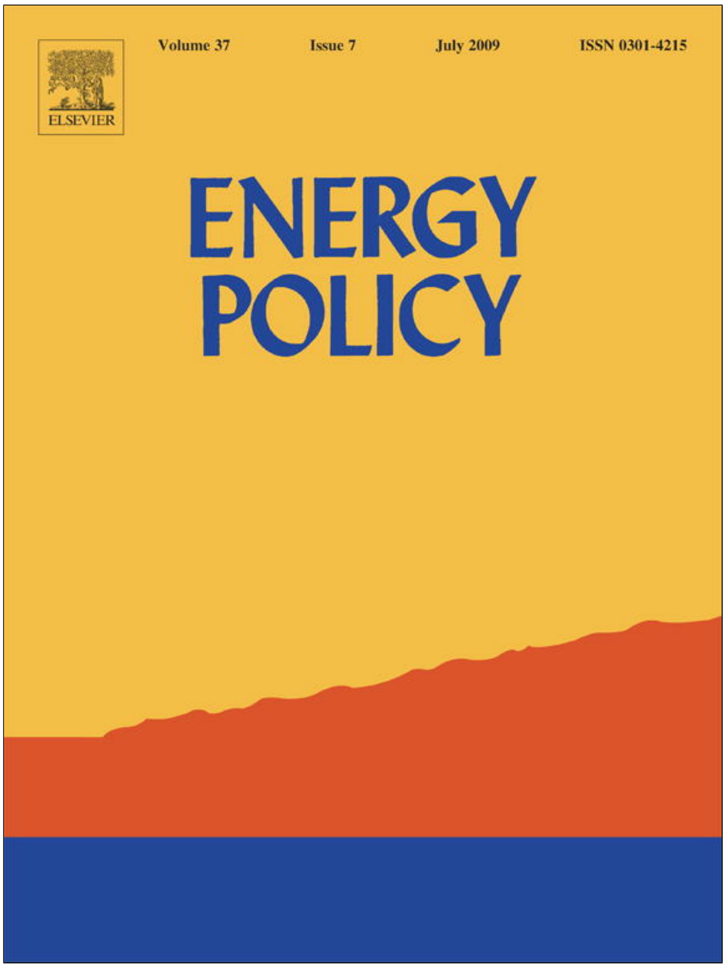
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Decision on optimal building energy efficiency standard in China—The case for Tianjin

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ABSTRACT

This paper investigates the optimal choice of building energy efficiency (BEE) standard in the context of centralised urban district heating system in northern China. By employing a techno-economic analysis approach, we demonstrate that the current BEE standard implemented in the Chinese cities should be tightened further in order to achieve a socially optimal level. Without considering the externality costs associated with carbon dioxide (CO_2) emissions, current BEE standards need to be upgraded to the equivalent level of French RT2005 standard coupled with a properly designed district coal-fired Combined Heat and Power (CHP). In contrast, the equivalent efficiency standard of Swedish building code is preferably to be implemented in the case of explicit carbon emission restriction as long as the marginal cost of carbon emission (carbon price) is sufficiently high. The fuel-switching policy (from coal to natural gas) in the urban district heating system would result in significant increase in overall costs if the BEE upgrade is not taken into account simultaneously. It is also found that BEE improvements in northern Chinese cities are more cost-effective than investing in low-carbon technologies such as wind power or Carbon Capture and storage in the EU and US with regard to CO_2 emissions mitigation.

1. Introduction

The concerns about building energy efficiency (BEE) in China have received considerable attention in recent literature (Lang, 2004; Wang et al., 2007; Zhou et al., 2007; Yang et al., 2008; Lee and Chen, 2008; Li, 2008). Wang et al. (2007) develop an interesting approach to set up an indicator that allows evaluating the most cost-effective way of buildings wall insulation in a northern city in China from a building life-cycle analysis perspective. Yang et al. (2008) analyse energy performance of building envelopes in different climate zones in China based on empirical study. Lee and Chen (2008) employ a benchmarking approach to assess the efficiency performance of the Chinese building efficiency regulations relative to the Hong Kong building code (HK-BEAM) in the context of warm climate where cooling demand dominates other energy uses in the buildings. Their results show that compliance with the Chinese building code is about 50% more efficient in energy use than the adoption of Hong Kong code.

However, most of these studies are focused on the demand-side efficiency improvement in buildings and few of them have integrated the dimension of energy supply and fuel choice options, in particular in the context of large-scale district heating in northern China where huge potentials of energy conservation and carbon emission mitigation remain untapped.

In addition, although all these studies suggest the current Chinese BEE[1] regulation could be upgraded without significantly incremental costs, explicit quantitative objective regarding the building efficiency advancement from economic analysis perspective has not been specified. This study aims to bridge this gap by coupling the BEE progress and energy supply options in an economic analysis framework. The modelling approach is employed extensively for exploring the energy savings potentials relating to sectoral efficiency policy implementation. In this paper, we model the energy demand scenarios and quantify the relevant cost implications on the basis of a physical-accounting model consisting of space heating and water heating consumption in residential and commercial buildings in a representative northern city of China, along with the upstream energy supply technology options. The primary objective of the paper is to investigate the different scenarios of BEE implementation and energy supply options in order to identify the optimal choice (least-cost option) of thermal efficiency requirements in the building code specification for new construction programme. Both the calculations with

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[1] BEE in this paper deals with solely heating consumption conservation in the northern city except otherwise stated.

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and without CO_2 emission costs will be undertaken. The results will allow the decision makers to adopt sound BEE investment strategy in today's new construction programme in the urban residential sector.

The paper is structured as follows. Section 2 briefly reviews the building consumption situation and building efficiency regulatory framework in China to date. Section 3 describes the methodology of quantification approach and assumptions on the model variables. Section 4 presents the modelling results and discusses policy implications. Some concluding remarks and policy recommendations are provided in Section 5.

2. Overview of building energy consumption and existing BEE regulatory framework

2.1. Heating consumption in buildings

Currently, nearly 45% of buildings in China need heating in the northern China where heat is primarily delivered by central or district heating plants fuelled predominantly by coal. It is projected that the housing stock in the heating zone would double by 2020 (Liu, 2006). Space heating and water heating together account for nearly 60% of energy consumption in residential buildings in China, while space heating and cooling represent the largest part in commercial buildings (IPCC, 2007). The share of water heating in household energy consumption is relatively high partly because of the cooking culture and, more specifically, the widespread use of independent electric-resistance water heater, which is an energy-intensive device. However, centralised domestic hot water systems have been hardly developed in the residential sector despite the fast-developing district heating networks in the northern cities.

2.2. Regulatory framework of BEE in China

In China, BEE policy making has been undertaken in the framework of central government's comprehensive national energy policy, formulated by the National Development and Reform Commission (NDRC) in collaboration with other government institutions. Consequently, energy conservation objectives in the building sector need to be compatible with the national energy policy framework. For example, the Chinese government aims to reduce 20% of GDP's energy intensity over the 11th Five-Year Plan period (2006–2010). Accordingly, the Chinese Ministry of Construction (MOC)[2] has set up a target of 110 million ton of coal-equivalent (mtce) energy conservation and 400 million tons of CO_2 emissions reduction in the building sector during the same period (Lang, 2008).

The MOC is in charge of formulating national objective of BEE improvement and energy conservation for different types of buildings in the whole country. The BEE policy is then enforced and implemented at provincial or municipal level by local authorities and their statutory institutions, notably the Commission of Construction. Under the current BEE regulatory framework, to strengthen the implementation of national codes, the local authorities are responsible for adapting national building code into specific technical standards of building energy conservation and designing implementation methods (e.g. employment of materials and construction techniques) at local level in accordance with the objective of national BEE standards. The Commission of Construction and Administration of Quality Control (AQC) are jointly responsible for monitoring and supervision of BEE policy implementation in all new construction projects. BEE design should be reviewed and approved by the Commission of Construction before endorsing the project and issuing the construction permit. Moreover, new construction is subject to random check and final examination of BEE application by the AQC and other public authorities at the stage of architectural and engineering works reception.

In most northern cities in China, the main regulatory framework of BEE implementation consists of several government bodies and institutions in charge of administration of urban development, buildings construction and heating supply services. The organizational structure of these institutions and their respective function are illustrated in Fig. 1.

Major cities and provinces like Beijing, Tianjin, Shanghai, Hubei, and Guangdong have all adopted local building efficiency regulations to address the specific characteristics related to building energy use. Provincial and municipal regulations and codes play an important role in implementing the national standards (Lee and Chen, 2008) given the diverse geographic and climate conditions as well as considerable difference of financial and technical capacities amongst different regions.

2.3. The current status of mandatory codes for BEE

Lang (2004) describes comprehensively the progress in mandatory building energy efficiency codes for residential buildings in China. In the framework of BEE and heat supply reform pilot project in Tianjin, financed by the World Bank, Liu (2006) outlined a brief description on the process of China's BEE regulatory standards enforcement and implementation in the cold climate regions in which the city of Tianjin is highlighted.

The object of this study is centred on buildings heating efficiency, the air conditioning (cooling) respect is out of the scope of this study. The following lines summarises succinctly the current situation of China building codes.

2.3.1. National BEE regulations development

According to the national "Standard of climatic regionalisation for architecture (GB50178-93)", China is divided into five climate zones, namely severely cold, cold, hot summer and cold winter, hot summer and warm winter, and moderate zone, respectively (MOC, 1993a). So far, four national building efficiency codes (MOC, 1995; MOC, 2001; MOC, 2003; MOC and NAQSMIQ, 2005) constitute the essential regulatory body setting mandatory efficiency requirement for both residential and commercial buildings in different climate zones: (1) JGJ-26-95 (MOC, 1995), with an energy savings goal of 50% was stipulated in 1996. (2) JGJ134-2001 (MOC, 2001), implemented to enhance electricity consumption efficiency for heating and cooling in residential buildings in the aforementioned hot summer and cold winter zone, which covers basically the Yangtze River Basin. (3) JGJ 75-2003 (MOC, 2003), introduced in 2003, is aimed at instituting technical standards for residential buildings in the warm climatic zone (southern provinces) to reduce the space cooling consumption. (4) The GB50189-2005 (MOC, 2005) becomes effective since 2005, prescribing compulsory provisions of minimum energy performance for public and commercial buildings throughout the country.[3]

Similar to the building codes implemented in other countries, two compliance approaches coexist in the Chinese building codes,

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[2] The MOC is now renamed as Ministry of Housing and Urban–Rural Development.

