Economic Dispatch and Unit Commitment of a Single Micro-Gas Turbine under CHP Operation

Johannes F. Rist
Technical University of Munich

Miguel F. Diaz
Instituto Superior Tecnico

Michael Palman , **Daniel Zelazo**, Beni Cukurel
Technion

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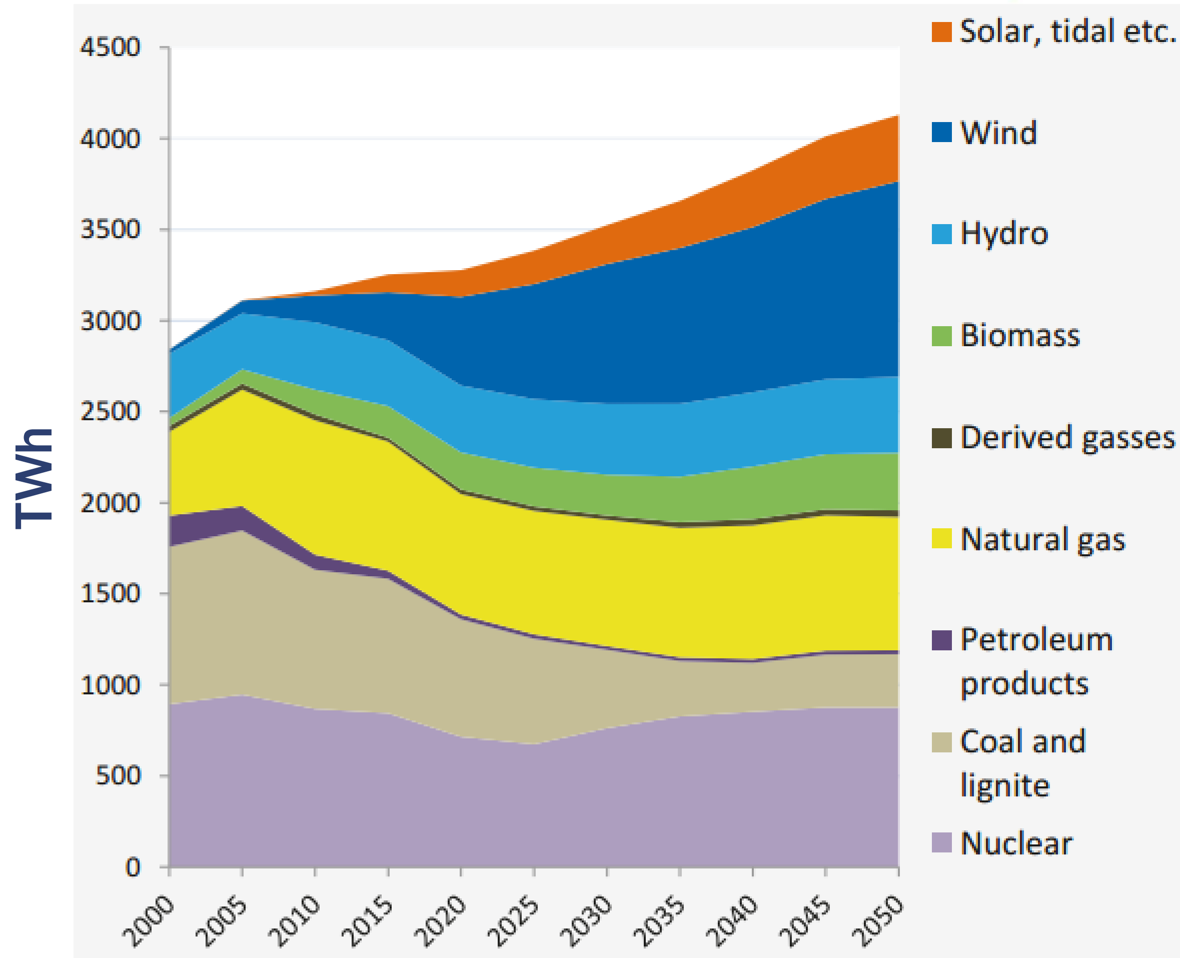
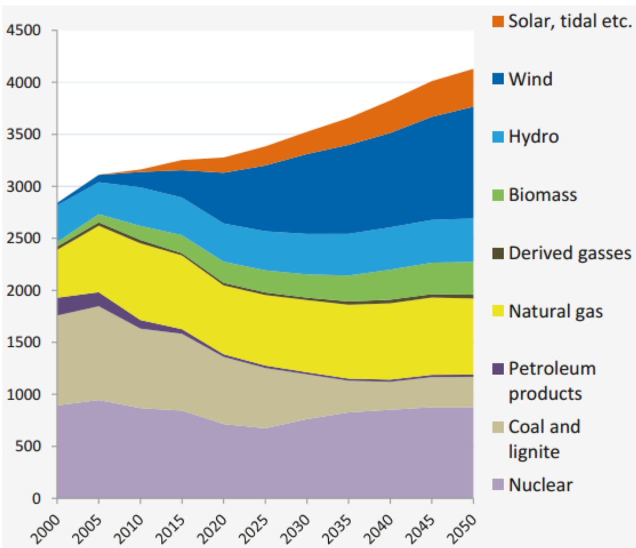
The Future Energy Landscape



EU electricity generation trends

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

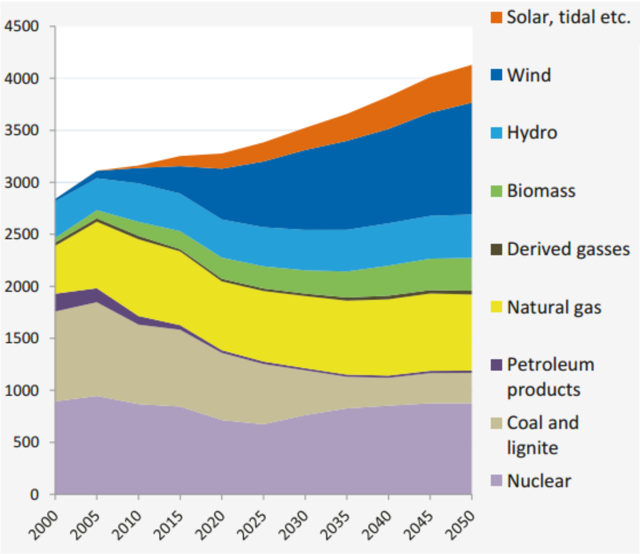
The Future Energy Landscape



Increasing integration
Into the grid!

…intermittent and not
on demand!

