# Integrated Residential Household Energy Consumption and GHG Emissions Modelling at Metropolitan Scale

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## ABSTRACT

Urban-scale policy, planning and development decisions can have significant resource use and environmental impacts. The energy consumption and related greenhouse gas (GHG) emissions of residential households, in particular, are mostly due to their housing and transport energy consumption. At the metropolitan scale, the type and location (or distribution) of housing can have a significant impact on the region's total energy and emissions profile. This paper presents a bottom-up methodology for assessing the impacts of alternative urban forms on the urban energy and GHG emissions footprint, combining housing and transport energy consumption across all households in the study area. The integrated assessment is built around a common household typology, and then extends separately towards housing energy consumption (based on sub-typologies of housing type and age, end-use demand categories and supply) and transport energy consumption profiles. The impact of the spatial distribution of households can be assessed from small geographical levels (comprising of about 200 - 250 households) to the whole municipality or Local Government Area (LGA), and to the whole metropolitan scale (i.e. all of the 31 LGAs in Metropolitan Melbourne). We present herein the calculation and validation of the total baseline energy consumption, and related GHG emissions of all households in Metropolitan Melbourne in the census year 2011. This approach can be used in the next stage to assess the impacts of alternative urban forms into the future.

***Keywords:*** *urban form, building energy simulation, transport energy*

## 1. INTRODUCTION

More than 75% of the world population are expected to live in cities in the next 10 years (UN Habitat, 2013). These agglomerations exacerbate existing urban challenges and bring new ones. The nature and diversity of stakeholders' decisions to address the increasing population and housing density and the changing demand and patterns of human mobility have a significant impact on resource consumption, particularly energy, and on the environment, particularly through the greenhouse gas (GHG) emissions caused by human activities (Jenks & Burgess, 2000). This has become even more important and urgent in the light of the global agreement (during the recent Conference of Parties, COP21, in Paris) to scale up the implementation of ambitious actions towards the "below 1.5 or 2°C" pathways. Different levels of government and stakeholders in urban governance and the building and construction sector need to map-out the most cost-effective options to contribute to this goal.

The assessment of urban energy includes the energy used in buildings, transport, industry, water management and wastes (Kennedy, 2012). Since the building and transport sectors have the largest contribution to energy consumption (SoE, 2014), the present study focuses in these two areas, but excluding their embodied impacts. Previous studies have traditionally looked at transport (e.g. Alford and Whiteman, 2009) and building stock (Foliente and Seo, 2012) separately.

Broadly, there are two general methods for modeling building stock energy use and associated GHG emissions: the bottom-up and the top-down approaches. Previous work by Crawford & Fuller (2010) and Rickwood (2010) integrated building and transport energy assessment based on a hybrid Input-Output (I-O) and Life Cycle Assessment (LCA) methodology considering urban form, housing types and residents' travel behaviour. These studies, like others that use aggregated data (i.e. the top-down approach), are useful to understand the impacts of broad policy, econometric or technological options, but are not practically useful to guide and assess the impact of specific decisions and/or actions of stakeholders. They could provide macro understanding of the entire housing sector, but are not concerned with individual end-users.

The bottom up approach is built from disaggregated data and analysis then combined according to the needs of the specific sector (Kavgic, 2010). Bottom-up studies that combine energy consumption in buildings (stationary energy) and transport (non-stationary energy) are very rare. In the Energy Efficiency Cities Initiative in the City Model (CiMo, 2014)) Project, bottom-up engineering models of energy demand, supply, and emissions from buildings and surface transport at the city scale were applied to the City of Westminster. This UK approach is similar to separate studies that have been undertaken separately for these sectors in Australia (Foliente and Seo 2012; Ren et al. 2013).

Considering household travel needs and activities from their place of residence, there is a need for a similar intermediate approach in this area that builds on disaggregated travel data and/or detailed transport modelling and simulation results but simplified for application to practical planning scenarios impact assessments based on selected household typologies. This paper integrates the residential households' location and mobility patterns with their housing stock characteristics to establish the combined energy consumption from the bottom up to metropolitan scale.

