Connecting District Energy and Power Systems for Future Singaporean New Towns (CONCEPT)

Final Report

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Project CONCEPT

Connecting District Energy and Power Systems for Future Singaporean New Towns

(NRF2016-ITS001-027)

Final Report

May 2019

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Contents

1 Description of Progress of the Project

1.1 Summary

Project CONCEPT (Connecting District Energy Systems in Future Singaporean New Towns) was undertaken as a joint project between the Singapore-ETH Centre (SEC) as well as TUMCREATE and has been successfully completed as of May 2019. The project has led to the development of a methodology for the integrated optimal planning of electric grids and operation of thermal building systems which has been implemented as a software framework and as such was included as an extension into the City Energy Analyst (CEA)[1]. Further, the project contributed to the development of a software framework for thermal building modelling, i.e., the Control-oriented Building Model (CoBMo)[2]. The work on the project has concluded with the submission of two journal papers (appendices C and D). The project outcomes have been discussed with the National Energy Transformation Office (NETO) of the Energy Market Authority (EMA) and were presented to the CREATE research community as part of the Future Cities Laboratory (FCL) Lunch Talk series (slides in appendix E).

1.2 Milestones and KPIs

The agreed-upon milestones and key performance indicators (KPIs) of the accepted project proposal (appendix G) are highlighted in tables 1.1 and 1.2 with their respective status. For reference, the progress report from July 2018 is included in appendix F.

As per table 1.1, the project team decided to disregard the work package WP 3.3 such that the quality of other milestones could be improved. In particular those of WP2 related to the demand side flexibility and investment cost reductions in the electric grid. These resulted into the core focus of the project.

Table 1.2 highlights that the relation of KPIs o the project. The project outcomes have been discussed with the National Energy Transformation Office (NETO) of the Energy Market Authority (EMA) and were presented to the CREATE research community as part of the Future Cities Laboratory (FCL) Lunch Talk series (see fig. 1.1).

The past meetings with NETO fueled a fruitful discussion regarding future research directions for both TUMCREATE and SEC. The project team suggested the attendees to complete a

[1] Available open source at: https://github.com/architecture-building-systems/CityEnergyAnalyst
[2] Available open source at: https://github.com/TUMCREATE-ESTL/cobmo

Table 1.1: Status of milestones

Milestone	Status
Project Kick Off	Completed
WP 1: Integrated Energy and Power System Planning	Completed
WP 1.1: Coupling of Energy System and Power System Tools	Completed
WP 1.2: Planning Strategy Development	Completed
WP 2: Flexible Operational Strategies for the New Towns	Completed
WP 2.1: Model Predictive Control Scheme	Completed
WP 2.2: Distributed Calculation Methodology	Completed
WP 2.3: Uncertainty Modelling	Completed
WP 3: Analysis	Completed
WP 3.1: Reliability	Completed
WP 3.2: Planning and Operational Cost	Completed
WP 3.3: Renewables	Discarded (see note above)
WP 3.4: Open source tool development	Completed
Interim Report	Completed
Final Report & Dissemination	Completed

Table 1.2: Status of key performance indicators (KPIs)

KPI	Goal	Status
Number of endorsement letters	At least one signed endorsement letter by a local agency	Under discussion with NETO at EMA, no official letter at the moment of writing.
Computational model for CEA	One open-source computational model for CEA	One open-source computational model for CEA + one new computational model called CoBMo
Number of scientific publications	At least two publications in a regional conference and at least one submission to a journal with an impact factor greater than 3.0	Two submissions to a journal with impact factor gerater than 3.0

questionnaire as an evaluation of the project outcomes, but NETO has so far declined to officially disclosed this evaluation. Official endorsement letters for the project are still pending.

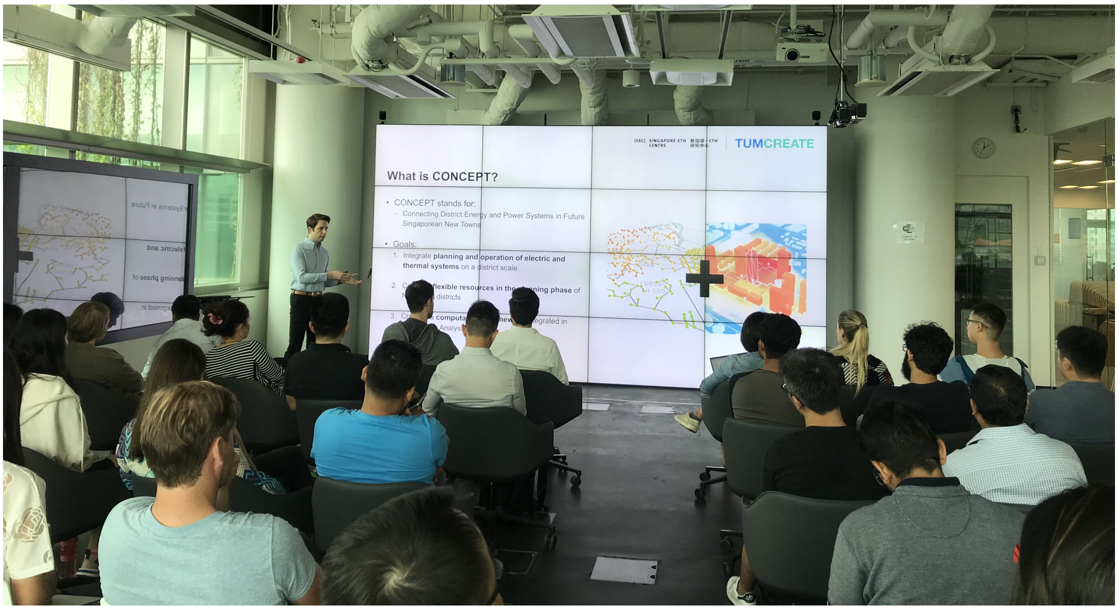

Figure 1.1: Future Cities Laboratory (FCL) Lunch Talk

In terms of open-sourced software modules, the project resulted in the publication of a module for CEA as well as the thermal building modelling software framework CoBMo, hence resulting in two rather than the agreed one open-sourced computational model. Lastly, publications for the project are well on track with two papers having been submitted to journals. No conference publications could be submitted, because NRF removed all funding for conference travel from the final approved project budget.

2 Outcomes and Impact of the Project

This project developed an methodology for the planning of electric grids with consideration for DSF of air-conditioned buildings. The integrated planning and operation problem was formulated as a numerical optimization problem. For a test case based in Singapore, the proposed methodology allows up to 27.9 % reductions in investment cost and up to 1.1 % reduction in total annualized cost. However, due to additional losses caused by the shifting of electric loads, the annualized electricity increased by up to 0.4 % (appendix C).

The results of the test case offer insights to three groups of stakeholders of the district energy system. First, for governmental urban planning authorities the results proof that DSF can readily improve the overall social welfare, since the total cost for planning and operation are effectively reduced with the presented methodology. Second, the urban developers and utility companies may note that there is significant potential for investment cost reduction through peak shaving with DSF, even though no additional storage deployment was considered in the presented test case. Third, for building operators who carry out operation and maintenance the results indicate that there may be a trend towards dynamic electricity tariffs to enable DSF. The building operators should adapt their control capabilities, e.g., towards MPC, to be able to avoid the high peak prices. Additionally, the results also point towards closer collaboration between urban planners and building operators at the planning phase such that appropriate DSF potential is leveraged for cost reduction.

3 Problems Encountered

Number of endorsement letters (kPI) are still under discussion with the relevant parties. See more in section 1.2.

4 Future Steps for the Project

4.1 Project sustainability

This pilot project concludes with new insights about the relation of land-use and flexible operation for New Towns. These insights will serve as a basis for the future development of projects at CREATE touching the aspect of flexible and resilient operation of energy systems in Singapore. Dr. Jimeno A. Fonseca - PI of this project, will personally use these findings as a basis for future research in the project "Digital twin-based resilience analysis and management of district energy systems", which is under consideration by the National Research Foundation of Singapore under the Future Resilient Systems program.

4.2 Relation of outcomes and interested parties

The outcome of this project touches aspects related to the impact of urban planning (land-use), and flexible operation on the investment and operation costs of energy infrastructure for future new towns in Singapore.

From the urban planning perspective, the output of the project should inform the Urban Redevelopment Authority about the potential impact that land-uses have on the investment and operational costs of energy in future new towns (appendix C).

From the energy systems planning and operation perspective, the output of this project should inform the Singapore Power group about the potential effects of flexible operation in buildings and demand-response schemes on both the investment costs and the operation costs of future new towns (appendix D).

5 Human Capital

Table 5.1 presents a summary of the next place of employment of staff on the project.

Table 5.1: Human capital

Singapore Academia	**Singapore Industry**	**Singapore Admin**	**Singapore Others**	**International**
Dr. Jimeno A. Fonseca: *Singapore ETH-Centre*				
Sebastian Troitzsch: *TUMCREATE*				
	Dr. Bhargava Sreepathi: *Unknown*			
				Dr. Sarmad Hanif: *PNNL, United States*

Appendix

A Information on Fund Management and Exceptions

B Audit

C Journal Paper: Optimal Planning and Operation of Electric Grids and Thermal Building Systems

Optimal Planning and Operation of Electric Grids and Thermal Building Systems

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Abstract

The planning of district-scale electric grids, i.e., distribution grids, has traditionally relied on finding the most cost-effective design such that they are able to supply the peak loads in a district. With the advent of electric demand side flexibility (DSF), there is the opportunity to reshape peak loads such that the investment cost of the electric grid decreases in exchange for a minor increase in the operation cost. This paper formulates an optimal planning approach for the electric grid at the district scale, which incorporates the DSF from thermal building systems, e.g., heating ventilation and air-conditioning (HVAC) systems. The problem is formulated as a mixed-integer linear program (MILP) and aims at minimizing the investment cost for the grid along with the operation cost of the flexible loads. This is subjected to the fixed electricity demand and thermal comfort constraints of building occupants. To this end, linear models for the thermal comfort in the buildings and the power flow in electric grid are considered. The approach is tested on a district planning test case based in Singapore, where the results show up to 27.9 % reductions in investment cost and up to 1.1 % reduction in total annualized cost. Urban planning authorities, developers and utility companies can all benefit from the presented approach to make optimized investment decisions. For building operators, the results point to the need of adopting their control systems for DSF.

Keywords: Demand Side Flexibility, Power System Planning, Optimal Planning and Operation

1. Introduction

The planning of electric distribution grids aims at designing the most cost-efficient grid topology while ensuring sufficient maximum capacity in the case of peak load conditions. The maximum capacity of the electric grid is constrained by 1) the thermal limits of the grid equipment, i.e., the maximum current which can be carried without causing damage, and 2) the voltage limits, i.e., the voltage range at which the electric devices of customers can operate. The peak load conditions can be characterized by the maximum coincident demand of the electric customers in the distribution grid, which can be inferred through load surveys [1]. The peak load however does usually not consider electric demand side flexibility (DSF) which can enable electric customers to shave their maximum demands.

DSF has first gained attention as a tool for balancing renewable generation [2, 3]. In particular, DSF helps to match generation and demand by shifting flexible loads to time periods with high renewable generation [2]. This helps in the avoidance of renewable generation shedding. In a microgrid, this can also help to decrease the need for additional energy storage systems, because a higher share of renewable electricity is instantly consumed [3]. DSF can also ensure that electric grid constraints, i.e., thermal limits and voltage limits, are maintained throughout the operation [4] or they can support the grid stability by offering reserves [5]. Hence, the integration of the electric planning problem with DSF may thus reduce the required maximum capacity of the electric grid.

Thermal building systems, e.g., HVAC systems, are an important candidate for DSF as they account for a large share of the electricity demand in buildings, particularly in tropical cities such as Singapore [6]. DSF from HVAC systems has seen increased attention with the advances in model predictive control (MPC) applications for buildings [7]. With MPC, the control problem of the HVAC system is expressed as an numerical optimization problem aimed at minimizing the operation cost, i.e., the costs for consuming energy, while satisfying the occupant comfort constraints, i.e., the acceptable limits for air temperature and indoor air quality. The building operator benefits from MPC through cost savings which arise from 1) more energy efficient control and 2) the ability to consider dynamic electricity tariffs [8], i.e., the electric demand is shifted to hours with low electricity prices. This paper aims at integrating DSF with the planning of electric grids at the district scale.

In the planning of electric grids, i.e., power system planning, there has also been increased intention for approaches based on numerical optimization [9, 10]. The electric grid planning problem can be expressed as a numerical optimization problem for the minimization of the investment cost, i.e., the acquisition

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and installation costs of electric grid equipment, while ensuring peak load satisfaction and the electric grid constraints, i.e., thermal limits and voltage limits. However, these approaches do not yet consider DSF and its ability to reduce peak loads. Similarly, investment and unit commitment strategies for electricity generation plants often consider the electric grid constraints to assess the grid hosting capacity [11], but do not consider investment decisions for expanding the electric grid. Other works have focused on the optimal operation, i.e., dispatch, of flexible resources subject to electric grid constraints [4, 12, 13]. In [4, 12], distributed optimization problems are proposed, where power limits [4] or nodal price increases [12] are imposed such that flexible loads are forced to respect the electric grid constraints. The work [13] develops a scheme in which flexible loads are centrally dispatched to follow a pre-defined demand schedule. However, none of the works [4, 12, 13] include the planning of electric grids.

This paper aims at integrating the planning of electric grids and the operation of thermal building systems on a district-scale, with the goal of reducing the maximum electric grid capacity requirement by considering the peak shaving capabilities due to DSF. The integrated problem is formulated as an optimization problem which aims at minimizing the investment cost of the electric grid along with the operation cost of the thermal building systems, subject to the electric grid constraints and the occupancy comfort constraints. In a similar fashion, [14] proposed a methodology for the integrated planning of building energy systems and the operation of these systems was proposed in through a combination of linear programming (LP) for the operation problem and genetic algorithm (GA) for the planning problem. Instead of such a multi-stage approach, this paper formulates the integrated planning and operation problem in terms of a single stage mixed integer linear program (MILP). To this end, linear thermal building and electric grid models are formulated to express the occupants comfort and the electric grid constraints.

In section 2, the required input data and workflow of the proposed framework is outlined. Section 3 presents the required pre-processing steps for the electric grid model. The linear electric grid and thermal building models are then formulated in section 4 and section 5. Section 6 discusses the setup of the numerical optimization problem. The test case is introduced in section 7 and is followed by results and discussion in section 8. Lastly, concluding remarks are compiled in section 9.

Nomenclature

Let $\mathbb{R}$ be the domain of real numbers. Non-bold letters x, X denote scalars $\mathbb{R}^{1\times1}$, bold lowercase letters $\boldsymbol{x}$ denote vectors $\mathbb{R}^{n\times1}$ and bold uppercase letters $\boldsymbol{X}$ denote matrices $\mathbb{R}^{n\times m}$. The transpose of a vector or matrix is denoted by $()^\intercal$. Symbols for physical properties are aligned with ISO 80000 and units are based on the international system of units (SI). Prices and costs are in Singapore Dollar (SGD) which is denoted by S\$.

Sets and indices

$\mathcal{T}$	Set of time steps
$\mathcal{N}$	Set of grid nodes
$\mathcal{L}$	Set of lines
$\mathcal{K}$	Set of line types
$\mathcal{Z}_b$	Set of zones in building b
$\mathcal{B}$	Set of buildings in the district
$\mathcal{S}_z$	Set of surfaces adjacent to zone z
$\mathcal{W}_z$	Set of windows adjacent to zone z
$t \in \mathcal{T}$	Time step
$i \in \mathcal{N}$	Grid node
$k \in \mathcal{K}$	Line type
$(i, j) \in \mathcal{L}$	Grid line connecting node i and j
$z \in \mathcal{Z}_b$	Zone
$b \in \mathcal{B}$	Building
$s \in \mathcal{S}_z$	Surface
$w \in \mathcal{W}_z$	Window
d	Direction / orientation of a surface

Variables and parameters (in order of appearance)

$P^{dem}_{i,t}$	Active power demand at node i and time step t	[W]
$P^{sup}_{i,t}$	Active power supply at node i and time step t	[W]
$P_{(i,j),k,t}$	Active power through line $(i, j), k$ at time step t	[W]
θ_i	Voltage angle at node i	[rad]
$X_{(i,j),k}$	Reactance of the line $(i, j), k$	[Ω]
$\alpha_{(i,j),k}$	Integer variable representing whether line $\alpha_{(i,j),k}$ is built $\alpha_{(i,j),k} = 1$ or not $\alpha_{(i,j),k} = 0$	[-]
$\omega_{(i,j),k}$	Auxiliary variable with the unit of power	[W]
C	Constant with the unit of power	[W]
T_z	Zone air temperature at zone z	[°C]
C^{th}_z	Thermal heat capacity of zone z	[J/(m^3 K)]
$\dot{Q}^{cnv,int}_{s,z}$	Convective heat transfer from surfaces s towards zone z	[W]
$\dot{Q}^{inf}_z$	Heat transfer to zone z due to infiltration	[W]
$\dot{Q}^{occ}_z$	Heat transfer to zone z due to occupancy gains	[W]
$\dot{Q}^{hvac,heat}_z$	Heat transfer to zone z from the HVAC system for heating	[W]
$\dot{Q}^{hvac,cool}_z$	Heat transfer to zone z from the HVAC system for cooling	[W]
$\dot{Q}^{cnv,ext}_s$	Conv. heat transfer from the exterior to surface s	[W]
$\dot{Q}^{irr,ext}_s$	Incident irradiation onto surface s	[W]
$\dot{Q}^{ems,sky}_s$	Emitted radiation from surface s to the sky	[W]
$\dot{Q}^{ems,gnd}_s$	Emitted radiation from surface s to the ground	[W]
$\dot{Q}^{ext,int}_s$	Heat transfer from the exterior to the interior side of surface s	[W]
$\dot{Q}^{cnv,int}_{s,z}$	Convective heat transfer from surface s to zone z	[W]
$\dot{Q}^{irr,int}_s$	Incident irradiation reaching surface s through exterior windows adjacent to the same zone z	[W]
A_s	Surface area of surface s	[m^2]
h^{ext}	Exterior conv. heat transfer coefficient	[W/(m^2 K)]
T^{amb}	Ambient temperature	[°C]
$T^{sur,ext}_s$	Exterior surface temperature of surface s	[°C]
α_s	Irradiation absorption coefficient of surface s	[-]
h^{sky}_s	Sky emission heat transfer coefficient	[W/(m^2 K)]
σ	Stefan-Boltzmann constant	[W/(m^2 K^4)]
ε_s	Surface emission coefficient of surface s	[-]
F^{sky}_d	View factor of direction d towards the sky	[-]
$T^{sur,ext,lin}_s$	Linearization constant for $T^{sur,ext}_s$	[K]

$T^{sky,lin}$	Linearization constant for T^{sky}	[K]
h_s^{gnd}	Ground emission heat transfer coeff.	[W/(m^2 K)]
F_d^{gnd}	View factor of direction d towards the ground	[-]
$T^{amb,lin}$	Linearization constant for T^{amb}	[K]
h_d^{int}	Interior conv. heat transfer coefficient	[W/(m^2 K)]
$\dot{q}_z^{irr,int}$	Interior irradiation at zone z	[W/m^2]
τ_w	Transmission coefficient of the window w	[-]
$h_s^{ext,int}$	Conductive heat transfer coeff.	[W/(m^2 K)]
V_z	Volume of zone z	[m^3]
$C^{th,air}$	Heat capacity of air	[J/(m^3 K)]
n_z^{inf}	Infiltration rate	[1/h]
$\dot{q}_z^{occ}$	Specific thermal gain due to occupancy	[W/m^2]
$\eta_b^{hvac,heat}$	Eff. factor for heating through the HVAC system	[-]
$\eta_b^{hvac,cool}$	Eff. factor for cooling through the HVAC system	[-]
$P_z^{hvac,heat}$	Elc. demand of the HVAC system for heating	[W]
$P_z^{hvac,cool}$	Elc. demand of the HVAC system for cooling	[W]
$\boldsymbol{x}$	State vector	[-]
$\boldsymbol{u}$	Input vector	[-]
$\boldsymbol{v}$	Disturbance vector	[-]
$\boldsymbol{A}$	State matrix	[-]
$\boldsymbol{B}_u$	Input matrix	[-]
$\boldsymbol{B}_v$	Disturbance matrix	[-]
$J^{inv,lin}$	Investment cost for electric grid lines	[S$]
$J^{inv,sub}$	Investment cost for substations	[S$]
$J^{inv,bld}$	Investment cost for building level transformers	[S$]
J^{elc}	Total electricity cost	[S$]
$L_{(i,j)}$	Length of line (i, j)	[m]
k_k^{inv}	Specific investment cost of line type k	[S$/m]
a_{40}	Annuity factor for 40 years	[-]
b_{om}	Operation and maintenance cost factor	[-]
$P^{sub,max}$	Maximum loading of the substation	[V A]
$k^{inv,sub}$	Specific investment cost of the substation	[S$/VA]
P_b^{max}	Maximum loading of building b	[V A]
$k^{inv,sub}$	Specific inv. cost of the building transf.	[S$/VA]
k_t^{elc}	Price of electricity at time step t	[S$/Wh]
$P_{z,t}^{base,el}$	Fixed base electric consumption of zone z	[W]
I_t^{max}	Maximum current of line type k	[A]
V_{base}	Voltage level of the distribution grid	[V]
N^{bld}	Number of building nodes	[-]
N^{sub}	Number of substation nodes	[-]
T_z^{min}	Minimum air temperature at zone z	[°C]
T_z^{max}	Maximum air temperature at zone z	[°C]

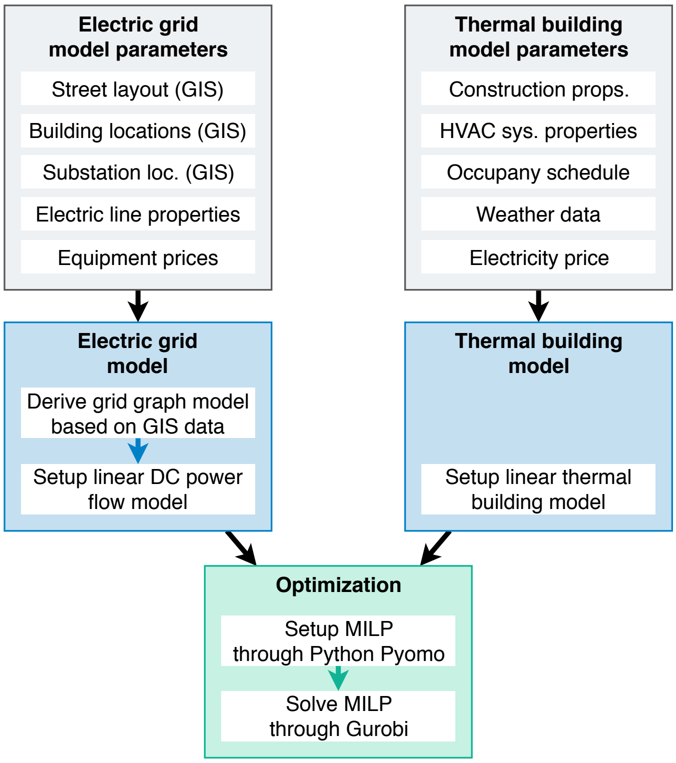

Figure 1: Workflow for the proposed optimal planning and operation framework.

2. Methodology

Figure 1 depicts the workflow for the proposed optimal planning and operation framework. The main steps are 1) the setup of the electric grid model, 2) the setup of the thermal building model to and 3) the setup and solving of the numerical optimization problem.

The input data required for the proposed planning and operation framework consists of electric grid model data and building model data. The electric grid data consists of the street layout, building and substation locations in terms of geographic information system (GIS) data as well as the electric lines' conductor properties and the acquisitions and installation costs of the electric grid equipment. Note that while this paper only considers the costs for lines, substations and building level transformers, further costs for secondary equipment such as breakers and sensors can easily be considered through extensions of the algorithm. The thermal building data consists of construction properties, i.e., geometric and technical information about the building structure including its intended occupancy structure, along with HVAC system properties, occupancy schedule, weather data and the electricity price.

For the setup of the electric grid model, the GIS data is first pre-processed to derive the grid graph model in terms of nodes, i.e., substation and building connection points, and lines, i.e., possible interconnections and line lengths between the nodes. Based on this information, a linear DC power flow model for the electric grid is formulated. Similarly, the thermal building model is generated based on the given construction properties and HVAC system properties for the building. Further data items, e.g., the electric grid equipment costs, occupancy schedule, weather data and electricity prices are passed along with the linear models for the setup of the optimization problem.

The planning and operation problem is formulated as a mixed integer linear program (MILP) in a single stage optimization. The objective is to minimize annualized investment cost of the electric grid along with the operation cost of flexible loads. The decision variables are the electric grid topology, i.e., the decision to build line interconnections, and the dispatch schedule of flexible loads. The thermal comfort constraints and electric line loading limits form the constraints of the MILP. The linear thermal building model expresses the thermal comfort constraints

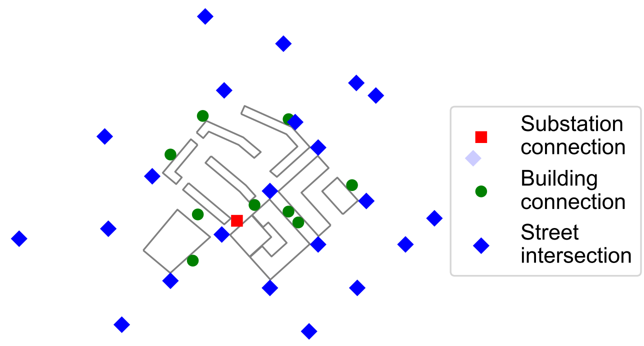

Figure 2: GIS data contained in the test case input data.

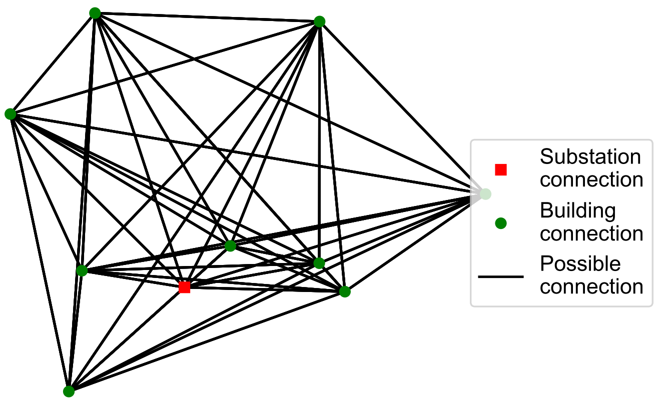

Figure 3: Possible electric grid inter-connections based on the test case input data.

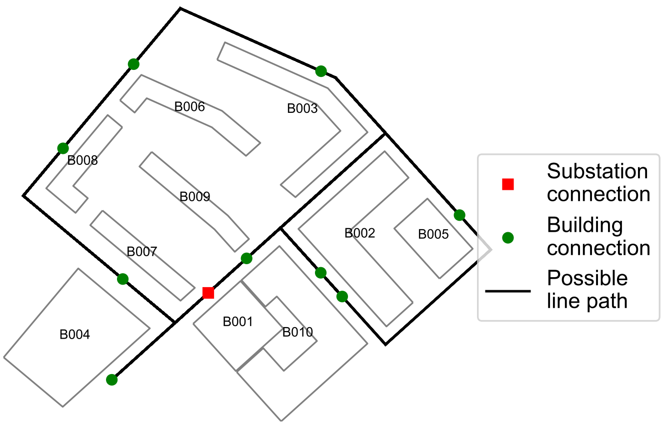

Figure 4: Possible electric grid lines paths based on the street network.

as a function of the scheduled electric load, whereas the linear power flow model translates the load schedule into the electric line loading.

3. Electric grid pre-processing

The test case input data comprises the GIS data of the street network, substation location and the geometrical building shapes as depicted in fig. 2. This data is pre-processed to derive the nodes and all possible lines of the electric grid. The possible lines consist of all interconnections between all the nodes in the grid as depicted in (fig. 3). This accounts for the fact that distribution grid line intersections only occur at grid nodes, i.e., buildings and substation, and not for example at street intersections [15]. Possible line paths are routed along the street network, as modern distribution grid lines are routed underground below streets. The path for each line is derived as the shortest path between the two nodes along the street network (fig. 4). Therefore, the building nodes, i.e., the points where the building transformers are connected to the electric distribution grid, are positioned along the streets. The locations of the building nodes (fig. 2) are found by seeking the shortest path from the centroid of the area of each building towards any nearby street.

4. Electric grid model

Since we consider a district-scale combined electric and thermal planning problem, a simple DC power flow is considered. The benefit of utilizing a higher fidelity power flow model in the considered planning problem is is considered out of the scope for this work and is left as a future work.