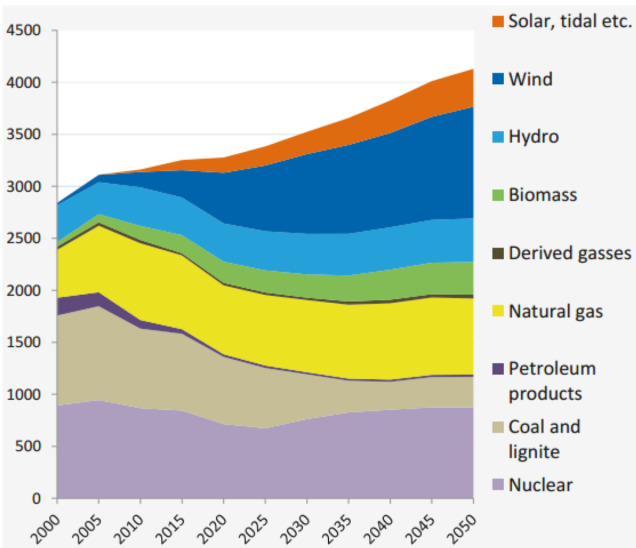
The Future Energy Landscape



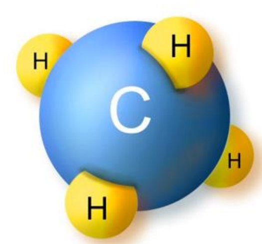
environmental concerns

finite resource

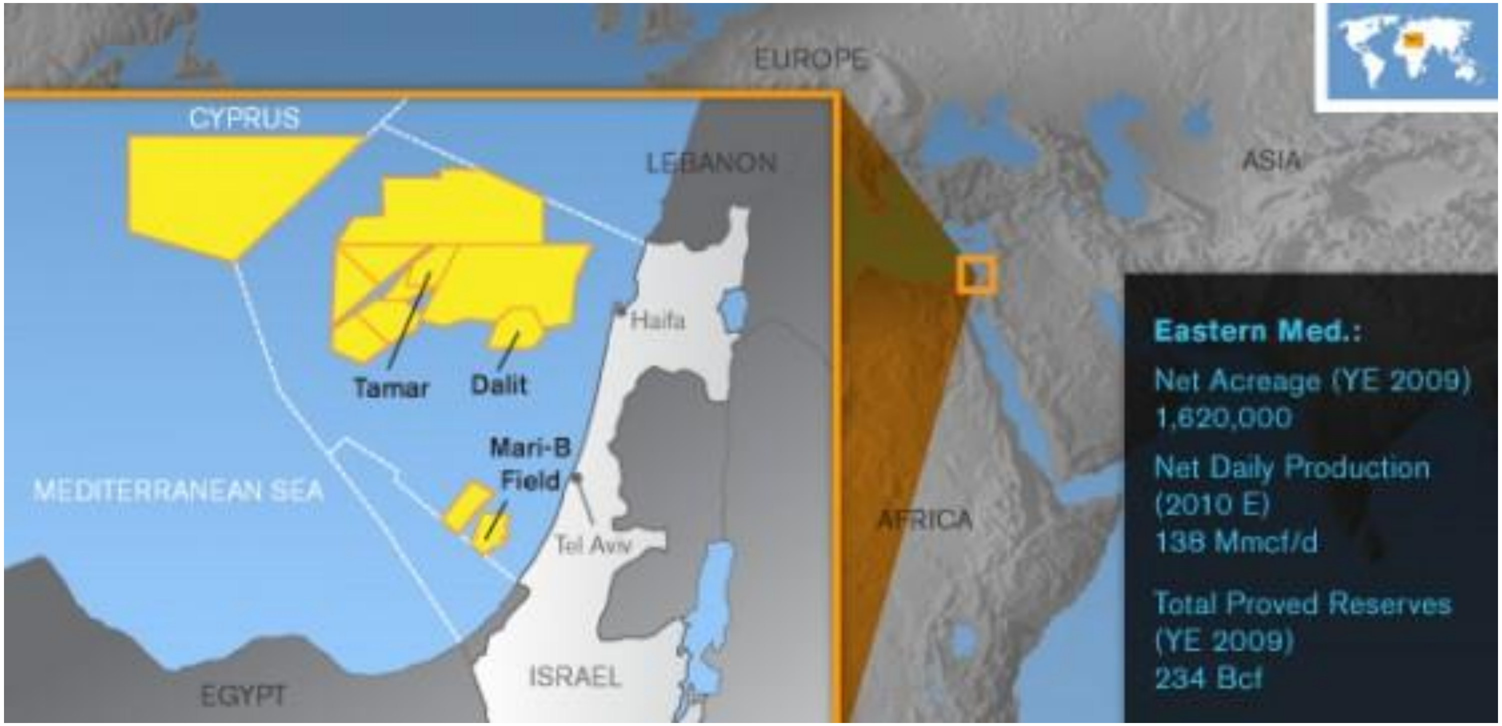
The Future Energy Landscape



Natural Gas is clean, cheap, and safe!



Energy Independence in Israel



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

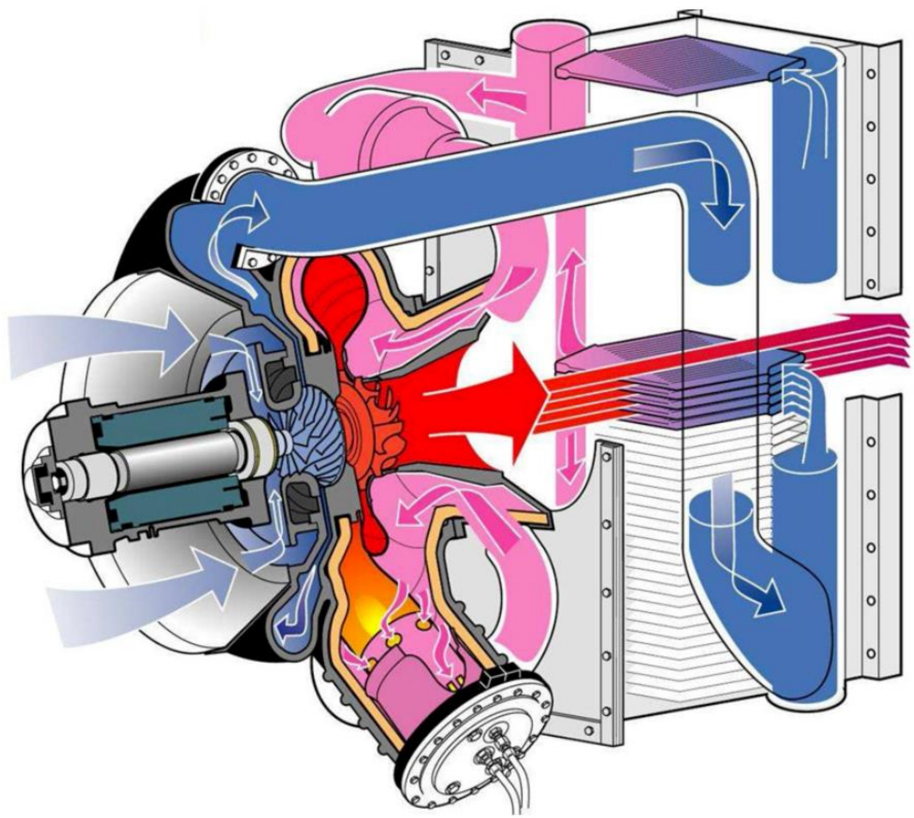
Leviathan - 22 trillion cubic feet
Tamar – 10.8 trillion cubic feet
Tanin - 3 trillion cubic feet

