Energy Semantic Network for Building Energy Management

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Abstract This paper proposes an engineering design framework and methodology for building an energy semantic network (ESN) which helps to create and evaluate possible scenarios of energy system structure of buildings (energy generation, conversion, and conservation measures). The developed ESN does not only focus on building thermal performance (i.e. insulation materials, geometry, and dynamic behavior of building occupants) but also integrates energy resources, Hybrid Energy Supply Unit, and source-load interconnection. In other words, the developed ESN supports the design and evaluation of micro energy grid for building with various options of energy generation and conversion. Parameters identification of building energy system and their range is an important step to successfully develop energy optimization within buildings. The developed ESN generates the possible scenarios of energy generation and conversion for evaluation and optimization purposes. The structure of the ESN provides heterogeneous presentation of the classes with flexible architecture to modify, add, or delete significant energy classes. In addition, the ESN structure is designed to avoid non-realistic computational burden during simulations and evaluation. The methodology of generating the minimal possible scenarios is introduced. For validation purposes, the proposed algorithm is examined using case study of a mid-size house with different energy sources and thermal zones. The ESN of this case study is discussed, the possible scenarios of energy generation, conversion and load type are produced and their simulation and

evaluation using five key performance indicators (KPIs) are introduced.

Keywords Semantic network · Building energy conservation · Micro energy grid · Key performance factors

Abbreviations

CHP	Combined heat and power
ESN	Energy semantic network
HENSU	Hybrid Energy Supply Unit
KPI	Key performance factor
MEG	Micro energy grid
PV	Process variables
PVC	Photovoltaic cell
WT	Wind turbine

Introduction

Building energy conservation is an active research area that guides energy engineers to design buildings and modify their structure energy wise [1]. Extensive use of energy in buildings sector that consume 41.1% of different energy resources and 74 % of the generated electricity [2], is one of the important factors that guide energy conservation research. Moreover, regulations that are issued by the national authorities and international communities [3,4] creates strict guidelines for engineers and planners to actively apply design and optimization tools to reduce building energy consumption. Major activities have been recoded to apply energy conservation measures in building to reduce the consumed energy for heating [5,6] as a result of availability of simulation tools such as EnergyPlus that facilitate heat

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energy simulation in the buildings. In [5] the authors proposed three measures to reduce heat and electricity demand: (1) attic insulation, (2) heat load control, and (3) electricity saving by using modern appliance. In [6] the authors compared two cases, typical dwelling and high performance dwelling using the best technology available. Both works of [5] and [6] are focused on one scenario without investigating the interaction between different energy conservation parameters in multiple scenarios.

While EnergyPlus models heating, cooling, lighting, ventilation, other energy flows, and water-use by exchange building information using spreadsheet, BEopt [7] provides user friendly graphical interface that can specify the building characteristic in graphical method. Both are simulation tools of energy conservation scenarios and they are beneficial to apply efficient use of energy. BEopt has the ability to optimize building design based on multiple objectives. However those software have no knowledgebase with inference mechanism to replace or add design parameters the software designer didn't include. Modern societies have complex building structures with vast varieties of applications. Accordingly, energy requirements and analysis of buildings get more complicated. Hence, the design of efficient energy systems that satisfies energy requirements of buildings with minimal faults, requires accumulated knowledge of the building energy expertise and validation check of all possible scenarios of energy system structure for buildings (energy generation, conversion, and conservation measures, (herein after called energy design scenarios)). Both EnergyPlus and BEopt do not have the ability to evaluate energy generation and conversion scenarios (renewables, converters and inverters). OpenStudio [8] is a cross-platform for multiple software tools that allow evaluation of different energy scenarios including renewables. It facilitate building energy modeling for evaluation.

Building energy forecasting models is the most active area of research that covers different types of models (physics-based, data-driven and combined models) [2]. Additional efforts to define performance parameters and establish performance indicators [1,9] facilitate the evaluation of energy scenarios of buildings. However, few activities were dedicated to the development of energy knowledgebase using semantic networks.

Energy semantic network (ESN) for buildings is a methodology to design efficient building energy wise. An early structure ESN was presented in [10] where ESN provides an energy knowledge domain with rule-based reasoning to support decisions related to energy system design and operation. A dynamic knowledge structure ESN was used for energy production chain assessment.

The ESN encodes the knowledge of wide spectrum expertise to be available for the energy designer. For complex buildings with complicated energy demands, the energy con-

servation measures, sources and loads design parameters are a challenge to identify. In [11], the author developed building thermal performance ESN that study the effect of insulation materials, dimensions, loads, and schedules of people interactions on selected KPIs. The effort in their work was to evaluate different Heat energy conservation technologies with respect to the dynamical thermal changes, and track the dominant sinks resulting from these changes. Other approaches to reduce cost and emission is to integrate MEG within the building itself or among its facilities. The term net-zero or zero energy building is used to identify the effort of research toward less total consumption of utility energy network [12,13].

Any designing process of energy efficient envelope for buildings go through three main steps:

- (1) Foundation of an energy knowledgebase for building classes allowing the generation of the design parameters according to its relation to building type.
- (2) Develop evaluation process for different scenarios presented by the design parameters generated by (1).
- (3) Optimize the design according to predefined evaluation parameters.

