Sharif University of Technology
Energy Engineering Department

Multi Objective Optimization of Distributed Energy Systems Considering Renewable and Fossil Fuel Resources

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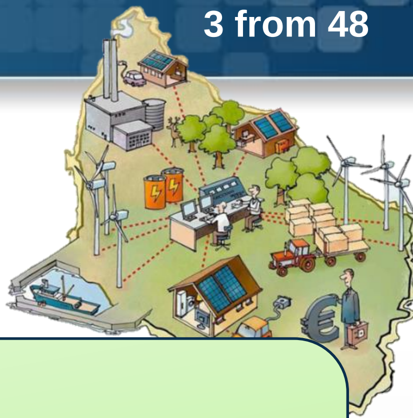
Co-supervisors From Canada: Dr. Ali Elkamel, Dr. Michael Fowler

Presentation Outline

- Introduction
- PhD Research
  - Objective & Contributions
  - Modeling Approach
- Phase 1
- Phase 2
- Phase 3
- Summary



Introduction

Urban energy system is responsible for **approximately three-quarters of the world's energy consumption** plays a major role in energy issues (economic security and climate change).

Distributed Energy Systems (DES) are faced with the competitive challenge of allocating energy to consumers from economic, environmental, and technical points of view.

The development of a system is complicated and needs thorough systematic analysis and evaluation of the entire procedure

Problem Definition

Given a small community , with its layout, its available renewable energies, Its buildings and their related consumption profiles;

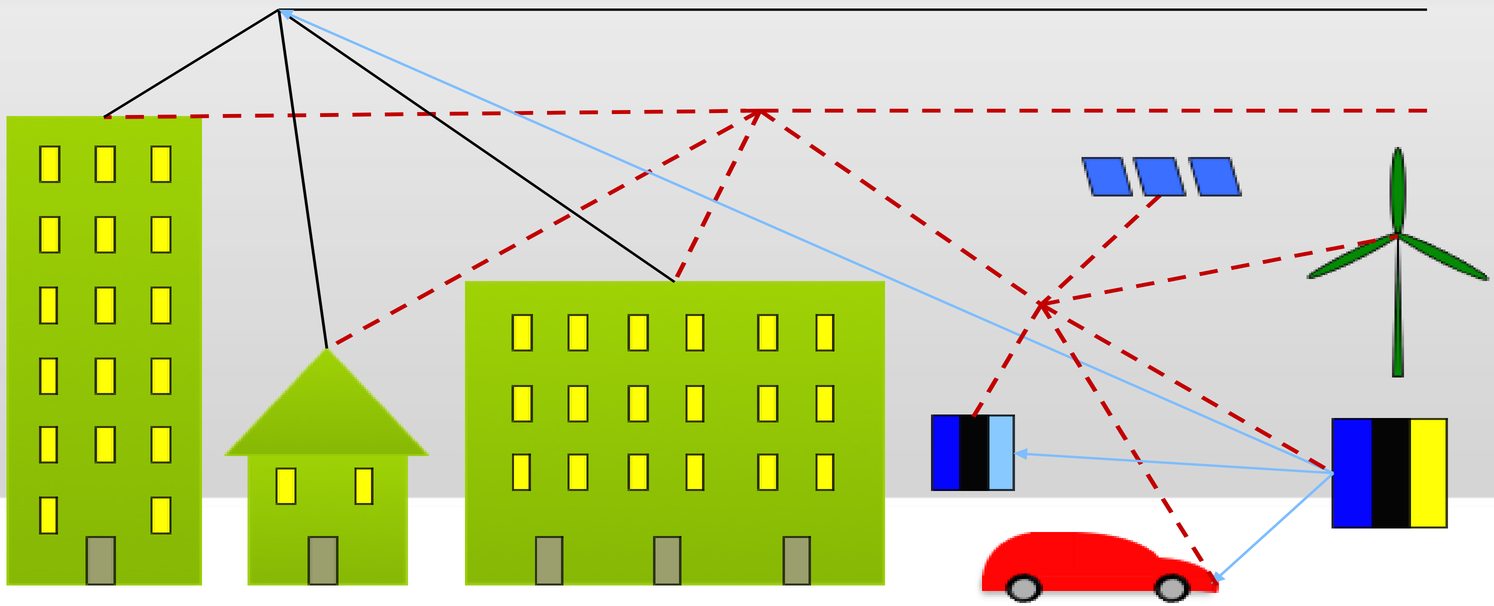
which combination of distributed energy conversion/storage technologies (and energy sources) will be best suited to meet the energy services?

how will these technologies be combined(The operational statue)?

how should the layout of the energy distribution network be arranged?

Research Objective

To provide a framework for the optimal planning, design, and operation of Distributed energy systems in Urban Areas based on Energy Hub Concept



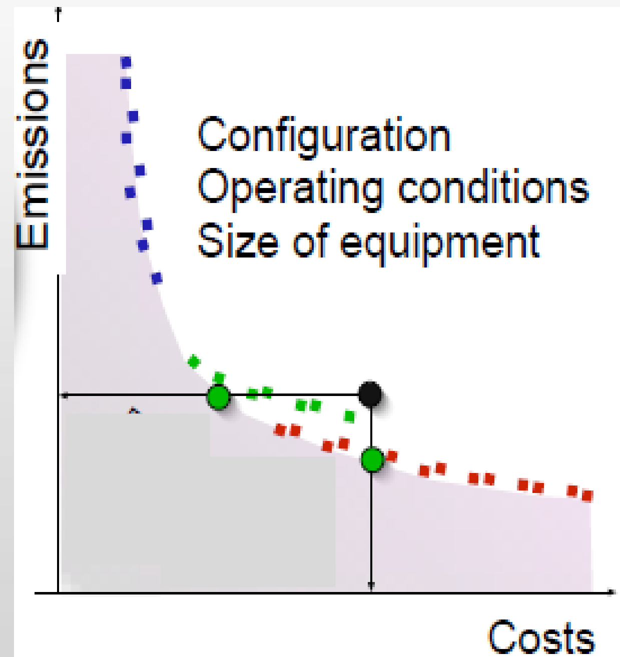
Modeling Approach

Problem
- Objectives
- Constraints
- Context

Data base
- Technologies cost
- Performance
- Energy demand
- Market Data

System
- Option list
- Superstructure
- Models
- Performance

Optimal System
- Multi Objective Optimization
- Multi Criteria evaluation
- Analysis
- Scenario making



Solution

The challenge of complexity

Variety of system components

- Multiple generation & storage technologies
- Multiple demand sources

Numerous interdependencies between components

- Multiple networks
- Multiple energy carriers

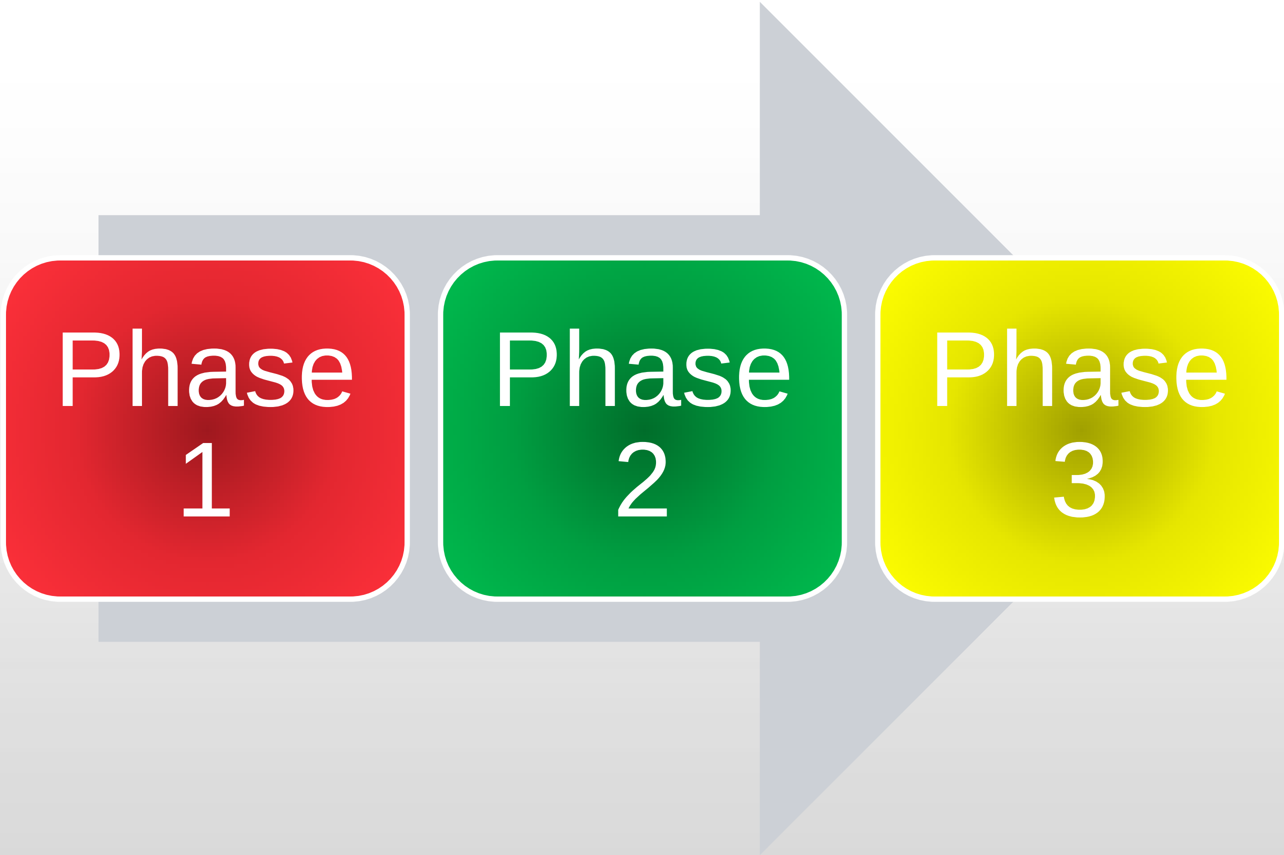
Multiple actors

- Different demand patterns
- Different preferences

Dynamic context

- Fluctuating meteorological conditions
- Development of the urban landscape

Research Contributions



Phase 1

- The generic form of the modified energy hub concept with network model is presented.
- Two case studies are presented to demonstrate the benefits of energy hub network.
- Distributed energy is shown to provide economic and environmental advantages.
- Multi criteria optimization of the economic and environmental performance is done.

Maroufmashat,A. , Elkamel,A. , Sattari khavas, S. , Fowler, M., Roshandel,R, Elsholkami,M., "*Development of the Energy Hub Networks Based on Distributed Energy Technologies*", SCSC 2015, July 26-29, 2015, Chicago, IL, USA. To be appeared in the ACM proceeding.

Azadeh Maroufmashat, Ali Elkamel, Michael Fowler, Sourena Sattari, Amir Hajimiragha, Sean Walker, Evgueniy Entcheve, "*Modeling and Optimization of a Network of Energy Hubs to Improve Economic and Emission Considerations*", *Energy,* vol. 93, Part 2, pp. 2546-2558, 12/15/ 2015

Phase 2

Developing a generic mathematical model for the optimal management of energy demands in a community where hydrogen is used as an energy vector.