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

utility

Meet the consumer power demand in an economically optimal way

The Economic Dispatch Problem

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**

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

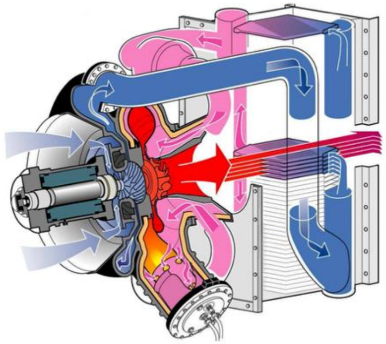
$$

Power Balance

D_P **Electricity Demand**

D_H **Heat Demand**

The Economic Dispatch Problem



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

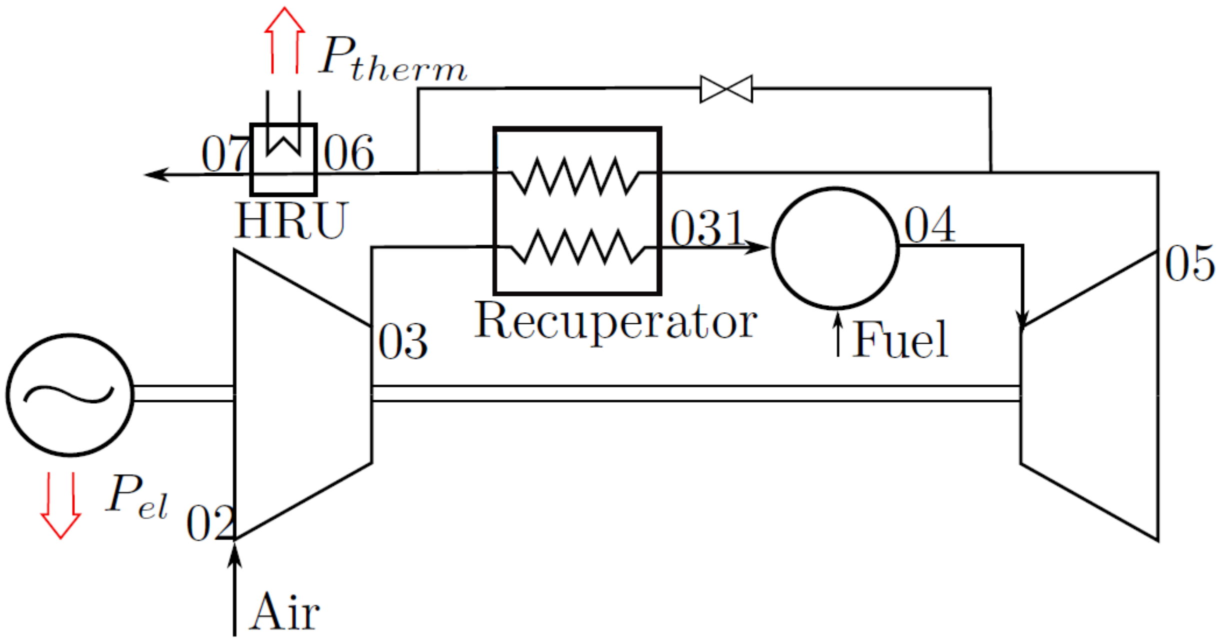
- how much does electricity cost
- electricity market for buying and selling power

Consumer Needs

- what are the power and heat demand profiles for consumers

MGT Modeling

Recuperated Gas Turbine Cycle Diagram

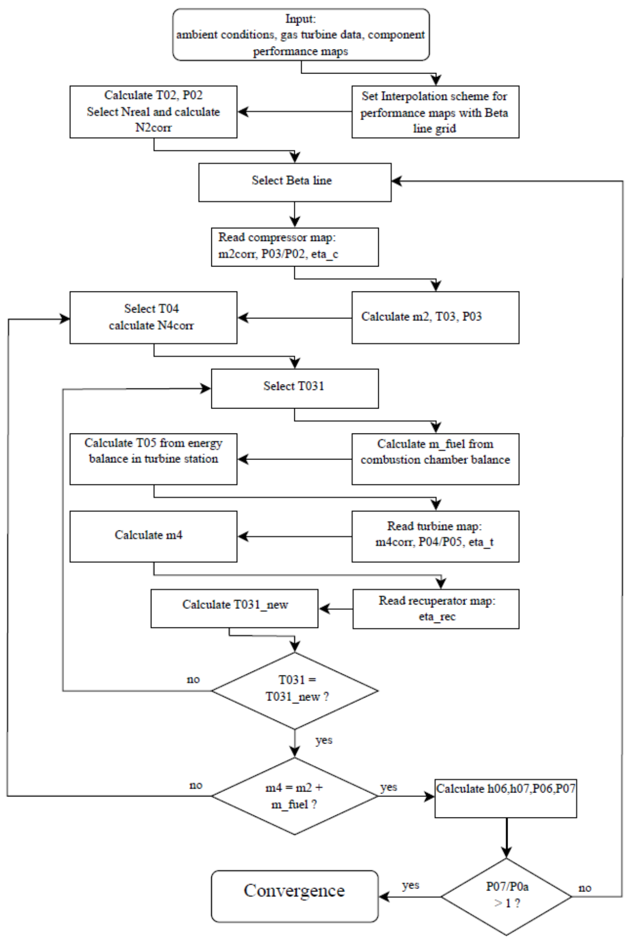


02 – 03 : Compressor – flow pressure rises.
03 – 031 : Recuperator – the temperature of the flow is further increased in the recuperator by energy recovering.
031 – 04 : Combustor – energy addition.

04 – 05 : Turbine – the thermal energy is converted into mechanical energy that is provided to compressor and the electrical power generator.

