Moving Energy through Time

Storage and Demand Side Response

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Contents

Background

Research track organised by James Cruise and Golbon Zakeri

- 11^{th} to 15^{th} March
- Talks on range of related research topics.
- Working group developed modelling framework for future research direction.

Wide range of participation from programme participates.

Importance of Energy Shifting

Energy shifting can provide a large range of services

- Price smoothing
- Network reinforcement
- Operating reserve
- Fast response
- Voltage support
- . . .

Wide range of technologies

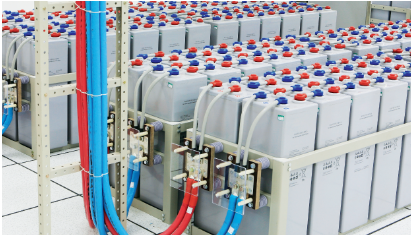
A wide range of technologies can provide energy shifting services

- Wide range of capacities
- Wide range of temporal scales

Examples:

- Pumped hydro,
- Compressed gas,
- Industrial demand response,
- Battery storage,
- Domestic demand response.

Dinorwig: capacity: 9 GWh rate: 1.8 GW efficiency 0.75–0.80



Industrial Demand Response

Golbon Zakeri, Mahbubeh Habibian, Anthony Downward, Miguel F. Anjos, Michael Ferris

Problem: Control of industrial demand response in a Co-optimized Energy and Reserve Market

- Considers the response of large industrial consumers,
  - Aluminium smelters
  - Steal production facilities.
- Consumers large enough to be price maker.
- Co-optimizes consumption bids and interruptible load reserve offers.

- ‘Multistage Stochastic Demand-side Management for Price-Making Major Consumers of Electricity’ (M. Habibian, A. Downward and G. Zakeri),
- ‘Co-optimization of demand response and reserve offers for a major consumer’, (M. Habibian, G. Zakeri, A. Downward, M. Anjos and M. Ferris), Energy Systems, DOI 10.1007/s12667-018-0312-x.

Control of Distributed Dynamic Demand

Ana Bušić, Prabir Barooah, Yue Chen, and Sean Meyn

Problem: Control of aggregated demand response and batteries

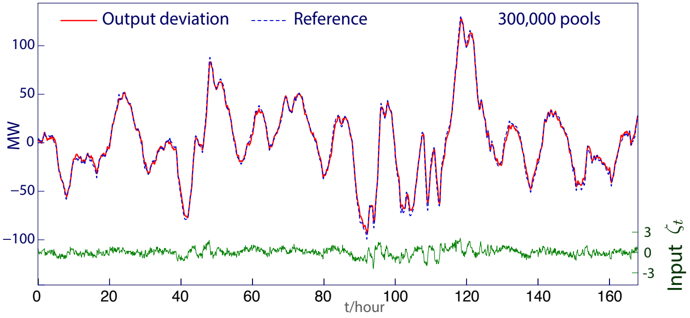
- Aims to develop a virtual energy storage through the control of flexible loads.
- Providing a useful service to the Grid.
  - eg. response and reserve services
- While respecting user QoS.
  - no frogs and algae in pools
  - privacy respected.

Tracking Grid Signal with Residential Loads

Example: 300,000 pools, 300 MW max load

Each pool consumes 1kW when operating
12 hour cleaning cycle each 24 hours

Power Deviation:



Nearly Perfect Service from Pools
Meyn et al. 2013 [CDC], Meyn et al. 2015 [IEEE TAC]

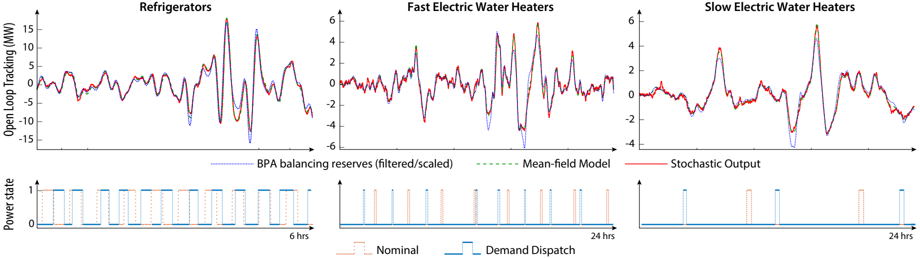
Tracking performance

and the controlled dynamics for an individual load

Heterogeneous setting:

- 40 000 loads per experiment;
- 20 different load types in each case

Lower plots show the on/off state for a typical load



References: this talk

- A. Bušić and S. Meyn. Distributed randomized control for demand dispatch. *55th IEEE Conference on Decision and Control*, 2016.
- A. Bušić and S. Meyn. Ordinary Differential Equation Methods For Markov Decision Processes and Application to Kullback-Leibler Control Cost. arXiv:1605.04591v2. Oct 2016.
- S. Meyn, P. Barooah, A. Bušić, Y. Chen, and J. Ehren. Ancillary Service to the Grid Using Intelligent Deferrable Loads. *IEEE Trans. Automat. Contr.*, 60(11): 2847-2862, 2015.
- P. Barooah, A. Bušić, and S. Meyn. Spectral Decomposition of Demand-Side Flexibility for Reliable Ancillary Services in a Smart Grid. *48th Annual Hawaii International Conference on System Sciences (HICSS)*. 2015.
- A. Bušić and S. Meyn. Passive dynamics in mean field control. *53rd IEEE Conf. on Decision and Control (CDC)* 2014.

Electric Vehicle Charging in Markets

Endre Bjørndal, Mette Bjørndal, Eivind Døvik, Jørgen Fostvedt

Problem: Developing charging tariffs to utilise flexibility from EV fleet

- Increasing number of electric vehicles connected to the grid.
- Could provide flexibility services to the grid.
- Empirical study using charging data.
- Understand the business model to realise the flexibility.

tibber

NHH

Energimarked 2.0

BKK

- Tibber customers offer flexibility
- Flexible devices are controlled by Tibber
  - EVs and domestic appliances
- Potential value of flexibility
  - Price-optimization (day-ahead market)
  - Fast frequency reserves (TSO)
  - Local grid (DSO)
- What is a good business model in order to activate flexibility and realize value for all participants?

Lagrangian Approach to Storage Control (Arbitrage)

James Cruise and Stan Zachary

Problem: How to control energy storage to maximise profit?

- Energy shifting participating in markets.
- Help to equalise prices and hence net demand.
- Often contracted for other purposes as well.
- For example, providing capacity or link reinforcement.

How should the operator control the store in these circumstances?

- Control of Energy Storage with Market Impact: Lagrangian Approach and Horizons, (Cruise, R. J. R., Flatley, L., Gibbens, R. J. & Zachary, S), OR https://doi.org/10.1287/opre.2018.1761
- Impact of storage competition on energy markets (James R. Cruise, Lisa Flatley, Stanley Zachary), EJOR https://doi.org/10.1016/j.ejor.2018.02.036
- The Optimal Control of Storage for Arbitrage and Buffering, with Energy Applications (James Cruise, Stan Zachary), FRM 2017: Renewable Energy: Forecasting and Risk Management pp 209-227

Deterministic Problem

Define the following (deterministic) optimisation problem:
P:Choose $s = (s_0, \ldots, s_T)$ with $s_0 = s_0^*$ so as to minimise

$$\sum_{t=1}^{T} [C_t(x_t(s)) + A_t(s_t)]$$

subject to the capacity constraints

$$0 \leq s_t \leq E_t, \quad 1 \leq t \leq T,$$

and the rate constraints

$$x_t(s) \in X_t, \qquad 1 \leq t \leq T.$$

Lagrangian Theory

Theorem

Let s^* denote the solution to the problem P. Then there exists a vector $\lambda^* = (\lambda_1^*, \ldots, \lambda_T^*)$ such that

1. *for all vectors s such that $s_0 = s_0^*$ and $x_t(s) \in X_t$ for all t (s is not otherwise constrained),*

$$\sum_{t=1}^{T} [C_t(x_t(s)) + A_t(s_t) - \lambda_t^* s_t] \geq \sum_{t=1}^{T} [C_t(x_t(s^*)) + A_t(s_t^*) - \lambda_t^* s_t^*] . \quad (1)$$

Lagrangian Theory

Theorem

2. *the pair* (s^*, λ^*) *satisfies the complementary slackness conditions, for* $1 \leq t \leq T$,

$$\begin{cases} \lambda_t^* = 0 & \text{if } 0 < s_t^* < E_t, \\ \lambda_t^* \geq 0 & \text{if } s_t^* = 0, \\ \lambda_t^* \leq 0 & \text{if } s_t^* = E_t. \end{cases} \tag{2}$$

Conversely, suppose that there exists a pair of vectors (s^*, λ^*), *with* $s_0 = s_0^*$, *satisfying the conditions* (1) *and* (2) *and such that* s^* *is additionally feasible for the problem* P. *Then* s^* *solves the problem* P.