As a starting point, the power balance of the electric grid is expressed as:

$$P^{dem}_{i,t} = P^{sup}_{i,t} + \sum_{\substack{(i,j)\in\mathcal{L} \\ k\in\mathcal{K}}} P_{(i,j),k,t} \tag{1}$$

Where $P^{dem}_{i,t}$ and $P^{sup}_{i,t}$ are the active power demand and the active power supply at each grid node $i \in \mathcal{N}$ and time step $t \in \mathcal{T}$, whereas $P_{(i,j),k,t}$ is the active power flowing in a grid line $(i, j), k$, connecting node i and j of line type $k \in \mathcal{K}$. The set $\mathcal{L}$ contains all grid lines (i, j), set $\mathcal{K}$ contains all line types, set $\mathcal{N}$ contains all grid nodes and set $\mathcal{T}$ contains all time steps.

The power flow $P_{(i,j),k,t}$ across each line $(i, j), k$ at time step t is expressed as:

$$P_{(i,j),k,t} = \frac{\theta_{i,t} - \theta_{j,t}}{X_{(i,j),k}} + \omega_{(i,j),k,t} \tag{2}$$

Where θ_i, θ_j are the voltage angle of the connected node i, j and $X_{(i,j),k}$ is the reactance of the line $(i, j), k$. The symbol $\alpha_{(i,j),k}$ is an integer variable $\alpha_{(i,j),k} \in 0, 1$ which describes the decision to build line $(i, j), k$, i.e., the line only exists when $\alpha_{(i,j),k} = 1$. The auxiliary variable $\omega_{(i,j),k}$ ensures that $P_{(i,j),k,t}$ can take the value of zero, in case the decision variable $\alpha_{(i,j),k}$ is assigned to the value of zero and no line is built between node i and j.

The auxiliary variable $\omega_{(i,j),k,t}$ is expressed as:

$$|\omega_{(i,j),k}| \leq (1 - \alpha_{(i,j),k})C \tag{3}$$

Where $C \gg P_{(i,j),k,t}$ is a very large constant.

5. Thermal building model

Thermal loads of a building can be shifted by leveraging the thermal inertia of the buildings. This lets HVAC systems to pre-cool or pre-heat a building while keeping an admissible interval of thermal comfort. This flexibility allows to shift the electric load of the HVAC system while maintaining thermal comfort constraints. In this work, the thermal comfort is expressed in terms of the indoor air temperature. Hence, the thermal building model expresses the relationship between the indoor air temperature, the electric load of the HVAC system, the local weather conditions and the building occupancy.

In the considered test case, each building comprises one zone per occupancy type, where the indoor air temperature, i.e., zone temperature, within each zone is uniformly distributed and there is no heat transfer between zones representing different occupancy types.

As a starting point, the differential equation of the zone temperature T_z of zone z is expressed as:

$$\frac{dT_z}{dt} = \frac{1}{C_{th,z}} \cdot \left(\left(\sum_{s \in \mathcal{S}_z} \dot{Q}^{cnv,int}_{s,z} \right) + \dot{Q}^{inf}_z + \dot{Q}^{occ}_z + \dot{Q}^{hvac,heat}_z \right) \tag{4}$$

Where C^{th}_z is the thermal heat capacity of zone $z \in \mathcal{Z}_b$, which is obtained according to ISO 13790. The symbol $\mathcal{Z}_b$ is the set of all zones z in building $b \in \mathcal{B}$ and $\mathcal{B}$ is the set of all buildings b. The heat transfer towards zone z is composed of the the convective heat transfer $\dot{Q}^{cnv,int}_{s,z}$ from surfaces $s \in \mathcal{S}_z$ towards zone z, heat transfer towards zone z due to infiltration $\dot{Q}^{inf}_z$, heat transfer towards zone z due to occupancy gains $\dot{Q}^{occ}_z$ and heat transfer towards zone z from the HVAC system for heating $\dot{Q}^{hvac,heat}_z$ as well as cooling $\dot{Q}^{hvac,cool}_z$, where $\mathcal{S}_z$ is the set of all surfaces adjacent to zone z.

The ground heat transfer is neglected in this work, because all buildings in the considered test case have a low footprint to volume ratio. All other heat transfer models are formulated in the following subsections.

5.1. Exterior surfaces

Exterior surfaces are modelled as a thermal resistance between the exterior and zone z. Each surface s is adjacent to exactly one zone z. The heat transfer across exterior surface s is described by the balance equation for the exterior side:

$$\dot{Q}^{cnv,ext}_s + \dot{Q}^{irr,ext}_s - \dot{Q}^{ems,sky}_s - \dot{Q}^{ems,gnd}_s = \dot{Q}^{ext,int}_s \tag{5}$$

Where $\dot{Q}^{cnv,ext}_s$ is the convective heat transfer from the exterior towards surface s, $\dot{Q}^{irr,ext}_s$ is the incident irradiation onto surface s, $\dot{Q}^{ems,sky}_s$ and $\dot{Q}^{ems,gnd}_s$ are the emitted radiation from surface s towards the sky and the ground. The symbol $\dot{Q}^{ext,int}_s$ describes the heat transfer from the exterior towards the interior side of the surface.

The balance equation for the interior side of surface s is expressed as:

$$\dot{Q}^{ext,int}_s = \dot{Q}^{cnv,int}_{s,z} - \dot{Q}^{irr,int}_s \tag{6}$$

On the interior side, $\dot{Q}^{cnv,int}_{s,z}$ is the convective heat transfer from surface s towards zone z and $\dot{Q}^{irr,int}_s$ is the incident irradiation reaching surface s through exterior windows adjacent to the same zone z.

The exterior convective term $\dot{Q}^{cnv,ext}_s$ is expressed as:

$$\dot{Q}^{cnv,ext}_s = A_s h^{ext} \left(T^{amb} - T^{sur,ext}_s \right) \tag{7}$$

Where A_s is the surface area of surface s and h^{ext} is the exterior heat transfer coefficient which is given according to ISO 6946 as $h^{ext} = \left(0.04\,\mathrm{m^2\,K/W} \right)^{-1}$. The symbol T^{amb} is the ambient temperature and $T^{sur,ext}_s$ is the exterior surface temperature of surface s.

The exterior irradiation term $\dot{Q}^{irr,ext}_s$ is expressed as:

$$\dot{Q}^{irr,ext}_s = A_s \alpha_s \dot{q}^{irr,ext}_d, \quad d = d(s) \tag{8}$$

Where α_s is the absorption coefficient of surface s assuming a uniform absorption across the spectrum of the incident irradiation. The symbol $\dot{q}^{irr,ext}_d$ is the total incident irradiation onto a surface oriented towards direction $d \in \{N, E, S, W, H\}$, i.e., vertically facing North N, East E, South S, West s or horizontally facing upwards H, depending on the respective surface's orientation $d = d(s)$.

The exterior sky emission term $\dot{Q}^{ems,sky}_s$ describes the radiative heat loss through emission towards the sky. The term is expressed as:

$$\dot{Q}^{ems,sky}_s = A_s h^{sky}_s \left(T^{sur,ext}_s - T^{sky} \right) \tag{9}$$

In this linear approximation, the symbol h^{sky}_s is introduced as the sky heat transfer coefficient of surface s, whereas T^{sky} is the sky temperature. The sky heat transfer coefficient h^{sky}_s in turn is defined as:

$$h^{sky}_s = 4 \sigma \varepsilon_s F^{sky}_d \left(\frac{T^{sur,ext,lin}_s + T^{sky,lin}}{2} \right)^3 \tag{10}$$

Where σ, ε_s and F^{sky}_d are the Stefan-Boltzmann constant, the surface emission coefficient of surface s for long-wave radiations and the view factor of direction $d(s)$ towards the sky. The temperatures $T^{sur,ext,lin}_s$ and $T^{sky,lin}$ are linearization constants that are defined as the average values of $T^{sur,ext}_s$ and T^{sky}.

The exterior ground emission term $\dot{Q}^{ems,gnd}_s$ radiative heat loss through emission towards the ground as well as the built environment. The term is expressed similar to $\dot{Q}^{ems,sky}_s$ as:

$$\dot{Q}^{ems,gnd}_s = A_s h^{gnd}_s \left(T^{sur,ext}_s - T^{amb} \right) \tag{11}$$

Where h^{gnd}_s is introduced as the ground heat transfer coefficient of surface s, whereas T^{amb} is the ambient temperature. The sky heat transfer coefficient h^{gnd}_s in turn is defined as:

$$h^{sky}_s = 4 \sigma \varepsilon_s F^{gnd}_d \left(\frac{T^{sur,ext,lin}_s + T^{amb,lin}}{2} \right)^3 \tag{12}$$

Where F^{gnd}_d is the view factor of direction $d(s)$ towards the ground. The temperatures $T^{sur,ext,lin}_s$ and $T^{amb,lin}$ are linearization constants that are defined as the average values of $T^{sur,ext}_s$ and T^{amb}.

The interior convective term $\dot{Q}^{cnv,int}_{s,z}$ is expressed as:

$$\dot{Q}_s^{cnv,int} = A_s h_d^{int}\left(T^z - T_s^{sur,int}\right) \tag{13}$$

Where h_d^{int} and T^z are the interior heat transfer coefficient and the zone air temperature. The interior heat transfer coefficient h_d^{int} depends on the surface's direction $d(s)$. According to ISO 6946, the term is expressed as:

$$h_d^{int} = \begin{cases} \left(0.13\,\mathrm{m^2\,K/W}\right)^{-1} & \text{for } d \in \{N, E, S, W\} \\ \left(0.17\,\mathrm{m^2\,K/W}\right)^{-1} & \text{for } d = H \end{cases} \tag{14}$$

The interior irradiation term $\dot{Q}_s^{irr,int}$ is expressed as:

$$\dot{Q}_s^{irr,int} = A_s \alpha_s \dot{q}_z^{irr,int}, \quad d = d(s) \tag{15}$$

Where $\dot{q}_z^{irr,int}$ is the interior irradiation incident to all surfaces of zone z. The interior radiation $\dot{q}_z^{irr,int}$ is in fact the irradiation which has entered zone z by passing through adjacent windows and is assumed to be uniformly distributed to all surfaces. This term is expressed as:

$$\dot{q}_z^{irr,int} = \frac{\sum_{w \in \mathcal{W}_z} A_w \tau_w \dot{q}_{d(w)}^{irr,ext}}{\sum_{s \in \mathcal{S}_z} A_s} \tag{16}$$

Where τ_w is the transmission coefficient of the window w. The sets $\mathcal{W}_z$ and $\mathcal{S}_z$ contain all windows w and surfaces s that are adjacent to zone z.

Finally, the coupling term $\dot{Q}_s^{ext,int}$ is expressed as:

$$\dot{Q}_s^{ext,int} = A_s h_s^{ext,int}\left(T_s^{sur,ext} - T_s^{sur,int}\right) \tag{17}$$

Where $h_s^{ext,int}$ is the heat transfer coefficient through surface s.

The complete convective heat transfer $\dot{Q}_s^{cnv,zone}$ from surface s towards zone z which is needed for eq. (4) can be obtained by solving the overdetermined equation system in eq. (5) to eq. (17). After eliminating the unknown surface temperatures $T_s^{sur,ext}$ and $T_s^{sur,int}$, the heat transfer through surface s towards zone z can be expressed as:

$$\begin{aligned} \dot{Q}_s^{cnv,zone} &= \\ &\Big(\alpha_s \dot{q}_d^{irr,ext} + h^{cnv,ext}\left(T^{amb} - T_s\right) \\ &+ h_s^{gnd}\left(T^{amb} - T_s\right) + h_s^{sky}\left(T^{sky} - T_s\right)\Big) \\ &\cdot A_s\Big(1 + \frac{h^{cnv,ext} + h_s^{gnd} + h_s^{sky}}{h_s^{cnv,int}} \\ &+ \frac{h^{cnv,ext} + h_s^{gnd} + h_s^{sky}}{h_s^{cnd}}\Big)^{-1} \\ &+ \alpha_s \dot{q}_z^{irr,int} \\ &\cdot A_s\Big(1 - \big(\frac{1}{h^{cnv,ext} + h_s^{gnd} + h_s^{sky}} \\ &+ \frac{1}{h_s^{cnv,int}} + \frac{1}{h_s^{cnd}}\big)^{-1}\Big) \end{aligned} \tag{18}$$

5.2. Infiltration

The heat transfer towards zone z due to infiltration $\dot{Q}_z^{inf}$ is defined as:

$$\dot{Q}_z^{inf} = V_z C^{th,air} n_z^{inf}\left(T^{amb} - T_z\right) \tag{19}$$

Where V_z is the volume of zone z, $C^{th,air}$ is the heat capacity of air and n_z^{inf} is the infiltration rate.

5.3. Occupancy gains

Assuming perfect knowledge of the building occupancy schedule, the heat transfer towards zone z due to occupancy gains $\dot{Q}_z^{occ}$, i.e., internal gains, is expressed as:

$$\dot{Q}_z^{occ} = A_z \dot{q}_z^{occ} \tag{20}$$

Where A_z is the area of zone z and $\dot{q}_z^{occ}$ is the specific thermal gain due to occupancy.

5.4. HVAC system

The heat transfer towards zone z from the HVAC system for heating $\dot{Q}_z^{hvac,heat}$ and cooling $\dot{Q}_z^{hvac,cool}$ is expressed as:

$$\begin{aligned} \dot{Q}_z^{hvac,heat} &= \eta_b^{hvac,heat} P_z^{hvac,heat} \\ \dot{Q}_z^{hvac,cool} &= -\eta_b^{hvac,cool} P_z^{hvac,cool} \end{aligned} \tag{21}$$

Where $\eta_b^{hvac,heat}$ and $\eta_b^{hvac,cool}$ is the efficiency factor for heating and cooling through the HVAC system of building b. Furthermore, $P_z^{hvac,heat}$ and $P_z^{hvac,cool}$ are the electric power consumption of the HVAC system associated with heating and cooling demand at zone z.

5.5. State space form

A state space form is chosen as the final representation, because this form allows a more compact representation which is independent from changes in model configuration or size. The thermal building model in eq. (4) is transferred into state space form by arranging the model variables into vectors and the model parameters into matrices according to:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}_u\boldsymbol{u} + \boldsymbol{B}_v\boldsymbol{v} \tag{22}$$

Where the vectors $\boldsymbol{x}$, $\boldsymbol{u}$ and $\boldsymbol{v}$ are the state, input and disturbance vectors. The matrices $\hat{\boldsymbol{A}}$, $\hat{\boldsymbol{B}}_u$ and $\hat{\boldsymbol{B}}_v$ are the state, input and disturbance matrices. Note that the state space model in eq. (22) is simply a representation of the differential equation for the zone temperature in eq. (4), where the model variables are arranged into the vectors as follows:

$$\begin{aligned} \boldsymbol{x} &= [T_z]^\intercal && \forall z \in \mathcal{Z}_b, \quad \forall b \in \mathcal{B} \\ \boldsymbol{u} &= \left[P_z^{hvac,heat}, P_z^{hvac,cool}\right]^\intercal && \forall z \in \mathcal{Z}_b, \quad \forall b \in \mathcal{B} \\ \boldsymbol{v} &= \left[T^{amb}, T^{sky}, \dot{q}_d^{irr,ext}\right]^\intercal && \forall d \in \{N, E, S, W, H\} \end{aligned} \tag{23}$$

The time-discrete form of the thermal building model which is required for the optimization problem is obtained by application of zero-order hold discretization, where $\hat{()}$ denotes the discretized matrices:

$$\boldsymbol{x}_{t+1} = \hat{\boldsymbol{A}}\boldsymbol{x}_t + \hat{\boldsymbol{B}}_u\boldsymbol{u}_t + \hat{\boldsymbol{B}}_v\boldsymbol{v}_t \quad \forall t \in \mathcal{T} \tag{24}$$

6. Optimization problem

The optimal planning and operation problem is expressed as an optimization problem for minimizing the cost of investment for the electric grid and the cost of operation for all buildings. The investment cost comprises the annualized investment costs for the electric grid lines and substations as well as annualized operation and maintenance costs of the electric grid equipment. The cost of operation for all buildings considers the annualized electricity cost for the HVAC system and the fixed base demand. As the constraints of the optimization problem are defined the linear electric grid model, the linear thermal building model, electric grid constraints and thermal comfort constraints.

6.1. Cost function

The total cost J is expressed as:

$$\min \quad J = J^{inv,lin} + J^{inv,sub} + J^{inv,bld} + J^{elc} \tag{25}$$

Where $J^{inv,lin}$, $J^{inv,sub}$ and $J^{inv,bld}$ are the annualized investment cost for all electric grid lines, substations and building level transformers. The symbol J^{elc} describes the annualized electricity cost for all buildings.

The annualized investment cost for the electric grid lines $J^{inv,lin}$ is expressed as:

$$J^{inv,lin} = \left(\sum_{\substack{(i,j)\in\mathcal{L}\\ k\in\mathcal{K}}} \alpha_{(i,j),t} L_{(i,j)} k_k^{inv} \right) a_{40}(1 + b_{om}) \tag{26}$$

Where $L_{(i,j)}$ is the length of line (i, j), k_k^{inv} is the specific cost of line type k and a_{40} is its annuity factor. The symbol b_{om} is the operation and maintenance cost factor.

The annualized investment cost for the substation $J^{inv,sub}$ are expressed as follows:

$$J^{inv} = P^{sub,max} k^{inv,sub} a_{40}(1 + b_{om}) \tag{27}$$

Where $P^{sub,max}$ is the maximum loading of the substation and $k^{inv,sub}$ is the specific investment cost for the substation.

The annualized investment cost for the building transformers $J^{inv,blg}$ are expressed as:

$$J^{inv} = P_b^{max} k^{inv,bld} a_{40}(1 + b_{om}) \tag{28}$$

Where P_b^{max} is the maximum loading of each building and $k^{inv,sub}$ is the specific investment cost for the building transformers.

The electricity cost J_b^{elc} for each building b are expressed as:

$$J^{elc} = \sum_{t\in\mathcal{T}} \sum_{\substack{z\in\mathcal{Z}_b\\ b\in\mathcal{B}}} \left(P_{z,t}^{hvac,el} + P_{z,t}^{base,el} \right) k_t^{elc} \tag{29}$$

Where k_t^{elc} is the price of electricity at time step t and $P_{z,t}^{base,el}$ is the fixed base electric consumption of each zone z, e.g., for lighting and appliances.

6.2. Electric grid constraints

The thermal limits of the electric grid equipment are defined as a function of the decision variables $\alpha_{(i,j),t}$, $P^{sub,max}$ and P_b^{max} as:

$$\begin{aligned} |P_{(i,j),k,t}| &\le \alpha_{(i,j),k} \cdot I_t^{max} \cdot V_{base} && \forall t \in \mathcal{T} \\ P^{sub,max} &\ge P_t^{sub} && \forall t \in \mathcal{T} \\ P_b^{max} &\ge P_{b,t}^{hvac} && \forall t \in \mathcal{T} \end{aligned} \tag{30}$$

Where I_t^{max} and V_{base} are the maximum current of line type k and the voltage level of the distribution grid. Note that this also ensures that no power is flowing across lines $(i, j), k$ for which $\alpha_{(i,j),t}$ is zero.

Typical distribution grids are operated in radial structures. To respect this form of configuration, the number of lines is limited according to:

$$\sum_{\substack{(i,j)\in\mathcal{L}\\ t\in\mathcal{K}}} \alpha_{(i,j),k} = 2 \cdot (N^{bld} - N^{sub}) \tag{31}$$

Where N^{bld} and N^{sub} are the number of building nodes and the number of substation nodes.

Lastly, connections between any two nodes (i, j) are limited to one line $(i, j), k$ according to:

$$\sum_{t\in\mathcal{K}} \alpha_{(i,j),k} \le 1 \quad \forall (i, j) \in \mathcal{L} \tag{32}$$

6.3. Thermal comfort constraints

The thermal comfort constraint is formulated based on the proposed thermal building model as:

$$\left[T_z^{min}\right]^{\intercal} \le \boldsymbol{x}_t \le \left[T_z^{max}\right]^{\intercal} \quad \forall z \in \mathcal{Z}_b, \quad \forall b \in \mathcal{B}, \quad t \in \mathcal{T} \tag{33}$$

Where T_z^{min} and T_z^{max} are the minimum and maximum permissible air temperature in zone z, depending on the zone's occupancy type.

7. Test case

The test case is based on a real greenfield urban planning project which is embedded in the port area of Tanjong Pagar, Singapore. In the near future, the port will be restructured into a multipurpose area, consisting of commercial, residential and office buildings. The test case is illustrated in fig. 2 and covers an approximate area of 300 000 m^2. In the chosen scenario 10 buildings are encased.

7.1. Electric grid model parameters

The electric distribution grid in Singapore is operated at V_{base} = 22 kV. The possible electric grid line paths and interconnections are derived according to section 3 based on the GIS data of the test case. The data for electric grid line types in table 1 are derived from local market data based on the work of [15], which was cross-validated with reference values from

[16] and [17]. The specific price for substations (66 kV / 22 kV) and building transformers (22 kV / 0.4 kV) is based on [16] and [17]. All the specific prices include the cost incurred by civil works, i.e., earthworks and installation. For the electricity price, the average of the Universal Singapore Energy Price (USEP) of 2017 is taken from [18]. These cost parameters are given in table 2.

Table 1: Electric line type data.

No.	Cross-section [mm^2]	Resistance [Ω/km]	Reactance [Ω/km]	Max. Current [A]	Price [S$/m]
0	10	2.54	0.165	65	41.86
1	50	0.487	0.135	163	74.42
2	185	0.127	0.114	325	113.74

Table 2: Electric grid planning parameters.

Parameter	Value
$k^{inv,sub}$	30 S$/kVA
$k^{inv,bld}$	50 S$/kVA
k^{elc}_t	80.9 S$/MWh
b_{om}	0.04

7.2. Thermal building model parameters

The geometric information of zones and surfaces, e.g., A_s are derived from the GIS data of the test case. Based on the default Singapore database of CEA [19], the heat transfer coefficient $h^{ext,int}_s$, the absorption coefficient α_s, the emissivity ε_s of each surface s the transmissivity τ_w of each window w, the thermal capacity C^{th}_z and the infiltration rate n^{inf}_z of each zone z are defined. Further, the HVAC system heating efficiency $\eta^{hvac,heat}_b$ and cooling efficiency $\eta^{hvac,cool}_b$ are calculated according to CEA based on the building's system setup.

Table 3: Thermal model parameters.

Parameter	Value
F^{sky}_d $(\forall d \in \{N, E, S, W\})$	0.5
F^{gnd}_d $(\forall d \in \{N, E, S, W\})$	0.5
F^{sky}_d $(d = H)$	1
F^{gnd}_d $(d = H)$	0

7.3. Weather data

Weather data is obtained from the default Singapore database of CEA [19]. The data comprises data items for the ambient temperature T^{amb} and the global horizontal irradiation $\dot{q}^{irr,ext}_{glb,hor}$. The incident irradiation $\dot{q}^{irr,ext}_d$ for each surface direction d is

Table 4: Thermal model linearization parameters.

Parameter	Value
$T^{sur,ext,lin}_s$	35 °C
$T^{sky,lin}$	17 °C
$T^{amb,lin}$	30 °C

calculated as a function of the global horizontal irradiation $\dot{Q}^{irr,ext}_{glb,hor}$ and the local time through the PVLIB toolbox [20]. The sky temperature T^{sky} is defined by an approximation for tropical climate as $T^{sky} = T^{amb} - 13\,\mathrm{K}$ according to ISO 52016-1.

7.4. Occupancy scenarios

The occupancy schedule and the fixed base electric load schedule $P^{base,el}_{z,t}$ are defined according to the occupancy type databases of CEA [19]. Seven occupancy scenarios are defined for the district, to study the impact of different occupancy types on DSF and the outcome of the planning and operation problem. In these scenarios, all the buildings are assigned the share of occupancy types as given in table 5.

Table 5: Building occupancy shares for each occupancy scenario.

Occupany scenario	Office	Retail	Residential
Mixed	33.33 %	33.33 %	33.33 %
Off.	100 %	0 %	0 %
Ret.	0 %	100 %	0 %
Res.	0 %	0 %	100 %
Off.-Ret.	50 %	50 %	0 %
Off.-Res.	50 %	0 %	50 %
Ret.-Res.	0 %	50 %	50 %

7.5. Fixed and flexible load operation

Fixed and flexible load operation scenarios are considered to evaluate the effectiveness of the integrated planning and operation approach. The fixed operation scenario refers to the status quo, where the building HVAC systems are operated such that the zone air temperature T_z follows a fixed set temperature T^{set} during operation hours. In the flexible operation scenario, the zone air temperature T_z is constrained to stay within the thermal comfort limits T^{min} and T^{max}. The temperatures T^{set}, T^{min} and T^{max} are defined depending on the occupancy scenario according to the occupancy database of CEA [19].

8. Results and discussion

Table 6 documents the categorized cost for the mixed occupancy scenario with fixed load operation. In this scenario, the electricity cost makes up the majority, i.e., almost 96 % of the annualized cost. Among the investment cost, the substation and building level transformers amount for the majority of the cost, i.e., approx. 90 % of the investment cost.

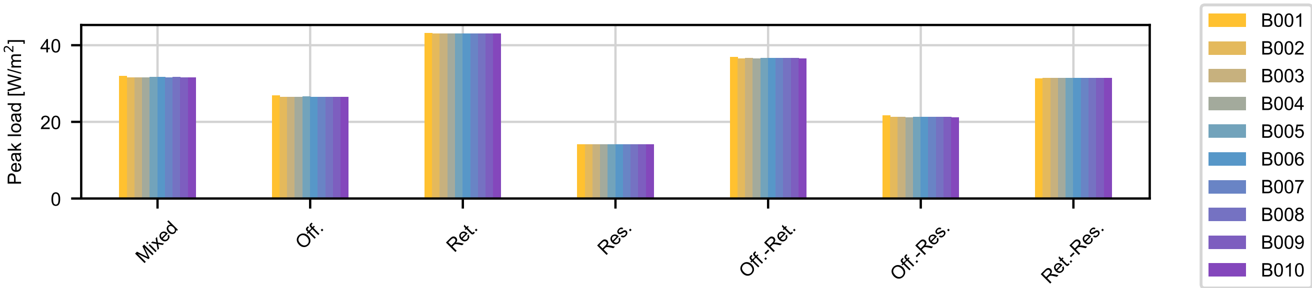

Figure 5: Building peak loads by occupancy scenario with fixed load operation.

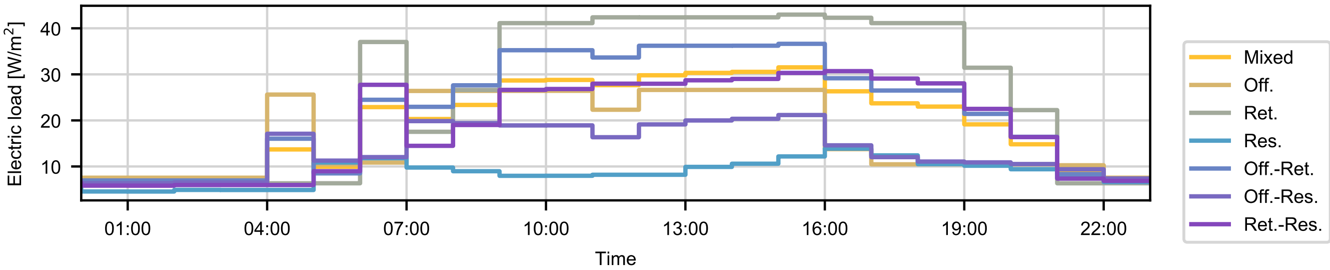

Figure 6: Electric load schedule by occupancy scenario with fixed load operation.

Table 6: Categorized annualized cost for the mixed occupancy scenario with fixed load operation.

Cost type	**Value** [S$]	**Share**
Electricity	1,740,456	96.0 %
Electric lines investment	7,755	0.4 %
Substation investment	23,994	1.3 %
Building transformer investment	39,991	2.2 %
Total	1,812,198	100.0 %

Figure 5 depicts the peak loads by occupancy scenario with fixed load operation for each building. In fact, for each occupancy scenario an identical peak load in W/m^2 is observed. This is due to the occupancy scenarios defining all buildings in the district to have identical properties except for the building size. Among all occupancy scenarios, the residential scenario has the lowest peak demand while the retail scenario has highest peak demand. This results from a relatively low occupancy density in residential buildings, whereas retail buildings, e.g., shopping malls, have a much higher occupancy density and experience higher internal gains.

The electric load schedule for each occupancy scenario is shown in fig. 6 for a typical weekday. For most occupancy scenarios the peak demand is observed during mid-day, but only for the residential occupancy scenario reaches its peak demand during the morning and early evening hours, which reflects the daily occupancy and appliance schedule of each occupancy scenario. Note that the sum of fixed base electric demand $P^{base,el}$ and the electric demand of the HVAC system $P^{hvac,el}$ is shown. Hence, even for office buildings the electric demand is greater than zero during the night hours. The peak in early-morning hours for some occupancy scenarios can be explained with the requirement to cool down the building after it has heated up during the night.