MGT Modeling

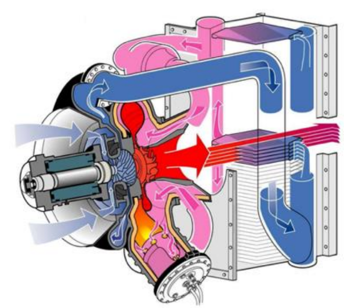
Recuperated MGT Simulation Model



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

Shaft Speed

Bypass Valve

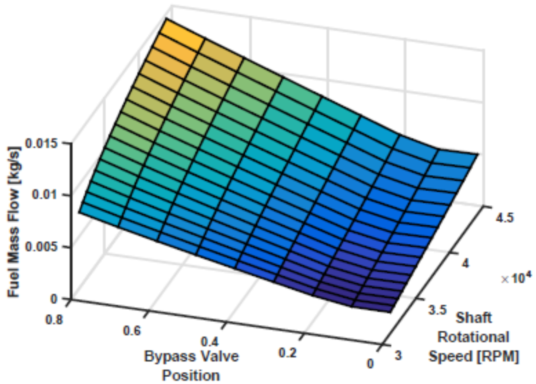


mass flow

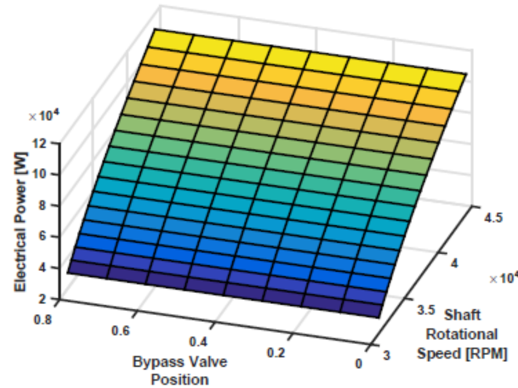
pressure ratio

efficiency

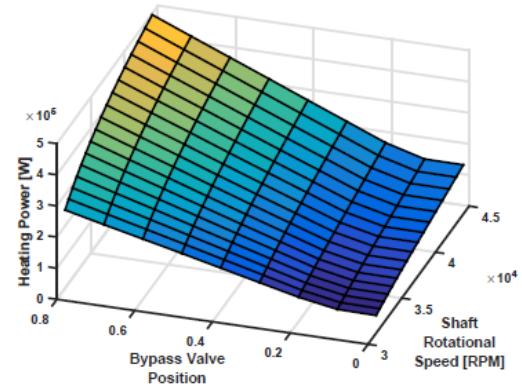
MGT Modeling



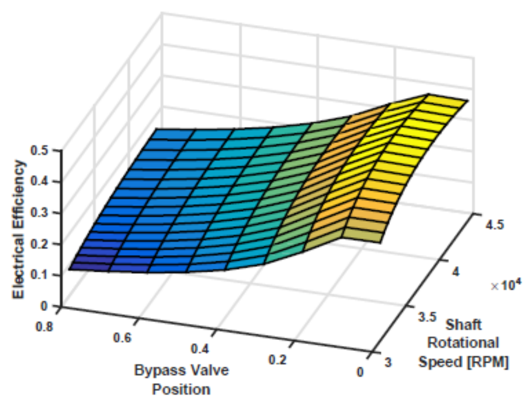
(a) Fuel Mass Flow.



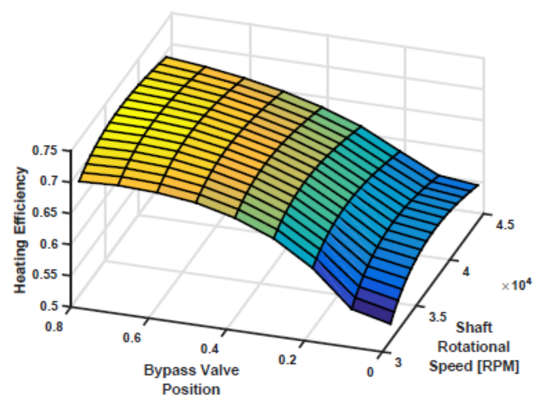
(b) Electricity Output.



(c) Heat output.



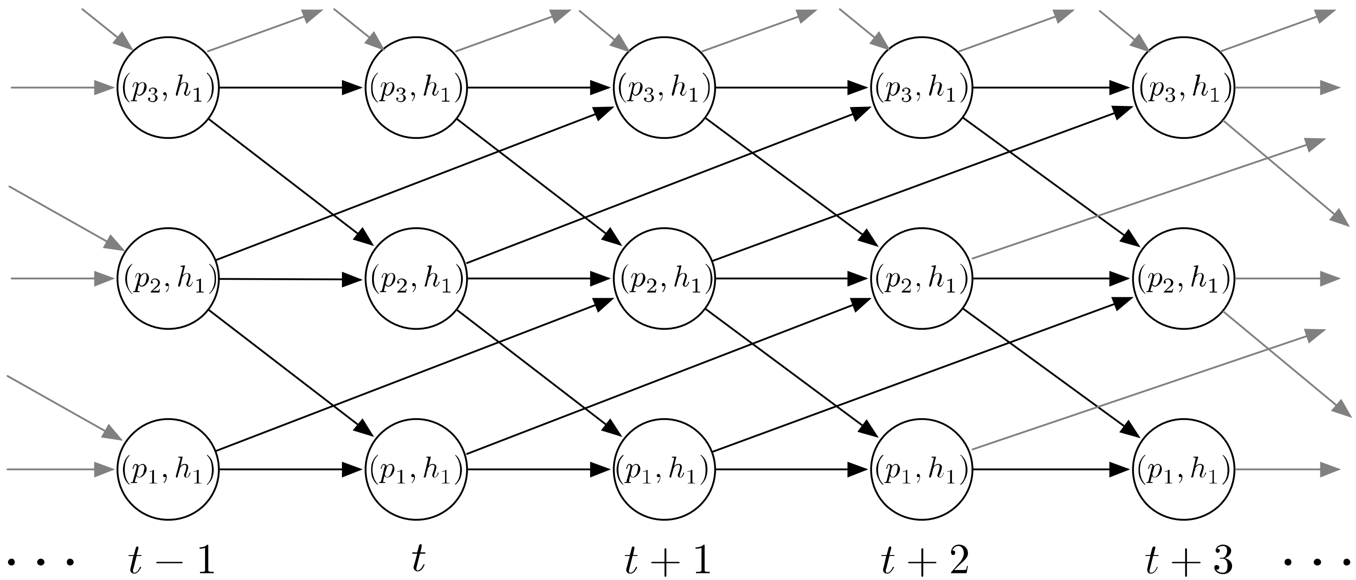
(d) Electrical Efficiency.



(e) Heat Efficiency.