The aim of this work is focus in the 1st step by building a general ESN to generate all possible energy design scenarios. The scenarios are not limited to thermal insulation technologies of building envelop, but includes energy generation and conversion technologies as well. Hence, the resources of the building under consideration can be deployed in building MEG. Unlike BEopt that optimizes design parameters that have been identified by the designer, the proposed methodology provide a way for systematic identification of design parameter of building energy components that have significant effect of energy production and consumption. The ESN structure is an essential of having an efficient semantic knowledgebase. It should be open, dynamic and minimal [14]. Open means, its structure allows the incorporation of new components. Dynamic means its ability to include new properties of existing components. Minimal is to reduce the computational burden during simulation and evaluation processes. ESN, aggregates metadata (structural and descriptive) and data (profile, measured, and statistical) regarding both thermal technologies of building envelope materials and the energy sources technologies, arranges them in knowledge layers. Inference mechanism is used to extract decisions and conclusions by navigating through knowledge layers based on requirement.

The rest of the paper is organized as follows: the next section identifies the problem formulation and objectives, ESN structure and scenario generation are discussed in "Building Energy Semantic Network Structure" section, ESN design consideration is discussed in "ESN Design Consideration"

Fig. 1 Mapping problem domain to the design domain

section. “Case Study” section discusses case study and the implementation of ESN, “Results and Analysis” section shows the results and analysis of the case study using energy design scenarios generated by the ESN, and the final section concludes the paper and some recommendations are made for future work.

Problem Formulation and ESN Objectives

As stated in the introduction section, previous energy conservation activities were focused on studying limited scenarios with no guide to form or generate other possible scenarios. This is because there is a lack of significant tools to produce all possible scenarios for energy evaluation. In [5,6,11] an evaluation of one scenario, according to implicational knowledge of the authors, has been conducted. The authors highlighted the significance of applying thermal insulation on buildings to reduce energy consumption. However, deep investigation of different energy design scenarios have not been demonstrated. This is due to two facts, (1) the absence of a tool to generate possible scenarios of exciting energy technologies and (2) the lack of information about other alternative energy technologies.

An energy semantic network is a knowledgebase network that describes the relation of different energy classes. It classifies buildings into energy types, thermal zones, possible energy supplies and energy requirements of the buildings. The semantic connection between energy classes of the building represent possible energy design scenarios. It can be

considered as a mapping tool between problem domain that describes building requirements and capabilities and design domain that describes possible energy design scenarios as shown in Fig. 1.

The inputs to the ESN are the building type, size, facilities, requirements, number of occupants and activities. The output of the ESN is the possible scenarios of energy system structure and energy conservation measures that can be implemented. ESN is a mapping hypersurface that is formed by knowledge of expertise, governmental, environmental, customer and stockholder constrains, as well as data about available energy technology (generation and conservation). With the dynamic and flexible structure ESN, it is possible to dynamically encode expertise knowledge, update constrains and rules, inject modern energy technology information into its knowledgebase. Hence, more alternative energy design scenarios can be generated and effective energy design can be achieved. The advantage of presenting building energy as semantic network is the ability for any new energy instance or class to share ESN knowledge and its inter structure once it is connected. This is because connection procedures of any new instance requires identifying its relation to one existing class only.

To achieve such effective ESN, its structure should satisfy the following objectives:

1. Building ESN should be dynamic: the semantic net is able to modify, add or delete energy classes, rules.
2. ESN classes should include energy loads, generators/source, energy conversion, and thermal zones.

3. Identify the Process Variables (PV) of each class (Static and dynamic variables).
4. Develop methodology for generating scenarios according to the following:
 - (a) The methodology generates all possible scenarios.
 - (b) The methodology allows implementation of different constraints implied by the designer (governmental, environmental, customer, or stakeholder constraints).
 - (c) The generated scenarios should be feasible.
 - (d) The scenarios should be finite.

The following section introduces the structure of the proposed building ESN, the dynamic learning mechanism of ESN and the propagation mechanism of design parameter selection through its structure and generation of energy design scenarios.

Building Energy Semantic Network Structure

The ESN is a hybrid semantic network used to encode knowledge of building energy. Three types of semantic networks

are used in hybrid model arranged in layers. In the top layer definitional semantic network is used to relate subclasses to general classes of buildings. At this layer, activity frame is used to characterize classes of building (residential, industrial ... etc.). The deeper the network, the more the network merge from definitional to conceptual structures. At the conceptual layer, the characters and structure of the building is clear, hence, its thermal zones and building facilities that can be used for energy sources deployment are described. Classes at this layer are associated with structure frames and action procedures that have potential to act as energy scenario. At this layer, implicational networks are used to develop conclusions about the procedures to be taken for energy conservation (size, organization of energy zones and insulation), renewable (size of renewables) and other possible sources deployment. At all layers, a learning procedure is added to allow expanding the knowledge of ESN. Figure 2 shows illustration of proposed ESN structure.

The structure of the ESN should provoke split portion of the semantic net that is only related to the design problem. To achieve this objective, a hierarchical design of ESN should be adopted. As stated before, at the top layer definitional semantic is used to relate building classes and source classes to

Fig. 2 illustration of ESN. Rounded shapes represent classes, *triangle shapes* represent characteristics of the class (in definitional classes) and *rectangular shapes* represent design parameters of that class that are used to generate energy scenarios

Fig. 3 Simplified ESN

subclasses. In the conceptual/implicational network layer, each class is presented by a class frame. The frame structure allows the presentation for multi-dimensional knowledge. A knowledge frame contains energy characters of the building class, action procedures for energy conservation and generation, and learning procedures to add knowledge once it is available.

