

City.Net IES: A Sustainability-Oriented Energy Decision Support System

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Abstract—A city’s energy system processes, as well as the interactions of the energy system with other systems in a city are imperative in creating a comprehensive energy decision support system due to the interdependencies between critical segments of the system. City.Net is a sustainability-oriented decision support system that represents the energy, water, waste, transportation and building systems in a city while taking into consideration the integration and interdependencies that exist between these systems. This paper, which is focused on the integrated energy infrastructure system of a sustainable city, builds on the previous work which employs hierarchical decomposition and multi-domain formulation for the design of complex sustainable systems. The City.Net energy system encompasses the generation, transmission, distribution and consumption of energy in different forms, in several domains and at diverse scales in a city. Also, the interactions of the energy system with other aforementioned systems are incorporated in City.Net. The result is a scalable and flexible energy decision support system which can be simulated and used as a sustainability-analysis tool, encompassing environmental, social and economic sustainability.

I. INTRODUCTION

City.Net¹ is a model-driven decision support system (DSS) with the objective of providing sufficient information and support for administering sustainability-influencing infrastructure systems – energy, water, waste, transportation, and building/land – barring the need for fully investigating these systems at the engineering level. City.Net offers a user with varying sets of options in various sections of the system and this flexibility ensures that real-life situations can be modeled and simulated as accurately as possible and therefore, inform and support administrative and decision-making processes. There are several system models and simulations that represent and assess infrastructures in sectors such as electric power grid, water supply, transportation networks, etc. However, there are few models that visualize and implement these infrastructures as a single system while taking their interdependencies into consideration. Also, not many infrastructure models are aimed at assessing the environmental sustainability, as well as economic and social sustainability of these systems. City.Net focuses on the interactions within systems and interdependencies between systems, including the City.Net Energy system which is the focus of this work.

¹City.Net is being developed by a joint group of researchers from Masdar Institute and MIT

City.Net’s Integrated Energy System (IES) encompasses energy generation, transmission, distribution and consumption. The IES, being a sustainability-focused energy DSS consists of sustainable energy generation methods such as wind farms, concentrated solar power (CSP) plants, photovoltaic (PV) stations, etc. However, renewable energy generation is yet to reach a state of full maturity and economic viability where all energy demands are met by these renewable energy generation methods. Conventional energy generation methods are still required to maintain a smooth passage to the extensive use of renewable energy generation methods. As a result, IES also incorporates conventional energy sources such as natural gas and this adds to the practicality of the IES. It is important to note that the IES, as well as City.Net as a whole, does not apply the diurnal time-modeling method but utilizes the annual method. City.Net is aimed at evaluating how sustainable a city is with a long-term perspective, which does not necessarily require the observation and analysis of the daily interactions in the systems. Also, City.Net does not apply a stochastic approach as it does not incorporate random events.

Section II provides an overview of related research and systems similar to City.Net and the IES. Section III summarizes the City.Net research approach. Section IV shows results of the IES development. Section V discusses the IES and areas of future work. Section VI provides a summary of the paper highlighting the scientific contribution of the IES.

II. RELATED WORK

There are several works on infrastructure systems, both in industry and academia, which are either directly or indirectly related to City.Net. Siemens City[18], IBM CityOne [11], Sustainable Systems Integration ModelTM [1], Urban Infrastructure Suite [15], Interdependent Energy Infrastructure Simulation System (IEISS) [15], UrbanSim [23], System Advisor Model (SAM) [13], and Land Use Evolution and Impact Assessment Model (LEAM) [14] are tools that model energy, water, transportation, finance, security etc. However, the listed tools employ different modeling methods, levels of fidelity, user involvement, interdependency structures (if any) and each tool presents results in a different form. The IES goes further by modeling energy generation technologies (both renewable and conventional) and energy distribution in a complex energy