Towards an Optimization Model

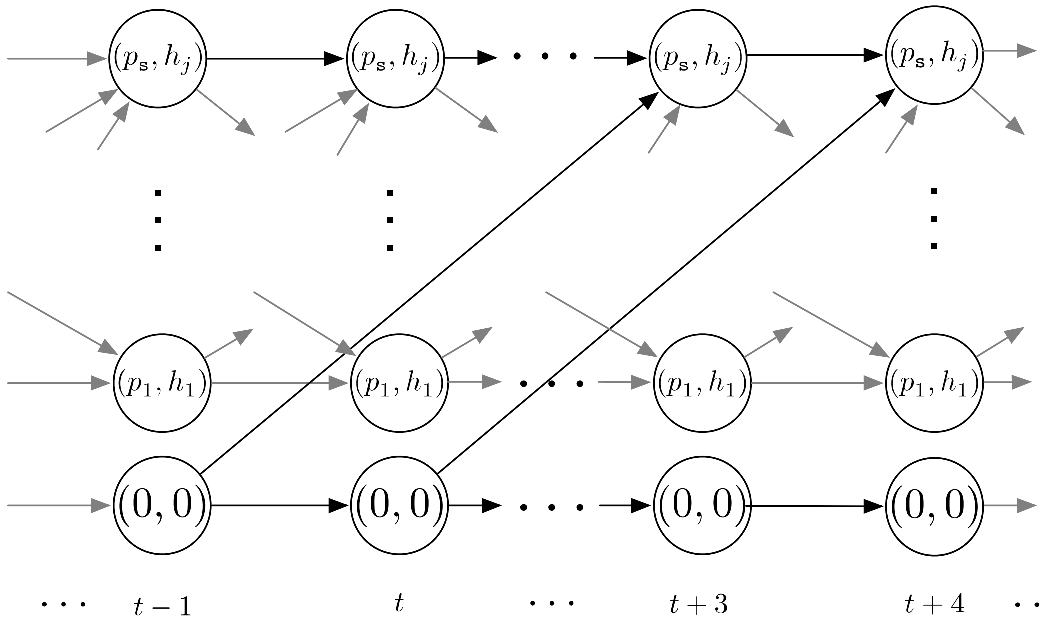
Operational Constraints as discretized state-transition graph



- 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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Towards an Optimization Model

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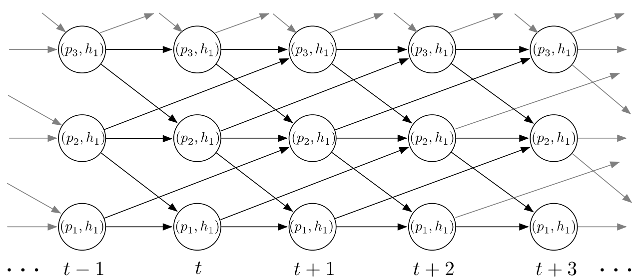
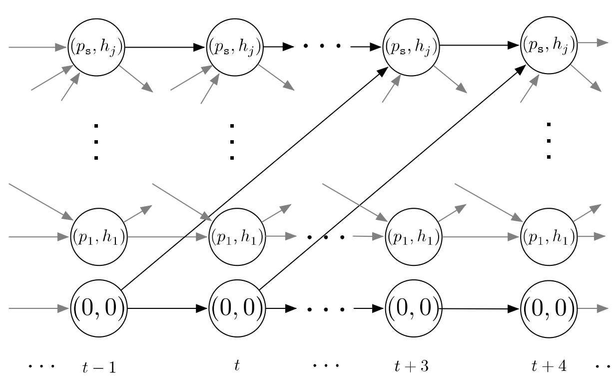
Operational Constraints as discretized state-transition graph



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

$$\min_{x_{GT},u_{GT},x^P_{UT},x^H_{UT}} \quad J(x_{GT},u_{GT},x^P_{UT},x^H_{UT})$$

subject to

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

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

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

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

$$x^P_{UT}(t) \geq 0,\ x^H_{UT}(t) \geq 0,\ t=1,\ldots,T.$$

Optimization over a *directed acyclic graph*

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

Case Studies

Full Service Restaurant
commercial medium electricity tariff

$511m^2$

Large Hotel
commercial tall electricity tariff

$11,345m^2$

Small Hotel
commercial medium electricity tariff

$4,013m^2$

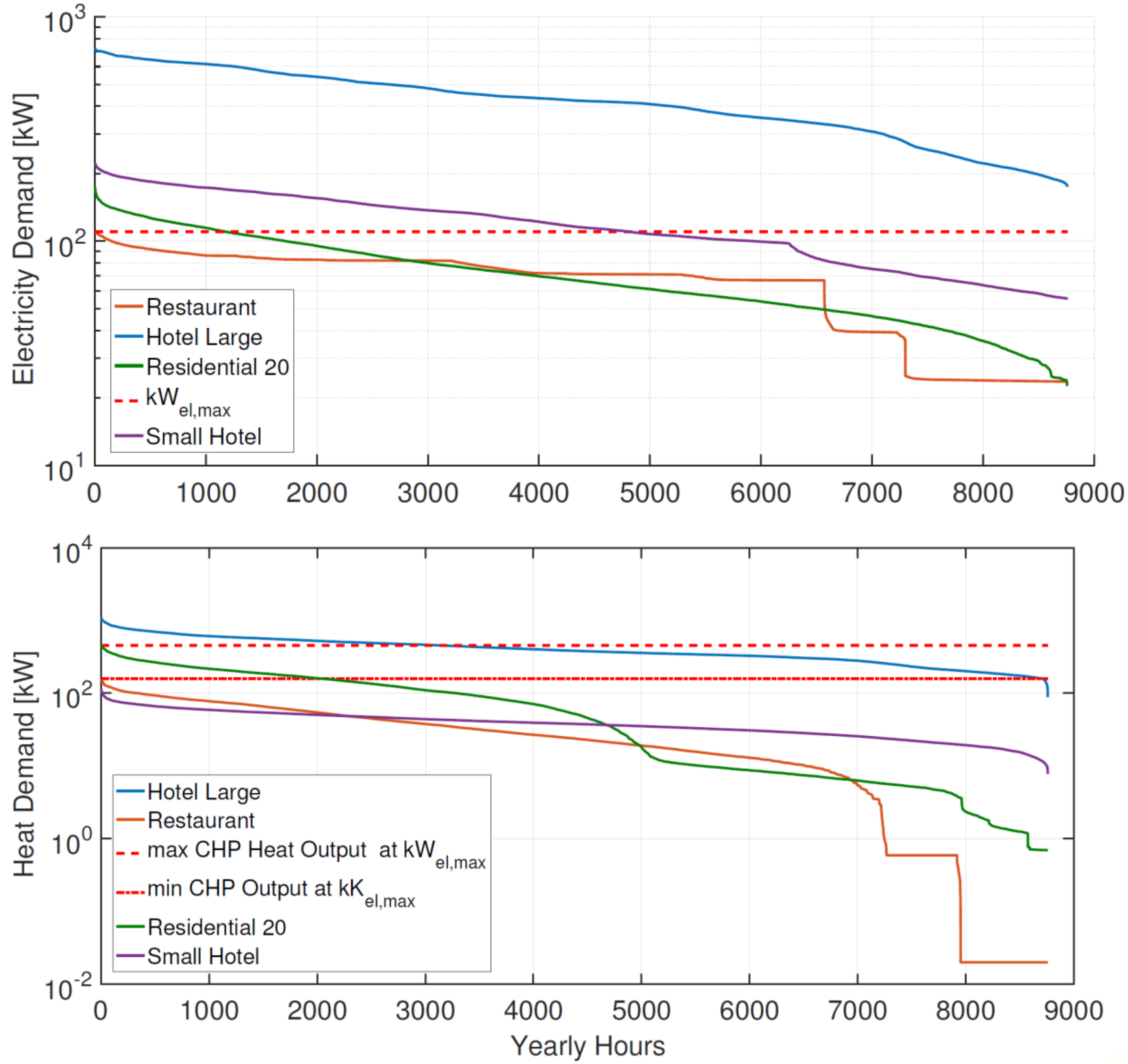
Residential Building
residential electricity tariff