The tree structure of ESN is adopted wherever it is possible. This structure allows minimum fired (active) classes. The child nodes, located at the root layer, is connected to parent nodes, at the top layer, with kind-of links. Another connection that describes the relation between classes in the conceptual layers uses Has-a/Supply-a links. Hence, a tree (common case) and inverted tree (common effect) are the main structure of the ESN. However, at deep layers of ESN, some classes are shared by multiple parental classes in a graph connection fashion.

ESN is presented by connection matrices. Each matrix represents the connection between the higher layer class and the successor sub-class. Using the indices system shown in Fig. 3, a general connection matrix is given by the equation:

$$C^i = \begin{bmatrix} c_{1,1}^i & \cdots & c_{1,J_{i-1}}^i \\ \vdots & c_{j,k}^i & \vdots \\ c_{J_{i-1},1}^i & \cdots & c_{J_{i-1},J_{i-1}}^i \end{bmatrix}_{J_{i-1} \times J_i} \quad (1)$$

where the dimension of C^i is $J_{i-1} \times J_i$, J_{i-1} and J_i are the number of classes defined in the predecessor and successor

layers respectively, i is the index of the successor class layer, and $c_{j,k}^i$ is the connection element. The knowledgebase of ESN is a group of connection matrices (presented by equation (1)) that links between knowledge layers. The knowledgebase of ESN can be easily modified by adding, deleting and/or updating knowledge layers, classes and associated parameters of each class applying flowchart shown in Fig. 4. The modification of developed ESN does not require a complete reconstruction of ESN. The ESN structure allow dynamic change of its knowledgebase whenever it is required. Energy expertise encode their knowledge in the connection matrices according to the building energy case of interest. The more new cases have been encoded in the knowledgebase, the more the knowledgebase expands. A well-developed ESN represents knowledge pool of energy expertise that can be used effectively by unexperienced persons. The following algorithm is used to form the ESN using the matrix presentation.

- (1) The connection element $c_{j,k}^i$ has one of the three values, 0, 1 or p_j^i where p_j^i represent the design parameters of class CC_j^i .
- (2) The parameters p_j^i are repeated in single row if a child in successor layer is connected to multiple parents in one predecessor layer (all connected classes at layer $i - 1$ to class j at layer i are affected by the parameters of CC_j^i) (see illustration 1-a in Appendix).
- (3) If the parameter set p_j^i of class j at layer i has parameters of independent effect to the connected classes at layer $i - 1$, new columns are inserted on the i th connection matrix and the class j is split to multiple subclasses with independent parameters. Accordingly, each split subclass will have one connected parent at layer $i - 1$ (see illustration 1-b in Appendix). Other alternative, is to add a complete replicate of layer i at layer $i + 1$ and replace class j with multiple subclasses with independent parameters at layer $i + 1$. In this case, all successor layers will be shifted by one and new connection matrix will be created (see illustration 1-c in Appendix).
- (4) The full presentation of the matrix elements indicates the connection of all the classes in predecessor layer with the sub-classes in the successor layer.
- (5) The elements replaced by 0 indicate no connection between classes.
- (6) The elements replaced by 1 indicate the class is related to the predecessor class however, it has no design parameters (descriptive only).
- (7) There is no direct connection between two non-adjacent classes.
- (8) If a connection between two non-adjacent classes is required, an additional replicate of the parent class is inserted within the intermediate classes with a connec-

Fig. 4 Flowchart to modify and process ESN knowledgebase

tion arrow and element value of 1 indicating no design parameters.

- (9) Multiplication operation between matrix elements replaced by AND operation ($\wedge$) and the addition replaced by OR operation ($\vee$).

During the learning process, an insertion of new class in layer i requires insertion of a column in connection matrix C^i and a row in connection matrix C^{i+1} . The input to the knowledgebase ESN is presented by selection vector with length J_i matching the number of classes at this layer. As the designer propagate through class layers of the network a new selection vector is generated. The selection vectors are binary vectors that present mapping relation from predecessor class to the successor class or object.

The selection vector is in the form

$$S^{iT} = [s_1^i \ s_2^i \ \cdots \ s_j^i \ \cdots \ s_{J_i}^i] \quad (2)$$

where s_j^i has the value 0 if the class at layer i is not selected or 1 if it is selected. The propagation vector is a vector that propagates selection vectors through different layers from

top of ESN to its bottom. The propagation vectors insure the propagation of selection vectors to provoke the portion of the semantic net that is only related to design problem and cancel out all unrelated classes and their associated parameters. The propagation vector is created using the following formula:

$$G^i = \text{sign} \left(C^i (\text{diag}(G^{i-1})) S^{i-1T} \right) \quad (3)$$

where

$$G^i = [g_1^i \ g_2^i \ \cdots \ g_k^i \ \cdots \ g_{J_i}^i]^T, \quad (4)$$

$$\text{diag}(G^i) = \begin{bmatrix} g_1^i & & 0 \\ & \ddots & \\ 0 & & g_{J_i}^i \end{bmatrix}_{J_i \times J_i} \quad (5)$$

and

$$\text{sign}(x) = \begin{cases} 0, & x \leq 0 \\ 1, & x > 0 \end{cases} \quad (6)$$

