Complex Urban Systems ICT Infrastructure Modeling: A Sustainable City Case Study

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Abstract—A modern and efficient information and communication technology (ICT) infrastructure is essential for managing the challenges in the complex urban systems development. The ICT infrastructure is a complex system consisting of many subsystems and interconnections, which makes the process of planning, designing, and maintaining a comprehensive ICT infrastructure expensive and difficult. Most approaches used for the ICT infrastructure modeling focus typically on a single ICT system, for example, a wireless network. This paper presents a systems modeling approach based on integrating different subsystems and their characteristics into a single model, applying system decomposition, establishing the logical relations between system components, and defining relevant key performance indicators. It is shown that this systems modeling approach facilitates holistic planning, design, and evaluation of the complex ICT infrastructure for a sustainable city. This is demonstrated in the form of a two-scenario Masdar city case study. The case study exhibits the practicality of the derived ICT model and the feasibility of the results.

Index Terms—Complex urban systems, information and communication technology (ICT) infrastructure, sustainable development, systems modeling.

I. INTRODUCTION

THE INFORMATION and communication technology (ICT) infrastructure is a major driver for the development of the sustainable cities. The ICT infrastructure offers different services to various urban complex system entities, most notably access to the networks, computational processing, and transmission of information. Applications are increasingly being shifted to large computing centers offering savings on space, energy, and costs. Even personal computing is shifting toward cloud computing, relying upon the use of large computing centers that provide infrastructure as a service (computing resources in the form of operating system images), platform as a service (software execution platforms), and software as a service (ready-to-use software such as word processing or customer relationship management software).

These computing centers should be considered a central part of the ICT infrastructure, and should therefore be integrated into the ICT planning process. Although these computing centers provide computational services (e.g., intensive computations for weather forecasting), high-level software services (e.g., e-mail processing), and data storage services (e.g., file storage), they are typically known as datacenters. In this paper, the ICT infrastructure system is treated as a single complex system consisting of networks and datacenters.

There is an increase in the recognition of the importance of the ICT infrastructure in urban complex systems planning [1]. Due to the importance of the ICT infrastructure, it is treated with the same level of importance as the other infrastructure systems such as electricity, water, and transportation. In the case of sustainable cities, the effectiveness of energy consumption and the minimization of pollution in the ICT system are of critical importance.

Research on the city of London identified the five key aspects of the ICT system [2]: network connectivity, data center capability, electrical power supplies, security and resilience, and skills. This paper focuses on the first three aspects—networks, datacenters, and energy consumption—and models these aspects using high-level parameters, including properties of the services provided, costs, etc. Visualizing and estimating the high-level impact of the ICT system in a sustainable city is imperative, as it enables developers to forecast the ICT requirements necessary to ensure the seamless operation of the other city infrastructure systems. In turn, it is important to understand the resource requirements the ICT system places on the other systems and to evaluate the sustainability of the ICT system. Thus, the main goal of this paper is to create a model suited for ICT system planning and development in sustainable cities. This ICT model is exhibited in a two-scenario sustainable city case study.

This paper is organized as follows. Section II discusses background work and similar ICT models. Section III provides the details of the functional and spatial modeling framework used to develop the ICT model. Section IV presents the process and details of developing the ICT model. Section V presents the case study results. Section VI presents a discussion of the ICT model and results. Section VII concludes the paper.

II. BACKGROUND AND RELATED WORK

A functional and spatial modeling framework is used for the ICT model development. This modeling framework originates

from [3] which discusses the use of hierarchical decomposition and multidomain formulation for modeling interdependent infrastructure systems. An application of the framework is presented in [4] and [5], where the framework is used to develop an integrated energy system model (City.Net IES). This modeling framework, which is further discussed in Section III, emphasizes system interdependencies existing in a system, and the dynamics resulting from these interdependencies. City.Net is a city infrastructure model comprising different city infrastructure systems such as energy, water, waste, transportation, and building. The ICT city system is modeled in accordance with this City.Net structure.

Typically, ICT interactions in interdependent infrastructure systems are classified as cyber interdependencies. As described by Tolone *et al.* [6], cyber interdependencies are interdependencies related to the flow of information between infrastructures, essential for the control and stability of these infrastructure systems. However, our paper offers a different perspective on ICT infrastructures, representing the ICT infrastructure system as a sustainable city system and identifying ICT-related interdependencies.

The work presented in our paper is related to the general discipline of systems engineering and the engineering of complex systems, incorporating the mechanical, electronic, software, organizational, and economic aspects of the system. From a requirements engineering perspective, our modeling approach assumes the set of requirements which the system has to fulfill, and does not go into detail about the particular approach to acquire and engineer these requirements. As a result, our approach is mostly related to high-level system analysis and design. In particular, it is related to the design and planning of complex infrastructures in sustainable cities.

Ergazakis *et al.* [1] present a methodology for the development of a digital city (DC). They emphasize the importance of the ICT infrastructure for the quality of life and business development, including business innovation and entrepreneurship. They also recognize that the efficient planning of a DC (including its ICT infrastructure) requires the alignment of the community needs, technical challenges, possibilities, and costs. As an important step in their methodology, they identify vital parameters such as population density and broadband penetration. The characterization of the DC comprises 220 indicators and the values of these indicators are used to drive the strategic interventions–actions that decision makers have to execute in order to create and improve a DC. Technically, the DC decision support system consists of a knowledge base with the best practices, indicators, indicator thresholds, weightings, and mechanisms from multicriteria decision making. The main goal of the DC decision support system is to produce a ranked list with the most appropriate strategic interventions. This methodology has a high-level focus, and is aimed at policy makers and administrators. On the contrary, our modeling approach incorporates technical modeling as well as economic modeling of the ICT infrastructure in a sustainable city, while implementing more definite parameters and parameter relations.

Waupotitsch *et al.* [7] present an approach for integrated wired and wireless network simulation, focused on simulating end-to-end population communication. This network simulation is based on the multiscale integrated information and telecommunications system (MIITS), which is a part of the urban infrastructure suite (UIS). The MIITS models extensive and complex communication networks and takes infrastructure interdependencies into account. MIITS simulates the dynamics of the network behavior, real-time network loads, and the network protocol stack. In order to make the simulation realistic, the MIITS developers analyzed statistical survey data about the communication patterns and devices used. MIITS performs simulations at the level of the packets transported in the network and executes rather low-level processes such as routing. However, the MIITS has lower-level technical goals compared to the high-level modeling implemented in our ICT model. Our model places more emphasis on the services offered (including their quality) and how these services relate to costs, energy consumption, etc., taking a holistic approach and integrating computational resources.

