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Economic Dispatch of a Single Micro Gas Turbine Under CHP Operation with Uncertain Demands

DEPARTMENT OF AEROSPACE ENGINEERING

CONNECT LAB
Cooperative Networks and Controls

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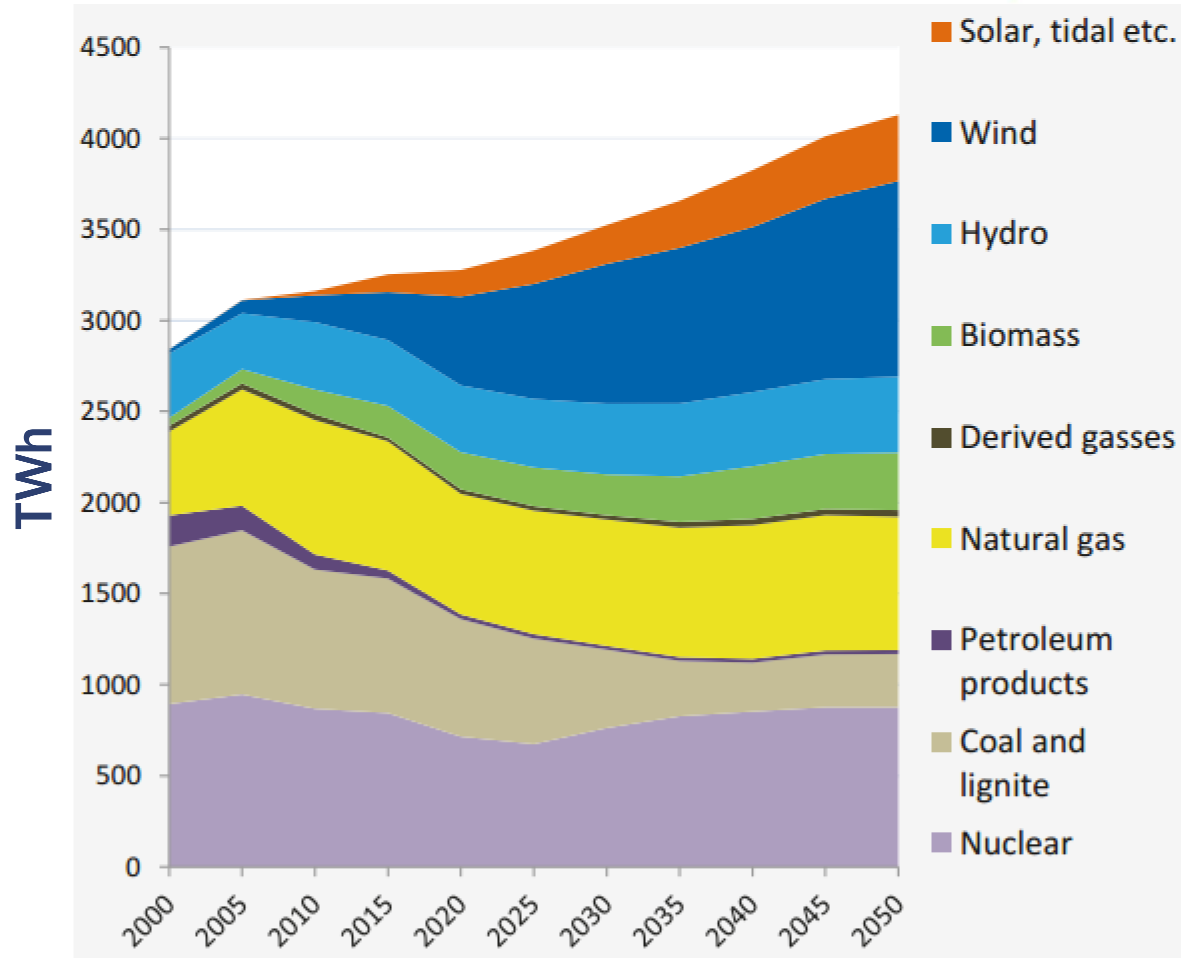
Technion

19th ISRAELI SYMPOSIUM ON JET ENGINES & GAS TURBINES 17.11.2022

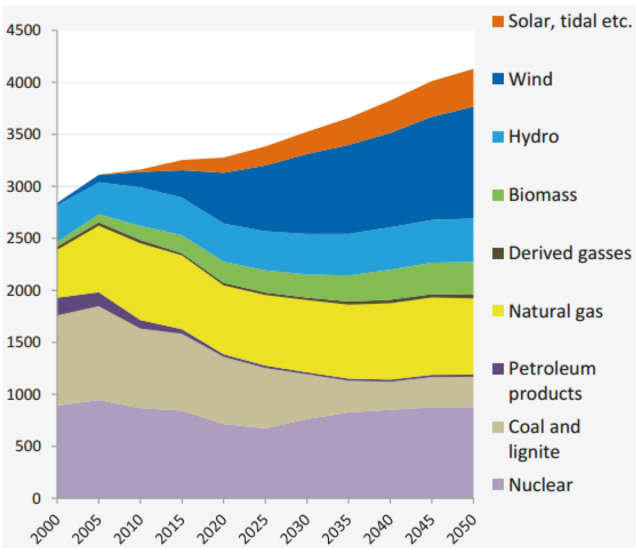
The Future Energy Landscape



EU electricity generation trends

(taken from "*EU Energy, Transmission, and GHG Emissions: Trends to 2050 – Reference Scenario 2013*")

The Future Energy Landscape



Increasing integration
Into the grid!

...intermittent and not
on demand!

The Future Energy Landscape

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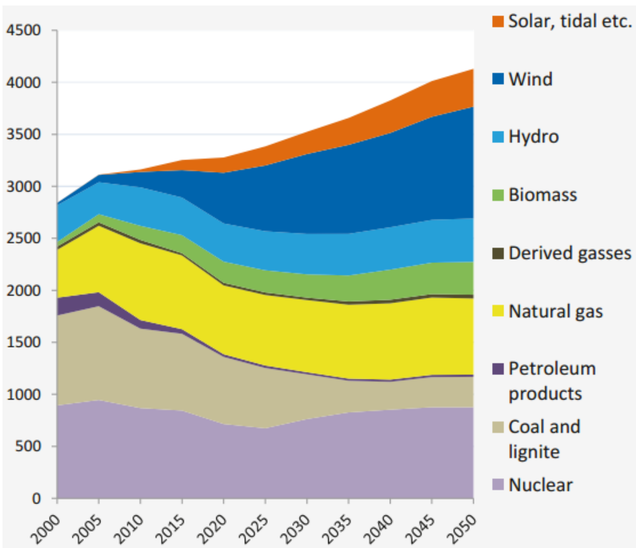
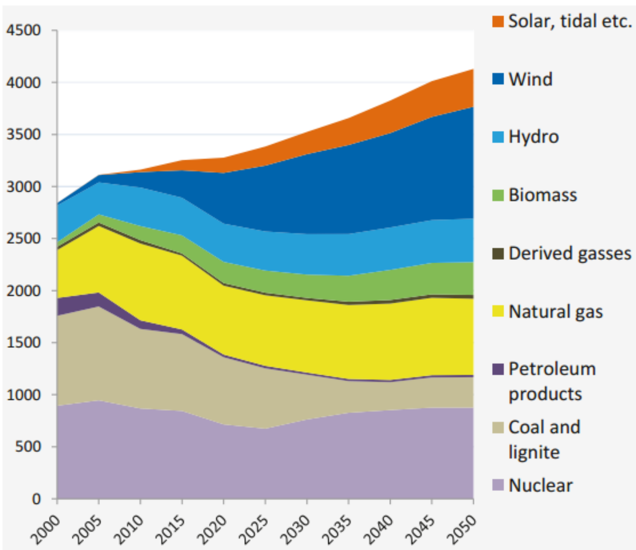