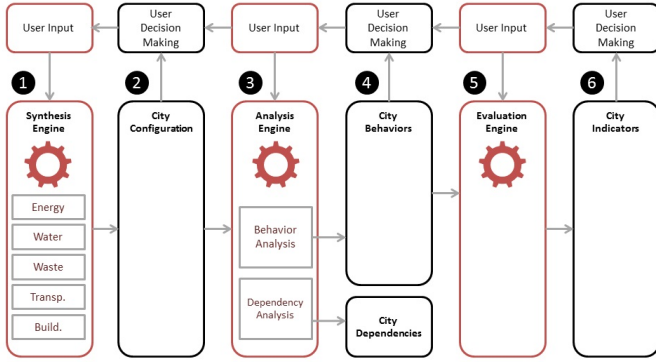


Fig. 1. City.Net Process

system tied to other aforementioned sustainability-related systems, paying attention to spatial data and the interdependencies between these systems. Furthermore, unlike some other tools City.Net takes a long-term modeling approach and is highly scalable and extendable (i.e., more technologies can be introduced) due to the City.Net model development method. City.Net also has the potential of being incorporated in a geographic information system (GIS).

The idea of critical infrastructure interdependencies is also vital to the conception of IES and City.Net at large. Critical infrastructure interdependencies have been researched in [4], [16], [17] and [21]. These works model the ripple effects of failures in interdependent systems howbeit with different approaches.

This paper is built on previous research on the hierarchical decomposition and multi-domain formulation for the design of complex sustainable systems [3] which provides a systematic multi-domain approach that can be used to simultaneously decompose a complex system and integrate the resulting sub-systems. It is important to note that changes in one sub-system could place constraints or requirements on another sub-system.

III. RESEARCH METHOD

A staged research approach was employed in developing City.Net: conceptualization, decomposition, formulation and simulation. This is an extended form of the research method used in [3]. The City.Net process which consists of the stages of City.Net usage is also explained.

A. Conceptualization

Conceptualization is the first step taken in developing City.Net. Conceptualization involves eliciting and specifying the requirements for the system to achieve its objective. The City.Net process shown in Figure 1 is developed at this stage. The City.Net process commences at the user and system inputs and terminates at the results obtained from the inputs and system constraints. Also, use cases visualizing how the model should work are devised.

B. Decomposition

Decomposition divides the system into logical stages, feeding the output from one stage as an input to the next stage.

These stages are the synthesis, analysis and evaluation. Besides dividing the system into stages, the City.Net decomposition follows the template in [3] and has a hierarchical format. In general, decomposition involves establishing the form parameters (FPs), behavior parameters (BPs) and key performance indicators (KPIs) which are the variables at the synthesis, analysis and evaluation stages respectively. The decomposition template used is shown in Figure 2. The idea of a system mode and network as seen in Figure 2 is to logically separate the main structures in a system which are called nodes from the links within and between these structures called edges.

C. Formulation

This comprises the identification of the parameter relations and the energy system's governing equations, i.e., relationships between the FPs, BPs and KPI's and the constraints involved. The FPs required for estimating each BP are identified and BPs required for estimating each KPI are identified. The formulation process is applied across every level of the system hierarchy as defined in the system decomposition and establishes the relationships between the different levels of the hierarchy.

D. Simulation

This involves the adaptation of the system parameters, relations and interdependencies into a software tool. The software tool is coded to match the City.Net process (Figure 1).

E. City.Net Process

The concept of the synthesis, analysis and evaluation modules are elaborated below. It should be noted that these are the stages that represent the usage of the IES as seen in Figure 1. The numbers in Figure 1 represent the order of the system phases.

- 1) **Synthesis:** This is the potential starting point for using the IES. The infrastructure and their parameters in the energy system are defined and configured by the user to form a custom energy system configuration. As a result, the development of the synthesis module for the IES requires the identification of the FPs, which are the constants and variables (with value constraints) that are or may be required in the definition of the properties of a node or an edge. The user-defined configuration is defined on a spatial layout and this layout represents the real-life locations of the configured infrastructures.
- 2) **Analysis:** At this phase of using the IES, the BPs are obtained from the user-defined FPs.
- 3) **Evaluation:** The user's system configuration is evaluated based on various sustainability measures, i.e., KPIs. The KPIs representing sustainability in a city and in an energy system are defined/obtained and stored in the evaluation module.

