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WHAT DOES IT TAKE FOR THE RESIDENTIAL BUILDING SECTOR TO REACH NET-ZERO ENERGY?

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ABSTRACT

As part of the World Business Council for Sustainable Development’s energy efficiency in buildings project, the authors have been involved in modelling various technology options for different building market segments so as to reach net-zero energy goal. This paper describes the modelling of the residential sector using representative submarkets of multi-family residence in China and single family residence in USA and France. Specifically, the process involved in establishing the stock data and the construction options for residential buildings that would allow one to reach the net-zero state, and the modelling procedures used will be described in detail. In addition, for the China market, the impact of increase in standard of living on energy consumption will be examined.

INTRODUCTION

Background

The residential building sector is the largest consumer of global building energy (IEA 2009), presenting the largest opportunity for energy reductions in the sector. In the United States, residences consume 55% of the total primary energy consumed by the building sector (Depart of Energy, 2009). Further, residences in the United States have an estimated total potential of just over half of the building roof-top generation capability (Denholm and Margolis, 2008). Given these statistics, any solution to reducing carbon and energy consumption must involve the residential building sector.

Despite this large potential, the means to transform this sector remains elusive. The residential sector and its value chain remain diffuse, unlike with power plants or other industries, there are no clear point sources to address that would have substantial impact. To transform the sector, a means is needed to change the decision making of billions of residential property owners and tenants. Yet, the micro-economic decision making of residential property owners has, to date, not been incorporated into carbon abatement forecasts and cost projections. In this paper, we present results on modeling the residential building stock evolution to 2050 under different scenarios, incorporating a micro-economic decision making model for what different technologies are selected by the multitudes of home owners. These different decisions are simulated over time as new construction and retrofit choices, and the results compiled into the changing building stock. This stock is then evaluated for energy efficiency over time. Different macro-economic conditions such as price of energy, price of carbon, technology improvement, and government policies were all assessed. From this, an understanding has been achieved as to what it will take to transform the residential building stock. Generally stated, we find works up to now do not underestimate the cost to transform the sector, but do over-estimate the impact of energy prices, incentives on individual materials or subsystems, and any carbon pricing scheme. We instead find the only reasonable means to transform the sector is a policy framework of whole building homeowner incentives combined with comparatively mild energy or carbon pricing.

Related Work

The International Energy Agency has completed several series of well researched reports on sector carbon emissions, trends, technology opportunities, and projections. The World Energy Outlook (IEA 2009) presents current demand trends. The Energy Technology Perspectives report (IEA 2010) presents global energy and carbon projections. These works provide the foundation for our work on refined costs for sector stakeholders.

Underlying the IEA projections is the MARKAL modeling framework (IEA 2010), used internationally by many groups. The United States using a different but similar modeling framework to project energy demands (EIA 2009). All represent the generation, transmission, conversion and end use of energy. Each of these functions has alternative technologies for which the MARKAL model makes economically

