ETH zürich

ESC Project: INMES
“Integrated model of the energy system”

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Presentation outline

1. Introduction: Modeling energy systems

- Background and motivation
- INMES: Integrated model of the energy system

2. The value of end-user energy storage in Smart Grids

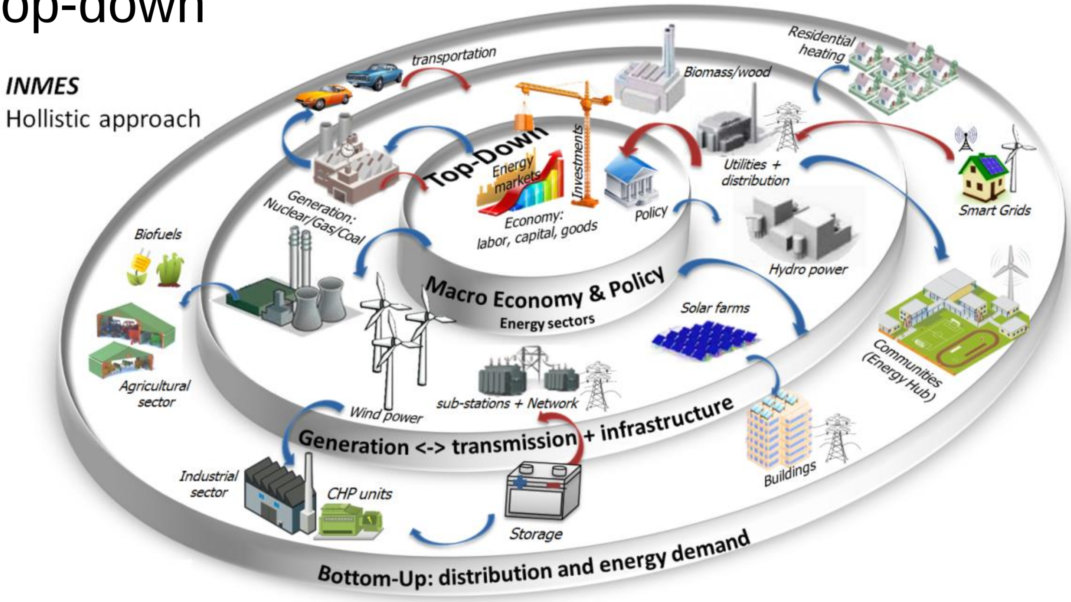
- The value of energy storage in residential buildings
- Community energy storage and wind uncertainty

3. Final remarks

- Summary, INMES expected contribution

What is INMES?

INMES is an analytical tool that encompasses a holistic approach on modelling energy systems under a single framework to analyse energy planning strategies from the regional to the national level. INMES considers a variety of energy and economic models that in combination can account for exogenous factors that in otherwise in the stand-alone models are overlooked. INMES combines top-down and bottom-up approaches to respectively account for interactions in energy demand-supply and macro energy-economic factors.



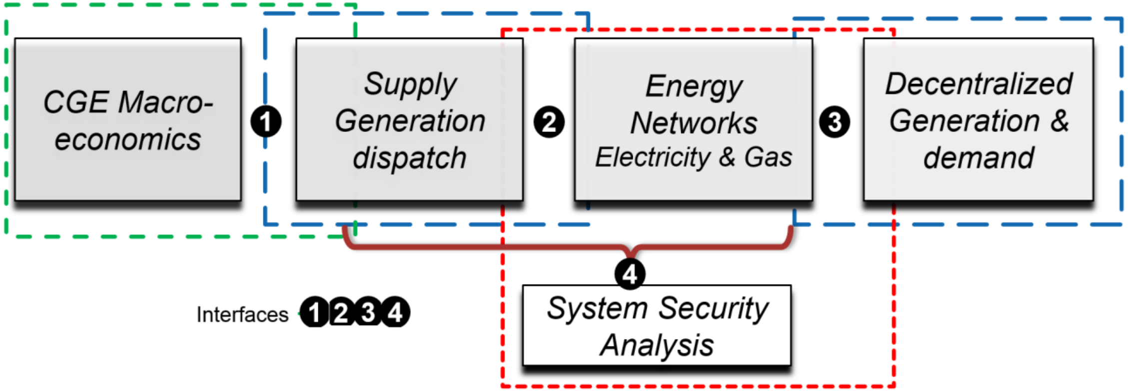
Research questions & objectives

INMES goal is to formulate a holistic modelling framework of the energy system, to then detail its platform implementation (software). The objective is to answer:

- *How to model the relationship among policy making, economic drivers and energy technologies under a unifying framework?*
- *What are the challenges to create a model that encompasses all features of the energy system?*
- *What is the synergistic added-value of a holistic approach compared to the independent use of existing models?*

Modeling INMES: a conceptual framework

- Find a unifying compromise among different model methodologies that encompass all the components of the energy system.
- Define main core models and key energy sectors
- Discuss the modeling challenges and the value of interfaces
- Indentify distinctive capabilities (i.e. Modular approach)


CGE Macro-economics
①
Supply Generation dispatch
②
Energy Networks Electricity & Gas
③
Decentralized Generation & demand
④
System Security Analysis

Interfaces ①②③④

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Energy systems modeling, an example

The value of energy storage with intermittent renewables: an end user perspective in smart grids