In general, our paper is related to the area of modeling and simulation of critical infrastructures. Rigole and Deconinck [8] present several approaches for the modeling and simulation of critical infrastructures and their interdependencies. These approaches are classified as macroscopic and microscopic; the former focuses on using high-level abstractions and formulas, and the latter focuses on a small isolated part or aspect of the infrastructure. The framework used in our paper falls in the macroscopic category. In addition, Rigole and Deconinck present the Supply-Demand Graphs approach as a way to model interdependent infrastructures by representing the flow of a commodity such as electric power or communications. For example, these graphs could be used to investigate the infrastructure vulnerabilities. If the links between suppliers and consumers are weighted or quantified, some other analysis and simulations can be performed (e.g., related to investment or performance). Although the provision of services is considered in this paper (e.g., offering a computational power or network access the customers), parameters of different systems are established and linked using formulas instead of graphs.

Other approaches for modeling and simulation, for example, petri nets and agent-based simulation, deal mostly with low-level and dynamic properties of the infrastructure such as stability or reliability. Additional complex urban system models include Siemens city [9], IBM CityOne [10], and UIS [11]. However, none of these models offers the detailed level of modeling and range of possibilities necessary for integrating different systems, as required for the goals of our paper. The aim of our ICT model is to present an approach for the analysis, planning, and simulation of the ICT infrastructure using systems engineering principles. In addition, the ICT model includes computational facilities such as datacenters, potentially modeling the cloud services that datacenters provide.

III. FUNCTIONAL AND SPATIAL MODELING FRAMEWORK

A functional and spatial modeling framework [4] for city infrastructure systems is used to develop the ICT model. These two aspects of the framework—functional and spatial—work

in parallel and complement each other in the system model development process. The functional aspect of the modeling framework comprises four processes.

1) *Conceptualization* is the process of developing the fundamental system ideas and concepts that are obtained based on the intended functionality of the system.
2) *Decomposition* is the process of systematically breaking down the system into components represented by Form Parameters (FPs), Behavior Parameters (BPs), and Key Performance Indicators (KPIs). The decomposition process is hierarchical, i.e., different parameters are placed at different levels of the system hierarchy. FPs represent the fundamental properties of the system infrastructure; BPs represent the behavior of the system based on the values of the FPs; and KPIs represent the performance of the system based on its BPs.
3) *Formulation* is the process of establishing the relationships between FPs, BPs, and KPIs, either within a single system or among different systems. Formulation involves the identification of the equations which are used to obtain the values of BPs and KPIs.
4) *Simulation* is the synthesis, analysis, and evaluation of user-defined scenarios using the developed system model.

Spatial modeling involves the synthesis and classification of the system components based on their geographical orientation and physical location. The aim of introducing the spatial orientation of the system infrastructure is to include the spatially-related parameters such as distance in the synthesis, analysis, and evaluation processes. For example, a WiFi network can be spatially synthesized based on the location of its wireless router and the range covered by the WiFi signal. The spatial modeling framework divides the system components into nodes and edges on different logical layers. Nodes represent system components and communicate through the edges. Using the WiFi network as an example, the nodes are the wireless routers and the end-user devices (e.g., smartphones and laptops) while the edge (edge region in this case) is the WiFi signal which connects the routers and end-user devices. This classification is similar to those used in geographic information system (GIS) environments [12]. It is important to point out that the functional and spatial aspects of the framework work in parallel rather than sequentially.

In addition, the modeling framework enables the final model to be used in the three main stages: synthesis, analysis, and evaluation. Synthesis is the definition of the values of the FPs and the physical orientation of the system components; analysis is the estimation of the BPs in order to understand the system behavior based on the predefined synthesis; and evaluation is the performance assessment of the user-defined system according to the existing KPIs.

IV. CITY.NET ICT MODEL

A. Conceptualization

The concept and purpose of each ICT subsystem is explained with a focus on the system inputs and outputs.

1) *Datacenter:* A datacenter provides storage, computing, and networking services to its customers. These services can be direct such as the Internet service or indirect such as cloud services. The datacenter functions as the information hub for all the other infrastructure systems. The datacenter is evaluated with respect to its environmental and financial sustainability. This is based on factors such as servers typically having a three-year or four-year lifecycles [13], and the possibilities of disposing, recycling, or reusing datacenter equipment.

2) *Networks:* A wireless network can be a part of a wide area network (WAN) or local area network (LAN) depending on the intended service area. A wireless network is defined by its coverage area and its available bandwidth. A wired network also comprises the LAN and WAN network categories. The fundamental properties for defining a wired network include bandwidth and termination points.

Riaz *et al.* [14] present a comprehensive network framework which combines wired and wireless network technologies. They discuss the trend toward the combination of wired and wireless technologies in order to improve users' networking experience. Furthermore, they point out the important parameters to be considered in networks, citing the bandwidth offered per customer as a vital parameter.

A good option for the wired WAN is the optical fiber technology. The 1000Base-LH standard has a data rate of 1000 Mbps and has a range of 70 km [15]. The other IEEE fiber optic standards are are 10Base-FL, 100Base-FX, 100Base-SX, 1000Base-LX, and 1000Base-SX [15]. These standards are incorporated in the ICT model to enable different system modeling options.

Wireless technologies include WiFi and WiMAX. WiMAX is the IEEE 802.16x standard and it supersedes the WiFi technology in both bandwidth and range. The current WiMAX standard which is the 802.16e-2005 has a bandwidth of about 70 Mbps, provides mobility, and covers a range of up to 8 km [14].

3) *Resource Consumption:* The major forms of resource use in the ICT system include energy use in datacenters and communication networks, water use in datacenters for cooling purposes, and land space occupied by ICT infrastructure. Sawyer [16] provides a detailed insight into energy consumption in a datacenter, taking critical loads of ICT equipment, cooling, lighting, and Universal Power Supply (UPS) inefficiencies into consideration as these are the major energy sinks in a datacenter. The datacenter load classification in [17] is consistent with the above-mentioned classification as it also classifies datacenter loads into the computing, cooling, and power categories.

However, one of the challenges of estimating energy consumption in datacenters is the absence of energy proportionality. In other words, resource utilization is not necessarily the same as power utilization and this poses a datacenter modeling problem. The typical capacity range at which servers work for most of the time is 10% to 50% of the full server capacity [18] but this does not result in a range of 10% to 50% power consumption.

Vereecken *et al.* [19] also study power consumption in communication networks, citing instances which show that an

operator's mobile network power consumption is about 20% of the total power consumption, while the fixed line access consumes about 50% of the total power consumption [20], [21].

