



International Conference – Alternative and Renewable Energy Quest, AREQ 2017, 1-3 February 2017, Spain

Using Material and Energy Flow Analysis to Estimate Future Energy Demand at the City Level

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Abstract

Cities undergoing rapid growth encounter tremendous challenges, not only in terms of providing services to meet demand, but also in ensuring that development occurs in a sustainable way. This research evaluates the potential contribution of the material and energy flow analysis framework to predicting future energy flows and corresponding CO₂ emissions in Riyadh, Saudi Arabia. The research presents a generic material and energy flow analysis model and applies it to the housing stock in Riyadh to estimate future energy demand and to assess associated effects. As the country starts to adopt sustainability measures and plan its transition from a fossil fuel-based energy system towards a renewable-based energy system, an understanding of future energy flows will allow early recognition of potential environmental impacts and provide information to enable accurate predictions of future demand for resources.

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Peer-review under responsibility of the organizing committee of AREQ 2017.

Keywords: Material and energy flow analysis; Sustainability; Urban development; Resource consumption; Developing countries

1. Introduction

In 2014, 54% of the global population resided in urban areas; this percentage is expected to reach 66% by 2050 [1]. Not only do cities have a higher population than in the past, but the typical resident in modern cities is also likely to consume more resources compared to the average out-of-city person [2]. Managing urban growth is a key challenge of the 21st century [3]. Rapid urban growth is usually associated with tremendous challenges, such as

increases in materials and energy flows that enter and exit urban systems [2]. This places considerable pressure on urban societies to adopt sustainability as the main mechanism for development.

Riyadh, in Saudi Arabia, is one of the world's fastest growing cities. The population of Riyadh has grown from almost one million in 1980 to nearly six million today and is expected to reach 8.2 million by 2029 [4]. Between 2004 and 2010, the population of Riyadh grew at an annual rate of 4%. The increase in population is still the most noticeable feature of Riyadh and has led to growth in other sectors; in 2015 the overall population of Riyadh reached 6,152,180 [4]. In addition, Riyadh's population growth is characterized by qualitative improvements in its residents' standard of living [4]. According to the Arriyadh Development Authority, Riyadh needs 510,000 housing units built before 2030 [5]. This growth is inextricably linked to the consumption of materials, energy, and water resources. There is, therefore, a need for a framework that provides information on future resource demand, because this type of information is valuable for the evaluation of future development.

This study applies a general dynamic material flow analysis to evaluate the long-term development of Riyadh's housing stock. This approach estimates the future energy demands and corresponding greenhouse gas (GHG) emissions. The advantage of applying this method is the ability of quantifying the flows and in-use stocks for each year under study. The analysis evaluates the dynamics of floor area of Riyadh's housing stock and corresponding energy demand. When analysing the built environment, a dynamic MFA approach should be used due to the long service life of built structures and their significant role in mobilizing flows such as materials, energy, emissions and wastes [7].

2. Literature review

The MFA comprises a systematic accounting of the flows and stocks of materials within a defined system. When implementing a dynamic MFA model, the system variables are functions of time [8]. A historical and future analysis of the system can be performed, the dynamic behaviour of which can be explained [9]. Dynamic MFA is a useful tool when analysing long-term changes in the system [10]. In the literature, assessment of building stock has been approached by using a dynamic MFA to analyse floor area and corresponding construction materials. Müller [11] has applied a dynamic MFA to Dutch dwelling stock to study the long-term changes of material flow cycles for the period 1900–2100. In his study, the author relates the material stock in use and flows to consumption of building services in order to satisfy the demands of the population and its lifestyle, which are the driving forces. Population lifestyle is further explained by introducing two parameters; average size (area) of a dwelling and persons per dwelling. To estimate the stock demand or stock in use, these parameters can be expressed as a function of time [11].

Several other studies on building stock modelling have followed the same approach proposed by Müller [11]. Bergsdal et al. [8] applied this method when studying the dynamics of floor area and material use in Norwegian residential stock. The same method was also applied in a study by Sartori et al. [12] to model the construction, renovation and demolition activities for Norwegian residential stock. In another study, Brattebø et al. [7] applied this approach when studying the material and energy metabolism of built environment stocks. This method was also applied in a developing country, China, with the aim of investigating the relation between the urbanization progress and resulting material flows [13]. In another study, Hu et al. [14] have applied a dynamic MFA to study the urban housing system in Beijing with the focus on understanding the mechanism of future construction and demolition waste generation.