Key questions

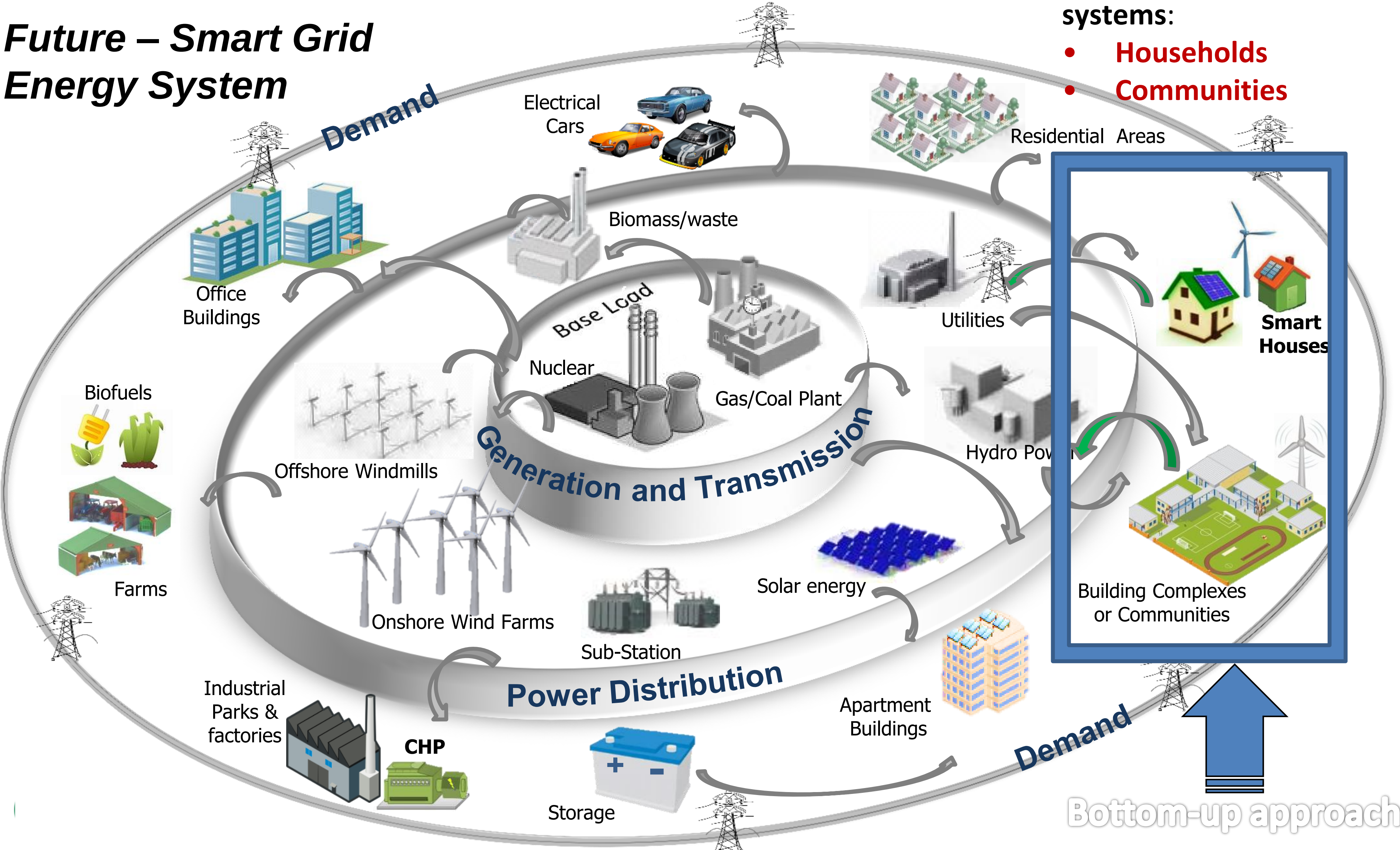
- How will increased renewables penetration affect the electricity balancing market and the opportunity for energy storage in this market?

- What are the economic implications of end-user storage and demand side measures for energy markets and the grid?

- **What is the value of energy storage for the end-user and the grid? Value of Flexibility!**

Future – Smart Grid Energy System

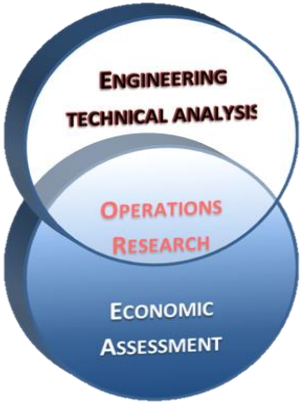
Focus on end-user energy systems:
- **Households**
- **Communities**



Research questions and approach

- What is the value of energy storage for the **end-user** in a smart grid?
  - The value from hedging local renewable supply and demand variations (value of flexibility)
  - The impact of demand response (load-shifting)
  - The effect of the portfolio of hybrid (mix) distributed generation (DG) to the value of energy storage

- How important is considering wind uncertainty to the valuation of end-user electricity storage?

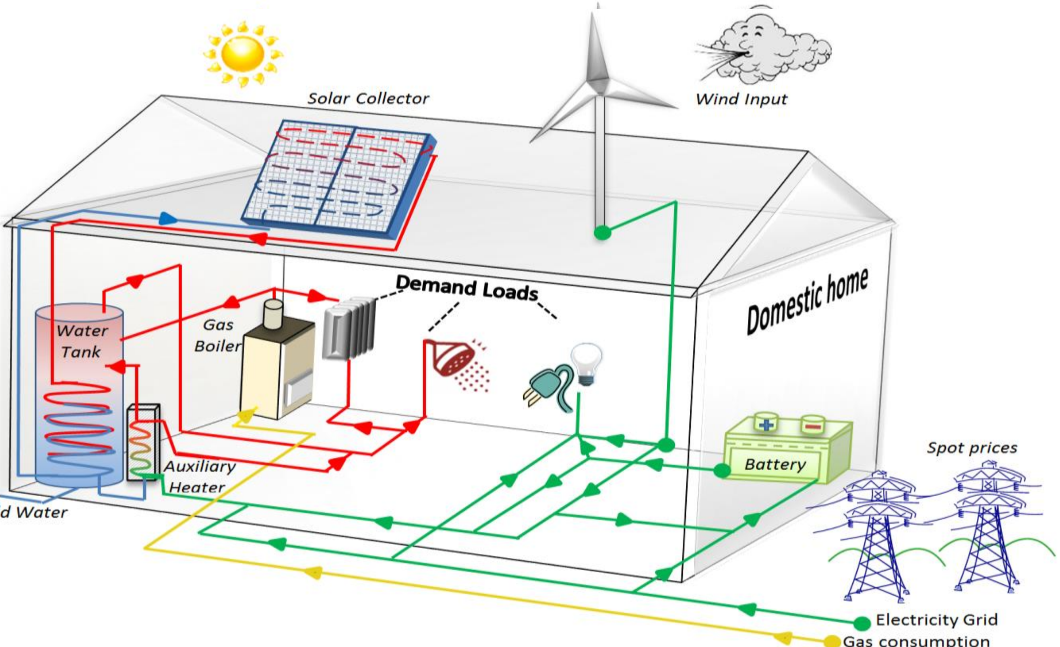


Assumptions and limitations

- Two-way communication exists: smart meter.
- Electricity spot prices (UK RPD data) as proxies for energy cost.
  - Assumed to be known (deterministic in nature).
- The models provide an assessment on the value of energy storage; not an operational model.
- Transmission and operational costs not included.
- Commercial maturity and detailed engineering aspects of storage units not considered.
- The end-user energy system does not deliver (only buys from the grid).