## 2. METHODOLOGY

The cross-typology bottom-up building stock energy assessment framework proposed by Foliente and Seo (2012) to assess the impacts of different technology, investment, policy instruments and actions by different stakeholders into the future provides a starting platform for this type of intermediate approach. This provides a systematic and detailed classification (or sub-typologies) of variables that impact the total energy consumption and GHG emission of building stock in a given area (e.g. building characteristics, space conditioning system, lighting, hot water system, plug-in appliances, occupancy type and pattern, and local energy supply system); different options at these sub-typologies can be assessed at different scales and level of details The cross-typology capability refers to a separate classification of intervention schemes.

The overall research has two main phases: (a) Calculation of a baseline building and transport energy profile, its validation at micro and macro scale (from Statistical Area 1 or SA1 level to SA3 and then metropolitan level); and (b) Application into future scenarios for the growth of Metropolitan Melbourne (business as usual vs alternative urban form scenarios) (Figure 1). This paper deals with the first phase only.

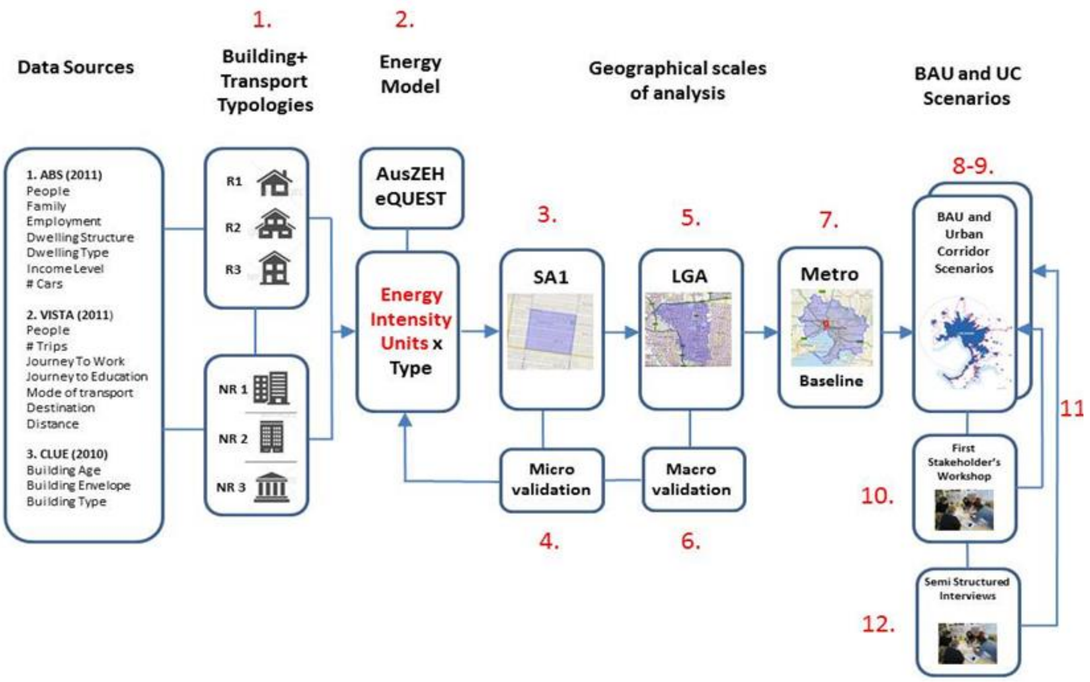


*Figure 1: The research methodology's overall scheme; the present paper covers only the first phase of the planned work program (i.e. up to item/ step 7 only)*

The residential building energy is modelled following the bottom-up building typology approach by Foliente and Seo (2012) and using the AusZEH software developed by CSIRO (Ren et al. 2012). The results were processed for distribution in the geographical scale using Microsoft Access and SQL queries to obtain the values per meshblock and per SA1. The Energy Intensity Units (EIU) and associated GHG emissions will take into consideration: a) Demand (Building, Load and Household type) b) Supply (Energy system: gas, electricity, solar, wind) and c) Consumption (Gross Energy and Energy Intensity Units x annum) with the Household type as integrating element (see Figure 2):


*Figure 2: Integration between residential building and transport energy consumption*

The smallest unit of building stock energy aggregation is at SA1 level (comprising of about 200 - 250 households) and the results are displayed within these boundaries. This is the smallest geographical unit that have available census data for modeling from the Australian Bureau of Statistics (ABS), mainly for dwelling type, household type and labour force. In addition, it is also compatible with the other datasets on dwellings, such as those from the Geoscience National Exposure Information System (Geoscience Australia, 2014)) database and property data from the Valuer's General for the State of Victoria. The SA1 scale also allows a finer grain visualization of the whole Metropolitan Melbourne, than other geographical scales that have been used previously by others.

