The Impact of Physical Planning Policy on Household Energy Use and Greenhouse Emissions

Peter Rickwood
University of Technology, Sydney
Faculty of Design, Architecture, and Building

Submitted for the award of Doctor of Philosophy

October 26, 2009

\[^1\]peter.rickwood@gmail.com
I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

(Peter Rickwood)
iv
Thanks

Thanks foremost to Beth, for giving up so much to give me the opportunity to do my doctorate, and for caring for both myself and our two children, Jack and Lily, while I undertook this thesis. Thanks also to Jack and Lily for accepting my occasional absences during the last few months writing up, even when they couldn’t really understand why dad was not around as much. Thanks to my supervisor, Garry Glazebrook, for his supervision, his encouragement, and his advice; our interactions were always edifying. Thanks also to Glen Searle, my co-supervisor, for his advice and encouragement, and for invaluable feedback on much of my writing. Thanks to Beth, Damien Giurco, Michelle Zeibots, Danny Rickwood, and Pete Gammie for their input and advice on various matters relating to this thesis. Thanks to Professor Malcolm Sambridge particularly for advice and assistance with some of the mathematics in Chapter 5. Thanks are owed to my mum and dad, for their love and support, and for letting me save time commuting to and from university by setting up a home office of sorts in their spare room for much of the duration of this thesis. Heinz Schandl at CSIRO provided administrative support, and was always helpful and friendly. Kerry Shaz, Grace Corpuz, and Annette Hay from the NSW Ministry of Transport were all helpful in providing data and advice for my analysis. Bee Thompson from the Independent Pricing and Regulatory tribunal was similarly obliging in providing data relating to in-dwelling energy use. Peter Maganov from Randwick City Council went out of his way to be helpful, and provided useful data on in-dwelling energy use. Pat Fensham and Rod Simpson were both of great help in providing their input and advice on various matters relating to the Sydney Metro Strategy. Thanks finally to Bev and Alejandra for being such generous (in time, spirit, and chocolate!) thesis companions in the post-graduate lab at UTS.

This thesis was supported by funds provided by UTS, the Australian government, and CSIRO, without which I could have never justified giving up full-time employment.
Publications related to this thesis

Four peer-reviewed papers have been published (or accepted) that summarize some of the research carried out for this doctorate, with one additional paper currently in review. This thesis draws heavily on these published accounts.


# Contents

1 Introduction ........................................... 1
   1.1 Cities and sustainability .................................. 1
   1.2 The land-use policy and energy debate .................. 3
   1.3 Key motivating question .................................. 4
   1.4 A note on measures of energy use ......................... 4
       1.4.1 Energy and greenhouse gases ....................... 6
   1.5 Thesis questions, scope & framework for analysis .......... 7
       1.5.1 Energy use: restricted to residential transport-related and residental dwelling-related energy ................. 7
       1.5.2 Planning policy: restricted to physical land-use and transport policies .......... 8
       1.5.3 Specific thesis questions ............................ 8
   1.6 The Contribution of this thesis .......................... 14
       1.6.1 Contribution 1: specific analysis of the link between dwelling type and energy use ..................................... 15
       1.6.2 Contribution 2: specific analyses of factors influencing urban household travel ...................................... 15
       1.6.3 Contribution 3: development of a model for integrated metropolitan-scale analysis ..................................... 15
       1.6.4 Contribution 4: developing a novel model of housing choice that can be easily calibrated using census data ................................. 17
       1.6.5 Contribution 5: application of the integrated model to estimating combined transport/dwelling-related energy use in Sydney ....................... 17
   1.7 Structure of this thesis .................................. 18
   1.8 Thesis setting - Sydney, Australia ........................ 20

2 Review of Literature .......................................... 23
   2.1 Scope of the literature review ............................. 25
   2.2 Introduction ............................................. 25
   2.3 Housing .................................................. 27
       2.3.1 Embodied energy in residential buildings ................. 28
       2.3.2 In-dwelling energy consumption ........................ 30
       2.3.3 Design .............................................. 33
       2.3.4 Behaviour ........................................... 35
       2.3.5 Summary .......................................... 36
2.4 Transport ......................................... 36
   2.4.1 The effect of urban form ................................ 37
   2.4.2 Alternate views .................................. 38
   2.4.3 Summary of transport-related energy use ............... 41
2.5 Discussion ........................................ 44

