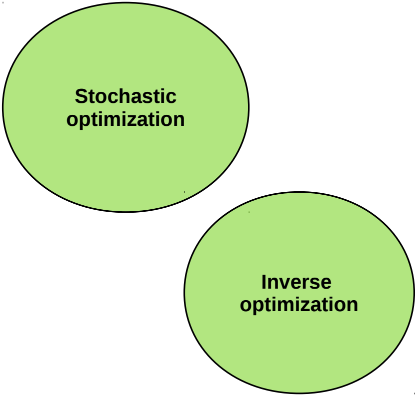
Inverse Optimization and Forecasting Techniques Applied to Decision-making in Electricity Markets

Javier Saez-Gallego

November 22$^{\mathrm{nd}}$, 2016

Papers inclued in the thesis



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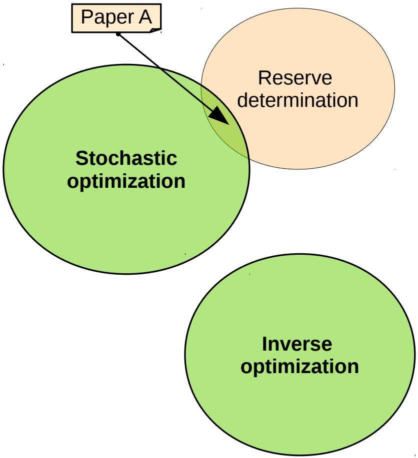

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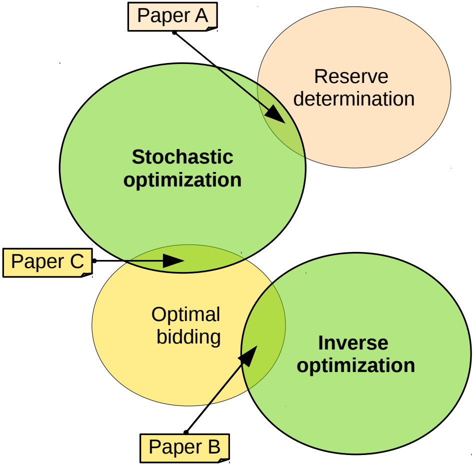

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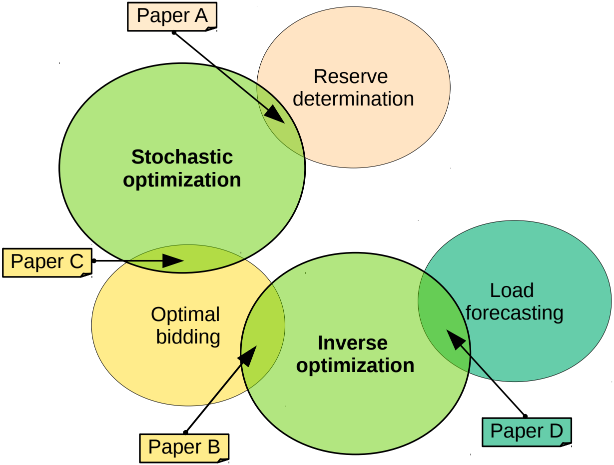

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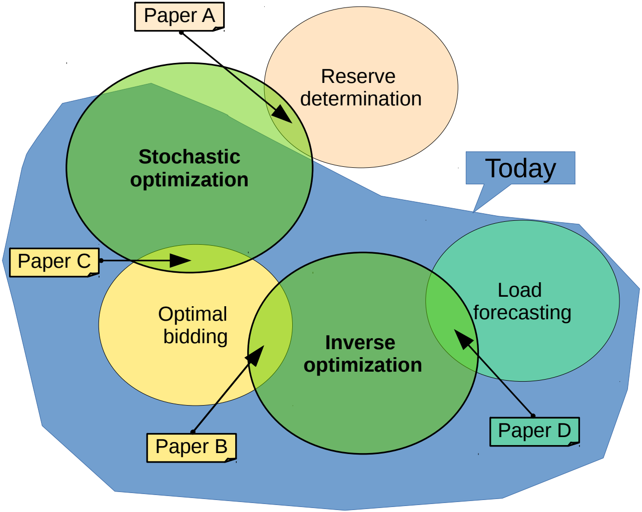
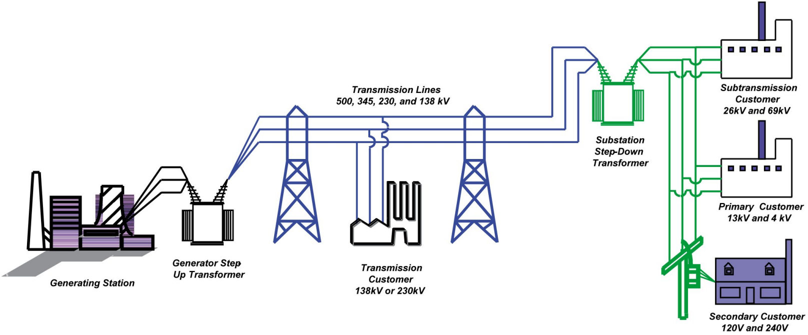