[3] The GB50189-2005 differs from the previous residential building codes in that, it not only regulates heating and cooling consumption, but also defines mandatory values for lighting, ventilation, electric appliances and end-use equipments as a whole.

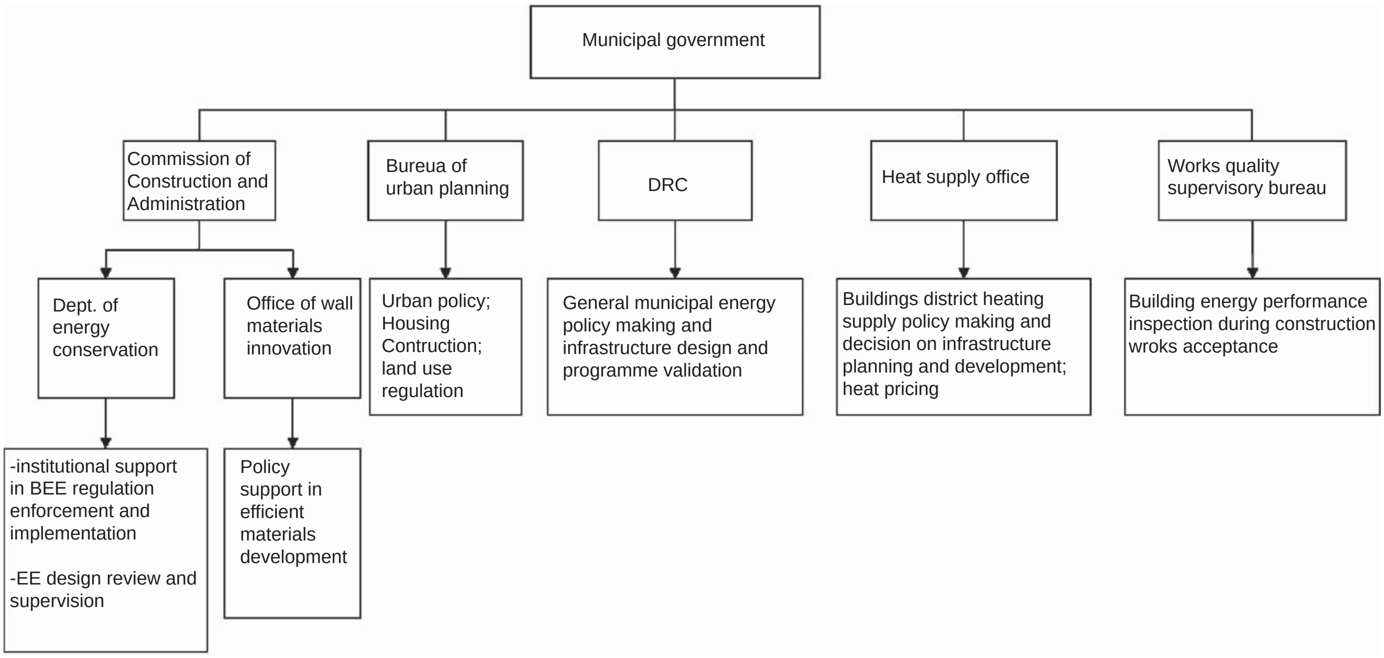

Fig. 1. Typical regulatory framework of BEE enforcement and implementation in Chinese cities.
Note: DRC is the abbreviation of Development and Reform Commission, a major institution in charge of local energy policy formulation.

which focus on buildings envelope performance. One is prescriptive that stipulates the maximum allowable heat transfer coefficients (*U*-value) for various building envelope components at the prescribed shape factors (ratio of area of building envelope to the floor area). Heat transfer coefficients, shape factors, window-to-wall area ratios based on orientations are stipulated for different climate zones. If the design of the residential building cannot satisfy the prescriptive requirements, the performance-based approach is used to assess the integral building efficiency (Liu, 2006; Lee and Chen, 2008). This approach stipulates the maximum allowable heating/cooling consumption of a building based on the baseline design, very commonly employed in the building energy efficiency assessment in the hot summer and cold winter climate zone where the designer can tradeoff between the heating and cooling performance as the building code prescribes both the overall energy consumption and specific envelope *U*-value of a building (Lee and Chen, 2008).

2.3.2. *Technical specification in the Tianjin building energy efficiency standard (1997 and 2004 update)*

As noted in Liu (2006), Tianjin was one of the pioneer cities to implement the building energy efficiency policies in residential sector in China during the 1980s. As mentioned above, National Residential Buildings Energy Efficiency Design Standard-95 (JGJ-26-95) sets the general guideline for efficiency design, it is then up to local construction administration (Municipal Commission of Construction in general) to transform the national standard into local building code by taking into account architectural and climatic characteristics. Tianjin adapted the National RBEEDS-95 into Tianjin RBEEDS in 1997 (TJRBEEDS-97) to achieve 30% improvement in building thermal performance compared with inefficient design, and introduced a revised RBEEDS in 2004 (TJRBEEDS-04), which raised the stringency of thermal integrity requirements and introduced requirements for heat metering and user control and regulation installations in new residential buildings. Compliance with TJRBEEDS-04 would result in a further reduction of specific heating energy consumption of new residential buildings by 30% from the level achieved by complying with TJRBEEDS-97 (TJMCC, 2004). Details of technical specification of TJRBEEDS are provided in Table A1 in Appendix (available online).

To compare the cost-effectiveness of compliance with different levels of energy performance in the building codes in Tianjin and other countries, we selected three foreign countries as the benchmark, Canada, France, Sweden, all of them have enforced and implemented the most stringent building codes in comparable climate. The international benchmark values in section 3.4 are derived from the relevant technical specifications in NRCC (2005), CSTB (2006) and SBHBP (1993).

3. Methodology

A techno-economic analysis model is elaborated by combining the building thermal efficiency and upstream energy supply system. The analysis process is divided into two major steps. First, we simulate the total final heating requirements in different BEE implementation scenarios in which buildings are assumed to comply with relevant energy performance regulations building codes. Second, primary energy supply and fuel combustion-related emissions will be estimated based on selected supply system accordingly. Six heating supply technology options are considered in the model, their relevant technical and economic features are compared with detailed description in Table A-3 and A-4 in Appendix. The modelling time frame covers a 20-year period, starting from 2006 to 2025, consistent with the lifetime of building insulation materials and small- and medium-sized district boilers. The discount rate used in the calculation is 8%, approximately equivalent to the indicative value of the long-term housing mortgage loan interest rate, set by the Chinese central bank. The use of marketplace real interest rates and savings rates is commonplace in widespread benefit–cost economic analyses on climate change. The debate on intertemporal and intergenerational discounting of the economics of the climate change is of out the scope of this study, further discussions can be found in Arrow et al. (1996), Mendelsohn (2007), Nordhaus (2007a, b) and Stern (2007, 2008).

Table 1
Breakdown of floor area by building types.

	Residential		Commercial		
	Low-rise buildings (6-storey)	High-rise buildings (10-storey)	Office	Hotel	Commercial centre
Single building size (in m^2)	5476	6507.5	20,000	14,000	17,000
Number of buildings	161	90	21	3	10
% in the total area in the zone	42	28	20	2	8

3.1. General buildings typologies and characteristics

We model the investment strategy in terms of BEE improvement and supply technology options for a new housing development programme in a residential district where different energy supply infrastructures can be envisaged. The district is assumed to cover an area of 10 km^2 located in the southeast of the new urbanised area (Binhai New Area) of Tianjin. It is also assumed that the plot ratio of land use within the district is 2.1[4]. Residential and commercial buildings are supposed to account for 70% and 30% of the built-up floor area, respectively.

It is assumed that all dwellings built in this area are multi-family apartments, in fact, the single detached house is very rare in China's urbanised area except for high-end luxury property programme. Low-rise (5–6 storey) and high-rise (10–12 storey) residential buildings are considered in the model. They are supposed to represent, respectively 40% and 60% of the total housing floor area. In addition, three types of commercial buildings, namely offices, hotels and shopping centres are included in the model to calculate the heat load and energy consumption of the entire area. The main characteristics of buildings are summarised in Table 1.

3.2. Heating intensity estimation

Five residential BEE scenarios are simulated in the model, denoted by TJ-97, TJ-2004, TJ-CAN, TJ-RT2005 and TJ-SWE, respectively. They refer to scenarios that require compliance with equivalent level of the current Tianjin (97 and 2004), Canadian, French, Swedish efficiency standards (building envelope thermal characteristics) in the new construction. In addition, TJWB97 and TJWB04 represent the actual values obtained from the World Bank/GEF Tianjin project.