A smart house model and energy storage

- ✓ We assume Smart metering is available
- ✓ Renewable generation and demand load variations are hedged and connected through energy storage over the optimization periods.



Model Objective:

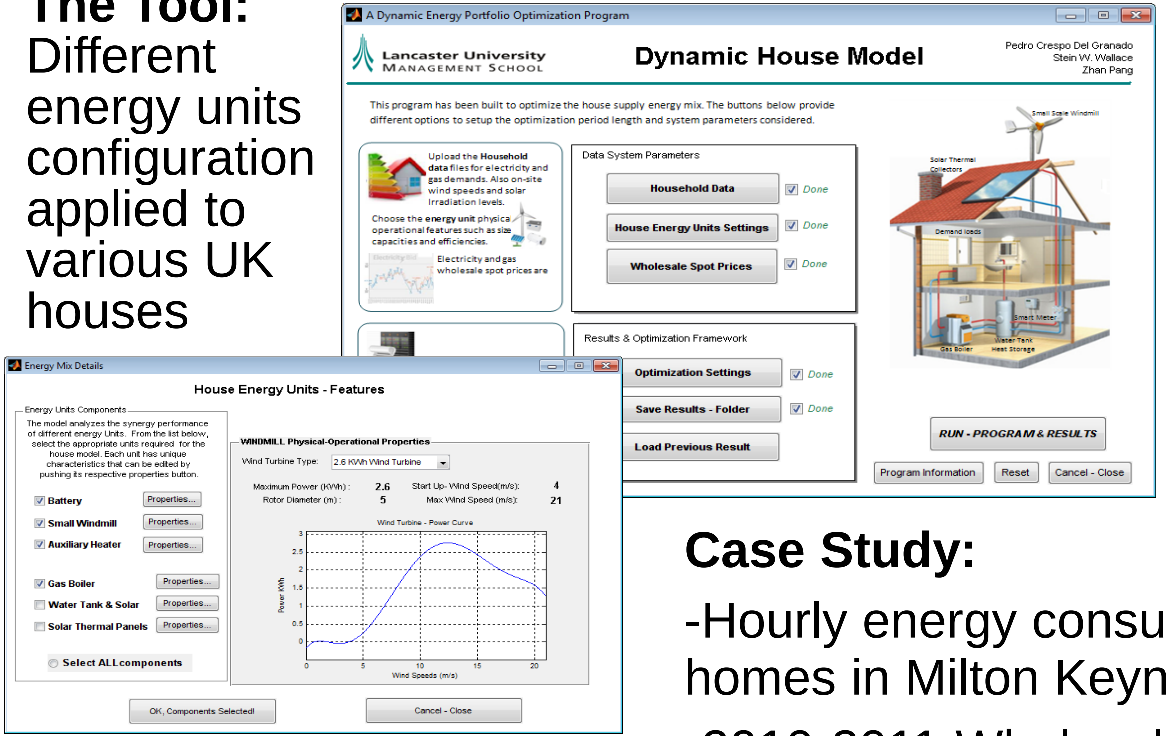
✓Minimize cost of grid consumption

Model Constraints:

- ✓Units’ Capacity & Efficiency
- ✓Demand
- ✓Supply Availability from Renewables
- ✓Storage Intertemporality

Model implementation: The tool + Case study

The Tool: Different energy units configuration applied to various UK houses



A Dynamic Energy Portfolio Optimization Program

Lancaster University Management School

Dynamic House Model

Pedro Crespo Del Granado
Stein W. Wallace
Zhan Pang

This program has been built to optimize the house supply energy mix. The buttons below provide different options to setup the optimization period length and system parameters considered.

Upload the **Household data** files for electricity and gas demands. Also on-site wind speeds and solar Irradiation levels.

Choose the **energy unit** physica operational features such as size capacities and efficiencies.

Electricity and gas wholesale spot prices are

Data System Parameters
- Household Data ☑ Done
- House Energy Units Settings ☑ Done
- Wholesale Spot Prices ☑ Done

Results & Optimization Framework
- Optimization Settings ☑ Done
- Save Results - Folder ☑ Done
- Load Previous Result

Energy Mix Details

House Energy Units - Features

Energy Units Components

The model analyzes the synergy performance of different energy Units. From the list below, select the appropriate units required for the house model. Each unit has unique characteristics that can be edited by pushing its respective properties button.

- ☑ Battery
- ☑ Small Windmill
- ☑ Auxiliary Heater
- ☑ Gas Boiler
- ☐ Water Tank & Solar
- ☐ Solar Thermal Panels
- ○ Select ALL components

WINDMILL Physical-Operational Properties

Wind Turbine Type: 2.6 KWh Wind Turbine

Maximum Power (KWh) : 2.6
Rotor Diameter (m) : 5
Start Up- Wind Speed(m/s): 4
Max Wind Speed (m/s): 21

Units considered in a House:

- •15kW Gas Boiler
- •1.35kW Small Win
- •2.8kW Battery
- •300l Water Tank
- •8 m^2 Solar Collector

Case Study:

-Hourly energy consumption data gathered from homes in Milton Keynes Park (North West London)

-2010-2011 Wholesale spot prices

- 4 bedroom - Detached Houses of 130m^2
- Annual electricity average demand: 3.4MWh
- Annual gas heating average demand: 14.4MWh

- 3 bedroom - Semi Detached Houses of 74m^2
- Annual electricity average demand: 2.7MWh
- Annual gas heating average demand: 9.7MWh