Let SC be a scenario set of all possible combinations of parameters' values presented at all ESN layers, $SC(k)$ is the

scenario set for k parameters where $k \in \{1, 2, \dots, \sum_{i=1}^I J_i\}$, $N(k)$ is the number of scenarios at the scenario set $SC(k)$, $SC(0) = 1$ and $N(0) = 1$. In addition, assume that, for layer i , the parameters $p_1^i, \dots, p_j^i, \dots, p_{N_j^i}^i$ have $N_1^i, \dots, N_j^i, \dots, N_{N_j^i}^i$ values respectively and the values of the parameter P_j^i is defined by the set $\left\{V_1^{p_j^i}, V_2^{p_j^i}, \dots, V_{N_j^i}^{p_j^i}\right\}$, then $SC(k)$:

$$SC(k)^T = [SC_1 \ \dots \ SC_l \ \dots \ SC_{N(k)}] \quad (7)$$

structure and processing are systematic; hence, easy development of ESN and associated scenario generation can be achieved by most common software. In addition, matrix presentation allow importing and exporting data and scenarios using spreadsheets and sharing those data with other supporting software such as EnergyPlus. Moreover, the clear presentation of classes' relations using connection matrices provides easy modification of ESN by adding, deleting or upgrading presented classes without complete destruction or reconstruction of ESN.

$$SC(k) = \begin{cases} \begin{bmatrix} [SC(k-1)]_{1 \times N(k-1)} \\ \vdots \\ [SC(k-1)]_{1 \times N(k-1)} \end{bmatrix}_{1 \times N_j^i} \wedge \begin{bmatrix} \begin{bmatrix} p_j^i(V_1^{p_j^i}) \\ \vdots \\ p_j^i(V_1^{p_j^i}) \end{bmatrix}_{1 \times N(k-1)} \\ \vdots \\ \begin{bmatrix} p_j^i(V_{N_j^i}^{p_j^i}) \\ \vdots \\ p_j^i(V_{N_j^i}^{p_j^i}) \end{bmatrix}_{1 \times N(k-1)} \end{bmatrix}_{1 \times N_j^i} & , \ N(k) = N(k-1) \times N_j^i \quad \text{if } s_j^i \wedge g_j^i = 1 \\ SC(k-1), & N(k) = N(k-1) \quad \text{if } s_j^i \wedge g_j^i = 0 \end{cases}$$

$$\forall k \in \left\{1, 2, \dots, \sum_{i=1}^I J_i\right\} \quad (8)$$

where $p_j^i(V_{N_j^i}^{p_j^i})$ is one of AND connected terms in the scenario argument represent the premise (if p_j^i is $V_{N_j^i}^{p_j^i}$). The total scenarios of ESN after processing all layers is $SC = SC(k)|_{k=\sum_{i=1}^I J_i}$. Illustration 2 in Appendix shows mathematical process implementation to the case study.

A set of restriction rules can be applied to the created scenarios at each ESN layer to represent governmental, environmental, customer, or stakeholder regulations, design consideration or system feasibility. Each scenario does not comply with restriction rules is eliminated from scenario set according to the following equation:

$$\forall (l \in \{1 : N(k)\}) \left\{ \overline{Res(SC_l)} \xrightarrow{Imply} (SC_l = null), (N(k) = N(k) - 1) \right\} \quad (9)$$

where $Res(x)$ is the restriction rule applied to the argument x . As can be seen from the proposed ESN that its

ESN Design Consideration

It is common that the number of the rules associated with semantic network grows exponentially with the number of classes, properties and attributes. The rule-base of the ESN could be complicated enough to have countless possible scenarios. The objective during the generation of the scenarios is to reduce them to the minimum possible number to avoid complexity during the building energy simulations and evaluations. The best approach is to consider multilayer rule-base, from large scale layer to small scale layer. The large scale layer handles the parent classes that describe the aggregate building energy requirements and sources. At this layer the rules consider global energy requirement and classification (Heat, electrical and gas). On the other hand, the small scale layer consider the selection of energy sources, their deployment within building facilities, thermal zones, the energy transformation and the connection of energy sources to different types of loads within the building (Heat, electrical and gas). Implementing distributed layer structure of ESN allows restriction rules at each layer instead of applying it to the global scenario of ESN. Hence, early reduction of generated scenarios at top layers of ESN reduce the complexity and size of generated scenarios. In addition, the breakdown

of building energy knowledgebase to multilayer gives better visualization of classes' parameters that can contribute to the generated scenarios and the possible restriction rules that can be applied to reduce them.

Case Study

The objective of the case study is to demonstrate implementation of ESN and highlight the expected outcomes. As the proposed ESN is generic; the building structure and hence, associated profiles of heat demand, electricity demand, and energy sources can be easily adjusted according to the case under study without effecting the validity of the methodology. A simplified structure, rectangular Prism, residential house, located in Toronto area, is used as a case study for ESN development. The house is a three stories with dimensions $10 \times 7 \times 9 \text{ m}^3$. Its total area is 200 m^2 and envelop area is 376 m^2 .

An islanded MEG composed of micro-CHP gas generator, wind turbine, and Photo Voltaic (PV) panel is used as energy supply to the house. The micro-CHP represent reliable energy source, to insure stability of energy supply, while wind turbine and PV are used as renewables. The loads are classified as heat, gas, electrical DC and AC. HENSU represents all energy conversion options (gas to heat, power to heat, AC/DC converter and DC/AC inverter). Presence of different energy supplies, energy conversion options and load types options (AC or DC) allow generation of more possible energy scenarios that can embed optimal solution.

The house model has two facility areas (roof and backyard area). It assumes 400 m^2 for backyard and 200 m^2 for roof.

The average load on Ontario for 200 m^2 house is 156 G Jules per year. Hence the average required power supply would be 4.95 kW. Energy consumption among different types of loads is shown in Table 1.