IV. CITY.NET IES

The IES is defined according to the decomposition and formulation specified in Section III. The FPs, BPs and KPIs

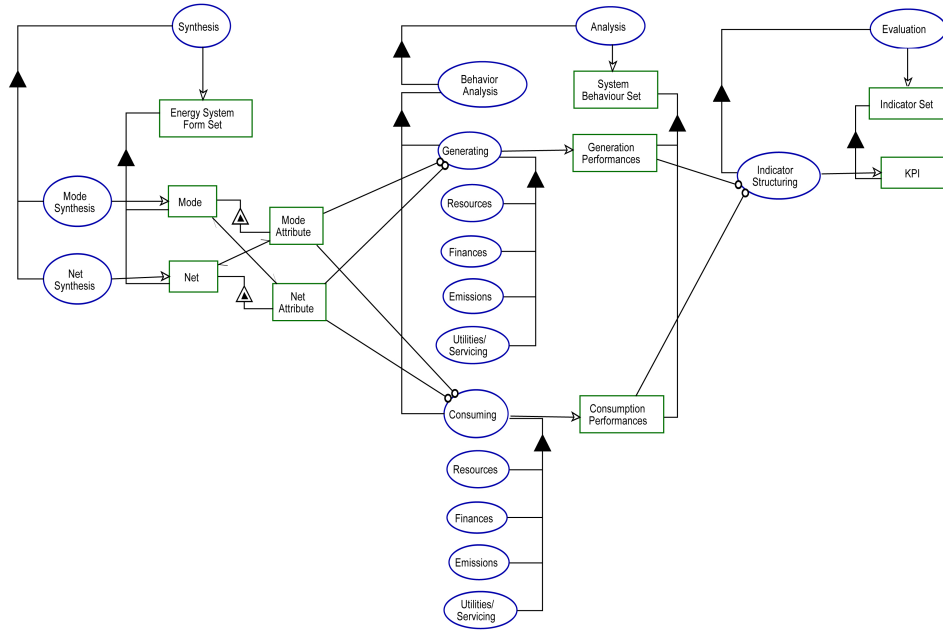


Fig. 2. Decomposition Template

are outlined and the purpose of system performances are explained. In addition, the IES is divided into layers based on the functions of the respective nodes and edges in the system.

A. Synthesis and Analysis

The FPs and BPs in different sections of the energy system are highlighted in Table I. Table I presents the FPs and BPs associated with energy generation, transmission and distribution, finances, emissions, and resource consumption (in the energy system).

There are generally two concepts of emissions: life-cycle emissions and actual emissions that occur during energy generation. Life-cycle emissions are used in estimating emissions from renewable energy methods such as PV and wind. These life-cycle emissions are the greenhouse gases (usually CO₂) produced while manufacturing the equipment used in the power plant [6]. Typically, the life-cycle emissions are estimated per unit energy generated by a power plant while that for actual emissions (CO₂, CO, CH₄ and NO_x) is estimated based on the amount of fuel used. NO_x removal from natural gas and carbon sequestration can be considered as emission reduction techniques but are not included in the current version of the IES. In addition, the greenhouse effect of CH₄ and N₂O are 21 and 310 times that of CO₂ respectively [9], [19]. This relation of the greenhouse effect of the gases is taken into consideration while estimating the environmental KPIs.