Challenges in the electricity supply service



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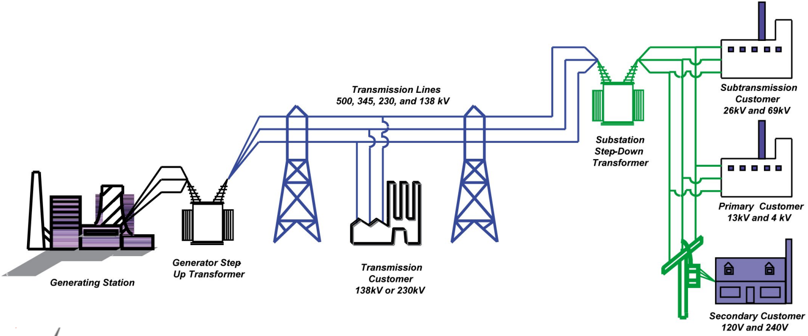
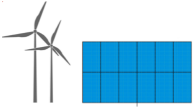
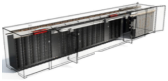




Renewables

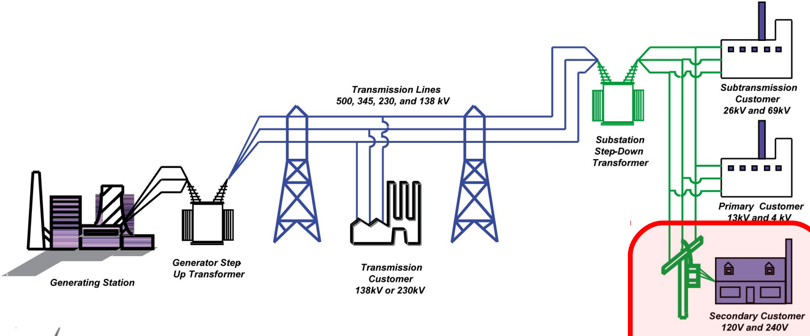


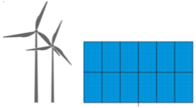
Energy storage

Electric vehicles

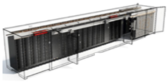
Demand response

Challenges in the electricity supply service





Renewables



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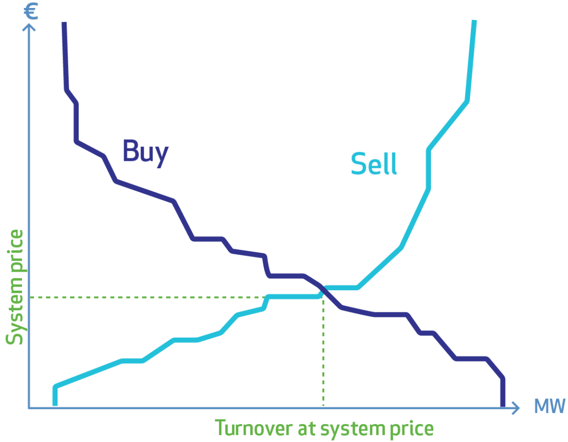
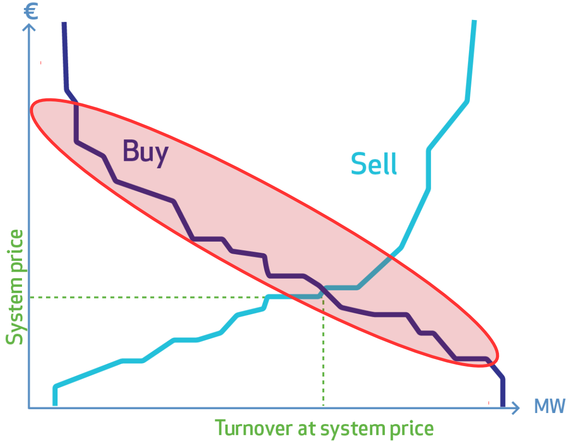
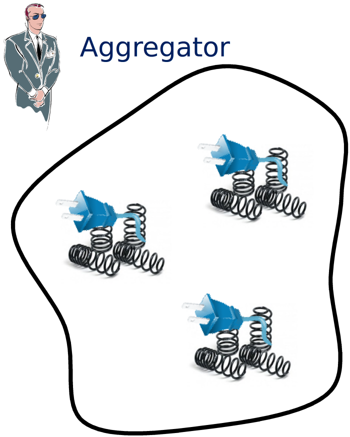