For household travel related energy consumption, the smallest unit of analysis used is the meshblock level, as it was possible to request the Victorian Integrated Survey for Travel and Activity (VISTA, 2009) at this small geographical level. The survey sampled meshblocks covering all 31 LGAs in Metropolitan Melbourne and geographically distributed in an even form to cover equally all territory. The transport consumption was modelled from the household level, then summated up to meshblock level, and finally aggregated at SA1 level to match the unit of analysis used for the residential dwelling's operational energy consumption.

The processing of input data from various sources (left most part of Figure 1) and the modelling results/output data was facilitated by a script coded in Python which extracted and processed the information from the databases used in the research ABS, NEXIS, Valuer's General and IMAP) and distributed the IMAP building typologies and their associated Energy Intensity Units (EIU) at SA1 level using the information from the requested datasets (ABS, NEXIS, Valuer's General and IMAP) and automated the aggregation and mapping in ArcGIS. The goal is to analyze patterns of energy consumption at the report neighborhood level scale (SA1), and their main difference according to distribution of dwellings types, household types and location at LGA scale and the metropolitan scale. GHG emissions were calculated using the emission conversion factors for different fuel types for housing and transport from Australian Energy Market Operator (AEMO, 2012) and Australia Energy and the Australian Energy Institute (AEI, 2012).

## 3. MODELING RESULTS AND DISCUSSION

Figure 3 shows the results of the residential building stock energy consumption calculations mapped at SA1 level for the whole Metropolitan Melbourne area. As expected, the most intense consumption areas are those associated with larger population density. However, many SA1 areas with lower population density showed larger residential energy consumption than the average, mainly related to dwelling type and household type variables including occupancy type (hours of use) and household size.

These results were verified and validated though different data obtained in surveys, government reports, energy providers and residential energy bills. Verification of the model results was undertaken by comparing the results obtained by the model with the results obtained using the same bottom-up building typology approach proposed in the Inner Melbourne Energy Consumption Report 2011 - 2016 (Seo et al., 2014). In this report, they modeled the energy consumption of residential and commercial operational energy for the four inner city councils: the City of Melbourne, City of Port Phillip, City of Yarra, and City of Stonington. The unit of analysis in this report was the meshblock geographical unit, as the information needed for the modelling was available at this fine grain unit, and the city officials wanted to see small variances between meshblocks in the different councils (IMAP, 2014).

The results of the IMAP work aggregated to a comparable SA1 level of geography were compared with the results of the model developed in the present research using the same energy modeling engine (AusZEH developed by CSIRO) but the latter energy mapping effort using a code developed in Python to automate the typologies distribution process. Figure 3 shows the comparisons of the percentage of difference between the IMAP results and the results obtained with the script developed in Python:

Model validation was undertaken using government reports, surveys and reports from energy providers and residential energy bills. The average consumption for the different sources was compared with the average operational energy results from the energy model. A micro validation (at building level) and a macro validation (SA1 level) were undertaken. The sources for the validation were selected depending on the availability of information for Victoria, as results can vary greatly between different states in different geographical zones. It is important to mention that some of the sources used for validation are surveys, and as such, they do not cover the whole population, instead only samples of the selected areas.

The main sources for the validation were:

- Victorian household energy survey report, May 2014
- Residential energy bill average (Lumo Energy, Brunswick) 2014
- Ausgrid report energy bill prices 2012 (medium size dual fuel household Melbourne)
- Energy Consumption Survey, ABS, 2012 (results for state of Victoria)