- MILP based model of energy hub network is developed.
- The benefit of a distributed hydrogen production is presented.
- A case study comprising of four energy hubs are considered.
- The greenhouse emissions and urban pollution offsets are investigated.
- Optimum results are compared with four scenarios to show its performance.

Azadeh Maroufmashat, Michael Fowler, Sourena Sattari, Ali Elkamel , Ramin Roshandel, Amir Hajimiragha, "*Mixed Integer Linear Programing Based Approach For Optimal Planning And Operation Of A Smart Urban Energy Network To Support The Hydrogen Economy*", accepted, doi:10.1016/j.ijhydene.2015.08.038, Journal of Hydrogen Enegry, Aug. 14, 2015.

Azadeh Maroufmashat, Michael Fowler, Sourena Sattari, Ali Elkamel , *Optimal Operation Of an Energy Hub Network in the Context Of Hydrogen Economy*", ICH2P, May 3-5, 2015, Oshawa, ON, Canada

Phase 3

- Multi-energy hub network framework is developed for DES planning in urban area.
- Multi-objective optimization based on augmented ε-constraint method is performed.
- Optimal design and operation of energy hubs and their network can be derived out of developed model.
- The proposed model is applied to a case study in Ontario, Canada where it is simulated under different scenarios.

A. Maroufmashat, S. Sattari, R. Roshandel, A. Elkamel, M. Fowler,, "Multi-objective Optimization for Design and Operation of Distributed Energy Systems through the Multi-energy Hub Network Approach," Applied Energy, Under Review, since Oct. 2015

Phase 1

In this phase the optimal operational scenario where existing technologies are networked together is demonstrated.

Energy Hub definition

✓ Energy hub is an interface between energy producers, consumers and the transportation infrastructure.

✓ From a system point of view, an energy hub is a unit that provides the basic features

- in- and output,
- conversion, and storage of multiple energy carriers.

holistic approach to distributed energy systems

Advantages

- greenfield approach for future energy supply systems
- integrating multiple energy carriers
- increased reliability, load flexibility, and system performance
- synergies among various forms of energy bring a great opportunity for system improvements and new technology entrance

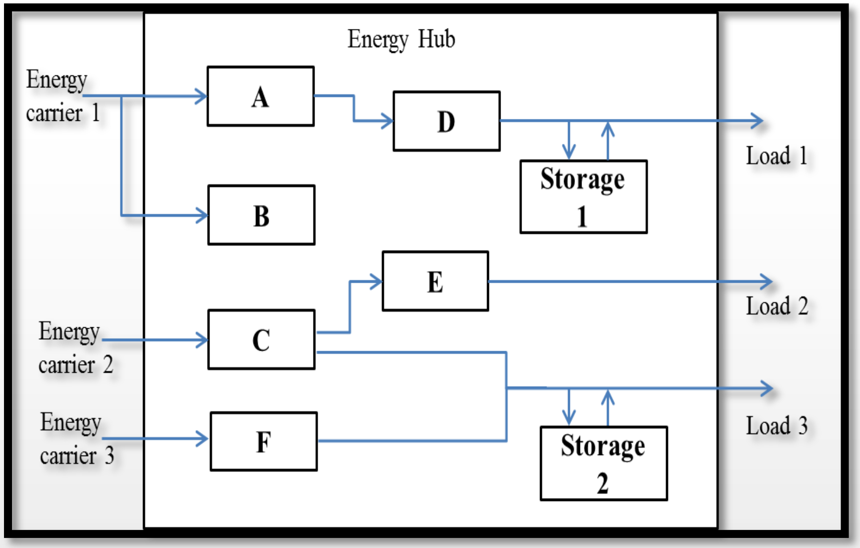
Geidl .M, et all, The Energy Hub – A Powerful Concept for Future Energy Systems ,Third Annual Carnegie Mellon Conference on the Electricity Industry, 13 – 14 March 2007

Energy hub Modeling Formulation

output energy flow

input energy carrier

$$\underbrace{\begin{bmatrix} L_1 \\ L_2 \\ . \\ L_i \\ . \\ L_I \end{bmatrix}}_{L(t)} = \underbrace{\begin{bmatrix} C_{11} & C_{12} & .. & C_{1j} \\ C_{21} & C_{22} & .. & C_{2j} \\ . & . & . & . \\ . & . \; C_{ij} & . & . \\ . & . & . & . \\ C_{I1} & . & . \; . & C_{IJ} \end{bmatrix}_{I\times J}}_{C(t)} . \mathrm{I}_{J\times J} . \vec{\mathrm{b}} . \underbrace{\begin{bmatrix} P_1 \\ P_2 \\ . \\ P_j \\ . \\ P_J \end{bmatrix}_{J\times 1}}_{P(t)}$$



Energy Storage Modeling

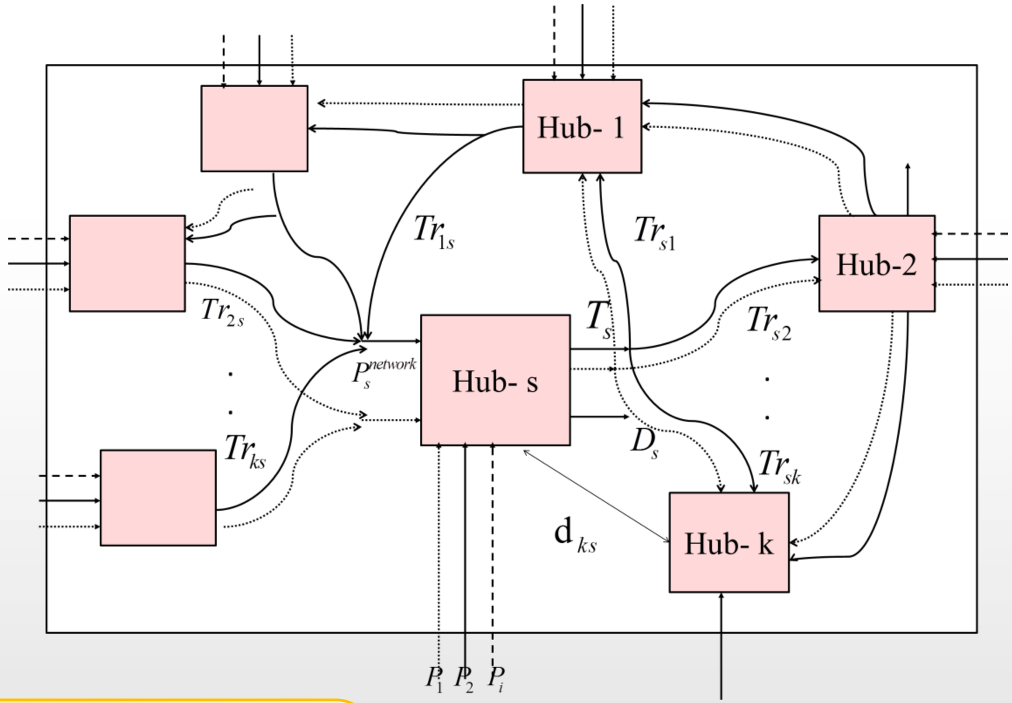
$$\mathrm{M(t) = M(t-1) + A^{ch}Q^{ch}(t) - A^{dis}Q^{dis}(t) - M^{stdby}}$$

$$L(t) = C(t).I_{J\times J}.b.P(t) - Q^{ch}(t) + Q^{dis}(t)$$

Network Modeling

$$T_s = \sum_{k \in S-\{s\}} Tr_{sk}$$

$$P_s^{network} = \sum_{k \in S-\{s\}} f(d_{ks}).Tr_{ks}$$



The output energy carrier divided into two parts:

- ❑ Energy for supplying the demand within the hub,
- ❑ and the rest for sending to other hubs.

Objective Function

- **Cost**
  - O&M Cost
  - Fuel Cost
- **CO_2 emission**
- Weighted sum method

Constraints

- **Hub energy flow balance**
- **Network balance equation**
- **Energy flow limit**

$$P_{s,j}^{min} \leq P_{s,j,m,h} \leq P_{s,j}^{max}$$

$$Tr_{sk,i}^{min} \leq Tr_{ks,i,m,h} \leq Tr_{sk,i}^{max}$$

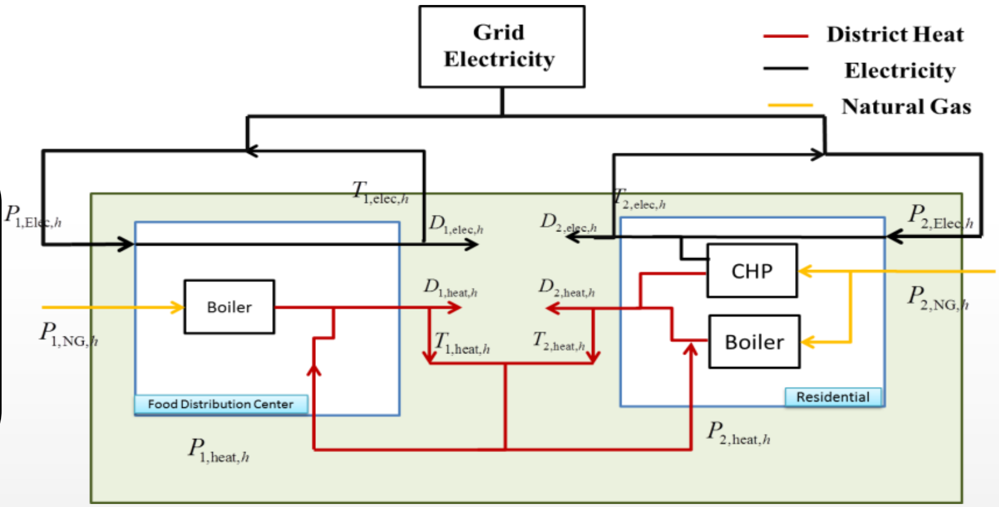
- **Energy conversion technology limit**

$$E_{s,j}^{min} \leq E_{s,i,j,m,h} \leq E_{s,j}^{max}$$

- **Simultaneous selling and purchasing energy carriers**

$$\begin{cases} P_{s,j,m,h} \leq \chi_{s,j,m,h} . M \\ T_{s,i,m,h} \leq \lambda_{s,i,m,h} . M \\ \chi_{s,j,m,h} + \lambda_{s,i,m,h} \leq 1 \end{cases}$$