Challenges in the electricity supply service



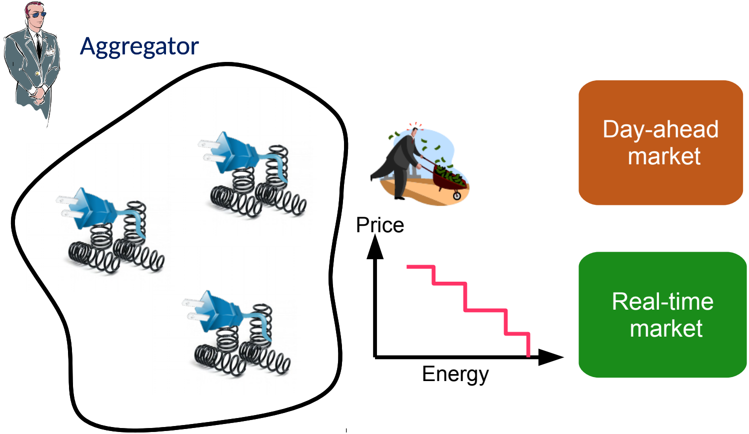
Optimal bidding

Optimal bidding

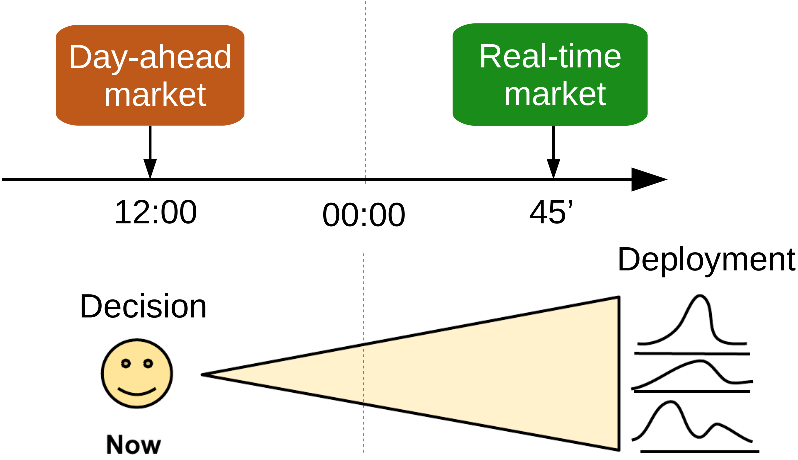


- Price-responsive units (households)
- Too small to participate in the
  Wholesale electricity market

Optimal bidding



Optimal bidding



The data

- Data of price-responsive households from Olympic Peninsula project from May 2006 to March 2007.
- The price was sent out every 15 minutes to 27 household
- Decisions made by the home-automation system based on occupancy modes and on price

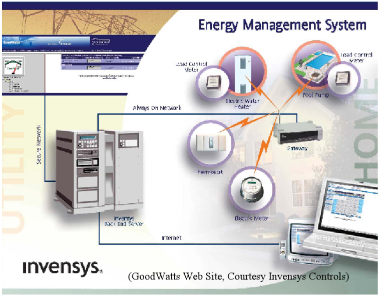
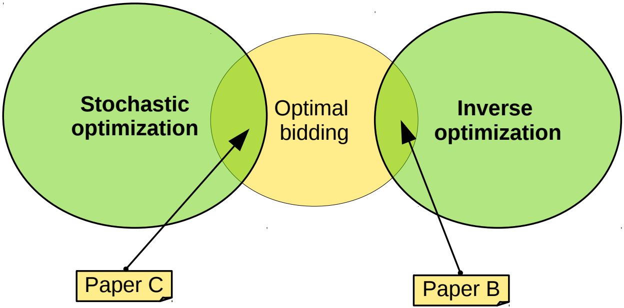


Figure 3.2. Invensys GoodWatts™ System Components

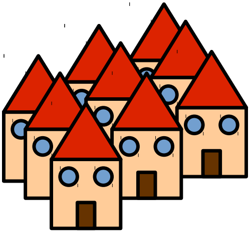
Two approaches



J. Saez-Gallego, M. Kohansal, A. Sadeghi-Mobarakeh and J. M. Morales
“**Optimal Price-energy Demand Bids for Aggregate Price-responsive Loads**”
Submitted to *IEEE Transactions on Smart Grid*, 2016

J. Saez-Gallego, J. M. Morales, M. Zugno, and H. Henrik,
“**A data-driven bidding model for a cluster of price-responsive consumers of electricity**”
In: *IEEE Transactions on Power Systems*, February, 2016

Paper C. Optimal Price-energy Demand Bids for Aggregate Price-responsive Loads



The setup

A cluster of price-responsive units under variable price of electricity

The goal

Obtain optimal bid in the day-ahead market that maximizes the profit of the retailer