neighborhood of 20 apartment buildings

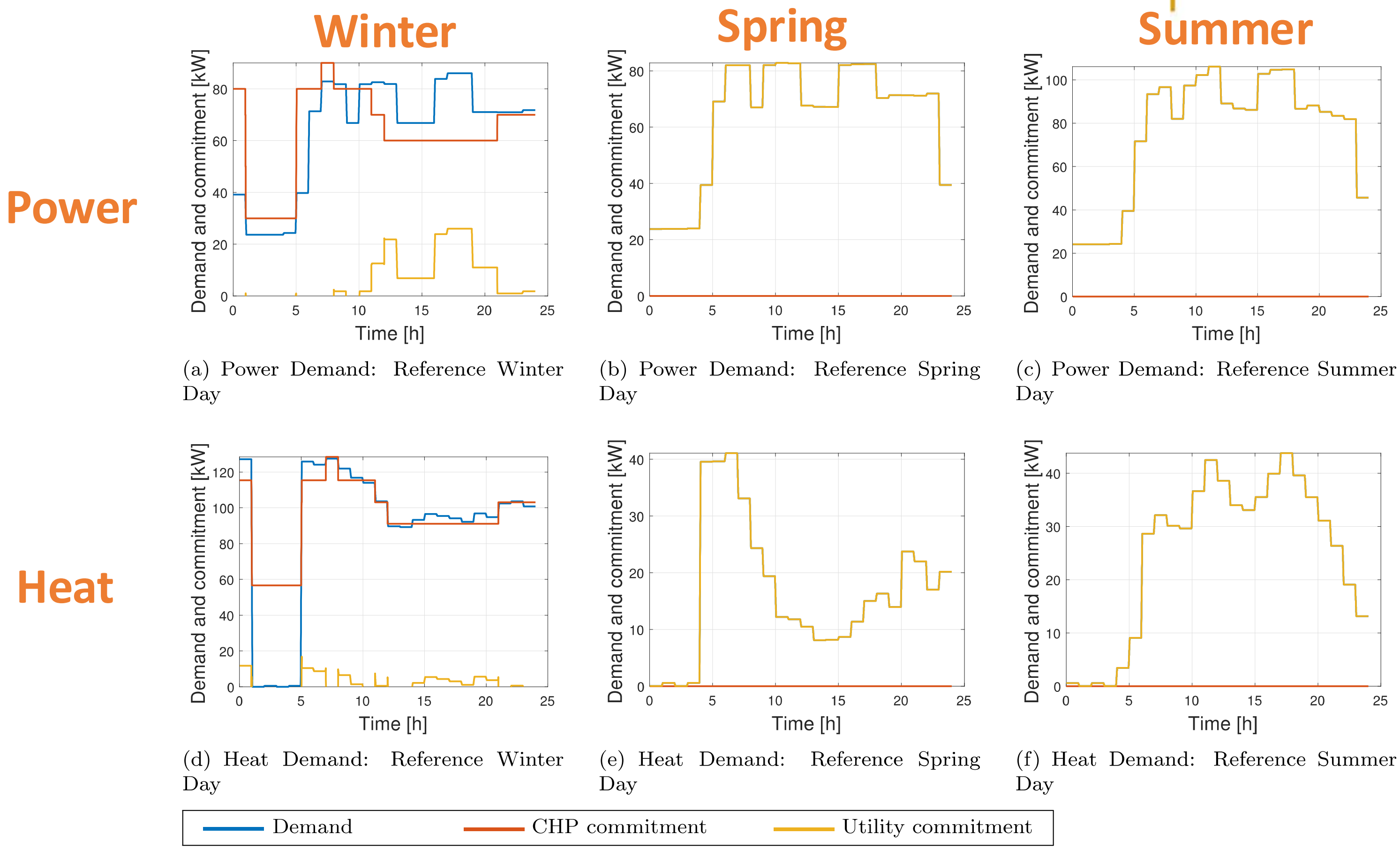
Demand and Tariff Data

US DOE 2004

Case Studies



Full Service Restaraunt



(a) Power Demand: Reference Winter Day
(b) Power Demand: Reference Spring Day
(c) Power Demand: Reference Summer Day
(d) Heat Demand: Reference Winter Day
(e) Heat Demand: Reference Spring Day
(f) Heat Demand: Reference Summer Day

Heat Driven Operation

During winter, electricity is a byproduct of meeting the heat demand.

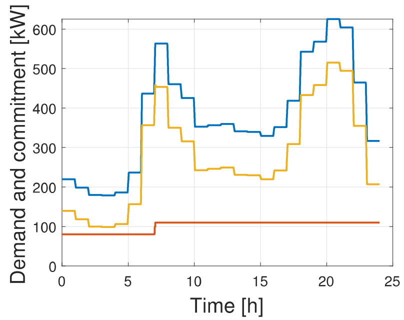
Maintenance Driven Operation

In Summer and Spring, startup and shutdown costs are too high to operate the MGT.