Illustrative Case Studies



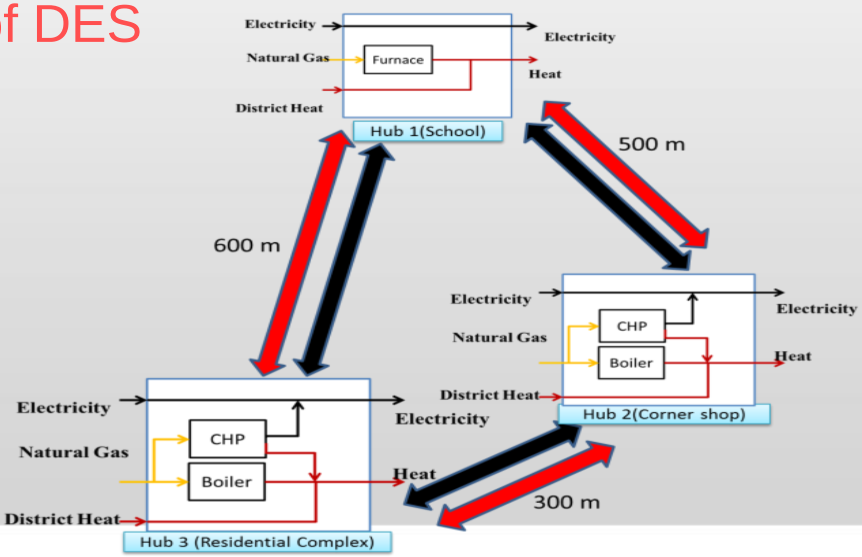
Input Data

- **Hourly energy demand**
- **Market information**
- **Technical information**
- **Environnemental information**
- **Energy Conversion technologies modeling**

Different scenarios illustrated the effect of network modeling between energy hubs and the use of DES

Decisions includes:

- Operation of energy conversion technologies.
- Operation of network



Results

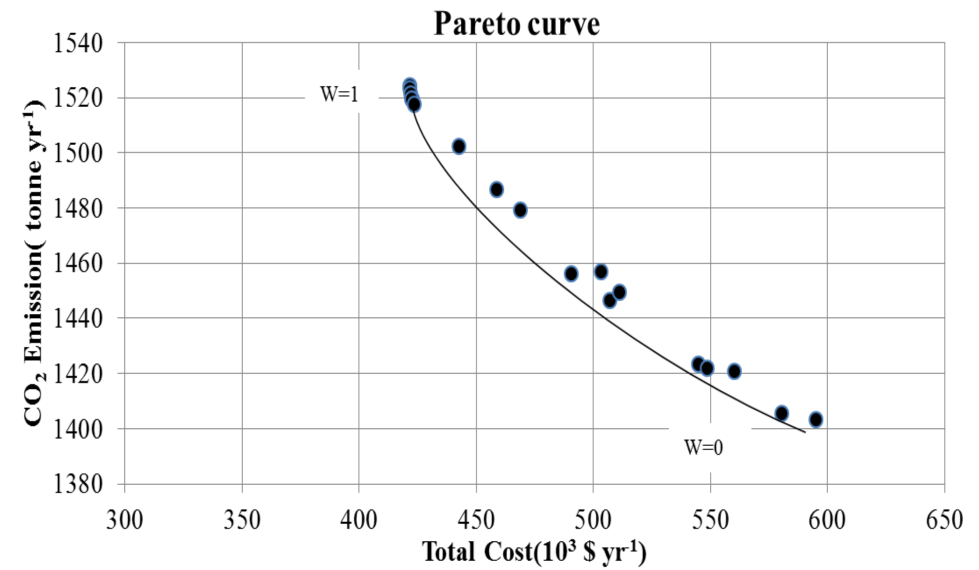
In Case Study 1:
0.5% reduction in total cost / 3% reduction in CO_2 emission.
In Case Study 2:
economic benefit (11% to 29%), and emission reduction benefit11%, and reduction in natural gas (13%).

The networks of energy hubs:
need for some diversity in load profiles,
and a larger number of hubs in order to achieve significant benefits.

Comparing Scenarios :
- the addition of a DES (CHP/PV/SC) and interaction between the energy hubs lowers overall energy costs.

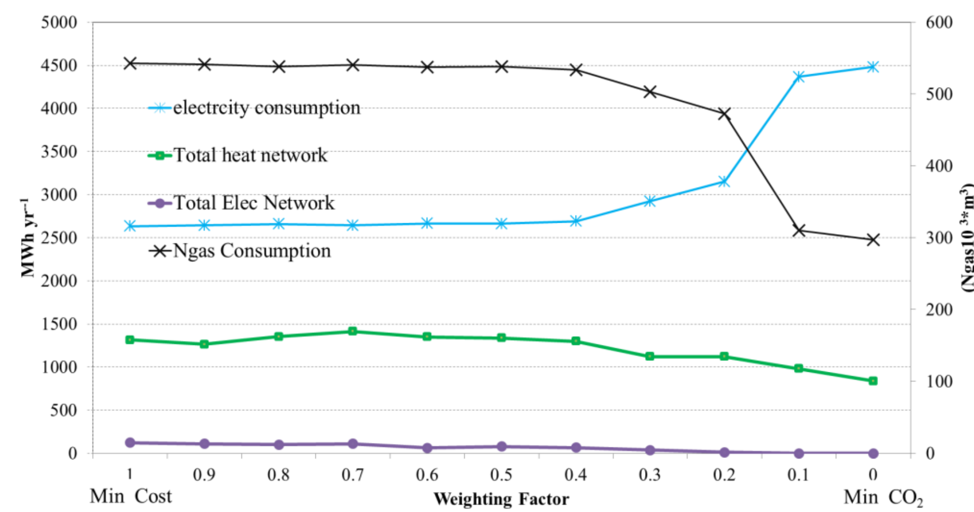
Results Cntd.

Relationship between Cost and CO_2 emissions for Scenario 4 with energy hub interactions and two CHPs total installed (one in the Shopping Plaza and one in the residential complex) in Case Study 2.



CO_2 emissions of Ontario's electricity grid less than that of Natural gas

the benefits of a distributed CHP are limited by a clean electrical grid system



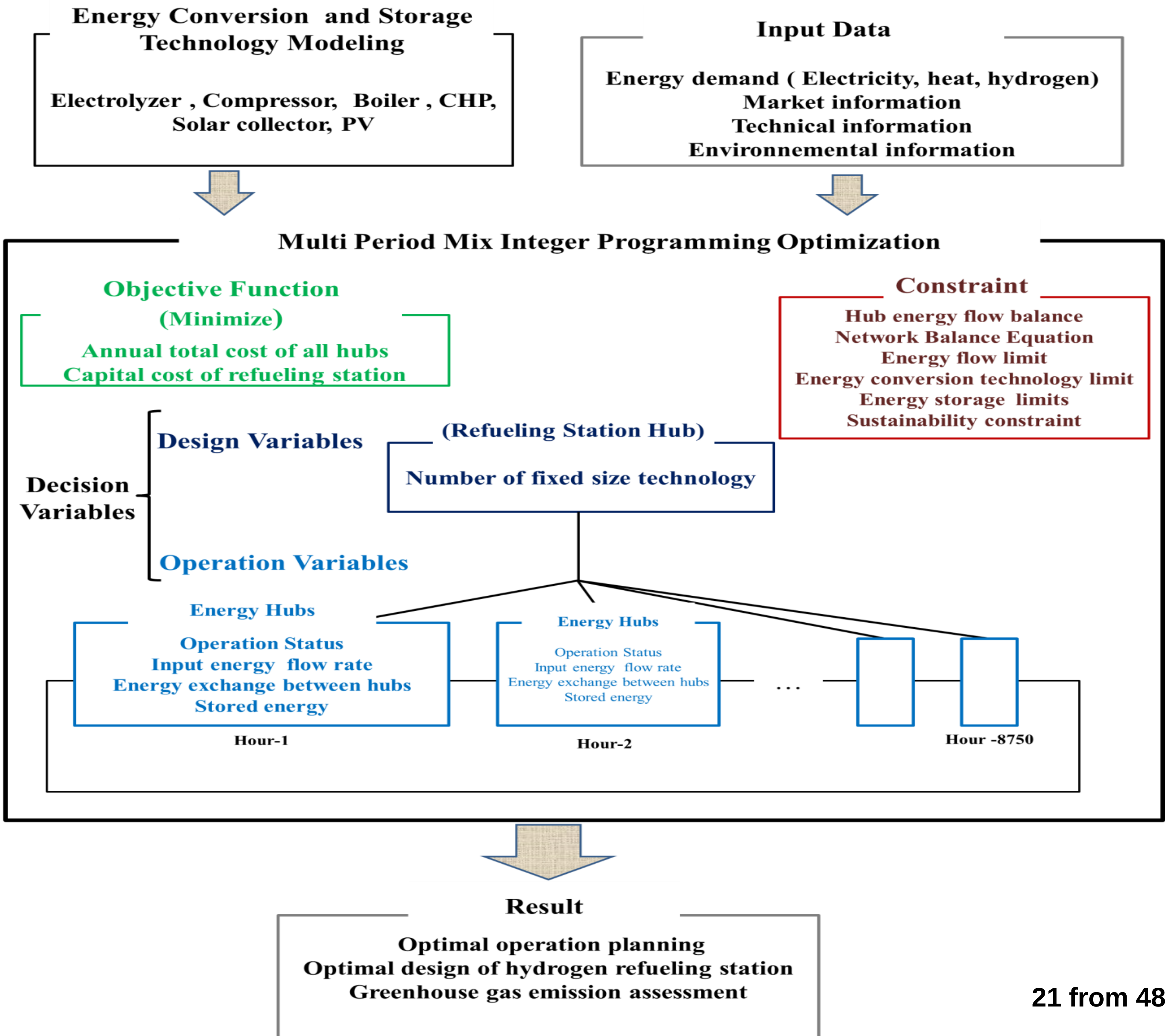
Phase 2

Developing a generic mathematical model for the optimal management of energy demands in a community where hydrogen is used as an energy vector.

how to optimally design a hydrogen refuelling station in an urban area where energy hubs can exchange their surplus energy with one another.

The generation of hydrogen in a distributed fashion is advantageous as it eliminates the need for pipeline or tanker truck distribution, while making use of existing electrical distribution system infrastructure.

The use of off-peak electricity from the grid makes optimal use of this existing infrastructure without generating grid congestion.