Table 7: Categorized costs by occupancy scenario with fixed load operation.

Occupancy scen.	**Electricity cost** [S$]	**Investment cost** [S$]	**Total cost** [S$]
Mixed	1,740,456	71,741	1,812,198
Off.	1,159,577	61,276	1,220,853
Ret.	2,027,746	95,472	2,123,219
Res.	613,193	35,458	648,651
Off.-Ret.	1,760,596	82,032	1,842,628
Off.-Res.	1,103,649	50,355	1,154,005
Ret.-Res.	1,632,464	70,789	1,703,253

Table 7 and fig. 7 show the categorized cost by occupancy scenario with fixed load operation, whereas table 8 documents the same with flexible load operation. The electricity cost scale proportionally to the electricity demand and the investment cost proportional to the peak load. Because the electricity demand is largely proportional to the peak load across all occupancy scenarios, the total cost also scale proportional to the peak loads.

Table 9 presents the cost difference by occupancy scenario

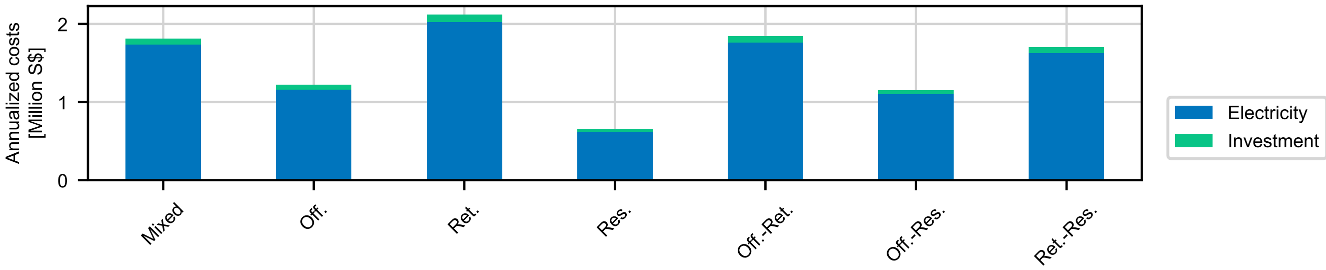

Figure 7: Categorized cost by occupancy scenario with fixed load operation.

Table 8: Categorized costs by occupancy scenario with flexible load operation.

Occupancy scen.	Electricity cost [S$]	Investment cost [S$]	Total cost [S$]
Mixed	1,747,439	55,368	1,802,808
Off.	1,163,752	44,161	1,207,913
Ret.	2,032,313	78,259	2,110,572
Res.	613,793	29,252	643,045
Off.-Ret.	1,764,247	60,813	1,825,061
Off.-Res.	1,108,342	39,340	1,147,682
Ret.-Res.	1,636,304	61,173	1,697,478

Table 9: Cost difference by occupancy scenario with flexible load operation relative to fixed load operation.

Occupancy scen.	Electricity cost	Investment cost	Total cost
Mixed	+ 0.4 %	- 22.8 %	- 0.5 %
Off.	+ 0.4 %	- 27.9 %	- 1.1 %
Ret.	+ 0.2 %	- 18.0 %	- 0.6 %
Res.	+ 0.1 %	- 17.5 %	- 0.9 %
Off.-Ret.	+ 0.2 %	- 25.9 %	- 1.0 %
Off.-Res.	+ 0.4 %	- 21.9 %	- 0.5 %
Ret.-Res.	+ 0.2 %	- 13.6 %	- 0.3 %

with flexible load operation relative (table 7) to fixed load operation (table 8). Across all occupancy scenarios, a slight increase in electricity cost of up to 0.4 % is observed along with a decrease in investment cost of up to 27.9 %, resulting in an total cost reduction of up to 1.1 %. The increase in electricity cost result from an increase in losses when load is shifted to a different time period. However, even with this slight increase, the total annualized cost could be reduced for all occupancy scenarios as the reduction investment cost is more significant.

Table 10 presents the peak load and investment cost reduction by occupancy scenario with flexible load operation relative to fixed load operation. The results indicate that the investment cost reduction is proportional to the peak load reduction, which can be expected due to the investment cost consisting largely of substation and building transformer cost which are modelled as

Table 10: Peak load and investment cost reduction by occupancy scenario for flexible load operation relative to fixed load operation.

Occupancy scen.	Absolute peak load reduction [W/m^2]	Relative peak load reduction	Investment cost reduction
Mixed	- 7.9	- 25.0 %	- 22.8 %
Off.	- 8.2	- 30.7 %	- 27.9 %
Ret.	- 5.2	- 24.6 %	- 18.0 %
Res.	- 10.2	- 27.8 %	- 17.5 %
Off.-Ret.	- 3.1	- 21.7 %	- 25.9 %
Off.-Res.	- 7.9	- 18.4 %	- 21.9 %
Ret.-Res.	- 4.8	- 15.3 %	- 13.6 %

a function of the peak load according to eq. (27) and eq. (28).

Figure 8 and fig. 9 show the electric load schedule for office and retail occupancy scenario with both fixed and flexible load operation. These occupancy scenarios are chosen, because in table 10 the office occupancy scenario allows for the biggest relative peak load and cost reduction, whereas the retail occupancy scenario results in the smallest relative peak load and cost reduction. Comparing between the flexible and fixed load operation for the office occupancy scenario, the peak load is shaved largely by shifting the load to the early-morning hours, i.e. pre-cooling the building. While a similar behaviors is exhibited for the retail occupancy scenario, the much higher occupancy density and resulting peak load exceed the inherent thermal storage capacity of the building structure. In this case, the building is only slightly pre-cooled during early-morning hours.

Figure 10 and fig. 11 depict the electric grid layout for the retail occupancy scenario with fixed load and flexible load operation. Comparing flexible and fixed load operation, the flexible load operation permits the use of smaller line types due to the reduced peak loads. However, the chose network layout is not impacted as the street lengths and the relative size of the building peak loads remain the same.

9. Conclusions

This work presented an methodology for the planning of electric grids with consideration for DSF of air-conditioned buildings. The integrated planning and operation problem was

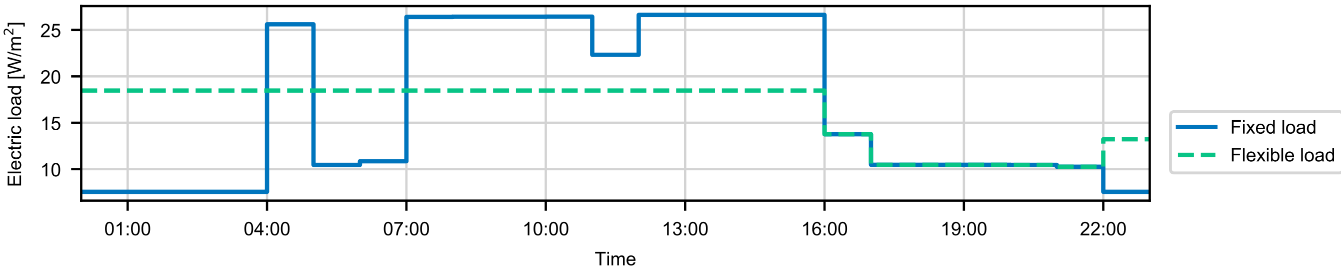

Figure 8: Electric load schedule for office occupancy scenario.

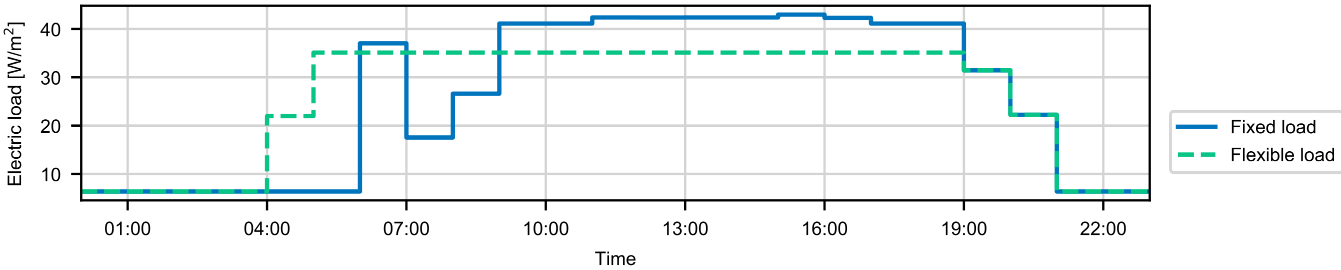

Figure 9: Electric load schedule for retail occupancy scenario.

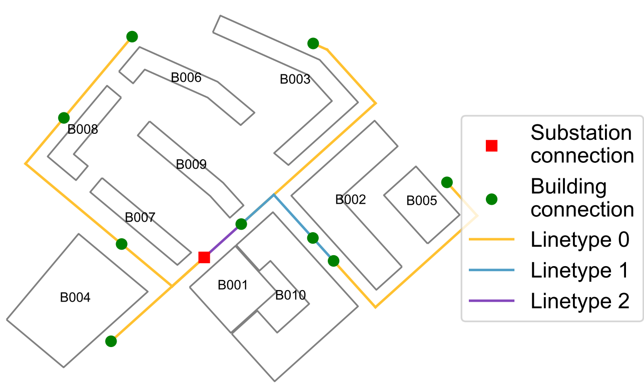

Figure 10: Electric grid layout for the retail occupancy scenario with fixed load operation.

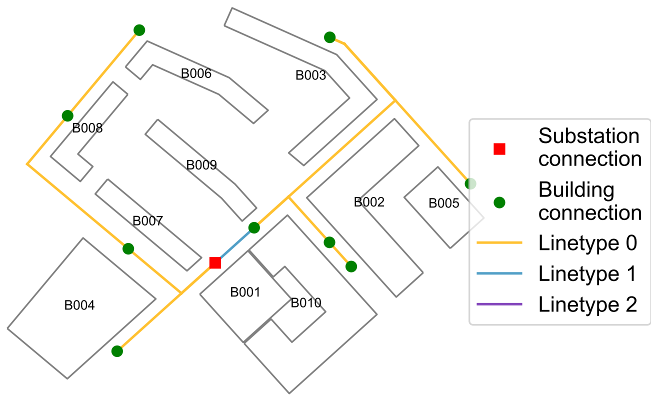

Figure 11: Electric grid layout for the retail occupancy scenario with flexible load operation.

formulated as MILP based on linear models for electric power flow and the thermal building dynamics. For a test case based in Singapore, the proposed methodology allows up to 27.9 % reductions in investment cost and up to 1.1 % reduction in total annualized cost. However, due to additional losses caused by the shifting of electric loads, the annualized electricity increased by up to 0.4 %.

The results of the test case offer insights to three groups of stakeholders of the district energy system. First, for governmental urban planning authorities the results proof that DSF can readily improve the overall social welfare, since the total cost for planning and operation are effectively reduced with the presented methodology. Second, the urban developers and utility companies may note that there is significant potential for investment cost reduction through peak shaving with DSF, even though no additional storage deployment was considered in the presented test case. Third, for building operators who carry out operation and maintenance the results indicate that there may be a trend towards dynamic electricity tariffs to enable DSF. The building operators should adapt their control capabilities, e.g., towards MPC, to be able to avoid the high peak prices. Additionally, the results also point towards closer collaboration between urban planners and building operators at the planning phase such that appropriate DSF potential is leveraged for cost reduction.

The office occupancy scenario demonstrated the largest total cost reduction along with a high peak shaving ability. In fact, DSF is also easier to realize in the HVAC system of such building, due to the existing centralized control architecture through a building management system (BMS) and the highly predictable occupancy schedule. This highlights the need to tap into office buildings a prime resource for DSF.

The investment cost of the electric lines play a minor role, i.e., approx. 5 %, in the investment decision of the presented test case. If this result can be validated for a larger test case with more buildings and a more complex street network, then the planning of the electric grid layout may in fact be performed downstream of the planning for the substation and building transformers. Such a hierarchical approach could lead to reduced computation as the mixed-integer problem, i.e. the electric grid planning, can then be separated from the large-scale linear problem, i.e. optimal scheduling of flexible loads considering the substation and building transformer investment cost.

The algorithm has been integrated as a module in CEA [19] and as such is available online and open source. Future works will focus on applying the algorithm to a larger test case and to consider a wider range of flexibility resources, e.g., battery energy storage systems and vehicle-to-grid enabled electric vehicle charging.

Acknowledgment

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References

[1] W. H. Kersting, Distribution System Modeling and Analysis, CRC Press, 2001.

[2] S. Hanif, C. Gruentgens, T. Massier, T. Hamacher, T. Reindl, Cost-optimal operation for a flexible building with local PV in a Singaporean environment, in: IEEE PES Innov. Smart Grid Technol. Conf., IEEE, 2016. doi:10.1109/ISGT.2016.7781232.

[3] R. Atia, N. Yamada, Sizing and Analysis of Renewable Energy and Battery Systems in Residential Microgrids, IEEE Trans. Smart Grid 7 (3) (2016) 1204–1213. doi:10.1109/TSG.2016.2519541.

[4] O. Sundstrom, C. Binding, Flexible Charging Optimization for Electric Vehicles Considering Distribution Grid Constraints, IEEE Trans. Smart Grid 3 (1) (2012) 26–37. doi:10.1109/TSG.2011.2168431.

[5] E. Vrettos, E. C. Kara, J. MacDonald, G. Andersson, D. S. Callaway, Experimental demonstration of frequency regulation by commercial buildings Part I: Modeling and hierarchical control design, IEEE Trans. Smart Griddoi:10.1109/TSG.2016.2628897.

[6] K. Chua, S. Chou, W. Yang, J. Yan, Achieving better energy-efficient air conditioning A review of technologies and strategies, Appl. Energy 104 (2013) 87–104. doi:10.1016/j.apenergy.2012.10.037.

[7] F. Oldewurtel, A. Parisio, C. N. Jones, M. Morari, D. Gyalistras, M. Gwerder, V. Stauch, B. Lehmann, K. Wirth, Energy efficient building climate control using stochastic model predictive control and weather predictions, in: Am. Control Conf., IEEE, 2010, pp. 5100–5105. doi:10.1109/ACC.2010.5530680.

[8] E. Vrettos, K. Lai, F. Oldewurtel, G. Andersson, Predictive Control of buildings for Demand Response with dynamic day-ahead and real-time prices, in: Eur. Control Conf., Zurich, Switzerland, 2013.

[9] S. Ganguly, N. C. Sahoo, D. Das, Recent advances on power distribution system planning: a state-of-the-art survey, Energy Syst. 4 (2013) 165–193. doi:10.1007/s12667-012-0073-x.

[10] P. S. Georgilakis, N. D. Hatziargyriou, A review of power distribution planning in the modern power systems era: Models, methods and future research, Electr. Power Syst. Res. 121 (2015) 89–100. doi:10.1016/j.epsr.2014.12.010.

[11] E. Lannoye, D. Flynn, M. O'Malley, The role of power system flexibility in generation planning, in: IEEE PES Gen. Meet., 2011. doi:10.1109/PES.2011.6039009.

[12] S. Troitzsch, S. Hanif, T. Hamacher, Distributed Robust Reserve Scheduling in Congested Distribution Systems, in: IEEE PES Gen. Meet., 2018. doi:10.1109/PESGM.2018.8586650.

[13] T. Logenthiran, D. Srinivasan, T. Z. Shun, Demand Side Management in Smart Grid Using Heuristic Optimization, IEEE Trans. Smart Grid 3 (3). doi:10.1109/TSG.2012.2195686.

[14] H. Wolisz, T. Schütz, T. Blanke, M. Hagenkamp, M. Kohrn, M. Wesseling, D. Müller, Cost optimal sizing of smart buildings' energy system components considering changing end-consumer electricity markets, Energy 137 (2017) 715–728. doi:10.1016/j.energy.2017.06.025.

[15] A. Trpovski, D. Recalde, T. Hamacher, Synthetic Distribution Grid Generation Using Power System Planning: Case Study of Singapore, in: Int. Univ. Power Eng. Conf., 2018. doi:10.1109/UPEC.2018.8542054.

[16] H. L. Willis, Power Distribution Planning Reference Book, CRC Press, 1997. doi:10.1201/9780824755386.

[17] Dena Deutsche Energie-Agentur, Ausbau- und Innovationsbedarf der Stromverteilnetze in Deutschland bis 2030 (2012). URL https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9100_dena-Verteilnetzstudie_Abschlussbericht.pdf

[18] EMA Energy Market Authority, Singapore Energy Statistics 2018 (2018).

[19] J. A. Fonseca, A. Schlueter, T.-A. Nguyen, F. Marechal, City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts, Energy Build. 113 (2016) 202–226. doi:10.1016/J.ENBUILD.2015.11.055.

[20] W. F. Holmgren, C. W. Hansen, M. A. Mikofski, pvlib python: a python package for modeling solar energy systems, J. Open Source Softw. 3 (29) (2018) 884. doi:10.21105/joss.00884.

D Journal Paper: A study on developing Urban Energy Systems for a neighbourhood with Flexible Building Loads

A STUDY ON DEVELOPING URBAN ENERGY SYSTEMS FOR A NEIGHBOURHOOD WITH FLEXIBLE BUILDING LOADS

A PREPRINT

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ABSTRACT

The traditional way of planning energy systems for a neighbourhood assumes the buildings follow a load profile, and design the energy systems to meet this profile. In this setup, the buildings are assumed to be rigid. In this paper, we look at buildings being flexible and thus help to reshape the peak loads such that there is a tradeoff between the investment cost of the energy system with the operation cost. This is of particular interest, as there is an increase in PV integration into the grids. PV generation is dependent on various environmental factors and thus can not be accurately predicted, making it a flexible energy supply source. It is difficult to match this with a fixed load profile, thus flexible building loads are important to match the load profile of supply and demand. This paper formulates an optimal planning approach for the electric grid at the district scale, which incorporates the DSF from thermal building systems, e.g., heating ventilation and air-conditioning (HVAC) systems. Based on this, the temperature profile of all the buildings in the neighbourhood are predicted. Using this profile, the demand of all the buildings is calculated which is further divided into heating, cooling and electricity loads. To provide for these loads, City Energy Analyst (CEA) is used, which generates various configurations of supply systems to provide the demand in the neighbourhood. The approach is optimized with objectives as annualized costs, greenhouse gas emissions and the total primary energy used. As these are conflicting objectives, a Pareto-front of the best tradeoff solutions is generated and presented in this paper.

Keywords Urban Energy Systems · Demand Side Flexibility · Linear Building Modelling

1 Introduction

Urban Energy Systems (UES) are designed to provide the overall energy requirement of a neighbourhood. The energy requirement of a neighbourhood consist of the heating demand, cooling demand, electricity demand and hot water demand of all the buildings in the neighbourhood. UES uses a combination of technologies, along with District Networks to provide the energy needs of the neighbourhood.

To plan the UES of a greenfield development, building models are used to forecast the demand of the neighbourhood based on the

Design of Urban Energy Systems to provide for the cooling demand, heating demand, hot water demand and the electricity demand of a neighbourhood. These demands are calculated based on the number of buildings present in the neighbourhood, building properties such as building orientation, building occupancy type.

*Use footnote for providing further information about author (webpage, alternative address)—*not* for acknowledging funding agencies.

In a traditional UES design, the energy supply is matched with the demand at all times. However, with the increased incorporation of renewables in the energy mix, the supply becomes unpredictable, as the generation of renewables is uncontrollable. Increased usage of renewables also has an impact on the stability of the electrical grid.

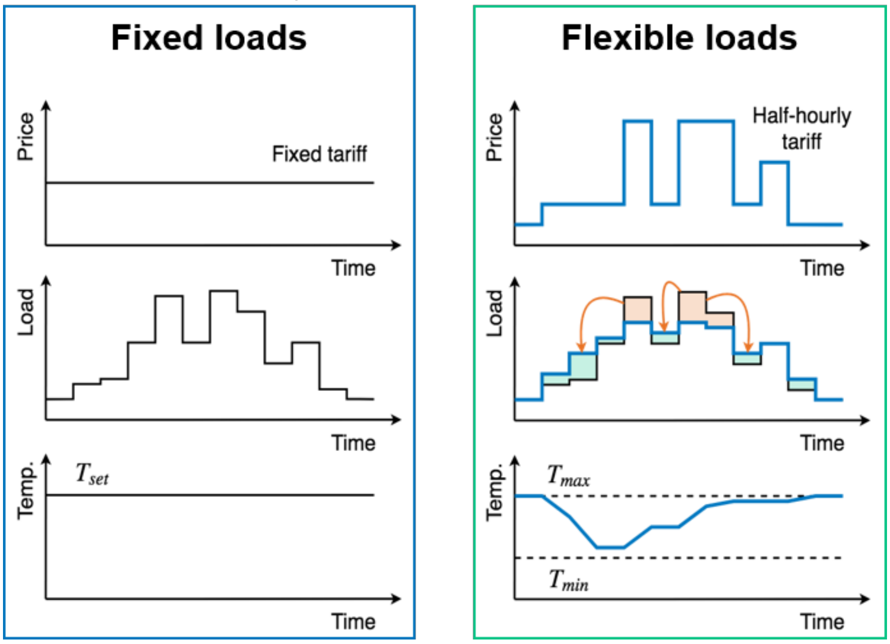
Therefore, it becomes important to make the demand flexible and controllable to match with the energy generation at all times.

Buildings being significant energy consumers in a neighbourhood, controlling their energy demand can make a large contribution to the flexibility of the overall neighbourhood. Thus the goal of this paper is to explore the design of UES with flexible buildings and provide a framework to integrate flexibility in the demand of the neighbourhood.

Thermal inertia present in the buildings are an import source of flexibility as it offer thermal storage in the neighbourhood

Increasing the renewable share in the electricity generation has a negative impact on the stability of the electric grid. Several renewable energy sources (RES) are intermittent in nature, which can neither be controlled nor predicted accurately. Thus increasing RES share causes difficulties in maintaining the balance between generation and usage of electricity, thus increasing the risk of a black-out.

Figure 1: Fixed vs Flexible Loads



2 Literature Review

Li and Pye [1] shows that the demand-side control increases system flexibility, enabling the integration of low carbon energy sources such as nuclear and wind. A model developed based on the model generator TIMES (The integrated MARKAL-EROM system), is used in this analysis. The study shows that with low level of flexibility of the Energy system to meet the Carbon Emission targets, the technologies selected were nuclear, carbon capture and storage (CCS). UKTM is an optimization model consisting of many alternate energy supply technologies and describing the whole UK energy system. One of the key findings of this work is that the system integration cost of low-carbon generation technologies will significantly depend on the level of system flexibility. Enhancing system flexibility reduces system integration cost of renewables by an order of magnitude. For instance, the whole system cost disadvantage of wind generation against nuclear reduces from £14/MWh in a low flexibility system to £1.3/MWh in a fully flexible system achieving 100 g/kWh emission intensity. At the same time, the whole system cost of solar PV reduces from being £2.3/MWh higher than nuclear to being £10.7/MWh lower than nuclear as the result of improved flexibility.

Good and Mancarella [2] developed a stochastic energy/reserve MILP for a community energy system. A key feature of this model is its robustness in ensuring occupant's thermal comfort. The model allows for various flexible conversion and storage devices such as Combined Heat and Power Plant (CHP), Electric Heat Pump (EHP). It also includes district flexibility namely multi-energy storage (electrical and thermal), power factor manipulation. It considers both the energy and reserve markets along with any local constraints imposed.

Kilkki et al. [3] studied the incentivization of demand-side resources to alter the consumption patterns of the occupants. This is done by varying the electricity price over time. An optimization problem has been set up to optimize the consumer electricity price in a space heating scenario. This leads to a game-theoretic scenario where procurement and consumption profiles of the retailer and consumer agents are based on the set electricity price. The relevance of price-based control is justified by the notion that the individual consumers best know the amount of load reduction that he can achieve. This is particularly true in the case where the consumers have storage potential.

Vandermeulen et al. [4] provides a review of techniques to quantify flexibility in district heating and cooling systems. It also emphasises the importance of a good control strategy to efficiently and effectively unlock the flexibility available due to the thermal inertia of the buildings, storage units and the distric heating/cooling network Thermal networks have many avenues that can act as sources as thermal inertia such as heat/cold carrier fluid, thermal storage devices, thermal inertia of the buildings.

Lund et al. [5] defined a fourth generation district heating and cooling systems where usage of both central heating/cooling generation along with Thermal Energy Storage (TES) is made, the overall district heating/cooling network temperatures decreased substantially. This paper emphasizes the necessity for the implementation of Smart Energy Systems to fulfill future low carbon strategies. The Smart Energy System moves away from single sector thinking to a coherent understanding of energy systems. This focuses on getting benefits from the integration of all sectors and infrastructures in district heating/cooling solutions.

3 Methodology

Building model

The constraints corresponding to the building model are the following:

$$\begin{aligned} &X_{b,t+1} = A_b \cdot X_{b,t} + B_{b,u} \cdot U_{b,t} + B_{b,v} \cdot V_{b,t}, \quad t = 0, \dots, N, \quad b \in B \\ &Y_{b,t} = C_b \cdot X_{b,t} + D_{b,u} \cdot U_{b,t} + D_{b,v} \cdot V_{b,t}, \quad t = 0, \dots, N, \quad b \in B \\ &X_{b,0} = X_{initial,b}, \quad b \in B \end{aligned} \tag{1}$$

The price vector

The price vector value also depends on the case_goal that is chosen by the user between 'set_temperature_tracking' and 'price_based_flexibility' in main_district.py.

For 'set_temperature_tracking', the electricity cost doesn't matter, so the electricity price variations do not matter. Therefore, the price vector is taken constant; I chose $P_t = 1\$/MWh$.

For 'price_based_flexibility', I took the real USEP electricity prices given by the Energy Market Company, for the considered dates and times. These are extracted by electricity_prices.py, that takes them from the monthly USEP prices, that you need to download from the Energy Market Company whenever you use a new year for the prediction horizon.

To be able to compare the electricity costs incurred by the 'set_temperature_tracking' and the 'price_based_flexibility', I defined the electricity cost calculation function electricity_cost_calculation that calculates electricity_cost based on electricity_prices_MWh that corresponds to the real USEP electricity prices given by electricity_prices.py.

State space equations

$X_{b,t+1} = A_b \cdot X_{b,t} + B_{b,u} \cdot U_{b,t} + B_{b,v} \cdot V_{b,t}, \quad t = 0, \dots, N, \quad b \in B$ corresponds to the state_space_equation_state_constraint_rule in optimisation_district.py, and $Y_{b,t} = C_b \cdot X_{b,t} + D_{b,u} \cdot U_{b,t} + D_{b,v} \cdot V_{b,t}, \quad t = 0, \dots, N, \quad b \in B$ corresponds to the state_space_equation_output_constraint_rule in optimisation_district.py.

The following matrices are defined for each building in building.py. They are used in optimisation_district with the following notations:
$A_b \rightarrow$ buildings_dic[building].state_matrix
$B_{b,u} \rightarrow$ buildings_dic[building].control_matrix

$B_{b,v} \rightarrow$ buildings_dic[building].disturbance_matrix
$C_b \rightarrow$ buildings_dic[building].state_output_matrix
$D_{b,u} \rightarrow$ buildings_dic[building].control_output_matrix
$D_{b,v} \rightarrow$ buildings_dic[building].disturbance_output_matrix

Initial conditions

$X_{initial,b} \rightarrow$ initial_state_dic[building] in optimisation_district.py

$X_{initial,b}$ is the initial state. It is defined in preliminary_setup_optimisation.py. I chose to define the initial state as the set temperatures of the initial time step, that is named time_start and chosen by the user in main_district.py.

Building comfort constraints The building comfort constraints are the following:

$$Y_{min,b,t} \leq Y_{b,t} \leq Y_{max,b,t}, \quad t = 0, \ldots, N, \quad b \in B \tag{2}$$

$Y_{min} \rightarrow$ minimum_output_dic in preliminary_setup_optimisation.py
$Y_{max} \rightarrow$ maximum_output_dic in preliminary_setup_optimisation.py

The output matrix is bounded by a minimal matrix and a maximal matrix, for each building.

The values of the minimal matrices and the maximal matrices depend on the min_max_source that is chosen by the user between 'from building.py', 'from occupancy variations', and 'constants' in main_district.py.

For 'from building.py', the minimal and maximal matrices are defined in building.py, depending on the values in building_zone_constraint_profiles.csv.

For 'from occupancy variations' and 'constants', the minimal and maximal matrices are defined in minimal_maximal_outputs.py. In these 2 cases, the window fresh air flow and the electric power are not bounded, it is only required that they are positive. Moreover, the minimum fresh air flow is defined by the number of occupants in the rooms and the minimal fresh air flow that each occupant needs, based on the CEA construction_properties.xlsx in the INDOOR_COMFORT tab. There is no maximal fresh air flow.