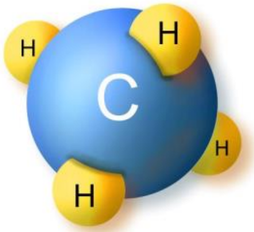
environmental concerns

finite resource

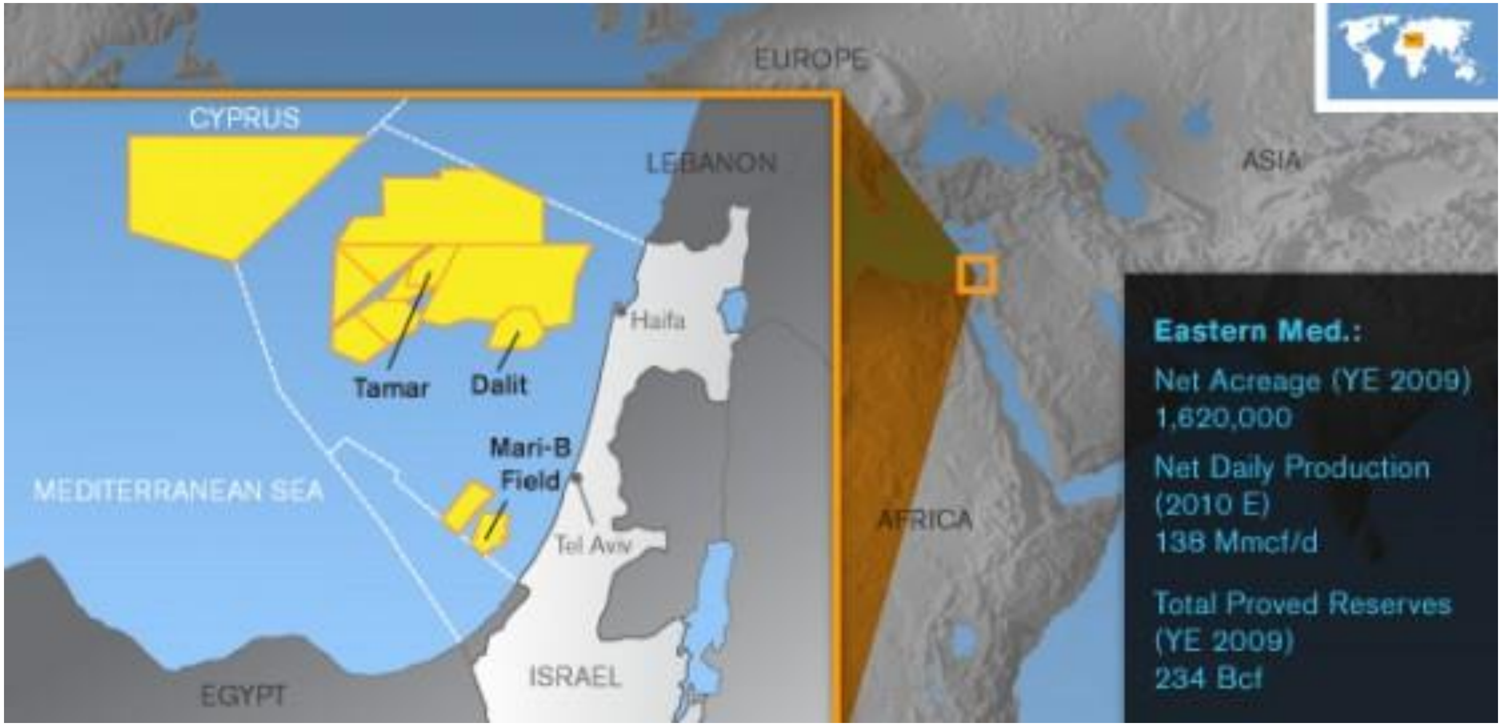
The Future Energy Landscape



Natural Gas is clean, cheap, and safe!



Energy Independence in Israel



source: https://www.greenprophet.com/2012/02/israel-lebanon-natural-gas-discovery/

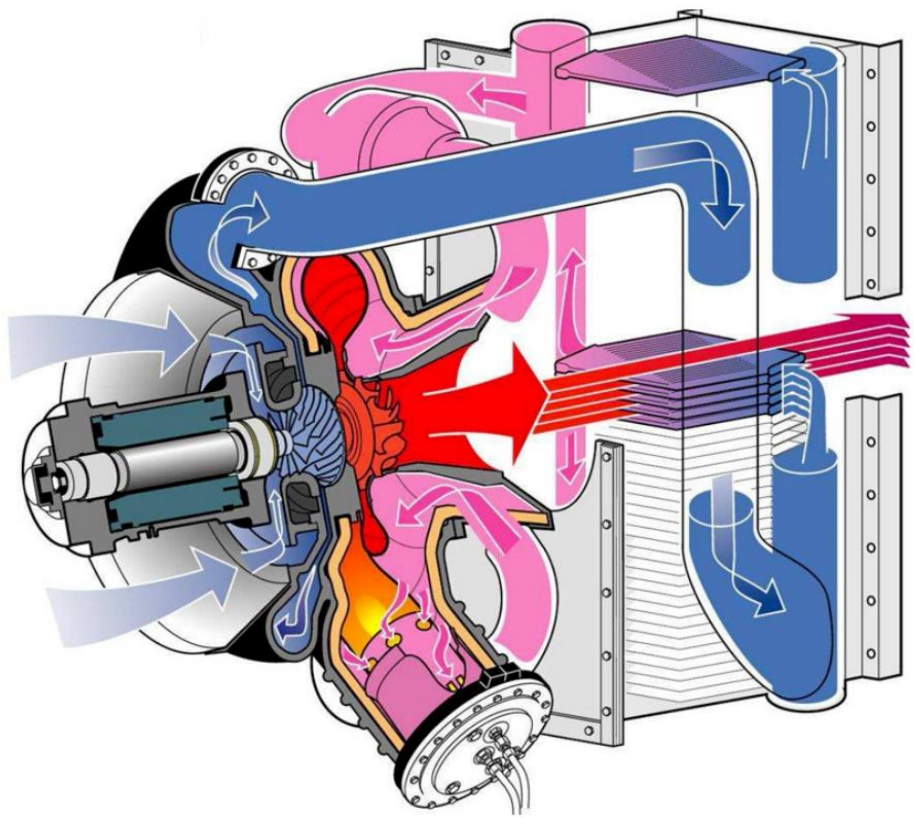
Leviathan - 22 trillion cubic feet
Tamar – 10.8 trillion cubic feet
Tanin - 3 trillion cubic feet

Natural Gas could transform Israel's energy market!