The house is divided into two thermal zones (core and perimeter) which can save up to 70 % of heat energy [16]. Perimeter zone is set at a low temperature (5°C), while core zone is set at a comfortable living temperature (21°C). Two scenarios are assumed for thermal zones. Scenario (1) Core zone at 2nd floor with area of 12 m^2 , envelop area of 12 m^2 and perimeter envelop of 364 m^2 . The interface area between the two zones is 54 m^2 . Scenario (2) Core zone at 2nd floor with area of 24 m^2 , envelop area of 30 m^2 and perimeter envelop of 376 m^2 . The interface area between the two zones is 72 m^2 . The thermal zones configuration and average thermal resistance of the walls are given in Table 2. A simulation is conducted, using Energy Plus, to generate two scenarios heat load profile.

Both simplified house structure and average thermal resistance of the walls are used to simplify the creation of heat demand profile of the house using EnergyPlus. The annual integration of this profile is matching the real data of med-size house in Ontario, Canada provided by Canada Statistics and shown in Table 1. The irradiance and wind speed profiles have been achieved using weather data given by University of Toronto, Department of Geography [17]. Hence, generated heat profile of case study is as close as possible to real case. The cooling load (air condition) is included in electrical baseboards presented by its annual average value in Table 1 and its profile is shown in Fig. 7a.

Figure 5 shows MEG used for the case study based on the previous data. The energy supply is conducted by four energy distribution systems, AC 120V 60Hz, DC 12V, gas and heat.

Table 1 The load consumption of med-size house in Toronto area. [15]

	Thermal (81 %)		Gas (7 %)		Electrical (12 %)	
Load type	Furnace	Boiler	Stove	Electric baseboards	Electric radiant heating	Others
Load %	81	5	2	7	4	1
Load consumption in G Jules/year	126.36	7.8	3.12	10.92	6.24	1.57

Table 2 Thermal zone dimension and average thermal resistance of the walls

	Total envelop area (m^2)	Total zone interface area (m^2)	Average thermal resistance (R) inner ($\text{m}^2 \text{ K/W}$)	Average thermal resistance (R) outer ($\text{m}^2 \text{ K/W}$)
1				
Core zone	12	54	1.5	2.5
Perimeter zone	364	54	1.5	2.5
2				
Core zone	30	72	1.5	2.5
Perimeter zone	376	72	1.5	2.5

Fig. 5 MEG schematic diagram

The graphical presentation of the developed ESN is shown in Fig. 6 where classes of building and energy sources are organized in ten layers with nine connection matrices. The HENSU (Hybrid Energy Supply Unit) composed of energy conversion technologies to satisfy the required type of energy demand.

The connection matrices of ESN layers are shown in Table 3. The connection matrices is a direct mapping of ESN schematic shown in Fig. 6. Connection cells with value of 1 is replaced by the parameter variable (p_j^i) for those classes with design parameters at any layer that are connected to previous layer classes. The parameter p_1^4 at layer four represent the penetration of DC power demand as a percentage of the total power demand. This parameter characterizes the replacement of AC loads percentage to DC (such as lighting). Hence, a scenario at which reduction of energy conversion losses from DC (output of PV panel) to AC will be investigated. In addition, the potential of reducing capital cost due to reducing the DC/AC inverter size will be examined. At the same layer, thermal zones are connected to heat demand and both connection cells have the same parameter (p_3^4) which is an application of point (2) of ESN algorithm stated in “Building Energy Semantic Network Structure” section. p_3^4 is a parameter representing the variation of aggregate heat demand of the house due to variation of thermal zone configuration. The parameter can be moved upward one layer and split to

two parameters associated with each thermal zone. However, because the thermal simulation conducted outside ESN algorithm using EnergyPlus, the parameter was considered to select between two different heat demand profiles achieved by EnergyPlus simulation of the two thermal zone scenarios. Moreover, thermal zone configuration affect economic and environmental KPI through heat demand reduction only. For other energy conservation measure, such as changing insulation materials, the economic KPI is affected by both heat demand reduction and materials’ prices. Hence the parameters should be placed on the proper layer with proper definition.

The DC/AC inverter and AC/DC converter sizes as a percentage of PV size and WT size and are presented by p_1^5 and p_2^5 respectively. The parameters p_7^5 and p_8^5 represent PV and WT area respectively (hence, their size is identified as a design parameter). The electrical heater size is a percentage of total power demand while the micro-CHP gas generator and the furnace size is in kW.

The selection vectors of ESN layers is shown in Table 4. It can be noted that residential class was selected at layer one and house class was selected at layer two. The rest selection vectors indicates the selection of all house sub-classes and energy sources’ classes. Some of energy classes are not identified in this ESN [energy storage classes (batteries and thermal storage)] to introduce simple and clear implemen-

Fig. 6 Building energy semantic net (BESN) Structure

tation of proposed ESN algorithm. The connection matrices should present all energy technologies and buildings classes. The designer should use the selection vectors to implement the energy concept of the building under investigation. For example, if the concept is not to include WT as an energy source then s_8^5 will be reset to zero.

Table 5 shows the design parameters of the selected case study with their value ranges. It should be noted that the connection matrices together with the classes' parameters

and their associated values shown in Table 5 represent the knowledgebase of developed ESN.