In conclusion, these studies shed light on the importance of using dynamic stock modelling to understand development patterns of urban systems from a long-term perspective. When sustainability is sought to guide urban development, the long-term aspect is essential. Dynamic material flow analysis provides a framework for analysing the development of building stock that is missing in static analysis [15]. However, this type of analysis requires a

good knowledge of the past stock characteristics and flows which allows analysis of historical and future flows of the system to be conducted and the dynamic behaviour of the system understood [9]. With cases where a high rate of urbanization is ongoing, it is important to apply a dynamic stock model to evaluate the possible impacts of urban development in the long-term [13].

3. Methods

Current research on building stock has been using the analysis of floor area and corresponding materials and energy consumption when developing a dynamic MFA model. In this case, the stock demand in the future is determined by two parameters, namely, population and floor area per capita. In other studies where more data are available, building stocks are grouped by type and age and for each group, data pertaining to persons per dwelling (PD) and the average size (area) of a dwelling (AD) are then used to build the dynamic stock model [8,7, 11].

A dynamic MFA model was developed by Müller [11] to estimate resource demand and waste generation. The model used four parameters: population, floor area per capita, material intensity, and lifetime. Several studies have applied the same model at different scales for different objectives. For instance, it was applied to analyse the dynamics of floor area and material use in Norway’s dwelling stock [8]. It was used as a projection tool to estimate future construction waste [6]. The same model was extended to include an energy intensity parameter, to estimate future energy demand for Norwegian dwelling stock [6].

The present study applies the dynamic MFA as illustrated by Müller [11] to housing stock in Riyadh, Saudi Arabia, presenting a material flow analysis of the floor area and construction materials (cement) of Riyadh’s housing stock, as shown in Figure 1. It also extends the model to include the energy required for use phase and energy required for producing construction materials needed for new housing inflow. In this study, we choose one type of construction material (cement) for several reasons. Cement is considered the cornerstone of the construction sector in Saudi Arabia. In addition, cement is mainly produced locally. Production of cement is a very energy-intensive process. Al-Nagadi reported that electrical energy consumption per ton of cement typically ranges between 90 and 130 kWh [16].

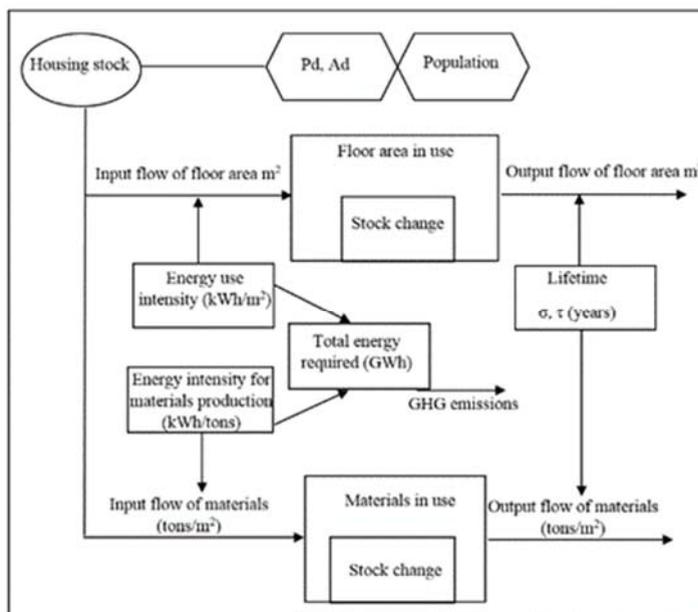


Fig. 1. Conceptual outline of the stock dynamic.

3.1. Model description

In this study, the main driving forces of the model are the population (P) and its lifestyle, which is represented by floor area per capita (A_p) as shown in equation (1).

$$A(t) = P(t) \cdot A_p(t) \quad (1)$$

To determine the input and output flows of the floor area, information about the lifetime needs to be added. There is no data available regarding building lifetime in Saudi Arabia; therefore, a normal distribution is used with default mean lifetime τ and standard deviation equal to 40 years and 8 years, respectively, as shown in equation (2).

$$L(t, t') = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{(t-t'-\tau)^2}{2\sigma^2}} \quad (2)$$

Building upon data from equation (2), the probability that housing units built in year t' will be demolished in year t is determined by equation (3).

$$\frac{dA_{out}(t)}{dt} = \int_{t_0}^t L(t, t') \cdot \frac{dA_{in}(t')}{dt} dt' \quad (3)$$