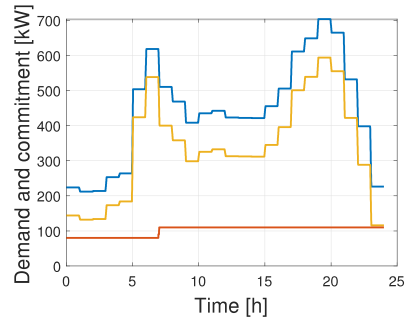
Large Hotel

Winter | Spring | Summer

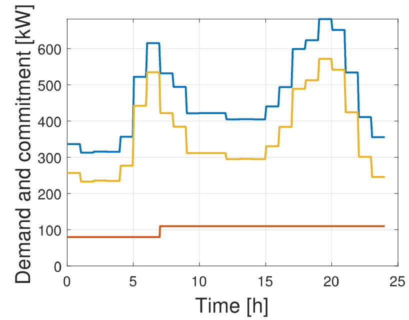
Power



(a) Power Demand: Reference Winter Day

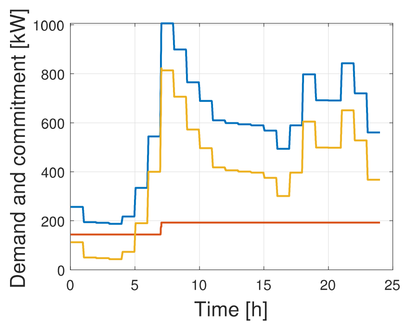


(b) Power Demand: Reference Spring Day

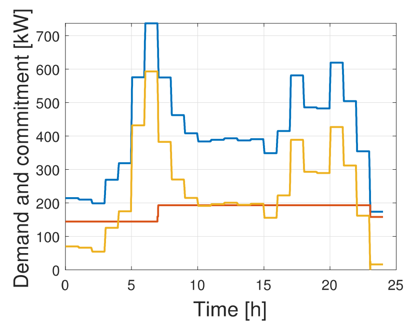


(c) Power Demand: Reference Summer Day

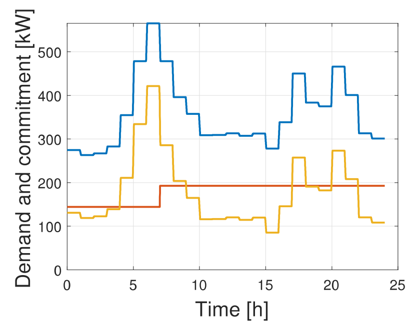
Heat



(d) Heat Demand: Reference Winter Day



(e) Heat Demand: Reference Spring Day



(f) Heat Demand: Reference Summer Day

Demand — CHP commitment — Utility commitment

Electricity Driven Operation

Power demand of the large hotel exceeds the maximum capacity of the MGT.

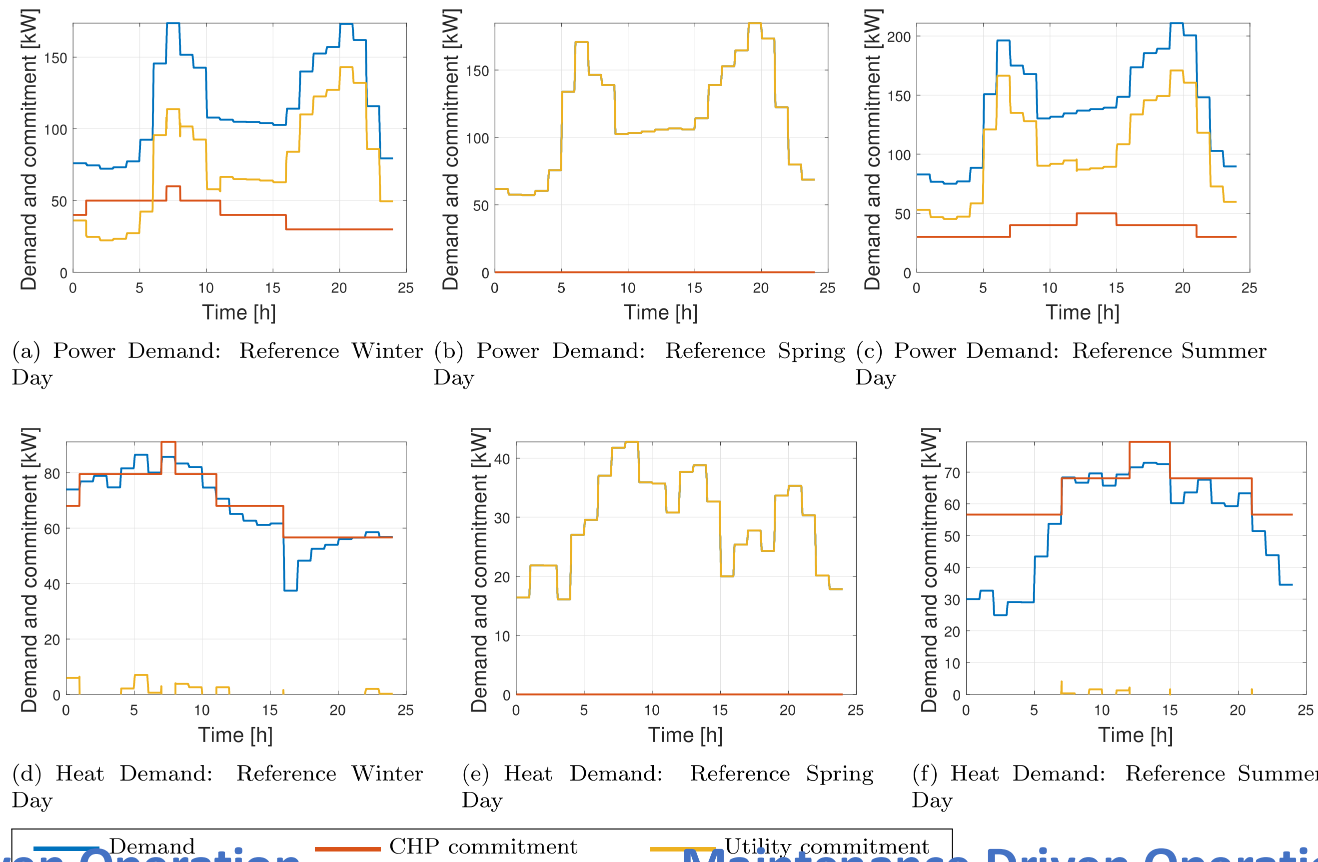
Optimal commitment requires contributions from both MGT and Utilitiy

Small Hotel

Winter | Spring | Summer

Power

Heat



(a) Power Demand: Reference Winter Day (b) Power Demand: Reference Spring Day (c) Power Demand: Reference Summer Day

(d) Heat Demand: Reference Winter Day (e) Heat Demand: Reference Spring Day (f) Heat Demand: Reference Summer Day

Heat Driven Operation

MGT operates at low power commitment levels, while heat demand is supplied at a competitive unit efficiency

Maintenance Driven Operation

During off-peak hours in summer, the MGT is operated to avoid additional startup/shutdown costs