Natural Gas and the Smart Grid

Natural gas is the *ideal* near-term solution to bridge the gap between traditional energy generation and renewables

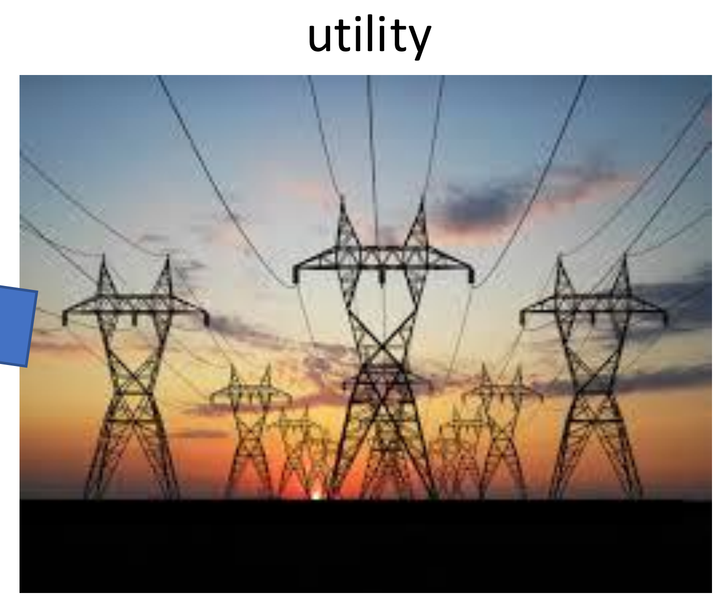
Micro-Gas Turbines for CHP



- runs on natural gas
- high power-to-weight ratio
- small terrain footprint
- reliable (few moving parts)
- quiet
- **agile and flexible** – on-demand!

Electricity and Heating/Cooling Generation

MGT Integration into the Grid



Meet the consumer power demand in an economically optimal way

The Economic Dispatch Problem

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Economic Dispatch is a short-term scheduling for the output of a number of electricity generation facilities required to **meet system demand** at the **lowest cost** subject to **operational constraints**

$$\begin{aligned} \min \quad & J(P,H) \\ s.t. \quad & P = D_P \\ & H = D_H \\ & \text{operational constraints} \end{aligned}$$

$$

Power Balance

D_P **Electricity Demand**

D_H **Heat Demand**

The Economic Dispatch Problem

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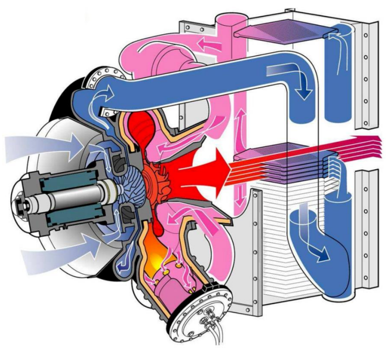


What is the cost of operating an MGT?

- relation of fuel consumption to heat and power output
- start-up and shut-down costs
- time constants for power delivery

Electricity and Heat Tariffs

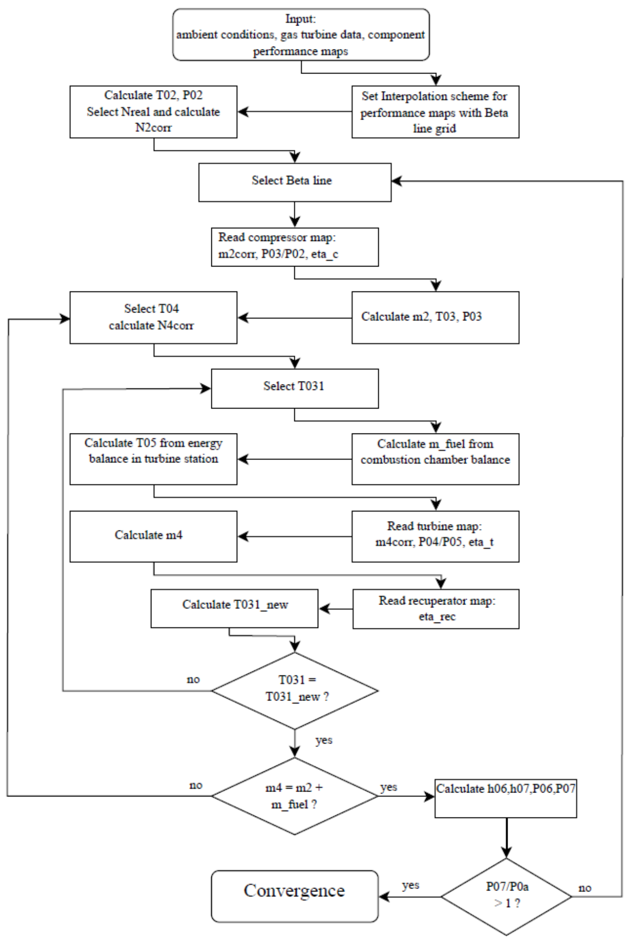
- how much does electricity cost
- electricity market for buying and selling power

Consumer Needs

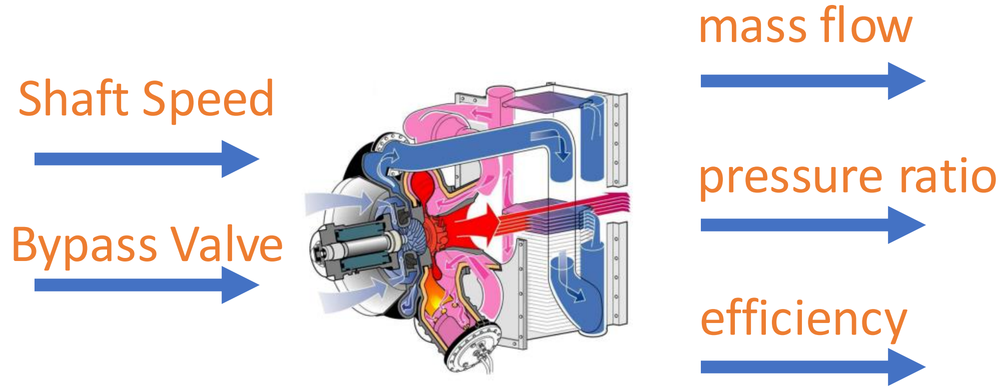
- what are the power and heat demand profiles for consumers