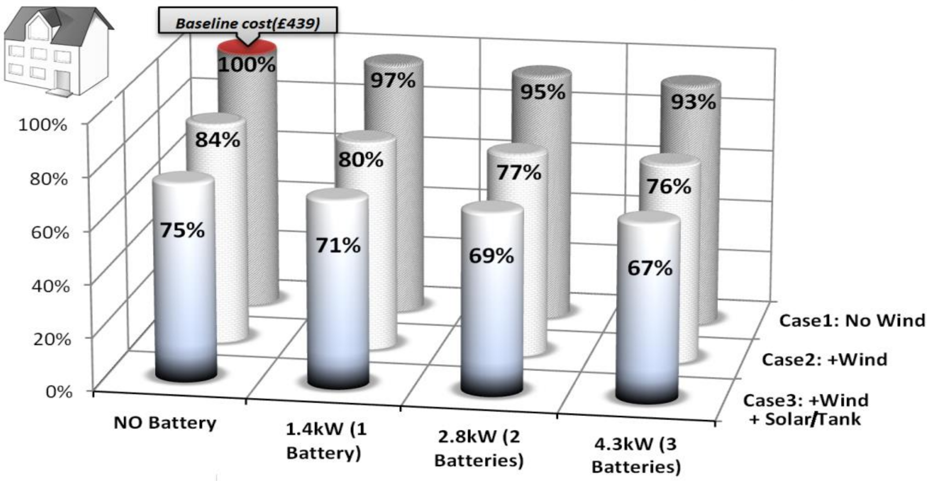
		With Battery Storage		
Case 1: Without Wind Turbine	**NO Battery**	**1 Battery (1.4kW)**	**2 Batteries(2.8kW)**	**3 Batteries(4.3kW)**
% of demand met by the battery	-	10.5%	19.1%	26.6%
% of demand met by the Grid	100.0%	89.5%	80.9%	73.4%
Total Grid Electricity Consumption (MWh)	3.64	3.75	3.84	3.92
Battery loses (MWh)	-	0.11	0.20	0.28
Total Heat Demand met by Boiler (MWh)	12.77	12.77	12.77	12.77
Cost Savings and % electricity savings	-	6%(-£13)	11%(-£22)	14%(-£29)
Case 2: WithWind Turbine	**NO Battery**	**1 Battery (1.4kW)**	**2 Batteries(2.8kW)**	**3 Batteries(4.3kW)**
% of demand met by the battery	0.0%	11.5%	19.7%	26.1%
% demand met by Wind	31.1%	30.7%	30.5%	30.2%
% demand met by the Grid	68.9%	57.8%	49.8%	43.8%
Total Grid Electricity Consumption (MWh)	2.51	2.39	2.35	2.35
Battery loses (MWh)	-	0.12	0.22	0.29
Total grid to the battery (MWh)	-	0.29	0.53	0.75
Total wind to the battery (MWh)	-	0.27	0.43	0.54
Total Heat Demand met by Boiler	98.3%	98.5%	98.4%	98.3%
Total demand met by ah	1.7%	1.7%	1.8%	1.9%
% of wind generation used	69.1%	82.2%	90.4%	96.2%
% electricity cost savings with wind	33%(-£70)	42%(-£89)	48%(-£101)	51%(-£107)
Case 3: With Wind Turbine + Solar/Tank	**NO Battery**	**1.4kW (1 Battery)**	**2.8kW (2 Batteries)**	**4.3kW (3 Batteries)**
Total Grid Electricity Consumption (MWh)	2.51	2.39	2.35	2.35
% of heat demand met by ah	3.7%	2.7%	2.1%	1.8%
% of heat demand met by the Tank	62.7%	63.6%	64.3%	64.5%
% of heat demand met by Boiler	33.6%	33.6%	33.7%	33.6%
Total Boiler input to tank (MWh)	5.97	6.10	6.16	6.21
Total Solar input to tank (MWh)	2.38	2.38	2.38	2.38
% of wind generation used (MWh)	84.6%	89.3%	91.7%	92.8%
% Electricity cost savings with wind	32%	41%	47%	50%
% Gas cost savings with Solar-Tank	18%(-£34)	17%(-£32)	16%(-£30)	16%(-£30)

Key results:

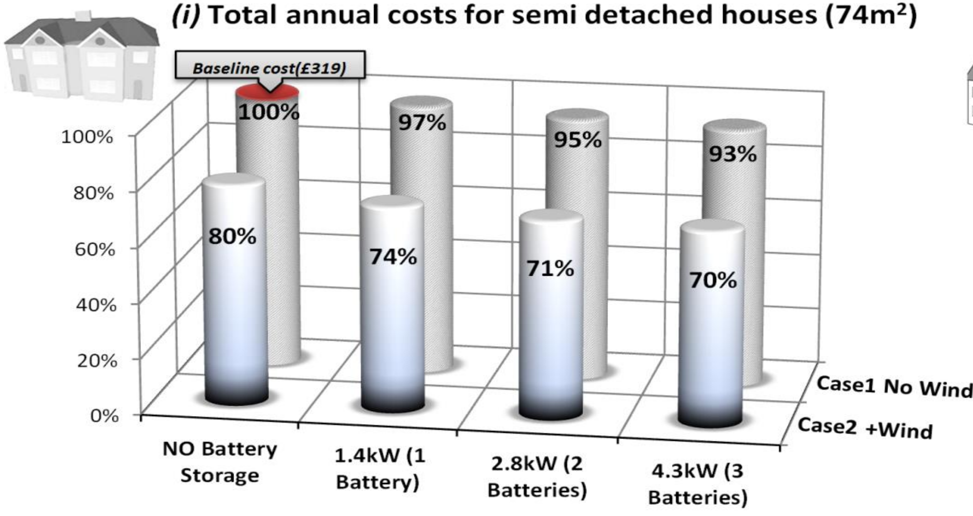
- Implementation of energy storage: **6% to 14%** savings of electricity costs

- Implementation of Small wind turbine:
  - **48%** savings of electricity costs
  - Value of storage increases **9% to 18%**

(ii) **Total annual costs for detached houses (130m²)**



(i) **Total annual costs for semi detached houses (74m²)**



The value of community energy storage with hybrid distributed generation under demand response

Community energy storage in hybrid DG

- Point of view: A large end-user (industrial site, office building complex, university campus).
  - Security of supply and reduce CO2 emissions
- Effect of demand response programs (smart grid).
- More complex energy mix (hybrid DG system): Local heating requiremes are more important
  - Specially flexibility in CHP operations and wind surplus
  - Heating and electricity systems interactions
- Analyze the interactions of heat and electricity storage units in the regulation of the energy system supply-demand balance.