In equation (4), the future floor area inflow is determined by adding the demand for new housing and the outflow of floor area together. Up to this point, the model deals with the inflows and outflows stock changes in floor area.

$$\frac{dA_{in}(t)}{dt} = \frac{dA(t)}{dt} + \frac{dA_{out}(t)}{dt} \quad (4)$$

By adding two more parameters, we can estimate the corresponding materials and energy. Equation (5) determines the dynamics of corresponding materials (stocks and flows) by introducing a material density parameter (M_{in}).

$$\frac{dM_{in}(t)}{dt} = \frac{dA_{in}(t)}{dt} \cdot M_A(t) \quad (5)$$

Equation (6) determines the material outflow based on the probability that materials entered the system in year t' would exit the system as outflow in year t ,

$$\frac{dM_{out}(t)}{dt} = \int_{t_0}^t L(t, t') \cdot \frac{dM_{in}(t')}{dt} dt' \quad (6)$$

Equation (7) determines the balance equation of material stock.

$$\frac{dM(t)}{dt} = \frac{dM_{in}(t)}{dt} - \frac{dM_{out}(t)}{dt} \quad (7)$$

Similarly, by adding an energy intensity parameter (e_i), the corresponding energy flows (E) is determined as shown in equation (8).

$$E(t) = A(t) \cdot e_i(t) \quad (8)$$

Equation (9) determines the energy required for materials production.

$$E_M(t) = \frac{dM_{in}(t)}{dt} \cdot e_{mi}(t) \quad (9)$$

Equation (10) defines the total GHG emissions associated with energy use where I is emission coefficient of energy mix.

$$GHG_{emission} = E(t) \cdot I \quad (10)$$

3.2. Data and assumptions:

3.2.1. Population and floor area per capita

Population (P) and its lifestyle represented by floor area per capita (Ap) are the main driving forces to determine the demand for new housing stock. In this study, data pertaining to population was obtained from several sources. The main data sources were reports from the Arriyadh Development Authority (ADA) including the Metropolitan Development Strategy for Arriyadh (MEDSTAR) and the Investment Plan for Riyadh reports. Other sources included the statistical yearbook published by the General Authority for statistics in Saudi Arabia. The only year, however, where data for floor area per capita was available was for 2012. To estimate floor area per capita for previous years, an approach consisting of dividing the reported residential area by population for the same year is used.

3.2.2. Energy intensity

To determine the energy intensity (kWh/m²) for housing stock, a top-down approach is applied. First, the total energy use for housing stock and total floor area at the city level was determined from local sources. Then for the purpose of simplicity, the total energy used value was then divided by the total floor area to estimate the energy intensity value. Although this approach inherently has some uncertainty, it was only used due to data being absent. Additionally, when comparing the results with other studies that looked at energy consumption at the building level, the values were within the ranges reported by Aldossary et al. [17]. Table 1 shows the values used in this study compared with other studies.

Table 1. Comparison with other studies.

	This study	Aldossary et al.
Energy intensity (kWh/m ²)	136	≈154*

*Notes: This value is estimated as an average of the six cases reported in the study.

3.2.3. Material density

Introducing this parameter to the model is critical to analyse material stocks and flows within the system. The focus here is only on one type of construction material, which is cement. Since there is no data available on material density in buildings in Saudi Arabia, a bottom-up approach is developed to estimate the material density. Construction materials constitute the largest stocks and flows of materials for cities, however, quantifying them as aggregates, cement, glass, steel and wood, etc. is challenging. This study adopted a bottom-up approach to estimate

the materials flows in Riyadh. This approach involves a process of classifying the buildings and other types of structures in a city and making representative groups with typical material characteristics. The quantities of the material components for each group represented were then established using bills supplied by local firms engaged in projects that have been completed in the city.

This approach involves classifying the building stocks into representative groups based on their types and material characteristics [18]. Riyadh housing stock typically consists of two types of building: villas and apartments [5]. In this paper, a bill of materials for a villa was obtained from local construction firms and material density was estimated from the architectural drawings. It is worth noting that the bill of materials only shows concrete and cement content is estimated based on the report by [19].

3.2.4. Lifetime

Introducing this parameter to the model is critical when analysing the demolition flow, which in return affects the new demands. This study uses a normal distribution with a default mean lifetime τ and standard deviation equal to 40 years and 8 years, respectively.