MGT Modeling

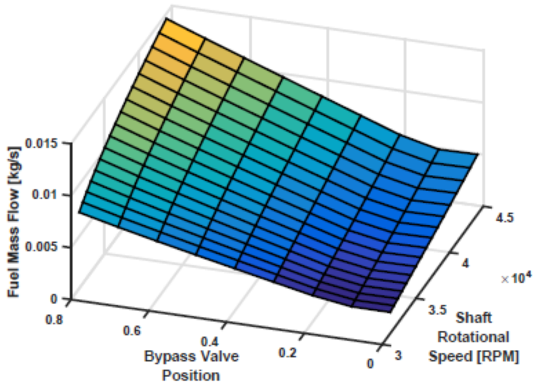
Recuperated MGT Simulation Model



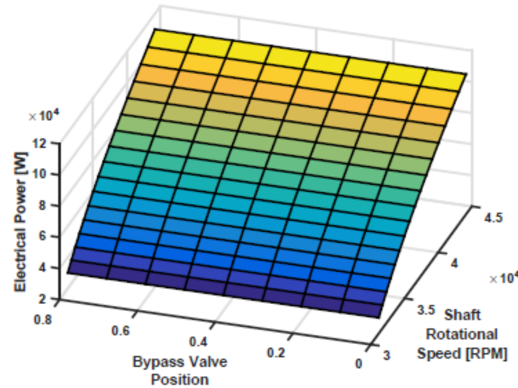
- NASA DYNGEN algorithm
- generates **steady-state maps**



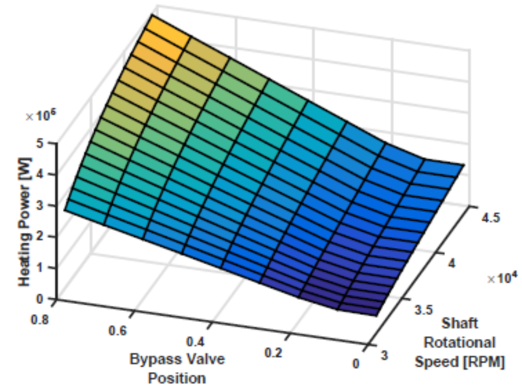
MGT Modeling



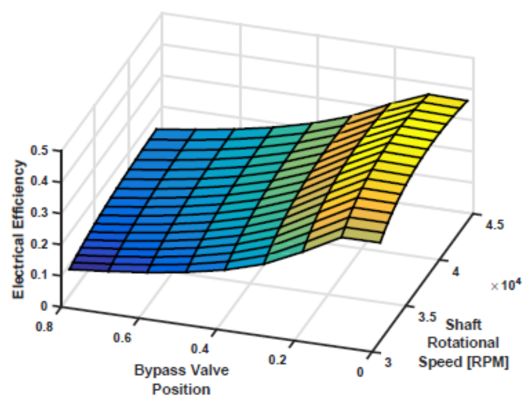
(a) Fuel Mass Flow.



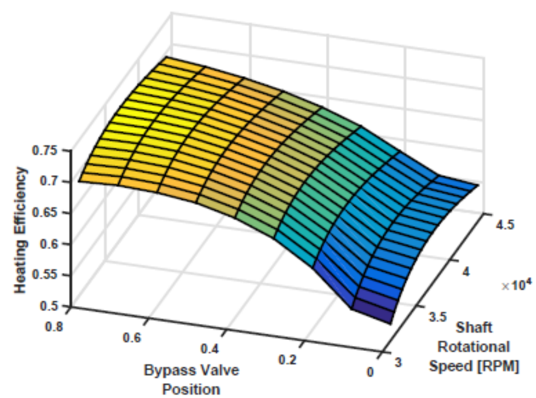
(b) Electricity Output.



(c) Heat output.



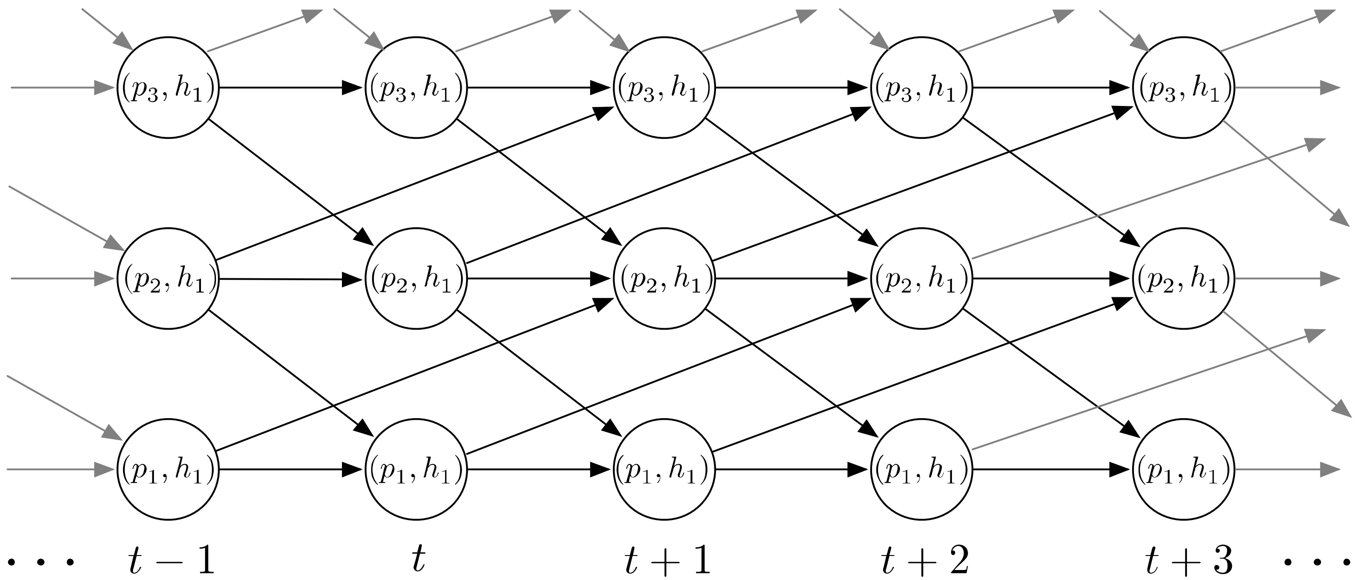
(d) Electrical Efficiency.



(e) Heat Efficiency.

Towards an Optimization Model

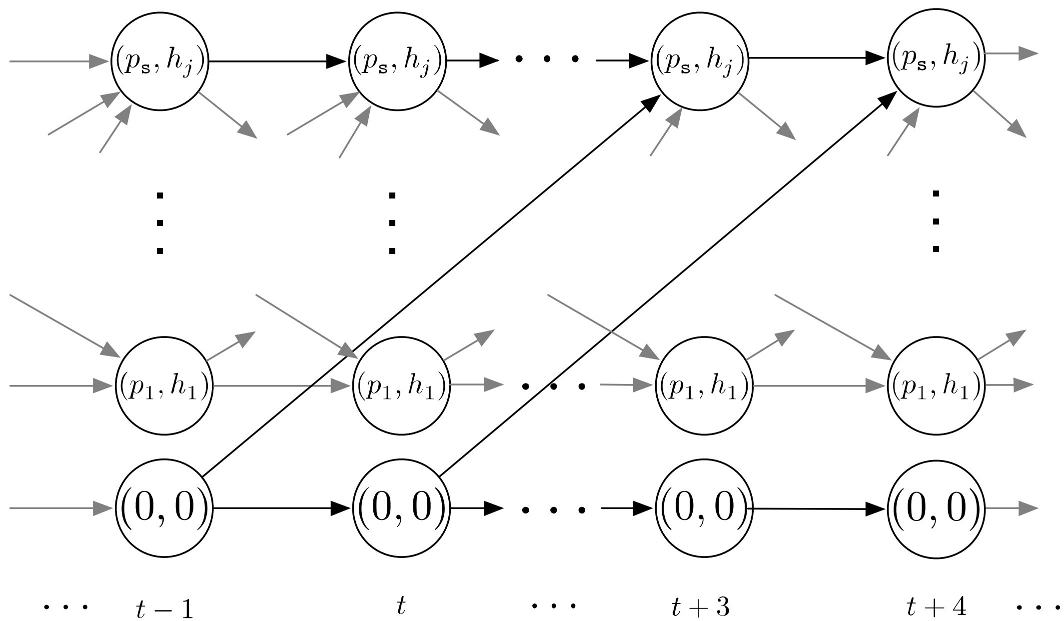
Operational Constraints as discretized state-transition graph