Heating intensity is calculated by using a simplified steady-state heat transfer equation, more technical details of thermal calculation in the Chinese building sector are provided in (MOC, 1993b, 1995; Lang, 2004; Jiang et al., 2007). Two specific indicators are defined, namely U_{env} and D_{bilint} in Eqs. (1) and (2) respectively. They are used as proxy of the building thermal integrity performance (including air tightness).

$$U_{env} = \frac{\sum_{i=1}^{i} U_i A_i}{F_{env}} \tag{1}$$

and

$$F_{env} = \sum_{i=1}^{i} A_l$$

$$D_{bldint_m} = \frac{\sum_{i=1}^{i} \psi_i U_i A_i + C_p \rho N}{FS_{bld}} - \frac{IHG}{\Delta T} \tag{2}$$

where D_{bldint_m} is the integrity energy efficiency parameter of building type m; ψ_i is the correction coefficient to take into account the solar heat gain of envelope i; U_i is the heat transfer coefficient of building envelope i (wall, window, roof, floor, etc.); A_i is the corresponding area of the envelope; C_p is the heating value of air in Wh/kgK; ρ is the air density in kg/m^3; IHG is the internal heat grain in w/m^2; ΔT is the average outdoor/indoor temperature difference during heating season; N is the air exchange rate in V/h or m^3/h; FS_{bld} is the floor space area (m^2).

The simulation of the heating consumption is carried out with the degree-days method by deriving the overall thermal transmittance value of building envelope (U_{env}) from the U-values of each façade and the overall floor area of the building. The per square metre useful energy demand (UE_{mn}) for space heating in a specific year $\boldsymbol{n}$ of building type $\boldsymbol{m}$ is then calculated simply by Eq. (3), where HDD stands for heating degree day:

$$UE_{mn} = D_{bldint_m} \times HDD_n \times 24 \tag{3}$$

The calculated values will allow benchmarking the overall envelope performance of compliance with relevant building codes in different countries.

3.3. Water heating consumption

The annual water heating energy consumption in residential buildings is calculated by the following equation:

$$Q = C(T_h - T_c)qN365/3600 \tag{4}$$

where Q is the energy consumption for water heating (KW); C is the specific heat capacity of water (4.19 KJ/Kg K); T_h is the hot water outlet temperature (°C); T_c is the cold water inlet temperature (°C); q is the daily hot water consumption per capita (litre per person per day); N is the household size (person per household).

It is assumed that the household hot water consumption will increase from 30 l/p/d in 2005 to 65 l/p/d in 2020, equivalent to the current level of Japanese households hot water consumption. This hypothesis is consistent with that in Zhou et al. (2007) in which annual household water heating consumption will increase from 3600 Mj per household in 2005 to 8500 Mj per household in 2020 for urban household in China. Centralised domestic hot water supply is assumed to be available in the case of district Combined Heat and Power (CHP) supply system. Individual independent gas boiler is assumed to meet the household water heating demand in the case of individual heating scenario.

3.4. Parameters of BEE improvement portfolios

As mentioned earlier, two types of buildings are considered to be erected in this virtual new residential zone.

1. Low-rise concrete structure residential building.
2. Reinforced concrete structure (medium- and high-rise housing).

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[4] The allocated plot ratio is regulated by local planning authority based on land use nature and location, the choice is thus far from discretionary, 2.1 is consistent with reference value in many similar property development projects in urban China.

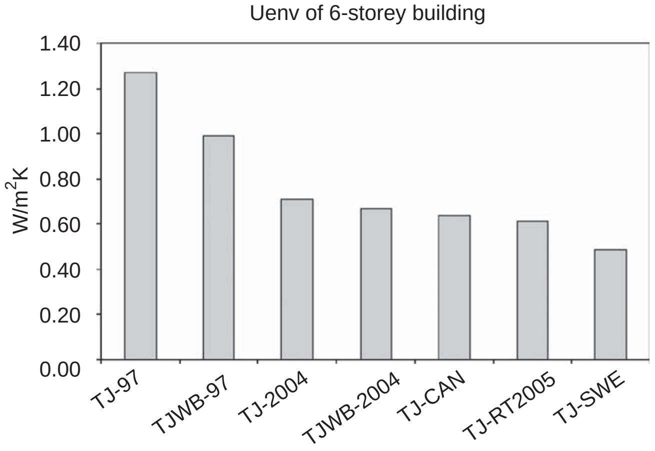

Fig. 2. overall *U*-value in low-rise buildings.

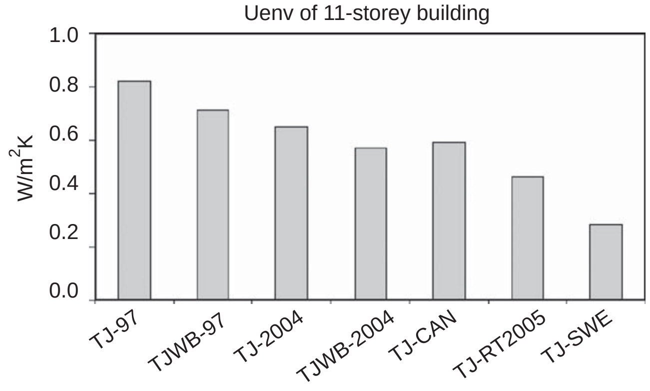

Fig. 3. Overall *U*-value in high-rise buildings. *Note*: The TJ-WB-97 and TJ-WB-2004 are the actual values measured in the BEE programme undertaken in Tianjin with the technical and financial assistance of the World Bank. Building envelope integrity *U*-value (*U_env*) is calculated by using Eq. (1).

The brick-laid low-rise building is excluded from this analysis because the use of clay brick has been outlawed in urban area since 2005.

The typical architectural design plans according to the 1983 standard are chosen for low-rise and high-rise buildings to establish the base case parameters for the house construction in this area. Table A2 in Appendix summarises the improvement measures of building envelope thermal performance in different scenarios for the high-rise building in the model.

Figs. 2 and 3 show the overall energy performance of 6-storey (low-rise) and 11-storey (high-rise) buildings complying with different BEE standard's prescriptive values, respectively. Note that air infiltration loss is also taken into account in the calculation of useful energy consumption, as shown in Eq. (2). In the case of compliance with equivalent energy performance requirements in Canadian, French and Swedish standards, reduction of heat loss through the air renewal is reflected by reduced quantity of cold air seeped into the heated interior spaces. Therefore, the calculation implies that the TJ-RT2005 and TJ-SWE are more favourable for reducing cold air infiltration energy loss by enhanced heat recovery ventilation. The U_{env} values vary between 0.4 and 1.46 depending on adopted efficiency standards. U_{env} is reduced by more than 2 times when building complies with the Swedish building efficiency code compared with the TJ-97 standard.

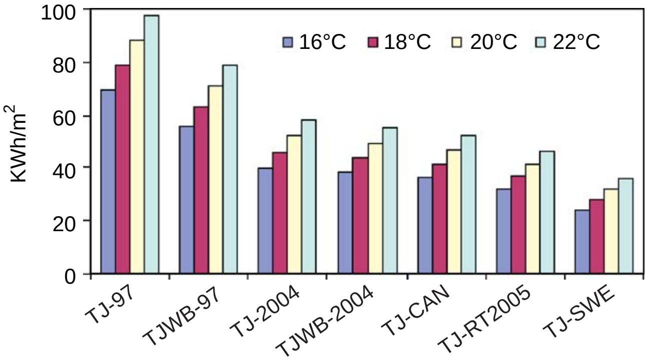

Fig. 4. Useful energy demand in 6-storey building according to BEE levels under different comfort assumptions.

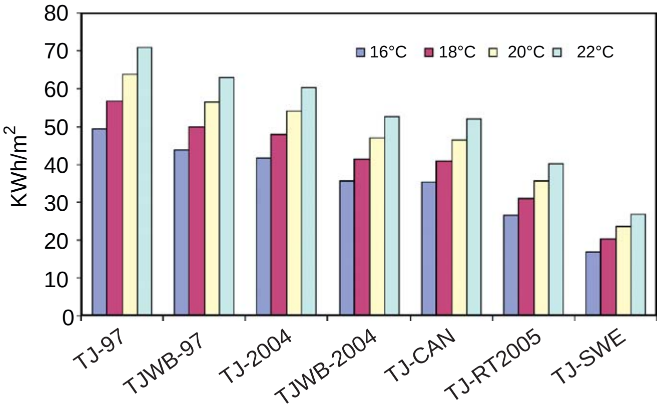

Fig. 5. Useful energy demand in 11-storey building according to BEE levels under different comfort assumptions.

As can be seen in the figures, as far as low-rise buildings are concerned, the Canadian, French RT2005 and Swedish codes are 10%, 21% and 40% more efficient, respectively as compared with TJ-2004. In the case of high-rise buildings, however, difference is more significant, TJ-CAN, TJ-RT2005 and TJ-SWE are 15%, 35% and 50% more efficient than the TJ-2004 building code, respectively.

Figs. 4 and 5 illustrate how the final heating consumption may vary with the indoor heating temperature given the same building efficiency standard. The current building code requires the minimum temperature during the heating period should not fall below 16 °C, which is much lower than the comfort level in developed country, in general 20–23 °C depending on climate zone and household's consumption behaviour.