The difference between the 'from occupancy variations' and 'constants' cases is the minimal and maximal room temperatures.
For the 'constants' case, the minimal and maximal temperatures are always the same, they are equal to a minimal constant ($\rightarrow$ min_constant_temperature) and a maximal constant ($\rightarrow$ max_constant_temperature) chosen by the user in main_district.py
For the 'from occupancy variations' case, the minimal and maximal temperatures of a zone depend on whether the zone is in set mode or setback mode for the considered time step:

$$T_{min,b,t} = T_{center,b,t} - \Delta_t$$

$$T_{max,b,t} = T_{center,b,t} + \Delta_t$$

where $\Delta_t = \Delta_{set}$ if the zone is in set mode, and $\Delta_t = \Delta_{setback}$ if the zone is in setback mode. Normally, $\Delta_{set} \leq \Delta_{setback}$. I have defined T_{center} as the set temperature for the set mode. In this way, the $[T_{min,b}; T_{max,b}]$ interval is always centered on the same $T_{center,b} = T_{set\_mode,b}$ temperature, and is wider when there is no occupant in the zone than when there is a least one occupant in the zone.

Bhargav Methodology

Design of UES of a neighbourhood has many combinations. Goal of designing a Urban Energy System that meets the demand of the neighbourhood. The variables that can be changes during this process can be classified into four categories:

1. Building Properties such as building geometry, building occupancy, building use type 2. Thermal supply system properties such as type of the supply system, size of the supply system, operational strategy of the supply system 3. Electrical supply system properties 4. Network Properties such as buildings that are connected/disconnected to the centralized plant

The planning and operation problem is formulated as a mixed integer linear program (MILP) in a single stage optimization. The objective is to minimize annualized investment costs of the electric grid along with the operation costs of flexible loads. The decision variables are the electric grid topology and the dispatch schedule of flexible loads. HVAC systems of commercial and residential buildings are considered as flexible loads. Hence, thermal comfort constraints and electric grid loading constraints form the constraints of the problem. To express the thermal comfort as a function of the scheduled electric load, a linear thermal building model is formulated along with a linear model of the thermal emission, distribution and generation systems. Similarly, the electric grid loading is formulated as a function of the scheduled electric load and the grid topology with a linear power flow model.

Electric grid planning employs Model Predictive Control (MPC) and generates the demand profile for all the buildings in the neighbourhood for both the status-quo (fixed demand scenario) and flexible demand scenario.

The constraints to be met while designing the energy system for the district are to meet the overall energy demand. The objective which we use to evaluate a UES are the total annualized costs involved in operation the UES, the total emeissions associated with operating the UES and the total non-renewable primary energy used while operating the UES. This along with the amount of interdependencies present between thermal and electrical systems form a classic optimization problem.

There are innumerable possible combinations based on the size of the neighbourhood, which will generate a feasible solution. It is near impossible to brute force our way through all the possible solutions. To make it possible to get a good trade-off solution, we use optimization techniques, which help us identify the solution in the entire solution space. To perform optimization, we are using the optimization module develeoped in City Energy Analyst (CEA). The overview of the optimization process is provided in the following figure. CEA optimization can be divided into two categories: 1. Building Scale , 2. District Scale.

Building Scale optimization decides the best energy system configuration for a standalone building by comparing the available technologies for a building. The possible colling technologies for a building scale optimization are Vapor Compression Chiller, Absorption Chiller, Direct Expansion. The possible electrical technologies are either Photovoltaic or National Grid. The possible hot water technologies are Solar Collector, Electrical Boiler or Gas Fired Boiler. Among all these possible options the best combination that results in the least costs, emission and primary energy are chosen.

District Scale decides the best energy system configuration for buildings connected to the District Cooling/Heating Plant. This in turn has two levels: Design Level and Operation Level.In Design Level, the supply system technologies are selected, and the sizing is done based on the peak load i.e. each technology will meet a percentage demand based on the peak load. For example, 40% of peak load is met by Vapor Compression Chiller, 40% by Absorption Chiller and 20% by thermal storage. In the Operation Level, the activation of each of these units is done and the corresponding emissions, costs are calculated.For the activation of the units, it is a rule-based system, where in the renewables are activate first and then followed by non-renewables.

Apart from having many options for the cooling technologies, heating technologies and electricity, this has another variable in terms of the buildings connected to the central network i.e. which buildings present in the district are connected to the district plant. This also considers the thermal/pressure losses incurred in the network.

Genetic Algorithm is used to perform multi-objective optimization of the District Energy Systems. After performing the optimization for a test case, the following Pareto-curve is generated (Figure), which shows the trade-off between the costs, CO2 emissions and the primary energy.

The paper extends the existing thermal energy system planning capabilities of the City Energy Analyst (CEA) toolbox ([6]) with algorithms for electric grid planning and flexible load operation.

—good—-

The electricity used for air cooling systems is a large part of building electricity consumption in Singapore. Thus, the goal is to optimize the electricity demand linked to air cooling systems of buildings on a district scale to contribute to the matching of generation and demand.

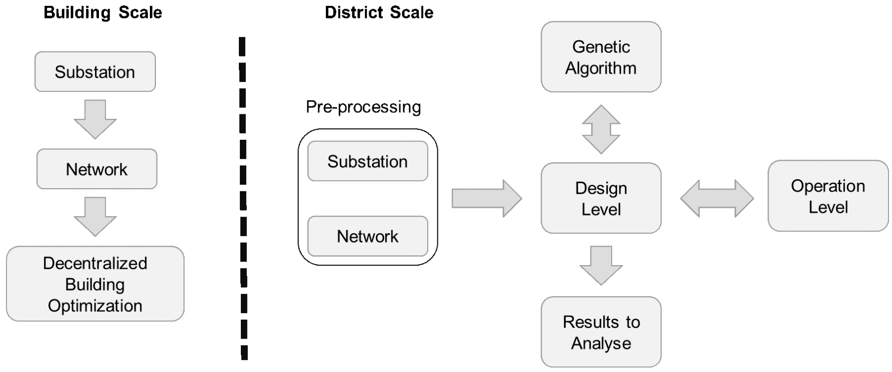
The electricity price being a good indicator of the matching between generation and demand, the goal of our sub-project is to minimize the cost of operations, which is directly linked to the electricity price pt at each time step t and the buildings electricity demand dt at each time step t:

Building model elaboration:

The first step of the sub-project is to elaborate a building model. Its goal is to express the different energy flows that occur in the building.

These energy flows include:

Figure 2: Optimization Strategy in CEA



- the energy flows due to the temperature differences between the outdoor air and the indoor air - the energy flows due to the solar radiations on the building windows, walls and roof - the energy flows due to leakages - the energy flows due to emissivity - the energy flows due to the heat released by the building occupants - the energy flows due to the heat released by the building electrical appliances - the energy flows due to Heatinb, Ventilation, Air-conditioning (HVAC) systems, including the ones due to the energy losses in these systems

These energy flows are directly linked to the building room temperatures. The required building model is linear, time-discrete and formulated in a state space form as follows:

Where X_t is the state vector and represents the building temperatures at time step t; Y_t is the output vector and mainly represents the building electricity demand and the room temperatures at time step t; U_t is the control vector and represents the commands given to the HVAC systems at time step t; V_t is the disturbance vector and represents the causes of the internal and external energy flows, apart from the HVAC system flows, at time step t. A, B_u, B_v, C, D_u and D_v are constant matrices that do not depend on the variables X_t, Y_t and U_t.

In order to validate our building model, we compared the results of our model and the ones of CEA, on various test cases created by CEA. During our comparison simulations, we used constant electricity pricing and tracked the CEA room temperatures, in order to be in the same conditions as the CEA. We compared our energy loads on three levels. The first level corresponds to the thermal energy that is delivered to the building rooms and is named 'Thermal Load'.

Average Electricity Tariff for 2017 in Singapore is about 20 cents per kWh

Table 1: Occupancy Profile of various buildings in the neighbourhood (WTP MIX small)

Building	Hotel	Office	Retail	Restaurant	Multi-Res
B01	0.3	0.7	0	0	0
B02	0	0.7	0.1	0.2	0
B03	0	0	0	0	1
B04	0	0	0.5	0.5	0
B05	0.3	0	0.5	0.2	0
B06	0	0	0	0	1
B07	0	0	0	0	1
B08	0	0	0	0	1
B09	0	0	0	0	1
B10	0	0	0.6	0.4	0

Future New Towns: The development is being done in a greenfield area. Based on studying the various building types in Singapore, a parametric urban generator is used to create pilot case studies. A matrix of use cases is developed based on the use type and the population density of the greenfield is generated.

Table 2: Total Demand of various buildings in a small case study (WTP MIX small) expressed in terms of electricity, all the demand is converted to electricity demand from the Grid

Building	Space Heating (MWh)	Space Cooling (MWh)	Hot Water Demand (MWh)	Electricity Demand (MWh)	Total Demand (MWh)
B01	0	9372.1	0	9034.2	18406.3
B02	0	2893.0	0	2373.1	5266.1
B03	0	855.1	623.8	1287.0	2765.9
B04	0	6219.9	950.2	3739.9	10910.0
B05	0	3828.8	0	3133.3	6962.1
B06	0	541.2	388.5	797.1	1726.9
B07	0	425.8	302.2	620.0	1347.9
B08	0	379.4	292.1	598.1	1269.6
B09	0	465.6	328.3	674.5	1468.4
B10	0	5301.4	0	3825.2	9126.6
Total Demand	0	30282.3	2885.1	26082.4	59249.8

Table 3: Occupancy Profile of various buildings in the neighbourhood (WTP CBD small)

Building	Hotel	Office	Retail	Restaurant	Multi-Res
B01	0	0	0.6	0.4	0
B02	0.3	0	0.5	0.2	0
B03	0	0	0	0.1	0.9
B04	0	0	0	0.1	0.9
B05	0	0.7	0.1	0.2	0
B06	0.3	0.7	0	0	0
B07	0	0.7	0.2	0.1	0
B08	0	0.7	0.2	0.1	0
B09	0	0.7	0.2	0.1	0
B10	0	0.7	0.2	0.1	0

Table 4: Occupancy Profile of various buildings in the neighbourhood (WTP RES small)

Building	Hotel	Office	Retail	Restaurant	Multi-Res
B01	0	0	0	0	1
B02	0	0	0	0	1
B03	0	0	0	0	1
B04	0	0	0	0	1
B05	0	0	0	0	1
B06	0	0	0	0	1
B07	0	0	0	0	1
B08	0	0	0	0	1
B09	0	0	0	0	1
B10	0	0	0.5	0.5	0

Table 5: Case studies

	Residential	Business District	Mixed
Small			
Medium			

$$f_{Cost}(U) = \alpha \cdot \sum_{t=0}^{N} P_t \cdot \Big(\sum_{i \in E, b \in B} Y_{b,i,t} \Big) + \beta \cdot \sum_{t=0}^{N} \sum_{j \in T, b \in B} |Y_{set,b,j,t} - Y_{b,j,t}| \tag{3}$$

The optimization problem for the thermal operations is the following:

where:
X : state matrix $\rightarrow$ states_variable in optimisation_district.py
Y : output matrix $\rightarrow$ outputs_variable in optimisation_district.py
U : control matrix $\rightarrow$ controls_variable in optimisation_district.py
V : disturbance matrix $\rightarrow$ disturbance_timeseries in building.py
P : electricity prices vector $\rightarrow$ price_vector in preliminary_setup_optimisation.py
$[0; N]$: prediction horizon $\rightarrow$ date_and_time_prediction in get_process_write_data.py
B : set of all the buildings in the district $\rightarrow$ buildings_names in extract_cea_data.py
E : set of the electric powers $\rightarrow$ sub-set of m.buildings_dic[building].i_outputs.index in building.py
T : set of the room temperatures $\rightarrow$sub-set of m.buildings_dic[building].i_outputs.index in building.py
C : set of the cooling electric powers
H : set of the heating electric powers

4 Problem Description

The attempt is to formulate an urban system deisgn mechanism for the case where the neighbourhoods have flexible loads. Based on an electrical pricing mechanism, the consumer's behaviour is influenced to shift the demand to a different time of the day.

Electricity details are acquired from the Singapore website where the electricity costs of every 30 mins for the entire year are present. We are currently using the costs of electricity in 2017 and using them to simulate the entire year of 2018.

City Energy Analyst (CEA) is used to model, simulate and optimize the Urban Energy Systems (UES). CEA is an integrated framework to evaluate the performance of a neighbourhood from the perspective of energy efficiency and in the context of urban transformation. CEA provides a holistic view of demand and supply of UES using modeling techniques and spatiotemporal visualization model.

Buildings can act as stockpiles for thermal energy (buiding inertia), where in you cool a building at a certain hour and it will reduce the consumption in the next hour. Leveraging this concept, a building model based on price-based demand flexibility is developed. This links the changes in electricity prices to the amount of cooling to be done in the buildings. Thus when the electricity price gets lower, the electricity consumption gets higher, therefore cooling the rooms. This enables to stockpile the cooling in the building (building inertia), to enable lower electricity consumption when the electricity price gets higher.

5 Cost function

The cost function is:

$$f_{Cost}(U) = \alpha \cdot \sum_{t=0}^{N} P_t \cdot \big(\sum_{i \in E, b \in B} Y_{b,i,t} \big) + \beta \cdot \sum_{t=0}^{N} \sum_{j \in T, b \in B} |Y_{set,b,j,t} - Y_{b,j,t}| \qquad (4)$$

$\alpha \rightarrow$ alpha is preliminary_setup_optimization.py $\beta \rightarrow$ beta in preliminary_setup_optimization.py

Their values depend on the case_goal that is chosen by the user between 'set_temperature_tracking' and 'price_based_flexibility' in main_district.py

5.1 The electric power output

For each building b and time step t, the $Y_{b,i,t}$ are the rows of the output vector that correspond to electric powers, that is to say, for which '_electric_power' is in the index.

5.2 The set temperature and the temperature output

For each building b and time step t, the $Y_{b,j,t}$ are the rows of the output vector that correspond to room temperatures, that is to say, for which '_temperature' is in the index.

$Y_{set,b,j,t}$ is the corresponding set temperature. The set room temperatures are defined in preliminary_setup_building.py. They depend on the set_temperature_goal that is chosen by the user in main_district.py, between 'follow_cea', 'constant_temperature' and 'set_setback_temperature'.

'follow_cea' corresponds to set temperatures that are equal to the room temperatures in City Energy Analyst. These temperatures are extracted by compare_with_cea.py, that takes the CEA data from the CEA outputs. This 'follow_cea' goal enables to compare the outputs that we get with our code, and the outputs that CEA gets with their code, when we are both using the same room temperatures.

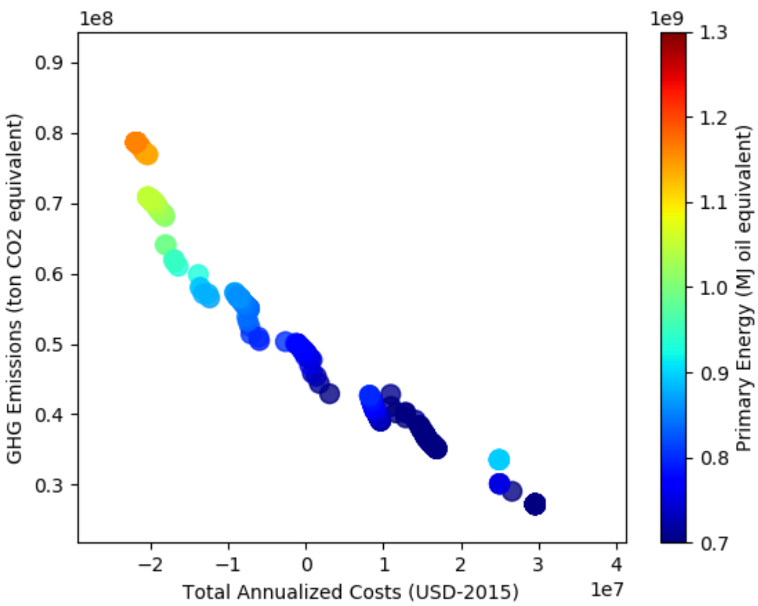
'constant_temperature' gives set temperatures that are always the same, and that are equal to constant_temperature defined by the user in main_district.py.

'set_setback_temperature' uses the set temperatures defined in set_temperatures.py. In this code, we first look whether the considered time step corresponds to a zero occupancy or a non-zero occupancy for the zone that is considered. A zero occupancy for a given zone means that there is no one in the zone, and therefore the setback mode temperature should be used for this zone and this time step. A non-zero occupancy for a given zone means there is a least one person in the room, and therefore the set mode temperature should be used for this zone and this time step. Then, we look at whether the time step is in the heating season or the cooling season. The resulting set temperature is then taken from the CEA construction_properties.xlsx in the INDOOR_COMFORT tab.

6 scientific innovation and relevance

7 Preliminary Results and Conclusions

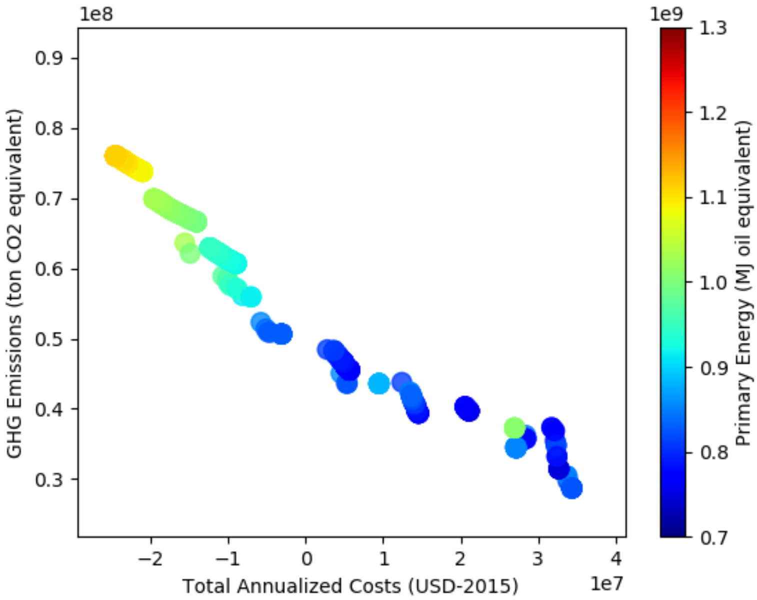
Figure 3: Mixed Case Study (fixed building loads)



8 Test case

The test case is based on a real reconstruction project which is embedded in the port area of Tanjong Pagar, Singapore. In the near future, the port will be restructured to a multipurpose area, consisting of commercial, residential and office areas. The test bed is illustrated in figure **??** (left) and covers an approximate area of $300,000m^2$. In the chosen scenario 10 buildings are encased.

Figure 4: Mixed Case Study (flexible building loads)



Appendix appendix appendix.

Acknowledgment

This work was financially supported by the Singapore National Research Foundation under its Campus for Research Excellence And Technological Enterprise (CREATE) programme.

References

[1] P.-H. Li and S. Pye, "Assessing the benefits of demand-side flexibility in residential and transport sectors from an integrated energy systems perspective," *Applied Energy*, vol. 228, pp. 965 – 979, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0306261918310237

[2] N. Good and P. Mancarella, "Flexibility in multi-energy communities with electrical and thermal storage: A stochastic, robust approach for multi-service demand response," *IEEE Transactions on Smart Grid*, pp. 1–1, 2018.

[3] O. Kilkki, A. Alahäivälä, and I. Seilonen, "Optimized control of price-based demand response with electric storage space heating," *IEEE Transactions on Industrial Informatics*, vol. 11, no. 1, pp. 281–288, Feb 2015.

[4] A. Vandermeulen, B. van der Heijde, and L. Helsen, "Controlling district heating and cooling networks to unlock flexibility: A review," *Energy*, vol. 151, 03 2018.

[5] H. Lund, N. Duic, P. Østergaard, and B. Mathiesen, "Future district heating systems and technologies: On the role of smart energy systems and 4th generation district heating," *Energy*, vol. 165, 09 2018.

[6] J. A. Fonseca, A. Schlueter, T.-A. Nguyen, and F. Marechal, "City Energy Analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts," *Energy Build.*, vol. 113, pp. 202–226, 2016. [Online]. Available: https://doi.org/10.1016/j.enbuild.2015.11.055

Figure 5: Office Case Study (fixed building loads)

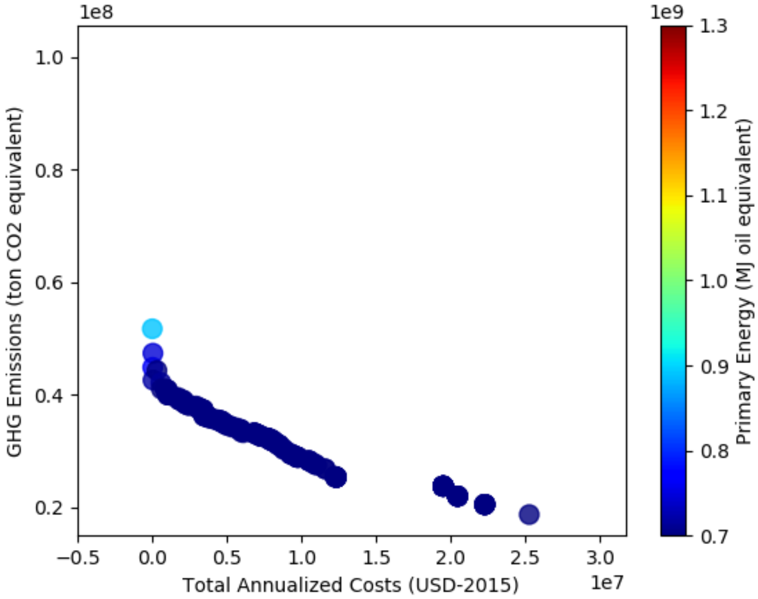


Figure 6: Office Case Study (flexible building loads)

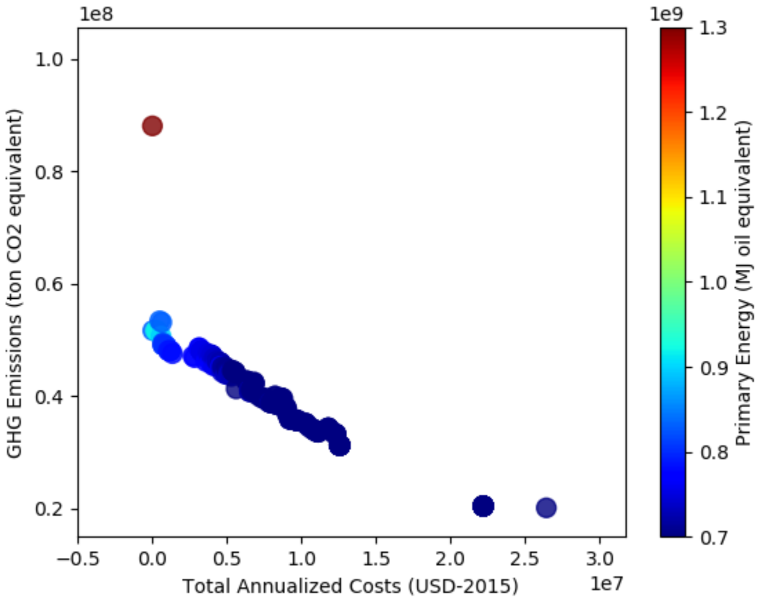


Figure 7: Residential Case Study (fixed building loads)

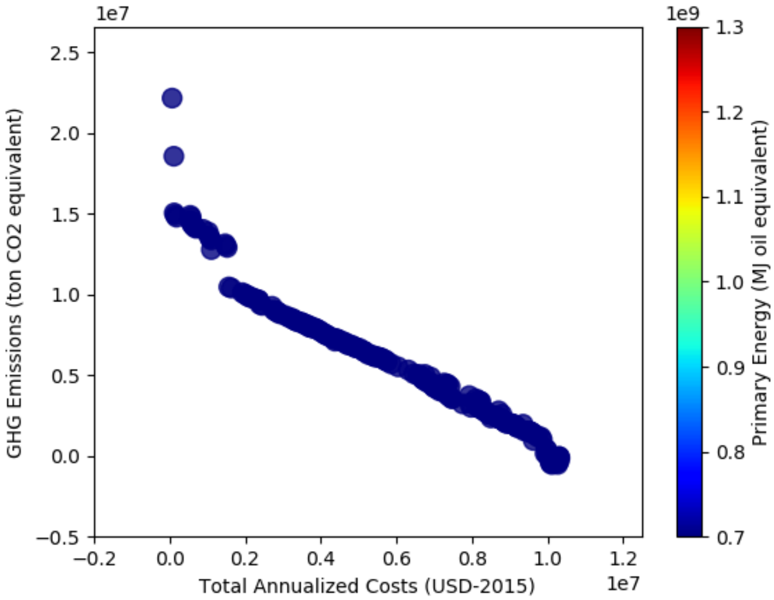
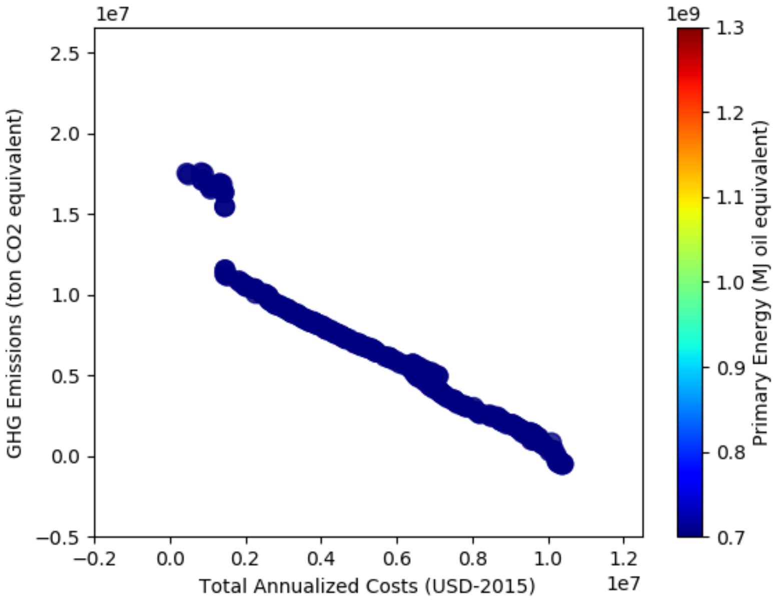


Figure 8: Residential Case Study (flexible building loads)



E Slides: Lunch Talk at Future Cities Laboratory (March 2019)

Project CONCEPT

CONne**C**ting District **E**nergy and **P**ower Systems in Future Singaporean New **T**owns

Sebastian Troitzsch, Sreepathi Bhargava Krishna - 13 March 2019

(SEC) SINGAPORE-ETH CENTRE 新加坡-ETH 研究中心 | TUMCREATE

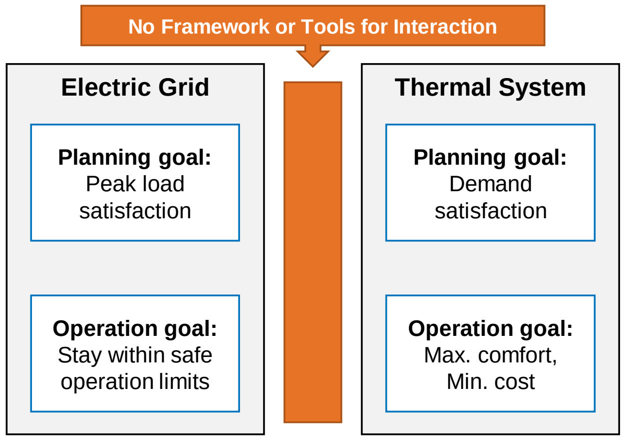
What is CONCEPT?

- CONCEPT stands for:
  - Connecting District Energy and Power Systems in Future Singaporean New Towns

What is CONCEPT?

- CONCEPT stands for:
  - Connecting District Energy and Power Systems in Future Singaporean New Towns
- Goals:
  1. Integrate **planning and operation of electric and thermal systems** on a district scale

Status Quo:



4

What is CONCEPT?