3.2.5. GHG emissions

The GHG emissions associated with energy consumption are calculated using the Saudi Arabia electricity mix ratio (45% natural gas, 55% oil) as reported in ECRA [20]. Emissions factors for electricity production are calculated using Simapro after modifying a unit process in Ecoinvent database to represent the electricity mix in Saudi Arabia. Table 2 shows the emission factors.

Table 2: GHG emission factor of current energy mix from Simapro (modified unit process).

kg CO ₂ eq/ kWh	0.789328242
kg CO ₂ eq/ MJ	0.219257845
g CO ₂ eq/ MJ	219.2578451

In this study, the TRACI method in Simapro was used to evaluate the global warm potential. Table 3 shows the impact assessment using TRACI for producing 1 kWh of the Saudi electricity mix. In addition, these processes have been modified to meet the same Saudi Arabia energy mix previously mentioned [20].

Table 3: Impact Assessment for producing 1 kWh.

Impact category	Unit	Total	Electricity, natural gas, at power plant/US U	Electricity, oil, at power plant/UCTE U
Global Warming	kg CO ₂ eq	0.78932824	0.31187798	0.47745026
Acidification	H ⁺ moles eq	0.38308576	0.14238949	0.24069627
Carcinogenics	kg benzen eq	0.00084154	0.00035394	0.00048761
Non carcinogenics	kg toluen eq	5.07877016	1.95953970	3.11923046
Respiratory effects	kg PM _{2.5} eq	0.00167891	0.00065646	0.00102245
Eutrophication	kg N eq	0.00032558	0.00002308	0.00030249
Ozone depletion	kg CFC-11 eq	0.00000006	0.00000000	0.00000006
Ecotoxicity	kg 2,4-D eq	0.12870826	0.03437042	0.09433785
Smog	kg NO _x eq	0.00171419	0.00020001	0.00151418

4. Scenario analysis:

4.1. Floor area per capita:

To better understand future energy demand for housing stock, this study investigates different scenarios regarding energy use. The first scenario assumes that the current trends in floor area per capita (A_p) would continue, while the second scenario is based on the assumption that floor area per capita would grow higher than current trends suggest. Table (4) shows the values for (A_p) associated with each scenario.

Table 4: Input parameters for each scenario

Input parameters	Baseline				High growth		
Year	2010	2020	2030	2050	2020	2030	2050
Population	5,254,560	6,792,504	8,280,024	12,303,681	Used same value reported in baseline scenario as this parameter was not the focus of this part of the study		
Floor area m ² /capita	43	40	40	38	46	53	59
GHG emission factors (kgCO ₂ -eq /kWh)	With current energy mix				Alternative energy mix		
	0.789328242				0.5366808		

4.2. Changes in Energy Mix

The electric power industry in Saudi Arabia is facing tremendous challenges due to growing demand for electricity. Different initiatives have been proposed with goals for shifting the current energy mix from oil dependent towards renewable resources. It is anticipated that 38% of the energy needed would be provided by solar power in 2032. Also, the King Abdullah City for Nuclear and Renewable Energy (KA-CARE) projected there would be 18 GWe of nuclear capacity by 2032 of a total of 123 GWe energy used, with 16 GWe solar PV, 25 GWe solar CSP, and 4 GWe from geothermal, wind and waste [21].

Based on the abovementioned report, an alternative energy mix is used to evaluate the impact of changes in energy mix. Emission factors for the proposed energy mix are obtained from modified unit processes from the Ecoinvent database using SimaPro software, and Table 5 shows the alternative energy mix and associated GHG emission factor.

Table 5: Alternative energy mix.

Source	Percentage
Oil	32%
Natural gas	28%
Solar	38%
Geothermal	2%
Emission factor (kg CO ₂ e/kWh)	0.5366808

5. Results and discussion:

5.1. Housing stocks and flows:

Figure 2 shows the stocks and flows of the housing sector in Riyadh, Saudi Arabia, which displays the following results:

- Even though the housing stock demand in Riyadh decreased in the 1990s, the housing floor stock has grown overall.
- In the late 2000s, there was a large increase in construction activities.
- Current trends would be likely to continue in the near future.
- Over the next three decades, there will be an increase in demolitions activities as many buildings reach the end of their life cycle

