (ESC). 2013. DG Applications Guide – 6. DG Natural Gas Rates, available online at: http://www.understandingchp.com.

[14] National Development and Reform Commission (NDRC). 2011. Baseline Emission Factors for Regional Power Grids in China. Climate Change Department, China...

[15] Wang, Z., D. Ren, H. Gao. 2011. China Renewable Energy Industry Development Report (in Chinese). China Chemical Industry Press. Beijing, China ISBN: 978-7-112-1313-7