Finding (s^*, λ^*)

Proposition

Suppose that the functions A_t are differentiable, and that the pair (s^*, λ^*) is such that s^* is feasible for the problem P, while (s^*, λ^*) satisfies the conditions of previous Theorem. For each t define

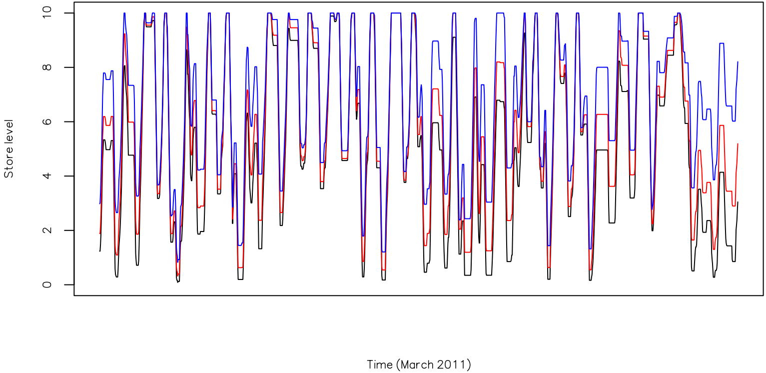
$$\nu_t^* = \sum_{u=t}^{T} [\lambda_u^* - A_u'(s_u^*)]. \tag{3}$$

Then the condition that (s^*, λ^*) satisfies the condition (1) of previous Theorem is equivalent to the condition that

$$x_t(s^*) \text{ minimises } C_t(x) - \nu_t^* x \text{ in } x \in X_t, \qquad 1 \le t \le T. \tag{4}$$

UK Market Example

$E/P = 5$ hrs $\qquad$ *Efficiency* $= 0.85$ (ratio of sell to buy price).
$A_t(S) = \nu/S$ (Black:$\nu = 0.02$,Red:$\nu = 0.2$, Blue: $\nu = 1$)



Storage and Adequacy

James Cruise and Stan Zachary

Problem: Using energy shifting to meet an energy shortfall.

Setup:

1. a nonnegative *demand process* $(d(t),\ t \in [0, T])$
2. a set S of *stores*,

Each store $i \in S$:

- serve energy at any rate $r_i(t)$ for each time $t \in [0, T]$
- rate (power) constraint P_i

$$0 \le r_i(t) \le P_i, \qquad t \in [0, T],$$

- capacity (energy) constraint E_i

$$\int_0^T r_i(t)\, dt \le E_i.$$

Expected Energy Unserved

Problem of optimally scheduling the use of the stores:

P: choose a policy $(r_{\S}(t),\, t \in [0, T])$ to *minimise*

$$E \int_0^T \left(d(t) - \sum_{i \in S} r_i(t) \right)^+ dt,$$

subject to

$$0 \le r_i(t) \le P_i, \qquad t \in [0, T],$$

$$\int_0^T r_i(t)\, dt \le E_i.$$

'Optimal scheduling of energy storage resources' J.Cruise and S. Zachary (https://arxiv.org/abs/1808.05901)

Also see work by M. Evans, D. Angeli, and S. H. Tindemans

Optimal Greedy Policy

Algorithm:

- For each store calculate E/P ratio (time to empty).
- Order stores by this ratio.
- Allocate capacity in greedy fashion using this order.
- Proportionally allocate those with equal E/P to maintain equality.