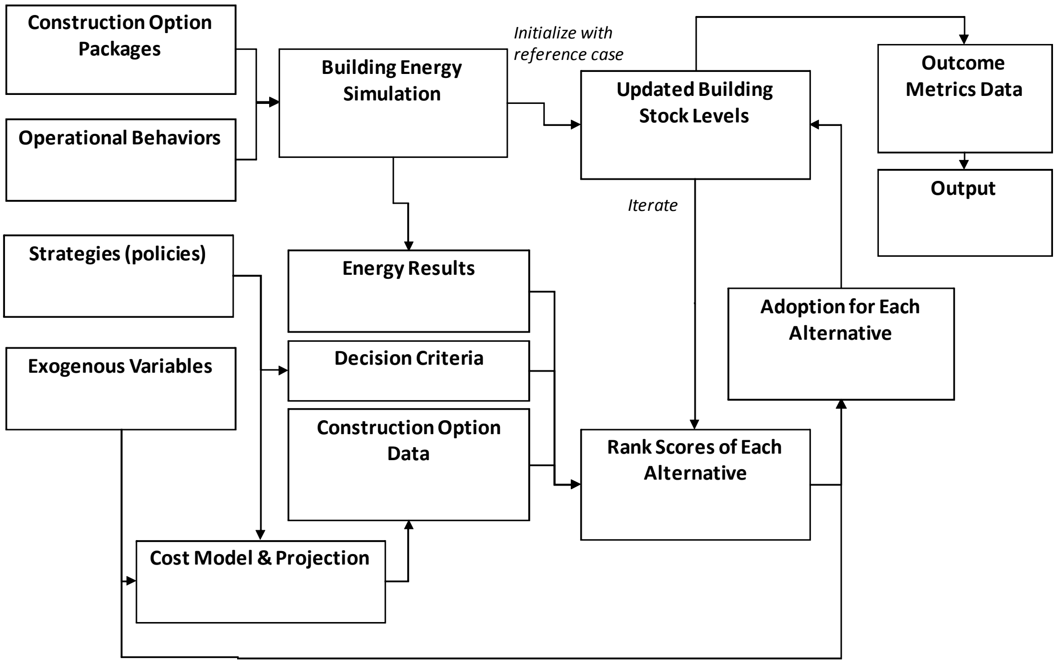


Figure 1 WBCSD Building Stock Decision Selection and Emission Projection Model.

optimal choices, given macro-economic scenarios such as carbon pricing, etc. These works all represent building efficiency choices as simple savings versus first cost decisions, considering each efficiency improvement as additive. This is sufficient for energy analysis of many sectors in a market, but insufficient for energy analysis within the building sector. We incorporate synergies between efficiency improvement interactions as well as their impact on economic decision making, and further explore interactions of incentives, prices, and building codes.

Other related works include studies of technology adoption rates in the building sector. Zhao et al (2009) define adoption rates for various residential and commercial building technologies in the Chinese market. The IEA has published cost improvement experience curves for various technologies (2000). The ACEEE has published capabilities for different building technologies (2004). These and other technology capability and cost projections were used in our work.

THE WBCSD MODEL OF DECISION MAKING IMPACT ON BUILDING STOCK EFFICIENCY

To understand the impact of decision making on the idealized sector results that consider costs to society as a whole, the WBCSD undertook to create a quantified model based estimate of micro-economic decisions on the build stock. This would also permit analysis of the impact of changes in macro-economic conditions including energy costs, technology change, or government policies.

Model Structure

As part of the Energy Efficiency in Buildings project, the WBCSD undertook a modeling effort to project what it will take to bring about radical transformation of the building stock, in terms of industry and stakeholder actions. Key questions included what are required of industry, construction, financing, trade organizations and governments. To quantify these considerations, a model of how the building stock changes due to micro-economic decisions of building owners and stakeholders was necessary. This is different from a traditional MARKAL model in that we were concerned only with the building sector end use, and the capital investment decisions needed to be modeled at higher fidelity than assuming complete adoption of all technologies with higher payback than others.

The modeled developed is a conglomeration of separate submodels, as shown in Figure 1. The analysis operates on a submarket basis, such as residential single family homes in the Southeast United States, or mid-rise Office buildings in the Kanto Region of Japan. A homogenous set of buildings is needed for the analysis, in terms of provided service levels. The model represents a building as 23 energy related subsystems and materials, including wall insulation, roof insulation, fenestration selections, lighting systems, daylighting levels, primary heating equipment, primary cooling equipment, thermal distribution systems, ventilation systems, passive thermal measures, renewable generation systems, etc. One each such subsystem, various technology options are defined with energy efficiency and first cost parameters. A building alternative is a selection of one technology option for each of the 23 energy related subsystems, defining a very large space of available building configurations. The year 2005 was chosen as the baseline reference year where data was more attainable on a global basis, and a representative set of buildings was defined in terms of energy related subsystem selections. In the model, each building alternative has a (possibly zero) level of building stock.