According to microeconomics theory, the consumer's willingness to pay for the energy services is influenced by both household income and prices of energy in the residential sector. It is quite often to observe that people tend to use more energy than that projected in the engineering models in which the factor of consumption behaviour is not necessarily captured. However, consumer's decision on choosing comfort level may vary with the building efficiency and perceived fuel price signal. Typically, in efficient house or with efficient appliance, households are likely to consume more energy than habitude since energy-efficient measures reduce the marginal price of the services they deliver, producing a so-called rebound effect that results from decrease in the price of effective comfort for end users. Thus actual energy conservation of BEE enhancement is often below engineering estimates for heating and cooing in the residential sector (Durbin et al., 1986; Haas and Biermayr, 2000). As can be seen in Figs. 4

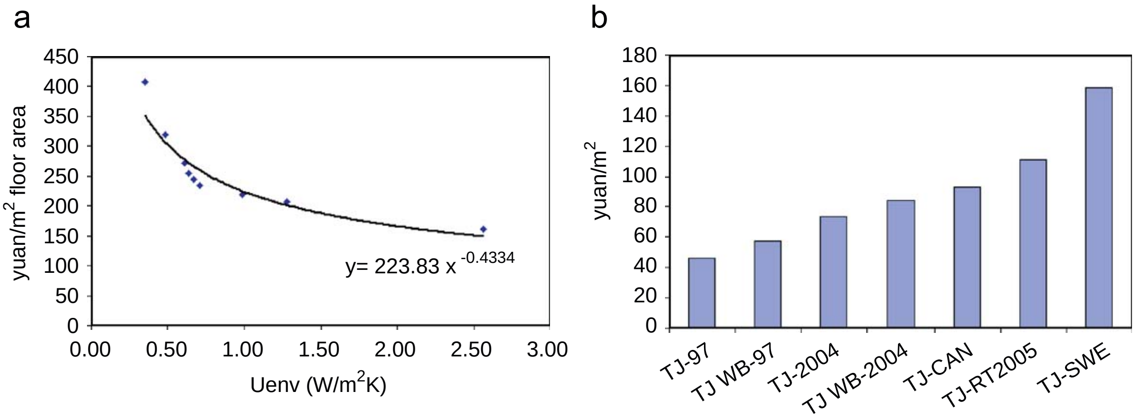

Fig. 6. (a) Low-rise building envelope cost with the envelope integrity thermal efficiency. (b) Additional cost related to BEE measures in 6-storey building.

and 5, in each of the scenarios of BEE compliance, differentiating the comfort requirement (indoor temperature) may result in 16–35% variation in the final energy demand. In other words, the benefit in terms of energy savings compared with the baseline would be offset by 7–30% as a result of improved thermal comfort (increase in indoor temperature during heating period). Importantly, we note a diminishing trend of reduction caused by rebound effect, the more the building is efficient (well insulated), the less the rebound effect will affect the actual consumption level.

Nevertheless, it is difficult to estimate the influence of variation in household income or energy price on actual consumption behaviour, since no empirical studies on rebound effect in the Chinese residential sector have been undertaken with robust techno-econometric models, further empirical studies are highly recommended. We use standard engineering approach to estimating the heating energy demand. In our modelling framework, the consumer's behaviour change in terms of growing demand for thermal comfort is captured by the factor of incremental indoor temperature and extended heating period in terms of *HDD* over the modelling period as a result of increase in household income. In the model, thermal comfort levels of households in Tianjin and western countries are expected to converge eventually.

No alternative scenario is simulated regarding the BEE improvement in commercial buildings since our study is focused primarily on residential building energy efficiency. Heating and water consumption intensities in commercial buildings used in the model are based on the reference values in MOC (2002). Also, data supplied by Jiang et al. (2007) and Zhou et al. (2007) are taken into account to complement the MOC's values when necessary, consequently, the indoor temperature during the heating period will grow gradually from 16 °C in the base year to 22 °C in 2025 in the model.

3.5. Costs

As mentioned above, the determining criterion of the optimal choice of BEE standard and relevant energy supply system requires the total cost being the lowest among all options over the modelling period. The programme is then to minimise the present value of total cost incurred in BEE option *i* with supply system *j* over the assessment period, putting it formally, our question is to select

Optimal BEE choice

s.t

$$\text{Min } LCC_{ij} = BEC_i + \sum_{k=1}^{20} CC_{ij}(1+a)^{-k} + \sum_{k=1}^{20} FC_{ij}(1+a)^{-k} + \sum_{k=1}^{20} OMC_{ij}(1+a)^{-k} + \sum_{k=1}^{20} EC_{ij}(1+a)^{-k}$$

where LCC_{ij} is the present value of the life-cycle cost of BEE option i coupled with energy supply system j; CC_{ij} is the capital cost of energy supply system j subject to compliance option i in buildings; BEC_i is the buildings envelope cost of BEE option i; FC_{ij} is the fuel cost of BEE option i coupled with energy supply system j; OMC_{ij} is the operation and maintenance cost of energy supply system j subject to the implemented BEE option i; EC_{ij} is the cost of externality associated with energy consumption in supply system j subject to the implemented BEE option i (emission of carbon dioxide and sulphur dioxide); a is the discount rate (8%).

3.5.1. Incremental cost associated with BEE improvement

This cost refers to the up-front incremental cost related to building energy performance enhancement in relevant BEE compliance scenarios. Estimation of costs of enhanced insulation and ventilation efficiency is based on Liu (2006) and author's personal interviews.[5]

Additional costs related to BEE enhancement relative to the *basecase* described above are accounted for on the per unit floor area basis. Figs. 6(a) and 7(a) illustrate the relationship between the building envelope costs and the thermal performance in terms of integrity *U*-value (U_{env}), while Figs. 6(b) and 7(b) delineate the rate at which the building envelope costs increase with the higher level of performance requirement in relevant efficiency standard in low-rise and high-rise buildings, respectively.

3.5.2. Capital cost of energy supply system

Both coal-fired and gas-fired energy supply systems are considered in the model. According to the municipal district heating plan, considerable capacity of coal-fired large CHP is expected to be added over the next decade (TJEG, 2007). To keep our analysis as simple as possible, large-scale renewable energy-based district heating system (solar, biomass, heat pump) is excluded in this study, their share in total energy mix is likely to remain small in the medium term perspective, although the ground-resource heating pump becomes very common in some new residential areas in Tianjin. Furthermore, uncertainty about the reliable renewable resources to ensure the continuous supply in large-scale residential area has not been addressed in terms of both technical and economic feasibility. Analysis integrating renewable heating is hopefully to be explored in detail in prospective researches.

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[5] Interviews were conducted with experts involved in the World Bank/GEF Tianjin project, Ministry of Construction, Tianjin Municipal Commission of Construction and of Tianjin Association of Buildings Materials in 2007 and 2008, names are available upon request.

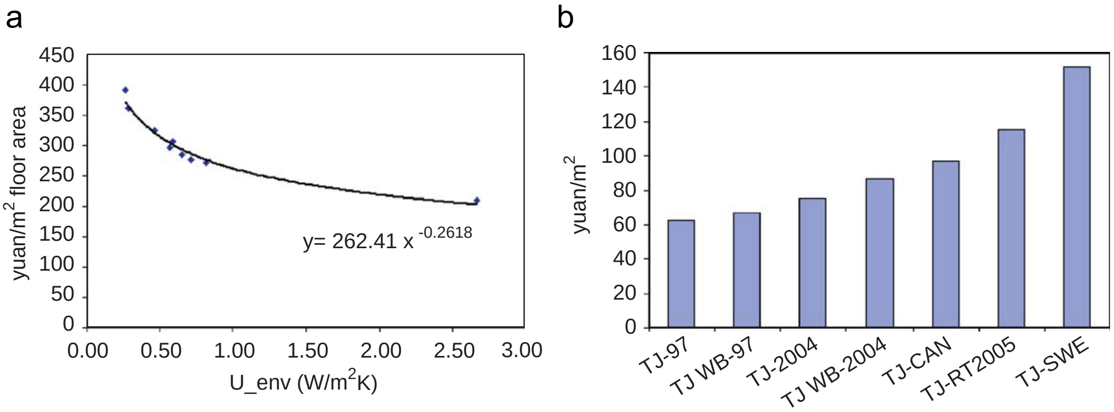

Fig. 7. (a) High-rise building envelope cost with the envelope integrity thermal efficiency. (b) Additional cost related to BEE measures in 11-storey building.

On the other hand, the discussion about whether China should opt for radical fuel-switching policy, primarily from coal to natural gas has led to intensive debates among the international energy analysts. Inside China, some argue that the rapid development of natural gas-based energy supply infrastructure will contribute to tackling the atmosphere pollution such as acid rain, resulting from intensive coal use in power generation and district heating in the northern cities. Indeed, switching to natural gas also contributes to curbing the CO_2 emissions, yet to a less extent in the Chinese energy policy priority. The objective of integrating the gas-fired heating supply system is to examine both environmental and economic implications of fuel-switching policy. In sum, five heating supply options based on the capacity, fuel type and generation technology are considered for heat supply, namely

1. district coal-fired heat-only boiler (1.4–7 MW/unit)
2. district gas-fired heat-only boiler (7 MW)
3. distributed medium-sized CHP (7–14 MW/unit, or 10–20 t/h)
    (a) coal-fired CHP
    (b) gas-fired CHP
4. municipal district heating (coal-fired CHP, 116 MW/unit)
5. individual heating with gas boilers (20–50 KW/household)

In the commercial buildings, gas- or coal-fired individual boilers will be installed in the case where the district heating networks are not available. At present the options 1 and 4 are the most common ways of district heating in the cities of northern China, gas-fired boilers hardly exist in Tianjin in the context of gas supply shortage, partly due to the undertaking of large-scale fuel-switching programme for district heating in Beijing.

The last category of heating system presents an extreme fuel-switching scenario, under which all buildings constructed in this area will be supplied with natural gas, individual gas boilers are supposed to be installed in all households and small-sized gas-fired boilers are installed in commercial buildings to meet space and water heating demand. This scenario presumes sufficient gas supply in this zone over the modelling period, albeit unrealistic from energy source availability perspective.

Technical characteristics and costs of each energy supply option are presented in Tables A3 and A4 in Appendix (available online).

3.5.3. *Cost of fuel resources*

Economic theory tells that the opportunity cost of the resource consumption should be used in social cost–benefit analysis since the market price does not necessarily reflect the real social cost (shadow price) of consuming the natural resources, in particular in the case where energy use is heavily subsidised by the government (Heaps, 2006). However, it is often very difficult to value this social cost in practice, we use the market price as a proxy of resource consumption cost. It is foreseeable that domestic energy price in China and international benchmark prices will be converging in the long run. In 2005, market price of fuel is at 0.086 yuan/kWh (LHV) for coal and 0.201 yuan/kWh (LHV) for natural gas in Tianjin. Price escalation for coal and natural are assumed to average 1.5% and 1% per year over the modelling period, respectively.