- system "state" is shaft speed and bypass valve
- arrows indicate allowable transitions to new steady-states, and their time

Towards an Optimization Model

Operational Constraints as discretized state-transition graph



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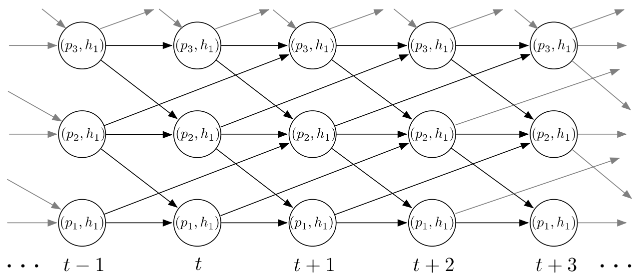
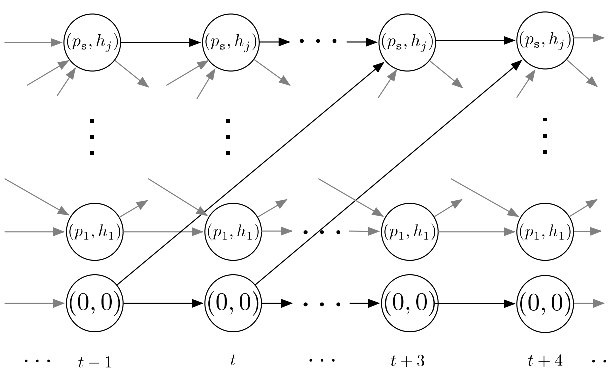




MGT Dynamics can be represented by graphs

$$x_{GT}(t + c\Delta T) = f_{GT}(x_{GT}(t), u_{GT}(t))$$

$$ Costs can be assigned to each edge

- relates to fuel price
- maintenance cost
- utility commitment and consumer demand

Towards an Optimization Model

$$\min_{x_{GT}, u_{GT}, x_{UT}^P, x_{UT}^H} \quad J(x_{GT}, u_{GT}, x_{UT}^P, x_{UT}^H)$$

subject to

(MGT Dynamics) $$x_{GT}(t + c\Delta T) = f_{GT}(x_{GT}(t), u_{GT}(t)),$$

(Power Balance) $$P_{GT}(x_{GT}(t)) + (x_{UT}^P(t) - P(t)) = 0,$$

(Heat Balance) $$H_{GT}(x_{GT}(t)) + (x_{UT}^H(t) - H(t)) = 0,$$

$$x_{GT}(t) \in \{(p_i(t), h_j(t)),\ i = 1, \ldots, \mathtt{s}, j = 1, \ldots, \mathtt{v}\}$$

$$x_{UT}^P(t) \geq 0,\ x_{UT}^H(t) \geq 0,\ t = 1, \ldots, T.$$

Optimization over a *directed acyclic graph*

Shortest Path Algorithm – complexity is linear in #nodes+edges

* J. F. Rist, M. F. Dias, M. Palman, D. Zelazo, B. Cukurel, *Economic dispatch of a single micro-gas turbine under CHP operation*, Applied energy 200 (2017) 1–18.

A Fundamental Flaw

$$\min_{x_{GT},u_{GT},x_{UT}^P,x_{UT}^H} \quad J(x_{GT}, u_{GT}, x_{UT}^P, x_{UT}^H)$$

subject to

(MGT Dynamics) $\quad x_{GT}(t + c\Delta T) = f_{GT}(x_{GT}(t), u_{GT}(t)),$

(Power Balance) $\quad P_{GT}(x_{GT}(t)) + (x_{UT}^P(t) - P(t)) = 0,$

(Heat Balance) $\quad H_{GT}(x_{GT}(t)) + (x_{UT}^H(t) - H(t)) = 0,$

$$x_{GT}(t) \in \{(p_i(t), h_j(t)),\ i = 1, \ldots, \mathtt{s}, j = 1, \ldots, \mathtt{v}\}$$

$$x_{UT}^P(t) \geq 0,\ x_{UT}^H(t) \geq 0,\ t = 1, \ldots, T.$$

power and heat demand are unknown!

- it is not possible to deterministically know the demand profiles
- we can only estimate based on data, forecast models, etc

Robust Shortest Path Problems

Robust Optimization

$$\min_{x} \max_{\xi \in \mathcal{W}} \{ F(x,\xi) : \phi(x,\xi) \leq 0, \ \forall \xi \in \mathcal{W} \}$$

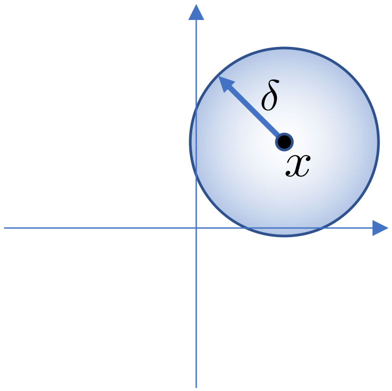
cost function

constraints

uncertainty set

example:

$$\mathcal{W} = \{ \xi : \ \|\xi\| \leq \delta \}$$



Robust Shortest Path Problems

Shortest Path

$$\min_{\text{Path}_{s\to q}} \left\{ \sum_{e \in \text{Path}_{s\to q}} w_e \ : \ \text{Path}_{s\to q} \in \text{PATH}_{s\to q}(\mathcal{G}) \right\}$$

Robust Shortest Path

$$\min_{\text{Path}_{s\to q}} \max_{w \in \mathcal{W}} \left\{ \sum_{e \in \text{Path}_{s\to q}} w_e \ : \ \text{Path}_{s\to q} \in \text{PATH}_{s\to q}(\mathcal{G}) \right\}$$

- generally *hard to solve!*
- NP-hard for general uncertainty sets

Robust Shortest Path Problems

Robust Shortest Path

$$\min_{\text{Path}_{s\to q}} \max_{w\in\mathcal{W}} \left\{ \sum_{e\in \text{Path}_{s\to q}} w_e \;:\; \text{Path}_{s\to q} \in \text{PATH}_{s\to q}(\mathcal{G}) \right\}$$