The consumption of energy in the ICT system is systematically derived based on the energy consumption of individual components in the datacenter and network.

4) Energy Generation: In a sustainable city, the ICT system can also be considered to generate energy resources in the form of rooftop Photovoltaics (PVs) and rooftop solar thermal collectors to serve electrical and cooling loads respectively. The City.Net IES PV model [4] is applied for PV energy generation in the ICT system. These energy sources can be used to serve part of the datacenter or network hub loads, mitigating the dependence of the ICT system on the energy system.

Heat obtained from rooftop thermal collectors is made useful for cooling purposes by absorption chillers. The collector type determines the efficiency of the collector. As expected, the cost of the collector is proportional to its efficiency. Also, the chiller-effect type determines the coefficient of performance (COP) of the cooling system. A single-effect chiller has a COP of 0.7 and is used with a flat-plate collector; a double-effect chiller has a COP of 1.2 and is used with a flat-plate collector as well; a triple-effect chiller has a COP of 1.7 and is typically used with evacuated tube collectors [22].

5) Service Provision: The primary purpose of the ICT system is to provide different ICT services to its users. Each service type is characterized with different parameters. For example, parameters for network access would be the bandwidth offered and the available amount of data to be transferred per time unit, data storage would be measured in Gigabytes or Terabytes, and the processing power is measured in GFLOPs. Platform as a Service is characterized by the properties of the virtual machines instances, where the processing power can also be measured in some form of a computer resource abstraction such as Amazon's elastic compute unit (ECU). The ECU has a processing power equivalent to the processing power of a 1.0–1.2 GHz 2007 Intel Xeon processor [23].

6) Costs: The costs in the ICT system include capital and annual costs. Capital costs comprise equipment costs and installation costs while annual costs comprise operational costs and maintenance costs. Since the ICT system consists primarily of the datacenter, wired and wireless networks, the aforementioned costs can be identified in these three ICT infrastructure classes. For example, the capital cost for setting up a datacenter would include the costs of ICT equipment such as servers, routers, switches, firewalls, external network circuits, cooling equipment, etc. The operational and maintenance costs can be set at a certain percentage of the capital cost. Kaplan *et al.* [24] present a sample cost analysis for a particular application in a datacenter, highlighting ICT equipment such as servers, network, and storage equipment. Another datacenter cost analysis, which uses the datacenter critical load power and server power as bases for estimating costs, is presented in [13] and this is the cost analysis method used in this paper.

7) Emissions: There are no direct emissions associated with the ICT infrastructure. However, indirect emissions exist in terms of the emissions resulting from the generation of energy consumed by the ICT infrastructure. These indirect emissions are incorporated in the ICT model.

B. Decomposition

The object process methodology (OPM) [25] is used to facilitate the decomposition process. OPM has objects as the core entities in a model, and processes that transform objects by creating objects, destroying objects, or somehow affecting objects. OPM represents the system structure and system behavior in the same model. This is one of the reasons why we decided to use OPM instead of a language such as unified modeling language (UML) [26].

Graphically, objects are represented by rectangles and processes by ellipses. Fig. 1 shows the OPM model of the ICT infrastructure system. There are two classes of parameters: form parameters (FP) and behavioral parameters (BP). FPs describe the systems components, attributes, and relationships. BPs describe behavior characteristics that are derived or expected from the system's form. For example, in Fig. 1, the ICT system form is a component (FP) that contains (the containment is represented by a full arrow) the Datacenter and the Network. The Datacenter has a number of parameters such as "land used" or "number of servers." The ICT System model also comprises behaviors classified under "resource demanding" and "resource providing," as well as the parameters defining these behaviors (e.g., "electricity generated," or "total power required"). The behaviors are also related to some of the FPs, for example, "number of PV panels" is related to "service providing." Table I provides a list of FPs and BPs in different sections of the ICT system and in ICT-related dependencies.

C. Formulation

The relations that define the BPs and KPIs of the ICT system are specified based on the conceptualization and decomposition of the ICT system. The symbols used to represent the parameters are listed in Table I.

1) Data Center: Energy sinks in a datacenter are typically divided into the following categories: ICT equipment, electrical equipment, and cooling. Sawyer [16] estimates the total datacenter power consumption, and some of the equations are listed below

$$P_{\text{ICT}} = \sum N_{\text{equipment}} \times P_{\text{equipment}} \tag{1}$$

$$P_{\text{UPSloss}} = 0.32 \times (P_{\text{ICT}} + P_{\text{non-ICT}} + P_{\text{ICT-future}}) \tag{2}$$

$$P_{\text{peak}} = 1.05 \times (P_{\text{ICT}} + P_{\text{non-ICT}} + P_{\text{ICT-future}}) \tag{3}$$

$$P_{\text{light}} = 0.0215 \times A \tag{4}$$

$$P_{\text{elec}} = P_{\text{light}} + P_{\text{UPSloss}} + P_{\text{peak}} \tag{5}$$