3.5.4. *Costs of externalities*

The energy-related emissions of pollutants and greenhouse gases (GHG) provoke damage costs and are externalities in that these costs are not reflected in the prices of energy. In the cost–benefit analysis of social project, the damage costs, also called external costs, should be considered (Rabl and Spadaro, 2006). In our analysis, the pollution control is expected to be installed in all the coal-based supply systems presented above, in particular the process of removal of sulphur dioxide (SO_2) from flue gas. SO_2 emission in power plants is being strictly regulated by the Chinese environment agencies. We assume that all coal-fired heat generation plants will be equipped with appropriate device to control the emission below the mandatory threshold prescribed in relevant environmental regulations. Currently, environmental regulation agencies in eastern cities levy SO_2 discharge at around 0.7 yuan (0.09 US$)/kg in coal-fired power plants. This tax is considered as the desulphurisation benchmark cost in the model. It is assumed that the emission allowance price of SO_2 discharge will continue to rise to reach 3 yuan/kg by 2025.

The GHG, in particular the CO_2 emission is considered as the largest global externality that the world has ever seen (Stern, 2007). Although China has not yet been subject to any compulsory CO_2 reduction targets and the post-Kyoto regime is still unclear, a global carbon emissions restriction scenario is very likely to occur under which China will have to implement policies to reduce carbon emissions in different sectors in order to ensure the global climate security. Moreover, the social opportunity costs of CO_2 (shadow price) exist regardless of whether the mitigation actions will be undertaken or not.

A carbon tax is assumed to be levied in the "*carbon emission restriction*" scenario in the model. Two carbon price evolution perspectives, low- and high-price scenarios will be simulated. In the low-price scenario, carbon emission is priced at 10 US$/t$CO_2$, while in the high-price scenario carbon price is set at 30 US$/t$CO_2$ throughout the modelling period. The Chinese Yuan is assumed to continue to appreciate against the US dollar, the exchange rate of US$/CNY is supposed to fall from 8.01 in 2005 to 6.5 in 2025.

In fact, the chemical process of desulphurisation may result in extra CO_2 emission; the quantity may vary depending on the process adopted. To simplify our analysis, the calculation of emission of CO_2 is focused on the fuel combustion-related emission since the desulphurisation-related emission must be estimated case by case. Additionally, technological advancement will allow significant reduction in the CO_2 emission originating from the desulphurisation process. For example, a new technology based on a combined removal system for separating carbon dioxide and sulphur oxide gases from furnace flue gases (Nolan, 2002) will lead to promising prospects of sulphur and CO_2 emission control in the coal-fired power plants in the future.

3.5.5. *Economic benefit of implementing BEE*

The benefits related to implementation of energy efficiency policies in buildings refer to the reductions in following costs:

1. cost associated with new generating capacity addition;
2. the fixed and variable charges associated with operation and maintenance of heat supply;
3. resource cost associated with heating consumption, maintenance and operation costs in the heat supply plants;
4. environmental pollution control costs, in particular the sulphur dioxide (SO_2) emission from coal-fired boilers.

Estimation of costs is based on research literature and government official documents (Ye et al., 2001; Cummins, 2004; NCMEDRI, 2006, 2007). Note that the cost associated with the development of heat supply infrastructure (networks, substations, exchangers, etc.) is included in the cost of investment in energy supply. The average cost of development of distribution infrastructure of urban district heating in northern China is around 45 yuan (5.6 US$) per square metres of constructed floor area in 2005.

3.5.6. *Benefits of cogeneration option (CHP)*

3.5.6.1. Electricity sale benefit in cogeneration units. The surplus of electricity generated in the local or municipal CHP plants is assumed to be sold to electric power grid and is thus considered as actual benefits (negative costs) in the cost–benefit analysis. Electricity wholesale price varies with production and quantity of MWh sold, load factor and so on. The wholesale price begins at 350 yuan/MWh (44 US$/MWh) in base year. We assume that the price follows a constant growth pace with 1.5% rise per year over the modelling period to be consistent with the actual electricity pricing development trend.

3.5.6.2. Carbon emission reduction benefit in cogeneration units. Apart from increased energy efficiency in CHP plants, electricity generation in CHP permit to reduce carbon emission compared with separated power and heat generation. Because the electricity is generated as a co-product in CHP otherwise it needs to be produced in power-only plant whose overall efficiency is significantly lower than CHP. Thus, the carbon emissions in CHP should be subtracted by the part associated with electricity that otherwise would be produced in the power plants in the baseline case. In 2005, the average heat rate in China's power sector is around 350 gce/kWhe, with 7% loss in distribution and transformation of power grid, thus the primary energy supply of kWh electricity consumed by the end users in buildings is 376 gce/kWhe, and average emission factor of steam coal in China is around 90 t C/GWh. Thus, it can be easily deduced that reference emission factor in power plants in the base year is approximately 1.03 kg CO_2/kWhe; thermal efficiency of power plant is assumed to improve 0.5% per year and grid loss is assumed to decrease 1% per year throughout the period. Thus emission factor in reference power generation plants will fall to 0.92 kg CO_2/kWhe in 2025. This assumption on reference carbon content of residential electricity consumption is rather robust since hydro power only represents a very small part in the North China Electricity Grid.

4. Results and discussions

4.1. *Primary energy supply and carbon emission*

Tables 2–7 report the simulation results of primary energy supply and carbon emissions of all scenarios discussed above. Improving BEE standard allows for significant reductions both in primary energy supply and associated carbon emissions. Implementation of the French RT-2005 in all residential buildings is likely to result in 29–30% reduction in primary energy supply

Table 2
Coal-fired district boiler (heat only).

	2006		2015		2025	
	GWh	1000 t C	GWh	1000 t C	GWh	1000 t C
TJ-97	3577	297	3982	318	4524	341
TJ-WB97	3192	265	3560	283	4059	303
TJ 2004	2825	235	3156	250	3615	266
TJ-WB04	2703	225	3023	239	3468	254
TJ-CAN	2648	220	2962	234	3402	249
TJ-RT2005	2438	203	2731	214	3147	228
TJ-SWE	2177	181	2421	189	2784	198

Table 3
Coal-fired district CHP.

	2006		2015		2025	
	GWh	1000 t C	GWh	1000 t C	GWh	1000 t C
TJ-97	4115	214	4561	238	5157	272
TJ-WB97	3692	199	4096	221	4645	252
TJ 2004	3288	186	3653	205	4157	232
TJ-WB04	3154	181	3506	199	3996	226
TJ-CAN	3094	179	3439	197	3923	223
TJ-RT2005	2862	171	3185	188	3643	212
TJ-SWE	2575	162	2844	175	3243	196

Table 4
Gas-fired district boiler (heat only).

	2006		2015		2025	
	GWh	1000 t C	GWh	1000 t C	GWh	1000 t C
TJ-97	3225	172	3573	191	4042	216
TJ-WB97	2896	155	3211	171	3644	195
TJ 2004	2568	137	2850	152	3247	173
TJ-WB04	2479	132	2753	147	3140	168
TJ-CAN	2431	130	2700	144	3082	165
TJ-RT2005	2273	121	2526	135	2891	154
TJ-SWE	2061	110	2279	122	2605	139

Table 5
Gas-fired district small CHP.

	2006		2015		2025	
	GWh	1000 t C	GWh	1000 t C	GWh	1000 t C
TJ-97	3741	100	4147	112	4688	128
TJ-WB97	3356	95	3724	105	4223	120
TJ 2004	2989	89	3321	98	3779	111
TJ-WB04	2868	88	3187	96	3633	109
TJ-CAN	2812	87	3127	95	3566	108
TJ-RT2005	2602	84	2895	92	3312	103
TJ-SWE	2341	80	2586	87	2948	96

Table 6
Municipal large CHP.

	2006		2015		2025	
	GWh	1000 t C	GWh	1000 t C	GWh	1000 t C
TJ-97	5266	163	5803	197	6500	242
TJ-WB97	4706	146	5188	177	5823	217
TJ 2004	4171	129	4600	157	5177	193
TJ-WB04	3994	124	4406	150	4964	185
TJ-CAN	3914	121	4318	147	4867	181
TJ-RT2005	3607	112	3981	135	4496	168
TJ-SWE	3228	100	3531	120	3966	148

Table 7
Individual gas boiler.

	2006		2015		2025	
	GWh	1000 t C	GWh	1000 t C	GWh	1000 t C
TJ-97	2227	119	2453	131	2755	147
TJ-WB97	2011	107	2216	118	2493	133
TJ 2004	1804	96	1989	106	2244	120
TJ-WB04	1736	93	1914	102	2161	115
TJ-CAN	1705	91	1880	100	2124	113
TJ-RT2005	1586	85	1750	93	1981	106
TJ-SWE	1440	77	1575	84	1776	95

Note: Primary energy demand consumed for electricity generation in CHP is not subtracted in Tables 2–7, this explain why CHPs have higher primary energy supply.

compared with TJ-97 case in 2025, and upgrading to Swedish code would allow for 35–38% reduction in the same year. Not surprisingly, CHP options allow significant reduction in carbon emissions compared with heat-only supply technologies in all scenarios.

However, prudence is necessary when interpreting the difference between the energy supply options. First, the scenario of individual gas boiler option appears to be the best scenario in terms of primary energy savings, but it disguises the fact that electricity is also generated in all the scenarios with cogeneration option. Indeed, the primary demand in heat-only scenarios must be much higher if upstream energy consumption for electricity generation is taken into account. Second, gas-fuelled energy supply system appears to be preferred to coal-fired district heating if the primary objective is the CO_2 emission mitigation. However, fuel-switching policy should be assessed much more deeply than just comparing the carbon emission outcome, the economic dimension should not be ignored. More convincing decision on investment strategies can be made through the insights in the analysis of costs in Section 4.2.