$\mathcal{L}_\infty$ uncertainty

$$\mathcal{W} = \left\{ (P(t), H(t))_{t=1}^{T} \;:\; \begin{array}{c} |P(t) - P_0(t)| \le \Delta P(t), \\ |H(t) - H_0(t)| \le \Delta H(t) \end{array} \right\}$$

- demand uncertainty "ball"
- equivalent to "normal" SP problem
- depending on confidence interval, solution may be too conservative or not robust

mixed $\mathcal{L}_1/\mathcal{L}_\infty$ uncertainty

$$\mathcal{W} = \left\{ (P(t), H(t))_{t=1}^{T} \;:\; \begin{array}{c} P(t) = P_0(t) + \eta_1^P(t) + \eta_\infty^P(t), \\ H(t) = H_0(t) + \eta_1^H(t) + \eta_\infty^H(t), \\ \sum_{t=1}^{T} \left[|\delta_{P,t}\eta_1^P(t)| + |\delta_{H,t}\eta_1^H(t)| \right] \le \mu_1, \\ |\eta_\infty^P(t)| \le \Delta P(t), |\eta_\infty^H(t)| \le \Delta H(t), \;\forall t \end{array} \right\}$$

- attempts to deal with unforeseen short demand spikes and long-term demand bias
- computationally more expensive (order because square of edges)

Robust Shortest Path Problems

Robust Shortest Path

$$\min_{\text{Path}_{s\to q}} \max_{w\in\mathcal{W}} \left\{ \sum_{e\in\text{Path}_{s\to q}} w_e \ : \ \text{Path}_{s\to q} \in \text{PATH}_{s\to q}(\mathcal{G}) \right\}$$

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- attempts to deal with unforeseen short demand spikes and long-term demand bias
- computationally more expensive (order because square of edges)

Case Studies: Residential Community

Residential Building

residential electricity tariff
neighborhood of 20 apartment buildings

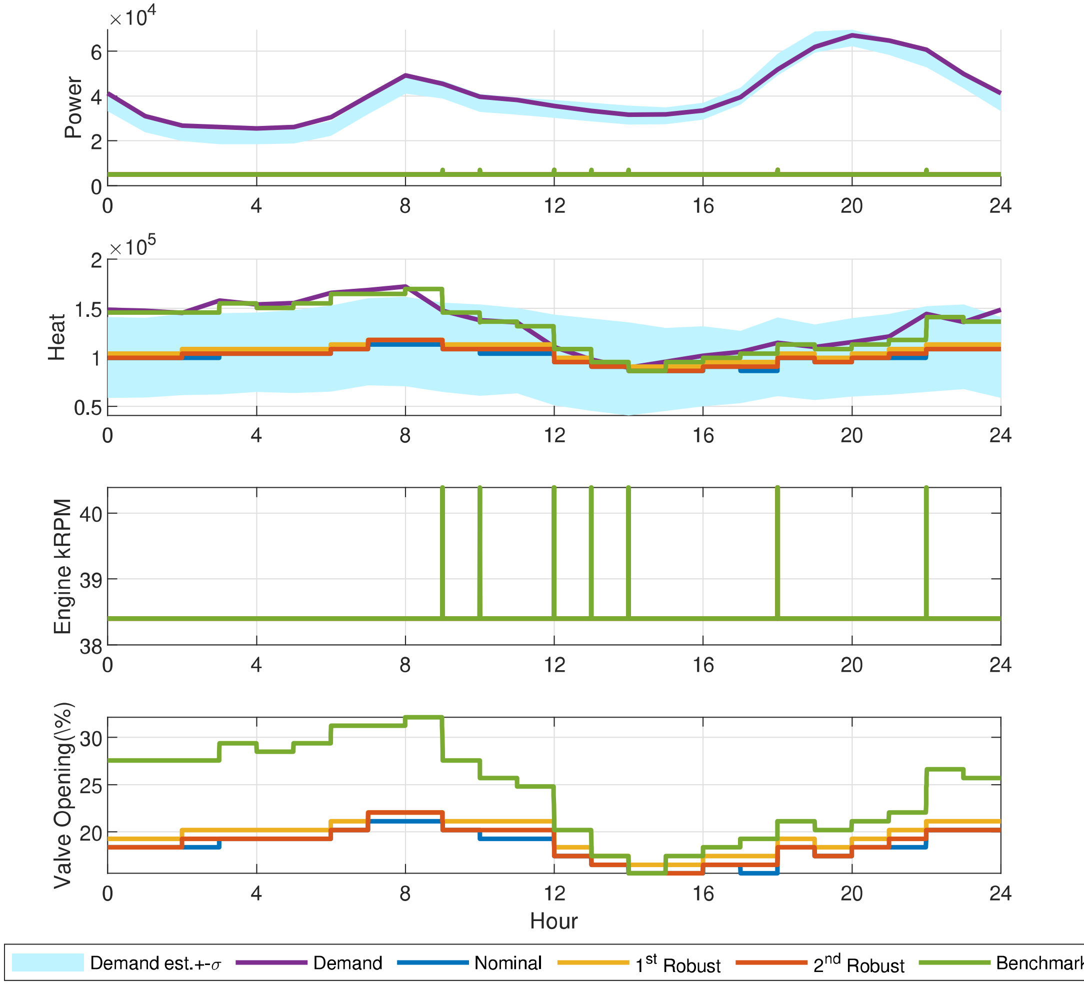
Demand and Tariff Data

US DOE 2004

- consider 4 “typical” days (24 hours in 15sec intervals): winter, spring, summer autumn
- demand forecasting based on previous 2 week data (mean and standard deviation)
- compare following algorithms:
  - *benchmark* : ED problem with perfect knowledge of demand
  - *nominal* : ED problem without demand uncertainty modeling
  - $\mathscr{L}_\infty$ *robust algorithm*
  - $\mathscr{L}_\infty/\mathscr{L}_1$ *robust algorithm*