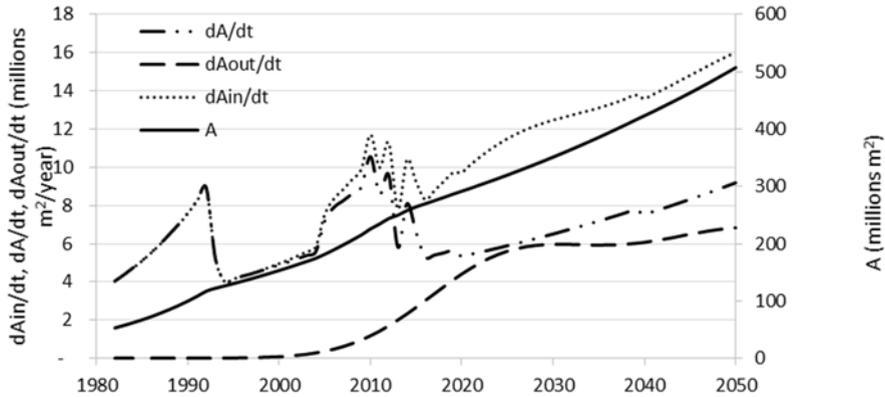


Fig. 2. The stocks and flows of the housing sector in Riyadh.

5.2. Material stock and flows:

Figure 3 shows the material stocks and flows of the housing sector in Riyadh. The results indicate that due to the connection in the model between materials and stock (material density), the material flows will follow the same pattern as the floor area.

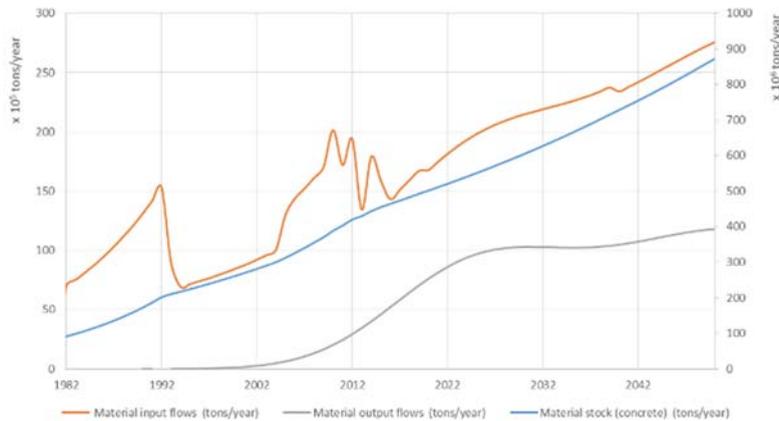


Fig. 3. Material stocks and flows of housing sector.

5.3. Energy flows:

The high growth rate in the population along with the urban expansion experienced by Riyadh during the last four decades has also resulted in an increase in energy use. Figure 4 shows the total annual energy flows for Riyadh housing stock.

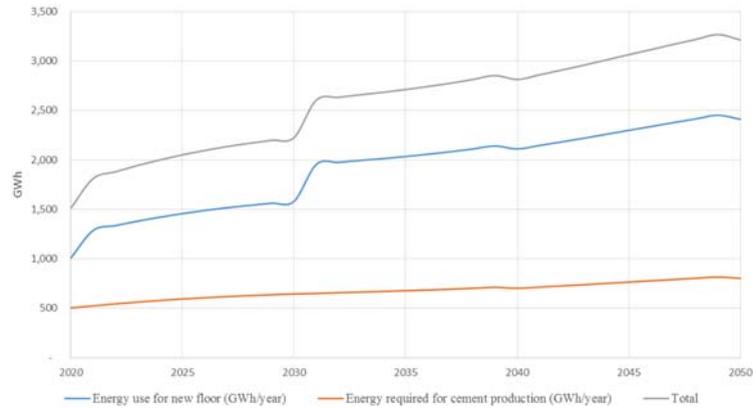


Fig. 4. The total annual energy flows for Riyadh housing stock.

Moreover, Figure 5 shows the energy demand of future housing, and shows the energy required to produce cement, which is the major construction material used in the Saudi building industry. While it is important to focus on end use energy when addressing energy reduction, it is also important to look beyond just one part of the system. As results indicate, about 33% of the energy demand in the future will go to cement production.