4.2. *Comparison of total costs across the scenarios*

All costs incurred in buildings and energy supply over the modelling are discounted to the base year (2006) and are accounted for as yuan/m^2 floor space to harmonise the criteria for comparison, since the unitary incremental cost related to BEE measures is expressed systematically in buildings construction programme. Cost scenarios with and without carbon price are both investigated.

4.2.1. *Exclusion of carbon emission cost*

Fig. 8 illustrates the total costs in all BEE and energy supply scenarios. Some important lessons can be drawn immediately by comparing the different scenarios:

1. All scenarios show that the current national BEE standard (TJ-97 equivalent efficiency requirements) is the most costly option, no matter what supply option will be selected.
2. Despite considerable progress compared with national objective, the BEE standard implemented in Tianjin (TJ 2004) is not stringent enough to allow achieving an optimal level since the present value of total costs incurred during a 20-year period can be reduced further by tightening the building code, even with a relatively high discount rate (8%).
3. Without any carbon price imposed, the optimal choice turns out to be the equivalent of current French RT-2005 building efficiency standard coupled with district coal-fired CHP, which allows for the lowest present value of the overall discounted costs (490 yuan/m^2 floor space).
4. Lastly but most strikingly, we observe that adopting the best available technology (BAT), or the equivalent energy performance prescribed in the Swedish BEE standards is less costly than the current BEE regulations enforced in China and Tianjin regardless of energy supply system.

These findings convey a very strong policy signal: China should tighten the BEE standards and needs to move quickly to adopt higher efficiency requirements in buildings since an obvious economic gain can be achieved from the long-term perspective.

Fuel-switching (gas supply) policy is a sub-optimal supply option despite its much lower carbon emissions compared with coal-based supply system. More specifically, the gas-fuelled scenarios are costlier than coal-fired system no matter whether the desulphurisation cost is taken into account or not. The overall cost of district gas-fired small CHP is 27–36% higher than properly-sized distributed coal-fired CHP.

Individual gas option seems to be an interesting option in terms of carbon emissions minimisation, however, the global costs are still much higher than coal-fired options. According to the result, the municipal large thermal power plant is also a sub-optimal choice in terms of global costs and total carbon emissions. High O&M cost and more energy loss due to long distance of distribution are the main defaults despite higher thermal efficiency in the large CHPs. Although the option of coal-fired district boilers (heat only) has lower costs than CHP, high carbon emissions make it less appealing.

If the municipality decides to decarbonise the energy supply infrastructure, the SWE BEE is unambiguously the best strategy except for individual gas option. However, it must be noted that the individual gas heating option is the most costly scenario despite its apparent benefits of energy savings and low-level carbon emission. Further, the result would be even worse in this

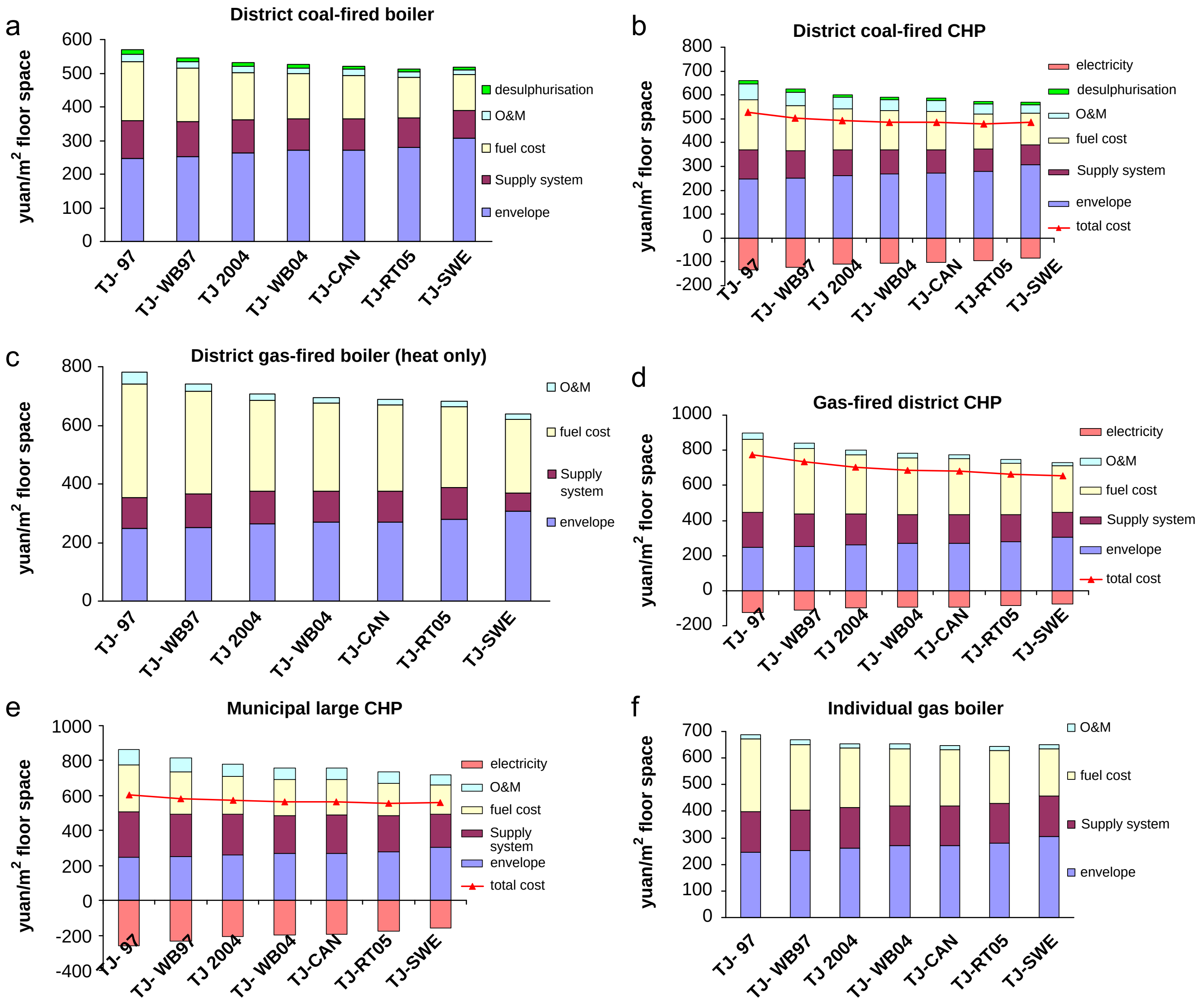

Fig. 8. Comparison of discounted total cost in different energy supply options (without carbon price).

case if the electric power consumption is taken into account (from electricity-only power plants). Also, individual gas heating will still remain a marginal part in the context of Chinese buildings sector and heat supply infrastructure in the northern Chinese cities.

4.2.2. *Inclusion of carbon emission cost*

As mentioned earlier, we simulate two carbon tax scenarios: low and high, respectively, the results are presented in Figs. 9 and 10. In fact, the sensitivity analysis shows that the results are almost identical regarding the optimal supply system under both carbon tax assumptions. Coal-fired district CHP still remains preferable supply option regardless of the degree of carbon tax imposed over the modelling period. However, with high carbon tax assumption, the Swedish code becomes more attractive than the RT 2005 in almost all the scenarios except for the individual gas heating, which is quite insensible to the carbon tax, primarily due to the low-level emission. RT-2005 is the best choice for heat-only system (coal or gas) but loses its economic attractiveness in the cogeneration system under high carbon tax constraint. Furthermore, the costs of gas-fuelled supply systems are still significantly higher than the coal-based system even under high carbon price constraint. This confirms that the choice of coal-based CHP energy supply infrastructure in the Chinese cities is the most pertinent decision.

4.2.2.1. Low-carbon price. As can be seen in Fig. 9, putting in place a low-carbon price does not change the preference order of scenarios. Coal-fired systems are still less expensive than gas-fired supply system. TJ-RT2005 with district coal-fired CHP is still the least cost option (best strategy) among all the scenarios whereas individual gas boiler option is still the most costly supply option.

4.2.2.2. High carbon price. Instituting high carbon price will change the preference order among different BEE scenarios. SWE performance becomes the least costly strategy, both in coal- and gas-fuelled heating system. Coal-fired small CHP remains the best supply solution. This result shows that the coal-fired supply systems remain more competitive than gas-fuelled systems no matter whether carbon price is imposed or not, providing that