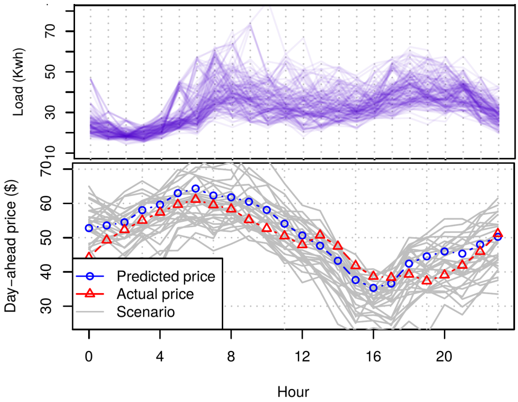
Paper C. Optimal Price-energy Demand Bids for Aggregate Price-responsive Loads

$$\underset{X_t^D, u_{t,b}}{\text{Maximize}} \ \mathbb{E}\left\{ \sum_{t=1}^{24} \left(\Pi_t X_t - \Lambda_t^D X_t^D - \Lambda_t^R (X_t - X_t^D) \right) \right\}$$

Total profit = revenue from selling - purchase cost in the day ahead - purchase cost/selling profit in the real-time

- **No risk considered**: analytic solution given
- **Risk constraints**: limit the probability of purchasing certain fraction of the load in the real-time market.

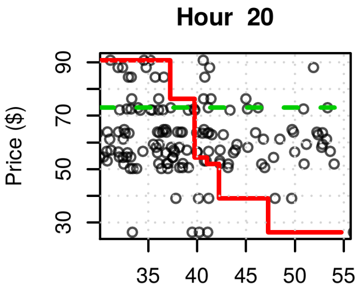
Paper C. Optimal Price-energy Demand Bids for Aggregate Price-responsive Loads



The solution

- Dynamic price-responsive behavior of consumers is modeled based on scenarios
- Scenarios based on non-parametric models

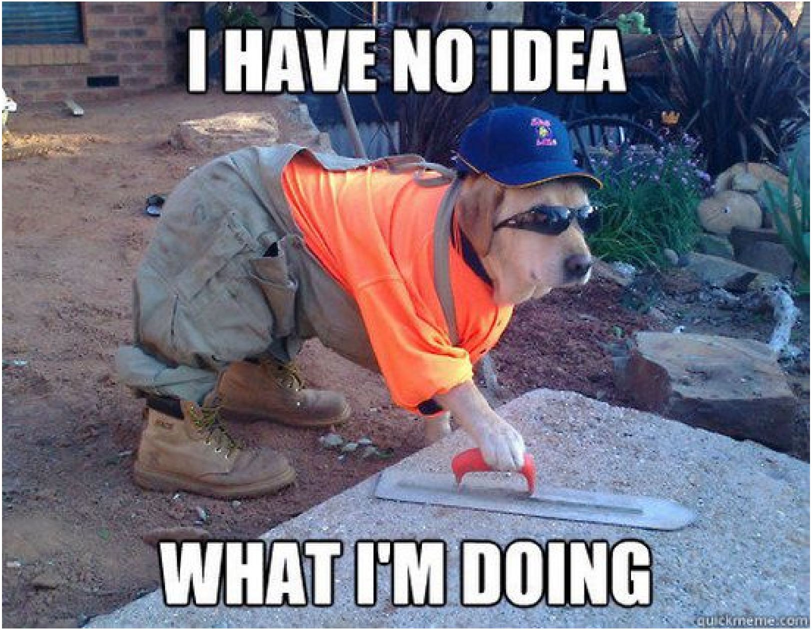
Paper C. Optimal Price-energy Demand Bids for Aggregate Price-responsive Loads



Results

- Risk-unconstrained bidding results in flat curve with highest expected profits
- Risk-averse bids are more steep with lower expected profits and lower variance too

Inverse optimization


I HAVE NO IDEA
WHAT I'M DOING
quickmeme.com

I HAVE NO IDEA

WHAT I'M DOING

Basics of inverse optimization

Traditional constrained optimization problems find the decision variable x that maximize (or minimize) a function

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What is the solution?

$$\underset{x,y}{\text{Maximize}} \;\; 3x + y$$

Subject to

$$x + y \leq 7$$
$$0 \leq x \leq 5$$
$$0 \leq y$$

Basics of inverse optimization

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What is the solution?

$$\begin{aligned} &\underset{x,y}{\text{Maximize}} \ \ 3x + y \\ &\text{Subject to} \\ &\qquad x + y \leq 7 \\ &\qquad 0 \leq x \leq 5 \\ &\qquad 0 \leq y \end{aligned}$$

The solution is $x^* = 5$, $y^* = 2$

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Basics of inverse optimization

Inverse optimization

What are the values of a and b such that $x^* = 5$ and $y^* = 2$?

$$\begin{aligned} &\underset{a,b}{\text{Maximize}} \quad a x^* + y^* \\ &\text{Subject to} \\ &\qquad x^* + y^* \leq b \\ &\qquad 0 \leq x^* \leq 5 \\ &\qquad 0 \leq y^* \end{aligned}$$

Basics of inverse optimization

Inverse optimization

What are the values of a and b such that $x^* = 5$ and $y^* = 2$?

$$\underset{a,b}{\text{Maximize}} \quad a x^* + y^*$$

$$\text{Subject to}$$

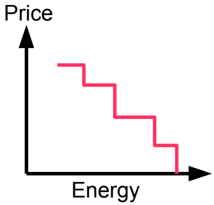
$$x^* + y^* \leq b$$

$$0 \leq x^* \leq 5$$

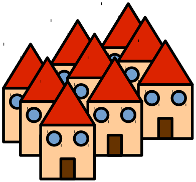
$$0 \leq y^*$$

The solution is $a > 1$ and $b = 7$.