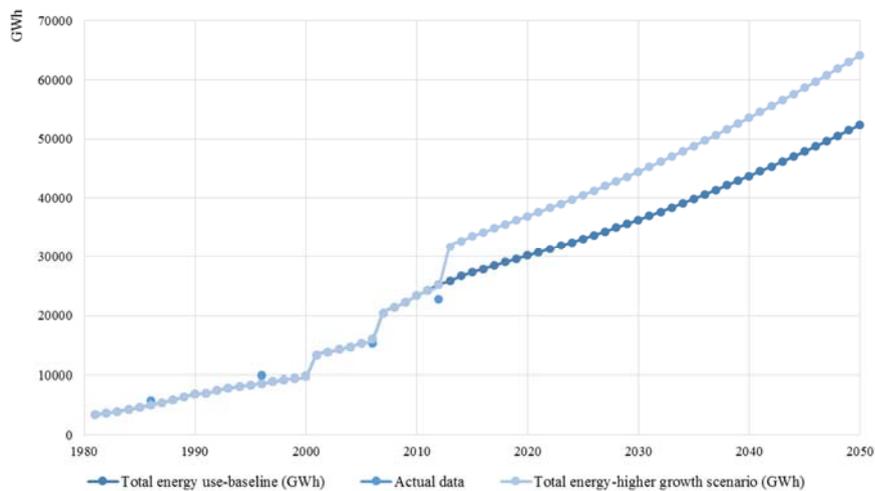


Fig. 5. The energy demand of future stock.

5.4. GHG emissions:

Estimated GHG emissions are shown in Figure 6. Emissions factors were estimated according to the TRACI method in SimaPro software for current and alternative energy mixes. Based on this method, the total GHG emissions associated with energy demand are 24.86, 29.94, and 43.25 million metric tons per year during 2020, 2030, and 2050, respectively. When compared with the alternative energy mix, GHG emissions would be reduced by about 30%. Figure 6 shows the significance of shifting towards renewable sources for energy production when considering emission reduction targets. It clearly shows that a significant impact reduction can be achieved by switching from oil-dependent energy production towards renewable sources.

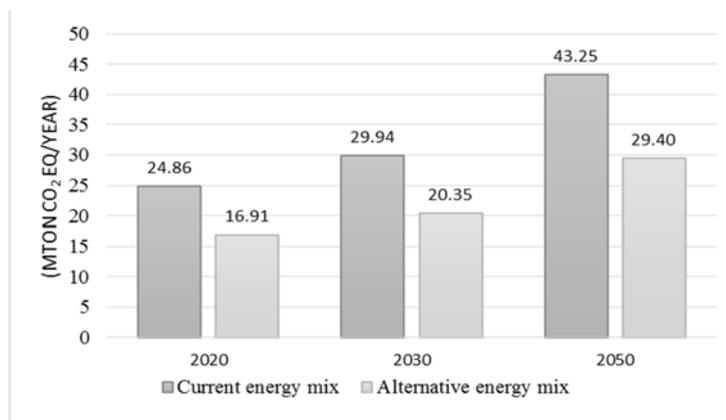


Fig. 6. Annual energy-related GHG emissions.

6. Conclusion:

The model discussed in this study used a dynamic stock approach to analyse the long-term dynamics of housing stock in Riyadh, Saudi Arabia. The aim was to use this approach as an estimation tool to predict future energy demands and analyse the associated impacts. Even though it relies upon estimates of past activities and some assumptions due to lack of data, it is useful to provide insight into understanding the impact of future development.

Preliminary results show that housing stock in Riyadh will continue its current pattern of growth. This will lead to an increase of material stocks and flows, which has a unique environmental impact. Results show that there was a significant decrease in construction activities in the 1990s as the economy was struggling after the Gulf War. In contrast, in the mid 2000s, a significant increase in construction activities was observed.

In the long-term, the model suggests that there will be an increase in construction activities not only to meet new demand, but also to replace many dilapidated housing units.

The energy demands increase as floor area stocks increase. Results show that the current trend for energy demands will continue. The energy demands for cement production will account for about 30% of the total energy demand for future housing stock from 2020 to 2050. When analysing the GHG emissions, two scenarios were evaluated. The first used the current energy mix and the second used a more environmentally friendly energy mix. The second scenario was developed based on current working projects in Saudi Arabia to move forward towards renewable energy. Results suggested that the alternative scenario would reduce GHG emissions by 33% by 2050. As illustrated in this study, although there is some degree of uncertainty, applying a material and energy flow analysis framework to predict future energy flows and corresponding emissions was useful to show the impact of future development in housing stock.

Acknowledgements

The authors acknowledge the University of Taibah, Saudi Arabia for its support. All opinions, findings, and conclusions expressed in this paper are those of the author(s) and do not necessarily reflect the views of the University.

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