According to Eq. 13 and Table 5, the number of created scenarios are 8192 before applying restriction rules. Three restriction rules were applied to generated scenarios at different layers. The 1st restriction was applied to total area of renewables (PV and WT) not to exceed 300 m^2 (50 % of building facility area). According to Eq. 14, the restriction was applied as follow:

Table 3 Connection matrices of ESN layers for the selected case study

C^1		C^2				C^3				
Building		Residential		Commercial	Industrial	House	Apartment	Hospital	Hotel	Shopping mall
Residential	1	House	1	0	0	Core zone	1	0	0	0
Commercial	1	Apartment	1	0	0	Perimeter zone	1	0	0	0
Industrial	1	Hospital	0	1	0	Power require-ments	1	1	1	1
Hotel	1	Hotel	0	1	0	Gas Require-ments	1	1	1	1
Shopping mall	1	Shopping mall	0	1	0	Roof	1	1	1	1
Factory	1	Factory	0	0	1	Backyard	1	1	1	1
Power plant	1	Power plant	0	0	1					
Mining site	1	Mining site	0	0	1					

C^4		C^5			
Core Zone	Perimeter Zone	Power Requirements		Backyard	
		DC Demand	AC Demand	Heat Demand	Gas Demand
DC demand	0	p_1^4	0	0	0
AC Demand	0	1	0	0	0
Heat demand	p_3^4	0	0	0	0
Gas demand	0	0	1	0	0
Facility area	0	0	0	1	0
				Heat supply	0
				PV area	0
				WT area	0

C^6		C^7			
DC/AC	1	DC supply		WT area	
		DC supply	AC supply	PV area	WT area
DC/AC	1	0	1	0	0
AC/DC	0	1	0	0	0
DC Supply	0	1	0	0	0
AC Supply	0	0	1	0	0
Gas supply	0	0	0	1	0

C^7		C^8			
DC/AC	1	DC supply		WT area	
		DC supply	AC supply	PV area	WT area
DC/AC	1	0	1	0	0
AC/DC	0	1	0	0	0
DC Supply	0	1	0	0	0
AC Supply	0	0	1	0	0
Gas supply	0	0	0	1	0

Table 3 continued

	C^6									C^7								
	DC/AC					AC/DC				DC/AC					AC/DC			
	DC supply	AC supply	Gas supply	Heat supply	WT area	DC supply	AC supply	Gas supply	Heat supply	PV area	WT area	DC supply	AC supply	Gas supply	Heat supply	PV area	WT area	
Heat supply	0	0	0	0	0	0	0	0	1	0	0							
Elec. heater	0	0	0	0	0	0	0	0	p_7^6	0	0							
PV Area	0	0	0	0	0	0	0	0	0	1	0							
WT Area	0	0	0	0	0	0	0	0	0	0	1							
C^8																		
PV	WT		Gas Gen		Furnace		Gas		C^9									
									Solar	Wind	Gas							
Solar	1	0	0	0	0	0	0	0	Sources		1	1	1					
Wind	0	1	0	0	0	0	0	0										
Gas	0	0	1	1	1	1	1	1										

Table 6 Sample of generated scenarios

Scenario index	1	2	3	4	5	371	372	373	374	375	988	989	990	991	992
Heat demand (Core/perimeter) Scenario	I	II	I	II	I	I	II	I	II	I	II	I	II	I	II
DC Demand (size %)	10	10	30	30	10	30	30	10	10	30	30	10	10	30	30
DC/AC (size %)	70	70	70	70	95	70	70	95	95	95	70	95	95	95	95
AC/DC (size %)	10	10	10	10	10	10	10	10	10	10	30	30	30	30	30
PV area (m ²)	300	300	300	300	300	300	300	300	300	300	100	100	100	100	100
WT area (m ²)	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100
Elec. heater (size %)	10	10	10	10	10	30	30	30	30	30	30	30	30	30	30
Gas gen size (KW)	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2
Furnace size (KW)	0	0	0	0	0	2	2	2	2	2	30	30	30	30	30

where $P_l(h)$ is the required load power profile. Total energy loss indicator KPI can be calculated by:

$$E_{Loss} = \sum_{h=1}^{8760} \left(\sum_{i=1}^n \delta E_i(k) \right) \quad (14)$$

Environmental KPI

The CO₂ emission is the most important environmental KPI. The annual CO₂ emission can be calculated by the following equation:

$$E_{CO_2} = \sum_{h=1}^{8760} \sum_{i=1}^n K_{CO_2}(i) \times P_g(i, h) \quad (15)$$

where $K_{CO_2}(i)$ is the emission equivalent kg CO₂/kW for i th generator.

Energy strategy that was adopted during KPIs evaluation is shown in Fig. 7 and is described as follow:

- (1) Generated energy from WT is used to satisfy AC loads while generated energy from PV is used to satisfy DC loads.
- (2) Excessive AC power converted to DC, if required, and excessive DC power converted to AC, if required, to satisfy remaining DC and AC load respectively with maximum limit identified by the size of both DC/AC inverter and AC/DC converter.
- (3) Any residual energy from WT and DC/AC converter is applied to electrical heater to satisfy heat demand.
- (4) Micro-CHP gas generator is used to supply any AC power deficiency. The generated heat is used to satisfy the remaining heat demand.
- (5) Any deficiency in heat demand is satisfied using the gas furnace.

Results and Analysis

The simulation was conducted based on load power, irradiance and wind profiles measured in Toronto area [17] as shown in Fig. 8. The heat profile is was generated for two scenarios of the thermal zones using EnergyPlus as discussed in “Case Study” section.