Further, each energy-related subsystem has an age, from new to end of useful life. For example, most HVAC equipment has a useful life of 20 years. With this representation, every year a percentage of the building stock in the model is refurbished and decisions over new subsystems selections made. Further, a fraction of the building stock is destroyed and removed from the stock model, and a fraction of new construction also occurs adding again new subsystems and building alternatives into the stock. These three modes of building stock change are used in the model, defining a year over year differential equation of the building stock.

The new and refurbished building stock is determined through a rank ordering of alternatives according to the micro-economic decisions of a modeled set of stakeholders. That is, each building alternative is simulated using a whole building energy simulation such as DOE2 or EnergyPlus (DOE 2010). These results provide the synergistic energy savings of different subsystem technology combinations for a building. The energy savings then provide a payback against the incremental first cost, where we also have a first cost model of materials and installation for each technology alternative. Using these figures, a rank ordering can be defined. This can substantially vary according to macro-economic conditions such as the price of energy, price of carbon, technology learning curves, and also due to government policy incentives or taxes. We further model the impact of building codes by eliminating from consideration alternatives that do not meet different building energy codes at different levels of code.

The micro-economic decision submodel represents several stakeholders who have impact on the capital equipment selection, depending on the decision dynamics of the submarket. We do this through allowing different economic criteria to be the objective function and other decision criteria to be filtering constraints on the selection decision. For example, owner-occupiers might make decisions based on simple economic payback. Owner-tenant buildings, however, do not, since the owner likely pays the first cost whereas the tenant might receives the benefit of lower monthly energy costs. In such arrangements, the linkage between an owner's decision over first costs and perceived benefits are tenuous. In our model, we represent these situations with a multi-stakeholder decision filtering method. That is, we assign one of the stakeholders as the decision maker, such as the owner. They likely have an objective of minimizing first costs. On the other hand, the tenants may prevent this unilateral choice because they will not accept systems with annual costs higher than a certain level. This would define one possible owner-tenant decision model. In our research with stakeholders, we found the typical situation is one where the owner will accept a maximum first cost increment over the lowest cost alternative, while minimizing the annual operating costs for the tenants. However, this varied by submarket.

Whatever the specific microeconomic objective criteria and filtering constraints, the year after year result is a sorted list of most preferred alternative building configurations for both new construction and retrofits. Our approach is to then convert this rank ordering into a distribution of building stock alternative increments for that year. If an alternative has high rank ordering, it is assigned a higher percentage of building stock increment that year. Thereby, the building stock alters year after year according to the micro-economic decisions being made. These incremental calculations on the building stock are iterative made from 2005 to 2050.

With the building stock level projections calculated to 2050, the associated energy consumption projections and carbon emission projections are also aggregated. This is done for any macro-economic scenario defined, in terms of energy prices, carbon prices, technology learning curves, and government policies such as incentive programs, tax programs, and building energy efficiency codes.

Generating Stock Data

A problem with much of building energy stock analysis and the impact of alternative strategies for improvement is the lack of available data with which to calibrate the analysis. Each submarket has different data available at different levels of resolution and completion, and therefore model calibration becomes a unique exercise for each submarket. We review here several residential submarkets of interest.

United States Southeast Single Family Residences

The United States conducts a periodic survey of the residential building stock (EIA 2010), which provides a dataset of building energy characteristics. The United States is composed of approximately 13 distinct climate zones (ASHRAE 2007), each of which can have unique energy-related construction practices. The United States was therefore subdivided along these zones.

Within the US Southeast climate zone, there are 4 million single family residences, with a range of envelope construction, fenestration, heating and cooling equipment, lighting systems, and other energy related equipment. Within the RECS database, there are 295 building descriptions representing this variety of stock. For our purposes on modeling changes to primary energy consumption through increasing efficiency in building stock, this set is excessive. A cluster analysis was completed to determine a representative set of building envelope materials, HVAC equipment, and lighting options. From this, the five most typical residence systems were determined adequate.