Energy Conversion and Storage Technology Modeling
Electrolyzer , Compressor, Boiler , CHP, Solar collector, PV
Input Data
Energy demand (Electricity, heat, hydrogen)
Market information
Technical information
Environnemental information
Multi Period Mix Integer Programming Optimization
Objective Function (Minimize)
Annual total cost of all hubs
Capital cost of refueling station
Constraint
Hub energy flow balance
Network Balance Equation
Energy flow limit
Energy conversion technology limit
Energy storage limits
Sustainability constraint
Decision Variables
Design Variables
(Refueling Station Hub)
Number of fixed size technology
Operation Variables
Energy Hubs
Operation Status
Input energy flow rate
Energy exchange between hubs
Stored energy
Hour-1
Energy Hubs
Operation Status
Input energy flow rate
Energy exchange between hubs
Stored energy
Hour-2
. . .
Hour -8750
Result
Optimal operation planning
Optimal design of hydrogen refueling station
Greenhouse gas emission assessment

Energy Conversion Technology Modeling

Electrolyser Modeling

$$P_{s,\mathrm{elec}_{H_2},m,h}.\eta_{El} = E_{s,\mathrm{elec},H_2\,FC,m,h}$$

$$E_{s,\mathrm{elec},H_2\,FC,m,h} = f\left(\frac{P_{s,\mathrm{elec}_{H_2},m,h}}{P_{elec,rated}}\right)\times 2\times \dot{n}_{elec,H_2,rated}$$

Compressor Modeling

$$P_{comp} = 2\times E_{s,\mathrm{elec},H_2\,FC,m,h}\,\frac{W_{comp,th}}{\eta_{comp}}$$

$$W_{comp,th} = \bar{z}RT_{in}\,\frac{k}{2(k-1)}\left[\left(\frac{p_{out}}{p_{in}}\right)^{k-1/k} - 1\right]$$

Boiler Modeling

$$P_{s,NG_{boiler},m,h}.\eta_{boiler}.\,\mathrm{LHV}_{NG} = E_{s,NG_{boiler},heat,m,h}$$

CHP Modeling

$$P_{s,NG_{CHP},m,h}.\eta_{CHP_{elec}}.\,\mathrm{LHV}_{NG} = E_{s,NG_{CHP},\mathrm{elec},m,h}$$

$$P_{s,NG_{CHP},m,h}.\eta_{CHP_{Thermal}}.\,\mathrm{LHV}_{NG} = E_{s,NG_{CHP},\mathrm{heat},m,h}$$

Solar PV Modeling

$$P_{s,Solar_{elec},m,h}.\eta_{PV}.\sigma_{s,solar} = E_{s,\mathrm{Sun,elec},m,h}$$

$$P_{s,Solar_{elec},m,h} = I.A_{s,PV}$$

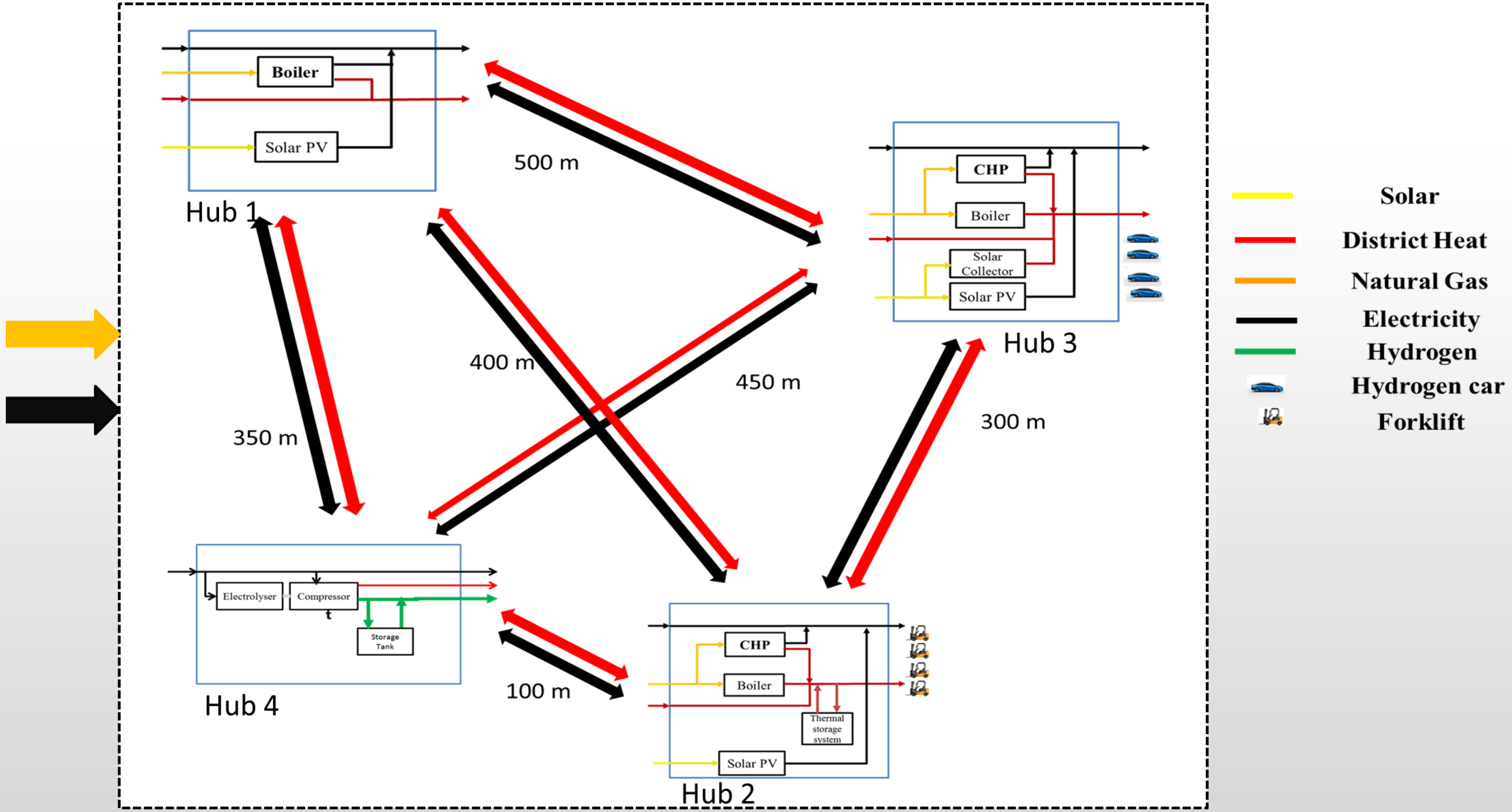
$$A_{s,PV} \le A_{s,\mathrm{PV}}^{\max}$$

Solar Collector Modeling

$$P_{s,Solar_{heat},m,h}.\eta_{SC} = E_{s,\mathrm{Sun,heat},m,h}$$

$$P_{s,Solar_{heat},m,h} = I.A_{s,collector}$$

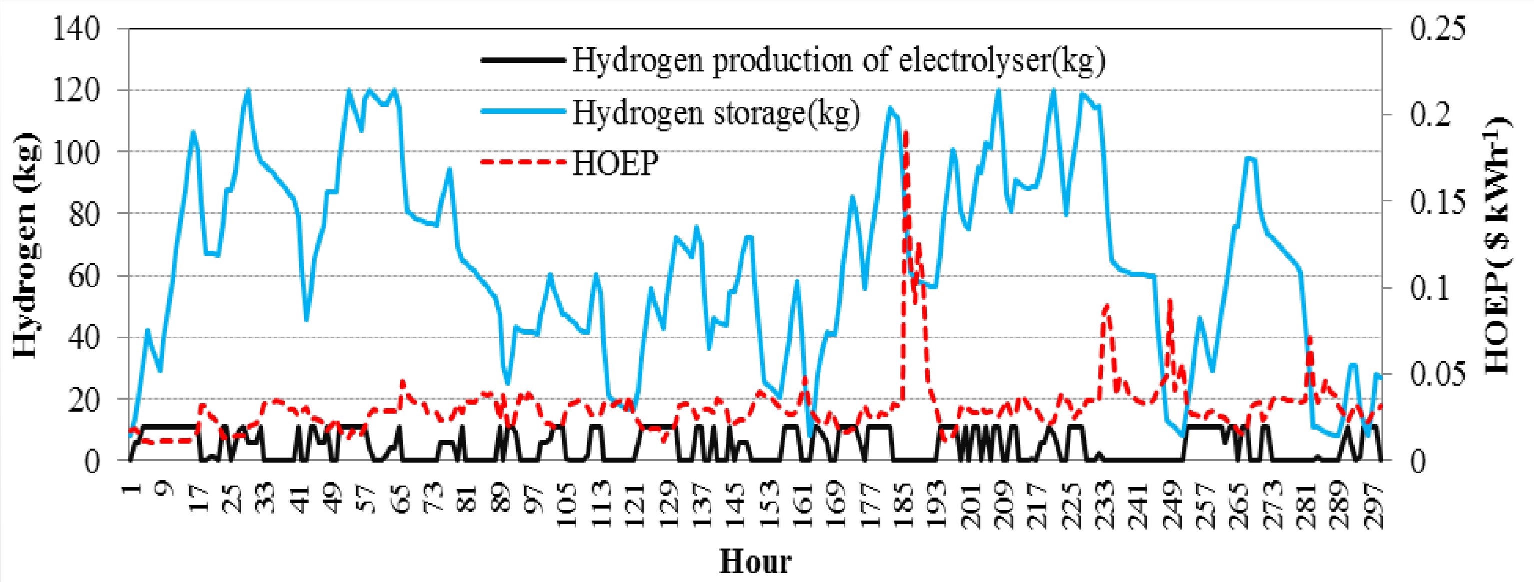
Case Study



Energy hub 1 : school (530-kW boiler/ solar PV of 50-m²)
Energy hub 2 : food distribution center (300-kW CHP/147-kW boiler/ HST/100-m² PV)
Energy hub 3 : Residential complex (100-kW CHP/300-kW boiler/SC 80-m² /PV 80-m²)

Results

Annual cost of optimal system	million $ 1.486
Annual CO_2 emissions	3,685 tonnes
Number of 290-kW alkaline electrolysers	2
Number of 30-kg hydrogen storage tanks	4

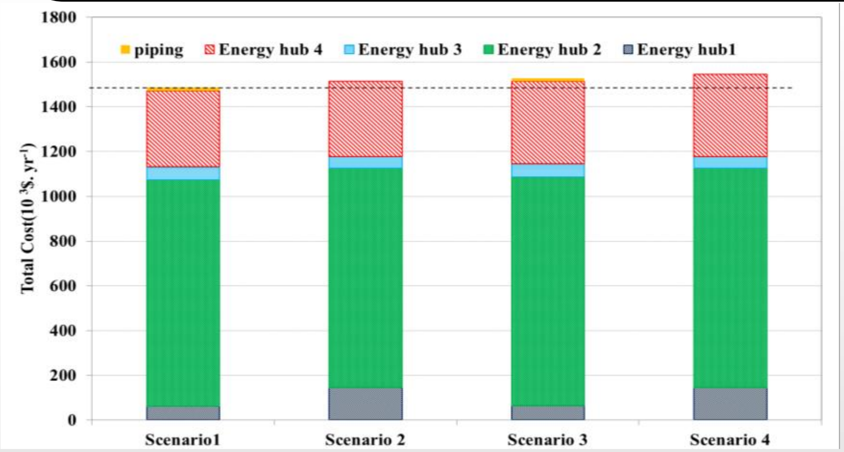


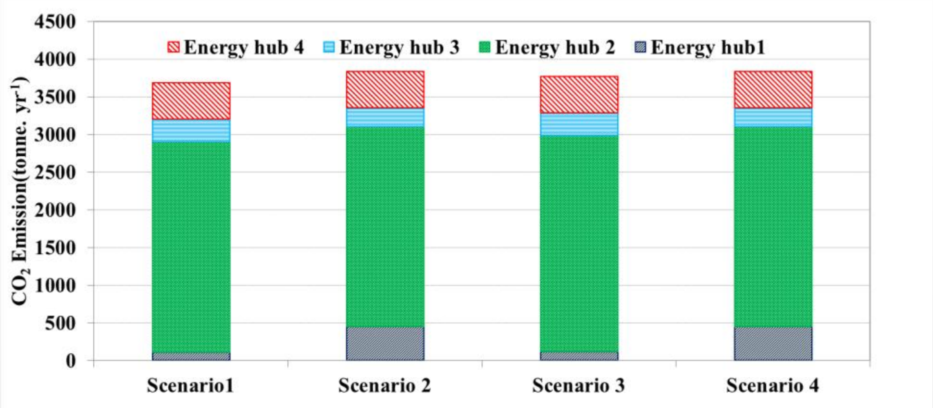
The average HOEP ≤ $0.036 per kWh/Electrolyser operates
The average HOEP≥ $0.13 per kWh/No operates