Resource consumption in the current version of the IES consists of water use and land requirements. Transportation and waste are currently not utilized or provided in the IES. Consequently, only the land requirements and water use in the energy system are defined. One assumption made is that the resource use in the energy system is linear with respect to

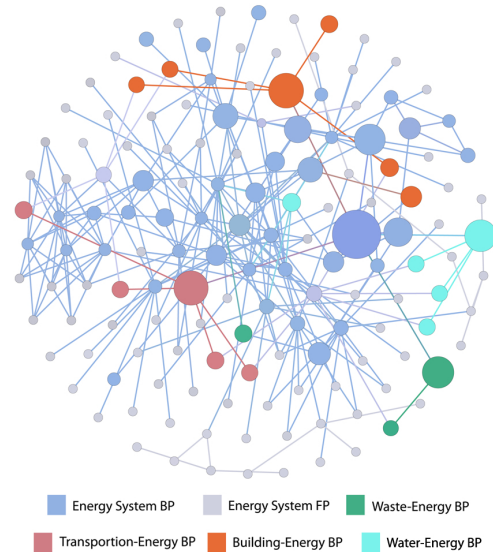


Fig. 3. Energy-Related Interdependencies

energy generated or plant capacity.

Table II outlines the generation and consumption of energy in other systems thereby highlighting the system interdependencies. Figure 3 provides a more detailed network overview of components in City.Net related to the energy system, showing the IES-related dependencies and interdependencies and the complexity of the system integration. The sizes of parameter network nodes in Figure 3 are proportional to the hierarchical levels of the parameters.

TABLE I
FORM AND BEHAVIOR PARAMETERS

Method	Form Parameters	Behavior Parameters
Energy Generation		
Wind Farm [20]	Annual wind speed distribution (wind speed v , duration of each wind speed t_v , wind turbine specifications (cut-in speed v_{in} , cut-out speed v_{out} , rated speed v_{rated} , coefficient of performance COP , blade length r and turbine rated capacity P_{rated}), number of turbines in wind farm n and air density ρ .	Electricity generated per year E , turbine power at each speed P_v and wind farm capacity $P_{station}$.
PV Station [20]	PV panel specifications (length l , width w , efficiency η , capacity P_{rated}), annual DNI and number of PV panels.	PV station capacity $P_{station}$, Electricity generated per year E .
CSP Station [20], [8]	Mirror surface area A , number of mirrors n , mirror thermal capacity P_t , plant solar-to-electric efficiency η_{S-E} (this encompasses efficiency from the solar field to the point of energy output) and annual DNI DNI .	Electricity generated per year E and CSP station thermal capacity $P_{t-station}$.
Hydropower [20]	Head h , inlet water speed v_{in} , outlet water speed v_{out} , volumetric flow rate \dot{v} , plant efficiency η , water density ρ and acceleration due to gravity g .	Plant capacity $P_{station}$, capacity factor CF and energy generated annually E .
Biomass [5]	Steam turbine capacity P_{st} , gas turbine capacity P_{gt} , power plant capacity P_{plant} , biomass heat content (low heating value) LHV , annual operating full load hours OH and plant energy-conversion efficiency at rated power η_p .	Plant capacity P_{plant} , Biomass flow rate M and energy generated per year E .
Natural Gas [19]	Gas turbine capacity P_{gt} , steam turbine capacity P_{st} , plant capacity P_{plant} , power plant efficiency η , net heat rate (higher heating value basis) H and plant capacity factor CF .	Plant capacity P_{plant} , Energy generated per year E and natural gas feed rate M .
Finances		
Revenue Generation	Total energy generated within the energy system supplied to the grid per year E_T , annual transmission losses E_{loss} and unit selling price of electricity SP .	Revenue generated from energy sale per year R .
Finance Consumption [10], [20]	Unit capital cost $C_{unit\ Cap}$, unit operational and maintenance (O&M) cost $C_{unit\ O\&M}$, unit fuel cost $C_{unit\ F}$, plant capacity P (or substation/transformer/power line capacity), mass of fuel consumed annually M , system lifetime N , year t , Cost at year 't' C_t , and discount rate d .	Capital cost C_{Cap} , O&M cost $C_{O\&M}$, fuel cost C_F , energy generated E and levelized cost LEC .
Emissions		
Emissions produced	Energy generated in power plant per year E_{plant} , fuel used per year M_{fuel} , mass of CO ₂ per unit energy CO_2/kWh , emissions per unit mass of fuel GHG/kg (CO ₂ , CO, CH ₄ and NO _x).	Annual emissions by power plant GHG_{LC} and GHG_{Gen} .
Resource Consumption		
Water Consumption	Water used per unit energy in plant $W_{per\ kWh}$ and energy generated per year in power plant E_{plant} .	Water consumed in power plant W_{plant} .
Land Use	Land required per unit kW in plant $L_{per\ kW}$ and infrastructure capacity P_{plant} .	Land used by power plant L_{plant} .
Transmission and Distribution		
Distribution Substation/ Power Lines[12]	Assumed load power factor pf , number of feeders N , base feeder voltage V_{feeder} , incoming voltage V_{in} , total feeder length l_{feeder} , number of customers connected to a feeder $N_{customers}$, number of phases in feeder cable ϕ , number of transformers connected to a feeder $N_{transformers}$, feeder allocated load kVA_{feeder} , feeder cable ampacity I_{max} , feeder cable resistance per unit distance $R_{per\ km}$ and demand equation ($A + B \cdot kWh$). The demand equation is way of estimating the consumer load from the amount of energy consumed where 'A' and 'B' are constants and 'kWh' is the average electricity consumed per month.	Substation capacity P , feeder current I_{feeder} , feeder power loss P_{f-loss} , feeder cable power-distance rating $feeder_{kVA-km}$, and annual feeder-energy loss $E_{f-loss-annual}$.