Optimal bidding



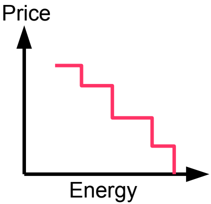
The bid represents the behavior of the aggregated pool in the market.



Parameters θ of the bid:

- Marginal utility ($a_{b,t}$)
- Maximum and minimum power consumption ($\overline{P}_t$,$\underline{P}_t$)
- Pick-up and drop-off limits (r_t^u,r_t^d) (equivalent to ramp limits)

The Bid

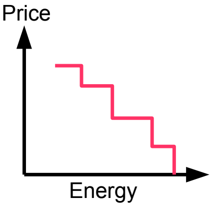


Unit-like problem

$\underset{x}{\text{Maximize}}$ (Total utility – cost energy)

Pick-up limit (r^u)
Drop-off limit (r^d)
Power bounds ($\underline{P}$,$\overline{P}$)

The Bid



Unit-like problem

Maximize (Total utility
x – cost energy)

Pick-up limit (r^u)
Drop-off limit (r^d)
Power bounds ($\underline{P}$,$\overline{P}$)

- The energy assigned to each block is x_{bt}
- And the total estimated load as $x_t^{tot} = \underline{P}_t + \sum_{b \in \mathcal{B}} x_{b,t}$

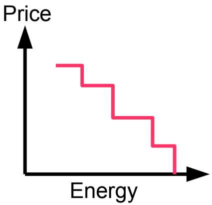
$$\operatorname*{Max}_{x_{b,t}} \sum_{t \in \mathcal{T}} \left(\sum_{b \in \mathcal{B}} a_{b,t} x_{b,t} - \text{price}_t \sum_{b \in \mathcal{B}} x_{b,t} \right)$$

Subject to

$$-r_t^d \leq x_t^{tot} - x_{t-1}^{tot} \leq r_t^u$$

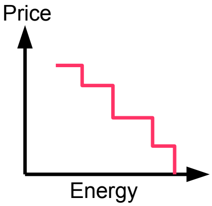
$$0 \leq x_{b,t} \leq \frac{\overline{P}_t - \underline{P}_t}{B}$$

The Estimation Process



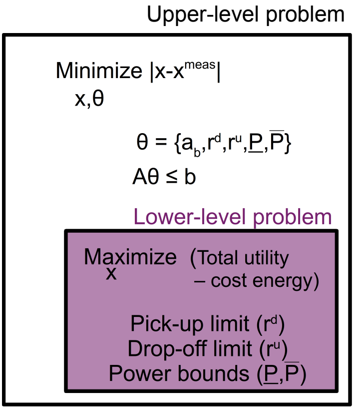
Time	Price	Load	External Info.
t_1	$price_1$	x_1^{meas}	z_1
t_2	$price_2$	x_2^{meas}	z_2
...	...	...	...

The Estimation Process



Time	Price	Load	External Info.
t_1	$price_1$	x_1^{meas}	z_1
t_2	$price_2$	x_2^{meas}	z_2
...	...	...	...

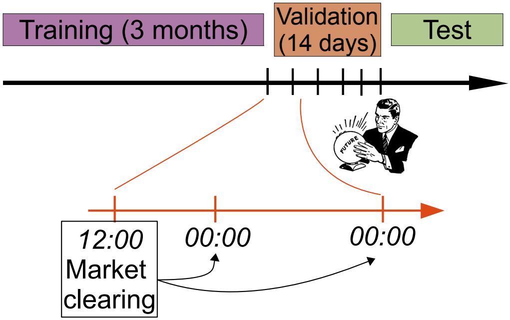
Estimation problem: inverse optimization and bilevel programming



Results

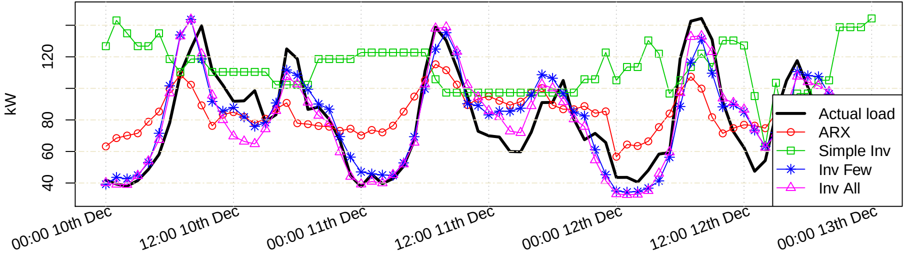
Cross-validation: In a rolling-horizon manner

