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Quantitative modelling of residential smart grids

Vashti Galpin

Laboratory for Foundations of Computer Science
School of Informatics
University of Edinburgh

MoKMaSD 2015, York

8 September 2015

COOPERATION

Outline

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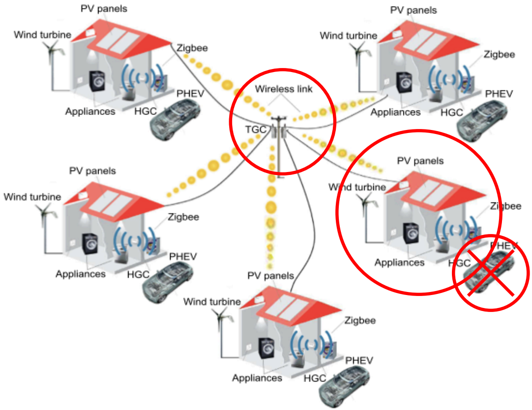
1. Motivation
2. Residential smart grids
3. Modelling
4. Policies
5. Scenarios
6. Results
7. Conclusion

Motivation

- changes in the way electricity is generated
  - more producers, small producers, prosumers
  - use of information technology
- modelling to investigate different approaches
  - residential smart grid
  - sharing of renewable energy between neighbourhoods
- stochastic HYPE
  - process algebra
  - continuous, instantaneous, stochastic behaviour
  - simulation, generation of trajectories for variables in model
- quantitative modelling of collective adaptive systems

Residential smart grids



[Oviedo *et al*, 2012, 2014]

Suburb energy scheme

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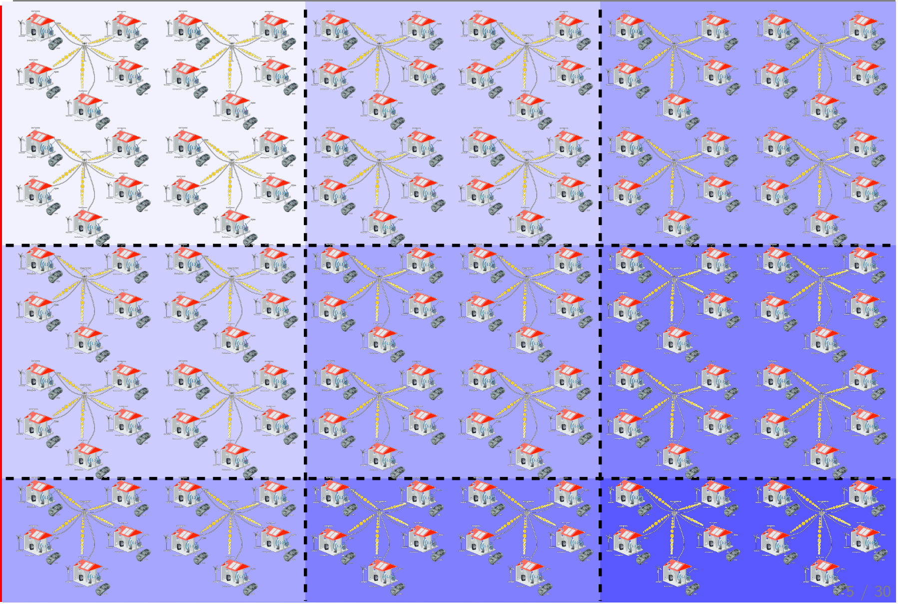


Quantifying residential smart grids

- n neighbourhoods where neighbourhood N_i has m_i houses
- at each house H_{ij} at time t
  - generation of $r_i(t)$ renewable energy
  - consumption: a_{ij} appliances and background consumption

$$l_{ij}(t) = b(t) + \sum_{k=1}^{a_{ij}} o_{ijk}(t) \cdot app_{ijk}$$

  - use of local renewable energy

$$e_{ij}(t) = \min(l_{ij}(t), r_i(t))$$

  - local excess demand

$$d_{ij}(t) = l_{ij}(t) - e_{ij}(t)$$

  - local excess renewable energy

$$x_{ij}(t) = r_i(t) - e_{ij}(t)$$

Quantifying residential smart grids

- assume maximal allocation of renewable energy within neighbourhood
- in each neighbourhood N_i at time t
  - renewable energy $R_i(t) = m_i \cdot r_i(t)$
  - consumption/demand