3 Detailed Analysis – Dwelling-related Energy Use 47
   3.1 Introduction ........................................ 49
   3.2 Dwelling-related energy use ................................ 49
      3.2.1 In-dwelling energy use ................................ 49
      3.2.2 Embodied energy in dwellings ......................... 54
      3.2.3 Summary ..................................... 57
   3.3 Study of residential in-dwelling energy use in Sydney 59
      3.3.1 Introduction ................................... 59
      3.3.2 Prior related work .............................. 59
      3.3.3 Method ...................................... 63
      3.3.4 Data ........................................ 63
      3.3.5 Analysis and results ............................... 65
      3.3.6 Discussion ................................. 70
      3.3.7 Conclusions ................................... 74
   3.4 Chapter summary .................................... 76

4 Detailed Analysis – Urban Travel and Energy 79
   4.1 Introduction ........................................ 81
   4.2 Urban structure and commuting in Australian cities .......... 85
      4.2.1 Introduction ................................... 85
      4.2.2 Review ...................................... 85
      4.2.3 Data ....................................... 86
      4.2.4 Analysis and results ............................... 89
      4.2.5 Discussion ................................. 98
   4.3 A disaggregate analysis of commuter mode choice in Sydney 101
      4.3.1 Data ........................................ 101
      4.3.2 Method ...................................... 106
      4.3.3 Analysis and results ............................... 107
      4.3.4 Discussion ................................. 109
   4.4 A computational study of activity distribution and travel behaviour 111
      4.4.1 Synthetic analysis of a circular city .................. 111
      4.4.2 Discussion ................................. 124
   4.5 Chapter summary .................................... 127

5 Detailed analysis – Housing Choice 129
   5.1 Introduction ........................................ 132
   5.2 Existing work ...................................... 133
   5.3 Heterogenous preferences without prices ..................... 134
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3.1 Homogenous preferences, completely observable choices</td>
<td>134</td>
</tr>
<tr>
<td>5.3.2 Heterogeneity of preferences</td>
<td>135</td>
</tr>
<tr>
<td>5.3.3 Partially observed choices</td>
<td>136</td>
</tr>
<tr>
<td>5.3.4 A practical approximate likelihood maximiser</td>
<td>138</td>
</tr>
<tr>
<td>5.4 Applying the technique – synthetic data</td>
<td>140</td>
</tr>
<tr>
<td>5.5 Applying the technique – real data</td>
<td>144</td>
</tr>
<tr>
<td>5.5.1 Data</td>
<td>145</td>
</tr>
<tr>
<td>5.5.2 Results</td>
<td>147</td>
</tr>
<tr>
<td>5.6 Limitations</td>
<td>152</td>
</tr>
<tr>
<td>5.7 Concluding discussion</td>
<td>153</td>
</tr>
<tr>
<td>5.8 A note on the calculation of residential location satisfaction</td>
<td>155</td>
</tr>
<tr>
<td>5.9 Addendum: Limitations of the housing choice model</td>
<td>155</td>
</tr>
<tr>
<td>5.10 Chapter summary</td>
<td>157</td>
</tr>
<tr>
<td>6 Approaches to Urban Analysis and Modelling</td>
<td>159</td>
</tr>
<tr>
<td>6.1 Modelling the impact of planning policy</td>
<td>161</td>
</tr>
<tr>
<td>6.2 Existing approaches: Analytical</td>
<td>161</td>
</tr>
<tr>
<td>6.3 Existing approaches: Computational</td>
<td>163</td>
</tr>
<tr>
<td>6.3.1 Urban modelling: Economic and engineering traditions</td>
<td>164</td>
</tr>
<tr>
<td>6.3.2 Land-use models</td>
<td>166</td>
</tr>
<tr>
<td>6.3.3 Transport models</td>
<td>167</td>
</tr>
<tr>
<td>6.3.4 Integrated land-Use/transport models</td>
<td>168</td>
</tr>
<tr>
<td>6.4 A detour on approaches to modelling</td>
<td>169</td>
</tr>
<tr>
<td>6.4.1 Requirements of a model</td>
<td>169</td>
</tr>
<tr>
<td>6.4.2 Tangled up in utility and rationality</td>
<td>170</td>
</tr>
<tr>
<td>6.5 Modelling approach taken in this thesis</td>
<td>171</td>
</tr>
<tr>
<td>6.5.1 Model complexity/applicability tradeoff</td>
<td>172</td>
</tr>
<tr>
<td>6.5.2 Models as oracles, or models as exploratory tools</td>
<td>173</td>
</tr>
<tr>
<td>7 Development of the Integrated Model</td>
<td>177</td>
</tr>
<tr>
<td>7.1 Introduction</td>
<td>179</td>
</tr>
<tr>
<td>7.2 Residential location model</td>
<td>180</td>
</tr>
<tr>
<td>7.2.1 Predicting residential location preferences in 2031</td>
<td>185</td>
</tr>
<tr>
<td>7.2.2 Supporting method 1: Regression</td>
<td>189</td>
</tr>
<tr>
<td>7.2.3 Supporting method 2: Spatial smoothing through Inverse Distance Weighting</td>
<td>193</td>
</tr>
<tr>
<td>7.3 Transport model</td>
<td>195</td>
</tr>
<tr>
<td>7.3.1 Car-ownership model</td>
<td>197</td>
</tr>
<tr>
<td>7.3.2 Daily trip/no-trip model</td>
<td>200</td>
</tr>
<tr>
<td>7.3.3 Household VKT model</td>
<td>201</td>
</tr>
<tr>
<td>7.3.4 Travel by public transport</td>
<td>205</td>
</tr>
<tr>
<td>7.3.5 Final adjustments to match 2006 aggregates</td>
<td>207</td>
</tr>
<tr>
<td>7.3.6 Obtaining an estimate of annual household transport energy use</td>
<td>207</td>
</tr>
<tr>
<td>7.3.7 Embodied energy of vehicles</td>
<td>212</td>
</tr>
</tbody>
</table>
CONTENTS