Figure 9 shows the KPIs values for the 992 scenarios. The scenarios of low indices represent the cases with minimum resources (low power rating for the micro-CHP gas generator, PV, the wind turbine, DC converters and AC inverters). As the scenario index increases the size of energy resources increases. Figure 9a shows the energy deficiency of DC, AC and heat. It can be noted that head deficiency decreases with the increase of heat generators size (CHP, electrical heater and furnace). The AC energy deficiency decreases significantly with increase of size of DC/AC inverter in addition to WT and micro-CHP gas generator. The DC energy deficiency decreases with the increase of PV and AC/DC converter. The total energy deficiency is shown in Fig. 9b. It can be noted that energy deficiency decreases with the overall increase of the energy resources size. Figure 9c shows the capital and operational cost. It can be noted that there is a general steady trend of capital cost while running cost general trend is increasing. This is because the CHP and furnace size increase in later scenarios and hence, more gas is consumed. The emission is shown in Fig. 9d and energy loss is shown in Fig. 9e. The emission and energy loss are following the same trend indicating that the sources of energy loss are the CHP and furnace.

To have complete evaluation of the scenarios, a summation of normalized KPIs is used as a cost function (CF) and is given by:

$$CF = \mu_1 \frac{C_{ann_cap}}{\max(C_{ann_cap})} + \mu_2 \frac{C_{ann_op}}{\max(C_{ann_op})} + \mu_3 \frac{E_{CO_2}}{\max(E_{CO_2})} + \mu_4 \frac{E_d}{\max(E_d)} + \mu_5 \frac{E_{Loss}}{\max(E_{Loss})} \quad (16)$$

Fig. 7 Energy strategy

Fig. 8 Power profiles **a** demand, **b** irradiance and **c** wind speed

where μ_1 to μ_5 are weighting coefficients to describe the significance of each term to CF. All weighting factors were set to 1. Figure 9f shows the cost function versus scenarios. The best scenarios were scenario 385, 705 and 945. The scenario lists are shown in Table 7.

It should be noted that the selection of CF is to demonstrate a possible method of scenario evaluation. However, a better evaluation of the scenarios would give terms of CF equation different significance by selecting different weighting coefficients.

Conclusion

The design of ESN for building energy management has been introduced. The structure of the design is based on hybrid semantic network. The proposed structure allows semantically connections between building energy classes, energy resources and conversion classes. The matrix structure is used to present the connection between different layers of the semantic network. It allows systematic manipulation, easy modification, addition and removal of any class. This leads

Fig. 9 KPIs of the case study for generated scenarios

Table 7 Scenarios of the minimum CF values

Scenario index	Heat demand (core/perimeter) Scenario	DC demand (size %)	DC/AC (size %)	AC/DC (size %)	PV area (m ²)	WT area (m ²)	Elec. heater (size %)	Gas gen size (KW)	Furnace size (KW)
385	I	10	70	10	100	100	30	0	2
705	I	10	70	10	100	100	30	0	8
945	I	10	70	10	100	100	30	0	30

to fixable structure that allow the energy expertise to supply their knowledge to the developed ESN. The mechanism of energy design scenarios generation has been discussed with a strategy to distribute design parameters to different layers instead of allowing them in one layer. To verify the developed ESN, a simplified mid-size house located in Toronto area, Canada has been selected as a case study. Different energy sources, load connections, thermal zones and energy conversion scenarios have been applied. The ESN was used to generate all the possible scenarios. The hierarchical layers of ESN allow simple implementation of restriction rules to allow only feasible scenarios and reduce the total generated

fuzzy membership values. As a future work, fuzzy sets will be implemented to have gradual transition from one set to another which will have better presentation of fuzzy knowledge of expertise.

Appendix A: Mathematical Process of Case Study

Illustration 1

How to present independent parameters of one class and how to insert new class to knowledge layer

scenarios. Hence, evaluation and optimization computational burden is reduced.

The reduced scenarios were tested using predefined KPIs. The results were introduced and analyzed. The algorithm of generating feasible scenarios allow effective evaluation and optimization of all energy components of the building. Compared with efforts that was conducted in [4–6, 11, 13, 16] to evaluate some selected scenarios, the proposed algorithm offer a wide range of energy technologies that can achieve multiple objectives.

It should be noted that a successful ESN is based on well-developed knowledgebase that requires wide range of energy technologies presented and encoded by group of expertise. The proposed methodology is a frame work that can be used effectively to form knowledgebase of ESN with clear and easy inference mechanism.

While matrix structure of ESN allow inference using classical sets with sharp boundary of classes, fuzzy sets can be implemented easily by replacing binary activation layer by

Illustration 1-a, original layer with class 2 in second layer that have two dependent parameters (see matrix presentation). Illustration 1-b, repeating class 2 (marked as CC_2^2) in second layer to separate parameter $P_{2,1}^2$ and $P_{2,2}^2$ during scenario generation see matrix presentation. Illustration 1-c, other alternative solution to illustration 1-b. The illustration demonstrates the insertion of new class to a knowledge layer or insertion of new knowledge layer.

Illustration 2

Mathematical Process of Case Study

$$C^0 = [1], G^0 = [1]$$

$$G^1 = \text{sign} \left(\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} (\text{diag}([1])) [1] \right) = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

$$SC(0) = 1, N(0) = 0$$

$$\begin{aligned}
 G^2 &= \text{sign} \left(\begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{bmatrix} \text{diag} \left(\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \right) \begin{bmatrix} 1 \\ 0 \end{bmatrix} \right) \\
 &= \text{sign} \left(\begin{bmatrix} 1 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \right) = \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \\
 \text{SC}(0) &= 1, N(0) = 0
 \end{aligned}$$

$$\begin{aligned}
 G^3 &= \text{sign} \left(\begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \text{diag} \left(\begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \right) \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \right) \\
 &= \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}
 \end{aligned}$$

$$\begin{aligned}
 G^3 &= \text{sign} \left(\begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \right) \\
 &= \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}
 \end{aligned}$$