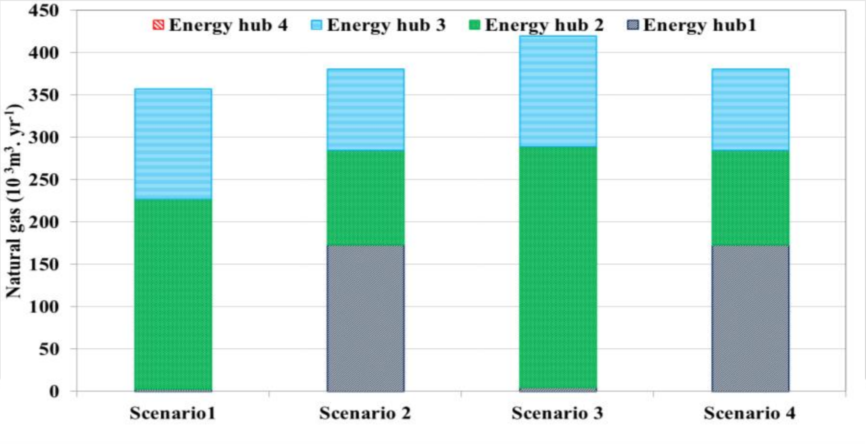
The levelized cost of hydrogen : $6.74 per kg

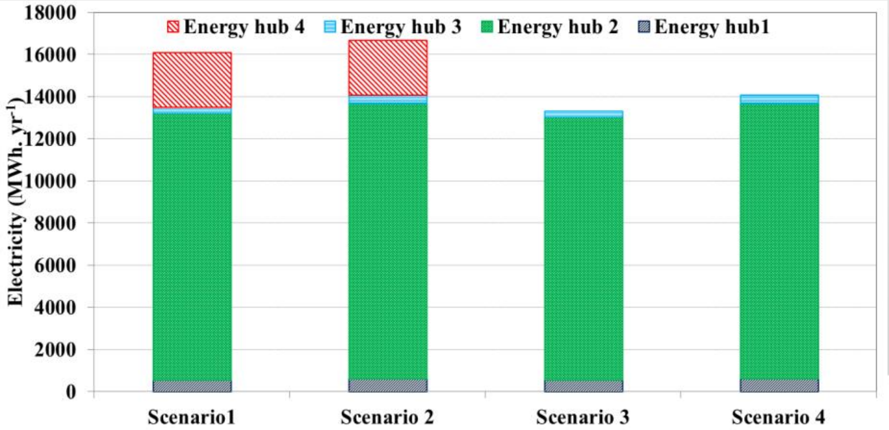
Results-Contd.

Scenario 1: Distributed hydrogen production and interaction between hubs;
Scenario 2: Distributed hydrogen production/No interaction between hubs;
Scenario 3: Hydrogen purchase and interaction between hubs; and,
Scenario 4: Hydrogen purchase/ No interaction between hubs.









Highlights

- ✓ A **MILP** optimized network of energy hubs that demonstrates the **benefit of a distributed hydrogen energy production** system within the context of interaction in a smart urban energy network

- ✓ **Distributed hydrogen production** is **better** than **H_2 delivery** in environmental and economic comparison;

- ✓ Greenhouse emissions and urban pollution will be decreased by **using hydrogen cars and forklifts** in urban energy systems;

- ✓ **A network of energy hubs** is **better** than **a single facility**, or an isolated hydrogen refuelling station;

Phase 3

- Multi-energy hub network framework is developed for DES planning in urban area.
- Multi-objective optimization based on augmented ε-constraint method is performed.
- Optimal design and operation of energy hubs and their network can be derived out of developed model.
- The proposed model is applied to a case study in Ontario, Canada where it is simulated under different scenarios.

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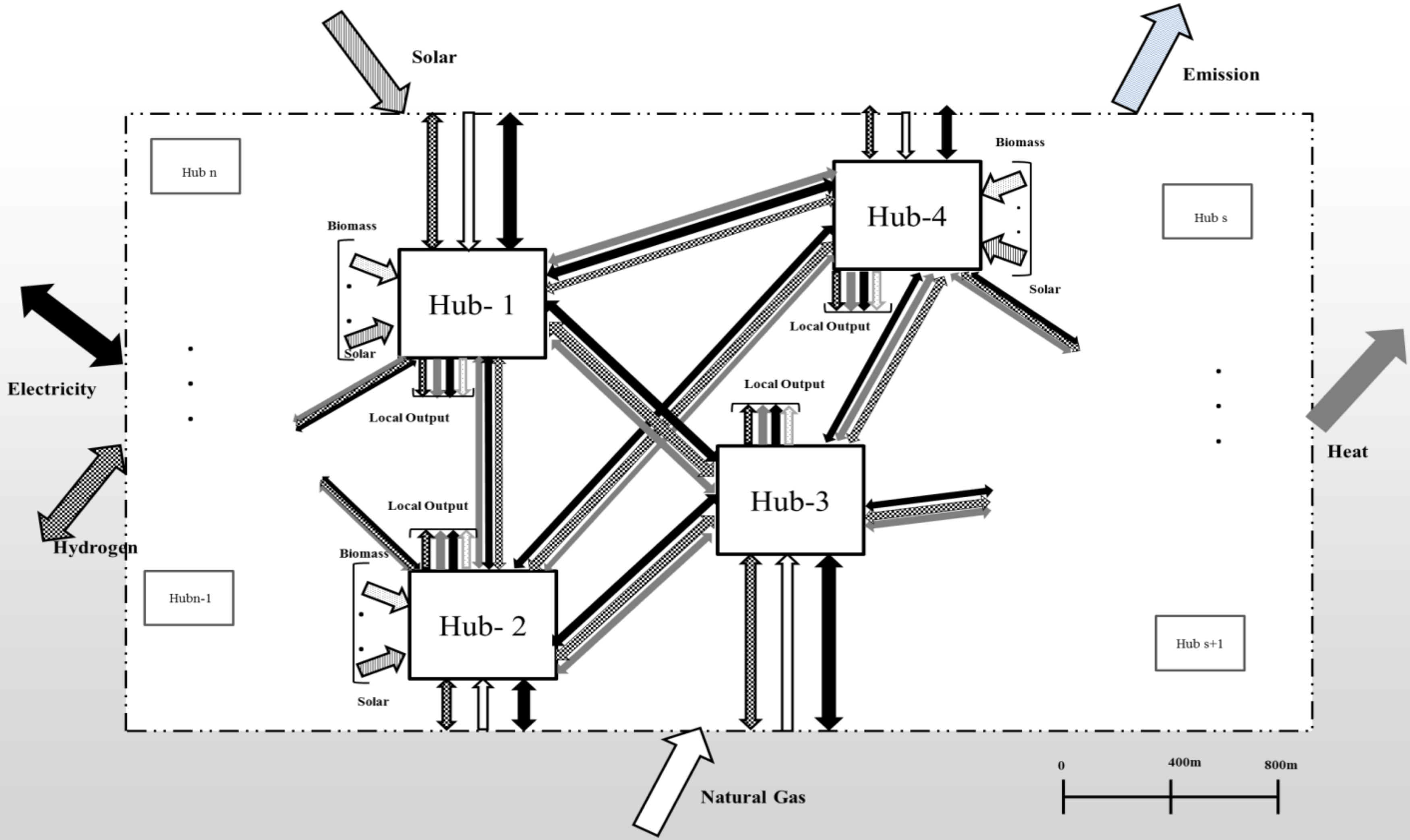
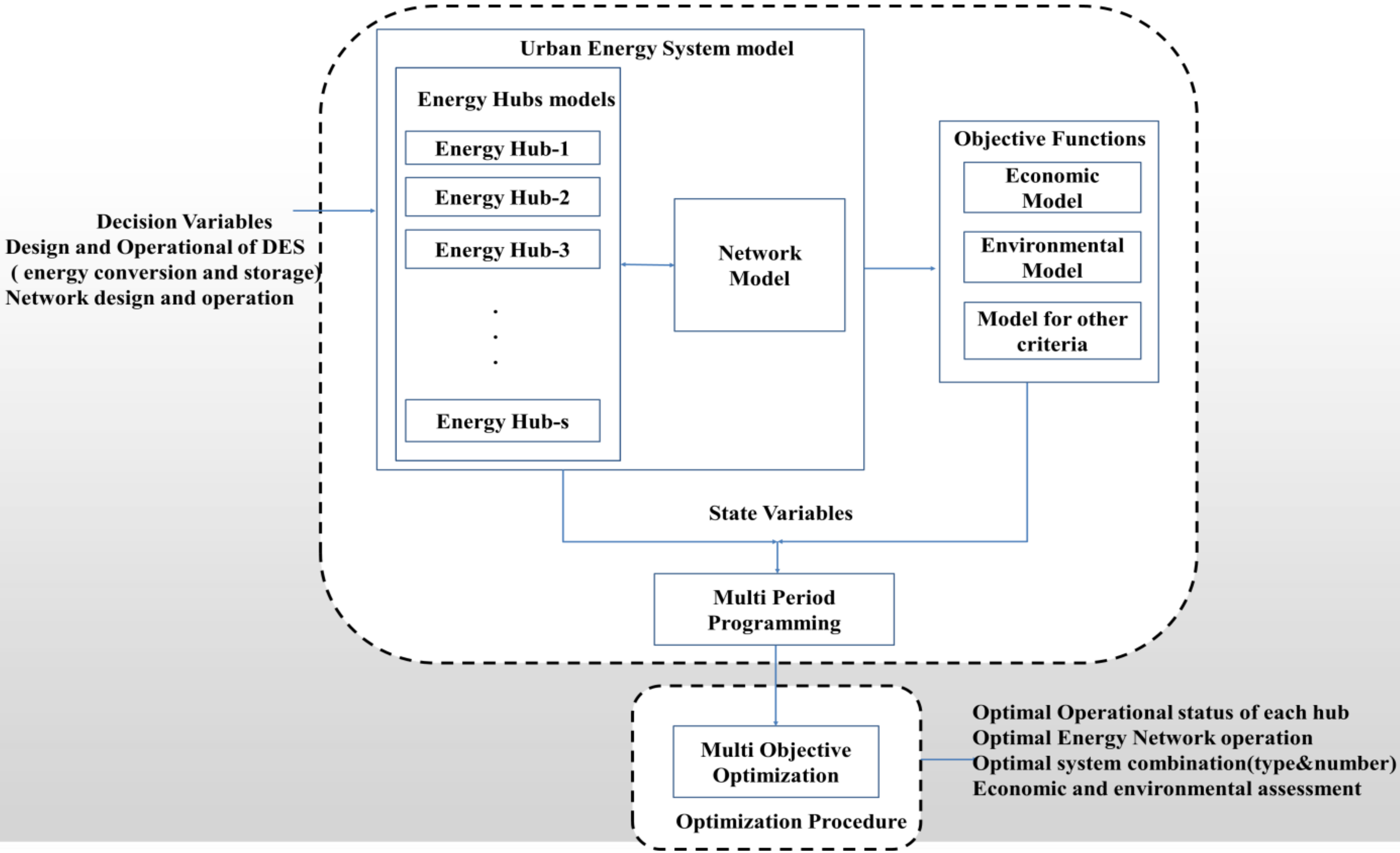
Superstructure