7.4 Dwelling-related energy-use model ........................................... 212
  7.4.1 In-dwelling energy ......................................................... 212
  7.4.2 Embodied energy in buildings .......................................... 215
7.5 Profiles of representative households ..................................... 215
  7.5.1 The five representative households .................................... 216
  7.5.2 Results for the representative households ........................ 217
7.6 Chapter summary ........................................................................... 220

8 Scenario Development and Model Inputs ........................................ 221
  8.1 Introduction .............................................................................. 223
  8.2 Demographic inputs ................................................................... 223
    8.2.1 Household income ............................................................ 225
  8.3 Housing policy inputs ............................................................... 228
  8.4 Other inputs & conversion parameters ....................................... 236
    8.4.1 Primary energy conversion factors .................................... 236
    8.4.2 How were the in-dwelling energy conversion factors derived? .... 236
    8.4.3 How were the private vehicle travel conversion factors obtained? ... 237
    8.4.4 How were the public transport conversion factors obtained? ....... 237
    8.4.5 Embodied energy conversion factors .................................... 238
  8.5 Variations to inputs for alternative scenarios ............................ 238

9 Integrated Modelling – Analysis and Results .................................. 241
  9.1 Introduction ............................................................................ 243
    9.1.1 Other metropolitan-scale estimates of the impact of land use on energy use 244
  9.2 Scenarios without land-use/transport feedback ............................ 248
    9.2.1 Scenario 1: baseline ......................................................... 249
    9.2.2 Scenario 2: +20% in centres, +0% in suburbs, -40% on fringe ....... 270
    9.2.3 Scenario 3: +0% in centres, +75% in suburbs, -40% on fringe ....... 273
    9.2.4 Scenario 4: +5% in centres, -20% in suburbs, +0% on fringe ....... 276
    9.2.5 Scenario 5: -10% in centres, -40% in suburbs, +40% on fringe ....... 279
    9.2.6 Scenario 6: -20% in centres, -7% in suburbs, +40% on fringe ....... 282
    9.2.7 Scenario 7: ‘mildly Parisian re-development’ (-40% fringe) .......... 285
    9.2.8 Scenario 8: ‘high-rise re-development’ (-40% fringe) ............... 290
    9.2.9 Scenario 9: ‘Parisian re-development’ (-67% fringe) ................ 293
    9.2.10 Scenario 10: ‘Hong-Kong style re-development’ (-67% fringe) .... 297
    9.2.11 Scenario 11: ‘Urban sprawl’ (+150% fringe) ....................... 301
  9.3 Scenarios with land-use/transport feedback .................................. 305
    9.3.1 Scenario 1a: baseline ....................................................... 307
    9.3.2 Scenario 2a: +20% in centres, +0% in suburbs, -40% on fringe ....... 309
    9.3.3 Scenario 3a: +0% in centres, +75% in suburbs, -40% on fringe ....... 310
    9.3.4 Scenario 4a: +5% in centres, -20% in suburbs, +0% on fringe ....... 311
    9.3.5 Scenario 5a: -10% in centres, -40% in suburbs, +40% on fringe ....... 312
    9.3.6 Scenario 6a: -20% in centres, -7% in suburbs, +40% on fringe ....... 313
    9.3.7 Scenario 7a: ‘mildly Parisian re-development’ (-40% fringe) ....... 314
CONTENTS