$$P_{\text{DC-Cool}} = k \times P_{\text{elec}} \tag{6}$$

$$P_{\text{total}} = P_{\text{DC-Cool}} + P_{\text{elec}} \tag{7}$$

$$P_{\text{Gen-Cool}} = 1.3 \times P_{\text{DC-Cool}} \tag{8}$$

$$P_{\text{Gen-Crit}} = 1.5 \times P_{\text{elec}} \tag{9}$$

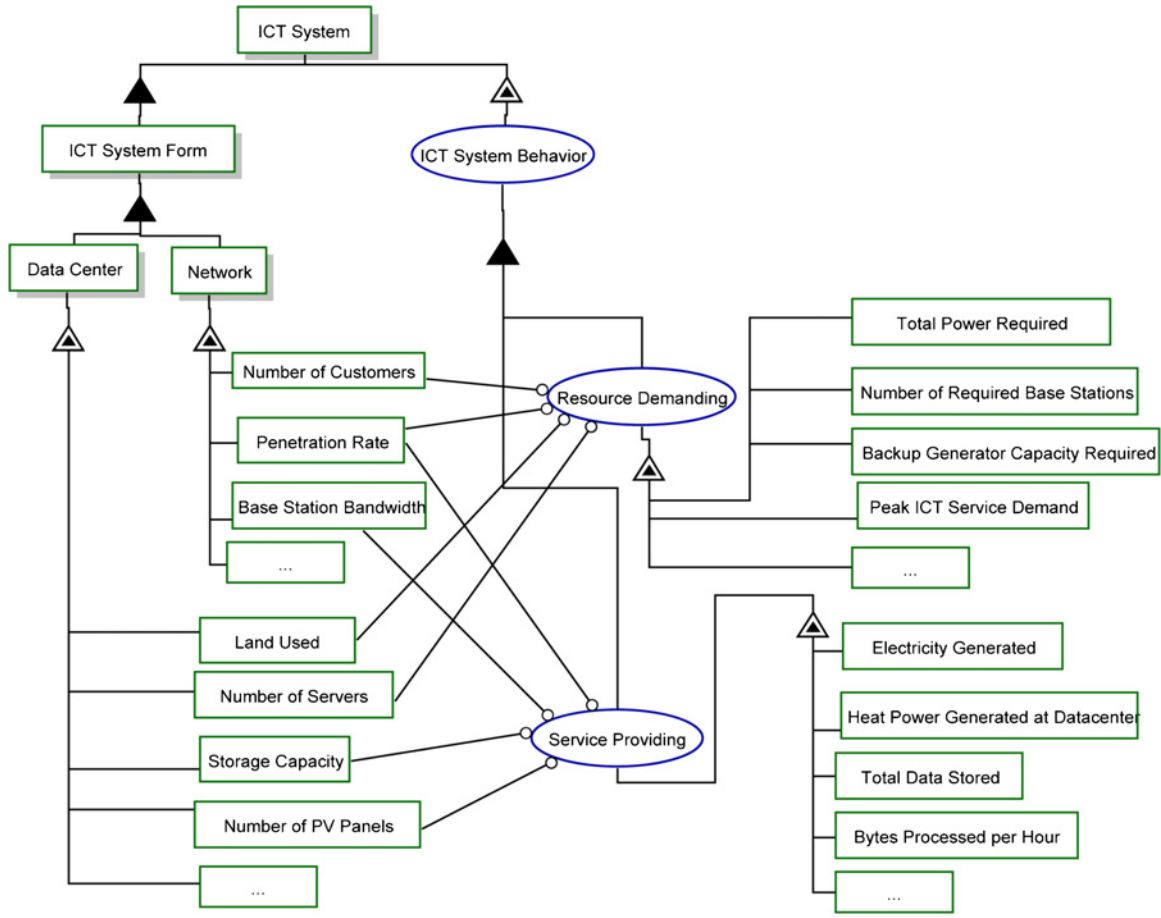$$P_{\text{Gen}} = P_{\text{Gen-Cool}} + P_{\text{Gen-Crit}}. \tag{10}$$

Fig. 1. Decomposition of ICT System.

In addition, the actual energy consumed within the datacenter is dependent on the utilization of the resources (servers, network, storage) available in the datacenter. However, the power utilization of the equipment is not necessarily the same as resource utilization of the same equipment, hence, the current enterprise for energy proportionality in the ICT industry. Fig. 2 shows the utilization of servers, network equipment, and storage devices related to the power consumption [13], [30]. Barroso and Hölzle [18] study energy proportionality of ICT equipment, and show a linear progression between resource utilization and power consumption. As a result, the values for the power consumption in storage and network devices have been linearly extrapolated from the power consumption during the idle states as presented in [30]. The power consumption and utilization graph of a sample server were obtained directly from [13].

$$\text{Utilization } \mu = \frac{\text{Demand}}{\text{Maximum Capacity}} \tag{11}$$

$$E_{\text{ICT}} = 8760 \times (P_S \mu_{P-S} + P_{\text{St}} \mu_{P-\text{St}} + P_{\text{Net}} \mu_{P-\text{Net}}) \tag{12}$$

$$E_{\text{DC-Cool}} = k \times (1.05(E_{\text{ICT}} + E_{\text{non-ICT}}) + E_{\text{UPSloss}} + E_{\text{light}}) \tag{13}$$

$$E_{\text{non-ICT}} = 8760 P_{\text{non-ICT}} \tag{14}$$

$$E_{\text{UPSloss}} = 0.32(E_{\text{ICT}} + E_{\text{non-ICT}}) \tag{15}$$

$$E_{\text{light}} = \mu_{\text{light}} \times 8760 P_{\text{light}}. \tag{16}$$

2) *Network:* The required bandwidth in the network is dependent on the maximum bandwidth, utilization, and availability of each customer during different periods of the day [14]. Network energy consumption is estimated based on the energy consumed in each base station

$$BW_{\text{req}} = Np\mu \times BW_{\text{plan}} \tag{17}$$

$$E_{\text{Network}} = E_{\text{perBS}} \times N_{\text{BS}}. \tag{18}$$

3) *Rooftop PV [29]:* The derivation of the energy generated by the PV panels is temperature dependent. The energy generated from PV panels is calculated based on hourly solar irradiation

$$T_{\text{mod}} = 0.943 T_{\text{amb}} + 28 DNI - 1.528 v_{\text{wind}} + 4.3 \tag{19}$$

$$E = df \times \frac{DNI}{1000} \times A \times N \times \eta \times (1 + \frac{(T_{\text{mod}} - 25) \times \delta_{P/T}}{100}). \tag{20}$$

4) *Rooftop Thermal [22]:* Energy generation for solar thermal cooling depends on the solar radiation and the system efficiency

$$E_{\text{solar}} = \rho \times A \times DNI \tag{21}$$

$$P = E_{\text{solar}} \times COP. \tag{22}$$

5) *Land Use:* The datacenter and the network base stations occupy significant land areas, while the area occupied by the