A case study implementation

- University campus distributed generation mix:

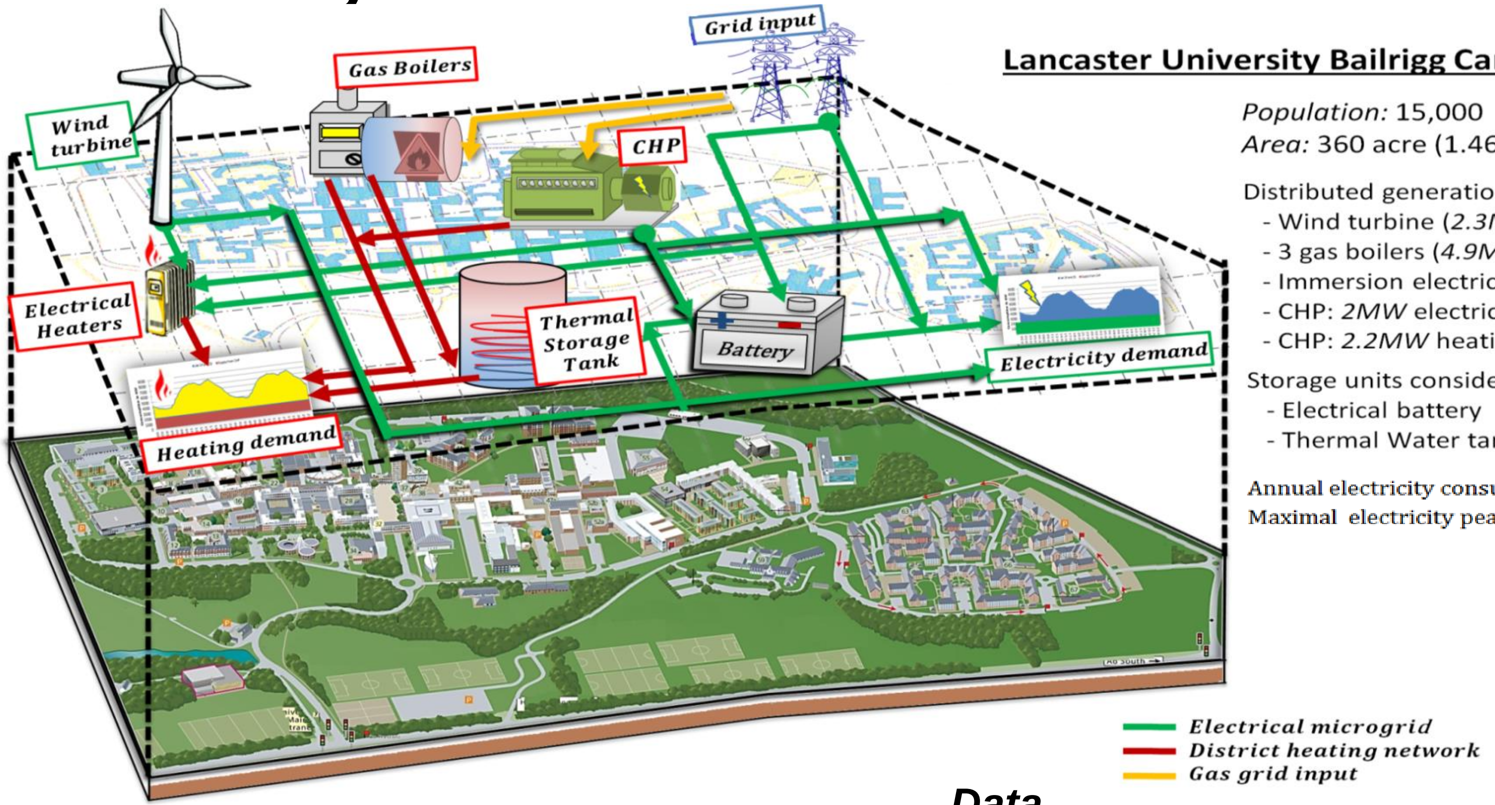
Combined heat & power engine (CHP)

3 High efficient thermal gas boilers (4.9MWh)

Micro-grid transformers

2.3MWh Wind turbine

Case study features



Lancaster University Bailrigg Campus

Population: 15,000
Area: 360 acre (1.46 km^2)

Distributed generation system:
- Wind turbine (*2.3MW*)
- 3 gas boilers (*4.9MW* each)
- Immersion electrical heaters
- CHP: *2MW* electricity output
- CHP: *2.2MW* heating output

Storage units considered:
- Electrical battery
- Thermal Water tank

Annual electricity consumption	33.3 GW
Maximal electricity peak demand registered	6.2MW

Storage Considered

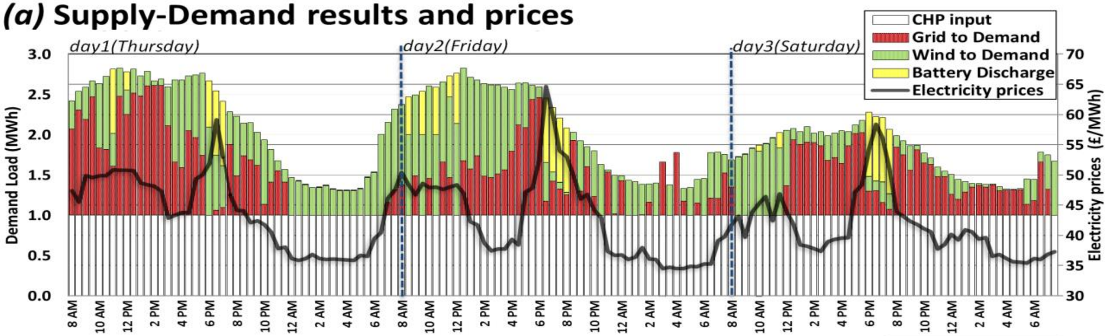
- Vanadium redox battery (VRB), Capacity: 2, 4, 8MW, roundtrip efficienfy:0.75

Data

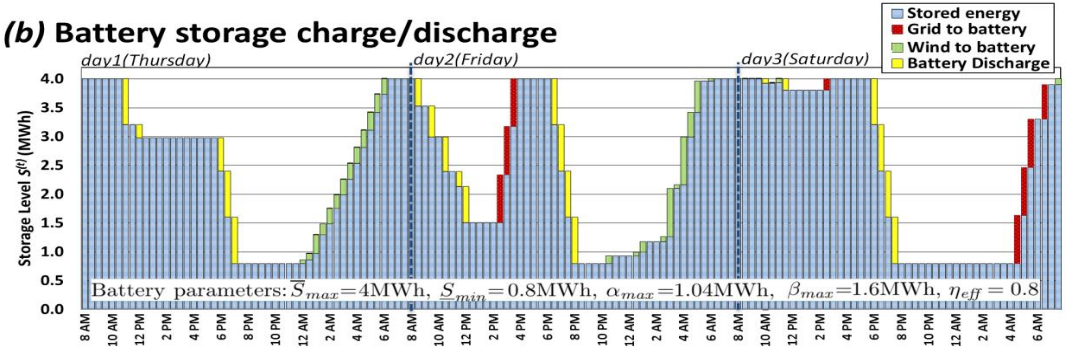
- Used the campus half hourly data electricity consumption in 2010
- National Grid sport market prices in 2010
- Historical wind data 2006-2010

