Techno-economic modelling of smart multi-energy districts

Dr Nicholas Good

Acknowledgements:  
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Dr Eduardo Alejandro (Alex) Martínez Ceseña  
Mr Lingxi (Kevin) Zhang

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- Motivation
- Framework overview
- Multi-energy district physical modelling
- Multi-energy stochastic energy/reserve co-optimisation model
- Aggregation and networks
- Value mapping methodology
- Barriers and enablers of Demand Response
- Concluding remarks
Motivation

- Increasing penetration of inflexible, variable generation
- Prospect of widespread electrification of heating and transport
- Exploitation of flexible resources at the district level is natural and desirable

<table>
<thead>
<tr>
<th>Salient aspects</th>
<th>Framework features</th>
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<tr>
<td>Energy service demand</td>
<td>Multi-energy physical modelling and optimisation</td>
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<tr>
<td>(Multi-energy) storage</td>
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<td>Demand response</td>
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<td>Aggregation of resources</td>
<td>Virtual/physical aggregation view</td>
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<td>Multi-energy network modelling</td>
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<tr>
<td>Complexity</td>
<td>Value mapping methodology</td>
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</tbody>
</table>
Framework overview

District model

Optimisation model

\[
\frac{dx(t)}{dt} = \sum_{i} x_{\text{energy}}(t) + B \cdot T \cdot e \cdot I \cdot s \cdot I \cdot c + I \cdot m - I \cdot v \cdot I \cdot s \cdot I \cdot w
\]

\[x \leq B\]

CBA tool

Revenue sharing agreements

Profit sharing model

Value mapping model

Fixed costs, discount rate, project life

Economic assessment

CBA metrics

Cash flow, by commodity, by actor

Other key outputs: Thermal comfort, peak loads, energy consumption, grid/local CO₂ emission, reserve availability
Multi-energy district physical models

Building simulation model structure

Multi-energy district physical models

Building sub-model

Multi-energy district physical models

Heat emitter modelling

Storage heater

System state-space equations

\[
\frac{d}{dt} \begin{pmatrix} x_{e\text{wo}} \\ x_{e\text{wi}} \\ x_i \\ x_{i\text{w}} \\ x_{\text{he}} \end{pmatrix} = [A] \begin{pmatrix} x_{e\text{wo}} \\ x_{e\text{wi}} \\ x_i \\ x_{i\text{w}} \\ x_{\text{he}} \end{pmatrix} + [B] \begin{pmatrix} T_e \\ I_{se} \\ I_{si} \\ I_v \\ H_{hs} \end{pmatrix}
\]


Multi-energy district physical models

Controls

Multi-energy district physical models

Controls

- Outdoor temperature
- Indoor temperature
- Heating system temperature
- Variable heat transfer

Other key features

- Heating system design phase
- Defrost cycle
- Detailed COP model (ambient and return temperatures as inputs)
- Temperature compensation

- Run time for one day simulation, one minute resolution
  - 1 house -> 1 minute
  - 500 houses -> 30 minutes

Energy profiles

Typical modern semi-detached house, typical winter day

Electricity consumption ASHP, electric cooking

Radiator heat emitter

Underfloor heat emitter

Electricity and gas consumption radiator, gas cooking

Gas boiler

Gas CHP
Inertia and coincidence

Building temperature, by emitter type

Heat stored in heat emitter

Coincidence factor, typical semi-detached house, typical winter day (left), extreme winter day (right)
Network impact studies


Stochastic multi-energy energy/reserve co-optimisation model

Optimisation model
\[ \min f(x) \]
\[ \text{s.t} \quad x \leq B \]

Resource parameters
Prices
Thermal comfort
Energy consumption

Environmental parameters
District cash flow
Energy service demand


Stochastic multi-energy energy/reserve co-optimisation model

Expected energy costs – no storage

Expected energy costs and cost savings on the gas boiler case per dwelling, no storage

Stochastic multi-energy energy/reserve co-optimisation model

Expected energy cost – with storage

‘With TES’ tests

‘No TES’ tests

Expected thermal discomfort cost

<table>
<thead>
<tr>
<th></th>
<th>No TES</th>
<th>300 litre TES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Price £/(°C·h)</strong></td>
<td>£1</td>
<td>£0.5</td>
</tr>
<tr>
<td>ICE</td>
<td>£0</td>
<td>£0.1</td>
</tr>
<tr>
<td>ICE/ASHP mix</td>
<td>£2</td>
<td>£0.5</td>
</tr>
<tr>
<td>SE/ASHP mix</td>
<td>£1</td>
<td>£0.1</td>
</tr>
<tr>
<td>SE</td>
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<tr>
<td>ASHP</td>
<td>£2</td>
<td>£0.1</td>
</tr>
</tbody>
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Annual average ETDC per dwelling for the deadband ‘No TES’ tests