TABLE II
ENERGY GENERATION AND CONSUMPTION IN OTHER SYSTEMS

System	Energy Generation	Energy Consumption
Water	-	Desalination, water treatment and water distribution.
Waste	Waste-to-energy	Waste processing and waste collection.
Building	Rooftop PV and rooftop solar thermal collectors	Residential use, commercial use, industrial use and parks and outdoor spaces.
Transportation	-	Electric cars, light rail, personal rapid transit (PRT) and metro.

The parameter relations and interdependencies of the IES are as follows (the symbols represent the FPs and BPs as specified in Table I):

1) *Wind Farm* [20]:

$$P_v = \begin{cases} COP \times \rho \times \pi r^2 \times \frac{v^3}{2} & \text{if } v < v_{rated} \\ P_{rated} & \text{if } v \geq v_{rated} \end{cases} \quad (1)$$

$$E = n \sum_{v_{in}}^{v_{out}} P_v \times t_v \quad (2)$$

$$P_{station} = n \times P_{rated} \quad (3)$$

2) *PV Station*:

$$P_{station} = n \times P_{rated} \quad (4)$$

$$E = \eta \times n \times l \times w \times DNI \quad (5)$$

3) *CSP Station* [20], [8]:

$$E = \eta_{S-E} \times n \times A \times DNI \quad (6)$$

4) *Hydropower* [20]:

$$P_{station} = (\rho g h + \frac{1}{2} \rho (v_{out}^2 - v_{in}^2)) \times \dot{v} \times \eta \quad (7)$$

$$E = P_{station} \times CF \times 8760 \text{hours} \quad (8)$$

5) Biomass [5]:

$$P_{plant} = P_{st} + P_{gt} \quad (9)$$

$$E = P_{plant} \times OH \quad (10)$$

$$M = \frac{P_{plant} \times 3600 \times OH}{\eta_p \times LHV} \quad (11)$$

6) Natural Gas (NG) [19]:

$$P_{plant} = P_{st} + P_{gt} \quad (12)$$

$$E = P_{plant} \times CF \times 8760hours \quad (13)$$

$$M = \frac{P_{plant} \times CF \times 8760hours \times 3600seconds}{\eta \times H} \quad (14)$$