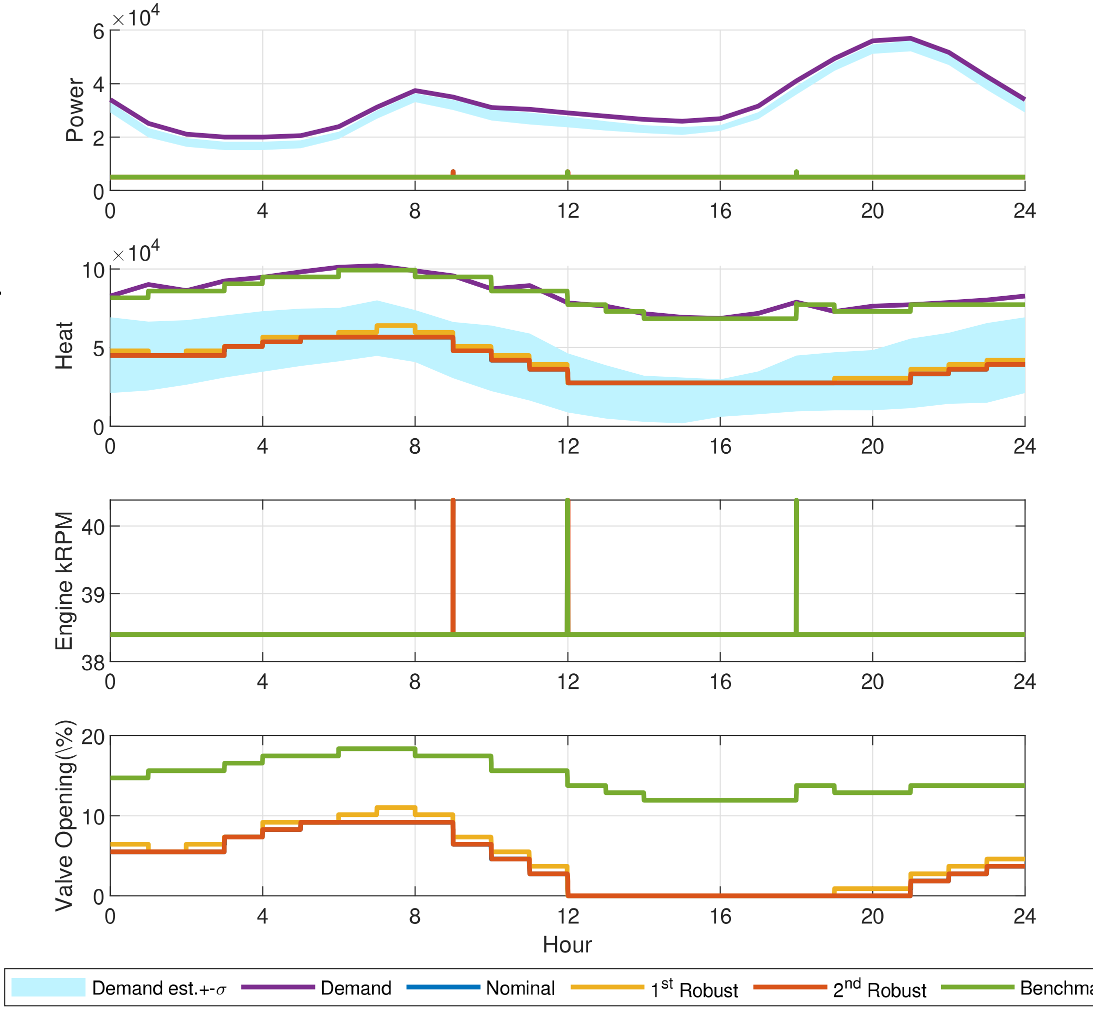
Case Studies: Residential Community

- based on data from 5.2.2004 (winter day)
- note conservativeness compared to benchmark
- heat driven operation



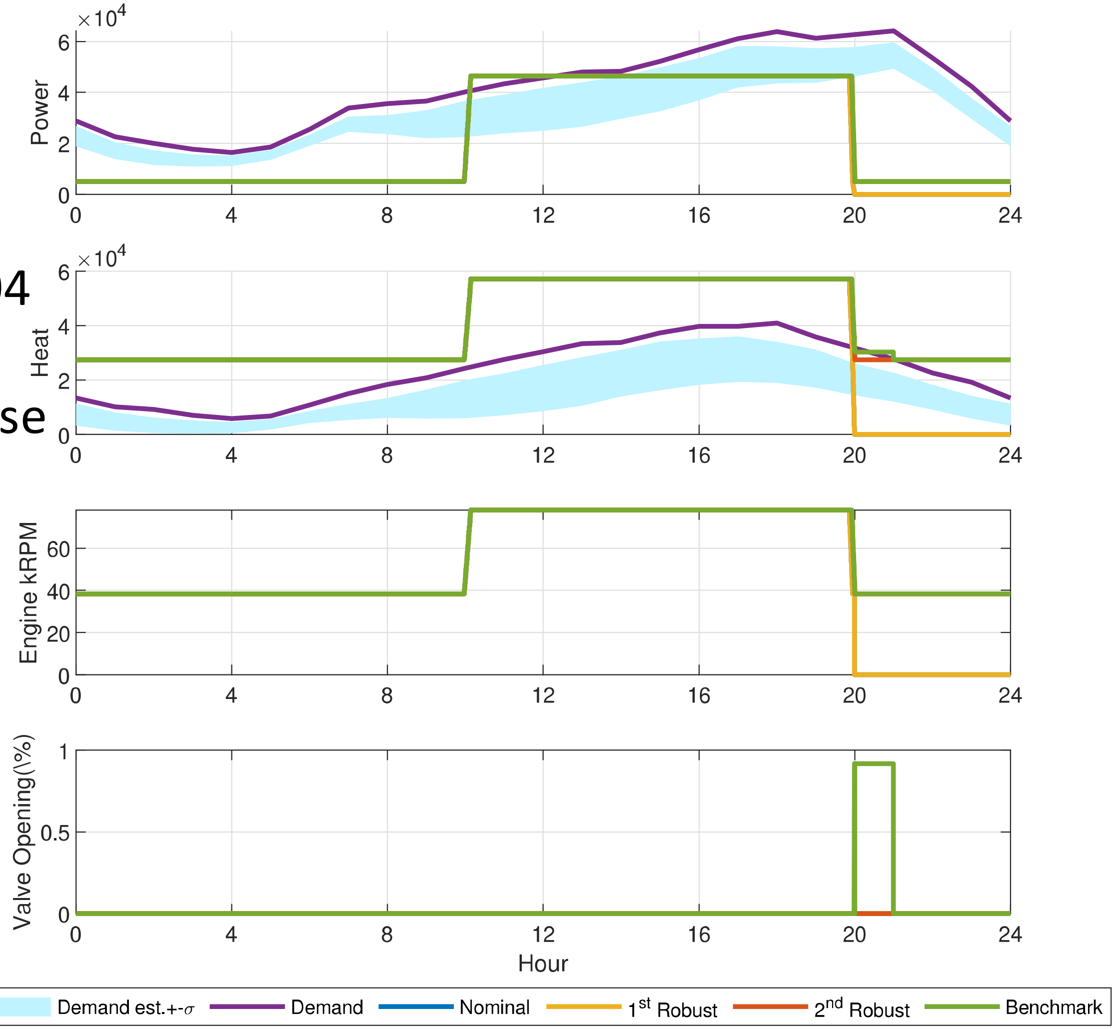
Case Studies: Residential Community

- based on data from 24.4.2004 (spring day)
- nominal and 2nd robust algorithm behave the same
- 1st robust results in different trajectory
- heat driven operation