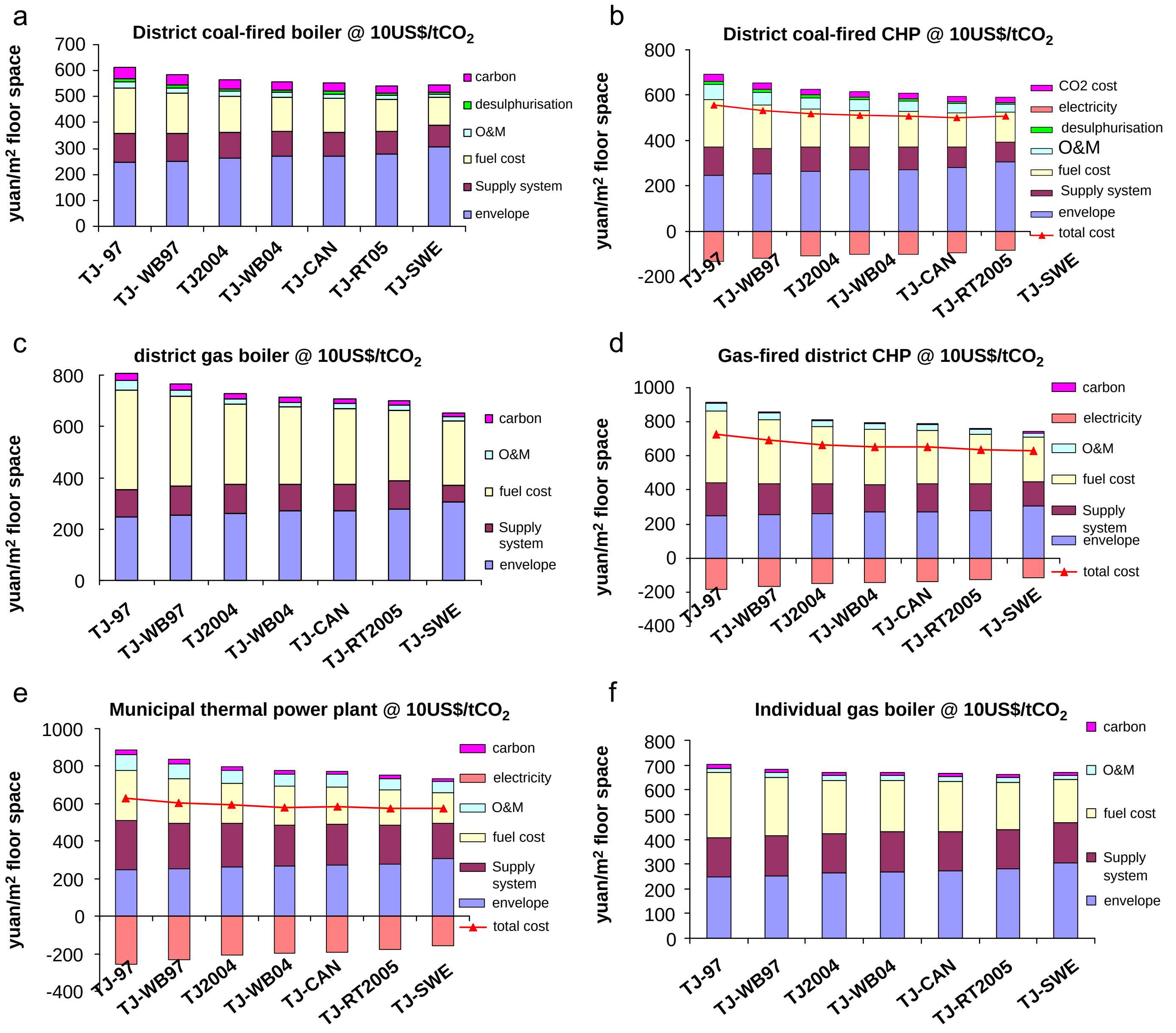

Fig. 9. Comparison of total costs with low-carbon price in different scenarios.

carbon price falls within the range of our assumption, or equivalent to the international benchmark price of CO_2 today (around 20 €/tCO_2 in the EU-ETS market).

5. Concluding remarks

In this study, we investigated the optimal decision on BEE standard and appropriate energy supply system in the context of district heating service provision in a new construction programme in a northern city of China. We compared the energy consumption and relevant economic and environmental implications of implementation of different Chinese and international BEE standards. The analyses strongly indicate that the current BEE standard implemented in China is a sub-optimal decision and should be tightened immediately in order to achieve a better energy and environmental performance while reducing the associated discounted life-cycle social costs. Improvement in BEE standards can be justified by the co-benefits resulting from the energy savings and carbon emission mitigation during the operation stage of buildings. The analysis suggests the French code RT-2005 (30% improvement in terms of overall efficiency compared with TJ-2004) allow for the lowest net present value of overall life-cycle costs thus should be adopted by BEE policy maker in China when external costs are excluded. In contrast, energy performance equivalent to the Swedish code (Best Available Technology) is preferable in the case of stringent carbon emission restriction (carbon emissions costs are included) such that the marginal cost of carbon emission (carbon price) is sufficiently high (25–35 US$/t$CO_2$ by 2020).

These findings have significant economic implications in the context of ongoing international debates on political economy of climate change. The price incentive that could enable the Chinese stakeholders in the building sector to adopt the most stringent energy-efficient standards is of the same order of the CO_2 emission allowance price in the EU-ETS 2008–2012 that averages about 30 US$/t$CO_2$. Moreover, recent literatures on economics of climate change and energy modelling all suggest the international

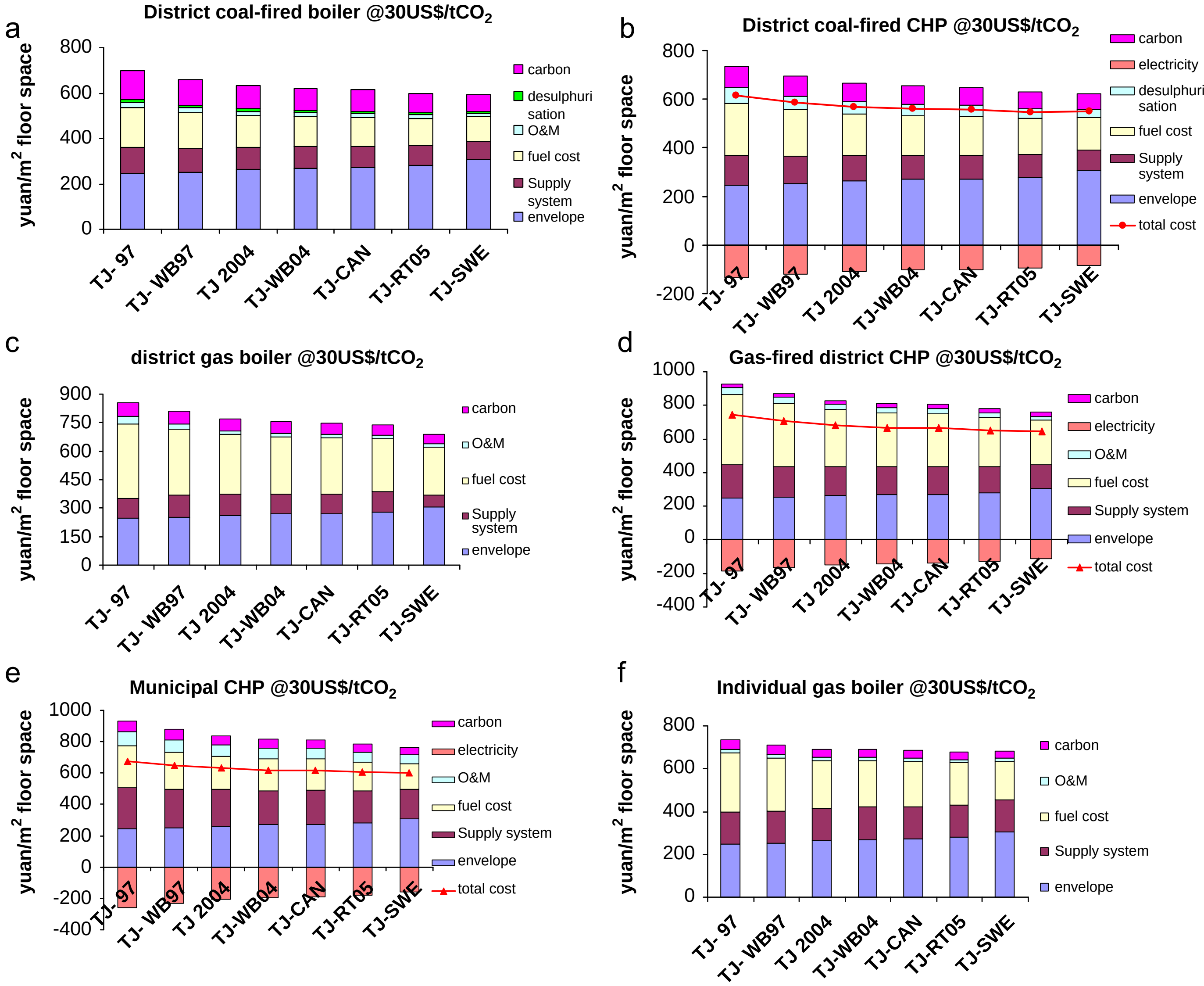

Fig. 10. Comparison of total costs with high carbon price in different scenarios.

benchmark price such as EU-ETS carbon allowance price and or the marginal abatement cost (MAC) of CO_2 in the European countries and other parts of the world are likely to range between 30 and 40 US\$/t CO_2 over the period 2020–2030 (Anderson, 2006; IPCC, 2007; Stern, 2007; Blanco and Rodrigues, 2008; Colombier et al., 2008). Although it is still difficult to predict precisely the longer term EU-ETS CO_2 price depending on various factors, the global trend of rise in CO_2 allowance price is very likely since the European Union has committed to attaining ambitious objectives of energy efficiency, renewable energy supply and CO_2 emission reduction by 2020 (Council of the European Union, 2007). Furthermore, the post-Kyoto climate regime will be necessarily more strict given the urgency of tackling global warming. Tougher mitigation objective is one of the major drivers that make CO_2 price move upwards.

On the other hand, financing the enhanced buildings energy performance in North China turns out to be more cost-effective compared with equivalent CO_2 mitigation by investing in low-carbon technologies such as renewable power supply or Carbon Capture and Storage (CCS) projects in developed countries. For example, the CO_2 price that would be needed to keep wind power financially viable in most European countries will range between 30 to 67 US\$/tCO_2 (Blanco and Rodrigues, 2008). Similarly, the levelised cost of CO_2 avoided by installing the CCS in the coal-fired power plants in the US averages around 50\$/tCO_2 when considering cost of transport (Rubin et al., 2007). In other words, the opportunity cost of retard implementing more stringent energy performance in new buildings in China is much higher compared with delayed investment in the new technologies for decarbonising energy supply in developed countries.

Despite the obvious environmental benefits in terms of polluting gases reduction, the policy of switching from coal to natural gas without integrating buildings efficiency improvement in the urban district heating system can hardly be justified for this policy implies significant increase in associated costs, the present value of overall cost of natural gas-fired district heating system is 30–35% higher than the coal-fired CHP with desulphurisation process, depending on building efficiency options.