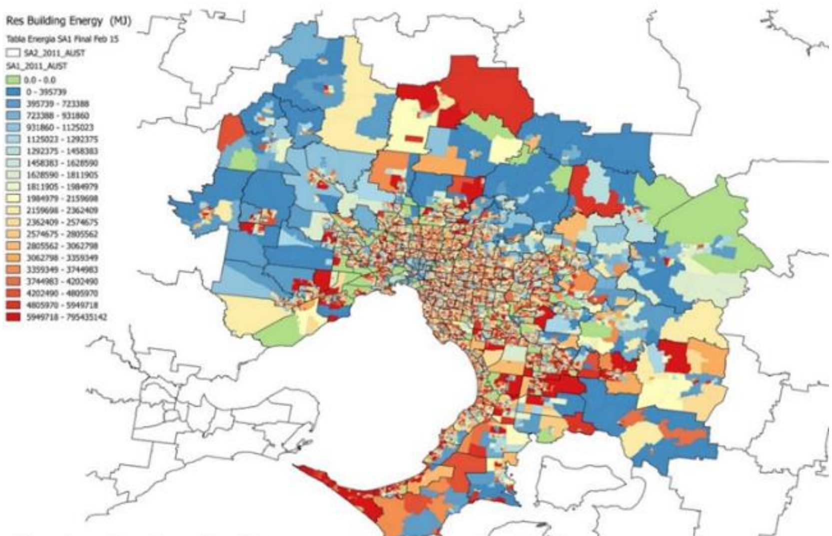


*Figure 3: Metro-wide distribution of the residential building stock energy consumption (by SA1)*

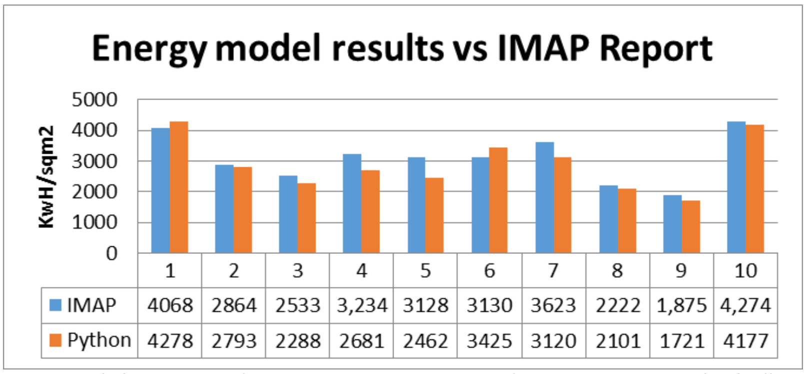


*Figure 4: Comparison of IMAP vs. script model results for residential energy (by SA1)*

Results show that the average consumption for a medium size dwelling type in this report was 19.671Kwh per annum for the micro validation level (residential building). For comparison, a random set of 10 SA1 from the simulated energy consumption were selected and its overall result per annum was divided in the number of dwellings reported in the ABS 2011 Census (see Figure 4). The results of the residential building average per dwelling of the selected SA1s was 20.003 KhW per annum, showing a difference of 3.5%, and generally a deviation of less than 10% is considered good for studies of this kind (IMAP, 2014).

Another type of macro-validation was undertaken using information from the Water and Energy Supply and Consumption (WESC) protocol or data standard developed by AURIN and CSIRO (combined monthly Meter Readings for aggregated electricity consumption by postcode for 2004 - 2012 in Jemena provider areas). The dataset is broken down into commercial, industrial, residential or unmetered uses, from postcode regions in the northwestern parts of Melbourne. Using this WESC information on residential energy, we compare the total residential operational energy consumption at a larger geographical scale (postcode), by aggregating the consumption of each SA1 conforming the Post Code area in the areas where Jemena Energy supplies energy. With the dataset in postcode 3058 (Coburg), our residential energy calculation under-predicted the actual aggregated data by 18.8% (estimated to be 2,692,638KwH vs Jemena's reported figure of 3,198,113kwH).

Overall, the Inner Melbourne area variations in residential energy consumption are related with the Household Type and Dwelling and Occupancy type variables. Building age also has an impact on the efficiency of the building envelope to reduce heating and cooling energy consumption; a large part of the residential building stock in Metropolitan Melbourne is more than 35 years old (Sustainability Victoria, 2013).

Regarding the residential transport energy consumption, analysis of the 2011 VISTA survey data shows that large households (Hh_structure) tend to use more private transport for everyday activities, although households located near the transport corridors (train and tram lines) showed a smaller proportion of private car use in the modal split. A Pearson's correlation analysis with the variable Distance (Sum_Dist) as dependent variable and other variables selected (Distance from CBD, Main transport mode, dwelling type, Household Structure, Income, and Number of cars). The relationship between dwelling type and household type and private car VKT (Vehicle Kilometer Travel), shows only a small impact of these variables on the overall residential transport energy consumption.

| | Correlation with Sum_Dist | Significance (R squared) |
|---|---|---|
| Hh_structure | 0.0408 | 0.0017 |
| Dwell type | -0.0952 | 0.0091 |
| Income | 0.0965 | 0.0093 |
| Distance to CBD | 0.2114 | 0.0224 |
| Nr of cars | 0.1628 | 0.0265 |

*Figure 5: Pearson's correlation analysis residential transport energy model*

Correlation analysis of the residential transport energy model shows a correlation between the dependent variable Sum_Dist (household Total VKT per mode) and the Nr of cars (# cars) and Distance to CBD (distance to CBD in Km) (Figure 5). Income and other socio economic variables were also considered, but in the case of the transport behaviour in Metropolitan Melbourne the correlation between income levels and use of private cars is not as strong as shown in other residential transport studies (Grosee et al, 2015).