Storage role example

(a) Supply-Demand results and prices

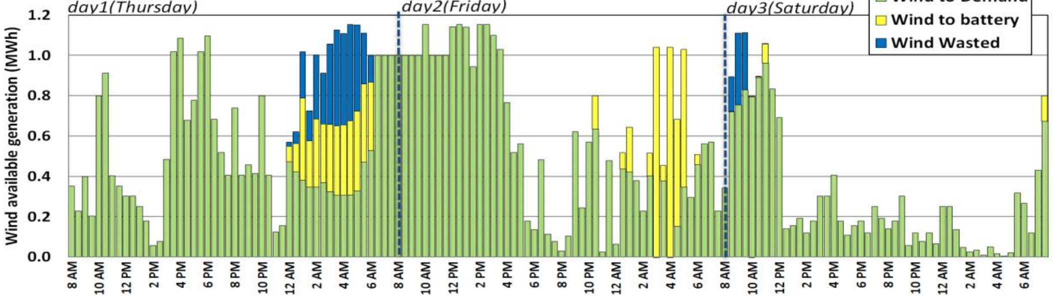


(b) Battery storage charge/discharge



Battery parameters: $\overline{S}_{max}$=4MWh, $\underline{S}_{min}$=0.8MWh, α_{max}=1.04MWh, β_{max}=1.6MWh, $\eta_{eff} = 0.8$

(c) Wind generation output



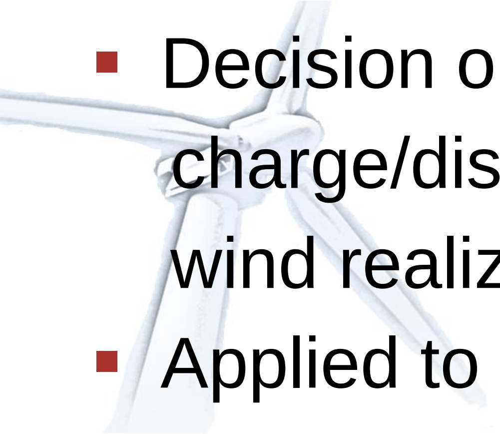
key insights from the case study

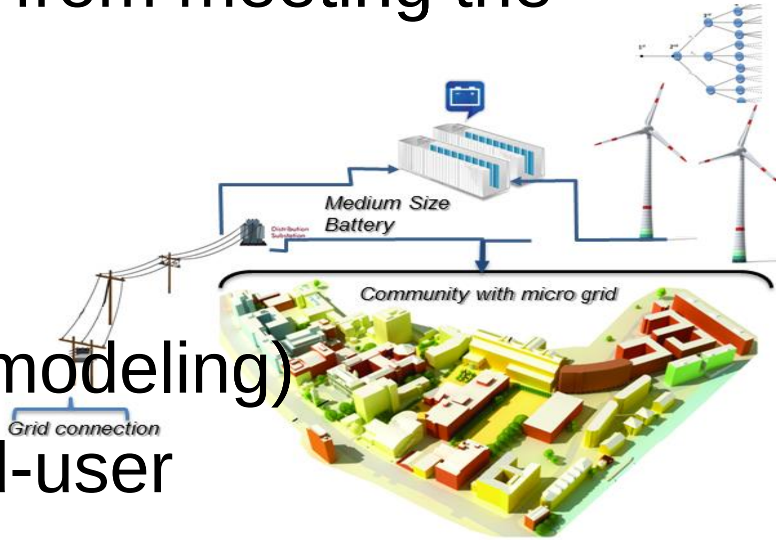
- High benefits for the heating system
  - Storage is more valuable for the heating system
  - Improve efficiency on boilers and CHP operations
- Demand response (DR) crucial to the value of electricity storage:
  - Cost savings, without DR: 2%, with DR: 7 to 15%
  - Cost savings under STOR mechanisms: 5%
  - Gas cost savings: Current DG: 2%, larger DG: 15%
- In a hybrid DG context, both storage devices are key complements to wind and the CHP.

Modeling wind uncertainty?

Wind uncertainty and energy storage

- Can the value of electricity storage be well estimated with a deterministic model?
  - A strategic model on the decision to install a battery
- Wind is modeled stochastically as some of the value of a storage unit comes from meeting the random wind
- Decision on the battery charge/discharge given wind realizations (event tree modeling)
- Applied to a generic large end-user





Optimization model

Input

Time varying data:
Wind scenarios
Demand
Wholesale Spot Prices

Storage Unit Parameters:
Charge rate
Discharge rate
Efficiencies
capacity

A day divided in 48 periods:

Model Objective:
✓Minimize cost of grid consumption

Model Constraints:
✓Storage Capacity & Efficiency
✓Demand – supply balance
✓Wind generation uncertainty
✓Storage balance (Intertemporality)

Output

Battery Charging/Discharging decisions

Cost reductions from wind smoothing and energy arbitrage

Multi-stage stochastic programming approach

$$\underset{C_{grid},S,B_{in},B_{out}}{\text{Minimize}} \left\{ \overbrace{\sum_{\omega\in\Omega_k}\sum_{t\in T_k} \pi_\omega \left[p_{el}^{(t)} \cdot C_{grid}^{(t,\omega)} \right]}^{\text{Minimize grid consumption}} \right\}$$

$$\underset{t\in T_k,\omega\in\Omega_k}{\text{such that:}}$$

$$\xi_{wind}^{(t,\omega)} + C_{grid}^{(t,\omega)} + B_{out}^{(t,\omega)} + L_{base} \geq d_{load}^{(t)} + B_{in}^{(t,\omega)}$$

$$S^{(t-1,\omega)} + \eta_{eff} \cdot B_{in}^{(t,\omega)} - B_{out}^{(t,\omega)} = S^{(t,\omega)}$$