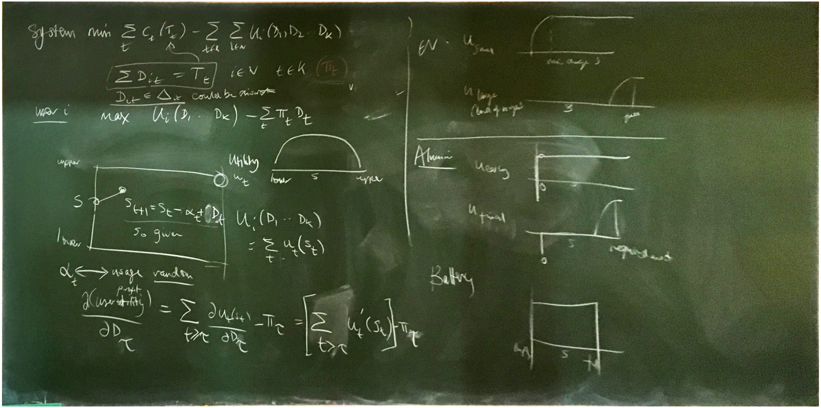
Notes:

- Looks to equalize E/P ratio across stores.
- Note this is a myopic policy, has no care about the future.
- Optimal for both deterministic and random demand profiles.

Further Results

Other results include:

- Classifying demand profiles which can be satisfied
- Determining marginal effective firm capacity in the presence stores.
- Differences when considering weighted EEU.


system $\min \sum_t C_t(T_t) - \sum_{t \in K} \sum_{i \in N} U_i(D_1, D_2 \ldots D_K)$
$\boxed{\sum D_{it} = T_t}$ $i \in V$ $t \in K$ π_t
$D_{it} \in \Delta_{it}$ could be discrete
user i
$\max\ U_i(D_1 \ldots D_K) - \sum_t \pi_t D_t$
upper
lower
S
$S_{t+1} = S_t - \alpha_t + D_t$
S_0 given
Utility
u_t
lower
S
upper
$U_i(D_1 \ldots D_K) = \sum_t u_t(S_t)$
$\alpha_t \longleftrightarrow$ usage random
$\frac{\partial(\text{user profit})}{\partial D_\tau} = \sum_{t \geq \tau} \frac{\partial u_t(S_t)}{\partial D_\tau} - \pi_\tau = \left[\sum_{t \geq \tau} u_t'(S_t)\right] - \pi_\tau$
EV
u_{same}
u_{large}
S
Alumni
u_{early}
0
u_{final}
0
S
Battery
S

Framework for storage and demand response

Model that is tool for thinking about a range of problems in which energy is moved through time.

Setup:

- Large population of users
- Single system operator
- Fixed time horizon T
- Each user has a utility function:

$$U_i(d_{i1}, d_{i2}, ...d_{iT})$$

  where d_{ij} is demand by user i in time period j.

- Consider system operator and individual problem

Utility function

Focus on two types of utility function:

1. Simple utility function with decoupling across time:

$$U_i(d_{i1}, d_{i2}, ...d_{iT}) = \sum_{t=1}^{T} u_{it}(d_{it}).$$

2. Utility depends on demand through a stock

$$s_{i,t+1} = s_{it} - \alpha_{it} + \beta_{it} d_{it},$$

then the utility function is

$$U_i(d_{i1}, d_{i2}, ...d_{iT}) = \sum_{t=1}^{T} u_{it}(s_{it}).$$

Here α_{it} is the depletion through exogenous factors at time t, and β_{it} corresponds to the efficiency. Examples include a factory carrying out demand response, a battery store, household thermal storage.

System Problem

Choosing X_t (total generation) and d_{it}, $i \in N$, $t = 1, 2, ..., T$, to

$$\begin{array}{ll} \text{maximize} & \sum_i U_i(d_{i1}, d_{i2}, ...d_{iT}) - \sum_t C_t(X_t) \\ \text{subject to} & \sum_i d_{it} = X_t + W_t,\ t = 1, 2, ..., T \\ & d_{it} \in D_{it},\ i \in N,\ t = 1, 2, ..., T \end{array}$$

- C_t is the generation cost function at time t,
- W_t is the zero cost renewable generation at time t,
- D_{it} is demand restriction for users.

User Problem

Choosing d_{it}, $i \in N$, $t = 1, 2, ..., T$, to

$$\max_{d_{it} \in D_{it}} \{U_i(d_{i1}, d_{i2}, ...d_{iT}) - \sum_t \pi_t d_{it}\}$$

where π_t is the electricity price (this should be the shadow price from the system problem).

Directions to explore

- Exploring the value of heterogeneity in users.
- Small N to large N limit
- Incorporating a distribution network

Future directions of research

- How do we extend the work to consider multiple energy shifting resources?
  - Collaborative?
  - Competitively?
- Understanding the role of the network, where should such facilities be located?
- How do we better understand energy sources providing multiple services concurrently?