7) Finances [10], [20]:

$$R = (E_T - E_{loss}) \times SP \quad (15)$$

$$C_{Cap} = P \times C_{unit\ Cap} \quad (16)$$

$$C_{O\&M} = P \times C_{unit\ O\&M} \quad (17)$$

$$C_F = M \times C_{unit\ F} \quad (18)$$

$$LEC = \sum_{t=0}^N \frac{C_t}{(1+d)^t} \quad (19)$$

8) Emissions:

$$GHG_{LC} = CO_2/kWh \times E_{plant} \quad (20)$$

$$GHG_{Gen} = GHG/kg \times M_{fuel} \quad (21)$$

9) Resource Consumption:

$$W_{plant} = W_{perkWh} \times E_{plant} \quad (22)$$

$$L_{plant} = L_{perkW} \times P_{plant} \quad (23)$$

10) Distribution Substation [12]:

$$P = \sum_1^N kVA_{feeder} \quad (24)$$

$$I_{feeder} = \frac{kVA_{feeder}}{\sqrt{\phi} \times V_{feeder}} \quad (25)$$

$$P_{f-loss} = \phi \times I_{feeder}^2 \times R_{perkm} \times l_{feeder} \quad (26)$$

$$Feeder_{kVA-km} = kVA_{feeder} \times l_{feeder} \quad (27)$$

$$E_{f-loss-annual} = \sum_1^{12} \frac{(P_{f-loss} - A)}{B} \quad (28)$$

B. Evaluation

At the evaluation stage in the IES, KPIs are used to estimate and rate the performance of the energy system. These KPIs which are combinations of environmental, social and financial indicators are as follows:

- 1) **Renewable Energy Fraction (REF) [22]:** This is the fraction of the total amount of energy consumed in a city obtained from renewable sources. The renewable energy fraction is an indicator for estimating how close an energy system is to total renewable energy generation.

$$REF = \frac{Renewable\ energy\ generated}{Total\ energy\ generated} \quad (29)$$

- 2) **Energy Cost Indicator (ECI) [2]:** This indicator can be applied to each energy generation source and to energy generated in the city as a whole. It is the levelized cost of generating energy as seen in Equation (19).

- 3) **Capital Cost Indicator (CCI) [2]:** The CCI is a measure of the capital cost of building a power plant compared with the estimated total energy generated by the plant during its lifetime. Like the ECI, it can be applied to a single power plant or all power plants in the City.

$$CCI = \frac{Capital\ cost}{Plant\ lifetime\ energy\ generation} \quad (30)$$

- 4) **Energy Consumption per Head (ECH) [22]:** This is a measure of the average energy consumption per person over a period of time.

$$ECH = \frac{Total\ energy\ consumed}{City\ population} \quad (31)$$

- 5) **Energy Intensity (EI) [22]:** The energy intensity is a measure of the energy consumed compared to the city's gross domestic product (GDP).

$$EI = \frac{Total\ energy\ consumption}{GDP} \quad (32)$$

- 6) **CO₂ Emissions per Head [22]:** This is a measure of the average CO₂ emission from the energy system per person over a period of time.

$$CO_2\ per\ head = \frac{CO_2\ emissions}{City\ population} \quad (33)$$

- 7) **CO₂ Savings [7]:** This is the deficit amount of CO₂ (not life-cycle emissions) that would have been produced from conventional energy generation, i.e., natural gas.

$$CO_2\ savings = (CO_2/kWh\ for\ NG \times Energy\ generated) - Actual\ emissions \quad (34)$$

- 8) **Area per MW [2]:** This is a ratio of the total installed power plants capacity in the city to the total area occupied by these plants. It shows the extent of land use in energy generation.

$$Area\ per\ MW = \frac{Total\ power\ plant\ area}{Total\ installed\ capacity} \quad (35)$$