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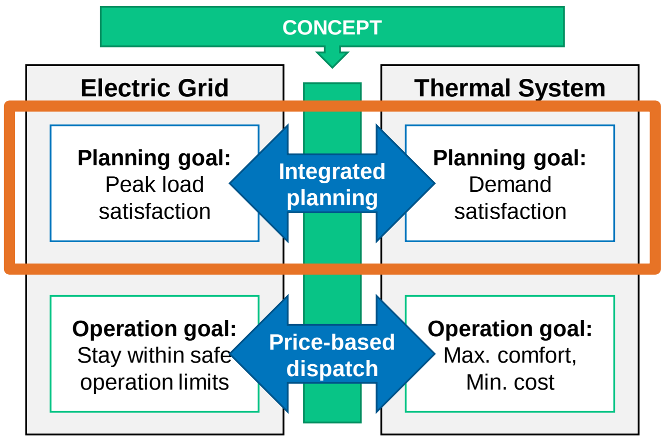
- Goals:
  1. Integrate **planning and operation of electric and thermal systems** on a district scale

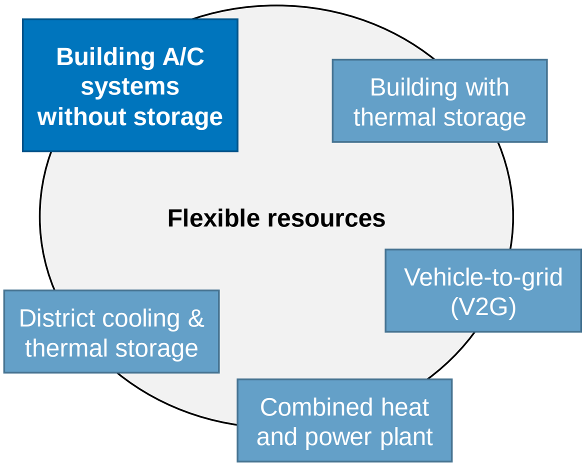
Proposal:



5

What is CONCEPT?

- CONCEPT stands for:
  - Connecting District Energy and Power Systems in Future Singaporean New Towns
- Goals:
  1. Integrate **planning and operation of electric and thermal systems** on a district scale
  2. Consider **flexible resources in the planning phase** of New Town districts



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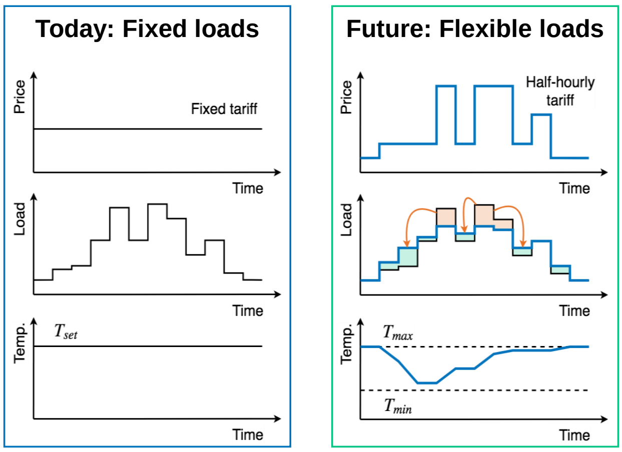
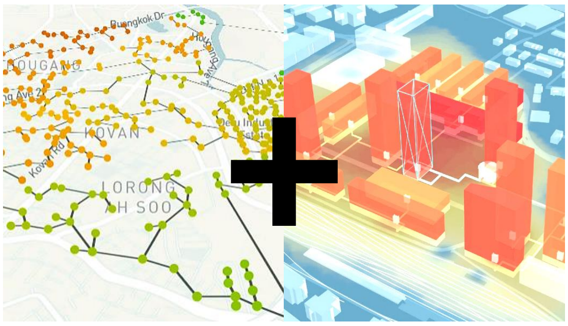


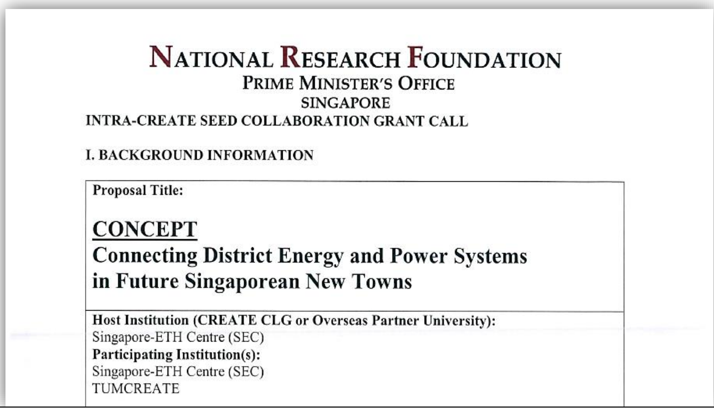
What is CONCEPT?

- CONCEPT stands for:
  - Connecting District Energy and Power Systems in Future Singaporean New Towns
- Goals:
  1. Integrate **planning and operation of electric and thermal systems** on a district scale
  2. Consider **flexible resources in the planning phase** of New Town districts
  3. Creating a **computational framework** integrated in City Energy Analyst (CEA)



What is CONCEPT?

CONCEPT is set up as **13-month pilot project** between the Singapore-ETH Centre (SEC) and TUMCREATE under the "**Intra-CREATE Seed Collaboration Grant**" of the National Research Foundation (NRF)



NATIONAL RESEARCH FOUNDATION
PRIME MINISTER'S OFFICE
SINGAPORE
INTRA-CREATE SEED COLLABORATION GRANT CALL

I. BACKGROUND INFORMATION

Proposal Title:

CONCEPT
Connecting District Energy and Power Systems in Future Singaporean New Towns

Host Institution (CREATE CLG or Overseas Partner University):
Singapore-ETH Centre (SEC)
Participating Institution(s):
Singapore-ETH Centre (SEC)
TUMCREATE

Who is CONCEPT?

Sebastian Troitzsch
Researcher
(TUMCREATE)

Jimeno A. Fonseca
PI
(SEC)

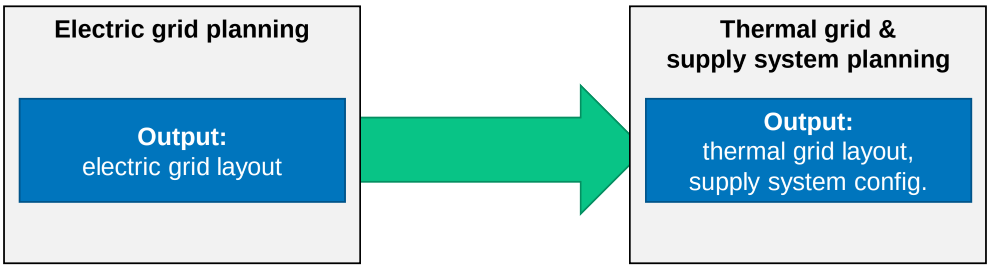
Tobias Massier
Adviser
(TUMCREATE)

Sreepathi B. Krishna
Researcher
(SEC)

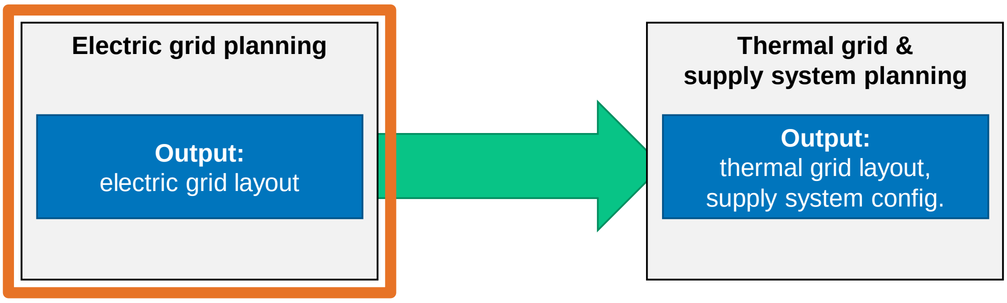
Sarmad Hanif
Co-PI
(TUMCREATE)

Arno Schlueter
Adviser
(SEC)

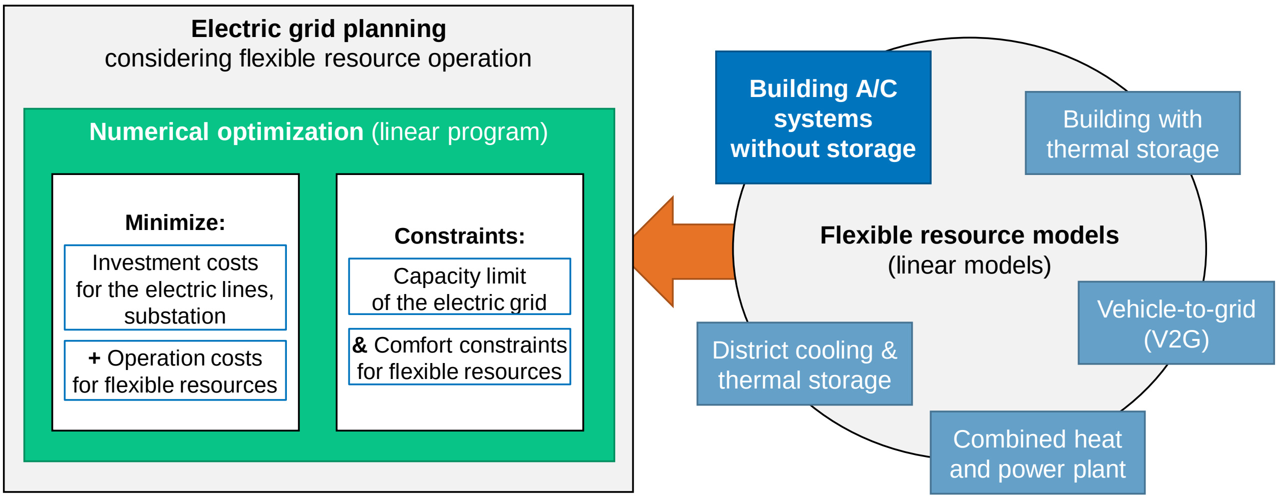
Methodology



Methodology



Methodology: Electric Grid Planning



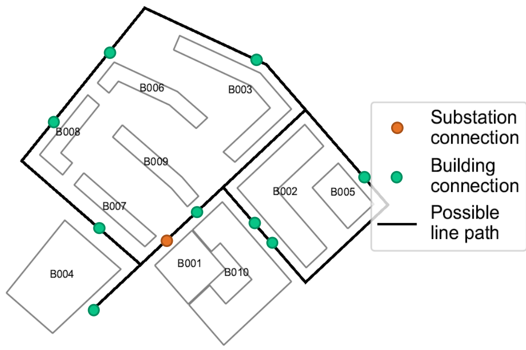
Methodology: Electric Grid Planning

Electric grid planning
considering flexible resource operation

Numerical optimization (linear program)

Minimize:
- Investment costs for the electric lines, substation
- **+** Operation costs for flexible resources

Constraints:
- Capacity limit of the electric grid
- **&** Comfort constraints for flexible resources



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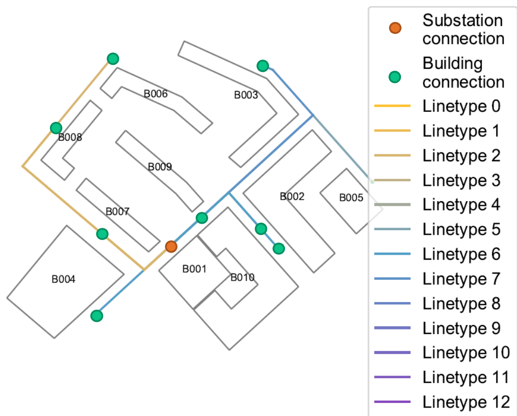
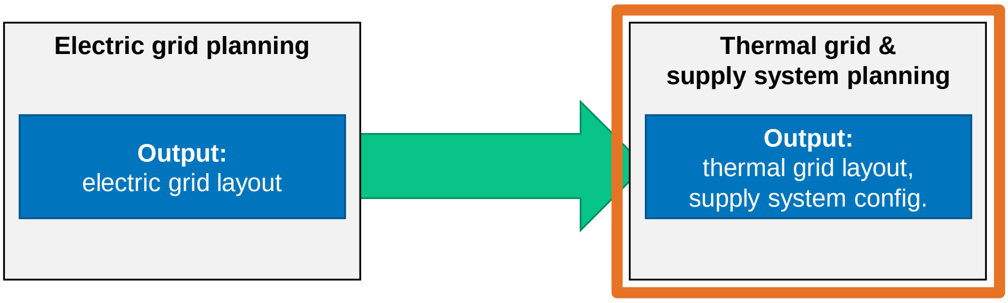
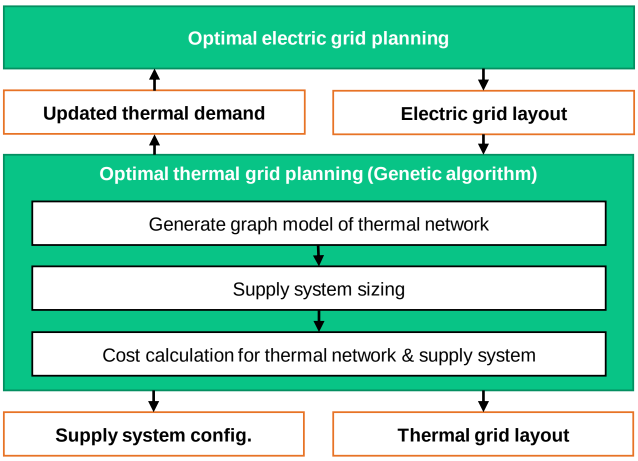
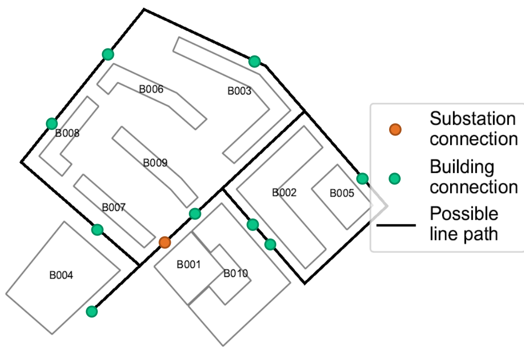


Methodology



Methodology: Thermal Grid and Supply System Planning





Methodology: Thermal Grid and Supply System Planning

Optimal electric grid planning

Updated thermal demand | **Electric grid layout**

Optimal thermal grid planning (Genetic algorithm)

- Generate graph model of thermal network
- Supply system sizing
- Cost calculation for thermal network & supply system

Supply system config. | **Thermal grid layout**

Building Connectivity	PV coverage (roof)	Major Supply System
70%	45%	Absorption Chiller

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Methodology: Thermal Grid and Supply System Planning

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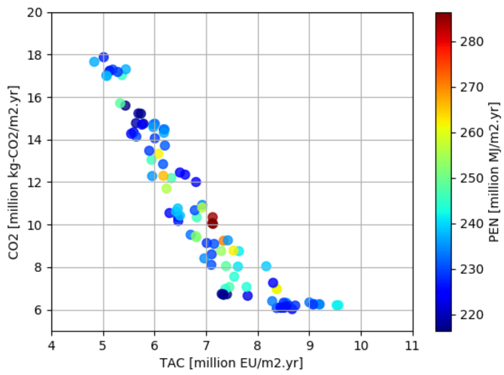

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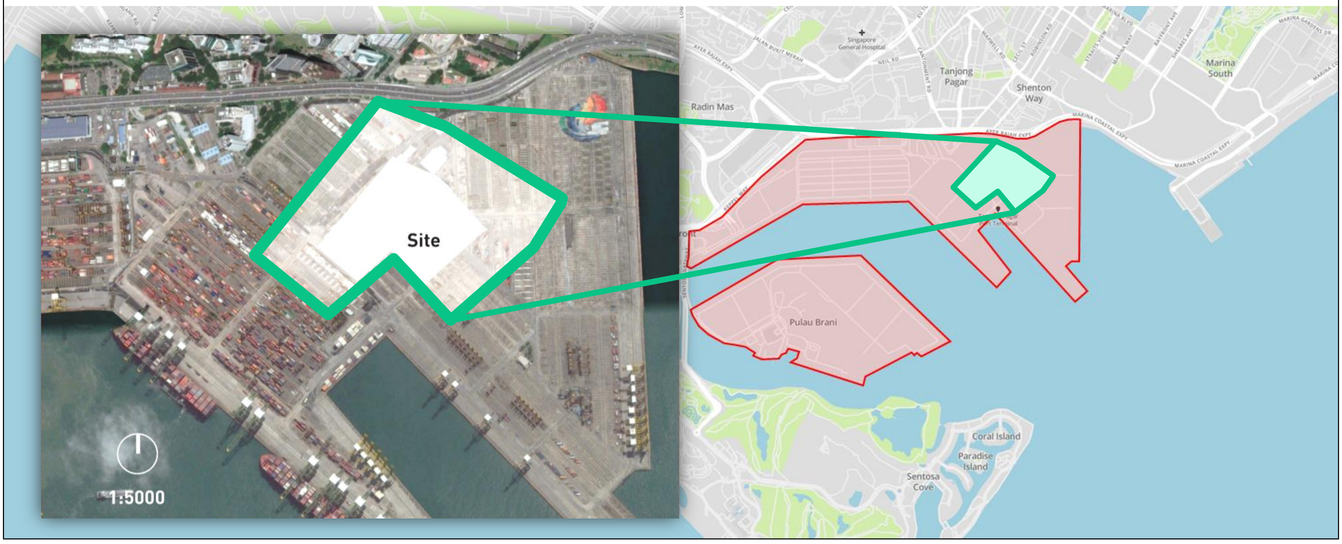
Case Study: New Town – Tanjong Pagar Water Front



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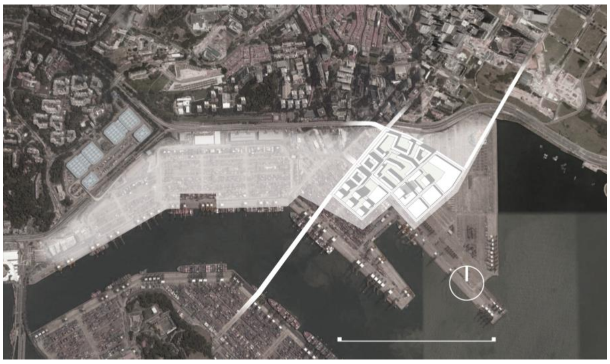
Case Study: New Town – Tanjong Pagar Water Front



MIXed-use

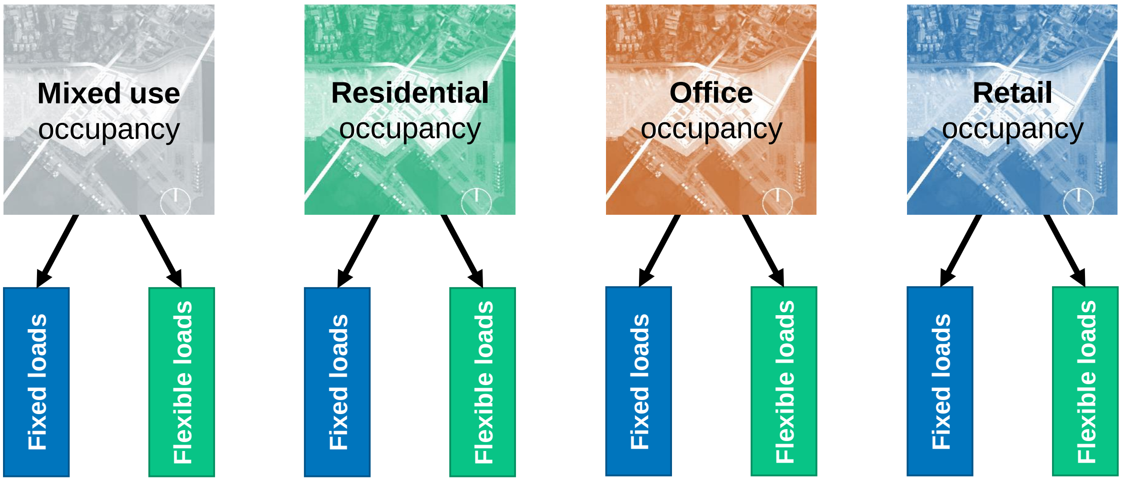
GFA = 374, 237 sqm

FAR = 4.62

People = 34,513

Buildings = 10

Case Study: Scenarios



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Results

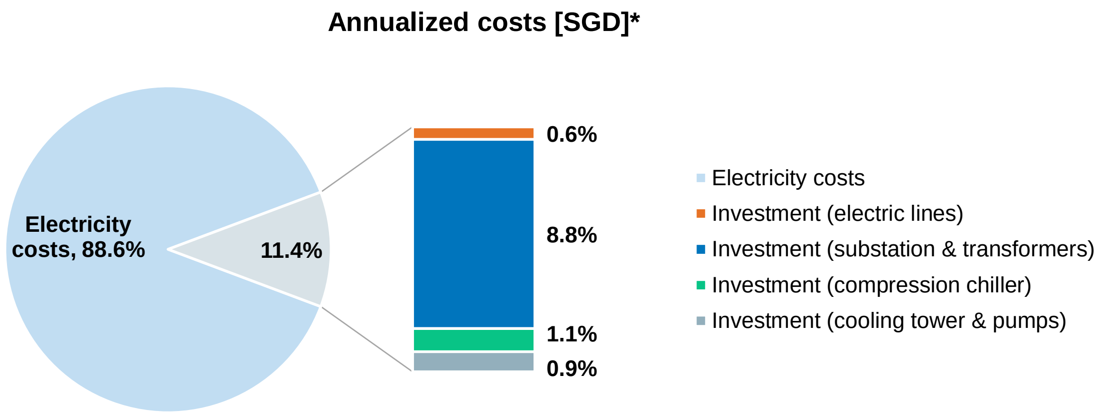
1. **Cost distribution** for fixed building loads

2. **Cost implications** of integrated planning and operation (Fixed vs. Flexible building loads)

3. **Energy implications** of integrated planning and operation (Fixed vs. Flexible building loads)

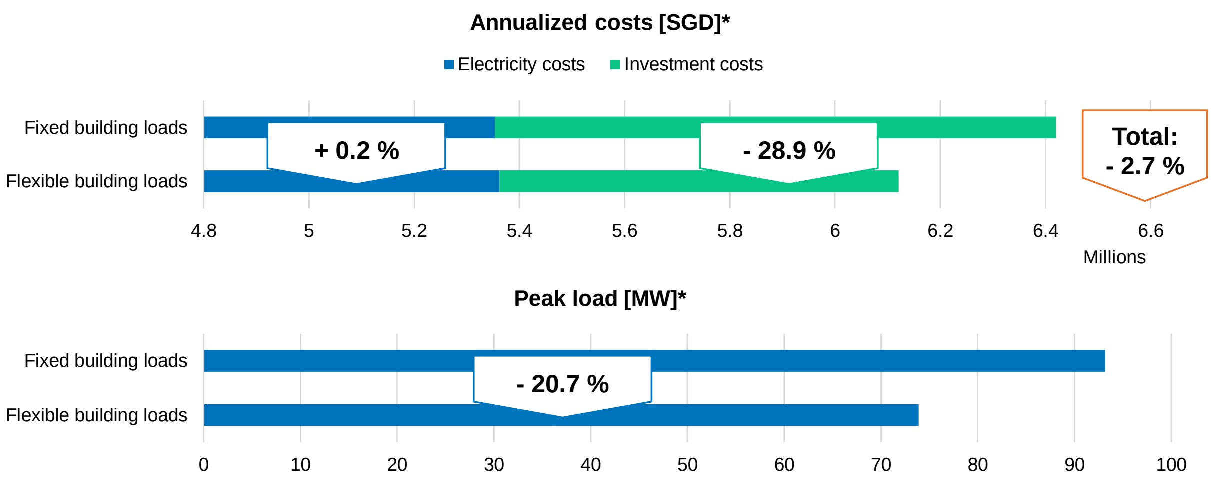
4. **Occupancy type dependency** of costs (Mixed, Office, Residential & Retail)

Results: Cost Distribution (Fixed Building Loads)



*(Preliminary results)

Results: Cost implications (Fixed vs. Flexible building loads)



*(Preliminary results)

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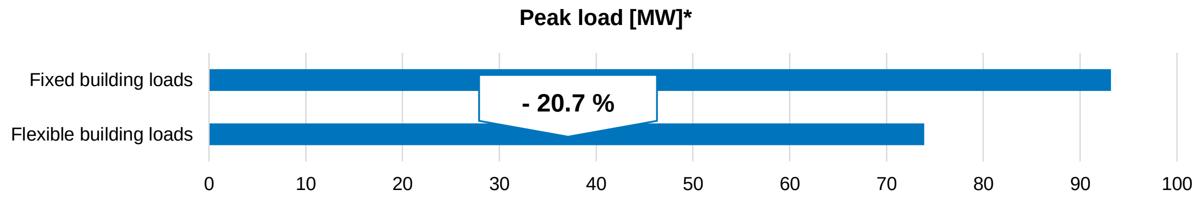
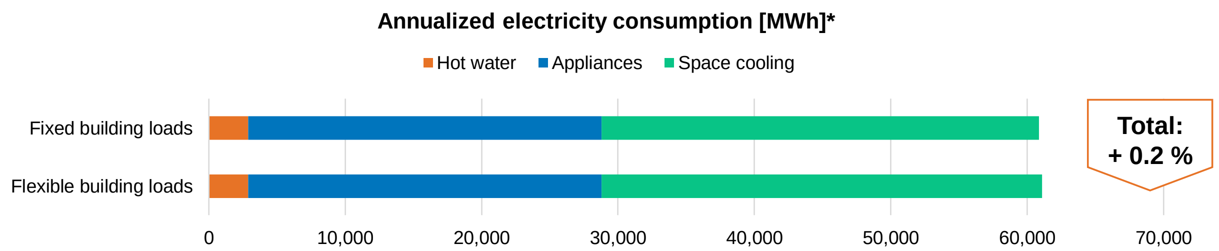
Results: Energy Implications (Fixed vs . Flexible Building Loads)





*(Preliminary results)

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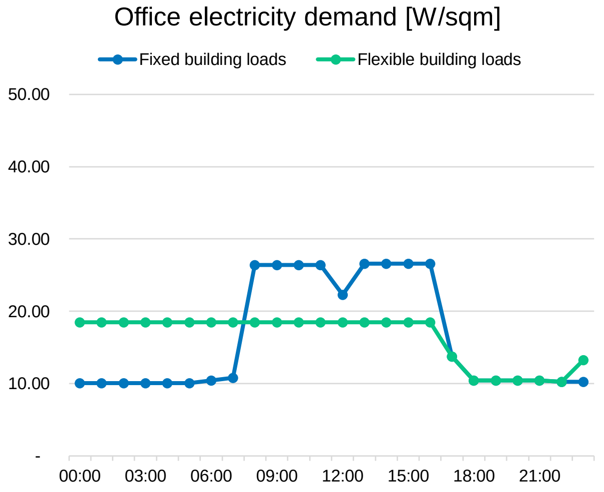
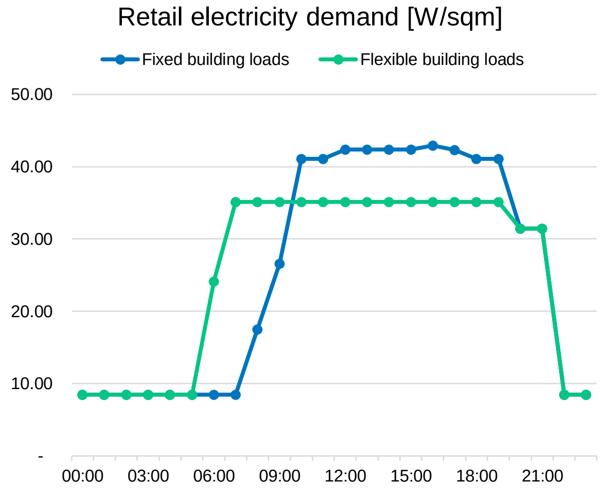
Results: Occupancy Type Dependency

	Mixed occupancy	Office occupancy	Residential occupancy	Retail occupancy
Annualized Total Costs	- 2.7 %	- 3.8 %	- 2.6 %	- 2.1 %
Investment Costs	**- 28 %**	**- 31 %**	**- 21 %**	**- 19 %**

Results: Occupancy Type Dependency





Conclusions

1. The **impact of flexible resources on the district energy system planning** is tested by using flexible building models at a pilot scale.
2. A detailed **computational framework** for generating **district energy systems** for neighbourhoods **with flexible buildings** has been developed and presented
3. Flexible building loads **could decrease the investment cost (- 28 %)*** of the energy systems by **decreasing the peak load**. This comes at the cost of **increased electricity consumption (+ 0.2 %)***.
4. Of all occupancy types, **offices allow for the biggest decrease in investment costs (- 31 %)*.**

***(Preliminary results)**

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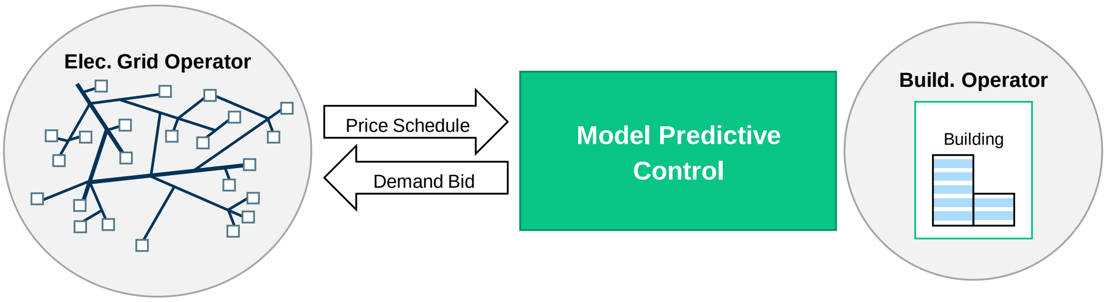
What about Implementation & Operation?