These buildings were simulated using DOE2 building energy simulation software, and the simulation operational parameters such as schedules and controls were adjusted until the energy statistics for the sector matched. This is shown in Table 1. The errors on electricity, fossil fuel and carbon are indicators of the modeling error, and are due to differences in the relative electricity and fossil fuel mix from the equipment and schedules we modeled versus that reported. As indicated, the representative buildings adequate represent electrical and gas consumption, and carbon emissions.

Table 1 US Southeast Homes Model Calibration.

	Predicted	Data	Delta
Annual Site Energy (kWhr)	136e11	136e11	0%
Electricity (kWhr/building)	22,400	19,700	14%
Fossil Fuel (kWhr/building)	11,100	11,300	2%
Annual Carbon (kg/building)	14,300	15,200	7%

France Single Family Residences

Unlike the United States, there is no equivalent statistical survey of residential properties in Europe. In France, however, the CEREN Center maintains a single database of energy and the environment (Ceren, 2009). This dataset was used to provide independent surveys data on envelope, heating, and hot water systems. From this, 13 typical residential construction options were defined.

These were again energy simulated, and the simulation operational parameters such as schedules and controls were adjusted until the energy statistics for the sector matched. This is shown in Table 2. As indicated, the representative buildings adequate represent electrical and gas consumption, and carbon emissions.

Table 2 France Homes Model Calibration.

	Predicted	Data	Delta
Annual Site Energy (kWhr)	3.1e11	3.1e11	0%
Electricity (kWhr/building)	6,400	6,460	1%
Fossil Fuel (kWhr/building)	15,200	13,700	13%
Annual Carbon (kg/ building)	3,900	3,700	5%

China Northern Urban Multi-Family Apartments

Unlike the United States and Europe, there is even less statistical data available on energy related subsystems or energy consumption of Chinese residential properties. However, Lawrence Berkeley National Laboratory has conducted a sample survey of homes (Zhao et al 2009). This dataset was used to determine levels of envelope, HVAC efficiency, and other energy related systems. From this, 8 typical residential construction options defined.

These were again energy simulated, and the simulation operational parameters such as schedules and controls were adjusted until the energy statistics for the sector matched. This is shown in Table 3. With this submarket, there was difficulty in matching the reported electricity consumption levels, without substantial reductions in use schedules for residential electrical loads, to the point of being seemingly unrealistic. It is unclear therefore what is covered by reported electrical consumption levels.

Construction Options

Energy Efficiency Improvements

For each building, several levels of increased energy efficiency and increased first cost were defined and incorporated into the cost model and building energy simulation studies. This included increasing levels of wall and roof insulation and increasing levels of window efficiency. This also included increasing performance of heating equipment, from standard to condensing boilers and from standard air conditioning equipment to geothermal combined heat pump systems. Lighting types were considered form incandescent to fluorescents to LED lighting. Large and small plug loads were also considered at higher efficiency levels.

Table 3 China Apartments Model Calibration.

	Predicted	Data	Delta
Annual Site Energy (kWhr)	2.51e11	2.55e11	1%
Electricity (kWhr/building)	60,585	35,336	42%
Fossil Fuel (kWhr/building)	210,300	231,800	10%
Annual Carbon (kg/building)	80,700	78,500	3%

For these systems, future efficiency improvements were considered, both the expected trajectories and scenarios of more rapid cost and efficiency improvements.

Beyond these higher efficiency standard systems, more passive measures were also considered. In northern climates, Passivhaus standard type construction was considered with no heating requirements. In hotter climates, passive measures such as tree shading and building orientation were incorporated.

Finally, renewable generation technologies were also considered, including solar thermal hot water and photovoltaic electrical generation. With these added systems, we had available net zero energy solutions for the single family home sectors in France and the United States South East, for example. We did not, however, have sufficient on-site solar electrical generation for multi-family apartments to achieve net-zero energy, such as with the Northern China multi-family structures.