TABLE I
FORM AND BEHAVIOR PARAMETERS

Method	Form Parameters	Behavior Parameters
ICT Services		
Data Center	Number of each ICT equipment (servers, routers, firewalls, switches, and storage devices) $N_{equipment}$, Power rating of each equipment $P_{equipment}$ (kW), Storage capacity, Network throughput to customers, Internet bandwidth, Number of switches, Capacity of switches, Number of routers, Capacity of routers, Number of servers, Server processor speed, Server storage capacity, Storage demand, Network demand, Processing demand, Power rating of non-ICT devices (excluding lighting and cooling devices) $P_{non-ICT}$ (kW), Power rating for future ICT devices $P_{ICT-future}$ (kW), Datacenter floor area $A(m^2)$, Cooling system type multiplier k,[1] Light utilization factor μ_{light}	Total ICT Power P_ICT (kW), UPS losses and battery capacity $P_{UPSloss}$, Lighting power requirement P_{light}, Expected critical load peak power P_{peak}, Total electrical power requirement P_{elec}, Total power requirement P_{total}, Generator backup for cooling $P_{Gen-Cool}$, Generator back up for critical load $P_{Gen-Crit}$, Backup generator capacity required P_{Gen}, Cooling power capacity $P_{DC-Cool}$ (kW), Resource utilization μ, Production server power utilization μ_{P-S}, Storage power utilization μ_{P-St}, Network power utilization μ_{P-Net}, Total storage power rating P_{P-St}, Total server power rating P_{P-S}, Total network equipment power rating P_{P-Net}, Energy consumed by ICT equipment E_{ICT} (kWh), Energy consumed by non-ICT equipment $E_{non-ICT}$ (kWh), Energy consumed by UPS inefficiency and battery charging $E_{UPSloss}$ (kWh), Energy consumed for lighting E_{light} (kWh).
Network [14]	Penetration rate p, Utilization rate $\mu_{network}$, Subscription plan bandwidth BW_{plan} (Mbps), Number of customers $N_{customers}$, Number of base stations N_{BS}, Energy consumed per base station E_{perBS} (kWh)	Total bandwidth required BW_{req} (Mbps), Energy consumption in network $E_{Network}$ (kWh).
Resource Generation		
Rooftop PV [27], [28], [29]	Overall DC-to-AC derate factor df, PV panel length l (m), PV panel width w (m), PV panel efficiency η, PV panel capacity P_{rated} (kW), Temperature coefficient of rated power $\delta_{P/T}$ (%/^{o}C), Number of PV panels N, Rooftop Area A_{roof} (m^2), Hourly DNI DNI (kWh/m^2), and Hourly wind speeds v (m/s)	PV module temperature T_{module} (^{o}C), and Electricity generated E (kWh).
Rooftop Solar Thermal [22]	Coefficient of Performance COP, Hourly DNI DNI (kWh/m2-a), Collector Efficiency ρ, Cooling Capacity $P_{cooling}$ (kW), Storage tank capacity $P_{storage}$ (kW), Collector area A(m2)	Heat collected per hour $E_{collected}$(kWh/m2), Available cooling power P (kW).
Land Use		
Land Use	Total floor area in datacenter $A(m^2)$, Number of floors in datacenter N_{floors}, Number of base stations N_{BS}, Area of each base station A_{perBS}	Total land occupied by ICT system L_{ICT}.
Costs		
Costs [13]	Datacenter capital expenditure $Capex_{Datacenter}$ ($/W), Server capital expenditure $Capex_{Serv}$ ($/W), Server depreciation δ_{Serv} ($/W), Server annual operating expenditure $Opex_{Serv}$ ($), Datacenter lifetime τ_{DC} (years), Server lifetime τ_{Serv} (years), Datacenter annual operating expenditure $Opex_{DC}$ ($), Power rating of server P_{Serv}, and Number of servers N_{Serv}.	Datacenter depreciation δ_{DC} ($), Total cost of ownership TCO ($/year)

network wires is minimal. As such, the total land use in the model is calculated as

$$L_{\text{ICT}} = \frac{A}{N_{\text{floors}}} + (N_{\text{BS}} \times A_{\text{perBS}}) \qquad (23)$$

6) *Costs [13]:* The datacenter costs are estimated using the Total Cost of Ownership (TCO) method

$$\delta_{\text{DC}} = \frac{\text{Capex}_{\text{DC}} \times P_{\text{peak}}}{\tau_{\text{DC}}} \qquad (24)$$

$$\delta_{\text{Serv}} = \frac{\text{Capex}_{\text{Serv}} \times P_{\text{Serv}} \times N_{\text{Serv}}}{\tau_{\text{Serv}}} \qquad (25)$$

$$\text{TCO} = P_{\text{peak}}(\delta_{\text{DC}} + \text{Opex}_{\text{DC}}) + (NP)_{\text{Serv}}(\delta_{\text{Serv}} + \text{Opex}_{\text{Serv}}). \qquad (26)$$

7) *KPIs:* Kipp *et al.* [31] describe a set of KPIs focused on the energy consumed by ICT infrastructures. These KPIs are termed green performance indicators (GPIs) and are placed in the different categories: ICT resource usage GPIs, application lifecycle GPIs, energy impact GPIs, and organizational GPIs. The application lifecycle GPIs focus on the performance of specific applications on servers. However, these application
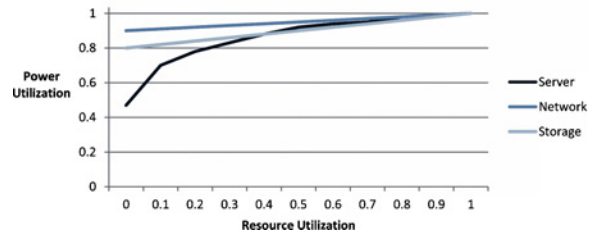
Fig. 2. Matching Power and Resource Utilization.

lifecycle GPIs are not applicable as KPIs in our ICT model due to the high-level orientation of our ICT model. The GPIs which are applicable in our ICT model are as follows.

a) *Power usage effectiveness (PUE) [31]:* This GPI is the most widely used datacenter KPI. It compares the power required for running ICT equipment with the total facility power. The PUE has a minimum value of one that indicates an ideal situation. A typical datacenter has a PUE of about two. The quality of

TABLE II

PUE CLASSIFICATION

PUE	DCiE(s)	Efficiency Classification
3.0	33%	Very Inefficient
2.5	40%	Inefficient
2.0	50%	Average
1.5	60%	Efficient
1.2	83%	Very Efficient

power use in a datacenter is inversely proportional to the PUE

$$\text{PUE} = \frac{\text{Total facility power}}{\text{ICT equipment power}}. \qquad (27)$$

b) *Data Center Infrastructure Efficiency (DCiE)* [31]: This GPI has the same purpose as the PUE. The DCiE is a percentage form of the PUE inverse

$$\text{DCiE} = \frac{\text{ICT equipment power}}{\text{Total facility power}} \times 100\%. \qquad (28)$$

Table II shows the classification for different PUE and DCiE values [32], [33].

c) *Datacenter density (DCD)* [31]: This GPI represents the space efficiency of a datacenter by comparing the total energy consumed in a datacenter with the land space occupied by the datacenter

$$\text{DCD} = \frac{\text{Energy Consumed in Datacenter}}{\text{Total Land Space Occupied}}. \qquad (29)$$

d) *Space, watts, and performance (SWaP)* [31]: This GPI aids the evaluation of a datacenter's performance with respect to the power consumed and the land space occupied

$$\text{SWaP} = \frac{\text{Performance}}{(\text{Space} \times \text{Power Consumption})}. \qquad (30)$$

e) *Deployed hardware utilization efficiency (DH-UE)* [31]: This GPI measures the efficiency of the datacenter server capacity with respect to the service demand

$$\text{DH-UE} = \frac{\text{Peak demand server requirement}}{\text{Number of servers in datacenter}}. \qquad (31)$$

f) *Compute power efficiency (CPE)* [34], [31]: This GPI measures the power efficiency of the datacenter with respect to the server computation.