- Electric grid operation:
  - Distribution grid market, with a bid and clearing structure similar to the transmission level
- Building operation:
  - Model predictive control (MPC) for air-condition system control
  - Allows for consideration of dynamic electricity prices
  - MPC is actively being distributed by start-ups (e.g. Meteoviva) & trialed by BMS providers (e.g. Siemens)



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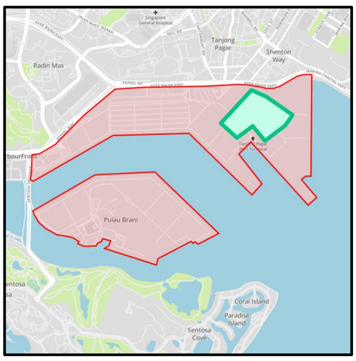
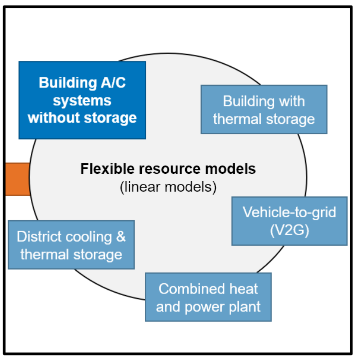
What is the Future of CONCEPT?

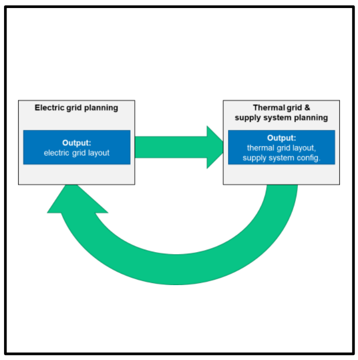
Size



Extension



Feedback

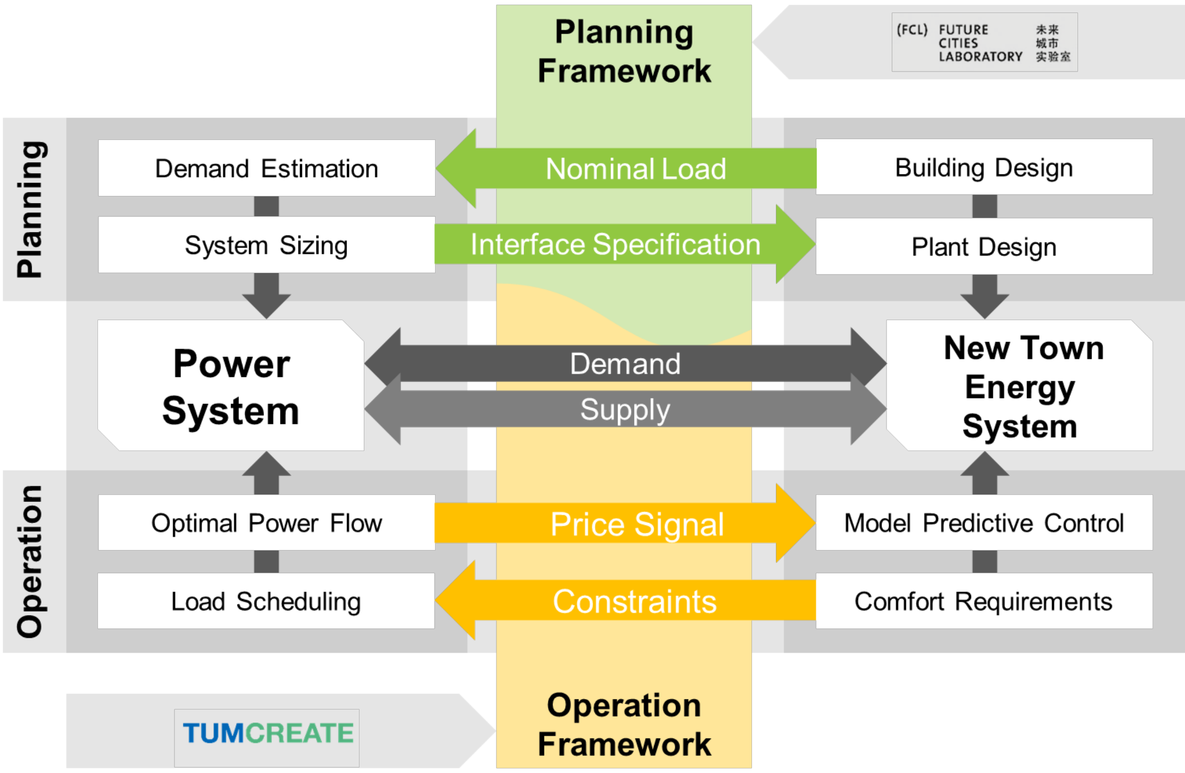


F Progress Report (July 2018)

CONCEPT:

Connecting District Energy and Power Systems in Future Singaporean New Towns.

PROGRESS REPORT
19.07.18



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Description of Progress of the Project

Overall project status (Please describe (a) current status of the Project)

One objective of the CONCEPT proposal is to facilitate an avenue for knowledge exchange and identifying the interdependencies in power grids and thermal energy systems. To this effect, four (4) workshops have been organized between Future Cities Laboratory (FCL) and TUMCREATE. Based on the workshops, three sub-projects were created from the CONCEPT proposal namely,

a. Thermal Operations using Multivariate Optimization
b. Simplified Electrical Network Model.
c. Refinement of Optimization of Thermal Systems

The Thermal Operations using Multivariate Optimization sub-project developed preliminary building models to handle demand-side flexibility linked to electricity prices.

The Simplified Electrical Network Model sub-project developed a new planning algorithm to generate cost-efficient electrical networks by considering power flow constraints.

The Refinement of Optimization of Thermal Systems sub-project enhanced the existing optimization module in City Energy Analyst (CEA) to fit the need of this project.

The Annex 1, 2 and 3, provide a detailed description of each sub-project.

Furthermore we have selected and modelled our first case study of a future New-Town in Singapore. This consists of a precinct with 22 building blocks to be located in the East-side of the the Waterfront Tanjong Pagar area.

Status of KPI’s and milestones ((b) KPIs and milestones achieved to date, referenced against agreed-upon milestones and KPIs in the approved Project. Any delay or deviation from KPIs, deliverables, milestones or implementation methodology (e.g. changes to key staff), as well as remedial actions should be explained)

There are neither delays nor deviations from the agreed-upon KPIs. The KPIs agreed-upon will be completed by the end of the Project, as they depend on the methodological outputs. There have been no changes to main project members. Further status of the agreed-upon KPIs are detailed in Table 1. The updated timeline based on the project approval is provided in Table 2.

Table 1 Status of the Key Performance Indicators

Key Performance Indicators	Status

At least one endorsement letter from the local agencies like EMA, SDC	In discussions with the local agencies for the same.
Computational Model for CEA	CONCEPT research models are being continuously developed/integrated in CEA.
Number of scientific publications	Yet to begin publications, but the research is on track. This project will also lead to a Master's thesis of a student.

Table 2 Updated Timeline (detailed) matching the Project period of support

Milestones	2017	2018				2019
	Q4	**Q1**	**Q2**	**Q3**	**Q4**	**Q1**
Project Kick Off	■					
WP 1: Integrated Energy and Power System Planning	■	■	■	■		
WP 1.1: Coupling of Energy System and Power System Tools	■	■	■			
WP 1.2: Planning Strategy Development		■	■	■		
WP 2: Flexible Operational Strategies for the New Towns		■	■			
WP 2.1: Model Predictive Control Scheme		■	■			
WP 2.2: Distributed Calculation Methodology		■	■			
WP 2.3: Uncertainty Modelling		■	■			
WP 3: Analysis			■	■	■	
WP 3.1: Reliability			■	■		
WP 3.2: Planning and Operational Cost				■	■	
WP 3.3: Renewables			■	■	■	
WP 3.4: Open source tool development	■	■	■	■	■	■
Interim Report			■	■		
Final Report					■	■
Dissemination			■	■	■	■

Opportunities and bottlenecks (Major opportunities encountered and critical technical bottlenecks should be described)

While discussing the interdependencies between the power systems and thermal systems, the potential benefits that can be achieved by combining these two systems were evident. A technical bottleneck encountered is the time-scale used in both systems. Power systems are modelled in the time-scale of 'seconds to minutes', whereas Thermal systems are modelled in the time-scale of 'hours'. Intuitive solution for this bottleneck will be to shift the thermal systems to the time-scale of power systems, but the optimization process will take a long time even for test cases. This bottleneck needs to be resolved to get results in an admissible computational time.

The resolution of the analysis will be up-scaled to the hour resolution for analysis of thermal networks and down-scaled to the minute resolutions for the analysis of the electrical network.

Outcomes and Impact of the Project

Outcomes (Please describe the outcomes and output that the Project has achieved. Interesting developments, such as innovative new products or important collaborations with industry or top research institutions, can be highlighted).

1. **THERMAL OPERATIONS USING MULTIVARIATE OPTIMIZATION:** Buildings can act as stockpiles for thermal energy (building inertia), where in you cool a building at a certain hour and it will reduce the consumption the next hour. Leveraging this concept, a building model based on price-based demand flexibility is developed in this Project. This links the changes in the electricity prices to the amount of cooling to be done in the buildings. Thus when the electricity price gets lower, the electricity consumption gets higher, therefore cooling the rooms. This enables to stockpile the cooling in the building (building inertia), to enable lower electricity consumption when the electricity price gets higher. The resulting plot as shown in Figure 4, represents this simulation based on flexible loads.

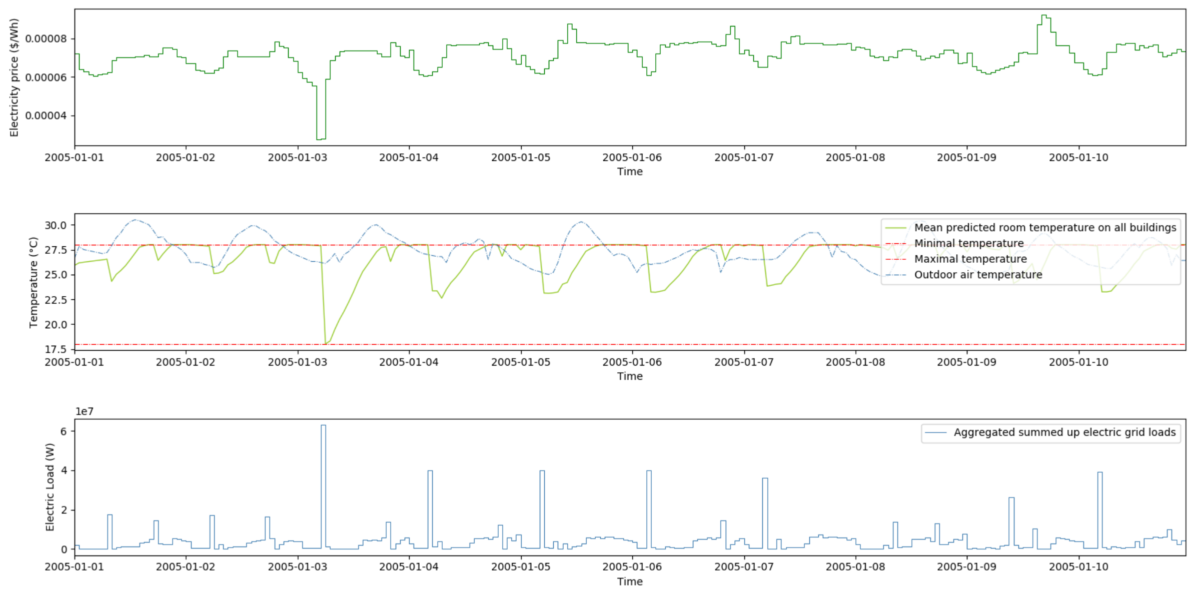

Figure 1 Room temperatures and energy loads on all buildings of the district in our model during the first ten days of January 2005 in Singapore, with price-based demand flexibility

2. **SIMPLIFIED ELECTRICAL NETWORK MODEL:** This project develops a simplified electrical network model including the constraints from the power flow, which is then integrated with thermal network models to generate a holistic network. Electrical network planning helps in generating cost effective electrical networks subject to power flow constraints. Thermal network model generates networks with the least amount of thermal/pressure losses encountered in the network. The computational time to achieve these two are very different: Electrical network (minutes to couple of hours), Thermal network (hours to days). To this effect, a solution achieved by electrical network is used as an initial estimate for

the thermal network and the models are further refined. This is an interesting development, where the best solution of electrical systems is used to build upon for the thermal systems. Activation curves (also developed in this Project), as shown in Figure 2, show the operation of different supply systems to satisfy the end-use energy demand of this generated network.

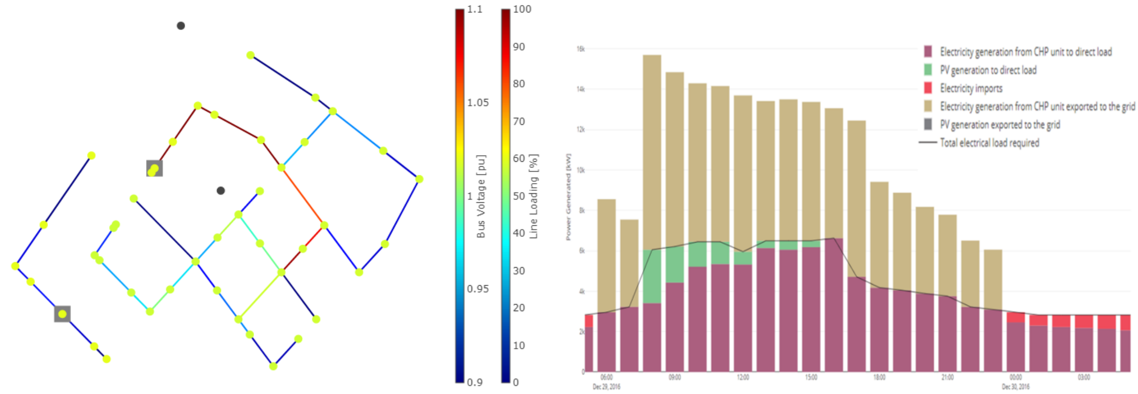

Figure 2 Electrical network model (left) and Electricity Activation Curve (right) of a week showing the various means of electricity supplied in the district

3. **REFINEMENT OF OPTIMIZATION OF THERMAL SYSTEMS:** CEA has a module for performing optimization of district energy systems. To satisfy the need of this project, this module has been refined and updated to understand the various trade-offs possible while considering costs vs emissions. Figure 3 depicts the Pareto-front generated as part of the Project. Activation curves (also developed in this Project), as shown in Figure 2, show the operation of different supply systems to satisfy the end-use energy demand. Activation curves along with Pareto-front and the thermal network provide the insight needed to make informed decisions about urban energy systems.

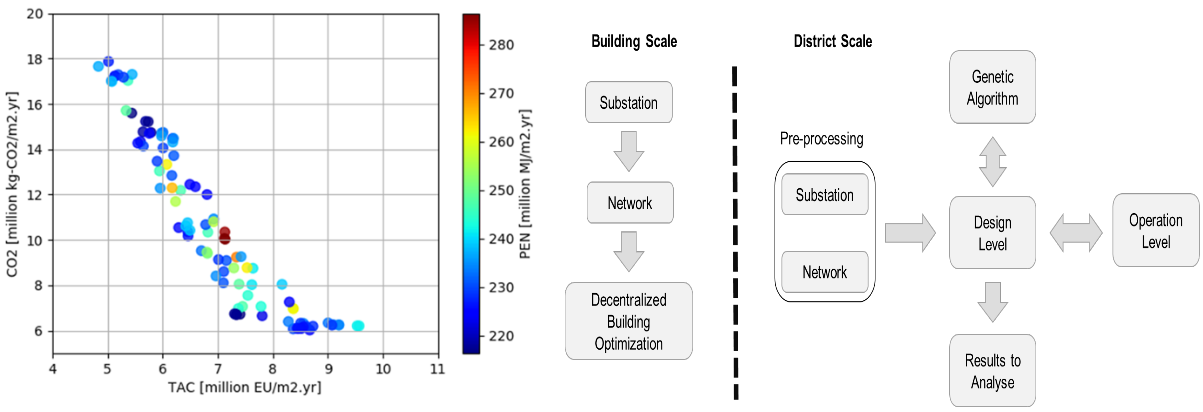

Figure 3 Pareto-front generated for a case study in CEA (left), this depicts the three objectives used in optimization. TAC is total annualized costs, CO2 is the CO2 emissions, PEN is the total non-renewable primary energy. Optimization strategy employed in CEA (right)

Expected impact (Please provide a succinct description of the impact of the project, including but not limited to the realisation or otherwise of value-add to economy and employment creation)

The CONCEPT project will provide a basis for future research in power systems and district energy systems as a whole. The project will enhance the understanding of interdependencies in thermal and electrical systems in districts. This knowledge will lead to a better design of energy infrastructure in New Towns in the near future. This in return, will have a positive financial and environmental impact in Singapore.

As an example, for our case study Water Tanjong Pagar area, the solutions obtained after optimization of thermal systems (sub-project 3) have registered up to 30% reduction in emissions and costs in comparison to current energy systems found in Singapore. Once this optimization is coupled with that of electrical systems, we expect to find higher savings, that can one day be expected in the development of optimal energy infrastructure in New Towns.

Problems encountered

There are no issues regarding the management of the project. The project is on-track for meeting the goals set in the proposal.

There has been no change in the project scope, but rather three sub-projects were created and distributed among the participating parties.

Information on Fund Management and Exceptions

Connecting District Energy and Power Systems	Original Approved Budget	Current Approved Budget	Expenditure	Balance
Manpower	198,071.38	112,623.33	25,909.05	86,714.28
Travel and Travel Related Costs	-	-	-	-
Expenditure on Equipment	6,000.00	3,000.00	-	3,000.00
Other Operating Expenses	-	-	-	-
Subtotal	**204,071.38**	**115,623.33**	**25,909.05**	**89,714.28**
Indirect costs	40,814.28	11,562.33	-	11,562.33
Total	**244,885.66**	**127,185.66**	**25,909.05**	**101,276.61**

Recommendation for continuation of Project

(The Progress Report must include a recommendation by the CLG Director (for CREATE entities) or the respective Offices of Research (for AUs) on whether the Project should continue, based on current performance.)

Prof. Dr. Gerhard Schmidt

Director Singapore ETH- Centre

ANNEX1. Thermal Operations using Multivariate Optimization

Motivation for price-based demand flexibility:

In the traditional power system design, the electricity generation is adjusted to match the current electricity demand, at all times. However, the incorporation of an increasing amount of renewables in the energy mix is a challenge, as renewable energy generation is uncontrollable. Therefore, it becomes important to make electric loads more flexible and controllable to match generation and demand at all times. Buildings being significant electricity consumers, controlling their electricity demand can make a large contribution to the flexibility of the overall electricity demand. The electricity used for air cooling systems is a large part of building electricity consumption in Singapore. Thus, the goal of the sub-project 'Thermal Operations using Multivariate Optimization' is to optimise the electricity demand linked to air cooling systems of buildings on a district scale to contribute to the matching of generation and demand.

The electricity price being a good indicator of the matching between generation and demand, the goal of our sub-project is to minimise the cost of operations, which is directly linked to the electricity price p_t at each time step t and the buildings electricity demand d_t at each time step t:

$$min_d \sum_t p_t \, . \, d_t$$

Building model elaboration:

The first step of the sub-project is to elaborate a building model. Its goal is to express the different energy flows that occur in the building.

These energy flows include:

- the energy flows due to the temperature differences between the outdoor air and the indoor air;
- the energy flows due to the solar radiations on the building windows, walls and roof;
- the energy flows due to leakages;
- the energy flows due to emissivity;
- the energy flows due to the heat released by the building occupants;
- the energy flows due to the heat released by the building electrical appliances;
- the energy flows due to Heating – Ventilation – Air-Conditioning (HVAC) systems, including the ones due to the energy losses in these systems.

These energy flows are directly linked to the building room temperatures. The required building model is linear, time-discrete and formulated in a state space form as follows:

$$\begin{cases} X_{t+1} = A.X_t + B_u.U_t + B_v.V_t \\ Y_t = C.X_t + D_u.U_t + D_v.V_t \end{cases}$$

Where X_t is the state vector and represents the building temperatures at time step t; Y_t is the output vector and mainly represents the building electricity demand and the room temperatures at time step t; U_t is the control vector and represents the commands given to the HVAC systems at time step t; V_t is the disturbance vector and represents the causes of the internal and external energy flows, apart from the HVAC systems flows, at time step t. A, B_u, B_v, C, D_u and D_v are constant matrices that do not depend on the variables X_t, Y_t and U_t.

In order to validate our building model, we compared the results of our model and the ones of CEA, on various test cases created by CEA. During our comparison simulations, we used constant electricity pricing and tracked the CEA room temperatures, in order to be in the same conditions as the CEA. We compared our energy loads on three levels. The first level corresponds to the thermal energy that is delivered to the building rooms and is named 'Thermal Load' in Figure A3. The second level corresponds to the thermal energy summed up with the distribution and emission losses of the HVAC and is named 'Intermediate Load'. The third level corresponds to the electric power taken from the electricity grid and is named 'Electric Load'.

The relative difference of loads between our model and the CEA model are as the following:

- For the thermal load, the relative difference is equal to 33.8%, which is acceptable to validate our model.
- For the intermediate load, the relative difference is equal to 33.2%, which validates our HVAC distribution and emission losses model.
- For the electric load, the relative difference is equal to 57.1%. Indeed, we still have work to do on the model of the losses that occur during the conversion of the grid electricity to the thermal energy used in the HVAC systems.

The time period used for the comparisons is ten days, which is good enough as the weather conditions in Singapore have negligible variations throughout the year.

Multivariate optimization

The second step of this sub-project is to formulate and implement the multivariate optimization problem that we aim to solve. The goal of this problem is to minimise the operations cost $\sum_t p_t \, . \sum_m Z_m . Y_{t,m}$ (which corresponds to the objective function, $Z_m . Y_{t,m}$ being the demand of building m at time step t), while maintaining indoor comfort (which corresponds to the inequality constraints), and of course has to respect the building model (which corresponds to the equality constraints).

The optimization is done on all the buildings (m) of the district at the same time, and is formulated the following way:

$$\min_{X,Y,U} \ \sum_t p_t \cdot \sum_m Z_m . Y_{t,m}$$

$$\text{subject to} \quad \begin{array}{c} X_{m,t+1} = A_m . X_{m,t} + B_{m,u} . U_{m,t} + B_{m,v} . V_{m,t} \\ Y_{m,t} = C_m . X_{m,t} + D_{m,u} . U_{m,t} + D_{m,v} . V_{m,t} \\ Y_{min,m,t} \le Y_{m,t} \le Y_{max,m,t} \\ Y_{m,t=0} = Y_{m,0} \end{array}$$

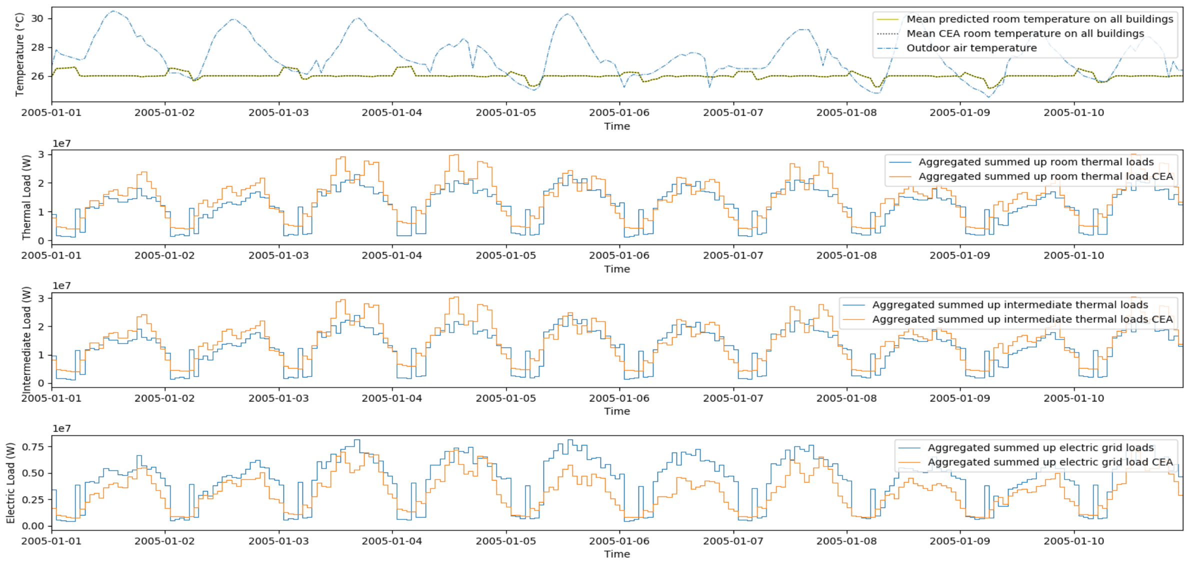

Figure A3 Room temperatures and energy loads on all buildings of the district in our model and the CEA model during the first ten days of January 2005 in Singapore, with CEA temperature tracking

The implementation of this optimization problem is done on Python with the optimization modelling language Pyomo. The prices used are based on the Uniform Singapore Energy Prices (USEP) from the Energy Market Company Pte Ltd.

You may find below the resulting plot (Figure A4) of a price-based demand flexibility simulation. When the electricity price gets lower, the electricity consumption gets higher, therefore cooling the rooms. This enables to stockpile the cooling in the building (building inertia), to enable lower electricity consumption when the electricity price gets higher.

Over this period of ten days, the cost defined as the objective function is 15% lower with the price-based demand flexibility scenario than with the CEA temperature tracking scenario.

ANNEX2. SIMPLIFIED ELECTRICAL NETWORK MODEL

This project subsumes the work of 'Developing a simplified Electric Grid Model' and 'Electrical Network Planning', as these two go hand in hand. It develops a planning algorithm to generate cost efficient electric power networks. This can be achieved by either following a heuristic approach (Genetic Algorithm) or an analytical approach (Linear Programming). Both approaches have their pros and cons, heuristic approach offers a satisfactory computational time for both small and large/complex network problems, but the global optimum is not guaranteed. Whereas analytical approach always guarantees a global optimum but the computational time for large network problems is very high.

Equation 2.1 defines the objective function of the electrical network model which is to minimize the total cost of the network. Considering the annual investment costs of each line, operation and maintenance costs and monetized power losses in lines.

$$\min \sum_{\substack{(i,j)\epsilon\mathcal{L} \\ t\epsilon\tau}} \dot{C}_{(i,j),t,inv} + \dot{C}_{(i,j),t,om} + \dot{C}_{(i,j),t,losses} \quad (2.1)$$

Equation 2.2 defines the annual investment costs of the network $\dot{C}_{(i,j),t,inv}$, which can be minimized by selecting the optimal decision variables $\alpha_{(i,j),t}$. If a line is built, the costs will be calculated by multiplying the length of the line $L_{(\boldsymbol{i,j})}$, with the specific cost of the line type $\boldsymbol{K_{t,inv}}$ and its annual factor $\dot{a}_{\boldsymbol{t}}$**.** Since installation cost can amount up to 50 % of the investment costs, the resulting costs will be multiplied by the factor of two.

$$\dot{C}_{(i,j),t,inv} = 2 \cdot \alpha_{(i,j),t} \cdot L_{(\boldsymbol{i,j})} \cdot \boldsymbol{K_{t,inv}} \cdot \dot{a}_{\boldsymbol{t}} \quad (2.2)$$

Annual operation and maintenance costs for the lines $\dot{C}_{(i,j),t,om}$ will be considered according equation 2.3. For that, the investment costs of each line $\dot{C}_{(i,j),t,inv}$ will be multiplied with its specific operation and maintenance factor $b_{t,om}$.

$$\dot{C}_{(i,j),t,om} = \dot{C}_{(i,j),t,inv} \cdot b_{t,om} \quad (2.3)$$

Annual power losses $\dot{C}_{(i,j),t,losses}$ will be calculated with equation 2.4. The squared current over a line $I^2_{(i,j),t}$ will be multiplied with the resistance of the line $R_{(i,j),t}$, cost for electricity K_{el} and the equivalent peak loss time $ELPT$.

$$\dot{C}_{(i,j),t,losses} = I^2_{(i,j),t} \cdot R_{(i,j),t} \cdot K_{el} \cdot ELPT \quad (2.4)$$

Figure A4 Room temperatures and energy loads on all buildings of the district in our model during the first ten days of January 2005 in Singapore, with price-based demand flexibility

Power flow constraints:

It is necessary, that the resulting electric network satisfies the electric constraints of a power grid. In this section, the approximations which applied to simplify the Ac power flow equations, P: active power (2.5) and Q: reactive power (2.6) are explained in order to convert these non-linear equations into a linear one (2.7).

$$P_i = \sum_{j=1}^{N} |V_i||V_j|(G_{ij}\cos(\theta_i - \theta_j) + B_{ij}\sin(\theta_i - \theta_j) \tag{2.5}$$

$$Q_i = \sum_{j=1}^{N} |V_i||V_j|(G_{ij}\sin(\theta_i - \theta_j) - B_{ij}\cos(\theta_i - \theta_j) \tag{2.6}$$

Assumption 1: the resistance R in the cable is significantly smaller than the reactance x and therefore, the resistance can be neglected. Where the admittance Y is equal to:

$$Y = \frac{1}{Z} = \frac{1}{r+jx} = \frac{1}{r+jx} * \frac{r-jx}{r-jx} = \frac{r-jx}{r^2+x^2} = \frac{r}{r^2+x^2} - \frac{jx}{r^2+x^2} = g + jb$$

since r<<x the term **g** (Conductance) will be very small compared to **b** (susceptance) and therefore, g tends to be 0.
This assumption eliminates entirely the real part of the Ybus in this model which results:

$$G_{(i,j)} = 0 \ \& \ B_{(i,j)} = -\frac{1}{x}$$

Assumption 2: the voltage phasor angles difference between two neighbour busses δ=θj-θi is very small and close to zero. By calculations, we find that the sin of small angle is equal to the angle itself while, the cos of small value which tend to zero is almost equal to 1.