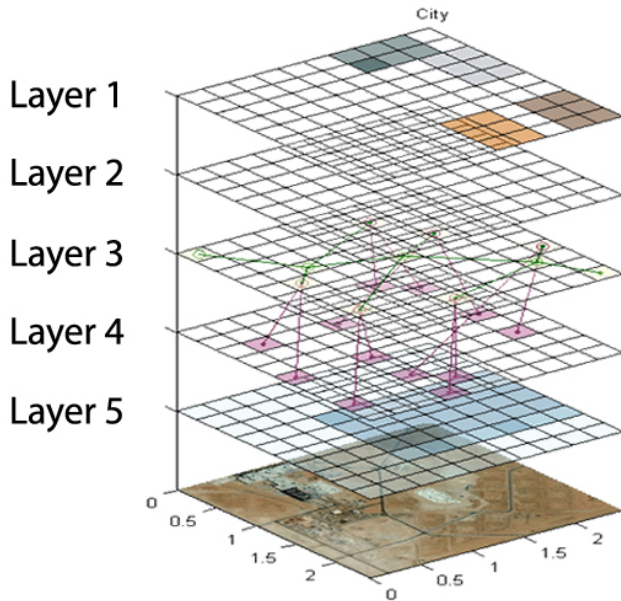


Fig. 4. Energy System Layers

C. IES Layers

The nodes and edges in the energy system are classified according to their functions in the energy system and are not strictly ordered. The classifications are listed in Table III. Figure 4 shows a sample energy system configuration with the different layers placed over the city's map. The energy system nodes on the different layers are visualized. Also, the connecting edges between the nodes across and within layers can be seen. Layer 2 (transmission) has no nodes or edges since this sample configuration was designed for a small city with no transmission infrastructure. The power plants (Layer 1) are distributed generation stations while Layer 5 (consumption) is broadly classified into residential and industrial consumers. In addition, the spatial-network orientation of City.Net is evident in Figure 4 and this spatial-network orientation improves the process of visualizing and analyzing city systems.

TABLE III
IES LAYERS

Layer	Node(s)	Edge(s)
1	Power plant	-
2	Transmission substation and bus	Transmission line
3	Distribution substation and bus	Sub-transmission line
4	Distribution transformer and bus	Primary distribution line
5	Consumer-end termination	Secondary distribution line

V. DISCUSSION AND FUTURE WORK

The City.Net IES is a city model that can be applied to different geographical locations. This ensures that the IES can be utilized to evaluate the sustainability of a city in almost any location of the world. The IES can also be used for modeling different city sizes, hence, the scalability of the IES.

The IES does not incorporate daily processes in the energy system ,i.e., diurnal modeling and might overlook some data for modeling a city's energy system. However, City.Net is aimed at modeling a city over long periods of time in order to estimate the city's long-term sustainability and this makes the annual estimations pertinent to the purpose of City.Net and adequate for estimating a city's processes. Therefore, any minor data relevant to hourly and daily processes are negligible.

One area of future work on the City.Net IES is the simulation of the IES together with other systems in City.Net. This would enable the model to be practical and easy to use. In addition, more relevant technologies especially sustainability-oriented technologies such as district cooling and heating, carbon sequestration, and geothermal energy would be added to the IES.

Furthermore, a case study that involves the application of the IES to a city's energy system and demonstrates the feasibility, flexibility and scalability of the IES is a possible direction of future work. The IES can be evaluated based on the validation of the results obtained and appropriate developments made if required.

VI. CONCLUSION

The IES is suitable for analyzing and forecasting the feasibility and sustainability of a city's energy system over extended periods of time. The interdependencies between the energy system and the other City.Net systems are critical in evaluating a city's energy system and this is what the IES offers. The IES does not only compute processes within the energy system, it also computes the aforementioned interdependencies. Thus, the IES can be applied as a comprehensive sustainability tool with a potential of being logically incorporated with other city systems, even beyond City.Net's current city systems. Also, the hierarchical decomposition approach taken in developing the IES gives the IES the potential to be expanded by the introduction of more energy system technologies including more energy generation and storage methods. In addition, the IES can be coupled with GIS applications due to the IES layers and spatial-network orientation of the layers.

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