$$\text{CPE} = \frac{\text{DCiE}}{\text{ICT Equipment Utilization}}. \qquad (32)$$

g) *IT Productivity per embedded watt (IT-PEW)* [31]: This GPI refers to the actual storage, network throughput, or executed processing cycles.

$$\text{IT-PEW} = \frac{\text{IT productivity}}{\text{Total embeddedpower}} \qquad (33)$$

h) *Datacenter energy productivity (DCeP)* [31]: This GPI compares the useful work done by the datacenter with the total energy energy consumed by the datacenter. Useful work done is represented by the number of bytes processed in the datacenter

$$\text{DCeP} = \frac{\text{Total bytes processed}}{\text{Energy consumed by datacenter}}. \qquad (34)$$

i) *CO_2 Emissions:* This GPI represents the carbon footprint of the ICT system. It is obtained by calculating the equivalent CO_2 emissions based on the total energy consumed by the ICT system. Although the average global CO_2 equivalent emissions per kilowatthour is about 500 gCO_2e/kWh, the actual unit emissions per kilowatthour varies by country. For example, the unit emissions per kilowatthour in Australia is about 875 gCO_2e/kWh, while it is approximately nil in Iceland [19], [31]

$$CO_2 \text{ Emissions} = \text{Energy consumed} \times CO_2/\text{kWh}. \qquad (35)$$

j) *MHz per Watt [35], [31]:* This GPI compares the processor performance of servers with the energy consumed by the servers

$$\text{MHz per Watt} = \frac{\text{Processor performance}}{\text{Energy Consumed}}. \qquad (36)$$

k) *Bandwidth per Watt [35], [31]:* This GPI compares the network performance with the energy consumed by the network devices

$$\text{Bandwidth per Watt} = \frac{\text{Total bandwidth utilized}}{\text{Energy Consumed}}. \qquad (37)$$

l) *Capacity per Watt [35], [31]:* This GPI compares the storage performance with the energy consumed by the storage devices

$$\text{Capacity per Watt} = \frac{\text{Storage capacity space}}{\text{Energy Consumed}}. \qquad (38)$$

D. ICT Layers

Since the ICT system provides data storage and network services, it consists of the datacenters and the network infrastructure. As described in [4] and [36], the concept of layers, edges, and nodes is used to classify the ICT system infrastructure components. The ICT layers, nodes, and edges are as follows.

1) Layer 1:

   a) Node: Datacenter.
   b) Edge: Wired WAN (Optical fiber).

2) Layer 2:

   a) Node: Base station.
   b) Edge: Wireless WAN (WiMAX).

V. MASDAR CITY CASE STUDY

This case study analyzes the requirements for implementing a city-scale ICT system in Masdar City and envisions the feasibility of such an infrastructure system. Masdar City is being built to be a sustainable, minimal emissions, and minimal waste community that will depend on renewable energy sources [37]. It is projected to have about 50 000 residents and 60 000 commuters. Based on this projection, the ICT service demand within the city can be estimated. The Masdar City area is geographically divided into the residential and commercial zones. Two scenarios are simulated in order to compare the range of results obtainable from different parameter values.

A. Synthesis

1) *Scenario 1:* Assuming an average of three residents per household results in approximately 16 667 households that require the Internet connections via the city datacenter. The datacenter acts as a central point of connection for the city network, controlling the network traffic and securing the lower layer networks. In order to reduce costs, save energy, and reduce the negative environmental impact, the residents and enterprises in Masdar City should reduce the number of typical home or office computers, and rely on the ICT services provided by specially designed and environmentally friendly datacenters. Since such datacenters are located within the city, potential issues concerning bandwidth or latency are neglected.

In addition, the case study considers 1000 offices in the Masdar City commercial district. This is based on the assumption that half of the commuters and half of the residents work within the city, and each office has an average of 55 employees. These numbers are used in the case study to highlight the flexibility in the ICT model's range of applications.

The end users are connected via the WiMAX network, and as in [14], several base stations are required. These base stations are connected to the datacenter via optical fiber cables. Fig. 3 shows the different functional layers in Masdar City ICT system. This is based on the expectation that the users have the penetration and utilization rates listed in Table III. The variation of the utilization and penetration rates captures the expected network customer dynamics during the course of the day. Typically, each base station should have a bandwidth capacity of 70 Mbps, but due to the high population density and consequently high demand, multiple WiMAX radio cards are mounted on the base stations. In addition, customers have different service packages, and Table IV itemizes the Internet service packages devised for this case study and the corresponding number of subscribers.

Furthermore, the hourly storage and processing demand placed on the datacenter through the course of each day are displayed in Figs. 4 and 5, respectively. The data used for evaluating the system is the load estimated based on the population of the city, the average storage, and computing requirements of each home and office. This includes the variation of the loads with respect to the office hours. The data is only used to show how the ICT model can be used in practice. In order to produce real-world estimations, the actual
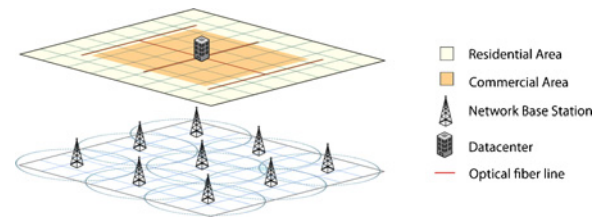

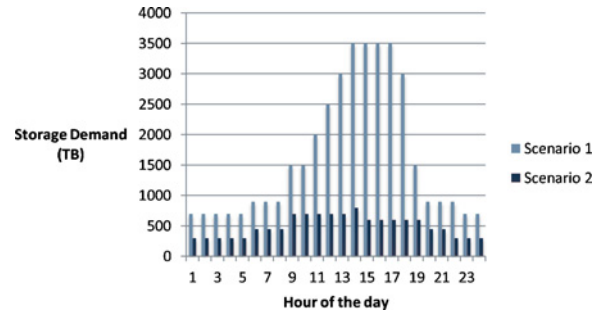Fig. 3. Synthesized Masdar City ICT Infrastructure
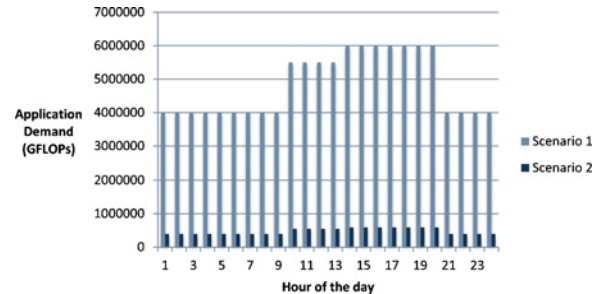

Fig. 4. Daily storage demand.