$$L_i(t) = \sum_{j=1}^{m_i} l_{ij}(t)$$

  - use of local renewable energy

$$E_i(t) = \min(L_i(t), R_i(t))$$

  - local excess demand

$$D_i(t) = L_i(t) - E_i(t)$$

  - local excess renewable energy

$$X_i(t) = R_i(t) - E_i(t)$$

- $(D_i(t) > 0) \Rightarrow (X_i(t) = 0)$ and $(X_i(t) > 0) \Rightarrow (D_i(t) = 0)$ each neighbourhood either has surplus renewable energy or excess demand but not both
- assume redistribution of surplus energy to N_i: $F_i(t)$
- use of shared renewable energy

$$S_i(t) = \min(D_i(t), F_i(t))$$

- use of grid energy

$$G_i(t) = D_i(t) - S_i(t)$$

- wastage of renewable energy

$$W_i(t) = F_i(t) - S_i(t)$$

assume maximal allocation within neighbourhood, wastage is energy which cannot be used by any house in neighbourhood

Redistribution policies

- requires definition of adjacent neighbourhoods: von Neumann (four compass points), Moore (eight compass points)
- how to divide up surplus energy from a neighbourhood between adjacent neighbourhoods
  - equally
  - proportional to excess demand
  - relative to wind speed, proportional to excess demand only to those neighbourhoods with lower wind speeds
- policy determines amount of energy moving in each direction, based on local information only
- how much energy to give to each neighbourhood in a direction
  - sufficient to cover excess demand
  - sufficient to cover some proportion of excess demand

Allocation in one direction

- general form, assuming direction is from 1 to n

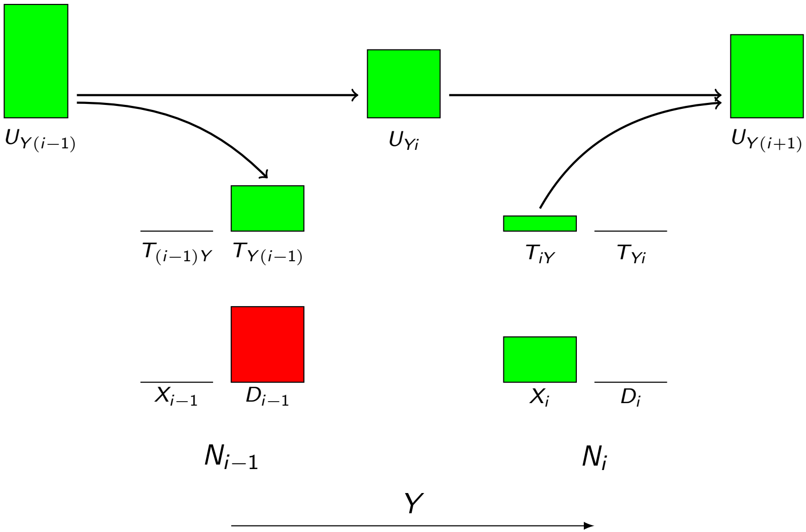
U_{Yi}	unallocated energy "moving" in direction Y at N_i
T_{Yi}	energy allocated to N_i from direction Y
T_{iY}	energy from N_i for direction Y (some fraction of X_i)
A_{Yi}	excess demand that may be satisfied from direction Y (some fraction of D_i)

$$U_{Yi}(t) = \begin{cases} 0 & i = 1 \\ U_{Y(i-1)}(t) - T_{Y(i-1)}(t) + T_{(i-1)Y}(t) & \text{otherwise} \end{cases}$$

$$T_{Yi}(t) = \begin{cases} U_{Yn}(t) & i = n \\ \min(U_{Yi}(t), A_{Yi}(t)) & \text{otherwise} \end{cases}$$