The French *RT2005* equivalent building energy performance combined with a properly designed district small coal CHP (20 t/h+2 MWe) turns out to be the optimal choice of BEE standard and heat supply infrastructure given the underlying assumptions in the model. However, the institutional barriers to deployment of distributed CHP need to be removed (Wang and Yu, 2003; State Council, 2007). The Swedish code equivalent energy efficiency or even more stringent objective should be targeted either in a high carbon tax scenario, or in preparation of large-scale fuel-switching policy in district heating, which is, however, unlikely to occur in the foreseeable future under supply constraints. The simulation results suggest the energy policy prioritising the development of small- and medium-sized distributed CHP for district heating in northern cities in China be reasonably recommendable.

Most strikingly, our estimates show that the discounted global costs of adopting the most stringent BEE standard in the world today (equivalent to Swedish building code) will be lower than implementing the current TJ2004 standard even without any considerations of carbon value. In other words, financing should not be a major barrier to BEE improvement in the Chinese cities provided that efficient institutions will be established. Improving building energy performance can produce effective benefits compared with the business as usual case. Consequently, the gain could be redistributed to finance research and development of more efficient low-carbon energy supply system such as combined cycle gas turbine (CCGT), biomass and urban wastes-fuelled district heating supply and CCS in the longer term. They could be used to substitute gradually part of coal-fired supply capacity to address the double challenge of energy supply security and carbon emissions mitigation. Biomass co-firing and refuse incineration for heat and power generation have been recognised as promising technologies to CO_2 emissions mitigation in power sector. However, improvement in BEE standard in residential buildings is the prerequisite condition before switching massively to low-carbon supply technologies in order to minimise associated costs. An efficient buildings stock will facilitate the technological transformation and will open a broader perspective of sustainable district heating in China's northern cities. Moreover, international financial and technical assistance can intervene to help China adopt low-carbon energy supply technologies (CCGT, CCS, etc.) in condition that the price of carbon credits is competitive, through alternative financing tools like the Clean Development Mechanism (CDM). In this case, significant BEE improvement is a necessary condition of introducing this mechanism otherwise the carbon price would be much higher, a detriment to the competitiveness in the global CDM market.

Finally, the "wait and see" option would be particularly costly for the society due to the long lifetime and inertia of buildings infrastructure, which would risks being locked into the inefficient technology and carbon-intensive trajectory over several decades in case of inaction at the stage of new construction. Experiences in developed countries show that retrofitting inefficient housing will be extremely costly and difficult during the operational stage of buildings. Chinese decision makers need to attach serious attention to substantial BEE improvement in the huge quantity of new construction throughout the country to avoid the irreversible carbon lock-in dilemma in the future.

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Appendix A. Supporting data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2009.01.014.

References

Anderson, D., 2006. Costs and Finance of Abating Carbon Emissions in the Energy Sector. HM Treasury, UK.

Arrow, K., Cline, W., Maler, K-G., Munasinghe, M., Squitieri, R., Stiglitz, J., 1996. Intertemporal equity, discounting, and economic efficiency. In: Bruce, J., Lee, H., Haites, E. (Eds.), Climate change 1995: Economic and social dimensions of climate change. Cambridge University Press, Cambridge, pp. 125–144.

Blanco, M., Rodrigues, G., 2008. Can the future EU ETS support wind energy investments? Energy Policy 36, 1509–1520.

Centre Scientifique et Technique du Bâtiment (CSTB). 2006. Réglementation Thermique 2005 Th-CE.

Cummins Inc. 2004. Comparison of different CHP systems. PowerPoint presentation. In: Proceedings of the Fifth Annual Conference of World Alliance for Decentralized Energy and CHP, Beijing.

Colombier, M., Crassous, R.,Criqui, P., 2008. EPE Étude FONDDRI "Scénarios sous contrainte carbone". Powerpoint presentation, Paris, May 2008.

Council of the European Union, 2007. 7224/1/07 Rev: Brussels European Council, 8–9 March 2007. Presidency Conclusions. Available at 〈www.consilium.europa.eu〉.

Durbin, J., Miedema, A., Chandran, R., 1986. Price effects of energy efficient technologies: a study of residential demand for heating and cooling. Rand Journal of Economics 17 (3), 310–325.

Haas, R., Biermayr, P., 2000. The rebound effect for space heating Empirical evidence from Austria. Energy Policy 28 (6), 403–410.

Heaps, C., 2006. Long-range Energy Alternatives Planning System User Guide. Stockholm Environment Institute, Boston Center.

Intergovernmental Panel on Climate Change (IPCC), 2007. Residential and commercial buildings. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK.

Jiang, Y., et al., 2007. China Buildings Energy Efficiency Report 2007. Tsinghua University. China Building & Architecture Press.

Lang, S., 2008. Building energy efficiency standards in China. In: Proceedings in the Second International Conference of Green Buildings and Energy Conservation, Shanghai.

Lang, S., 2004. Progress in energy-efficiency standards for residential buildings in China. Energy and Buildings 36 (12), 1191–1196.

Li, J., 2008. Towards a low-carbon future of China's building sector—a review of long term models forecast. Energy Policy 36 (5), 1736–1747.

Liu, F., 2006. Economic analysis of residential building energy-efficient design standards in Northern China: a case study of Tianjin City. World Bank Interim Report.

Lee, W.L., Chen, H., 2008. Benchmarking Hong Kong and China energy codes for residential buildings. Energy and Buildings 40 (9), 1628–1636.

Mendelsohn, R., 2007. Comments on the Stern Review. In: Yale Symposium on the Stern Review, Yale Center for the Study of Globalization, New Haven, CT, pp. 93–103 (Chapter 8).

Ministry of Construction (MOC), 1993a. National standard of climate regionalization in architecture (GB-50178-93), enforcement 1 February 1994.

Ministry of Construction (MOC) 1993b. Thermal Design Code for Civil Buildings (GB/T50176-1993).

Ministry of Construction (MOC). 1995. Industrial Standard of the People's Republic of China (JGJ 29-95). Energy Conservation Design Standard for New Heating Residential Buildings. Ministry of Construction Enforcement, 1 July 1996.

Ministry of Construction (MOC) 2001. Industrial Standard of the People's Republic of China (JGJ 134-2001), Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Cold Winter Zone. Ministry of Construction Enforcement, 1 October 2001.

Ministry of Construction (MOC) 2002. Industrial Standard of the People's Republic of China (CJJ34-2002), Design Standard for Urban District Heating Distribution Network. Ministry of Construction Enforcement, 1 January 2003.

Ministry of Construction (MOC) 2003. Industrial Standard of the People's Republic of China (JGJ 75-2003). Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Warm Winter Zone. Ministry of Construction Enforcement, 1 July 2003.

Ministry of Construction (MOC), National Administration of Quality Supervision and Monitoring and Inspection and Quarantine (NAQSMIQ). 2005. National Standard of the People's Republic of China (GB50189-2005). Design S tandard for Energy Efficiency of Public Buildings. Ministry of Construction Enforcement, 4 April 2005.

Natural Research Council Canada (NRCC). 2005. The 2005 National Building Code.

Nordhaus, W., 2007a. A review of the Stern Review on the economics of climate change. Journal of Economic Literature 45 (3), 686–702.

Nordhaus, W., 2007b. Critical assumptions in the Stern Review on climate change. Science 317 (5835), 201–202.

Nolan, Paul S., 2002. Combined flue gas desulphurisation and carbon dioxide removal system. US Patent no. 6399030.

North China Municipal Engineering Design and Research Institute (NCMEDRI). 2006. Tianjin Urban District Heating Planning (2005–2015).

North China Municipal Engineering Design & Research Institute (NCMEDRI). 2007. District Heating Planning of Tianjin Binhai New Area.

Rabl, A., Spadaro, J.V., 2006. Environmental impacts and costs of energy. Living in a chemical world: framing the future in light of the past. Annals of the New York Academy of Sciences 1076, 516–526.

Rubin, E., Chen, C., Rao, A., 2007. Cost and performance of fossil fuel power plants with CO_2 capture and storage. Energy Policy 35 (9), 4444–4454.

State Council; National Development and Reform Commission; National Office of Energy. 2007. Notice on accelerating closing down the small thermal power units.

Stern, N., 2007. The Economics of Climate Change: The Stern Review. Cambridge University Press, Cambridge, UK.

Stern, N., 2008. The economics of climate change. American Economic Review: Paper and Proceedings 98 (2), 1–37.

Swedish Board of Housing, Building and Planning (SBHBP). 1993. Building Regulations Mandatory Provisions and General Recommendations. (2006 Revision.)

Tianjin Municipal Commission of Construction (TJMCC). 2004. Tianjin Residential Buildings Energy Efficiency Design Standard. 2004 (DB-1-29-2004), 2007. Updated on 1 June 2007.

Tianjin Jinneng Energy Group (TJEG). 2007. Tianjin Municipal CHP Development Planning 2005–2015.

Wang, Y., Huang, Z., Li, H., 2007. Cost-effectiveness assessment of insulated exterior walls of residential buildings in cold climate. International Journal of Project Management 25 (2), 143–149.

Wang, Z., Yu, G., 2003. Present status and prospect of heat-power cogeneration and policy recommendations in China. China Electric Power, Vol. 9.

Yang, L., Lam, J., Tsang, C.L., 2008. Energy performance of building envelopes in different climate zones in China. Applied Energy 85 (9), 800–817.

Ye, Y., Shi, Z., Wu, X., Zhang, H., Zhang, R., Li, X., Sha, X., Fan, J., Zhou, J., Zhao, Y., Zhao, Y., Xiong, W., 2001. Research on Urban Heating Supply System in Beijing. China International Engineering Consulting Co.

Zhou, N., McNeil, M.A., Fridley, D., Lin, J., Price, L., De la Rue du Can, S., Sathaye, J., Levine, M., 2007. Energy Use in China: Sectoral Trends and Future Outlook. Lawrence Berkeley National Laboratory, 96pp.