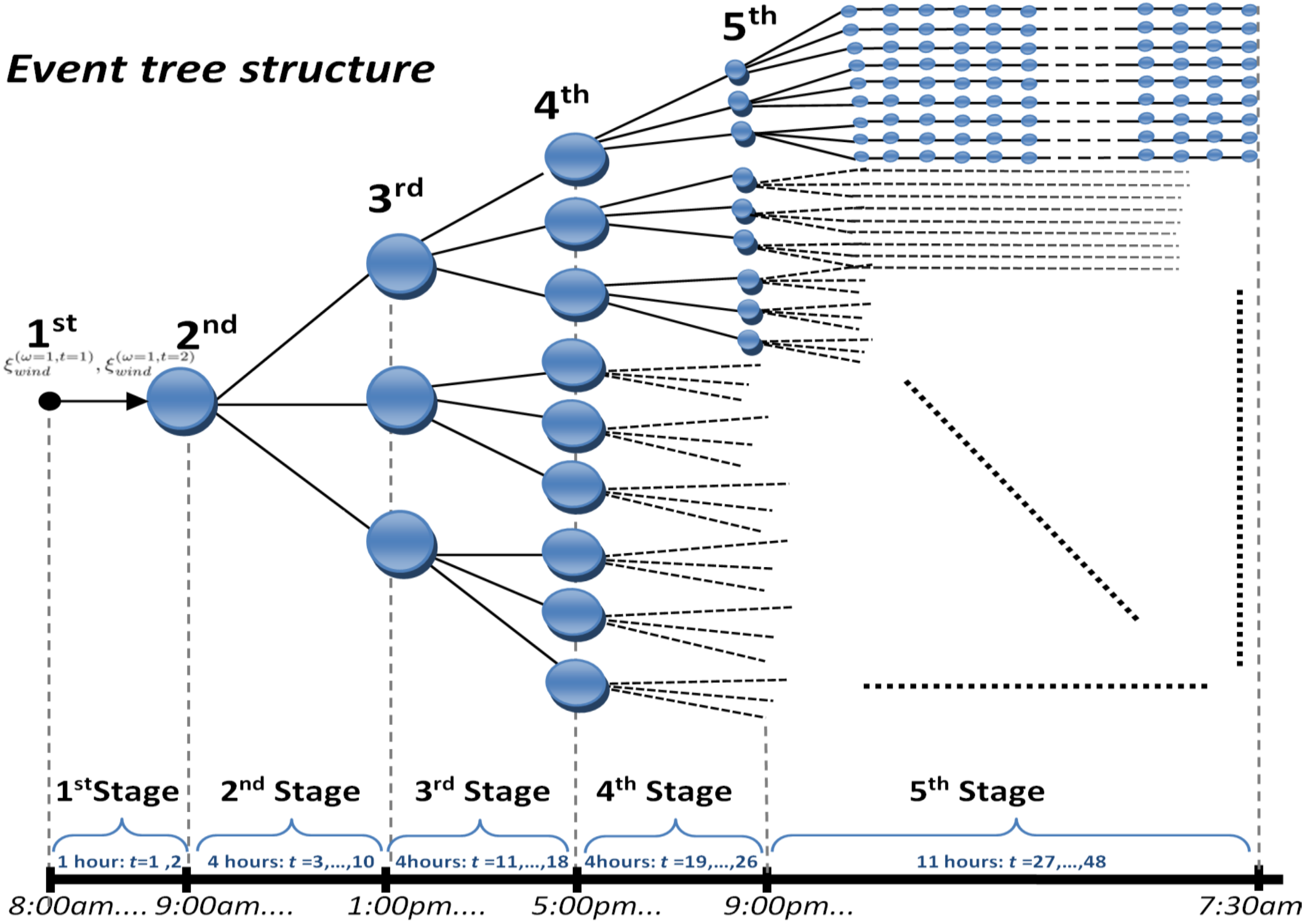
$$\underline{S}_{min} \leq S^{(t,\omega)} \leq \overline{S}_{max}.$$

$$B_{in}^{(t,\omega)} \leq \alpha_{max}$$

$$B_{out}^{(t,\omega)} \leq \beta_{max}$$

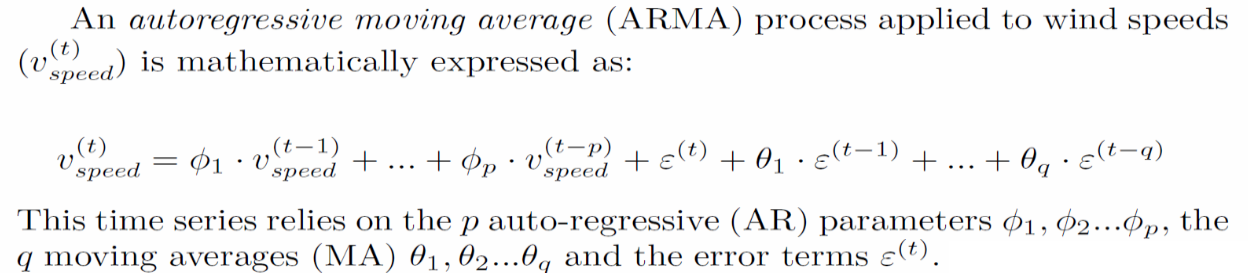
$$C_{grid}^{(t,\omega)}, S^{(t,\omega)}, B_{in}^{(t,\omega)}, B_{out}^{(t,\omega)} \geq 0$$

Event tree structure



Scenario generation of wind uncertainty

- ARMA model generates scenarios to represent the stochastic process(wind)



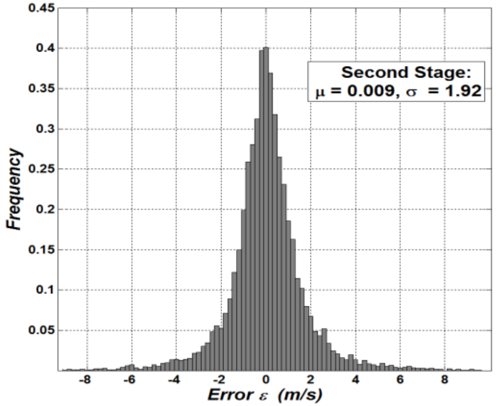
An *autoregressive moving average* (ARMA) process applied to wind speeds ($v^{(t)}_{speed}$) is mathematically expressed as:

$$v^{(t)}_{speed} = \phi_1 \cdot v^{(t-1)}_{speed} + \ldots + \phi_p \cdot v^{(t-p)}_{speed} + \varepsilon^{(t)} + \theta_1 \cdot \varepsilon^{(t-1)} + \ldots + \theta_q \cdot \varepsilon^{(t-q)}$$