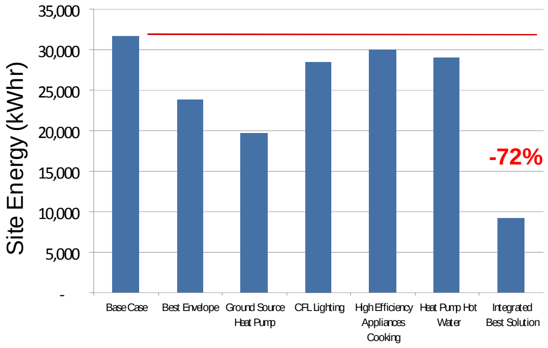


Figure 2 Alternatives for one of the US Southeast Single Family Residences.

For example, Figure 3 depicts selected alternatives for one of the United States Southeast single family residences on energy consumption.

Standard of Living Changes

An important consideration for much of global energy projections is the increasing standard of living and its impact on energy consumption. For example, this is a primary consideration with the Northern China multi-family residences. To consider this, a two-state representation was developed, modeling both a lower standard of living and a future higher standard of living. An equation is developed to project the shift over time from the lower to the higher as fraction of the population. For Northern China urban apartments, a projected higher standard of living was used comparable to the current Japanese urban apartment. Then, based on population projections, a switch from a baseline low energy consumption level to the high energy consumption level was made. For example, the percentage estimates for Northern China are shown in Figure 3.

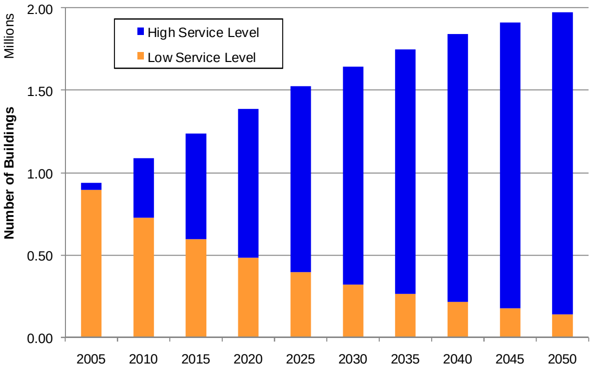
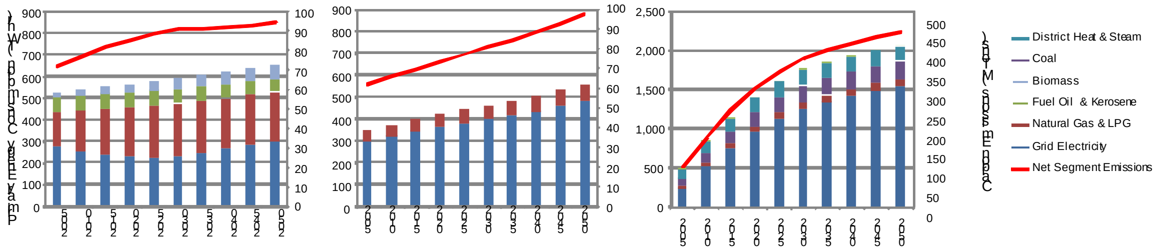


Figure 3 Projected Standard of Living Energy Consumption Switch for Northern China.



French Single Family *US Southeast Single Family* *Northern China Multi-Family*

Figure 4 Business as Usual Scenario.

SCENARIO GENERATION

Given the matching of current conditions and prices of energy efficient alternatives, the impact of micro-economic decision making can be simulated. However, the micro-economic decision criteria must be established for the submarket. To do this, the current building stock was assessed on first cost and payback, relative to the lowest cost possibilities. This defines a potential upper limit on first cost expenditures and a payback period.

With this, each submarket is projected to 2050 under baseline macro-economic conditions of 2005, the Business-as-Usual projection to 2050. The projections can be compared with other group's projections. For example, the WBCSD computes a carbon emission growth of 41% by 2030 in the US Southeast single family residences, whereas the US EIA projects a growth of 48%. Generally, the WBCSD projects within the margin of error with government or IEA baseline projections. Other scenarios considered are shown in Table 4.