$$F_i(t) = \sum_{Y} T_{Yi}(t)$$

Allocation in one direction



Model parameters

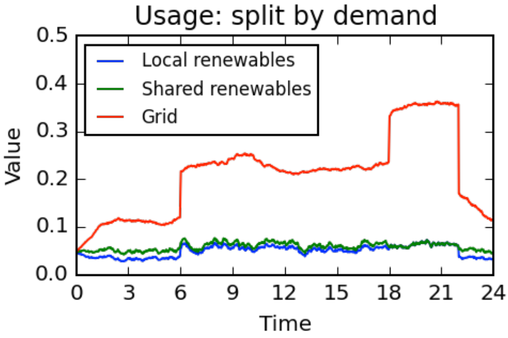
- 7 neighbourhoods in a row (also 4×4 grid)
- each neighbourhood has 4 houses
- electricity cost: peak 0.272 £/kWh, mid-peak 0.194 £/kWh, off-peak is 0.107 £/kWh [Oviedo *et al*, 2012]
- appliance consumption: washing machine 0.82 kWh for one hour, dishwasher 2.46 kWh for 1.5 hours, probability distribution of starting time [Oviedo *et al*, 2012]
- background consumption: daytime 0.3 kWh, evening 0.5 kwH, nighttime 0.1kWh [Yao and Steemers, 2005]

Model parameters

- 80% probability of wind strong enough to drive a turbine in the UK [Sinden, 2007]
- 25% to 35% generation capability of a wind turbine rated at x kWh in the UK [Sinden, 2007]
- stochastic wind pattern consists of
  - wind strength: constant value w_{str}, varying in intensity by neighbourhood
  - wind presence: exponentially distributed with rate $1/w_{pres}$
  - wind absence: exponentially distributed with rate $1/w_{abs}$
  - defines a Markov modulated Poisson process
- fix w_{pres} and vary w_{abs} for a range of wind probabilities from 50% (1.2 and 1.2) to 80% (1.2 and 0.3)

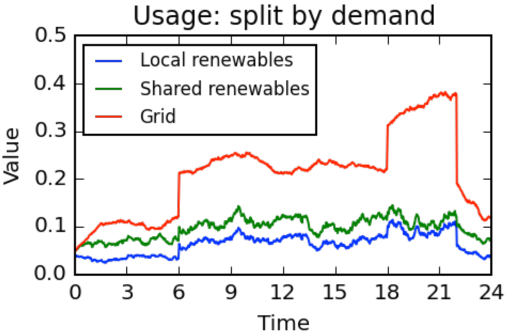
Scenario: one wind

N_1	N_2	N_3	N_4	N_5	N_6	N_7
1.00	1.00	0.50	0.50	0.25	0.25	0.25



Scenario: two winds

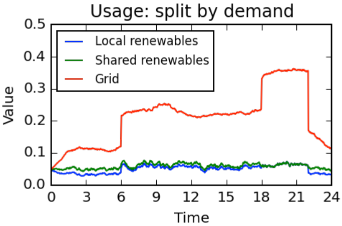
N_1	N_2	N_3	N_4	N_5	N_6	N_7
1.00	0.50	0.25		0.25	0.50	1.00



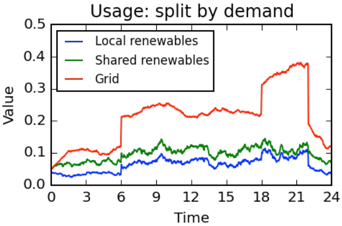
Comparison

- scenario comparison

one wind



two winds



- sharing in one wind scenario
  - increases usage of renewables from 55% to 70%
  - decrease wastage of renewables from 57% to 27%

Heat map

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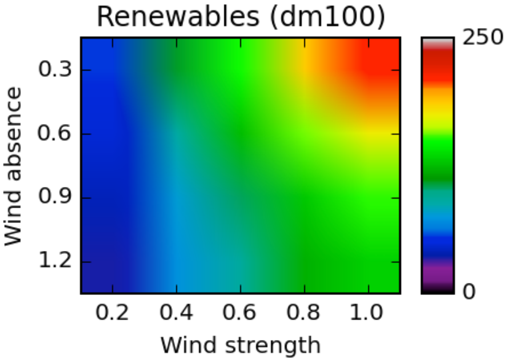
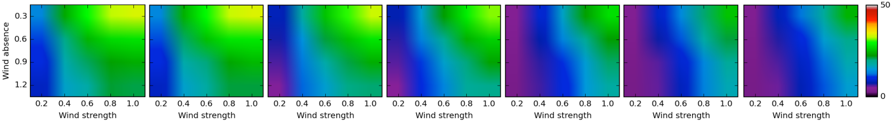
- range for w_{str}: 0.2, 0.4, 0.6, 0.8, 1.0
- range for w_{abs}: 0.3, 0.6, 0.9, 1.2
- w_{pres}: 1.2