Fig. 5. Daily processing demand.

demand data collected and obtained from datacenters should be used in the ICT model.

A 500 m^2 datacenter that provides storage, processing, and network services is modeled in this case study. The values of the FPs are listed in Table V. The server used in the datacenter synthesis has 12 processors with a total processor capacity of 25 088 GFLOPs. This estimation is based on the Intel Xeon X5660 2.80GHz processor which has a processor capacity of 194 GFLOPs. This processor capacity was obtained by using the *QwikMark 0.4* tool [38].

Also, 90% of the rooftop area is assumed to be useful for PV panels and solar thermal collectors. This available rooftop area is equally allotted for electricity generation via PV panels and feeding the datacenter cooling demand via the solar thermal collectors.

2) *Scenario 2:* The second simulation scenario has a lower demand and fewer ICT facilities than Scenario 1. The expected network customers are shown in Table IV and with the same network customer dynamics as in Table III. In addition, the storage and processing service loads are shown in Figs. 4 and 5, respectively. The FP values are shown in Table V. These facilities comprise a 200 m^2 datacenter and nine base stations for the wireless network. However, the base stations have a lower average capacity than in the Scenario 1.

TABLE III
HOURLY UTILIZATION AND PENETRATION RATES
FOR NETWORK DEMAND

Hour	Residential		Commercial	
	Utilization Rate	Penetration Rate	Utilization Rate	Penetration Rate
1	10 %	10 %	10 %	5 %
2	10 %	10 %	10 %	5 %
3	10 %	10 %	10 %	5 %
4	10 %	10 %	10 %	5 %
5	10 %	10 %	10 %	5 %
6	10 %	10 %	10 %	5 %
7	20 %	10 %	10 %	5 %
8	20 %	15 %	20 %	10 %
9	20 %	15 %	20 %	20 %
10	20 %	20 %	30 %	20 %
11	30 %	20 %	30 %	30 %
12	30 %	20 %	50 %	50 %
13	30 %	20 %	50 %	50 %
14	30 %	20 %	60 %	60 %
15	30 %	20 %	60 %	60 %
16	30 %	20 %	50 %	45 %
17	30 %	20 %	50 %	45 %
18	30 %	20 %	30 %	30 %
19	20 %	20 %	20 %	20 %
20	20 %	20 %	10 %	10 %
21	20 %	15 %	10 %	5 %
22	10 %	15 %	10 %	5 %
23	10 %	10 %	10 %	5 %
24	10 %	10 %	10 %	5 %

TABLE IV
NETWORK SERVICE SUBSCRIPTION DETAILS

Customer Type	Bandwidth	Price (monthly)	No. of Customers	
			Scenario 1	Scenario 2
Residential	5 Mbps	20$	10,300	3,000
Residential	10 Mbps	35$	6,367	1,000
Commercial	25 Mbps	70$	900	300
Commercial	50 Mbps	120$	100	30

B. Simulation Results

The BPs and KPIs obtained from simulating the two scenarios are shown in Table VI. As expected, the ICT system in Scenario 1 has an ICT energy consumption of 5.35 GWh/year, and the ICT system in Scenario 2 has an ICT energy consumption of 1.76 GWh/year. In both cases, the energy generated from the PV panels and solar thermal collectors comprise a small fraction of the energy requirement of the datacenter. As a result, a larger PV or solar thermal installation would be required in order to produce a significant reduction in the datacenter's dependence on the power grid.

In Scenario 1, the server, storage, and network utilization percentages show that the system resources are not being used to the maximum level. This implies that the ICT system in Scenario 1 could handle a growth in demand. However, the utilization percentages in Scenario 2 show that the ICT system is being used to its maximum capability. Based on the hourly demand-capacity variations in Scenario 2, there were periods

TABLE V
CASE STUDY FPS

Parameter	Scenario 1	Scenario 2
Datacenter FPs		
Number of production and development servers	800	300
Total storage capacity	5000 TB	1000TB
Number of network servers	30	5
Number of external circuits	30	8
Number of firewalls	10	2
Total Internet bandwidth	50,000 Mbps	5,000 Mbps
Number of switches	15	4
Power rating of server	0.4 kW	
Power rating of switch	0.2 kW	
Power rating of router	0.25 kW	
Power rating of firewall	0.03 kW	
Power rating of non-ICT equipment	5 kW	2 kW
Total datacenter floor area	500 m^2	200 m^2
Server FLOPs	25,088 GFLOPs	
Datacenter Capex	10 $/W	15 $/W
Number of years of datacenter depreciation	13 years	
Server Capex	8 $/W	
Number of years of server depreciation	4 years	
Annual Datacenter Opex	0.6 $/W	
Server Opex Percentage	5 %	
Number of routers	10	3
Cooling system type factor	0.7	
Light Utilization Factor	75 %	50 %
Number of floors	1	
Building Height	12 m	
Storage power rating	0.0005 kW/GB	
Emissions per kWh	0.5 kg	
Cost of electricity	0.05 $/kWh	
Solar Thermal Collector FPs		
Absorption chiller COP	1.7	
Thermal collector efficiency	20 %	
Chiller capacity	20 kW	10 kW
Storage tank capacity	10 kW	5 kW
Thermal collector area	200 m^2	100 m^2
PV FPs		
Number of PV panels	128	64
PV Panel Width	1.956 m	
PV Panel Length	0.992 m	
PV Panel Efficiency	14.14 %	
PV Temperature Coefficient of Pmax	-0.44 %/K	
PV Derate Factor	0.83	
Network FPs		
Number of base stations	9	
Number of sectors per base station	8	2
Bandwidth per sector	70 Mbps	
Power per sector	2.3 kW	
Base Station Area	10 m^2	

during which the storage and the Internet facilities were not able to meet the demand. This implies that the storage and the Internet facilities need to be upgraded in Scenario 2.