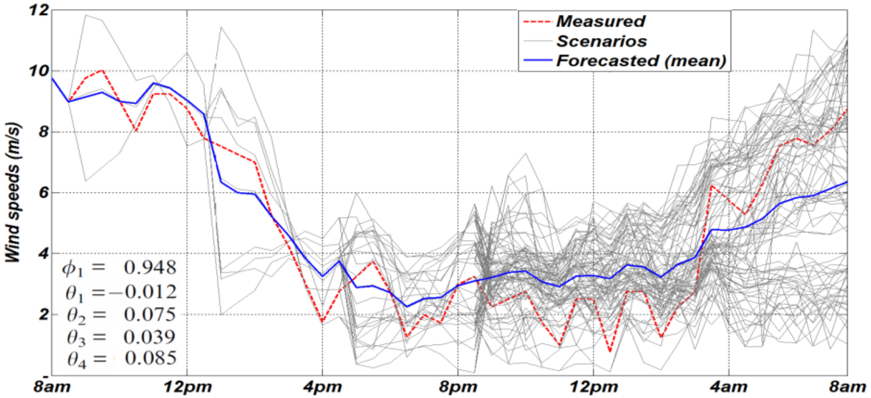
This time series relies on the p auto-regressive (AR) parameters $\phi_1, \phi_2 \ldots \phi_p$, the q moving averages (MA) $\theta_1, \theta_2 \ldots \theta_q$ and the error terms $\varepsilon^{(t)}$.

- Probability discretization into subsets : low, medium, high wind realizations

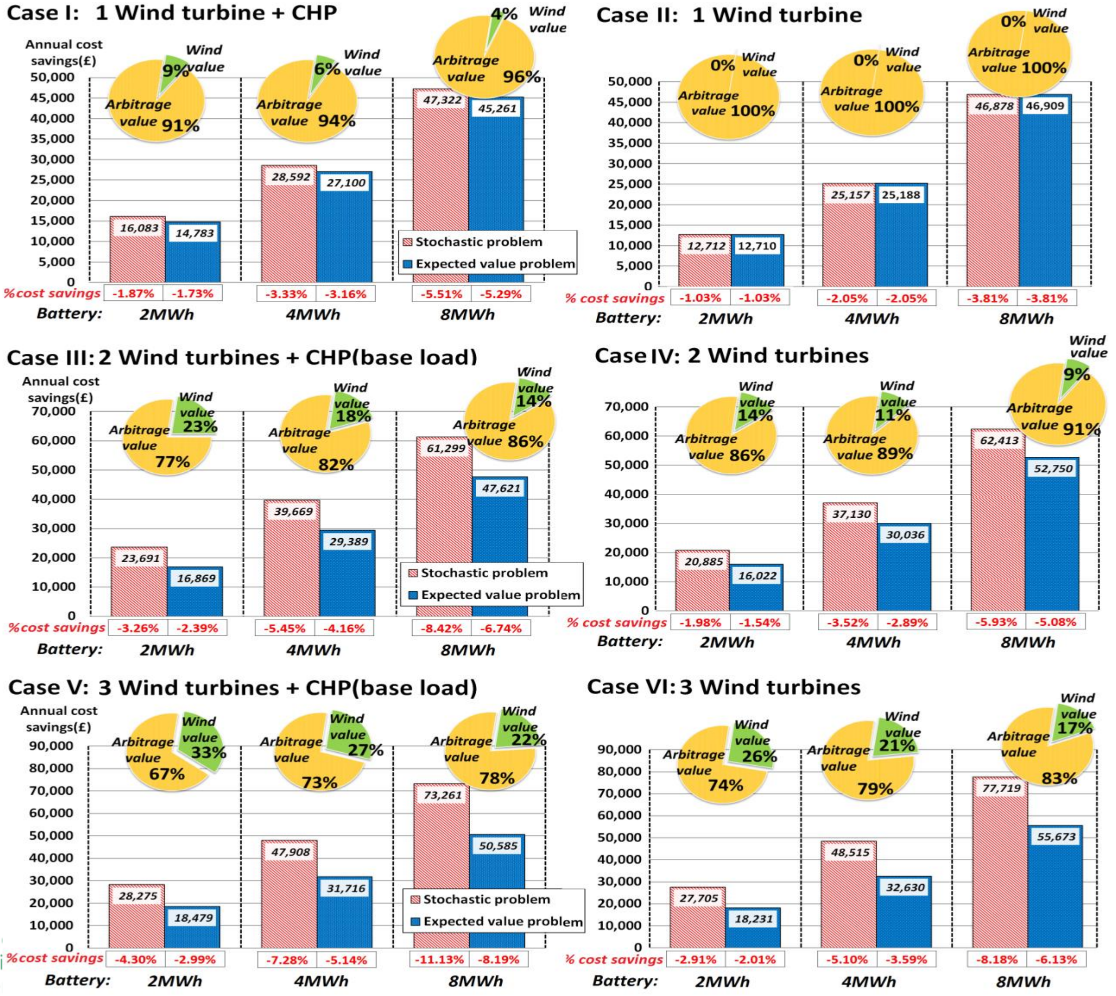
***(a)*Wind speeds error forecast distribution**



(b) Scenario generation from an ARMA(1,4) model



Results: Value of energy storage and uncertainty



- Uncertainty becomes relevant in large DG capacity cases

- Deterministic case underestimates the value of the battery up to 50% compared to the stochastic case.

Value of modeling uncertainty: summary

- Model analysis,
  - Supply surpasses demand: Uncertainty becomes relevant in large DG capacity cases.
  - Otherwise, uncertainty is less important (Demand>supply).
- Deterministic case underestimates the value of the battery
  - By around 30% (2-wind case) compared to the stochastic case.
  - The expected case (deterministic) underestimates the value of energy storage due to its limitations of not identifying strategic options.

Final Remarks

Final remarks and perspectives

- Modeling the ‘whole’ scope of the energy system is key to address long-term challenges. For example, understanding the new (or evolving) flexibility of the system is key to support policy incentives and regulation.
- For our example, storage produces interesting cost savings for end-users (around 10-15%, a moderate estimate)
  - Note that peak shaving leads to more efficient units being used for production.
- INMES framework brings research opportunities on valuating this new emerging mix generation group of technologies (whose effectiveness remains somewhat unproven economically and physically.)

Thank you for listening

Contact : pedro@esc.ethz.ch

Papers,

The impact of wind uncertainty on the strategic valuation of distributed electricity storage” 2014, *Computational Management Science*, *to appear.*

The value of electricity storage in domestic homes: A smart grid perspective. 06/2014 in: *Energy Systems*. 5, 2, p. pp 211-232

Synergy of smart grids and hybrid distributed generation on the value of energy storage, submitted, 2015

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