Assumption 3: in the per unit system, the voltage magnitude values of any bus are very close to 1.0. The assumption Vj=Vi=1.0 could be applied only when they occur as a multiplying factor. While we cannot apply this approximation where they occur as a difference (ex, the reactive power equation) because the difference of two numbers close to zero can range significantly. Hence, the standard operating range is between 0.95 and 1.05.

Assumption 4: by applying assumption 3, we can note clearly that reactive power flow depends on the difference between voltage magnitude of the terminated buses j and i and the susceptance B**(i,j)**. Here, the maximum difference in phasor voltage magnitude will be 1.05-0.95=0.1 while, the active power flow equation is proportional to the susceptance and the difference of voltage phasor angles. Where the maximum angles difference will be 0.52 radian. The active power flow across the network tends to be significantly larger than the reactive power $\mathbf{P_{(i,j)}} \gg \mathbf{Q_{(i,j)}}$ and therefore, reactive power could be neglected. The equation 1.5 introduces the final power balance constraint which satisfies the active power demand of each demand node.

$$P_i^d = P_i^g + \sum_{\substack{(i,j)\epsilon\mathcal{L} \\ t\epsilon\tau}} P_{(i,j),t} \tag{2.7}$$

The power over each line $P_{(i,j),t}$ can calculated by applying equation 2.8. The power is dependent on the voltage angles $\theta_{i/j}$ of the connected nodes and the reactance of the line $X_{(i,j),t}$. An auxiliary variable $\omega_{(i,j),t}$ is necessary to ensure, that $P_{(i,j),t}$ can take over the value of zero, in case there is no line between node i and j.

$$P_{(i,j),t} = \frac{\theta_i - \theta_j}{X_{(i,j),t}} + \omega_{(i,j),t} \tag{2.8}$$

The auxiliary variable $\omega_{(i,j),t}$ is defined in equation 2.9 and takes over the value of zero if the decision variable $\alpha_{(i,j),t}$ is one. Otherwise, $\omega_{(i,j),t}$ can take over any other value within the defined boundaries of constant C to satisfy equation 5.

$$\omega_{(i,j),t} \leq \left(1 - \alpha_{(i,j),t}\right) \cdot C \tag{2.9}$$

After that, the line loading percentage must be calculated which is one of the main constraints to make sure that cable rating does not exceed the in the network. From the apparent power equation, where $\mathbf{V_j}$ is the bus j nodal voltage phasor and $\mathbf{I^*_{(i,j)}}$ is the phasor of the flowing current from bus I to j. $I_{(i,j)}$ can be calculated as the following:

$$S_{(i,j)} = P_{(i,j)} + JQ_{(ij)} = V_j I^*_{(i,j)} \tag{2.10}$$

$$I_{(i,j)} = \left(\frac{P_{(i,j)} + JQ_{(i,j)}}{V_j}\right)^*$$

By taking the magnitude of both sides:

$$|I_{(i,j)}| = \frac{\sqrt{{P_{(i,j)}}^2 + J{Q_{(i,j)}}^2}}{|V_j|} \tag{2.11}$$

By applying the approximation that explained above, the value of the reactive power **Q**$_{(i,j)}$ has been ignored and the voltage magnitude at each bus assumed to be equal to 1 pu. As the result, we can find that the Current overline is equal to the power overline in the approximated DC power flow model.

$$|I_{(i,j)}| = \frac{\sqrt{{P_{(i,j)}}^2}}{|V_j|} = |I_{(i,j)}| = \frac{|P_{(i,j)}|}{|V_j|} \simeq P_{(i,j)} \tag{2.12}$$

<u>Component Limits:</u> Equation 2.13 ensures, that the power over the lines is zero if the decision variable $\alpha_{(i,j),t}$ is zero. Furthermore, it verifies, that the power over the lines are within the limits of the component limits. For that, the maximum current of the line type I_t^{max} and the voltage level of the network V_{base} are considered.

$$|P_{(i,j),t}| \leq \alpha_{(i,j),t} \cdot I_t^{max} \cdot V_{base} \tag{2.13}$$

Network Planning with Genetic Algorithm:

Genetic Algorithm, based on the idea of evolution is used to solve the network planning. In this, random initialization of a population which consists of a fixed number of individuals is performed at the start of optimization. These individuals represent a network for the given problem and is equal to the number of possible lines and represent the decision variables for the algorithm. In Figure 5, an overview of the Genetic Algorithm is presented. Each individual has to be processed regarding its structural properties, to connect every demand node to at least one substation node.

In the next step, an electric grid is modelled using 'pandapower' toolbox in Python framework. The electric distribution grid model considers three different types of cable with different diameters, loading capacity and therefore, different cable cost. The network configuration and components depend on the available case-study data. Therefore, it includes only buses, lines, loads and external grid in single phase AC system. This is followed by a feasibility test which takes into consideration two constraints: the voltage level at each bus and the loading on each line. If the voltage level at any bus is over or under the acceptable limit or the line loading is exceeding the cable limit, this particular network will be excluded.

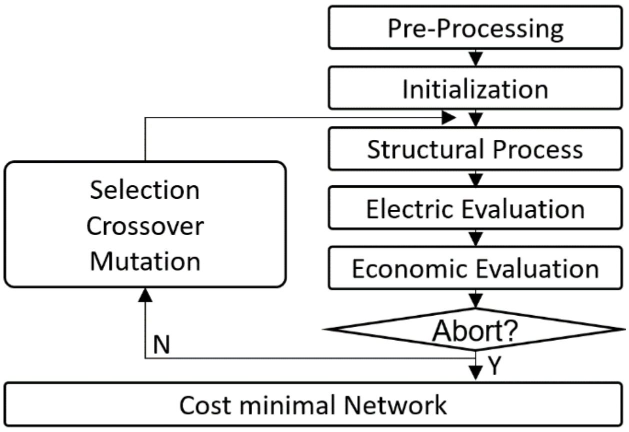

Figure A5 Genetic Algorithm Flow Chart

The following figures show a randomly picked results of two different networks generated by GA approach where the first solution (left) has some overloading lines and therefore, it has been excluded for not satisfying the constraints. While, the second solution (right) is an accepted network.

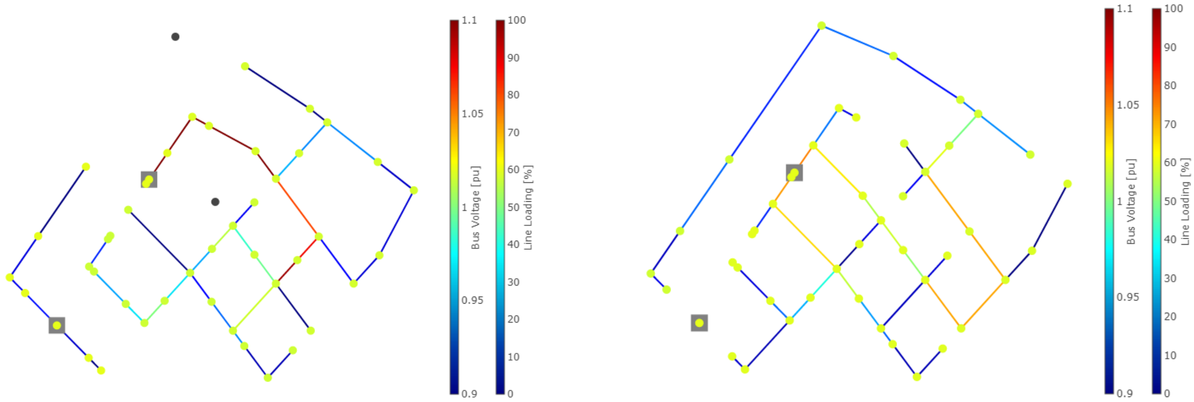

Figure A6 Network result of GA Approach

Following this, the individuals will be evaluated based on the network costs. The next generation of individuals will be generated by performing genetic operators such as selection, crossover and mutation of the existing individuals. Selection will choose individuals as base for the next generation of individuals. Hereby, individuals with low network costs will have higher preference and individuals with high costs will have lower preference. Crossover will recombine genes of two individuals to create new individuals for the next generation. Mutation will ensure that the algorithm will not get stuck in a local minimum and arbitrary replaces genes with random values. If the abortion rule is fulfilled, the evolutionary process will stop and returns the network with the lowest cost.

Exemplary results can be seen in Figure 7. The Genetic Algorithm takes about two hours to generate a cost optimized network for a given district. In the future, multiprocessing ability and repair algorithms should be implemented to enhance the optimizing process.

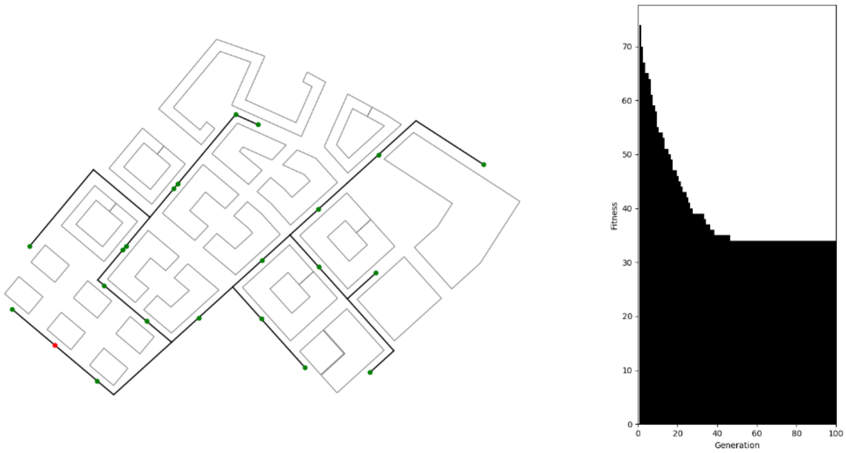

Figure A7 Results of Genetic Algorithm Approach

Network Planning with Linear Programming

In the following an analytic approach to generate cost efficient electric networks will be introduced. The input data for the linear program will be the same as for the Genetic Algorithm. Exemplary results with a single line type shows a superior computational time of the linear program compared to the Genetic Algorithm (Figure 8). For a given district with 21 buildings the linear program takes about 15 seconds to generate a cost optimized electric network on a computer with Intel I5-3470. If the choice of multiple different line types is given, the computational time of the linear program rises exponentially and results in several hours of computation. The next step is a thorough performance investigation of the algorithms and their further development.

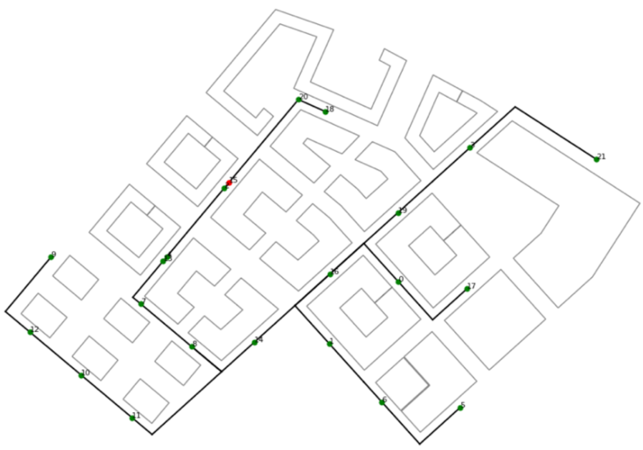

Figure A8 Result of using the Analytical approach with the approximated DC power flow model for single line type

ANNEX3. REFINEMENT OF OPTIMIZATION OF THERMAL SYSTEMS

The goal of the project is to design a District Energy System for New Towns that meets the end demand of the District. The end demand includes cooling demand, heating demand and electricity demand of the District. The variables that can be changed during this process can be classified into 4 categories:

1. Building properties (building geometry, occupancy, use type)
2. Thermal supply system properties (type and size of supply system, operation strategy)
3. Electrical supply system properties
4. Network properties (which buildings are connected/disconnected)

The constraints to be met while designing the energy system for the district are to meet the overall energy demand. The objectives which we use to evaluate a District Energy System are the total annualized costs involved in operating the system, the total emissions associated with operating the system and the total non-renewable primary energy used while operating the system. This along with the amount of interdependencies present between thermal and power systems form a classic optimization problem.

There are an innumerable combinations of these variables possible, which will generate a feasible solution. It is near impossible to brute force our way through all the possible solutions. To make it possible to get a good trade-off solution, we use optimization techniques, which help us identify the solution in the entire solution space. To perform optimization in CONCEPT, we are using the optimization module present in CEA. The overview of the optimization process in CEA is provided in the following figure. CEA optimization can be divided into two categories: 1. Building Scale, 2. District Scale.

Building Scale Optimization decides the best energy system configuration for a standalone building by comparing the available technologies for a building. The possible cooling technologies for a building scale optimization are Vapor Compression Chiller, Absorption Chiller, Direct Expansion. The possible electrical technologies are either Photovoltaic or National Grid. The possible hot water technologies are Solar Collector, Electrical Boiler or Gas fired Boiler. Among all these possible options the best combination that results in the least costs, emissions and primary energy are chosen.

District Scale decides the best energy system configuration for buildings connected to the District Cooling/Heating Plant. This in turn has two levels: Design Level and Operation Level. In Design Level, the supply system technologies are selected, and the sizing is done based on the peak load i.e. each technology will meet a percentage demand based on the peak load. For example, 40% of peak load is met by Vapor Compression Chiller, 40% by Absorption Chiller and 20 % by thermal storage. In the Operation Level, the activation of each of these units is done and the corresponding emissions, costs are calculated. For the activation of the units, it is a rule-based system, where in the renewables are activate first and then followed by non-renewables.

Apart from having many options for the cooling technologies, heating technologies and electricity, this has another variable in terms of the buildings connected to the central network i.e. which buildings present in the district are connected to the district plant. This also considers the thermal/pressure losses incurred in the network.

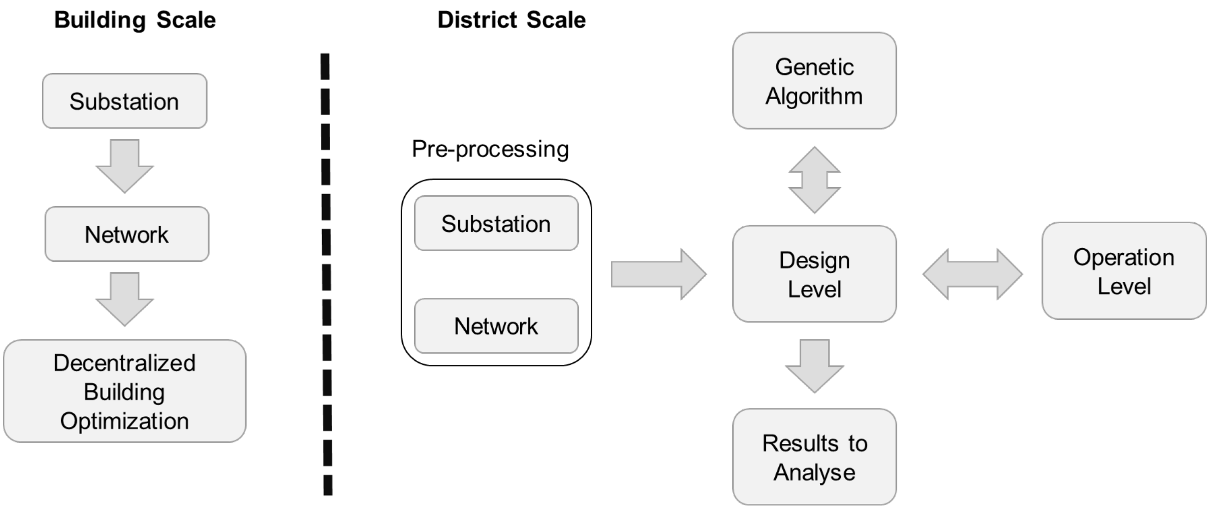

Figure A9 CEA Optimization Overview

Genetic Algorithm is used to perform multi-objective optimization of the District Energy Systems. After performing the optimization for a test case, the following Pareto-curve is generated (Figure), which shows the trade-off between the costs, CO2 emissions and the primary energy.

For further analysis of these solutions, visualization tools have been developed in CEA as part of this Project. For a selected solution from the Pareto-front, the thermal network of the district can be generated as shown in Figure 5. This figure shows the thermal network, the plant location, the location of the centralized buildings (buildings connected to the central thermal grid) and the decentralized buildings (standalone buildings), which will further provide knowledge about a solution. Further, to understand the activation pattern, CEA can develop activation curves similar to the ones shown in Figure 6, where it is shown, the operation of different technologies to meet the total electricity demand of the district (for the selected solution from the Pareto-front). The excess electricity if any is supplied to the grid, if the local production is not sufficient, the electricity is imported from the grid.

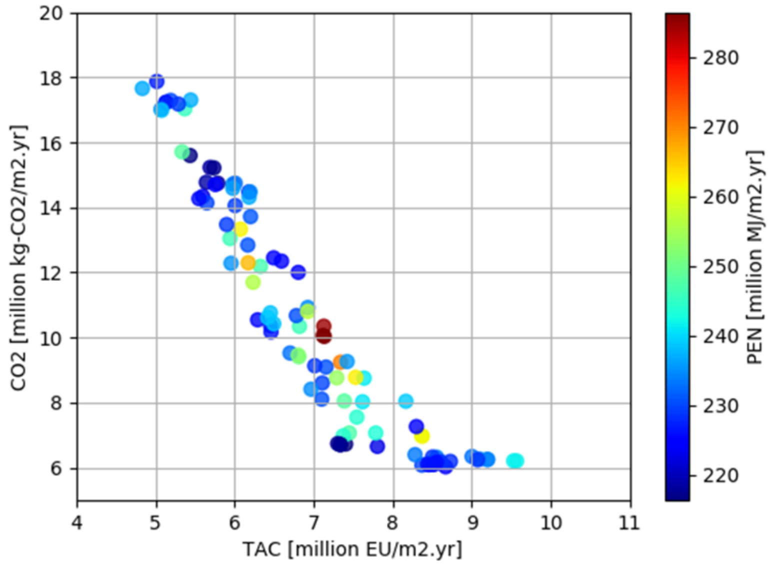

Figure A10 Pareto-front generated for a case study in CEA, this depicts the three objectives used in optimization. TAC is total annualized costs, CO2 is the CO2 emissions, PEN is the total non-renewable primary energy

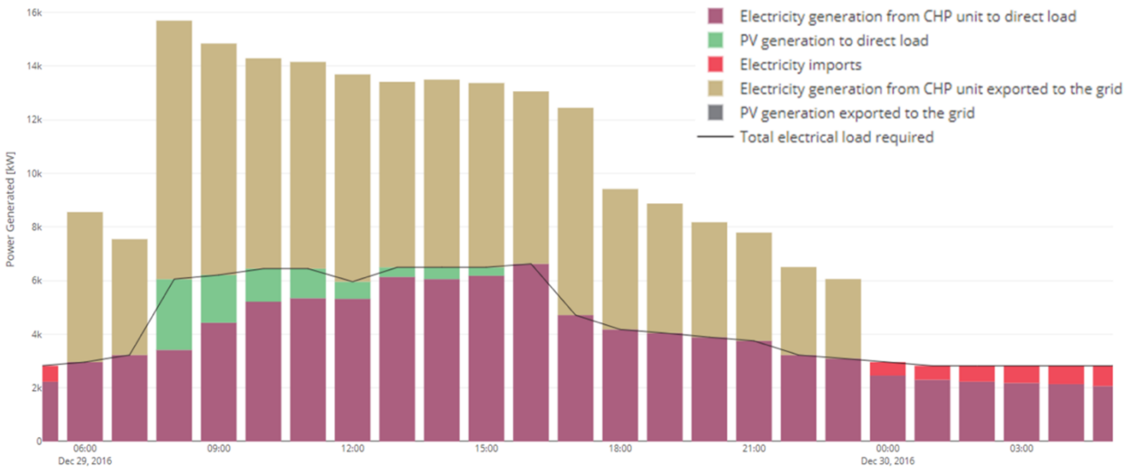

Figure A12 Electricity Activation Curve of a week showing the various means of electricity generation in the district

G Project Proposal (March 2017)

NATIONAL RESEARCH FOUNDATION
PRIME MINISTER'S OFFICE
SINGAPORE

INTRA-CREATE SEED COLLABORATION GRANT CALL

I. BACKGROUND INFORMATION

Proposal Title: **CONCEPT** **Connecting District Energy and Power Systems in Future Singaporean New Towns**
Host Institution (CREATE CLG or Overseas Partner University): Singapore-ETH Centre (SEC) **Participating Institution(s):** Singapore-ETH Centre (SEC) TUMCREATE

Budget Requested (Including Indirect Costs):	**Period of Support:**
$249,835.67	01/06/2017 – 31/06/2018 (13 months)

Lead Principal Investigator and Team Members

Role in Proposal (e.g. PI, Co-I, Collaborator)	**Name**	**Institution** (e.g. NUS, MIT)	**Designation / Department**	**CREATE Programmes Currently Participating In** (N.A. if not currently participating in any)
PI 1	Dr. Jimeno Fonseca	ETH Zürich	Senior Researcher & Project Coordinator / Singapore ETH-Centre	FCL
PI and postdoctoral associate	Sarmad Hanif	TUM	Research Associate/ Electrification Suite & Test Lab	TUM CREATE
Collaborator	Prof. Dr. Arno Schlueter	ETH Zürich	Principal Investigator / Architecture and Building Systems, ETH Zurich	FCL

Collaborator	Tobias Massier	TUM	Principal Investigator/ Electrification Suite & Test Lab	TUM CREATE

II. SCIENTIFIC ABSTRACT

*In **no more than 300 words**, provide a succinct and accurate scientific description of the proposal. This should include the specific aims, the problem(s) it aims to solve/address, the proposed methodology, and how the project is able to strengthen an existing research theme in CREATE or seed opportunities for future research themes in CREATE.*

Currently, the development of district-scale energy systems such as district cooling is not coordinated with the design or operation of broader power systems. This aspect could hinder the design of reliable, cost-efficient, and low-carbon districts in Singapore. This project introduces an integrated framework for planning and operation of future district and power systems applicable to Singaporean new towns and regional hubs (NTs).

To this end, we link cutting-edge mathematical approaches developed at FCL and TUM CREATE into the Open-source CEA tool developed at FCL. This would allow simulating a multi-scale (from a building to >1000 building) and multi-temporal (from 15min to 50 years) knowledge of district-scale demand side along with power system topology, grid layout and renewable energy generation.

The new integrated computational approach is used to devise key operational strategies that could simultaneously exploit synergies from district energy and power system infrastructures such as ancillary services in air-conditioning, thermal and electrical storage equipment etc.

For validation purposes, the devised operational strategies will be benchmarked against the current market mechanisms (e.g. Interruptible Loads and Demand Response from Energy Market Authority of Singapore) and operational standards (e.g. reliability and losses) of the Singapore power grid.

This project will strengthen the knowledge in power grids within TUMCREATE and the work on multi-scale district energy systems at FCL. This allows a more comprehensive view on power system operation and demand side flexibility in Singapore in an era of renewable energy and mixed-use urban development.

On a broader scale, the project will provide a basis for future research in power systems and district energy systems analysis in Singapore and the region.

The deliverables of this proposal are (i) a prototypical computational approach and (ii) a list of key operational strategies for further research of integrated district energy systems in Singapore.

III. RESEARCH PROPOSAL

In no more than 8 pages (excluding the reference section), include the following sections in the research proposal.

A) Aim and Hypothesis: *What are you trying to do? What problem are you trying to address? Clearly state the problem to be addressed with neither jargon nor acronyms and explain why it is significant.*

The project introduces an integrated framework for planning and operation of energy and power systems in district neighbourhoods, namely Singapore's future new towns (NTs). Currently, neither the planning nor the operation of residential and commercial energy systems such as air-conditioning and cooling systems is coordinated with the power system design and operation. Not only can this coordination lead to efficiency improvements, but it becomes especially important to enable flexible resources of the energy and power system to relieve each other's burden. To achieve this flexibility for Singapore's NTs, the challenge lies in finding synergies between the relevant energy and power system components. This is a non-trivial task for system planners and operators as it requires qualifying and quantifying the most important parameters from planning all the way to operating both energy and power systems. To this end, an integrated framework is proposed, which intends to optimally plan and operate Singaporean NTs.

Even with the wide recent interest in optimization algorithms of district scale energy systems [1–3], its interdependence with the power system has not been entirely considered in a detailed manner. This means that the capacity of the electrical grid in NTs is determined independently by the power system operator, leading to oversized and uneconomical power systems. By looking at the integrational aspect of the energy infrastructure in NTs with power systems, a more cost-effective solution for the design, sizing and positioning of both the district energy systems and the power system can be obtained. By definition, NTs are self-contained, mixed-use districts with both residential and commercial activities. These two sectors make up the majority of Singapore's total electric energy consumption (37% in commercial and 15% in residential) [4]. Hence, improvement in planning these NTs is important for improving energy efficiency of Singapore.

Another motivation for integrating energy and power systems on district scale is the exploitation of demand side flexibility. For the case of NTs, this means that inherent flexibility of district energy system and power system components can be coordinated to destress the whole system and improve the overall cost of the system. Moreover, if present in NTs, it also aids achieving higher renewable energy utilisation. This is very important for Singapore, as due to its dense structure, it may not be practical in the future to construct new power plants and distribution grid lines to follow the demand growth. By introducing the Demand Response [5] and Interruptible Load [6] programs, Singapore's Energy Market Authority has already recognized the need for the existence of more proactive flexible demand to destress the power grid. This also provides flexible demand strategies of this project to be benchmarked and evaluated against practical market rules and settings. Furthermore, this project aims to bring consideration for demand side flexibility into the planning and operation of energy and power systems of NTs for the first time.

B) Method and Approach:

i) ***How is it done today, who the leading researchers studying the problem are, and what is your understanding of the limitations of their current approaches?***

Figure 1 depicts the current approach for planning and operating power systems and energy systems. While planning and operating a power system, the objective is to improve the reliability of the system while minimising the overall operational cost of the grid [7, 8]. In the planning phase, demand forecast is used to determine the grid topology and capacity. However, this demand forecast does not consider detailed information regarding its underlying building and energy systems. Similarly, in the operation phase, the power system maintains safe voltage and power quality for its underlying assets by calculating optimal power flows in the grid. Even though flexible loads have been considered in these optimal power flow calculations [9–12], the design consideration of energy systems has still not been addressed.

Similar arguments hold for the planning and operation of district energy systems, aiming to maximize occupant comforts and minimize the total system costs [1–3]. During the planning phase, the plants for air-conditioning, heating and cooling are designed based on the requirements of architectural and building design, without incorporating the underlying power system infrastructure supplying this energy. While operating, the energy system is operated via rule-based controls, maintaining pre-defined comfort conditions within the building [13, 14]. These control mechanisms do not consider the current condition of power flows. Hence, it can be seen that there exists no single framework or tool to integrate planning and operation of power systems and energy systems.