Table 4 Example of a table

SCENARIO	FEATURES
Typical Policy Intervention	2005 prices, Typical subsystem incentives, $30/ton carbon price
20 Year Payback	2005 prices, Typical subsystem incentives, $30/ton carbon price, 20 yr payback
$60/ton Carbon Price	2005 prices, Typical subsystem incentives, $60/ton carbon price
NZEB New Construction	2005 prices, Code requiring NZEB construction after 2020
Inefficient Construction Ban	2005 prices, Code banning construction with high energy intensity
Energy Price Spike	5, 10 and 25X energy price increases
Transformation	2005 prices, Whole building only incentives, $30/ton carbon price

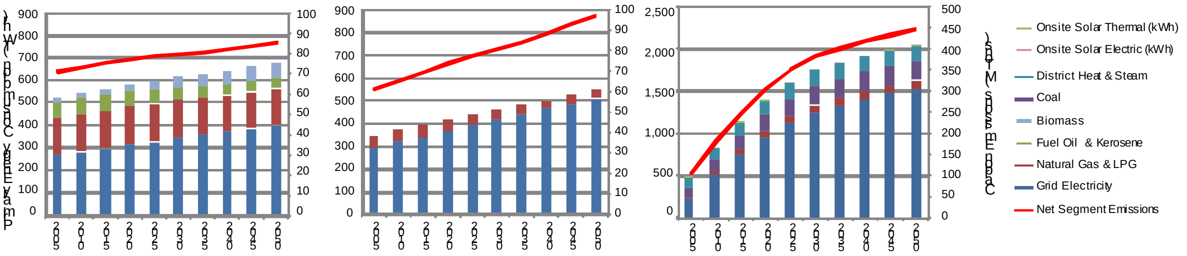
The business as usual scenario is shown for the three submarkets in Figure 4. Without influence, substantial energy consumption and carbon emission growth will occur.

RESULTS

We find current policies considered by most nations as inadequate to motivate homeowners to transformation. Policies such as price incentives on insulation, price incentives on high efficiency equipment, bans on incandescent lighting, and 50% subsidies of renewables are inadequate and do not motivate homeowners to change their buildings. Rather, we find homeowners prefer to do a few measures only, and not invest to do all of them as required for transformation. This is shown in Figure 5, where these policies have little effect compared to the Business as usual scenario.

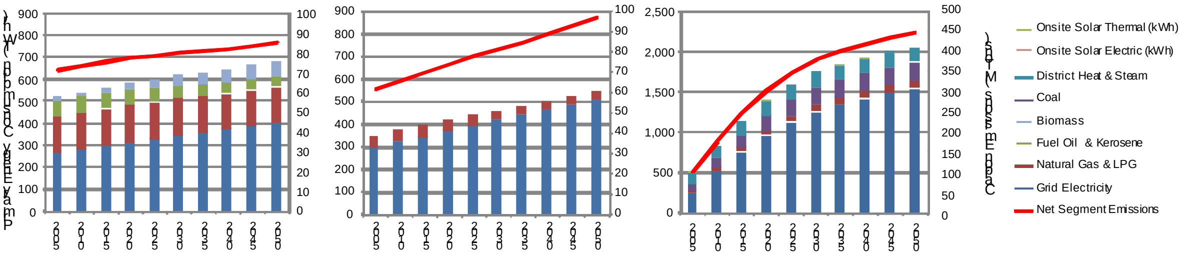
A problem observed in the results is that often homeowners become satisfied using some, but not all, available incentives. Only partial improvements are made. To counteract this effect, we developed whole building incentives where a first-cost subsidy is made available, but only when the energy intensity is reduced below a threshold such as 50 or 75 kWhr/m2/yr. We find these measures do have an impact, as shown in Figure 7.