The efficiencies of both scenarios are similar, with Scenario 1 having a PUE of 2.42 and Scenario 2 having a PUE of 2.43. However, it is important to note that these PUE values

TABLE VI
CASE STUDY BPs AND KPIs

Parameter	Scenario 1	Scenario 2
BPs		
Rooftop Thermal Energy Generation	136.76 kWh	68.38
PV Energy Generation	52,538.47 kWh	26,269.24 kWh
Network Land Use	90 m^2	90 m^2
Total Land Use	590 m^2	290 m^2
Total Production Server Power	320 kW	120 kW
Total Network Server Power	12 kW	2 kW
Total Switch Power	3 kW	0.8 kW
Total Router Power	2.5 kW	0.75 kW
Total Firewall Power	0.3 kW	0.06 kW
Total Storage Power	2.5 kW	0.5 kW
Total ICT Power	340.3 kW	124.1 kW
Server Opex	0.4 $/W	0.4 $/W
TCO	1.52 X 10^7 $/year	6.24 X 10^6 $/year
UPS losses	110.50 kW	40.36 kW
Critical Load Peak	362.57 kW	132.42 kW
Lighting Power	10.75 kW	4.3 kW
Cooling Capacity	338.67 kW	123.95 kW
Total Electrical Power	483.81 kW	177.07 kW
Total Facility Power	822.48 kW	301.02 kW
Generator Cooling	440.26 kW	161.13 kW
Generator Critical	725.72 kW	265.61 kW
Generator Total	1,165.99 kW	426.74 kW
Max Server Utilization	29.89 %	79.72 %
Min Server Utilization	19.93 %	53.15 %
Server Annual Energy Use	1.32 GWh	0.49 GWh
Max Storage Utilization	70 %	100 %
Min Storage Utilization	14 %	70 %
Storage Annual Energy Usage	17,520 kWh	3,504 kWh
Max Internet Utilization	33.62 %	100 %
Min Internet Utilization	2.58 %	25.78 %
Datacenter Network Annual Energy Use	95,133.60 kWh	20,927.64 kWh
Total ICT Equipment Energy Use	1.43 GWh	0.52 GWh
UPS Energy Losses	471,666.4 kWh	171,525.0 kWh
Light Energy Use	70,627.5 kWh	18,834.0 kWh
Cooling Energy Use	1.99 GWh	0.71 GWh
Final Thermal Load	1.98 GWh	0.71 GWh
Electrical Energy Use	1.97 GWh	0.71 GWh
Datacenter Energy Use	3.90 GWh	1.40
Energy Use per Base Station	0.16 GWh	0.04 GWh
Network Energy Use	1.45 GWh	0.36 GWh
Total ICT Energy Use	5.35 GWh	1.76 GWh
KPIs		
DCD	7,797.25 kWh/m^2	6,986.73 kWh/m^2
DH-UE	0.30	0.80
PUE	2.42	2.43
DCiE	41.37 %	41.23 %
CPE	1.72	0.64
CO_2 Emissions	2,674.64 Tonnes	880.00 Tonnes

represent the worst-case PUE values (as long as chillers are used) since the PUE values can be improved with datacenter modifications [39] such as energy efficient lighting, deep raised floors, economical UPS operations, optimal rack layout, and optimal tile placement. Furthermore, the datacenter in Scenario 1 has a higher CPE which means it has a better

efficiency-utilization performance. However, the DCD of the datacenter in Scenario 2 is slightly better than that in Scenario 1, i.e., the Scenario 2 datacenter uses its space more effectively.

Based on the results shown in Table VI, the performance improvement recommendations are as follows.

1) The datacenter in Scenario 1 is underused and as a result, there is no need for making expansion plans until there is a significant growth in the city. This recommendation is drawn from its low DH-UE value. However, this datacenter should endeavor to use its land space more effectively.

2) The datacenter in Scenario 2 needs to invest in more ICT equipment in order to meet the city's ICT demand and provide better service to the customers. This recommendation is drawn from the 100% storage and network utilization, and the CPE value.

3) In both scenarios, a larger PV station (or some other source of renewable energy) would be required in order to significantly reduce the carbon footprint of the ICT infrastructure.

VI. DISCUSSION

Modeling the ICT system without focusing on microprocesses, such as applications on each server and single network transactions, poses a challenge of adequately representing the behavior of the ICT system. However, the ICT model presented in this paper does not focus on microprocesses since the ICT model only aims to estimate the ICT system behavior and ICT-related interdependencies at the level of the city infrastructure. The ideas and concepts applied in the ICT model have been obtained from industrial and academic standards that represent datacenters, networks, and service provision.

While city communication networks are not typically controlled by a single provider as depicted in the ICT model, the model is still useful for planning and forecasting purposes. Moreover, there is a trend leading toward sustainable cities with integrated datacenters, and unified wired and wireless networks, thus making the presented ICT model potentially even more useful and applicable.

The structure of parameters presented in this paper contributes to the usability of the ICT model. The presented ICT model uses hourly variations during the day to represent the demands placed on the ICT system. Accessibility to specific user data such as the Internet bandwidth requirements, server GFLOPs requirements, storage requirements in ICT infrastructure, and the relation of these requirements to population density would improve the precision of the model. However, this specific user data is often not available at the modeling stages, and often changes even after the infrastructure system deployment.

In summary, the main contributions of this paper are as follows:

1) a hierarchical decomposition of an ICT system in order to identify the structural and behavioral parameters which adequately represent the structure and behavior of a typical city-level ICT system;

2) an ICT model comprising industry standard equations, relations, and KPIs, that can be used to forecast a planned ICT system or evaluate an existing ICT system;

3) a case study implementation of the ICT model using fiber optic, mobile WiMAX, datacenter, and renewable energy technologies; and a simulation consisting of two different scenarios, demonstrating how the ICT model could contribute to the ICT system planning process of a sustainable city.

For the future versions of the model and similar developments, additional parameters could be included in order to make the model more comprehensive. Moreover, additional systems such as sensor networks which monitor weather or surveillance cameras could be introduced. Also, in order to be fully generalizable and applied in systems engineering, the ICT model has to be integrated with the models of the other city systems, such as energy, waste management, water management, etc. The integrated tool and model support would allow us to generate a large number of possible models. However, we would need to develop a systematic process for reasoning and using these models for engineering the respective systems in the future. This is a part of our future work focused on model integration within our strategic requirements engineering method [40].

VII. CONCLUSION

This paper presented a sustainable city ICT model systematically developed using a functional and spatial modeling framework. The ICT model comprises datacenter and network facilities as the two major parts of the system. This paper focused on the ability of these facilities to meet certain user-defined demands, therefore showing the capabilities of the developed ICT model. The parameters and parameter equations have been obtained from academic and industrial sources in order to ensure the relevance of the model. A case study consisting of two different scenarios was employed to show how the ICT model works and how it can be used in sustainable city planning.

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