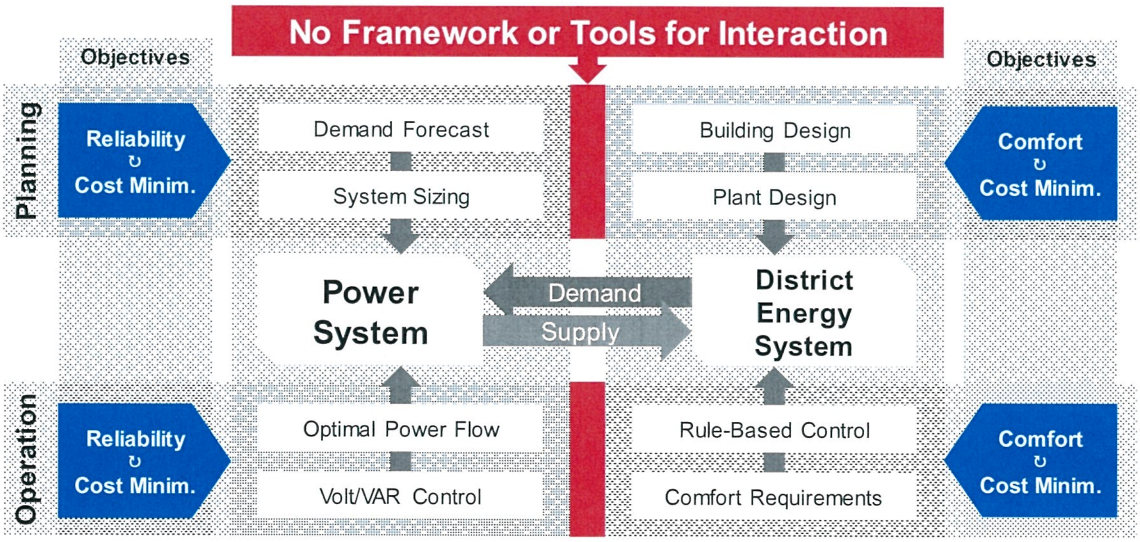

Figure 1: Current status of planning and operation of power systems and district-scale energy systems.

In recent past, there have been attempts to address energy systems and power systems in a unified manner [9, 12, 15–17]. However, these studies do not concurrently address the three major considerations that this project brings together. Firstly, the interconnection of planning and operation phases is not considered. This is especially important considering both energy and power systems are inherently feedback systems, requiring information exchange between both the long-term planning and the short-term operational time scales. Secondly, previous studies do not exploit the role of demand flexibility from the context of integrated energy and power systems operation. The true enabler of integration of energy and power system is in equipping demand with flexibility. Thirdly, this project develops optimization algorithms and models to improve the integrated configuration of the coupled components of energy systems and power systems. Such an approach is not found in the above-mentioned studies.

ii) *What is your approach and how does it differ from what others are working on?*

This proposal intends to combine modelling, optimisation and design expertise of district energy systems analysis of FCL with that of power system operation and flexible demand integration in distribution grids of TUMCREATE (Figure 2). Both entities have shown individual competencies regarding their respective functional blocks of Figure 2. Through this project, the conceptual integration of energy and power system as well as organizational collaborations is going to be strengthened. The energy and power systems of the NTs are going to be designed, modelled and operated to offer flexibility measures under the business-as-usual and drastic conditions. Compared to the conventional approach shown in Figure 1, the proposed framework has exchangeable flexible demand and interoperability between the energy and power systems. In principle, the demand of energy systems can be manipulated by the power system operator through the prediction of price signals and renewable energy forecasts. In this way, the exploited demand flexibility of NTs considers comfort constraints of the residential and commercial buildings, as well as technical constraints of the energy and power systems. Another notable improvement from the conventional approach (Figure 1) in the proposed framework is the incorporation of building and plant design information for the purpose of demand estimation for power system expansion. In turn, the plant design of the energy system considers power system constraints for harnessing the demand flexibility.

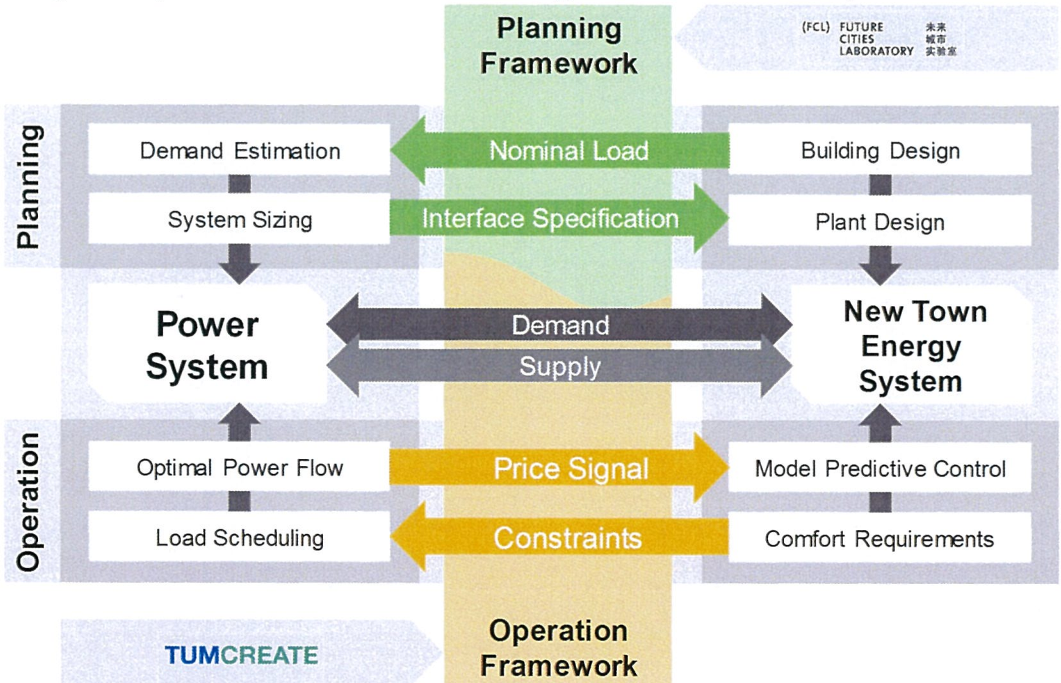

Figure 2: Proposed framework for integrated planning and operation of the power system and new town energy systems.

iii) Project Description

The proposed framework of Figure 2 is organized into three main work packages (WP), as shown in (Figure 3). These modules cater for (1) planning, (2) operation and (3) analysis tasks.

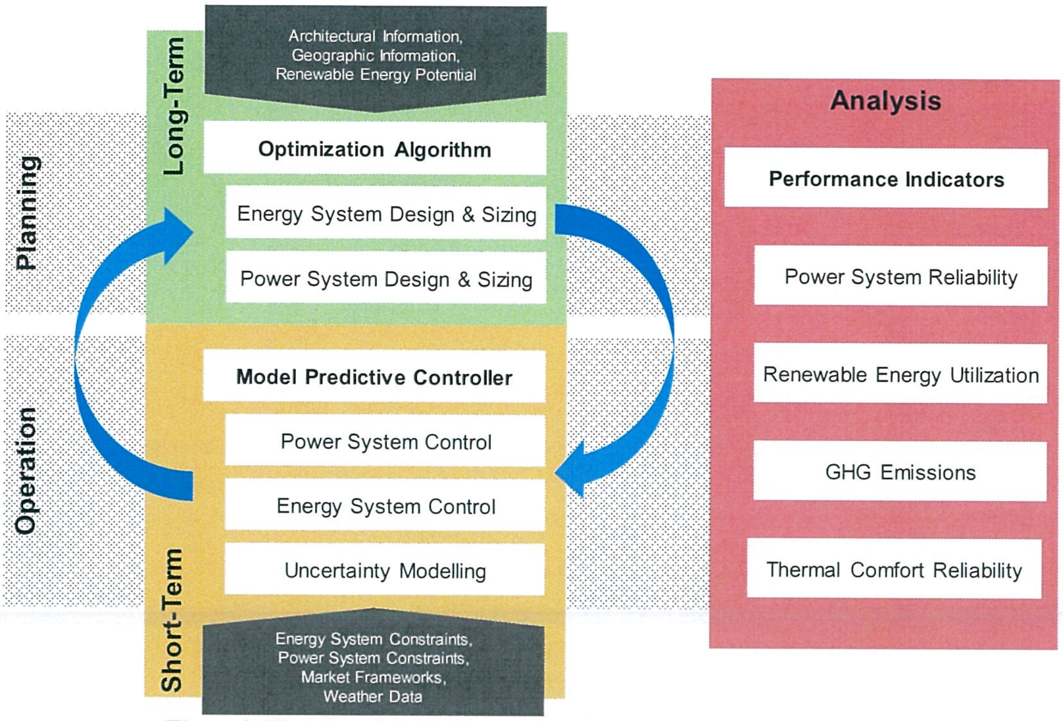

Figure 3: Modules of the proposed planning and operation framework.

WP 1: Integrated Energy and Power System Planning

The planning phase considers the integrated energy and power system design and sizing. These tasks consider a long-term time horizon of 30 years, which aligns with the expected lifetime of most energy plants and power system assets such as transformers and underground cabling. However, as the energy system design must incorporate the proposed flexibility strategies to be employed during the operation of NTs, there must exist a timely feedback from the operation phase, e.g. about the utilization of assets and cost of operation. Therefore, the optimization algorithm must coordinate with the results of the operation phase.

WP 1.1: Coupling of Energy System and Power System Tools

For the energy and power system design and sizing, analytical models will be developed. For energy systems, the methods and models that are available at the Open-source City Energy Analyst (CEA) (www.cityenergyanalyst.com) from FCL are taken as a starting point [2]. CEA provides individual component models to effectively simulate a district energy system with a focus on heat exchange between buildings, thermal networks, users and the environment. The existing CEA models will be complemented with the power distribution system modelling and simulation platform of TUMCREATE [12]. With coupling of these two tools, the required models can address dynamic forecasting of energy demand in residential and commercial sectors, power grid simulation, and simulation of technologies for energy conversion and storage as well as investment cost, operation cost and life-cycle analysis of the NTs.

WP 1.2: Planning Strategy Development

The strategy for determining the nominal capacity of the underlying energy and power systems along with necessary technologies is determined by formulating an optimization algorithm, such as a genetic algorithm. In principle, a multi-objective optimization problem can be formulated which considers the long-term indicators from the planning as well as the results from the operation phase. The models and methods deployed in WP 1.1 are used by the optimization algorithm of this sub-WP. In the end, the main output of the proposed algorithm will be an optimized design and size of energy and power system components, while ensuring adequate flexibility options to be exercised in the short-term (operation) operation phase.

WP 2: Flexible Operational Strategies for the NTs

This WP is concerned with developing flexible operational strategies of the energy and power system components of NTs. Moreover, flexibility in terms of privacy of participating entities and uncertainty of the available demand/supply is also considered. To this end, a hierarchical control scheme based on model predictive control is designed that considers energy and power system constraints of NTs, along with comfort constraints of users. Furthermore, the results and constraints of the control scheme are simultaneously evaluated with the planning phase to establish a closed-loop feedback with the system design and sizing procedure of WP 1.

WP 2.1: Model Predictive Control Scheme

The main task within the operation phase is to control the energy and power systems within their respective constraints. To achieve this, at the heart of the operation phase, a model predictive controller (MPC) is designed. The MPC predicts the behaviour of the underlying system by leveraging information from the short time-scale (hourly or sub-hourly) models. TUMCREATE and FCL both have expertise in developing thermal building and network [18, 19] as well as electric network models [12, 20] which can be used as a starting point for designing this MPC. In addition to technical constraints of the systems that are defined during the planning phase, the MPC also considers operational constraints such as comfort constraints of buildings, network peak loads and short-term renewable generation forecast in the NTs. For example, a simplified strategy could be an automated procedure of utilizing thermal inertia of buildings to pre-cool a building during low-price/high-renewable-generation hours in order to be switched off during high-price/low-renewable-generation hours [19, 21].

WP 2.2: Distributed Calculation Methodology

Due to the complexity of short-term detailed modelling, the MPC controller might not be able to evaluate control actions in a due course of time (hourly/sub-hourly). Furthermore, as energy and power system operations are done by different entities, privacy in the developed calculation scheme must be achieved. For this, the MPC is designed in a hierarchical and/or distribution manner [12, 20]. TUMCREATE has been extensively involved in developing a distributed control scheme for preserving privacy of various entities in the power grid [22]. In principle, price-based control is established between various entities to coordinate and achieve a common consensus. This price reflects grid conditions and helps to align the objective of the power system operator with retailers. This price-based control has proven as a main component in transmission grids and electricity markets. This project will be the first of this kind to demonstrate the applicability of indirect load control for Singaporean NTs. By the help of this project, the novelty of the already developed tools by TUMCREATE will also be immensely enhanced by including new energy system models and entities for the case of NTs.

WP 2.3: Uncertainty Modelling

In addition to short-term models for energy systems and power systems, the operation phase requires models for the uncertainty within the system. Dealing with uncertainty in the operation phase is crucial, as planning for NTs is riddled with uncertainties including demand uncertainty, weather uncertainty, model uncertainty etc. As NTs are planned to last for up to 90 years, the energy system to be in place needs to be robust to handle uncertainties. Two approaches to handle uncertainties are gaining prominence in recent times. They are s-Pareto frontier or dynamic formulation of optimization [24] and Pareto optimal process design under uncertainty [25]. These approaches will be tested along with the framework developed in the previous work packages. The essence of this work package is in developing a reliable system when facing an uncertain environment.

WP 3: Analysis

With the planning and operation phase resulting in a set of feasible solutions for the district energy and power system, the analysis module takes into account the results of both phases and focuses on crucial indicators for the derived solutions. The NT's model should incorporate the power system reliability, renewable energy utilization, GHG emission mitigation as well as thermal comfort reliability into the design and provide alternatives based on the amount of uncertainty they possess. The importance of this step is twofold. First, due to various non-trivial parameters involved in the project, it is important for finding the right trade-off between reliability, utilisation and cost of the system. Second, it also serves as a tuning nob for the overall planning (WP 1) and operation (WP 2) of the NTs, as it can guide the NT designer in adopting a solution based on individual needs and Singapore's policies.

WP 3.1. Reliability

This project is going to propose many new methodologies for achieving flexible operation of the NTs. However, this flexibility should not come at the cost of the system reliability. Hence, the most commonly used reliability indices for distribution grid operations are going to be evaluated in this work package. This analysis is especially important for the case of Singapore, where System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) indices are one of the world's lowest, i.e. 0.02 and 0.74 respectively. Furthermore, reliability analysis with respect to the delay in grid reinforcement (less congestion/high utilization) is also analysed in this track.

WP 3.2. Planning and Operational Cost

This sub-WP comprehensively analyses the cost from all the way of planning the NTs to operating it efficiently. Furthermore, this track pin points the associated cost of the critical components of power systems and energy systems. These costs are then investigated in detail by the design and operational strategy output of WP 2 and 3. Due to dynamic interaction of planning and operation phases, these costs are coupled with the adopted design and operational strategy by the optimization algorithm. Furthermore, a term "risk factor" needs to be provided with each design along with the monetary burden and the GHG emissions involved in that design. This will provide a sense of uncertainty to make decisions 'here-and-now'.

WP 3.3. Renewables

This analysis is concerned with the integration of renewable energies into the NTs. The idea is to generate scenarios with varying level of variable renewable such as solar PV supply and analyse its impact on the cost and reliability of the NT. The main goal of this track is to help the user (planner or operator) to envision the ambitious renewable energy goals set by the Singaporean authorities [23].

WP 3.4. Open-source Tool Development

In order for the developed framework to be used by power and energy system planners and operators, this work package develops a tool which works in tandem with the existing CEA. This tool combines the planning and operation phase of the NTs in an interactive and user-friendly manner, allowing users to create customised case studies and scenarios. The above defined analyses are to be integrated in this tool, along with the developed models and optimization algorithms of WP 2 and 3. As a starting point for this tool, CEA from FCL can be utilized and modular enhancements in the form of power grid models can be performed. Later on, subsequent functionalities proposed in this project can be added to conclude the development of the tool.

C) Impact of project and how it is aligned with the objectives of the seed collaboration grant:
(1) What potential value can this project create for Singapore and the society? What are the pathways towards realizing this impact?

A new generation of load flexibility strategies could facilitate the design of more adaptive district energy systems and power systems. These systems should be able to cope with morphological changes in Singapore NTs as they are transformed and constructed over time. In the future, our approach could be extended to evaluate multiple configurations and determine which strategies are safe for investment and which parts tend to involve higher uncertainty, thus making them riskier. The results of this approach may improve decision-making in cross-sectorial energy planning looking to increase the long-term performance of urban areas with a notion of risk. With respect to operation of these systems, the current energy market programs concerning the demand side of power systems are going to be strengthened. This project may also lead to the refinement of these programs to consider wider varieties of thermal loads and transactional activities.

(2) How does this project strengthen an existing research theme in CREATE or seed opportunities for future research themes?

Through this project, the demand side flexibility expertise within TUMCREATE is strengthened with the district energy systems know-how of FCL. This allows a more comprehensive view on power system operation and demand side flexibility within Singapore. Furthermore, this work may be integrated with the smart charging capabilities that are developed for public transport systems in TUMCREATE for developing a holistic energy management framework. On the other hand, the City Energy Analyst actively developed within FCL, is extended towards power system and micro grid capabilities through this project. The analysis of the integration of power system and district energy system planning will provide insights on future research directions and further strengthen the know-how at CREATE.

This seed project will lead to 'New Proposal' in future to further the integration of district power and energy system planning.

D) Milestones and KPIs: *What are the scientific milestones / metrics that can be used to measure success when the project is completed?*

i) Deliverables

1. Report stating new algorithm for the assessment of flexibility strategies in future district energy systems in Singapore.
2. An open-source computational application for analysis of flexibility strategies in future district energy systems inside the platform City Energy Analyst tool.
3. Three scientific publications (2 conferences and 1 Journal).

i) Milestones

The milestones and timeline of the project are described in the next table:

Milestones	2017		2018		
	Q3	Q4	Q1	Q2	Q3
WP 1: Integrated Energy and Power System Planning	■	■	■	■	
WP 2: Flexible Operational Strategies for the NTs		■	■		
WP 3: Analysis			■	■	■
Final Report				■	■

ii) KPIs

The Key Performance Indicators of the project are:

1. **Number of endorsement letters:**
   - Goal: At least one signed report evaluating the positive impact and usability of the research findings by a local agency (E.g., EMA, SDC or SP).

1. **Computational Model for the CEA**
   - Goal: Open-Source computational model for the City Energy Analyst framework.

3. **Number of scientific publications**
   - Goal: At least two publications in a regional conference proceeding.
   - Goal: At least one submission to a publication in a Journal with an impact factor greater than 3.0.

E) References: *List the references in the order cited in this proposal.*

[1] R. Niemi, J. Mikkola and P. D. Lund, "Urban energy systems with smart multi-carrier energy networks and renewable energy generation", *Renewable Energy*, vol. 48, pp. 524–536, 2012, URL: http://dx.doi.org/10.1016/j.renene.2012.05.017.

[2] Jimeno A. Fonseca, Thuy-An Nguyen, Arno Schlueter and Francois Marechal, "City energy analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts", *Energy and Buildings*, vol. 113, pp. 202–226, 2016, URL: http://dx.doi.org/10.1016/j.enbuild.2015.11.055.

[3] Samira Fazlollahi, Gwenaelle Becker, Michel Guichard and François Maréchal, "Multi-objective, multi-period optimization of district energy systems: Networks design" in *Computer Aided Chemical Engineering, 23rd European Symposium on Computer Aided Process Engineering*: Elsevier, 2013, pp. 463–468.

[4] EMA Energy Market Authority, "Singapore energy statistics 2016" [Report], 2016, URL: https://www.ema.gov.sg/cmsmedia/Publications_and_Statistics/Publications/SES/2016/Singapore%20Energy%20Statistics%202016.pdf, Accessed on: 9/28/2016.

[5] EMA Energy Market Authority, "Demand response programme" [Website], URL: https://www.ema.gov.sg/Demand_Response_Program.aspx, Accessed on: Mar. 02 2017.

[6] EMC Energy Market Company, "A guide to providing interruptible load in Singapore's wholesale electricity market" [Guide], URL: https://www.emcsg.com/f146,16653/Guide_to_providing_IL_website_21082012.pdf, Accessed on: Mar. 02 2017.

[7] Risheng Fang and D. J. Hill, "A new strategy for transmission expansion in competitive electricity markets", *IEEE Trans. Power Syst.*, vol. 18, no. 1, pp. 374–380, 2003.

[8] E. O. Crousillat, P. Dorfner, P. Alvarado and H. M. Merrill, "Conflicting objectives and risk in power system planning", *IEEE Trans. Power Syst.*, vol. 8, no. 3, pp. 887–893, 1993.

[9] Yoash Levron, Josep M. Guerrero and Yuval Beck, "Optimal Power Flow in Microgrids With Energy Storage", *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 3226–3234, 2013, URL: https://doi.org/10.1109/TPWRS.2013.2245925.

[10] Luis F. Ochoa and Gareth P. Harrison, "Minimizing Energy Losses: Optimal Accommodation and Smart Operation of Renewable Distributed Generation", *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 198–205, 2011, URL: https://doi.org/10.1109/TPWRS.2010.2049036.

[11] G. P. Harrison and A. R. Wallace, "Optimal power flow evaluation of distribution network capacity for the connection of distributed generation", *IEE Proc., Gener. Transm. Distrib.*, vol. 152, no. 1, p. 115, 2005, URL: https://doi.org/10.1049/ip-gtd:20041193.

[12] Sarmad Hanif, Tobias Massier, Hoay Beng Gooi, Thomas Hamacher and Thomas Reindl, "Cost optimal integration of flexible buildings in congested distribution grids", *IEEE Trans. Power Syst.*, p. 1, 2016, URL: http://dx.doi.org/10.1109/TPWRS.2016.2605921.

[13] Abdul Afram and Farrokh Janabi-Sharifi, "Theory and applications of HVAC control systems – A review of model predictive control (MPC)", *Building and Environment*, vol. 72, pp. 343–355, 2014, URL: http://dx.doi.org/10.1016/j.buildenv.2013.11.016.

[14] F. Oldewurtel, A. Parisio, C. N. Jones, M. Morari, D. Gyalistras, M. Gwerder, V. Stauch, B. Lehmann and K. Wirth, "Energy efficient building climate control using stochastic model predictive control and weather predictions" in *2010 American Control Conference (ACC 2010)*, pp. 5100–5105, URL: http://dx.doi.org/10.1109/ACC.2010.5530680.

[15] Dirk Müller, Antonello Monti, Sebastian Stinner, Tim Schlösser, Thomas Schütz, Peter Matthes, Henryk Wolisz, Christoph Molitor, Hassan Harb and Rita Streblow, "Demand side management for city districts", *Building and Environment*, vol. 91, pp. 283–293, 2015, URL: http://dx.doi.org/10.1016/j.buildenv.2015.03.026.

[16] Evangelos Vrettos, Frauke Oldewurtel and Goran Andersson, "Robust energy-constrained frequency reserves from aggregations of commercial buildings", *IEEE Trans. Power Syst.*, pp. 1–14, 2016, URL: http://dx.doi.org/10.1109/TPWRS.2015.2511541.

[17] Evangelos Vrettos, Emre C. Kara, Jason MacDonald, Goran Andersson and Duncan S. Callaway, "Experimental Demonstration of Frequency Regulation by Commercial Buildings – Part I: Modeling and Hierarchical Control Design", *IEEE Trans. Smart Grid*, p. 1, 2016, URL: https://doi.org/10.1109/TSG.2016.2628897.

[18] Jimeno A. Fonseca and Arno Schlueter, "Integrated model for characterization of spatiotemporal building energy consumption patterns in neighborhoods and city districts", *Applied Energy*, vol. 142, pp. 247–265, 2015, URL: http://dx.doi.org/10.1016/j.apenergy.2014.12.068.

[19] Sarmad Hanif, Christoph Gruentgens, Tobias Massier, Thomas Hamacher and Thomas Reindl, Eds., "Quantifying the effect on the load shifting potential of buildings due to ancillary service provision", IEEE PES General Meeting, 2016, URL: https://arxiv.org/abs/1605.07876, Accessed on: Jul. 10 2016.

[20] Sarmad Hanif, Dante Fernando Recalde Melo, Mehdi Maasoumy, Tobias Massier, Thomas Hamacher and Thomas Reindl, "Model predictive control scheme for investigating demand side flexibility in Singapore" in *50th International Universities Power Engineering Conference (UPEC)*, 2015, pp. 1–6, URL: http://dx.doi.org/10.1109/UPEC.2015.7339769.

[21] Weijie Mai and C. Y. Chung, "Economic MPC of aggregating commercial buildings for providing flexible power reserve", *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2685–2694, 2015, URL: http://dx.doi.org/10.1109/TPWRS.2014.2365615.

[22] Sarmad Hanif, Hoay Beng Gooi, Tobias Massier, Thomas Hamacher and Thomas Reindl, "Distributed Congestion Management of Distribution Grids under Robust Flexible Buildings Operations", *IEEE Trans. Power Syst.*, p. 1, 2017, URL: https://doi.org/10.1109/TPWRS.2017.2660065.

[23] Joachim Luther, Thomas Reindl, Armin Aberle, Darryl Kee Soon Wang, Wilfred Walsh, André Nobre and Grace Guoxiu Yao, "Solar photovoltaic (PV) roadmap for Singapore: A summary" [Report], URL: https://www.nccs.gov.sg/sites/nccs/files/Roadmap_Solar_20140729.pdf, Accessed on: Nov. 12 2016.

[24] Patrick K. Lewis, Morgan W.P. Tackett, Christopher A. Mattson, "Considering Dynamic s-Pareto Frontiers in Decision Making", *53rd Structures, Structural Dynamics and Materials Conference, Honolulu, Hawaii, 2012.*

[25] Laurence Tock, Francois Marechal, "Decision support for ranking Pareto optimal process designs under uncertain market conditions", *Computers and Chemical Engineering,* vol. 83, pp. 165-175, 2015.

IV. BUDGET REQUESTED

i) Man power, roles and justification of Budget for PI.

- One PI and postdoctoral associate (TUMCREATE) will lead and execute the modelling and analysis of flexibility strategies in the power grid. The PI –postdoctoral associate will be dedicating 60% of his time for the entire duration of the project. This will mean his current dedication and contract at TUM will be reduced in an equivalent percentage to give time partial exclusivity to this project. As a result, the funding requested will not overlap to any other existing funding by NRF or CREATE.
- One research associate (TUMCREATE) will work in tandem with the PI-postdoctoral associate and will be hired in a 60% basis for dedication to the project.
- One postdoctoral associate (SEC) will be hired to facilitate the simulation and optimization of district energy systems. For this task, the associate will be hired on a 80% contract.

ii) Equipment

Computing equipment will be necessary to carry out the simulation work.

iii) Indirect costs

10% of indirect costs will be charged as part of the overhead proposed by the host institution.

A. Manpower		
Type of EOM	**Qty**	**Total (S$)**
PI and Postdoctoral Associate - 60 % (TUMCREATE)	13 months	S$57,200.00
Postdoctoral Associate - 80 % (SEC)	13 months	S$112,623.33
Research Associate - 60 % (TUMCREATE)	13 months	S$46,800.00
Manpower Sub-total		S$216,623.33
B. Equipment		
Type of Equipment	**Qty**	**Total (S$)**
Computing equipment	2	S$6,000.00
Equipment Sub-total		
C. OOE		
Type of OOE	**Qty**	**Total (S$)**
	N.A.	N.A.
OOE Sub-total		
D. Travel		
Type of Travel Costs	**Qty**	**Total (S$)**
Conference attendance	2	S$4,500.00

Travel Sub-total	

Total (A+B+C+D)	S$227,123.33
Indirect Costs	S$22,712.33
Total Budget Requested	**S$249,835.67**

V. SIGNATURES OF PRINCIPAL INVESTIGATORS AND CO-INVESTIGATORS

In signing the grant application, the Principal Investigator and all Co-Investigators undertake to:

- Declare that all information is accurate and to the best of their knowledge.
- Ensure that the requested manpower, equipment and/or resources are not being funded by another agency or research project.
- Drive the project to the best of their ability to achieve the milestones and KPIs set out in the proposal.

Name	Signature	Date
Dr. Jimeno A. Fonseca Principal Investigator (PI)	[signature]	31/03/2017
Sarmad Hanif Principal Investigator (PI)	[signature]	31/03/2017

VI. SUPPORT FROM CREATE HOST INSTITUTION

To be completed by the CEO of the CREATE host institution (or equivalent).

In signing the Grant Application, the Host Institution UNDERTAKES to:

- Confirm the accuracy and completeness of the form submitted.
- Ensure that the budget is appropriate and reasonable (e.g. no double funding / excessive purchase of equipment), and is aligned with the Host Institution's HR and other policies.
- Ensure that the proposed research will be driven by the Host Institution.
- Ensure that the funds provided are used for appropriate purposes, and in alignment with the Terms and Conditions laid out in the Letter of Award.
- Ensure that the research complies with all the rules and regulations pertaining to the Host Institution's operating procedures and guidelines.

Name	PETER EDWARDS		
Designation	DIRECTOR	Institution	SEC
Signature		Date	31.03.2017