Framework

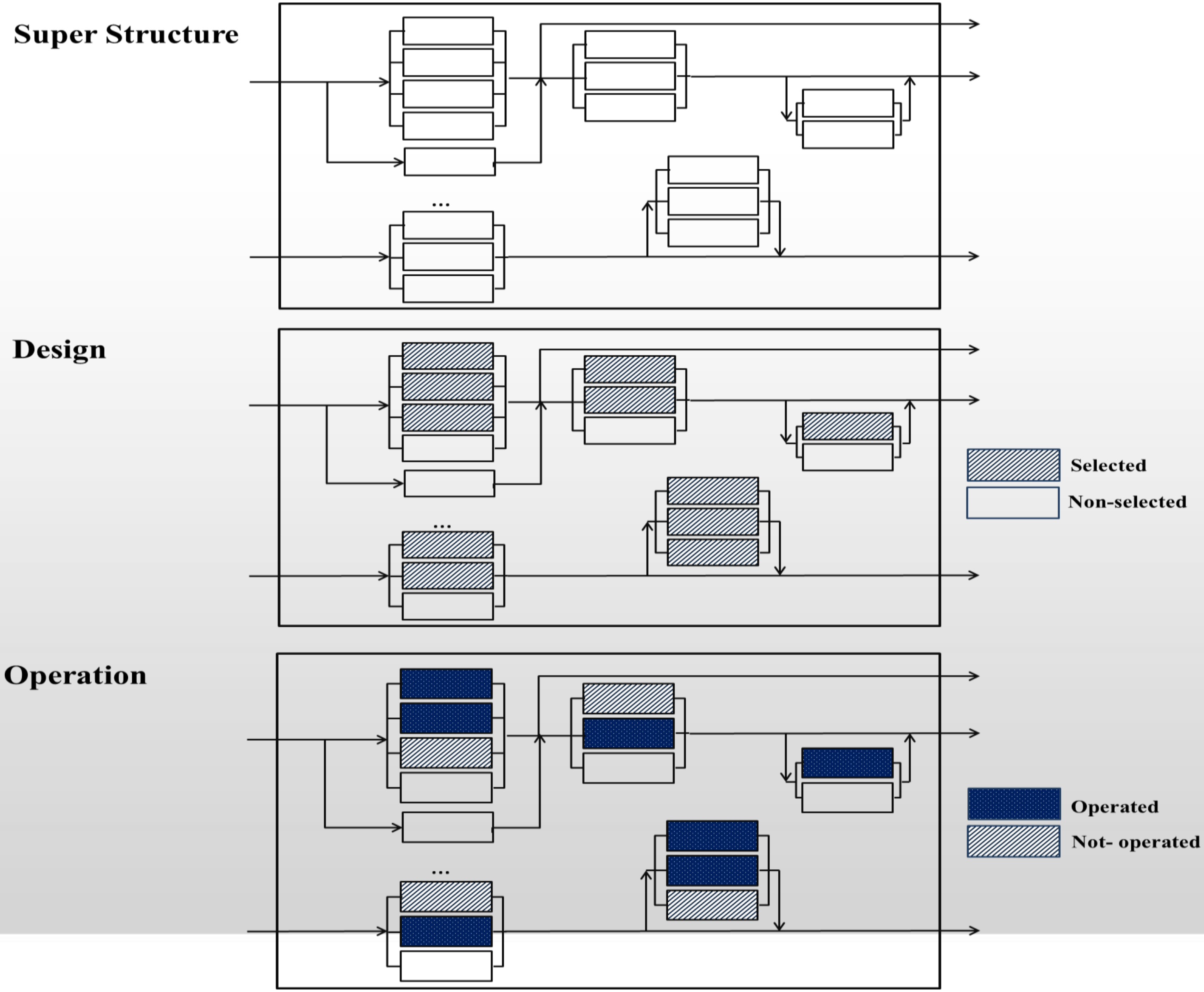


Urban Energy System model
Energy Hubs models
Energy Hub-1
Energy Hub-2
Energy Hub-3
Energy Hub-s
Network Model
Objective Functions
Economic Model
Environmental Model
Model for other criteria
Decision Variables
Design and Operational of DES
(energy conversion and storage)
Network design and operation
State Variables
Multi Period Programming
Multi Objective Optimization
Optimization Procedure
Optimal Operational status of each hub
Optimal Energy Network operation
Optimal system combination(type&number)
Economic and environmental assessment

Model output

- Optimal types, capacities, and numbers of DES installed in each building
- Optimal capacities of the storages installed in each building
- Optimal structure of the energy distribution networks
- Optimal dispatch of DES
- Amount of energy stored or released by the storages in each period
- Amount of energy transferred through each pipeline/wire in each period
- Amount of Primary energies purchased from the external grid in each period
- Minimized annual total cost and CO_2 emission

Generic Energy hub Superstructure



Objective Function

Augmented ε Constrained Method

$$\mathrm{Min}Z = (Z_1 + \mu \times \frac{Sl_2}{r_2})$$

$$Z_2 + (S_2) = e_{2,i}$$

Total annual Cost

CO_2 Emission

$$Z_2 = \sum_s \sum_j \sum_h \sum_m CI_j \times P_{s,j,m,h} \times b_j$$

Capital Cost

$$Cost^s_{Cap} = \sum_j N_{s,j} \times E^{\max}_{s,i,j} \times c^{cap}_j \times CRF_j + \sum_i \sum_q NS_{s,i,q} \times c^{cap.stor}_i \times Sto^{\max}_{s,i,q} \times CRF_{i,q} + C^s_{replac.}$$

Operational Cost

$$Cost^s_{op} = \sum_m \sum_h \sum_i \sum_j E_{s,i,j,m,h} \times c^{op}_j + \sum_i \sum_j fr_j \times N_{s,j} \times E^{\max}_{s,i,j} \times c^{cap}_j + \sum_i \sum_q \sum_m \sum_h c^{op.stor}_i Sto_{s,i,m,h,q}$$

Fuel Cost

$$Cost^s_{fuel} = \sum_m \sum_h \sum_j P_{s,j,m,h} \times c^f_{j,h}$$

Network Cost

$$Cost^{network}_{Cap} = \sum_{k \in S-\{s\}} \omega_{sk} \times dist_{sk} \times c^{pipe}_i \times CRF$$

$$Cost^{network}_{op} = \sum_{k \in S-\{s\}} frac_i \times \omega_{sk} \times dist_{sk} \times c^{pipe}_i$$

Income

$$Income^s = \sum_m \sum_h \sum_i T_{s,i,m,h} \times price^{sell}_{s,i,m,h}$$

Constraints

Energy hub Modeling

- Energy balance of individual hub
- Energy flow constraint
- Energy conversion technology constraint
- DES selection constraint
- Energy Storage technology
- Sustainability constraint

Network Modeling

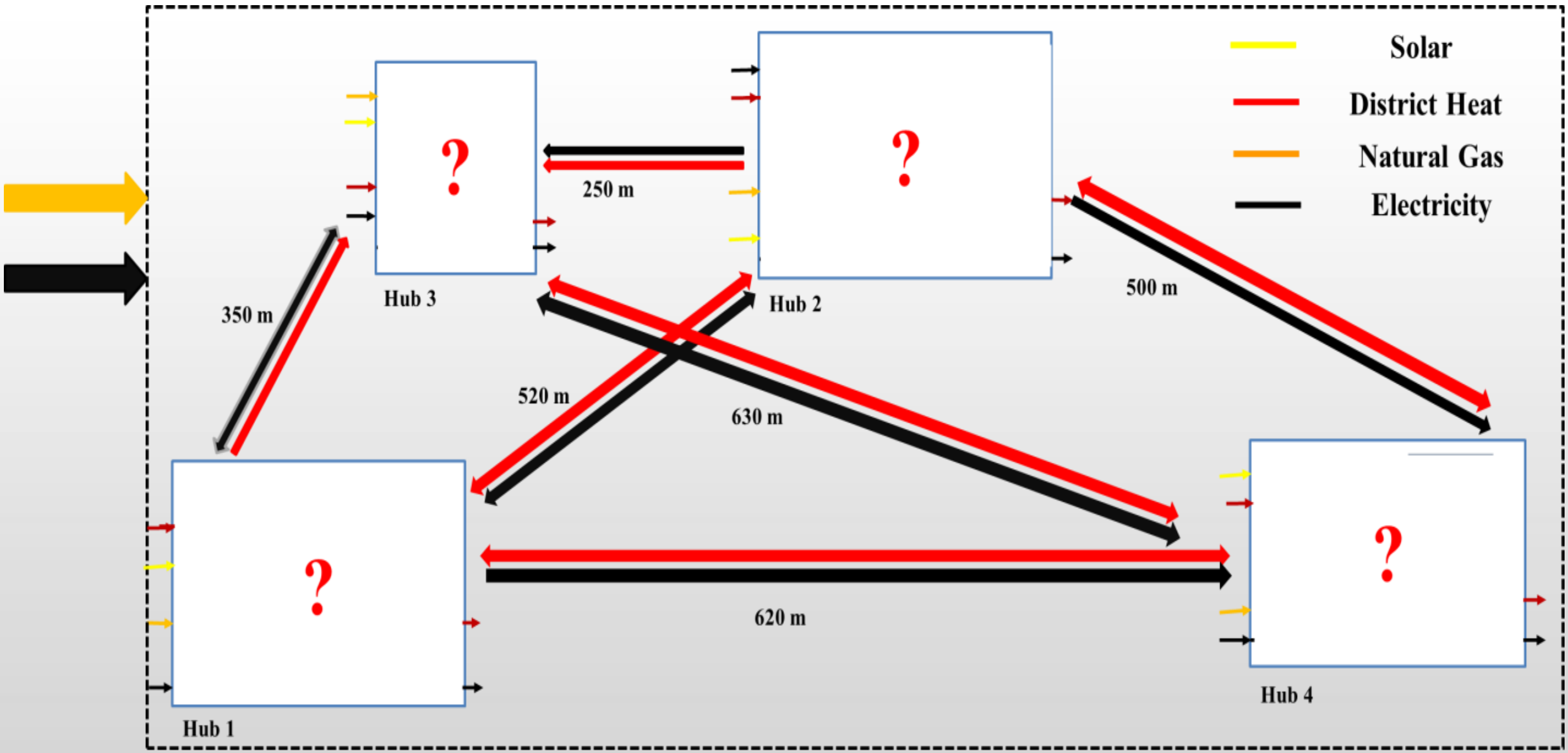
- Energy balance of hub network
- Network flow constraint

Energy conversion technology modeling

- Combined Heat and Power (CHP) technology
- Solar Collector and PV
- Heat storage/ Battery