Comparison across neighbourhoods

Local renewable usage

N1 N2 N3 N4 N5 N6 N7



1.00 1.00 0.50 0.50 0.25 0.25 0.25

Wind intensity

Comparison across neighbourhoods

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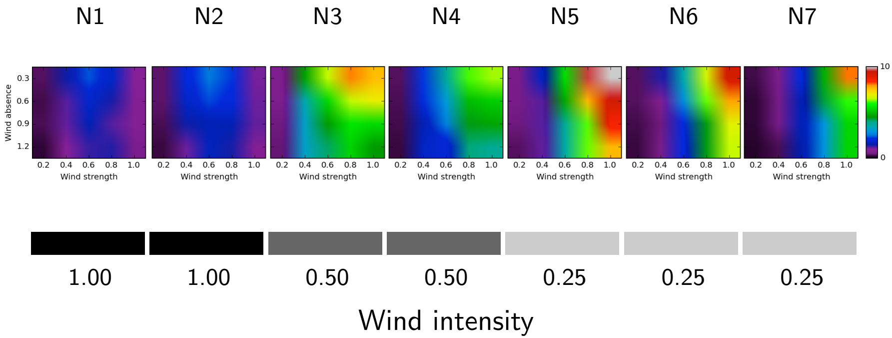
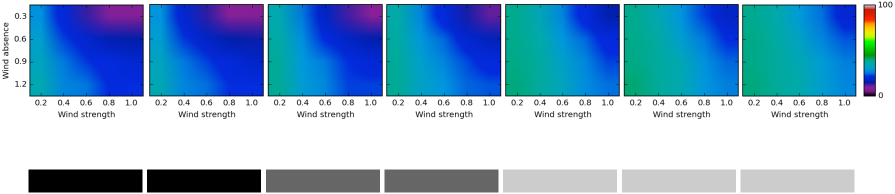
Shared renewables usage



Comparison across neighbourhoods

Grid usage

N1 N2 N3 N4 N5 N6 N7



1.00 1.00 0.50 0.50 0.25 0.25 0.25

Wind intensity

Comparison across neighbourhoods

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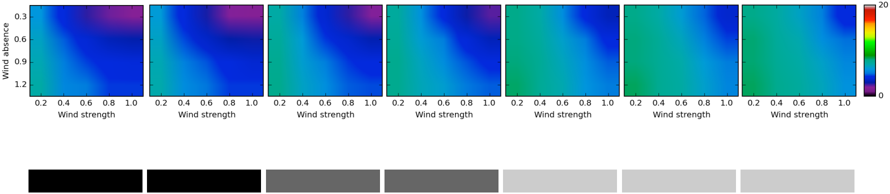
Cost

N1 N2 N3 N4 N5 N6 N7



1.00 1.00 0.50 0.50 0.25 0.25 0.25

Wind intensity

Comparison across neighbourhoods

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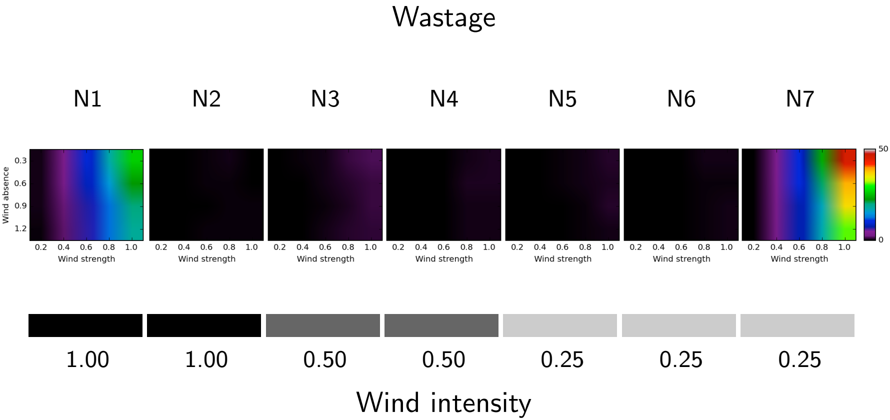
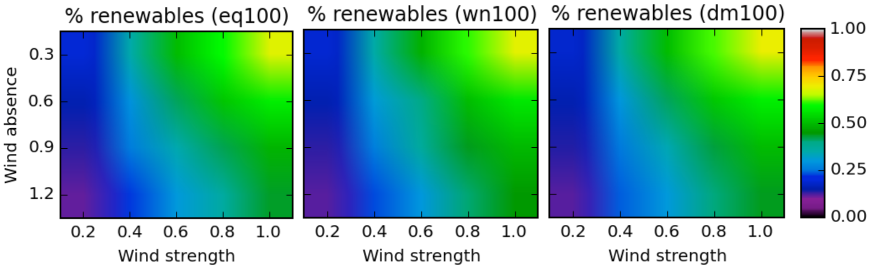