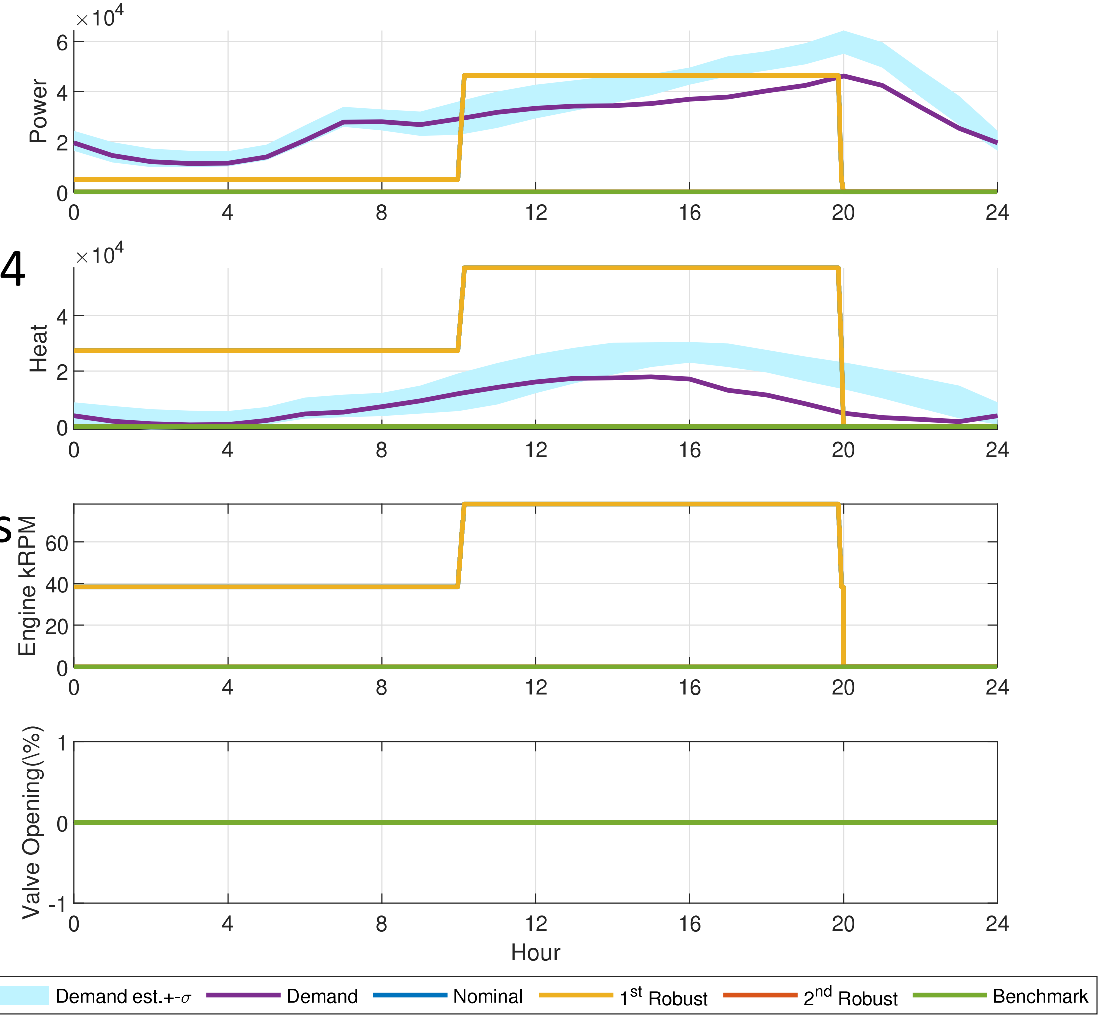
Case Studies: Residential Community

- based on data from 28.6.2004 (summer day)
- 2nd robust algorithm very close to benchmark
- 1st robust algorithm close to nominal algorithm
- maintenance and electricity driven operation



Case Studies: Residential Community

- based on data from 19.9.2004 (autumn day)
- benchmark is maintenance driven – shuts MGT down
- 2nd robust algorithm captures this as well
- 1st robust and nominal algorithms do not



Case Studies: Residential Community

Schedule cost in $ (Reduction in excess cost in %)	Winter Feb. 5th	Spring Mar. 24th	Summer Jun. 28th	Autumn Sep. 19th
Benchmark case	293.02	196.86	188.83	126.48
Nominal algorithm	299.39	202.30	191.35	133.32
First robust algorithm	*298.48 (14.29%)*	*202.16 (2.57%)*	191.35 (0.00%)	133.32 (0.00%)
Second robust algorithm	299.16 (3.61%)	202.30 (0.00%)	*188.83 (100.00%)*	*126.48 (100.00%)*

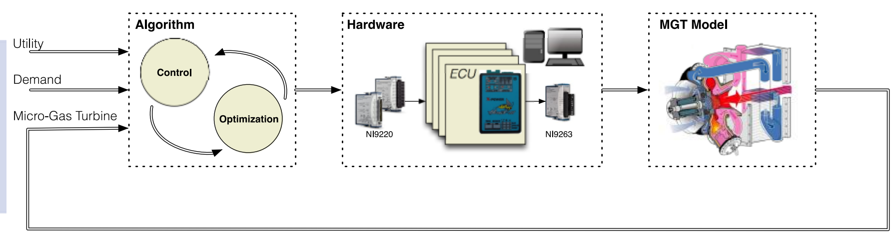
Future Directions

Multi-Unit ED
- implementation with MGT model
- extension to combined CHP

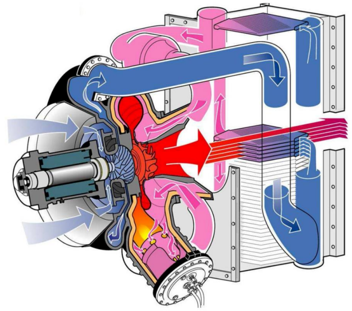
Robust Multi-Unit ED
- extension of robust ED to multi-unit case

Hardware-in-the-loop
- simulation with real MGT
- "virtual" smart grid

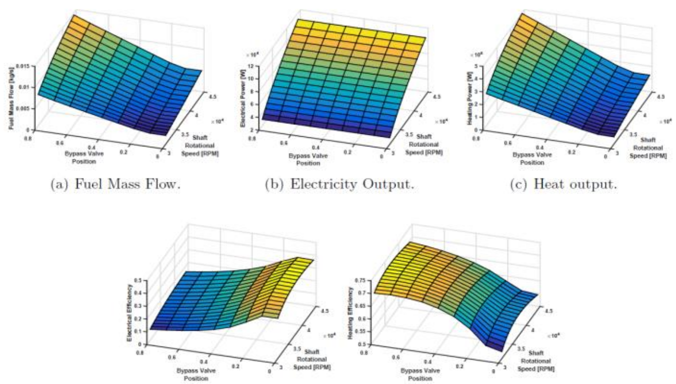
Real-time MGT Control



Conclusions



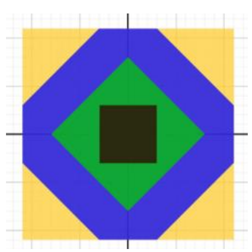
Micro-Gas Turbines using natural gas is an economically viable solution towards a distributed power generation economy



(a) Fuel Mass Flow. (b) Electricity Output. (c) Heat output.

(d) Electrical Efficiency. (e) Heat Efficiency.

Detailed modeling required to gain a better understanding of the economic operational modes of the MGT



robust optimization methods can manage demand uncertainty in numerically tractable way

Acknowledgements

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Miel Sharf, Iliya Romm, Michael Palman, Daniel Zelazo, Beni Cukurel, *Economic dispatch of a single micro gas turbine under CHP operation with uncertain demands*, Applied Energy, Volume 309, 2022, 118391.

Questions?