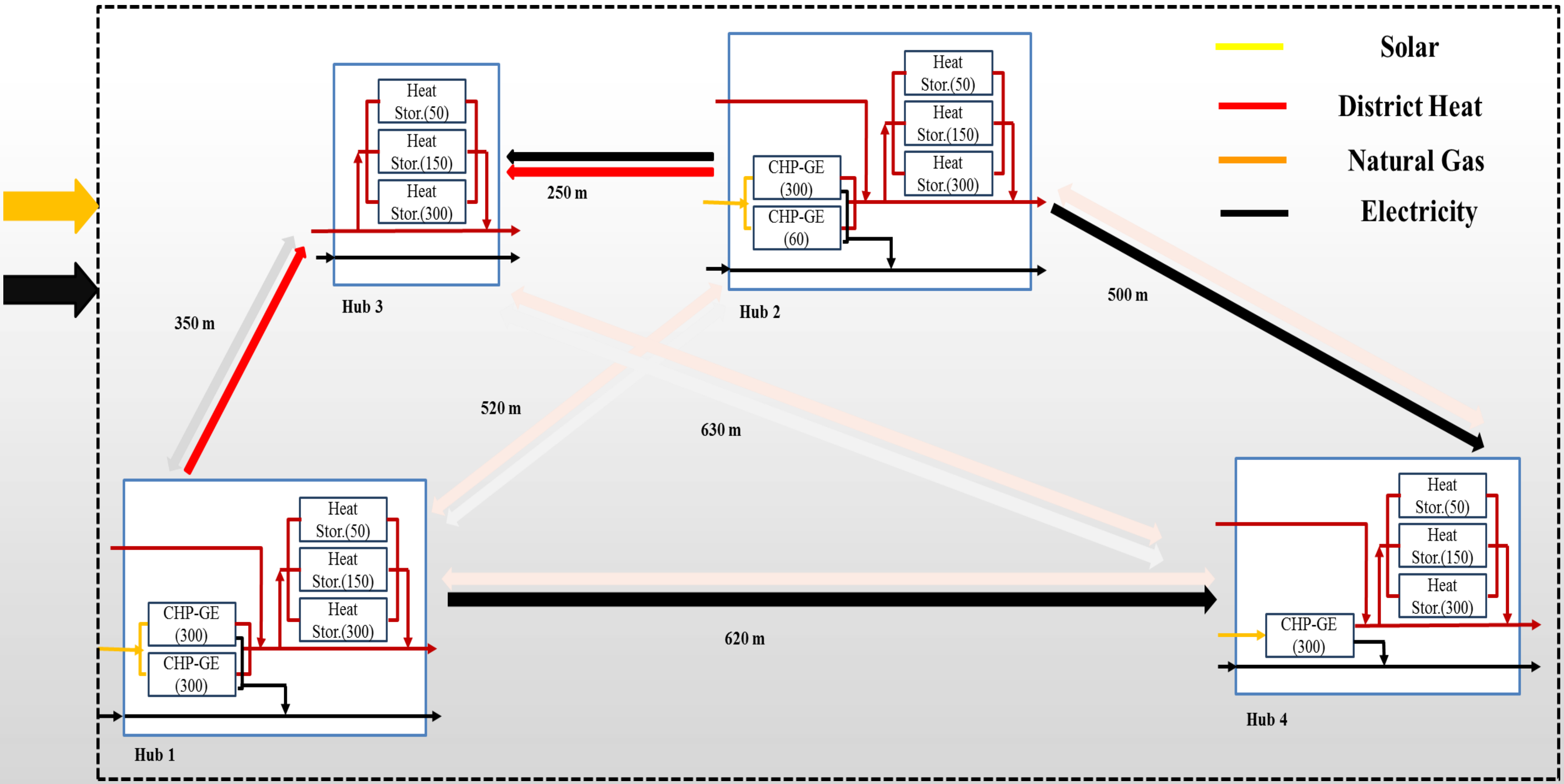
Case Study

residential complex (7765 m²),
office building (1000 m²),
commercial building (75,000 m²),
Restaurant (1000 m²)

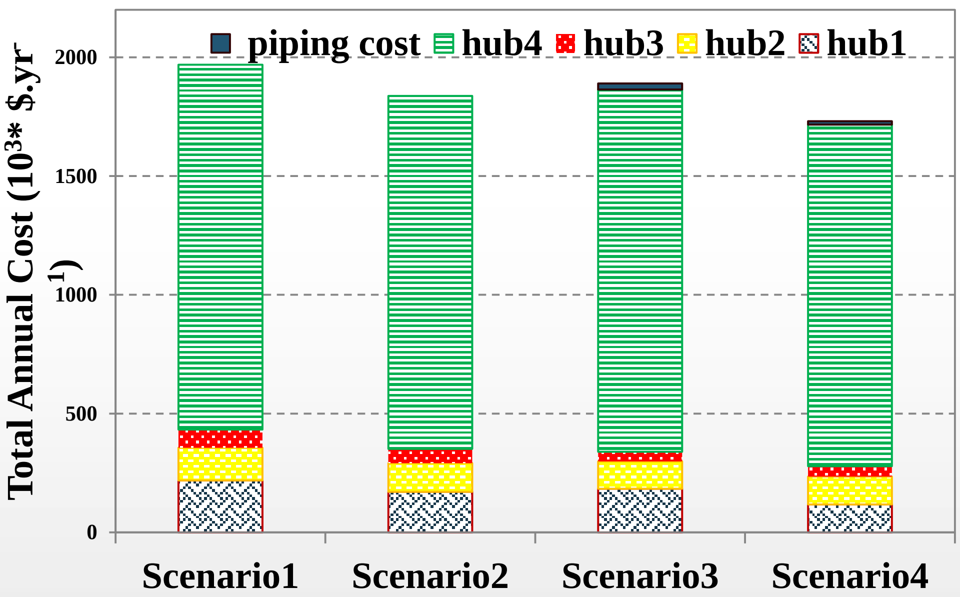


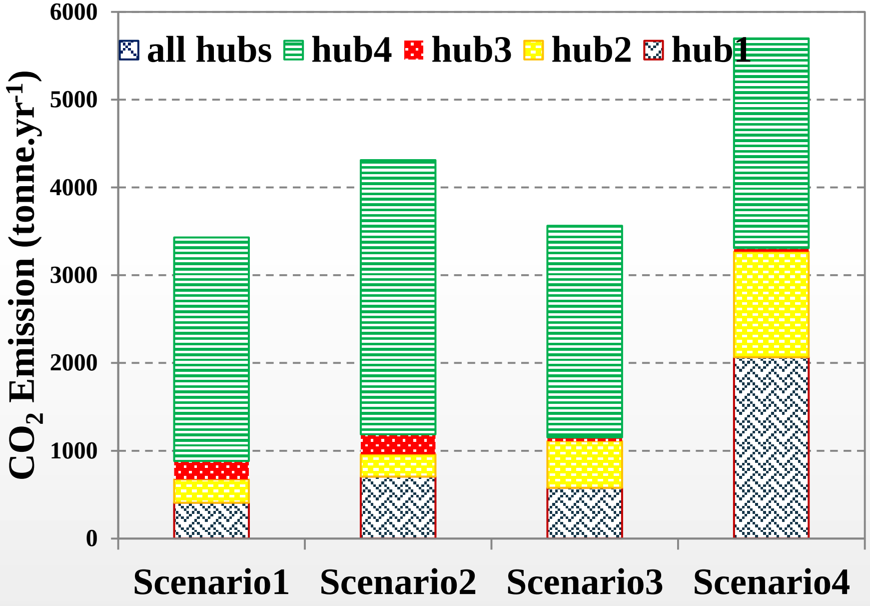
Different scenarios illustrated the effect of **<u>interaction/ DES/ Storage</u>**