Policies considered

- dividing up surplus between adjacent neighbourhoods
  - eq Split equally
  - dm Split proportionally by demand
  - dw Split weighted by demand
  - da Direction of highest demand receives all surplus
  - wn Split proportionally by demand among adjacent neighbourhoods that have lower wind speed
- allocation to neighbourhoods as surplus moves
  - 100 100% of excess demand allocated
  - inc Proportion of excess demand allocated increases in the direction of supply
  - wnd Proportion of excess demand allocated is inversely proportional to wind speed
- policies considered
  eq100, dm100, dminc, dmwnd, dw100, da100, wn100

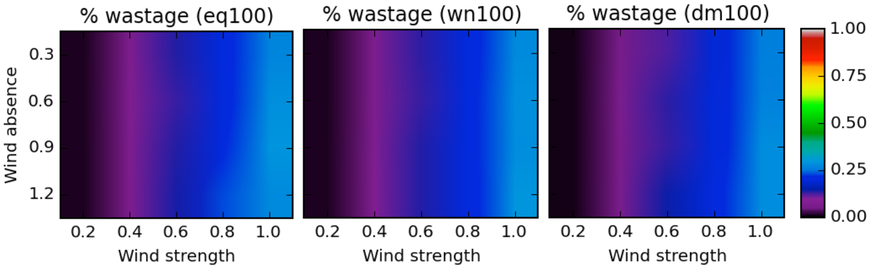
Policies: one wind

$$\text{Proportion renewables} = \frac{\text{Local and shared renewable usage}}{\text{Total usage}}$$



Policies: one wind

$$\text{Proportion wastage of renewables} = \frac{\text{Renewables not used}}{\text{Total renewables generated}}$$



Scenario: one wind on grid

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$N_{1,1}$ 1.20	$N_{1,2}$ 1.00	$N_{1,3}$ 0.80	$N_{1,4}$ 0.60
$N_{2,1}$ 1.00	$N_{2,2}$ 0.80	$N_{2,3}$ 0.60	$N_{2,4}$ 0.40
$N_{3,1}$ 0.80	$N_{3,2}$ 0.60	$N_{3,3}$ 0.40	$N_{3,4}$ 0.20
$N_{4,1}$ 0.60	$N_{4,2}$ 0.40	$N_{4,3}$ 0.20	$N_{4,4}$

- no major differences between policies
- consider larger grids or different wind strengths

Policy comparison: two winds

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	N_1 1.00	N_2 0.50	N_3 0.25	N_4	N_5 0.25	N_6 0.50	N_7 1.00
da100	1.09	1.16	1.19	1.46	1.18	1.13	1.11
wn100	1.11	1.14	1.22	1.37	1.21	1.16	1.16
dw100	1.10	1.14	1.22	1.43	1.20	1.13	1.15
eq100	1.15	1.13	1.25	1.44	1.22	1.13	1.13
dm100	1.13	1.15	1.28	1.47	1.20	1.19	1.13
dmdec	1.07	1.21	1.31	1.48	1.29	1.17	1.06
dmdwn	1.07	1.30	1.32	1.30	1.32	1.28	1.10

- cost per day
- full wind strength and 50% wind presence

Policy comparison: two winds

	mean	variance	Grid	W%	R%
da100	1.19	0.0130	159.3	15.9%	47.4%
wn100	1.20	0.0064	158.4	16.2%	47.5%
dw100	1.20	0.0110	158.6	17.1%	47.6%
eq100	1.21	0.0111	160.9	18.6%	46.7%
dm100	1.22	0.0129	163.7	16.8%	45.9%
dmdec	1.23	0.0192	165.0	19.2%	45.3%
dmdwn	1.24	0.0101	165.6	19.6%	45.2%

Conclusions

- modelling smart residential grids
  - assumption of within-neighbourhood sharing
  - policies for between-neighbourhood sharing
  - evaluation of policies in different scenarios

- further research
  - different scenarios
  - model size
  - scalability
  - spatial moment closure

Thank you