9.3.8 Scenario 8a: ‘high-rise re-development’ (-40% fringe) ..................... 315
9.3.9 Scenario 9a: ‘Parisian re-development’ (-67% fringe) ..................... 316
9.3.10 Scenario 10a: ‘Hong-Kong style re-development’ (-67% fringe) ........ 317
9.3.11 Scenario 11a: ‘Urban sprawl’ (+150% fringe) ............................. 318
9.4 Miscellaneous scenarios/analyses ............................................. 319
  9.4.1 Peak oil ............................................................................ 320
  9.4.2 Scenario 13: Multi-pronged approach, weak response ................. 324
  9.4.3 Scenario 14: Multi-pronged approach, moderate response .......... 326
  9.4.4 Scenario 15: Multi-pronged approach, strong response .............. 327
  9.4.5 Scenario 16: Multi-pronged approach, very strong response ....... 328
9.5 Chapter summary ........................................................................ 329
  9.5.1 Implications for planning policy in Sydney ................................. 331
  9.5.2 Conclusions ....................................................................... 332

10 Conclusions ................................................................. 335
  10.1 Summary of key findings relating to thesis questions ...................... 337
  10.1.1 Question 1: “How does dwelling type affect residential dwelling-related energy use?” .................................................. 337
  10.1.2 Question 2: “How does transport and land-use policy influence household travel behaviour (and resulting energy use)?” ......................... 338
  10.1.3 Question 3: “How does housing location policy influence aggregate dwelling-related and transport-related household energy use?” .................... 339
  10.2 General discussion .................................................................. 340
  10.3 Future research ...................................................................... 341
  10.3.1 Building life ........................................................................ 342
  10.3.2 The land-use → transport feedback, and the nature of urban feedback systems in general ......................................................... 342
  10.3.3 The proper role of government and markets in planning ............ 343
  10.4 Concluding remarks .............................................................. 344

A Thesis Related Software .................................................. 347
Abstract

This thesis investigates the impact of physical planning policy on combined transport and dwelling-related energy use by households. Separate analyses and reviews are conducted into dwelling-related and transport-related energy use by households, before a model is developed to investigate the city-wide implications of different land-use scenarios in Sydney, Australia.

The analysis of household energy use in Chapter 3 suggests that medium density housing (i.e. low-rise apartments, townhouses, and terraces) is likely to result in the lowest per-capita energy use, while also allowing for sufficient densities to make frequent public transport service viable.

The analysis of transport energy in Chapter 4 confirms that increasing urban density is associated with decreased car ownership and use, independent of other factors. However, land use changes alone are likely to result in modest changes to travel behaviour.

The results of the scenario modelling in Chapters 7-9 support the view that changes to land use alone can reduce household energy consumption, but the changes, even over a long time period (25 years) are small (≈ 0 – 10%) for all but the most extreme land-use policies. Instead, a coordinated (land-use/transport and other policy levers) approach is much more effective. The results confirm that it is transport energy that is most sensitive to planning policy, but that a combined consideration of dwelling-related and transport-related energy use is still useful. The micro-simulation model developed to assess the impact of different land-use planning scenarios allows the establishment of a lower-bound estimate of the effect that housing policy has on household energy use, assuming ‘business as usual’ transport policy, household behaviour, and technology.