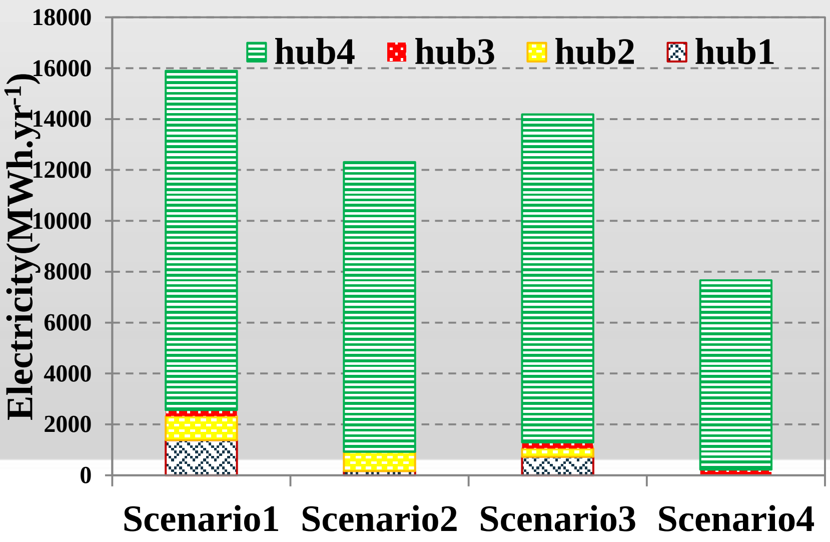
Optimal Technologies selection

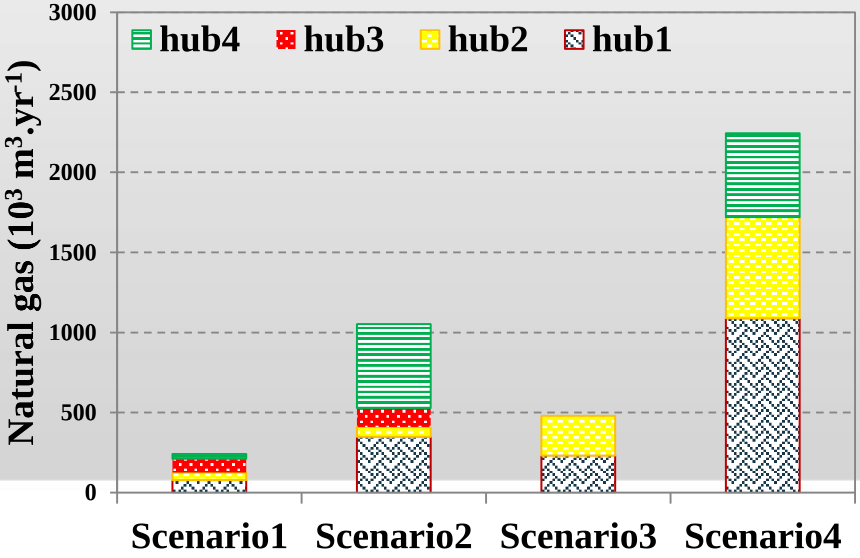


Scenario Results









Scenario Results

Considering **DES/ Network/ Storage**

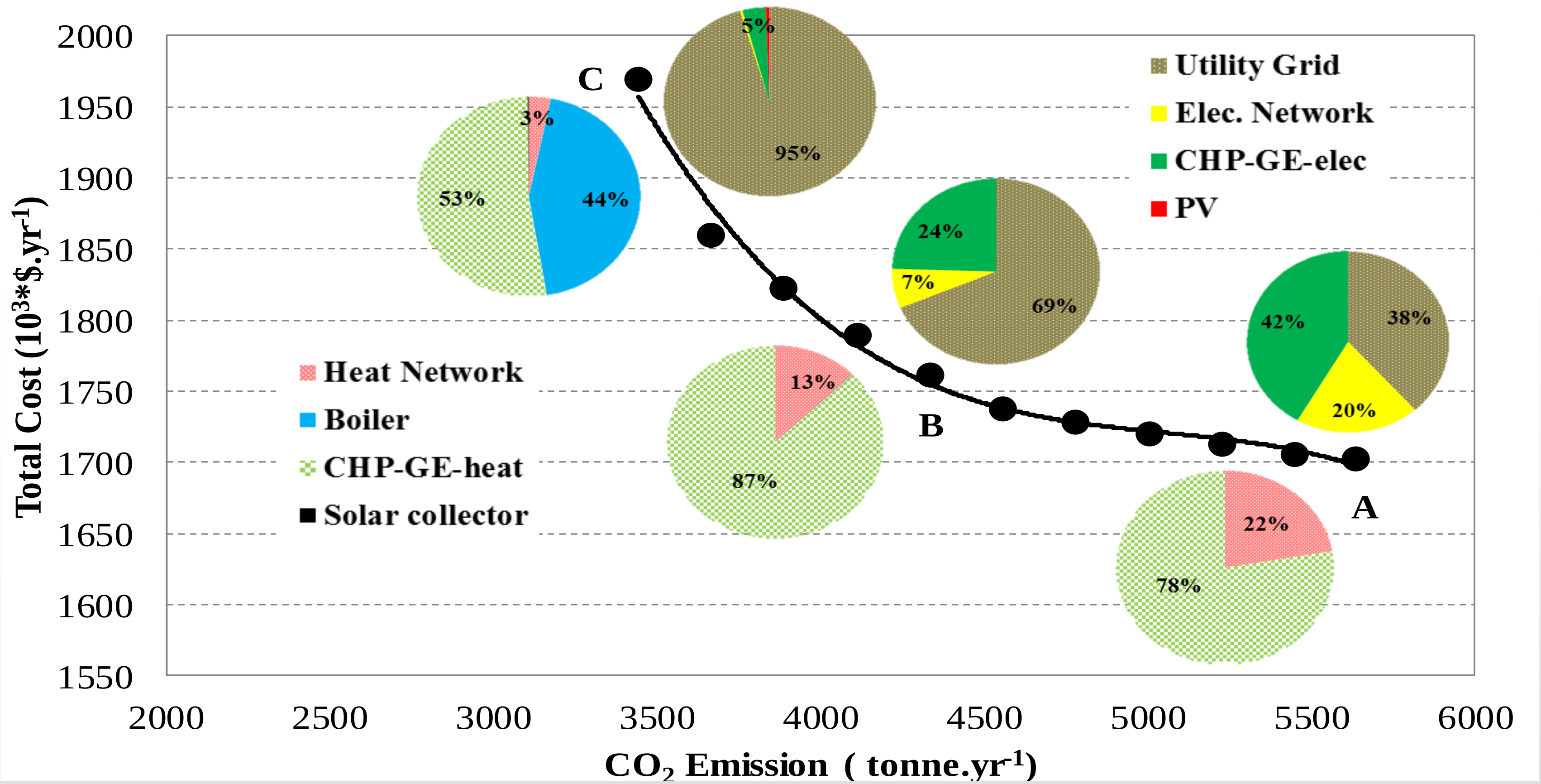
- 6% to 12 % reduction in total cost
- No reduction in CO_2 emission due to DES operation(66% increase!)
- Increase in Natural Gas Consumption/ Decrease in Electricity

- **Storage systems and energy network** (scenario3) have a **positive influence** on the **adoption of DES** in the system

- **Storage system** has **more effect** than **energy interaction** on **cost &electricity reduction**.

- DES (**ICE** based CHP and **thermal energy storage** systems are the most **suitable** for **adoption** in the optimal system, while the renewable DES are not.

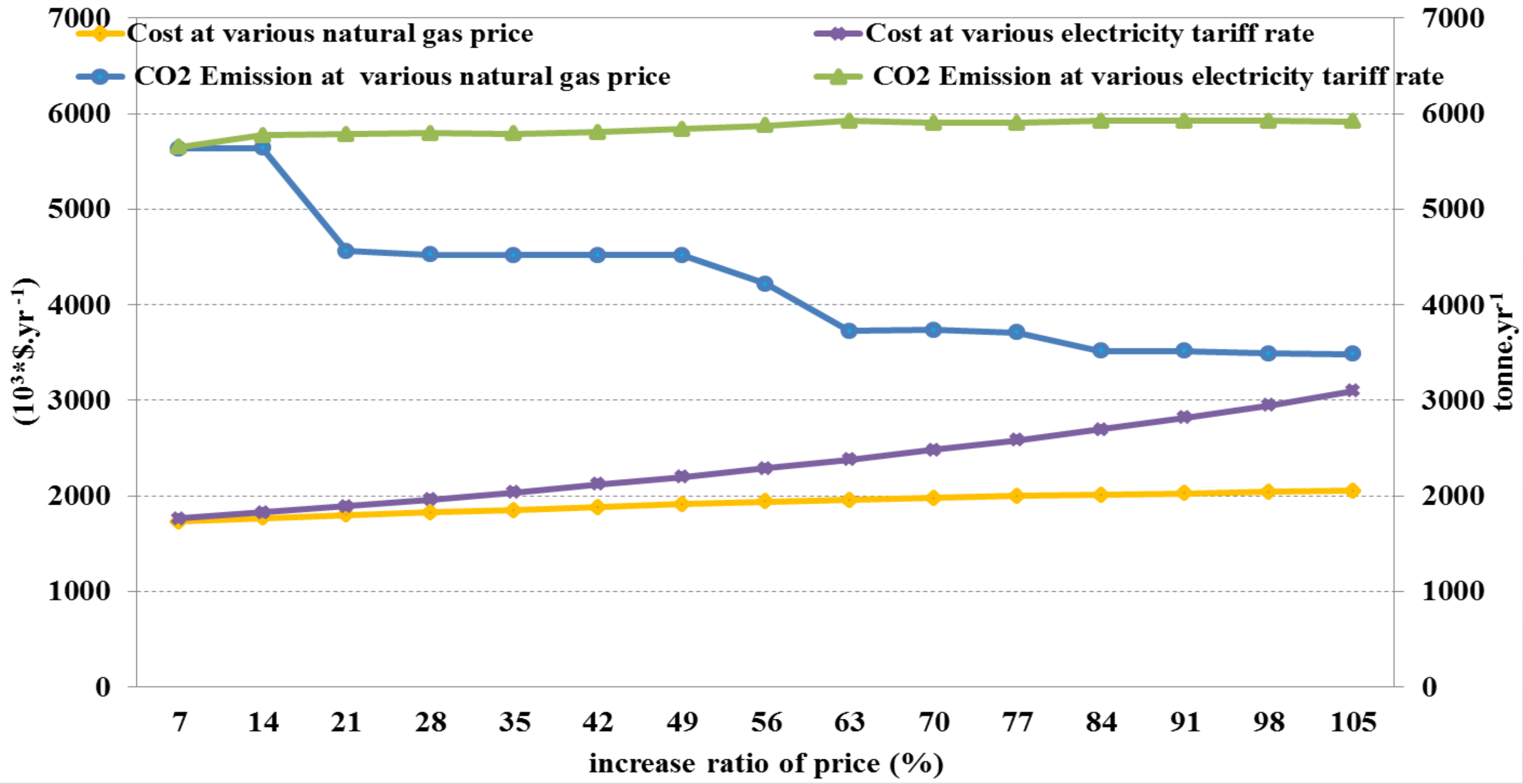
Multi-Objective Results



- **Decrease** in the **contribution of DES** by an **increase** in **significance of CO_2 emiss**
- The emission factor of Ontario's utility grid is less than that of natural gas.

❖ decision makers : Considering the **emission factors of the grid electricity** prior to **commitment to the DES cost**.

Sensitivity Analysis



- ➢ Doubling the **electricity tariff rate** : 75% **increase of cost**/ Emission increase)
- ➢ An **increase in natural gas price** : **No** significant effect on cost (**Technology change**) / reduction in emission.

❖ It demonstrates that **the cost** is more sensitive to the **electricity tariff rate** than **natural gas price** for **this specific case study**.

Summary

- The aim of this thesis was

  "***To provide a framework for the optimal planning, design, and operation of Distributed energy systems in urban areas based on energy hub concept***"

- The contributions of this dissertation fall into three areas:
  - **Modified formulation of Energy hub and its network Model**
  - **Consideration of Hydrogen economy in the smart energy network**
  - **Development of generic framework for DES allocation based on multi energy hub approach**
- Mixed-Integer programming was used as the modeling scheme.

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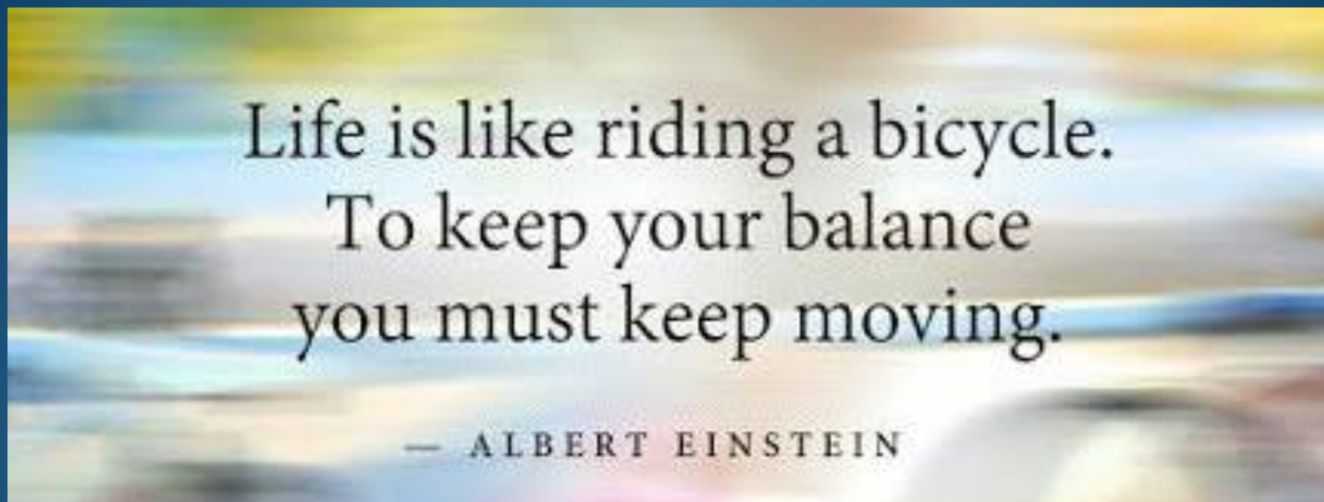

Thank you very much for your attention