1. Compute optimal bid
2. Input the price
3. Error: estimated load vs actual load.

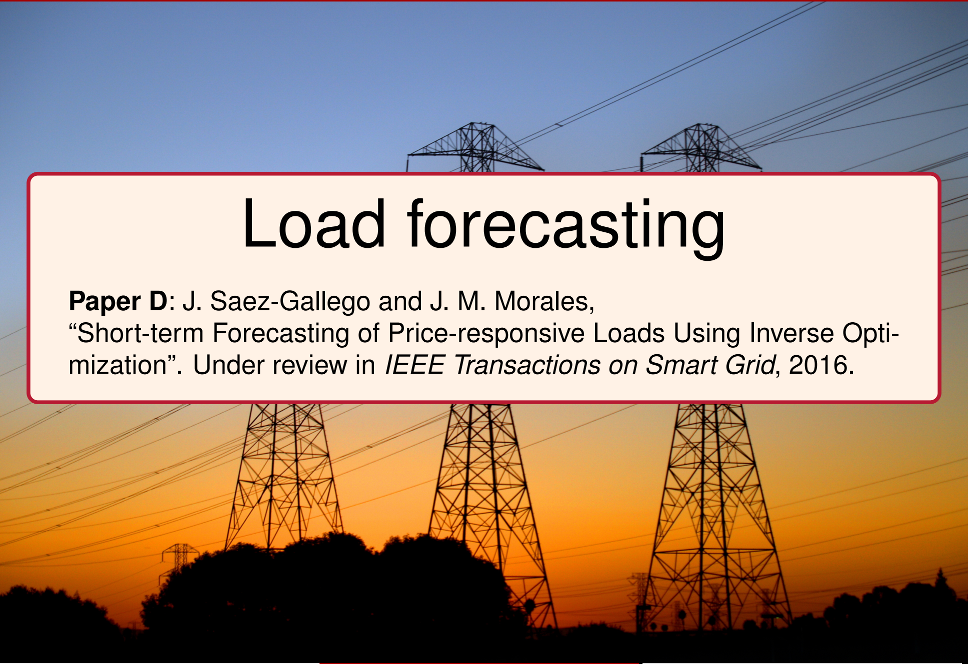


Results

Prediction capabilities of different benchmarked methods



	MAPE
ARX	0.2752
Inv Few	0.1846
Inv All	0.1987



Load forecasting

Paper D: J. Saez-Gallego and J. M. Morales,
"Short-term Forecasting of Price-responsive Loads Using Inverse Optimization". Under review in *IEEE Transactions on Smart Grid*, 2016.

Energy demand forecasting as solution

- Plan grid expansion
- Mitigating grid congestions
- Minimizing cost of over or under contracting
- Facilitating adoption of demand response

Energy demand forecasting as solution

- A cluster of price-responsive buildings is considered
- Economic Model Predictive Control (EMPC)

Forecasting the demand

Model the hourly demand using a linear problem

Unknown variables:

- the **marginal utility** $u_{b,t}$
- the **bounds of the power** $\bar{P}_t, \underline{P}_t$

Available historical information:

- measured load $x_{b,t}$
- electricity price $price_t$
- external variables

Forecasting the demand

Model the hourly demand using a linear problem

Unknown variables:

- the **marginal utility** $u_{b,t}$
- the **bounds of the power** $\bar{P}_t, \underline{P}_t$

Available historical information:

- measured load $x_{b,t}$
- electricity price $price_t$
- external variables

$$\begin{aligned} \underset{x_t}{\text{maximize}} \quad & \sum_{b=1}^{B} x_{b,t}(u_{b,t} - price_t) \\ \text{subject to} \quad & \underline{P}_t \leq \sum_{b=1}^{B} x_{b,t} \leq \bar{P}_t \\ & 0 \leq x_{b,t} \leq E_{b,t} \end{aligned}$$

Forecasting the demand

Challenges

- Non-linear nature of the original problem
- Issues with feasibility and optimality
- Unable to solve for small-to-medium sized datasets