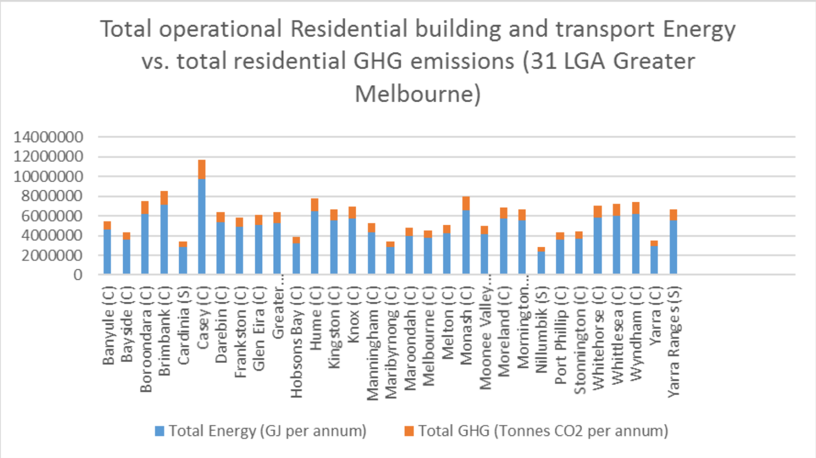


*Figure 6: Combined residential building and transport energy and associated GHG emissions for 31 LGA Greater Melbourne*

Once the residential buildings and transport energy was modelled, we calculated the GHG emissions based on the energy supply ratio established in the IMAP typologies (70% households with electricity+gas, 30% households with electricity only and 5% households with all sources installed); this also corresponds with the building stock report for residential energy supply from ABS (Households Energy Use and Cost, 2012). The Greenhouse Emission factors applied were the coefficient values reported by the Australian Institute of Energy (AEI, 2012) and the Australian Energy Market Operator (AEMO, 2016) for electricity and natural gas for the State of Victoria.

The residential transportation fuels emissions factors were provided by the Environmental Protection Authority (EPA, 2006) Assuming that 60% of private cars use petrol and 40% diesel (ABS, 2014) and the public transport (trams, trains) use electricity providing from coal energy plants, except for buses (100% Diesel).

Figure 6 shows the results of the combined residential building energy (in GJ x annum) and combined total GHG emissions (in Tonnes $CO_2$ x annum) at LGA level (31 LGA) for Greater Melbourne. the areas with higher dwelling density and car ownership have the largest impact on the operational energy (GJ per annum) and $CO_{2\text{-equiv}}$ emissions, and the distance to the CBD and car ownership density are clearly showing a larger $CO_{2\text{-equiv}}$ emission impact that the areas of Melbourne's Inner City.

## 4. CONCLUSIONS AND FUTURE WORK

We developed a new energy modeling methodology for calculating the total residential household energy, combining housing and transport energy consumption across all households in Metropolitan Melbourne. The integrated assessment is built around a common household typology, one branch was focused on housing energy consumption (based on sub-typologies of housing type and age, end-use demand categories and supply) and the other was on transport energy profiles (based on household and dwelling type information from VISTA 2011). The GHG emissions for residential buildings and residential transport have been modelled and distributed geographically at SA1 level, facilitating a spatial comprehension of consumption patterns in Metropolitan Melbourne. The distribution of household energy intensities was mapped from small geographical SA1 level to the whole municipality or Local Government Area (LGA), and to the whole metropolitan scale (i.e. all of 31 LGAs or 9650 SA1s across all of Metropolitan Melbourne). The total baseline energy consumption was spot-validated using various sources for the census year 2011. These capability and results bring us to the next stage of analyses considering the environmental impacts of alternative urban forms to accommodate the expected population growth in Melbourne.

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