$$\text{SC}(0) = 1, N(0) = 0$$

$$G^4 = \text{sign} \left(\begin{bmatrix} 0 & 0 & p_1^4 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ p_3^4 & p_3^4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \text{diag} \left(\begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \right) \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \right)$$

$$\begin{aligned}
 G^4 &= \text{sign} \left(\begin{bmatrix} 0 & 0 & p_1^4 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ p_3^4 & p_3^4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \right) \\
 &= \text{sign} \left(\begin{bmatrix} p_1^4 \\ 1 \\ p_3^4 \vee p_3^4 \\ 1 \\ 1 \vee 1 \end{bmatrix} \right)
 \end{aligned}$$

$$G^4 = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}, p_1^4 = \{10, 30\}, N_1^4 = 2$$

$$\because g_1^4 \wedge s_1^4 = 1$$

$$\therefore SC(1) = \begin{bmatrix} 1 \\ 1 \end{bmatrix}_{1 \times 2} \wedge \begin{bmatrix} p_1^4 = 10 \\ p_1^4 = 30 \end{bmatrix}_{1 \times 2}$$

$$= \begin{bmatrix} p_1^4 = 10 \\ p_1^4 = 30 \end{bmatrix}_{1 \times 2}, N(1) = 1 \times 2 = 2$$

$$p_3^4 = \{I, II\}, N_3^4 = 2$$

$$\because g_3^4 \wedge s_3^4 = 1$$

$$\begin{aligned}
 \therefore SC(2) &= \begin{bmatrix} p_1^4 = 10 \\ p_1^4 = 30 \\ p_1^4 = 10 \\ p_1^4 = 30 \end{bmatrix}_{1 \times 2} \wedge \begin{bmatrix} p_3^4 = I \\ p_3^4 = I \\ p_3^4 = II \\ p_3^4 = II \end{bmatrix}_{1 \times 2} \\
 &= \begin{bmatrix} (p_1^4 = 10) \wedge (p_3^4 = I) \\ (p_1^4 = 30) \wedge (p_3^4 = I) \\ (p_1^4 = 10) \wedge (p_3^4 = II) \\ (p_1^4 = 30) \wedge (p_3^4 = II) \end{bmatrix}, \\
 N(2) &= 2 \times 2 = 4
 \end{aligned}$$

$$G^5 = \text{sign} \left(\begin{bmatrix} p_1^5 & 0 & 0 & 0 & 0 \\ 0 & p_2^5 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & p_7^5 \\ 0 & 0 & 0 & 0 & p_8^5 \end{bmatrix} \text{diag} \left(\begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \right) \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \right)$$

$$G^5 = \text{sign} \left(\begin{bmatrix} p_1^5 & 0 & 0 & 0 & 0 \\ 0 & p_2^5 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & p_7^5 \\ 0 & 0 & 0 & 0 & p_8^5 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \right)$$

$$= \text{sign} \left(\begin{bmatrix} p_1^5 \\ p_2^5 \\ 1 \\ 1 \\ 1 \\ 1 \\ p_7^5 \\ p_8^5 \end{bmatrix} \right) = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix}$$

$$p_1^5 = \{70, 50\}, N_1^5 = 2$$

$$\therefore g_1^5 \wedge s_1^5 = 1$$

$$\therefore SC(3) = \left[\begin{array}{c} \left[\begin{array}{c} (p_1^4 = 10) \wedge (p_3^4 = I) \\ (p_1^4 = 30) \wedge (p_3^4 = I) \\ (p_1^4 = 10) \wedge (p_3^4 = II) \\ (p_1^4 = 30) \wedge (p_3^4 = II) \end{array} \right]_{1 \times 4} \\ \left[\begin{array}{c} (p_1^4 = 10) \wedge (p_3^4 = I) \\ (p_1^4 = 30) \wedge (p_3^4 = I) \\ (p_1^4 = 10) \wedge (p_3^4 = II) \\ (p_1^4 = 30) \wedge (p_3^4 = II) \end{array} \right]_{1 \times 4} \end{array} \right]_{1 \times 2} \wedge \left[\begin{array}{c} \left[\begin{array}{c} p_1^5 = 70 \\ p_1^5 = 70 \\ p_1^5 = 70 \\ p_1^5 = 70 \end{array} \right]_{1 \times 4} \\ \left[\begin{array}{c} p_1^5 = 95 \\ p_1^5 = 95 \\ p_1^5 = 95 \\ p_1^5 = 95 \end{array} \right]_{1 \times 4} \end{array} \right]_{1 \times 4}$$

$$= \left[\begin{array}{c} (p_1^4 = 10) \wedge (p_3^4 = I) \wedge (p_1^5 = 70) \\ (p_1^4 = 30) \wedge (p_3^4 = I) \wedge (p_1^5 = 70) \\ (p_1^4 = 10) \wedge (p_3^4 = II) \wedge (p_1^5 = 70) \\ (p_1^4 = 30) \wedge (p_3^4 = II) \wedge (p_1^5 = 70) \\ (p_1^4 = 10) \wedge (p_3^4 = I) \wedge (p_1^5 = 95) \\ (p_1^4 = 30) \wedge (p_3^4 = I) \wedge (p_1^5 = 95) \\ (p_1^4 = 10) \wedge (p_3^4 = II) \wedge (p_1^5 = 95) \\ (p_1^4 = 30) \wedge (p_3^4 = II) \wedge (p_1^5 = 95) \end{array} \right]_{1 \times 8}, N(3) = 4 \times 2 = 8$$

And the process continue to the last layer.

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