Annual average ETDC per dwelling for PoTD tests

Stochastic multi-energy energy/ reserve co-optimisation model

Modelling reserve from electro-thermal devices

**Electricity consuming devices**

- Electric heat pump/electric boiler

**Device operation**

- Max Power
- Min Power
-footroom

**Thermal energy storage**

- Max Energy content
- Min Energy content
-footroom

**Electricity generating devices**

- Combined heat and power unit

- Max Power
- Min Power
-headroom

- Max Energy content
- Min Energy content
-headroom

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Stochastic multi-energy energy/reserve co-optimisation model

District of 50 detached houses, winter weekday – Optimisation, with reserve

<table>
<thead>
<tr>
<th></th>
<th>No reserve</th>
<th>Reserve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy cost</td>
<td>£ 61.80</td>
<td>£ 62.02</td>
</tr>
<tr>
<td>Reserve revenue</td>
<td>£  -</td>
<td>£ 27.64</td>
</tr>
</tbody>
</table>

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DNCM service

<table>
<thead>
<tr>
<th>Test</th>
<th>Size of flexible resource, per building</th>
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<tbody>
<tr>
<td>1</td>
<td>230 litre TES</td>
</tr>
<tr>
<td>2</td>
<td>Auxiliary gas boiler, sized at 14% of peak load</td>
</tr>
<tr>
<td>3</td>
<td>5.5kWh/0.55kW battery</td>
</tr>
<tr>
<td>4</td>
<td>4.5kWh/0.45kW battery, 0.675kVA inverter</td>
</tr>
<tr>
<td>5</td>
<td>$\delta_{i,l}^{\text{high}} = 0.1$</td>
</tr>
<tr>
<td>6</td>
<td>$\delta_{i,l}^{\text{high}} / \delta_{i,l}^{\text{low}} = 0.05$</td>
</tr>
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Battery power/energy ratio set at 10%

Battery inverter size set at 150% battery power rating
DNCM service

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Aggregation

**Premises to GCP mapping**

- Premises electricity/gas profiles
- GCP level electricity/gas profiles

- Premises 1
- Premises 1 GCP
- Premises 2
- Premises 2 GCP
- \( \vdots \)
- Premises \( N \)
- Premises \( N \) GCP

- Common GCP

**GCP to commercial agent mapping**

- GCP level electricity/gas profiles
- Commercial level electricity/gas profiles

- GCP 1
- Agent 1
- GCP 2
- Agent 2
- \( \vdots \)
- GCP \( N \)
- Agent \( N \)

- Common agent

---

Aggregation

Change in annual district cash flows – private wire adoption

Networks

Non-linearities #1
- the hydraulic network constraints $Q^2 \propto \Delta P |\Delta P|

Thermal storage (heat networks)

Non-linearities #2
- the electrical network constraints $S = V(YV)^*$

Non-linearities #3
- thermal network constraints $H \propto Q\Delta T, \Delta T \propto e^{1/q}$

Computational difficulties
- thermal network storage capacity
- thermal network dynamics

Thermal storage (buildings)
- Electrical storage (flexible devices)

Other buildings / installations
- Other gas demand
- Electrical storage (flexible devices)
- Building heating
- Renewable
- Hot water
- Storage
- Other electrical demand
A unified network model is solved using an enhanced version of the well known Newton-Raphson method.
District “Energy Efficiency” Engine

- District energy management system and flexibility “optimizer”
- Complex (stochastic) MINLP problem
- A methodology that iteratively couples (‘software-in-the-loop’) more practical
- Under real implementation

Source: E. A. Martínez Ceseña, and P. Mancarella, “Operational optimization and environmental assessment of integrated district energy systems,” in PSCC 2016,

Value mapping methodology

Energy system map-Ireland

Energy system map-UK


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Value mapping methodology

Value mapping methodology

Ireland

Electricity prices

Gas prices
Value mapping methodology

Optimisation and value mapping output

Extreme infrastructure case

- Change in operational revenue, £/year
- Cons. Mod. Ext. Smt Ext. (cost) Smt. Ext. (emis)
- O&MGas DUoS Wholesale gas ESO & VAT BSUoS Electricity TUoS Electricity DUoS CMSC Imbalance Wholesale electricity Net

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Barriers and enablers of Demand Response

Applications

SEAF project – financing energy investments

- Smaller projects often require finance
- But projects often too small for financiers, who must understand the project and risk
- SEAF will construct a platform to bring together project developers and financiers and standardise their interactions, lowering transaction costs
- Demand response is a key revenue stream
Applications

SEAF project – financing energy investments
Concluding remarks

- Assessment of smart energy districts requires integrated and holistic modelling, considering multiple energy vectors and technical and economic aspects

- Key features are:
  - Multi-energy physical model
  - Multi-energy optimisation model
  - Aggregation and network modelling
  - Value mapping methodology

- This approach is vital for efficient integration of variable RES and electrification of heating and transport

- Future work - Analysis of the value of energy positivity/autarky and flexibility
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https://www.seaf-h2020.eu/
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Selected references


Selected references


• E. A. Martínez Ceseña, and P. Mancarella, “Operational optimization and environmental assessment of integrated district energy systems,” in PSCC 2016


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Submission of final manuscripts:

Contact email: christine.wal@manchester.ac.uk

Conference dinner
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