Residential Community

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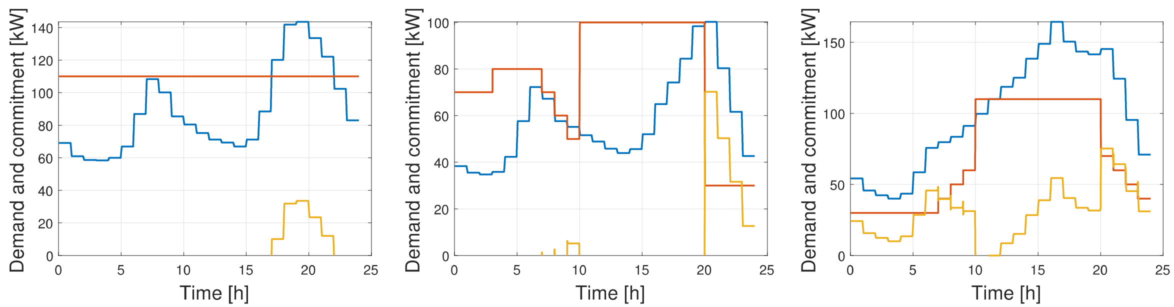
Winter | Spring | Summer

Power

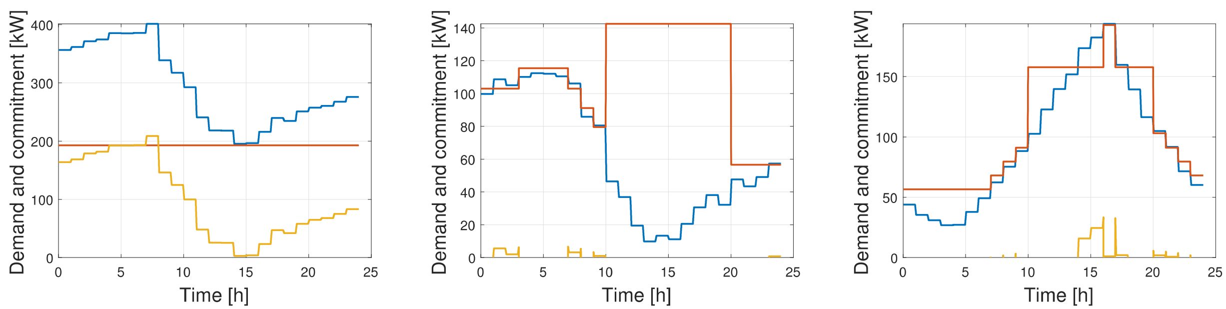


(a) Power Demand: Reference Winter Day

(b) Power Demand: Reference Spring Day

(c) Power Demand: Reference Summer Day

Heat



(d) Heat Demand Reference Winter Day

(e) Heat Demand: Reference Spring Day

(f) Heat Demand: Reference Summer Day

Demand — CHP commitment — Utility commitment

Revenue Driven Operation

In intermediate tariff hours, the MGT operates above the demand, selling electricity back to the grid

Flexible Operations

During off-peak hours, the MGT either operates **electricity, heat, or maintenance** driven, depending on situation

MGT Economic Modes

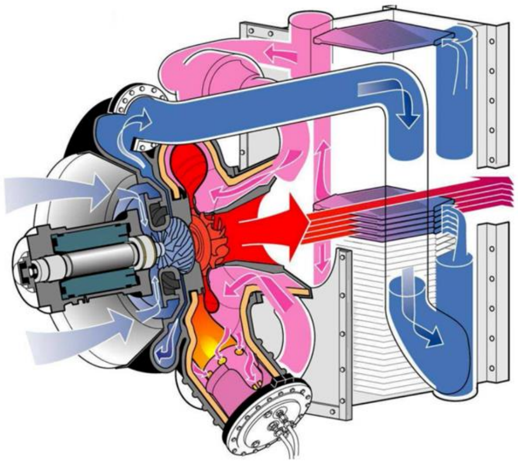
Electricity Driven: In case of the large hotel, when power and heat demand exceed the MGT capability permanently.

Heat Driven: Small hotel and restaurant due to more competitive energy generation with respect to the demand profiles.

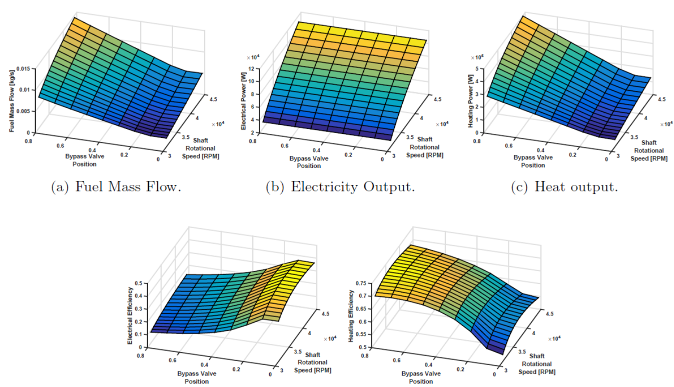
Maintenance Driven: In off-peak hours of the small hotel and restaurant where utility prices are low to avoid cycle costs.

Revenue Driven: Operation in residential neighbourhood aims to generate excess electricity that can be sold to the grid.

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

Future Work

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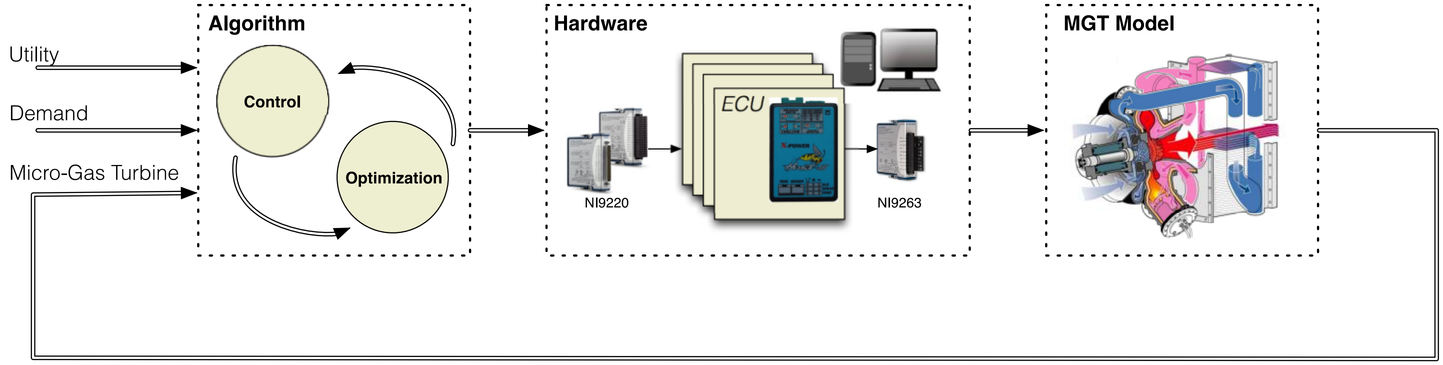
a dynamic real-time algorithm for integration of the MGT into the smart-grid

operation of MGT “banks” for distributed economic dispatch



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Questions?