ρ, x', A

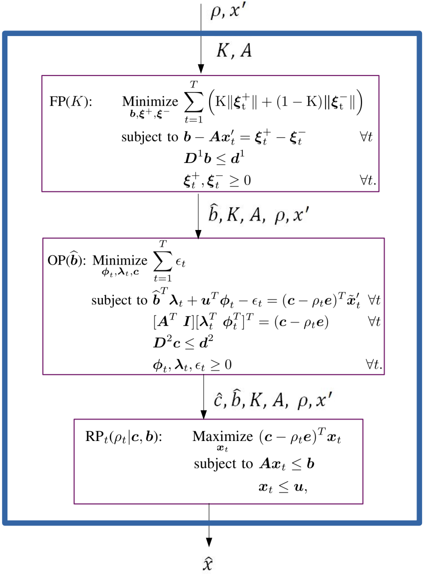
$$
\begin{aligned}
\text{GIOP:}\quad & \underset{\boldsymbol{b},\boldsymbol{\phi}_t,\boldsymbol{\lambda}_t,\boldsymbol{c}}{\text{Minimize}} \sum_{t=1}^{T} \epsilon_t \\
\text{subject to}\quad & \boldsymbol{b}^T\boldsymbol{\lambda}_t + \boldsymbol{u}^T\boldsymbol{\phi}_t - \epsilon_t = (\boldsymbol{c} - \rho_t\boldsymbol{e})^T\boldsymbol{x}'_t \quad \forall t \\
& [\boldsymbol{A}^T\ \boldsymbol{I}][\boldsymbol{\lambda}_t^T\ \boldsymbol{\phi}_t^T]^T = (\boldsymbol{c} - \rho_t\boldsymbol{e}) \quad \forall t \\
& \boldsymbol{A}\boldsymbol{x}'_t \leq \boldsymbol{b} \quad \forall t \\
& \boldsymbol{\phi}_t, \boldsymbol{\lambda}_t, \epsilon_t \geq 0 \quad \forall t
\end{aligned}
$$

$\hat{x}$

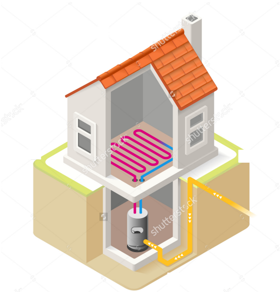
Forecasting the demand

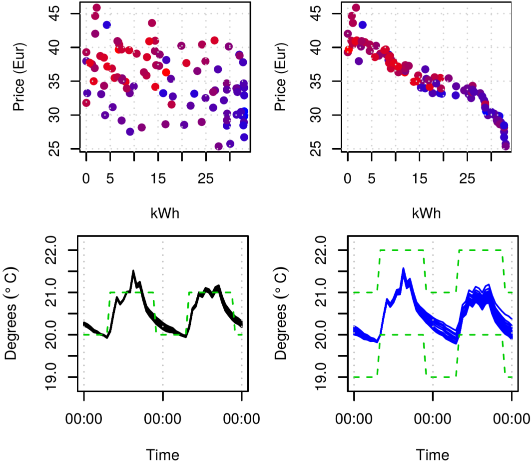
Solution

- Iterative estimation process: single linear problems
- Fast to solve (10 seconds)
- Attractive statistical properties: suited for out-of-sample estimation



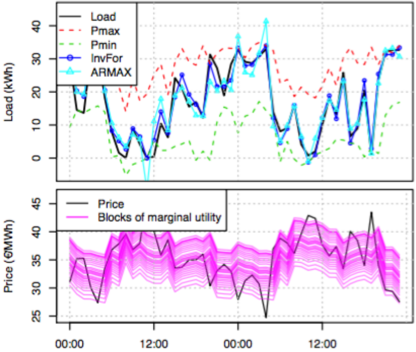
Case study





100 buildings equipped with **heat pumps**

Case study



BENCHMARK FOR THE TEST SET

	No Flex NRMSE	No Flex SMAPE	Flex NRMSE	Flex SMAPE
Persistence	0.1727	0.1509	0.3107	-
ARMAX	0.10086	0.08752	0.13107	0.08426
InvFor	0.10093	0.0886	0.08903	0.07003

Summary of contributions

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- Inverse optimization
  1. Formulation of generalized inverse optimization models
  2. Practical solution methods
  3. Application to optimal bidding and time series forecasting
  4. Use historical data and external variables

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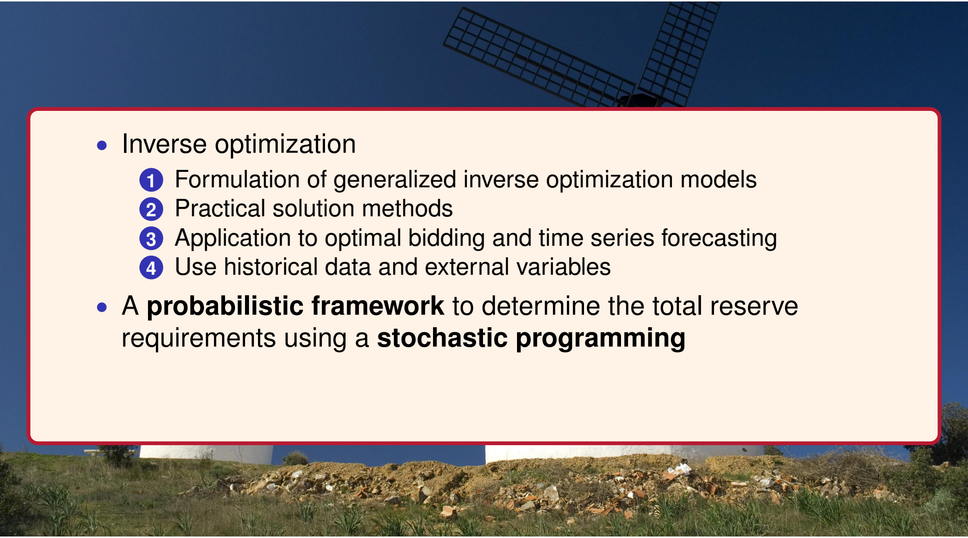