Further analyses of these runs indicated the very inefficient buildings remain attractive, given their very low first costs. Therefore, additionally an energy code based ban on buildings with very high energy intensity is also effective. A problem with this scenario, however, is the intensive costs to government for the inentive programs. People being to really use the incentive programs on all subsystems created net zero energy buildings. Therefore, we combined the whole building incentives and bans with a mild $30/ton carbon price, which creates a scenario with a net balance of payments to government which is cost neutral and capable of paying for the incentives. These results are shown in Figure 8. Note the electric



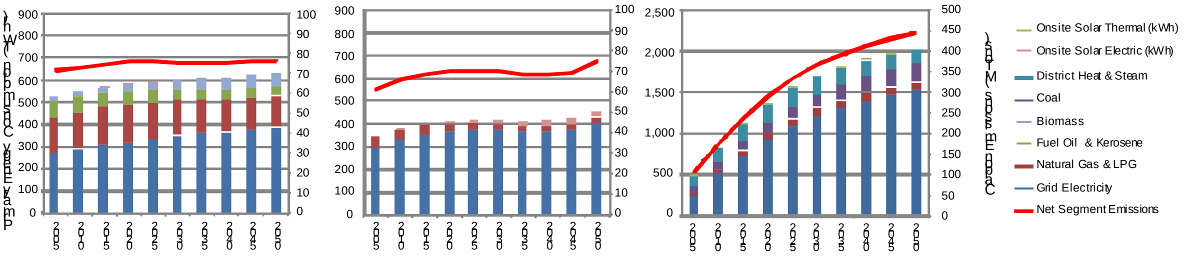
French Single Family　　US Southeast Single Family　　Northern China Multi-Family

Figure 5 Typical Policy Intervention Scenario.



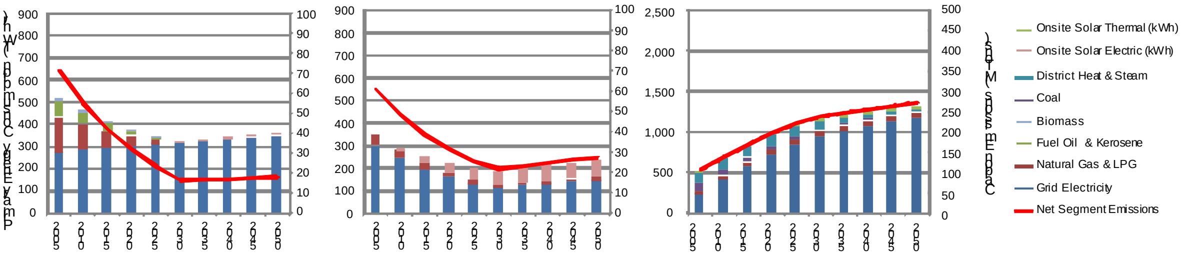
French Single Family　　US Southeast Single Family　　Northern China Multi-Family

Figure 6 $60/ton Carbon Pricing with Typical Incentives Scenario.



French Single Family　　US Southeast Single Family　　Northern China Multi-Family

Figure 7 Whole Building Intensity Incentives Scenario.



French Single Family　　US Southeast Single Family　　Northern China Multi-Family

Figure 8 Transformation Scenario.

consumption going up with carbon going down is reflective of the adoption of renewable electrric generation.

CONCULSION

In summary, we find studies to date have not underestimated the cost to transform the residential sector nor the potential impact of the residential sector. However, we do find the impact of carbon pricing and incentive programs have been vastly over-estimated. We find residential homeowners will not respond with capital-intensive energy-efficiency improvements when faced with increases in energy or carbon costs. The first costs of the efficiency improvements are deemed excessive in comparison. We also find subsystem based incentive programs ineffective when implemented individually. Rather, we find such incentives should only be provided on subsystems when they contribute to a building that achieves a whole-building energy intensity below a target such as 50 kWhr/m2/yr. In general, to get the the residential sector to achieve net zero energy status, we find the only solutions that impact homeowner decisions on capital decisions are aggressive whole building incentives combined with carbon or energy pricing to pay for these incentives.

ACKNOWLEDGMENT

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