- Inverse optimization
  1. Formulation of generalized inverse optimization models
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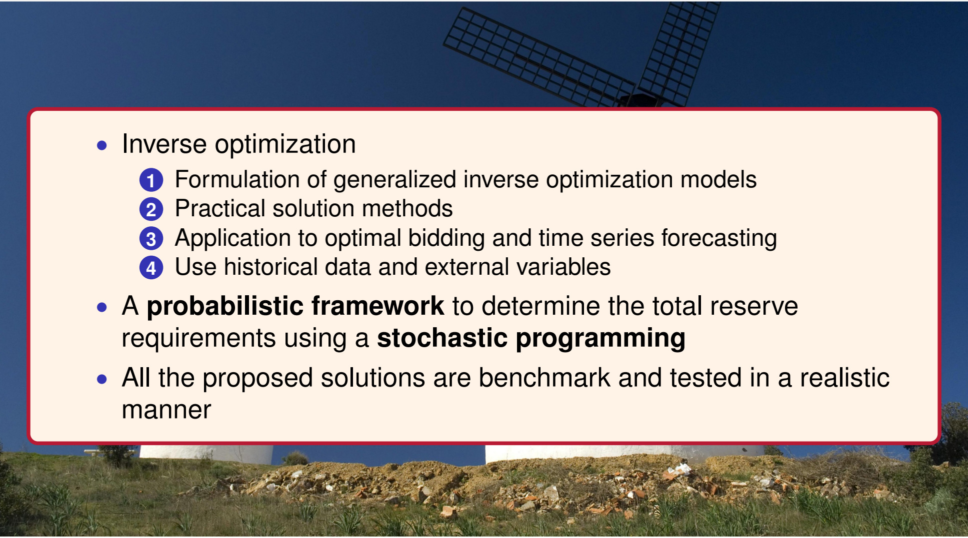
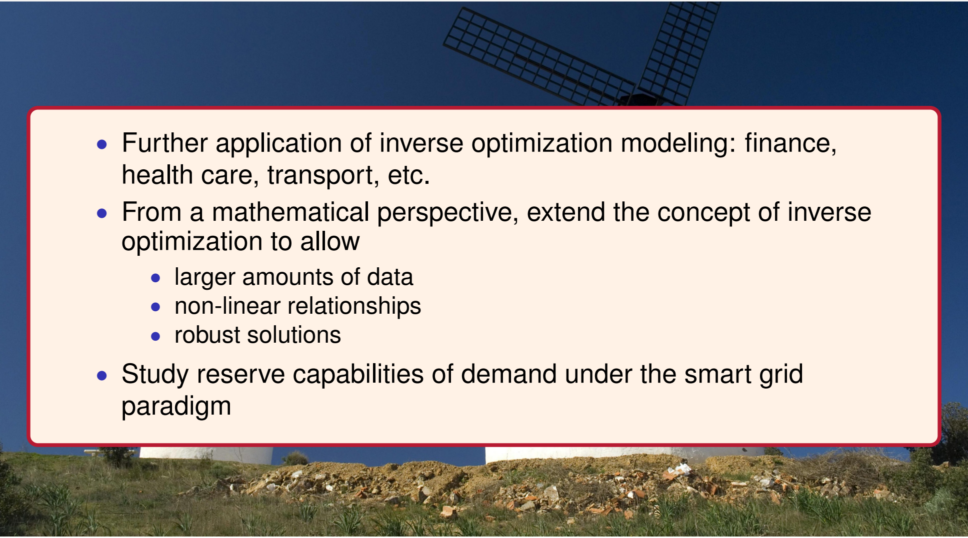
- A **probabilistic framework** to determine the total reserve requirements using a **stochastic programming**

Summary of contributions



- Inverse optimization
  1. Formulation of generalized inverse optimization models
  2. Practical solution methods
  3. Application to optimal bidding and time series forecasting
  4. Use historical data and external variables
- A **probabilistic framework** to determine the total reserve requirements using a **stochastic programming**
- All the proposed solutions are benchmark and tested in a realistic manner

Future perspectives



- Further application of inverse optimization modeling: finance, health care, transport, etc.
- From a mathematical perspective, extend the concept of inverse optimization to allow
  - larger amounts of data
  - non-linear relationships
  - robust solutions
- Study reserve capabilities of demand under the smart grid paradigm

Thank you for listening